EE421/521
Image Processing

Lecture 4
HUMAN VISUAL SYSTEM
COLOR THEORY

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Color Perception

- Color perception is a psychophysical phenomenon that combines two main components:
  1. The *physical* properties of light sources (usually expressed by their spectral power distribution, SPD) and surfaces (e.g., their absorption and reflectance capabilities).
  2. The *physiological* and *psychological* aspects of the human visual system (HVS).

Human Eye

Human Visual System

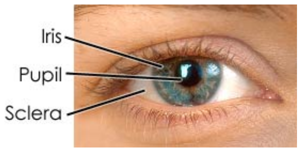
Used to determine the shape & color of objects & their movement.

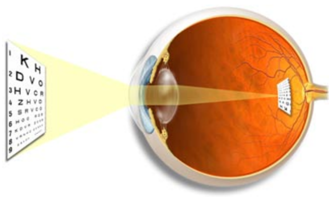
Eye:
Functions like a camera to focus light on the retina using a lens and an aperture (pupil) whose size can be adjusted to change the amount of entering light.

Vision:
Process by which light reflected from external objects are translated into a mental image. This process consists of 3 steps:

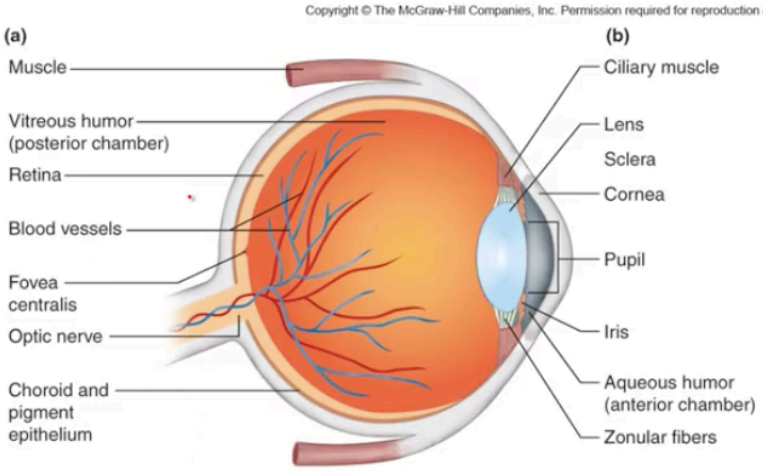
1. light enters the eye and is focused by a lens on to the retina.
2. retinal photoreceptors transduce light energy into electrical signal.
3. processing of the electrical signals through neural pathways.

Human Vision





Human Eye



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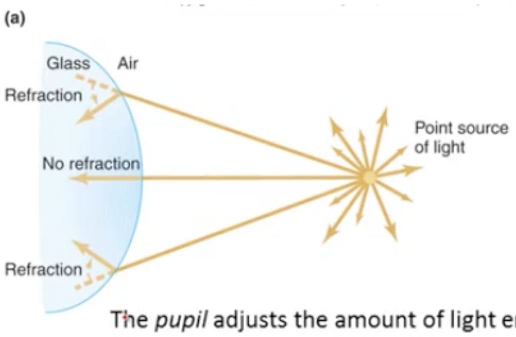
Refraction of Light



The *pupil* adjusts the amount of light entering.
Changes in the shape of the *lens* focus the light onto the retina.
The *retina* contains the photoreceptors, *rods* & *cones*.

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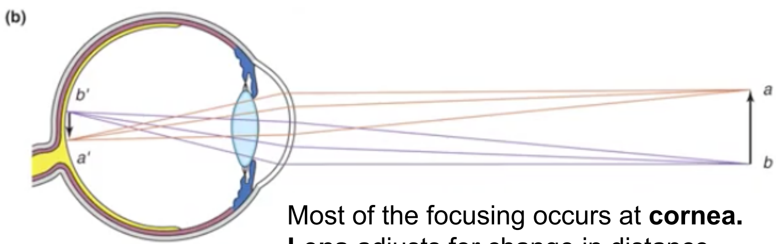
Focusing of Light



Most of the focusing occurs at **cornea.**
Lens adjusts for change in distance.

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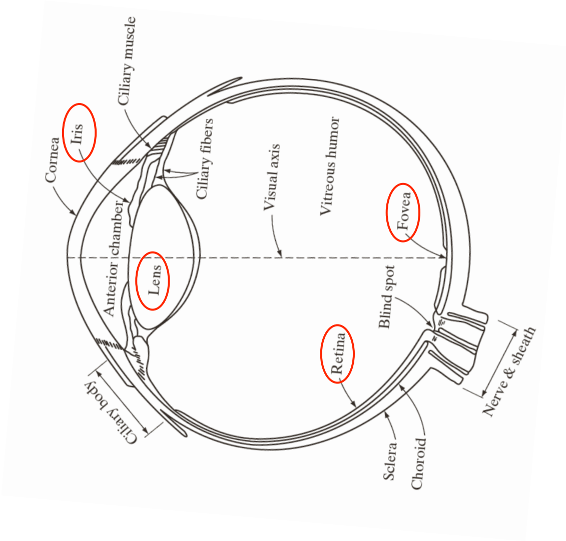
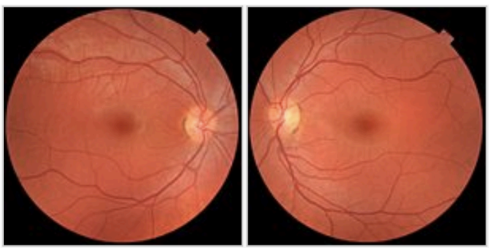
Fovea & Blind Spot



The Macula

- Absorbs excess blue and ultraviolet light
- Has a diameter of around 6 mm
- Contains the fovea at its center



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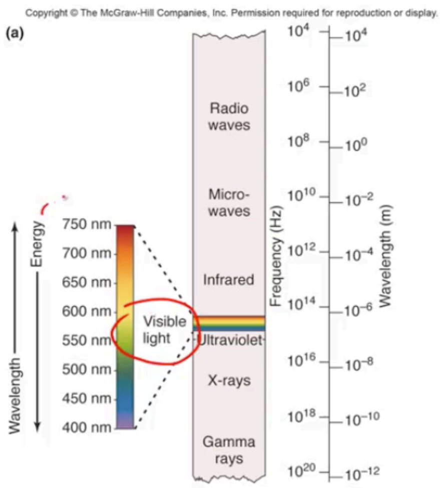
Central (Fovea) Vision

We think we see like this:

But really we see like this:

Images by Stuart Anstis

Light Spectrum



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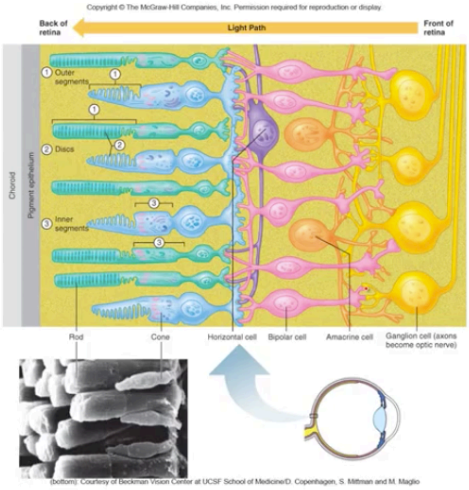
Rods and Cones: Photoreceptors

- Light images are converted into electro-chemical signals inside the photoreceptors called rods and cones.



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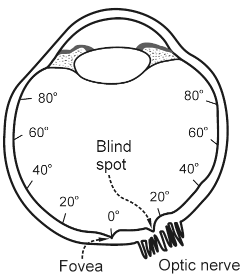
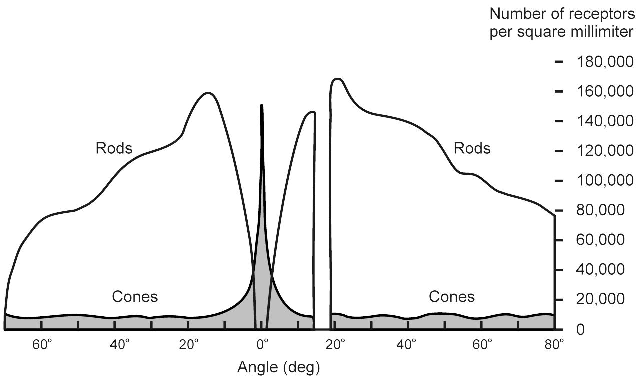
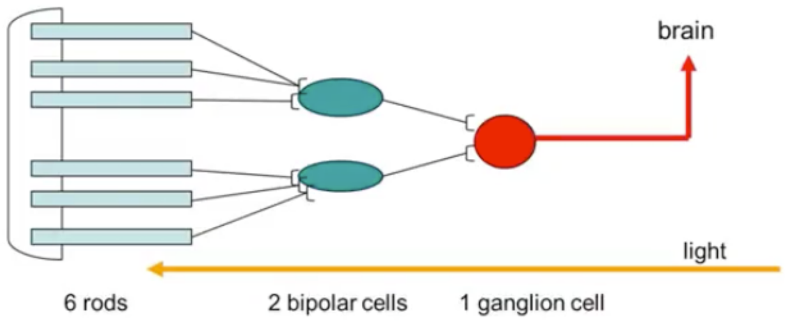
Distribution of Rods & Cones





Trunsduction of Visual Signals



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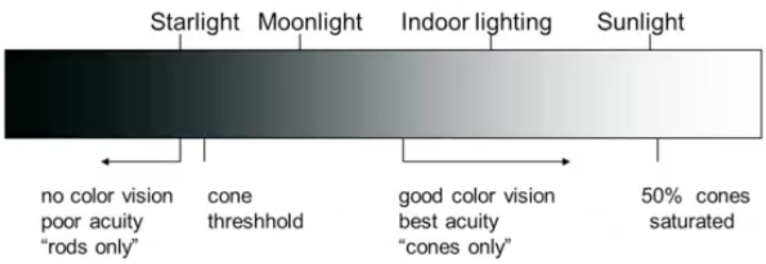
Rod and Cone Vision



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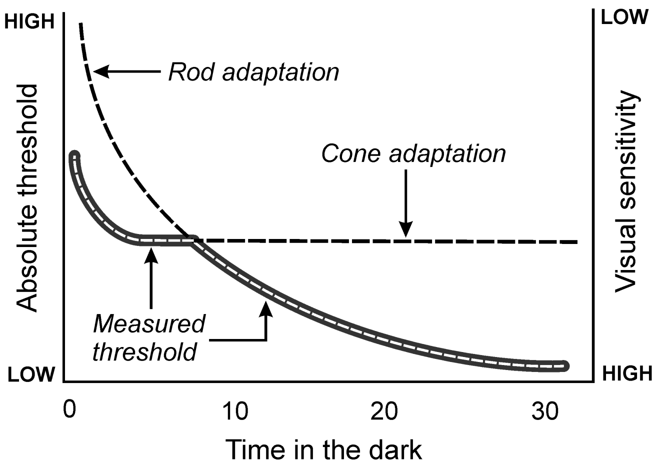
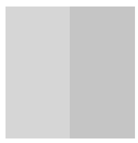
Change in Visual Threshold during Dark Adaptation

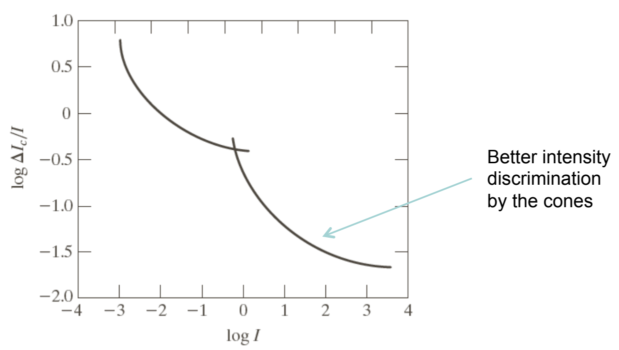


Brightness Discrimination of the Eye



I : Light intensity

ΔI_c : Noticeable difference in light intensity



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Brightness Adaptation and Dynamic Range of the Eye

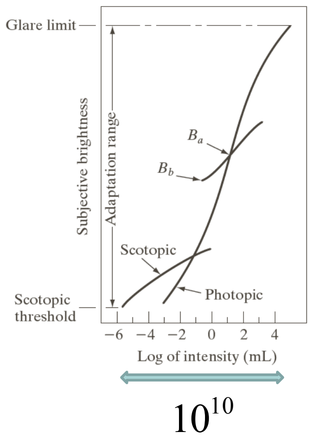

FIGURE 2.4 Range of subjective brightness sensations showing a particular adaptation level.

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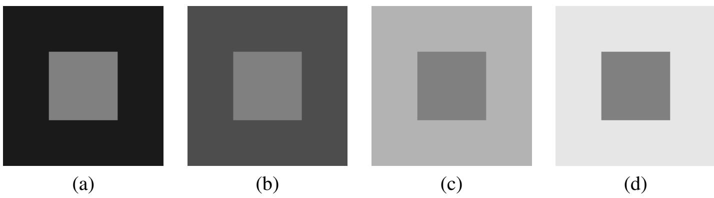
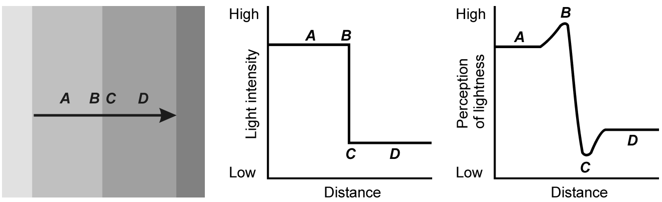
Brightness Adaptation



Mach Bands

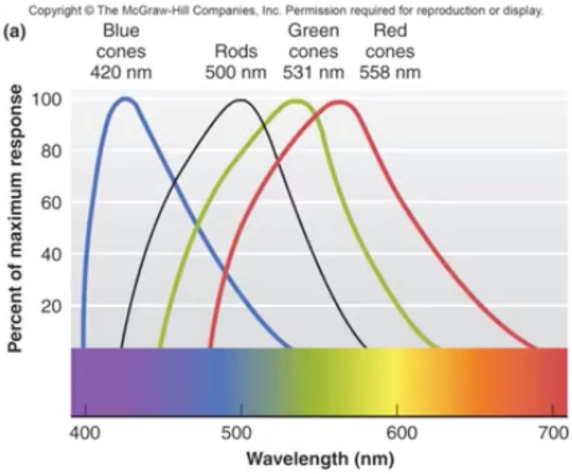
- Our visual system tends to overshoot and undershoot at the boundaries of regions with different intensities.
- Explains the ability to seperate objects even in dim light.



(a) (b) (c)

Color Vision

Color Vision



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Blue Cone Distinctions

Blue is less-focused

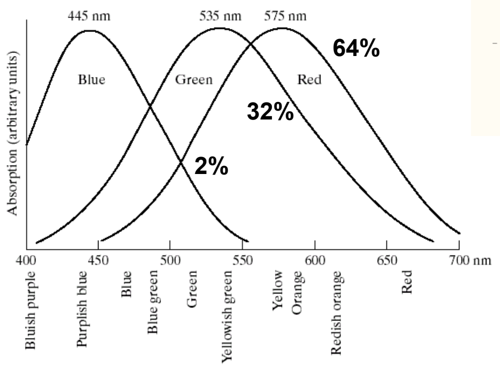
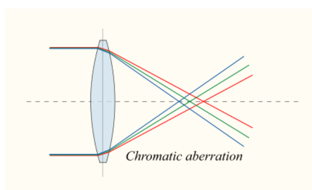
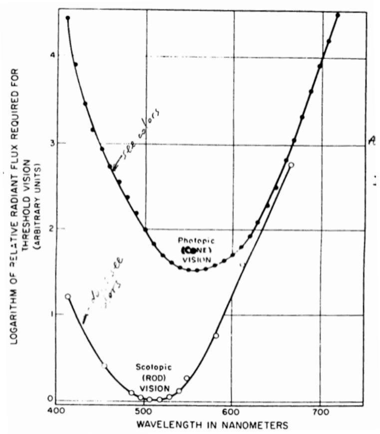


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.



Vision Threshold vs. Wavelength



Eye Fatigue

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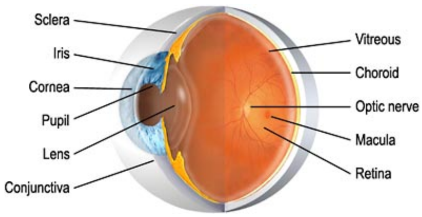
Summary

- Lens focuses the image.
- Movements of the lens are controlled by the specialized ciliary muscles.
- Iris diaphragm controls the amount of light that enters the eye.
- Central opening of the eye is called the pupil, diameter varies between 2mm to 8mm, inversely proportional with the incoming light.
- Innermost membrane is called the retina, which is coated with prosensitive receptors.

Human Eye vs. Camera



Camera components	Eye components
Lens	Lens, cornea
Shutter	Iris, pupil
Film	Retina
Cable to transfer images	Optic nerve to send the incident light information to the brain

Spatial Resolution of the Human Eye

- Photopic (bright-light) vision: Approximately 7 million cones
- Scotopic (dim-light) vision: Approximately 75-150 million rods
- (HDTV: 1920x1080 = 2 million pixels)

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Color Mixing

Three Types of Cones and their Frequency Response

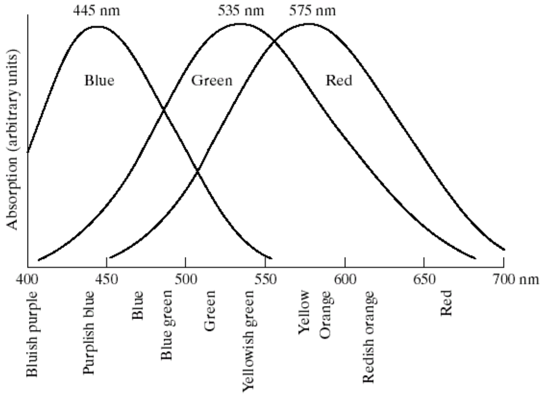
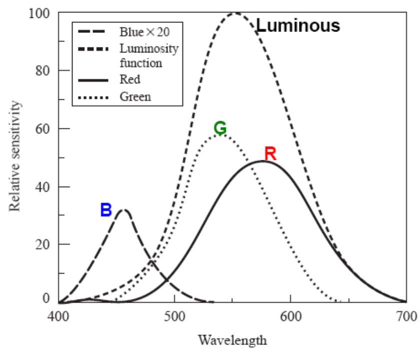


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Frequency Responses of Cones, Luminous Efficiency Function

- Same amount of energy produces different sensations of brightness at different wavelengths
- Green wavelength contributes most to the perceived brightness.



$$a_Y(\lambda) = a_R(\lambda) + a_G(\lambda) + a_B(\lambda)$$

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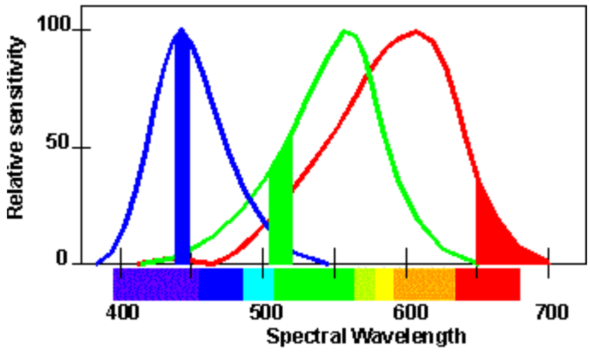
Luminance & Chrominance

- Luminance (brightness) refers to **achromatic intensity**
- Chrominance (chromaticity) refers to **hue** and **saturation**
  - Hue: color tone (depends on the peak wavelength of the light)
  - Saturation: color purity (depends on the spread of bandwidth of the light)
    - Hence, addition of white decreases saturation

Color Mixing



incoming light distribution

$$C_i = \int C(\lambda) a_i(\lambda) d\lambda, \quad i = r, g, b, y$$

Frequency responses, relative absorbency functions of cones

Trichromatic Theory of Color

- Any color can be obtained by mixing three primary colors with the right proportion

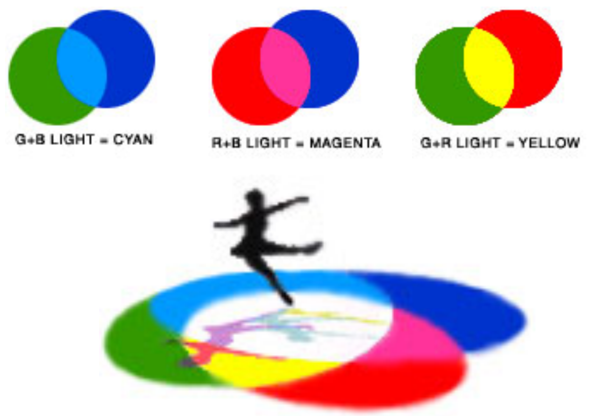
$$C = \sum_{k=1,2,3} T_k C_k, \quad T_k : \text{Tristimulus values}$$

- Primary colors for illuminating sources: Red, Green, Blue (RGB)
- Primary colors for reflecting sources (also known as secondary colors): Cyan, Magenta, Yellow (CMY)

Light Sources

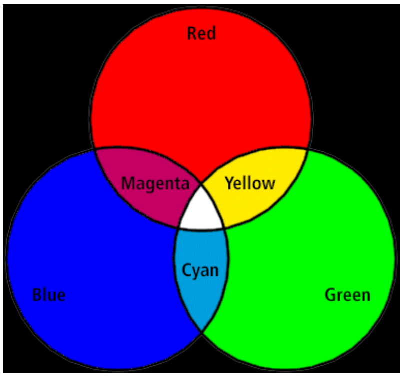
- Illuminating sources:
  - Emit light (e.g., the sun, light bulb, TV monitors)
  - Perceived color depends on the emitted frequency
  - Follows **additive** rule
    - R + G + B = white
- Reflecting sources:
  - Reflect an incoming light (e.g., the color dye, matte surface, cloth)
  - Perceived color depends on reflected frequency (= incident frequency – absorbed frequency)
  - Follows **subtractive** rule
    - C = W – R
    - R + G + B = black

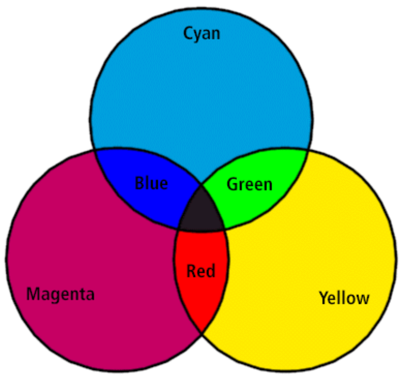
Additive Color System



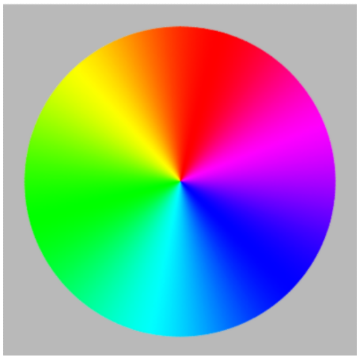
Subtractive Color System

RGB vs. CMY





Color Wheel & Complementary Colors

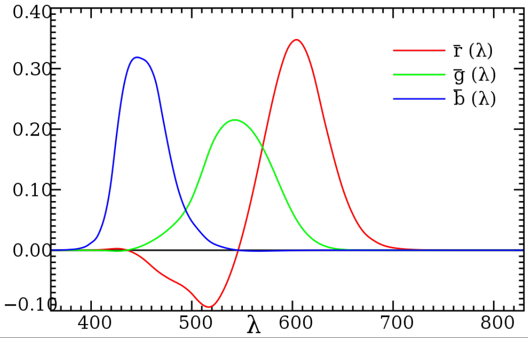


Tristimulus Values

- The tristimulus values of a color are the amounts of three primary colors in a three-component additive color model needed to match a test color.
- The tristimulus values denoted X, Y, and Z form the CIE XYZ color space.

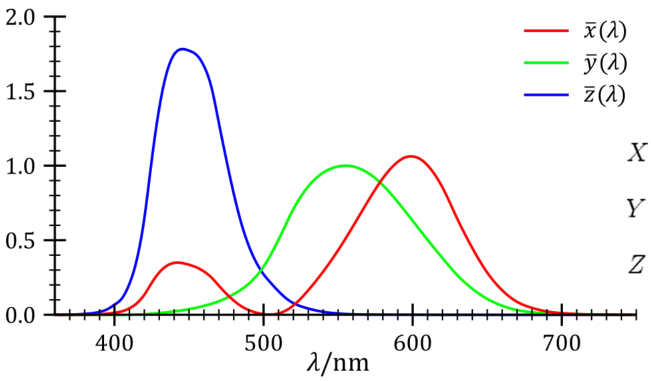
RGB Color Matching

- Subjects were asked to adjust the amount of red, green and blue on one patch that were needed to match a color on the second patch.
- Negative values mean adding the color to the given patch.
- The amounts of additive primary colors on the first patch needed to match a test color on the second patch are called tristimulus values.



XYZ Color Matching Function (CIE 1931)

- To remove the inconvenience of having to deal with negative values, CIE defined a new set of curves based on a new set of tristimulus values: X, Y and Z.



$$X = \int_0^\infty I(\lambda)\,\bar{x}(\lambda)\,d\lambda$$
$$Y = \int_0^\infty I(\lambda)\,\bar{y}(\lambda)\,d\lambda$$
$$Z = \int_0^\infty I(\lambda)\,\bar{z}(\lambda)\,d\lambda$$

Color fundamentals

- The CIE XYZ color model
- The tristimulus values of X, Y and Z are linearly related to the R, G and B values as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.431 & 0.342 & 0.178 \\ 0.222 & 0.707 & 0.071 \\ 0.020 & 0.130 & 0.939 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.063 & -1.393 & -0.476 \\ -0.969 & 1.876 & 0.042 \\ 0.068 & -0.229 & 1.069 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Color fundamentals

- The CIE XYZ color model is designed such that Y corresponds to a measure of the *brightness* of a color.
- The *chromaticity* of a color is specified by two other parameters, x and y, known as chromaticity coordinates.
- Normalized tristimulus values: x, y and z.

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

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

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

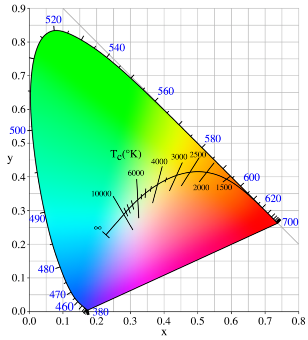
$$X = \frac{x}{y}Y$$

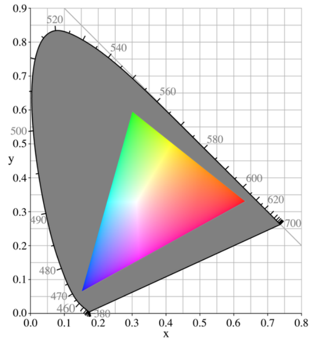
$$Z = \frac{1-x-y}{y}Y$$

$$x + y + z = 1$$

Chromaticity Gamut (CIE-XYZ Color Space) and Color Triangle

- Using the CIE XYZ to represent color gamut of different devices.
- Color Gamut: A range of colors that can be produced by a physical device.
- The greater the gamut, the better the device's color reproduction capabilities.





Color Spaces

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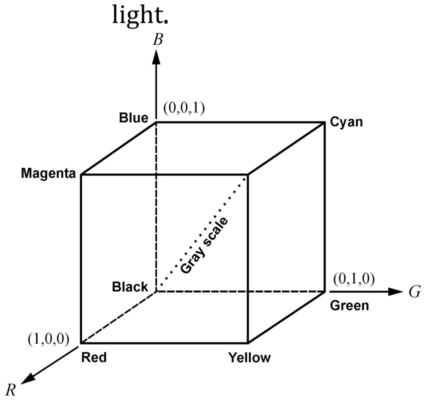
Color models

- A color model (also called color space or color system) is a specification of a coordinate system and a subspace within that system where each color is represented by a single point.
- Contemporary color models have evolved to specify colors for different purposes (e.g., photography, physical measurements of light, color mixtures, etc.).

RGB color space

- A cartesian coordinate system whose axes represent the three primary colors of light (R, G, B).
- The eight vertices correspond to the three primary colors of light.



Color name	R	G	B
Black	0	0	0
Blue	0	0	1
Green	0	1	0
Cyan	0	1	1
Red	1	0	0
Magenta	1	0	1
Yellow	1	1	0
White	1	1	1

The CMY(K) color model(s)

- The CMY model is based on the three primary colors of pigments (*C*yan, *M*agenta and *Y*ellow).
  - Used for color printers, where each primary color usually correspond to an ink (or toner) cartridge.
  - The conversion from RGB to CMY is straightforward:

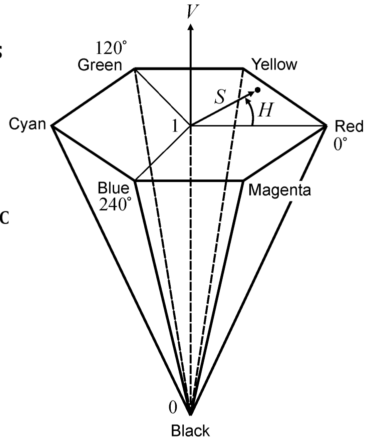
$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

HSV color space

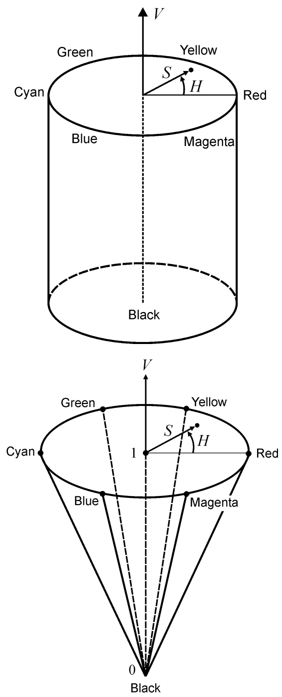
- Human perception of light is best described in terms of hue, saturation, and lightness.
  - Hue describes the color type, or tone, of the color.
  - Saturation provides a measure of purity (or how much it has been diluted in white).
  - Lightness refers to the intensity of light reflected from objects.
- For representing colors in a way closer to human perception, a family of color models have been proposed.
- These color models seperate the dimension of intensity (also called as brightness or value) from chromaticity (expressed as a combination of hue and saturation) of a color.

HSV Color Space

- HSV color model can be obtained by looking at the RGB color cube along its main diagonal (or gray axis) , which results in a hexagonal shaped color palette.
- As we move along the main axis, the hexagon gets smaller, corresponding tc decreasing values of V, from 1 (white) to 0 (black).
- Hue is specified as an angle relative to the red axis.
- Saturation is the distance to the axis: the longer the distance, the more saturated the color.

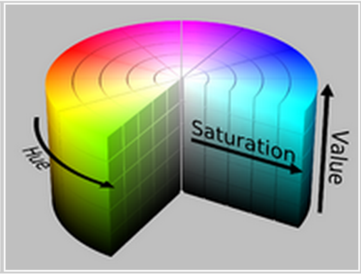


HSV color space



- An alternative representation of the HSV color model is the cylinder.
- Another represention: a cone with a circular base.
- Advantages of HSV color model:
  - Matches the human way of describing colors.
  - Allows for independent control over hue, saturation, and intensity.
  - The isolation of intensity from the other two (chromaticity components) is a requirement of many color image processing algorithms.
- Disadvantages of HSV model:
  - Discontinuity of numeric values around red.
  - Computationally expensive conversion to/from RGB.
  - Hue is undefined for saturation 0.

HSV Color Space



HSV cylinder

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YIQ (NTSC) color space

- Used in American standard for analog color TV.
- Ability to seperate grayscale contents from color data.
  - Color TV transmission needed to be backward compatible with black and white predecessors.
    - Y: luminance
    - I: orange-blue
    - Q: purple-green

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.274 & -0.322 \\ 0.211 & -0.523 & 0.312 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

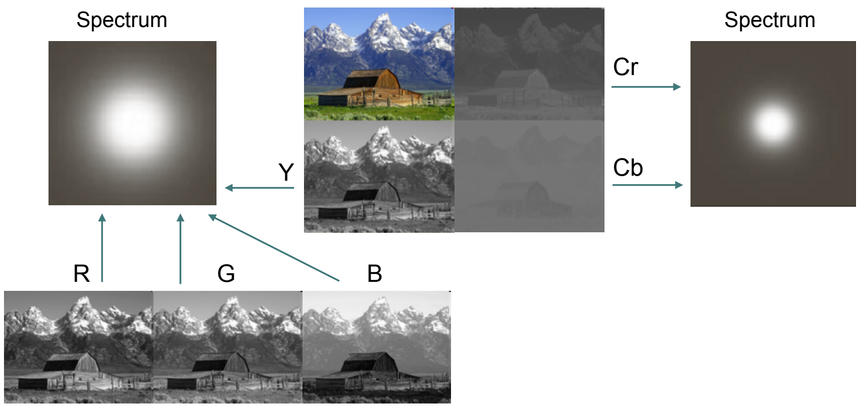
YUV Color Space

- Similar to YIQ. Most popular color representation for digital video.

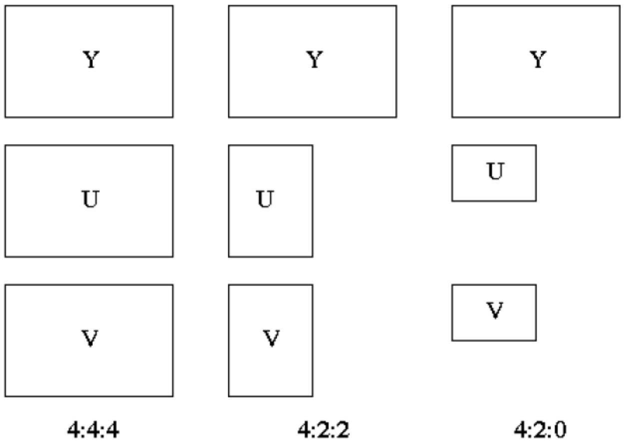
$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.14713 & -0.28886 & 0.436 \\ 0.615 & -0.51499 & -0.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.13983 \\ 1 & -0.39465 & -0.58060 \\ 1 & 2.03211 & 0 \end{bmatrix} \begin{bmatrix} Y' \\ U \\ V \end{bmatrix}$$

Smaller Bandwidth Enables More Compression



YUV Sampling Formats



Color Representation Models Summary

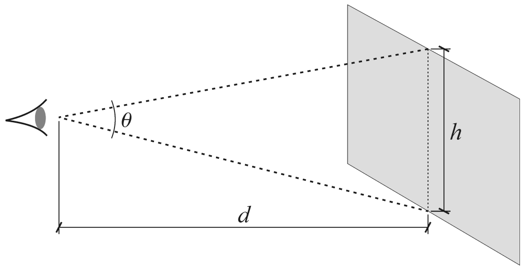
- Specify the tristimulus values associated with the three primary colors
  - RGB
  - CMY
- Specify the luminance and chrominance values
  - HSV (Hue, saturation, value)
  - YUV (used in digital color TV)

Spatial Frequency & HVS

Resolution

- The ability to seperate two adjacent pixels, that is, resolve the details in test grating.
- This ability depends on several factors such as:
  - Picture (monitor) height (h)
  - Viewer's distance from monitor (d)
  - The viewing angle (theta)

Viewing Angle



Spatial Frequency

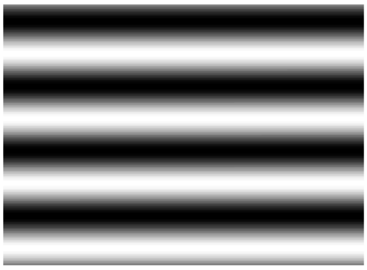
- Spatial Frequency: measure of the number of changes in image intensity for a certain test grating.
- Spatial frequency can be completely characterized by:
  - f_x : Horizontal frequency (cycles / horizontal unit distance)
  - f_y: Vertical frequency (cycles / vertical unit distance)
  - Horizontal and vertical frequency can be combined and expressed in terms of magnitude and angle:

$$f_m = \sqrt{(f_x^2 + f_y^2)}$$

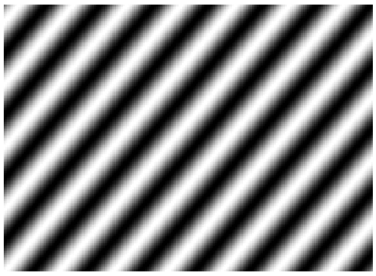
$$\theta = \arctan\left(\frac{f_y}{f_x}\right)$$

Spatial Frequency

- Sinusoidal gratings commonly used for measures of resolution

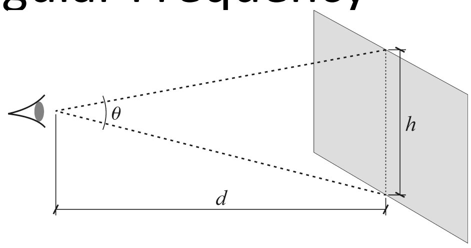


(fx, fy) = (0,4)



(fx,fy)=(7,4.5)

Angular Frequency



- The previous definition does not take into account the viewing distance.
- More useful measure is the angular frequency, expressed in cycles per degree:

$$\theta = 2\arctan\left(\frac{h}{2d}\right) \approx \frac{h}{2d}(radian) = \frac{180h}{\pi d}(\deg.)$$

$$f_\theta = \frac{f_s}{\theta} = \frac{\pi d}{180h} f_s(cpd)$$

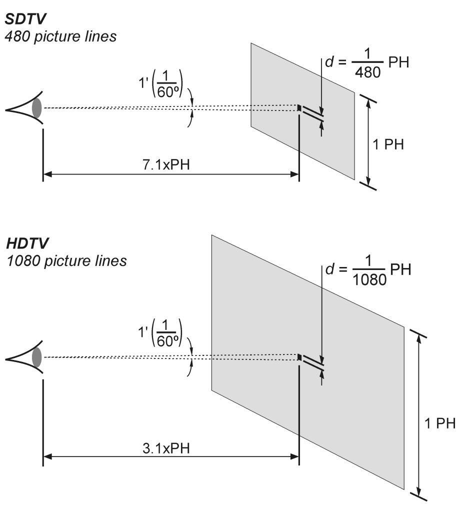
Angular Frequency

$$\theta = 2\arctan\left(\frac{h}{2d}\right) \approx \frac{h}{2d}(radian) = \frac{180h}{\pi d}(\deg.)$$

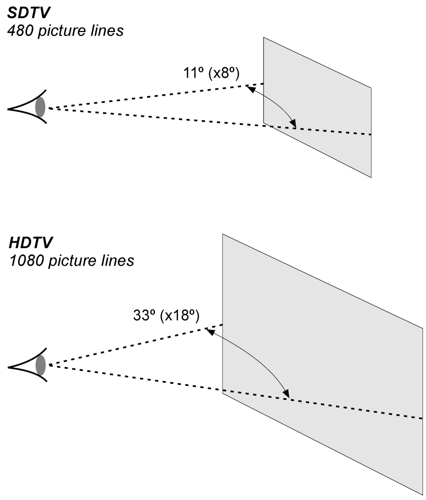
$$f_\theta = \frac{f_s}{\theta} = \frac{\pi d}{180h} f_s(cpd)$$

- For the same picture and picture height (h), angular frequency increases with distance.
- For fixed viewing distance (d), larger displays give less angular frequency.
- Optimum viewing distances for.
  - SDTV = 7.1 x PH (picture height)
  - HDTV = 3.1 x PH

Viewing Distance



Viewing Angles at Optimum Distances

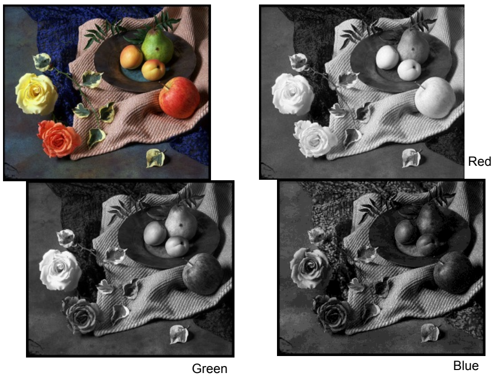


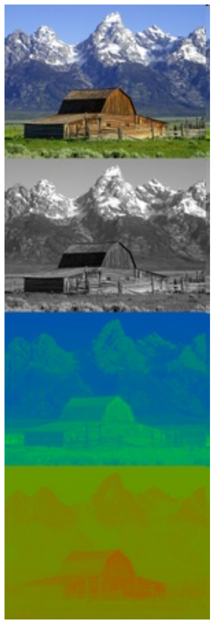
Project 1.4

YUV Color Space

Due 24.10.2013

RGB vs. YUV





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Project 1.4

1. Select an arbitrary color image.
2. Extract and display individual R, G, B bands.
3. Extract and display individual Y, U, V bands.
4. Keep Y band as is; low-pass filter each of U and V bands by a factor of 4 in both horizontal and vertical directions, then combine all three bands, and display the resulting color image.
5. Keep U band as is; low-pass filter each of Y and V bands by a factor of 4 in both horizontal and vertical directions, then combine all three bands, and display the resulting color image.
6. Keep V band as is; low-pass filter each of Y and V bands by a factor of 4 in both horizontal and vertical directions, then combine all three bands, and display the resulting color image.
7. Compare the images obtained in Steps 4, 5 and 6 and comment on any differences.

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Next Lecture

- IMAGE TRANSFORMS

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