PERCEIVING COLOR

Visual Perception

Functions of Color Vision

- Object identification
  - Evolution : Identify fruits in trees
- Perceptual organization
- Add beauty to life

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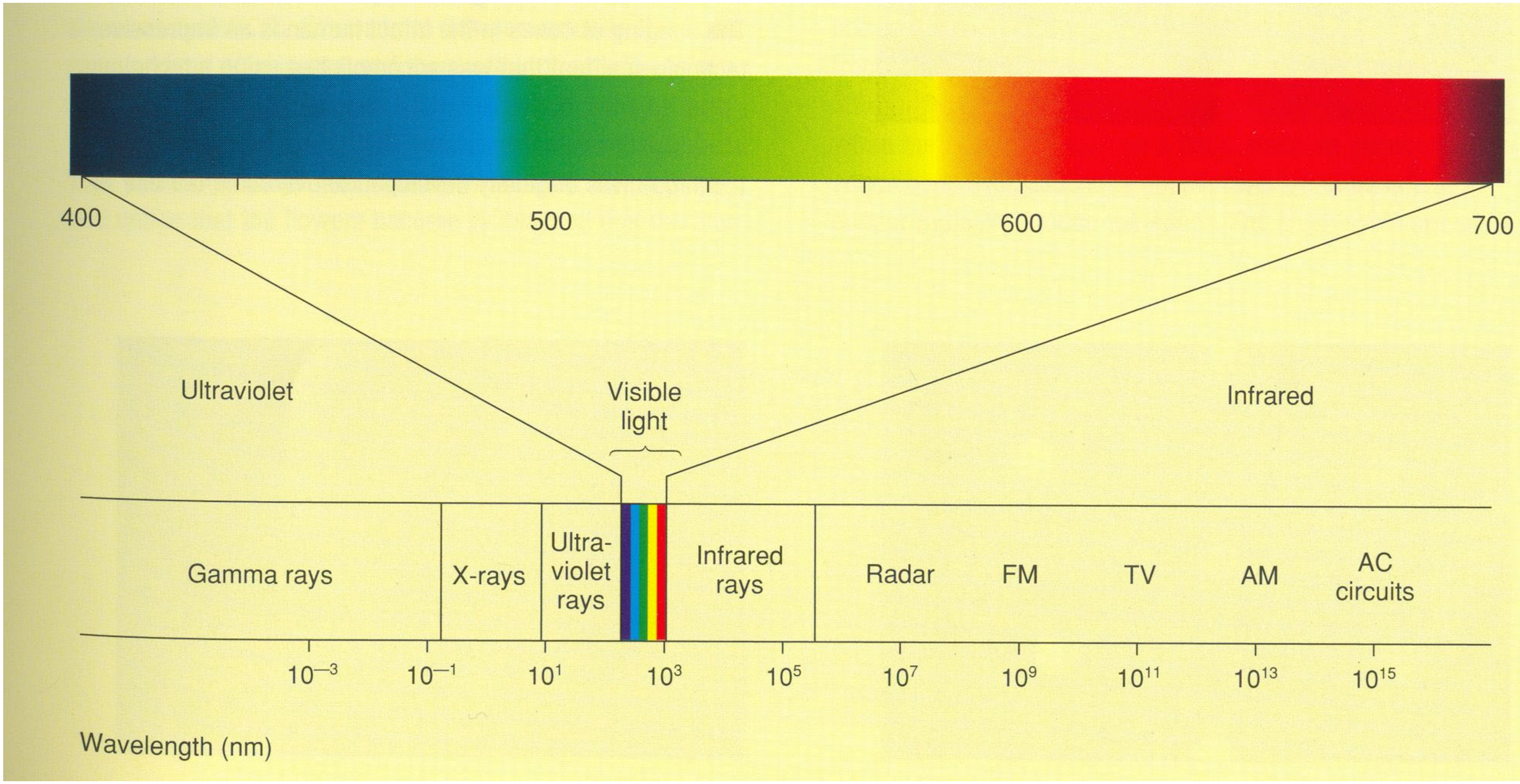
Theories of Color

- Trichromatic Theory
- Opponent Theory
- Adaptation Theory
- Higher Visual Mechanisms
- Category Based Perception

The Color Stimuli



Color is due to..

- Selective emission/reflection of different wavelengths by surfaces in the world
- Different response to different wavelengths of the eye

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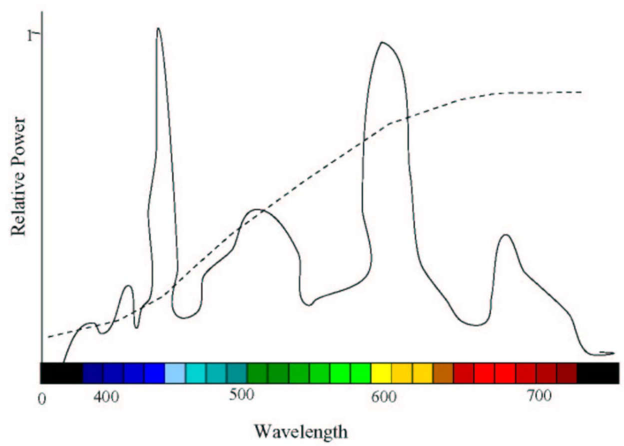
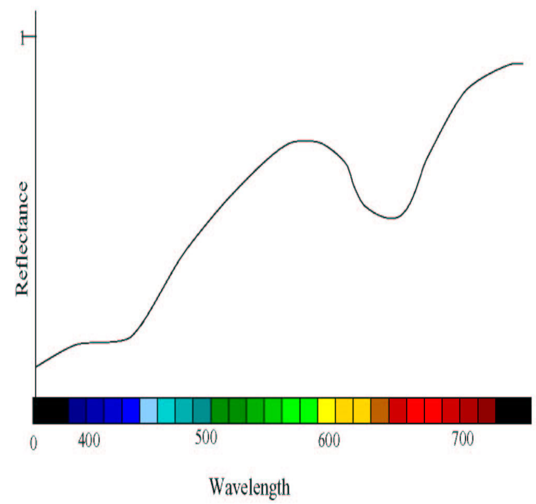
Color

- Left: illumination spectrum of a flouroscent (bold line) and tungsten lamp (dotted line) I(λ+#
- Right: reflectance spectrum of a red apple R*λ+#



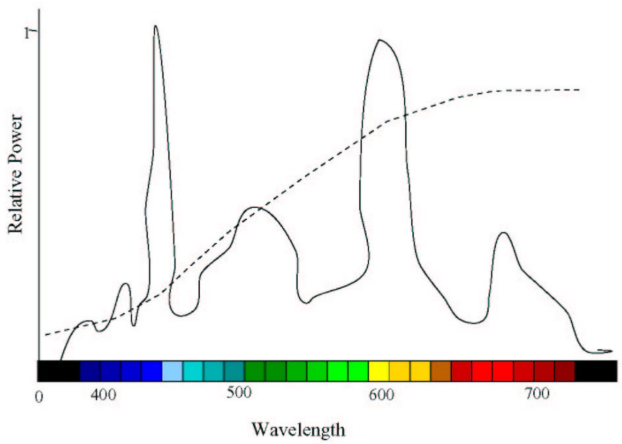
Illumination



Reflectance

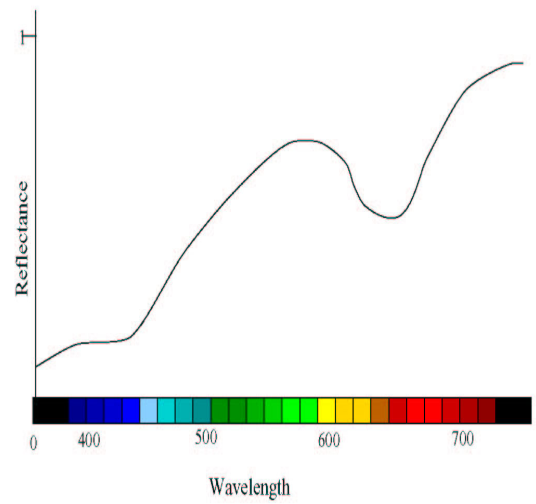
Color Stimuli

$$C(\lambda) = I(\lambda) \times R(\lambda)$$



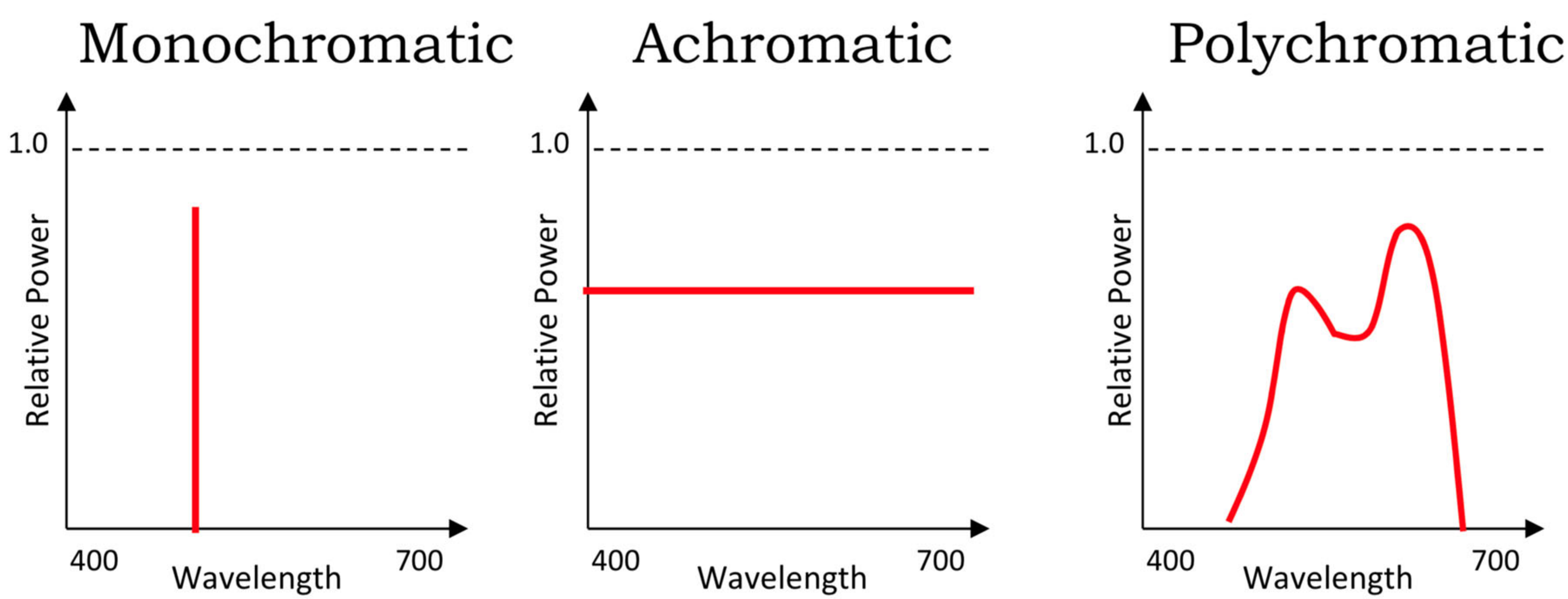
Illumination

x



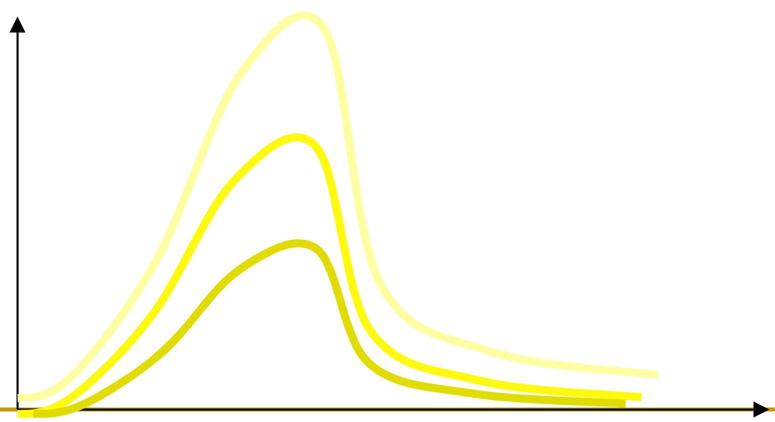
Reflectance

Types of Color Stimuli



Properties of Stimulus

- Brightness/Intensity
  - Total energy of the color spectrum
  - Estimated by the area under the curve



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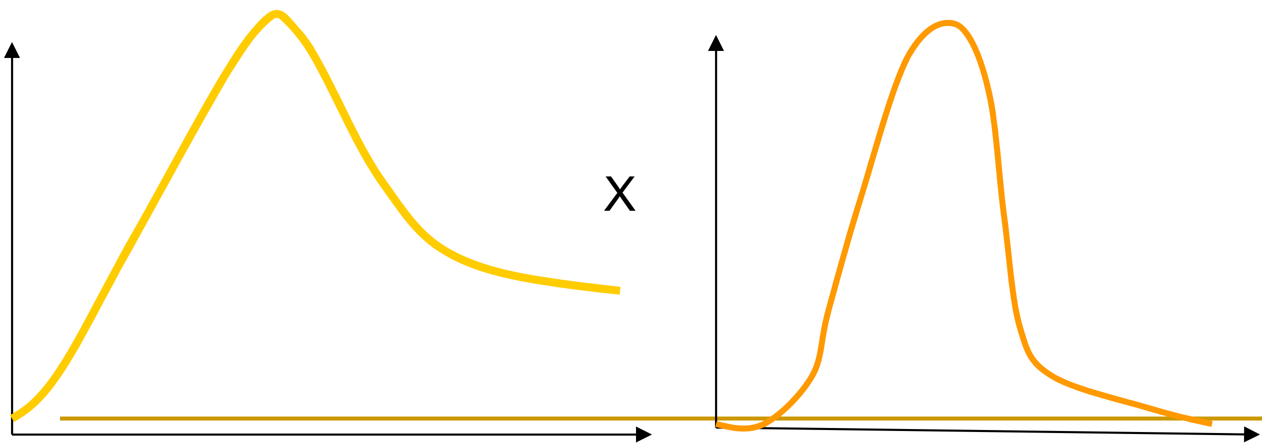
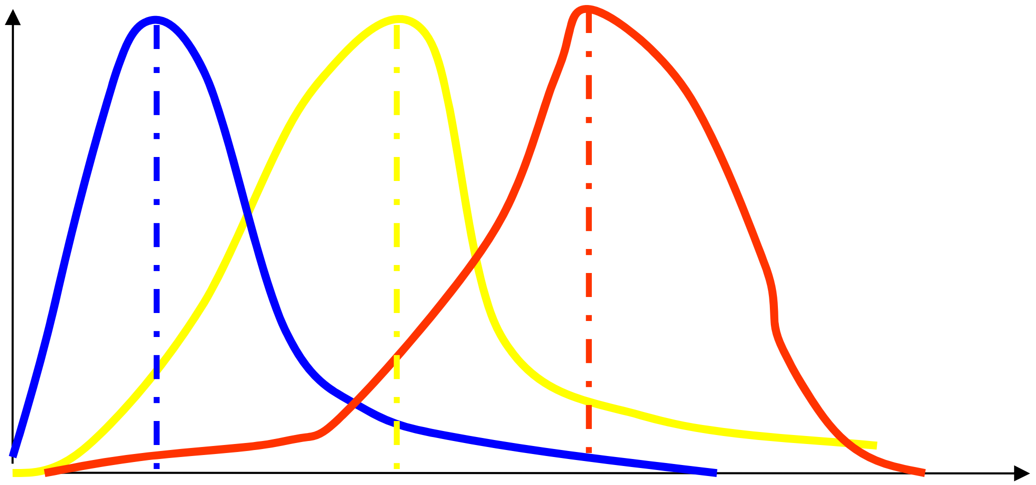
Properties of Stimulus

- Luminance
  - Perceived brightness
  - Depends also on the response of the eye
  - Multiplication of color spectrum with the luminous efficacy function



Properties of Stimulus

- Hue
  - Predominant wavelength
  - Weighted Mean



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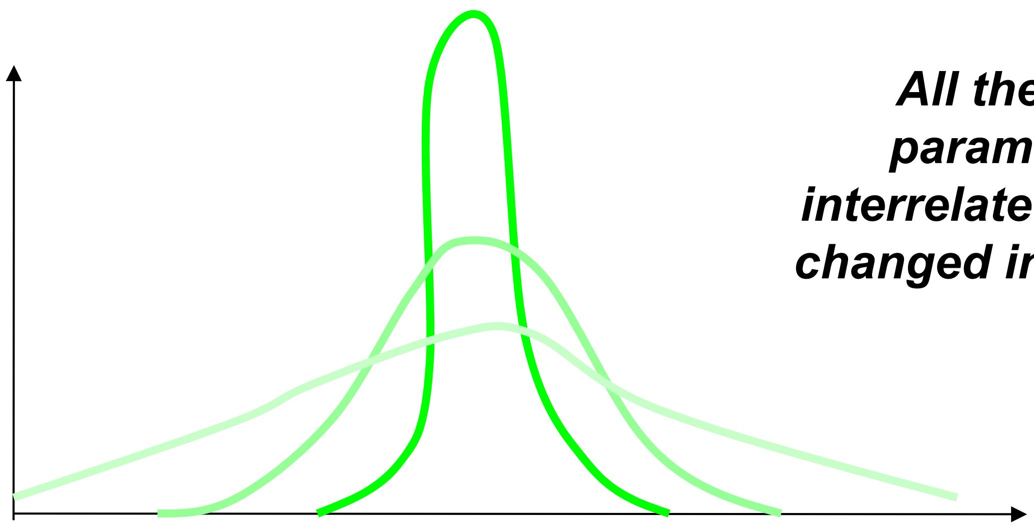
Properties of Stimulus

- Saturation
  - Amount of Achromatic light
  - Variance from the weighted mean



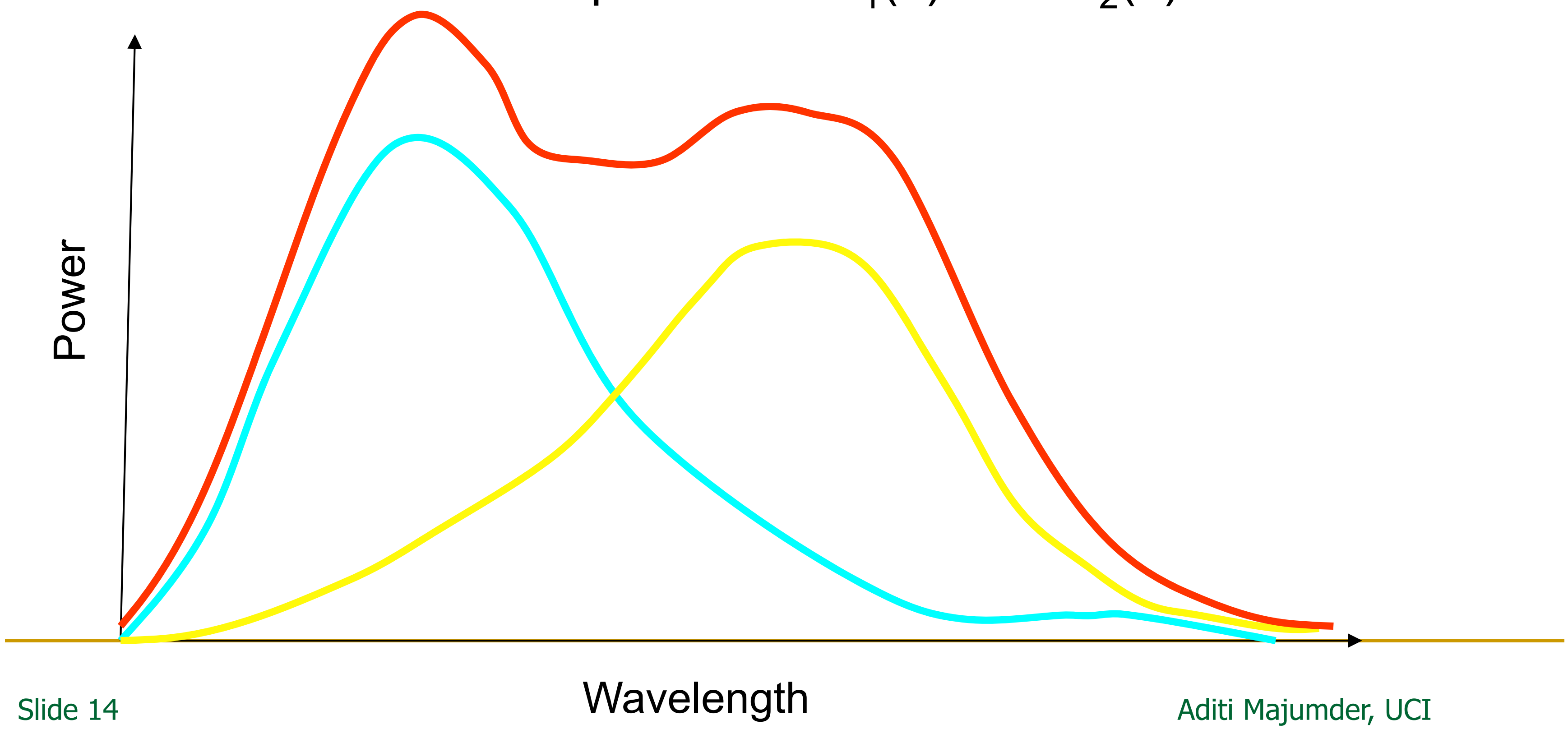
All these three parameters are interrelated. Cannot be changed independently

Lightness

- Relative amount of light reflected
- A black ball does remains black both outside and inside
  - Relative amount of light reflected remains same
  - Absolute amount of light reflected changes
  - Lightness remains same, brightness changes

Color Mixtures

- Additive
  - Union of the wavelengths present in each spectrum
    - Addition of two spectrums $C_1(\lambda)$ and $C_2(\lambda)$



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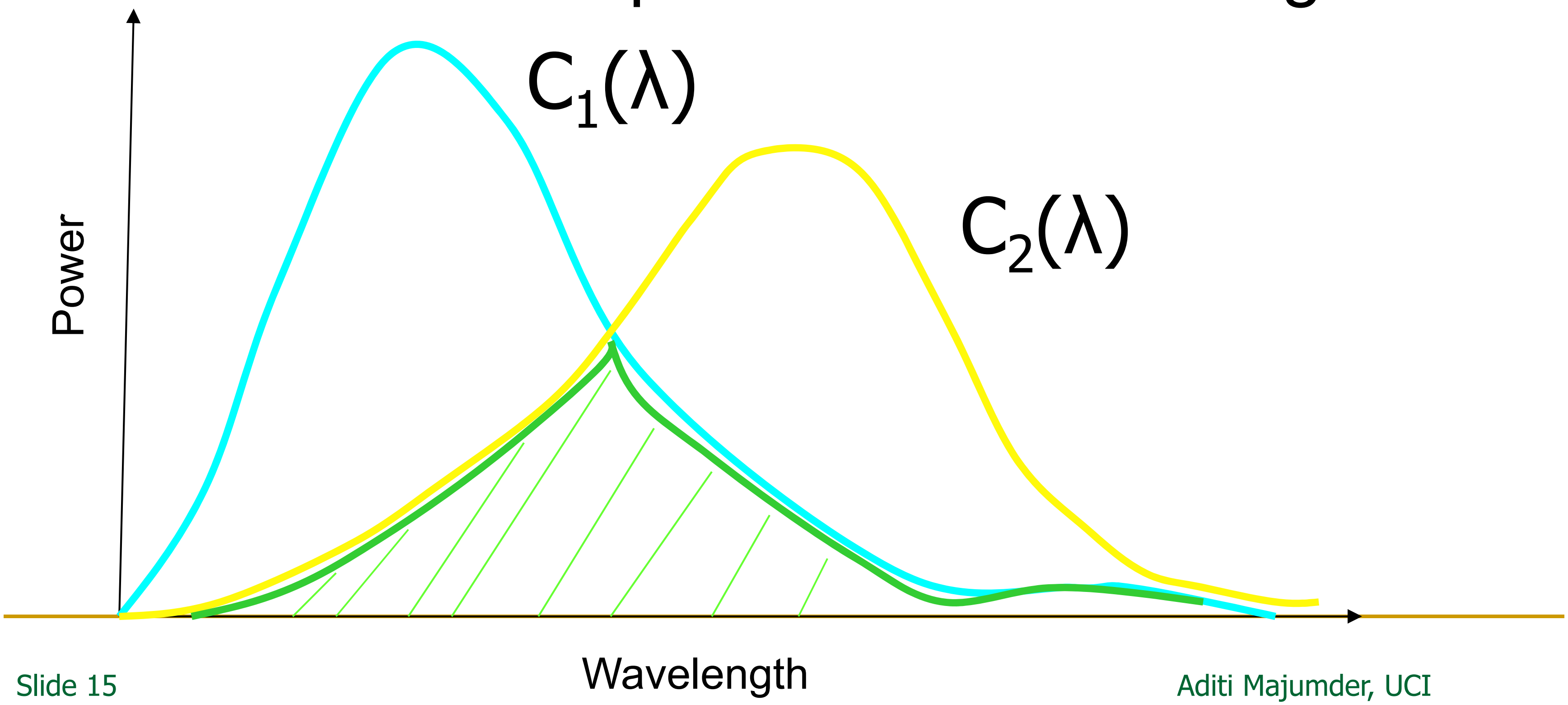
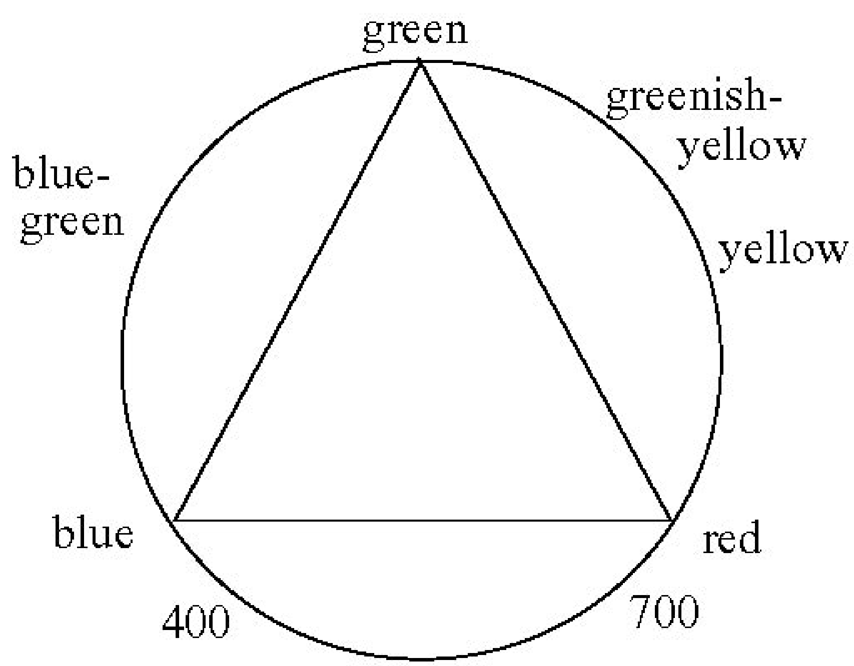
Color Mixtures

- Subtractive
  - Intersection of the wavelengths in each
- Difference: Absorption of the remaining ones



Newton's Additive Color Wheel

- Boundary is saturated color
  - Unsaturated colors in the interior
- Combination of two colors generate a color on the line joining them
- Displays create color likewise



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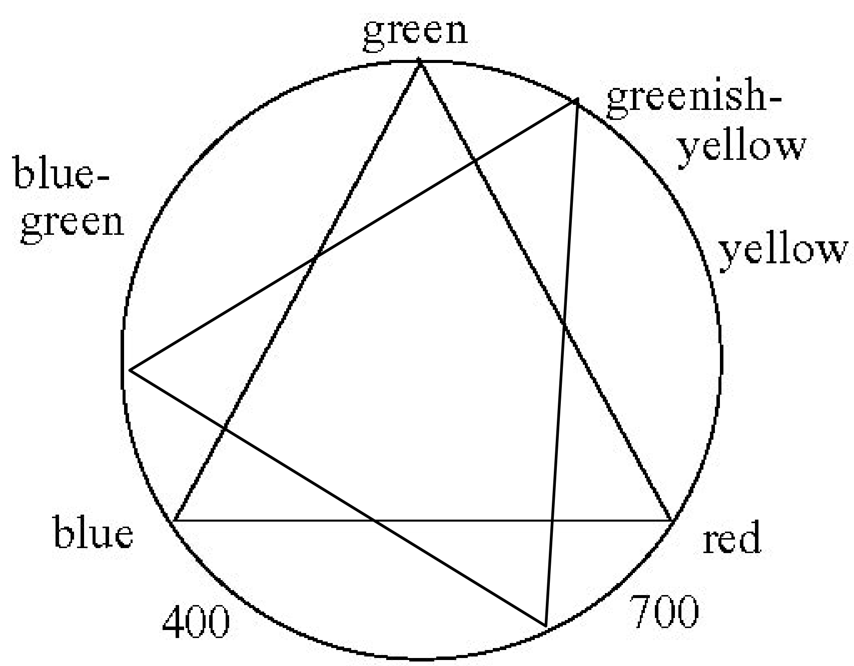
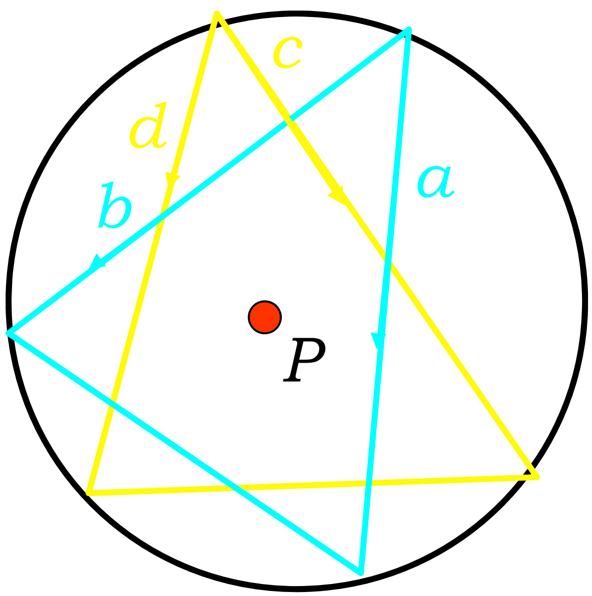
Newton's Additive Color Wheel

- Three colors to create a reasonable subset
  - Devices
  - Even Eye
- Same color can be created by a different set of primaries



Linear Transformation of Primaries



- A set of primaries is a linear transformation of another set of primaries
  - Since they define different 2D coordinates

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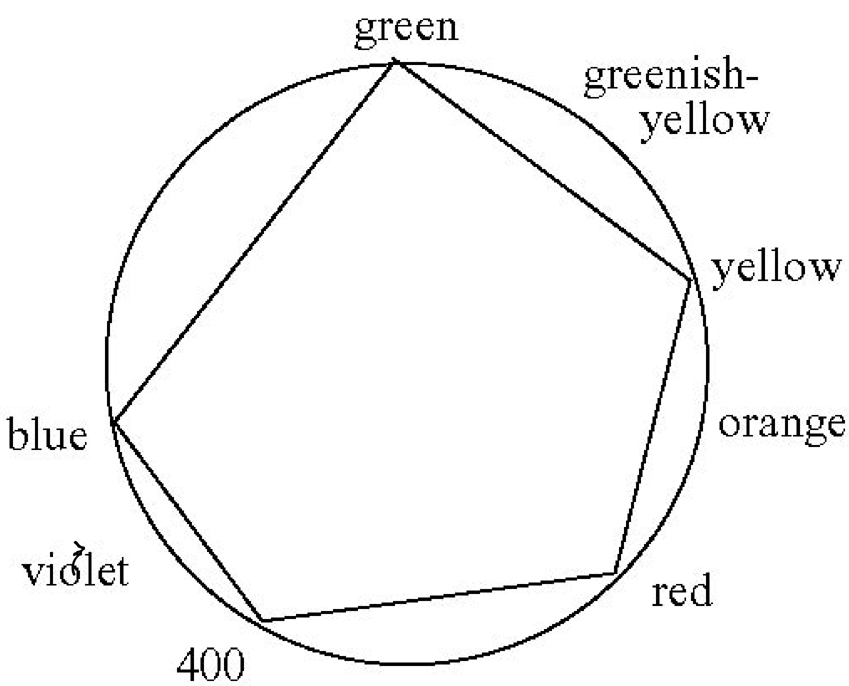
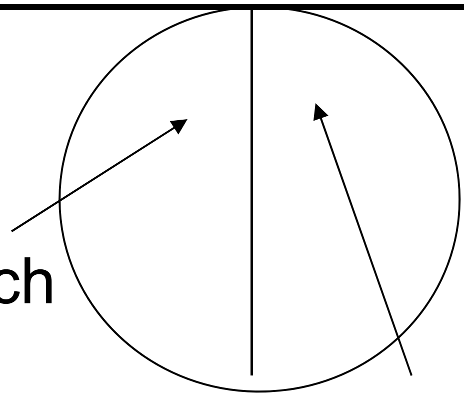
Newton's Additive Color Wheel

- Increasing the number of primaries
- More colors can be represented
- Do you see a problem?



Helmholtz/Maxwell's Color Matching Experiment



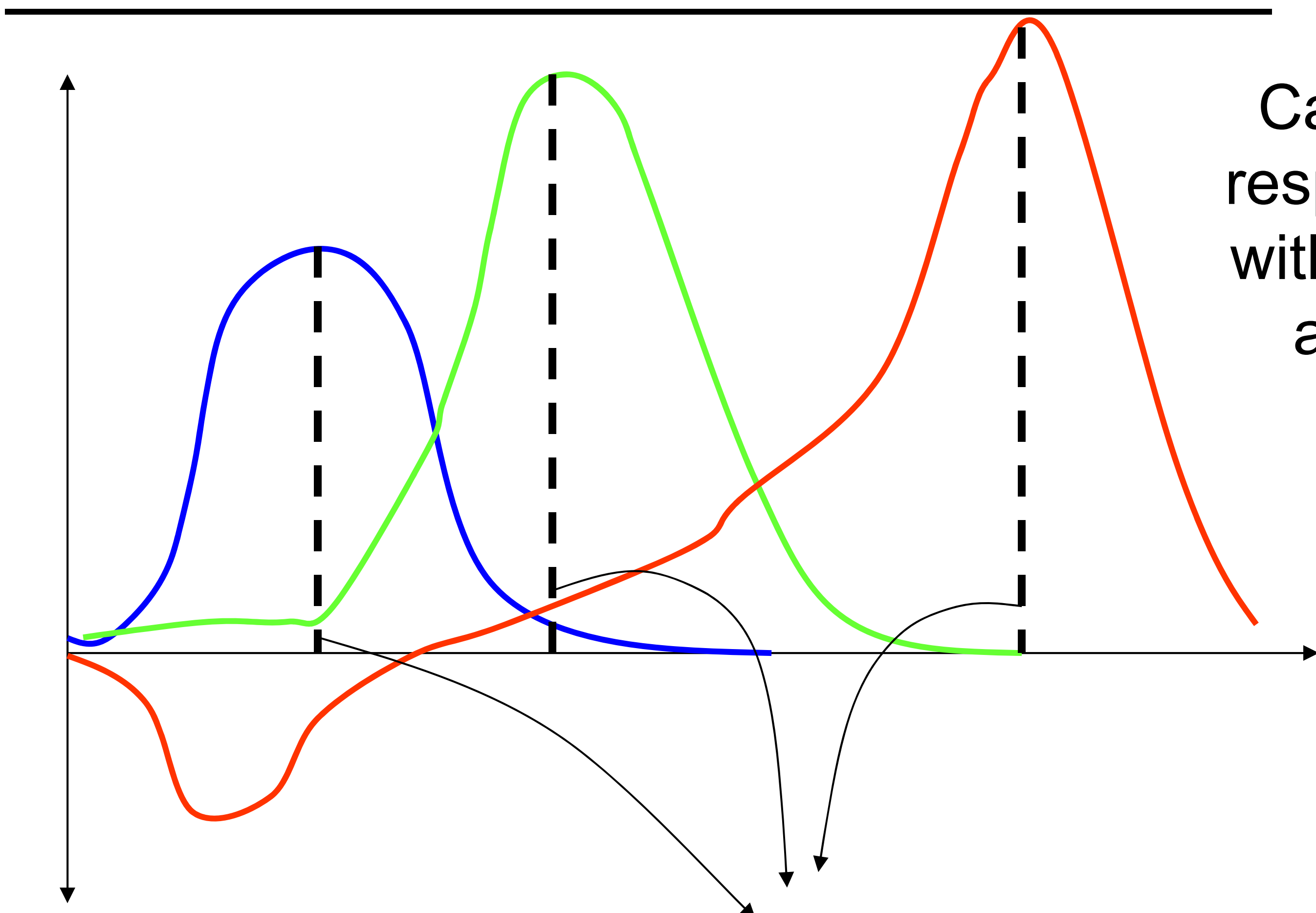
Present each visible wavelength

Add the wavelength here

Match by adjusting amounts of three wavelengths (420nm, 560nm, 640nm)

- All colors can be produced by different amounts of three wavelengths
- Cannot match certain wavelengths
- Register as negative amount

Color Matching Functions



Can be thought of response of sensors with peak sensitivity at the matching wavelengths

Three wavelengths used for matching

CIE Standard Color Matching Functions

- Negative weights do not make sense
- The sensitivities of the cones cannot be mapped directly to properties like brightness, hue and saturation
- Need to organize colors based on these perceptual properties
- Need some color matching functions that would be able to span the entire range
  - With only positive weights
- Imaginary color matching functions
  - Can be found by linear transformations
  - Does not correspond to real colors

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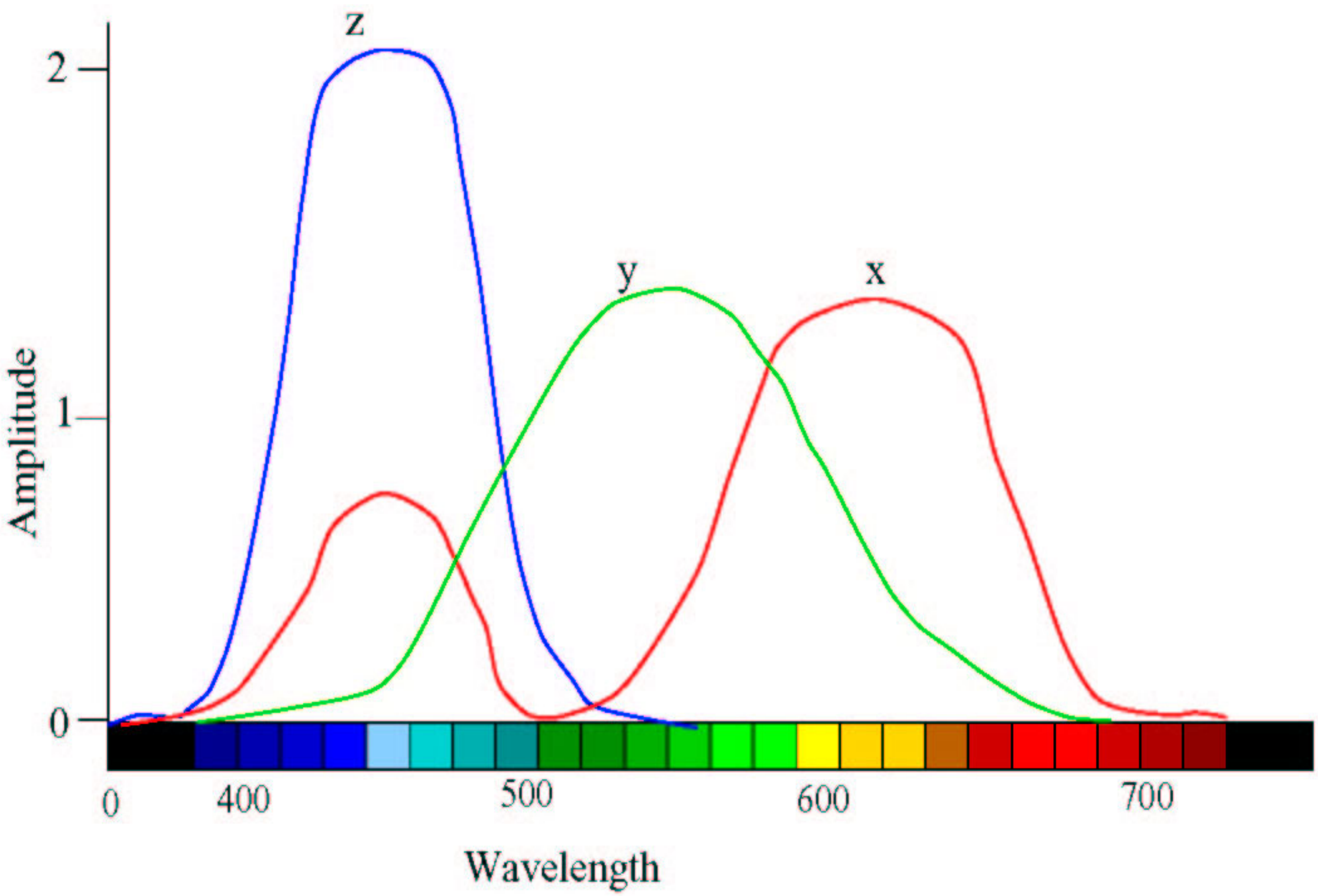
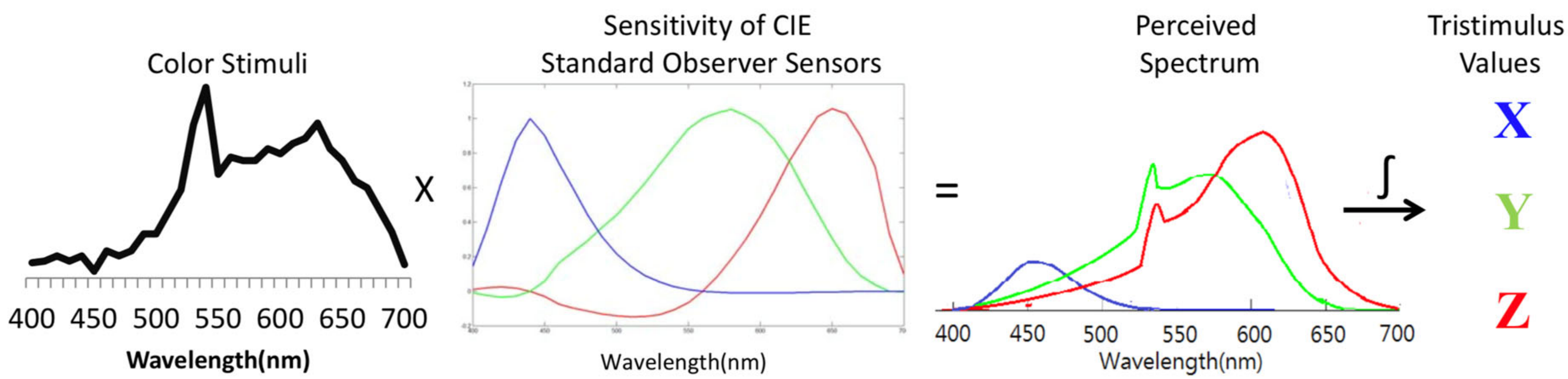
CIE Functions for Standard Observer



Perceived Color

- The response generated by a stimulus in the cones gives the perceived color
- Three responses



Metamerism

- Because of this selective response
  - Two dissimilar stimuli can generate equal strength of *x*, *y* and *z*
  - Phenomenon is called metamerism
  - The two stimuli are called the metamers
  - So, we experience all the metamers similarly

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Tristimulus Values

- Integration over wavelength

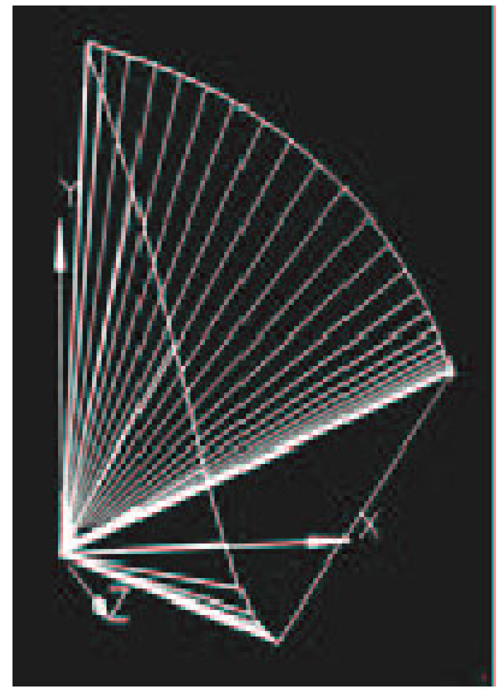
$$X = \int_{\lambda} C(\lambda)x(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)x(\lambda)$$

$$Y = \int_{\lambda} C(\lambda)y(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)y(\lambda)$$

$$Z = \int_{\lambda} C(\lambda)z(\lambda) = \sum_{\lambda=400}^{\lambda=700} C(\lambda)z(\lambda)$$

Tristimulus Values

- Metameric colors have same value
- Real colors span a sub-set of the XYZ space
  - Since imaginary primaries



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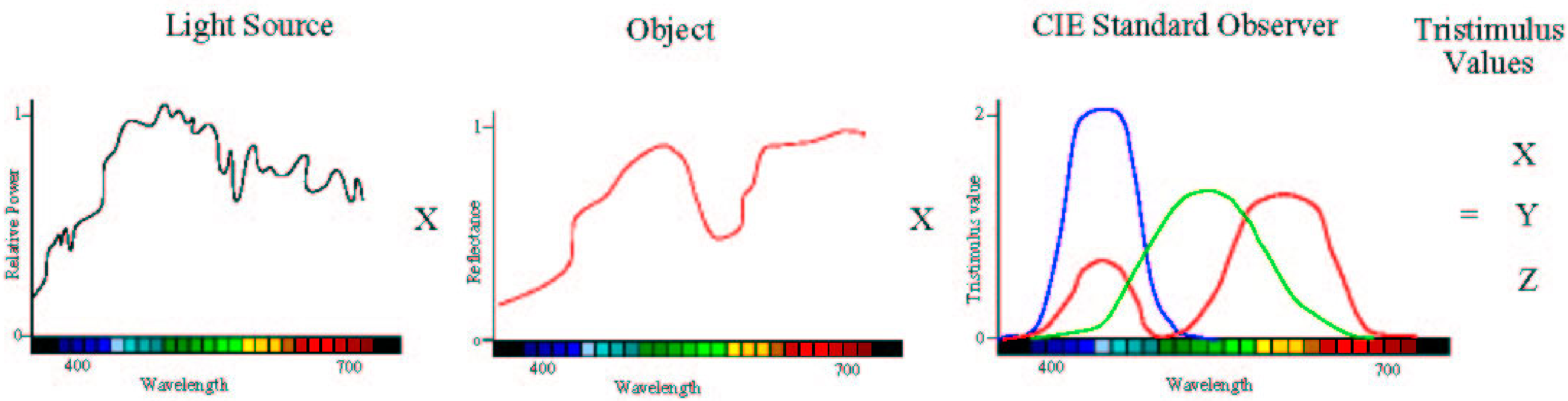
Tristimulus Values



- XYZ forms a three dimensional space to define color
- Two colors added by just adding the XYZ coordinates

Perceptual Parameters

- No physical feel as to how colors are arranged
- How are saturated hues arranged?
- How are unsaturated hues arranged?
- Perceptually not easy to deal with
- Experiment with color palette

Chromaticity Chart

- Relative proportions of X, Y, and Z are more important
- For example, equal proportions of each signifies an achromatic color
- Chromaticity Diagram: 2D projection of 3D colors on X+Y+Z = d plane

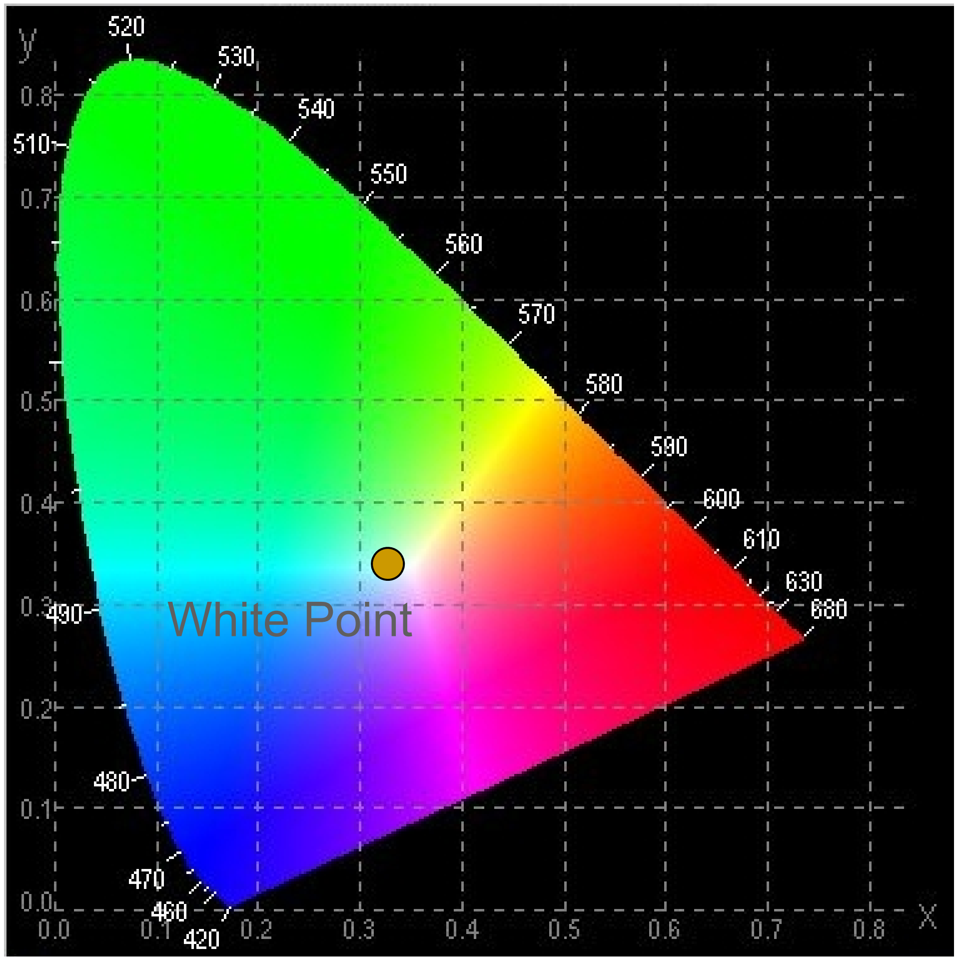
$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$

Chromaticity Chart

- Energy of the spectrum (Intensity) estimated by X+Y+Z
- Points on a vector originating at zero coincide at the same point
  - (X,Y,Z) and (2X,2Y,2Z) generate same (x,y)
- Colors on this vector have same intensity but different chrominance
- NOTE: Luminance is perceived brightness, given by Y, and different from energy of the spectrum
- Problem with current color nomenclature

Chromaticity Coordinates

- Shows all the visible colors
- Achromatic Colors are at (0.33,0.33)
  - Why?
  - Called white point
- The saturated colors at the boundary
  - Spectral Colors



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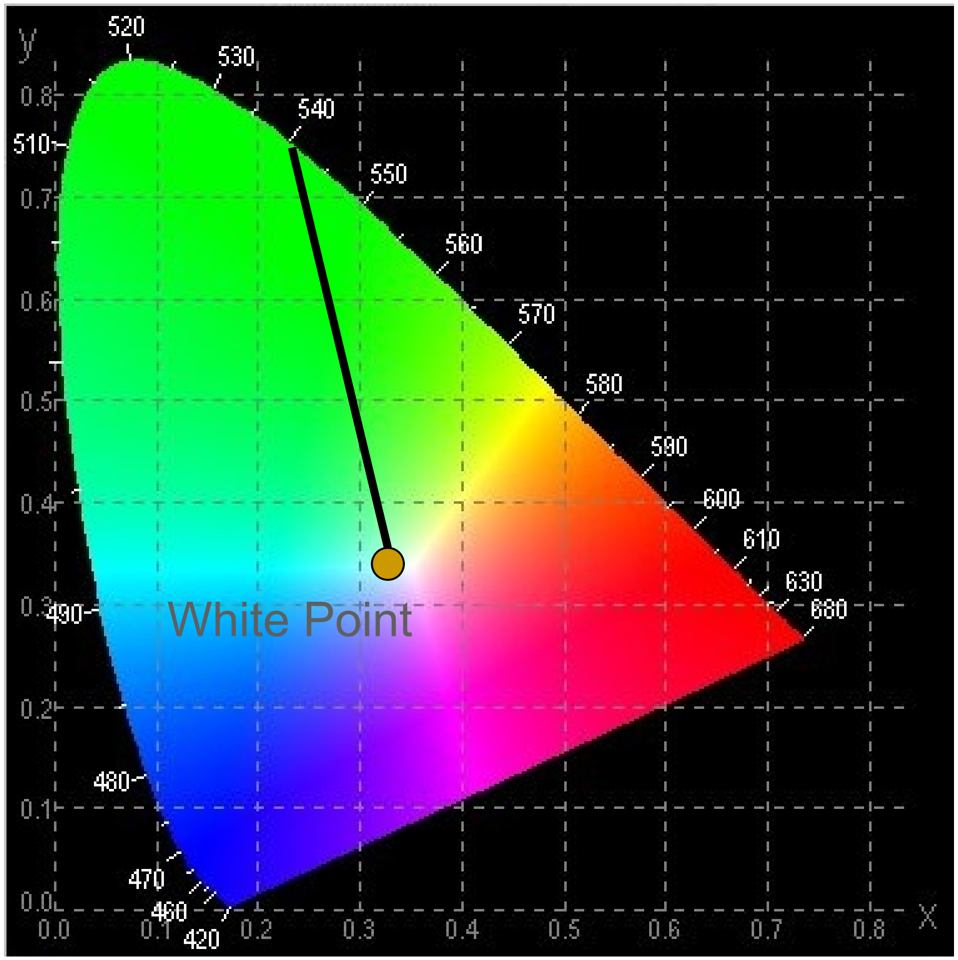
Chromaticity Chart

- Exception is purples
  - Non-spectral region in the boundary
- All colors on straight line from white point to a boundary has the same spectral hue
  - Dominant wavelength



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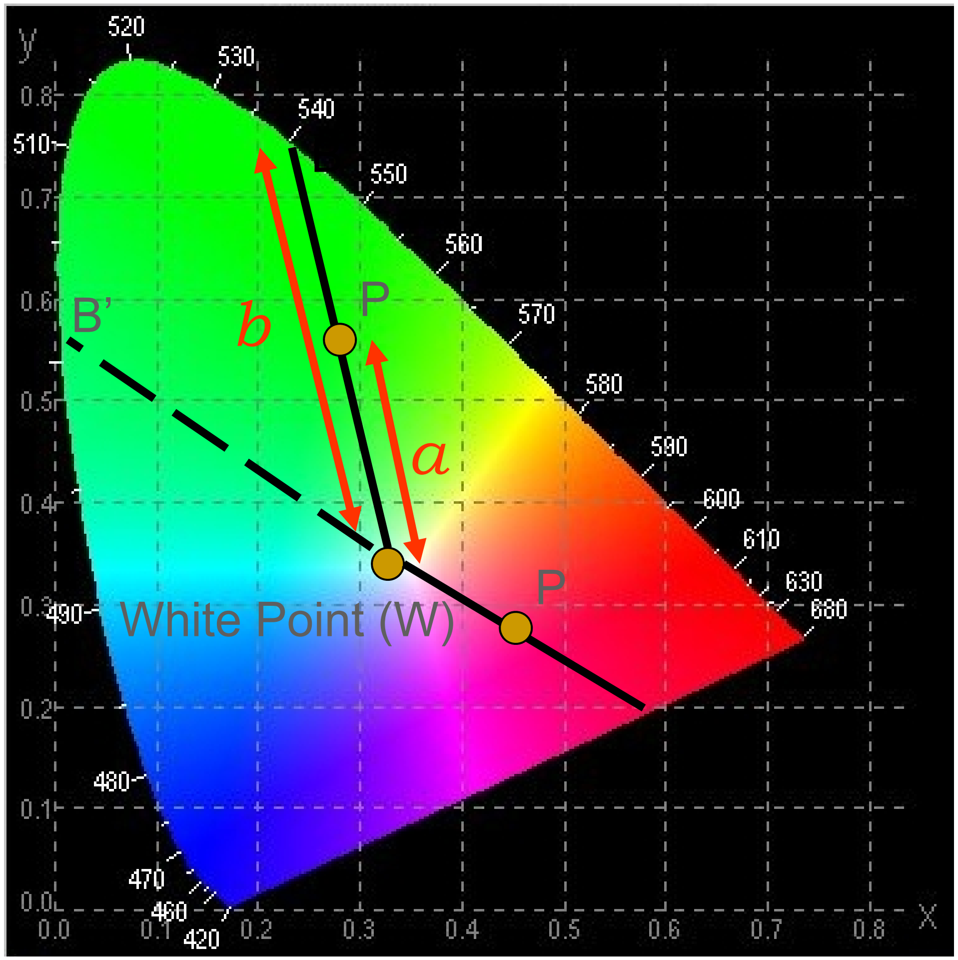
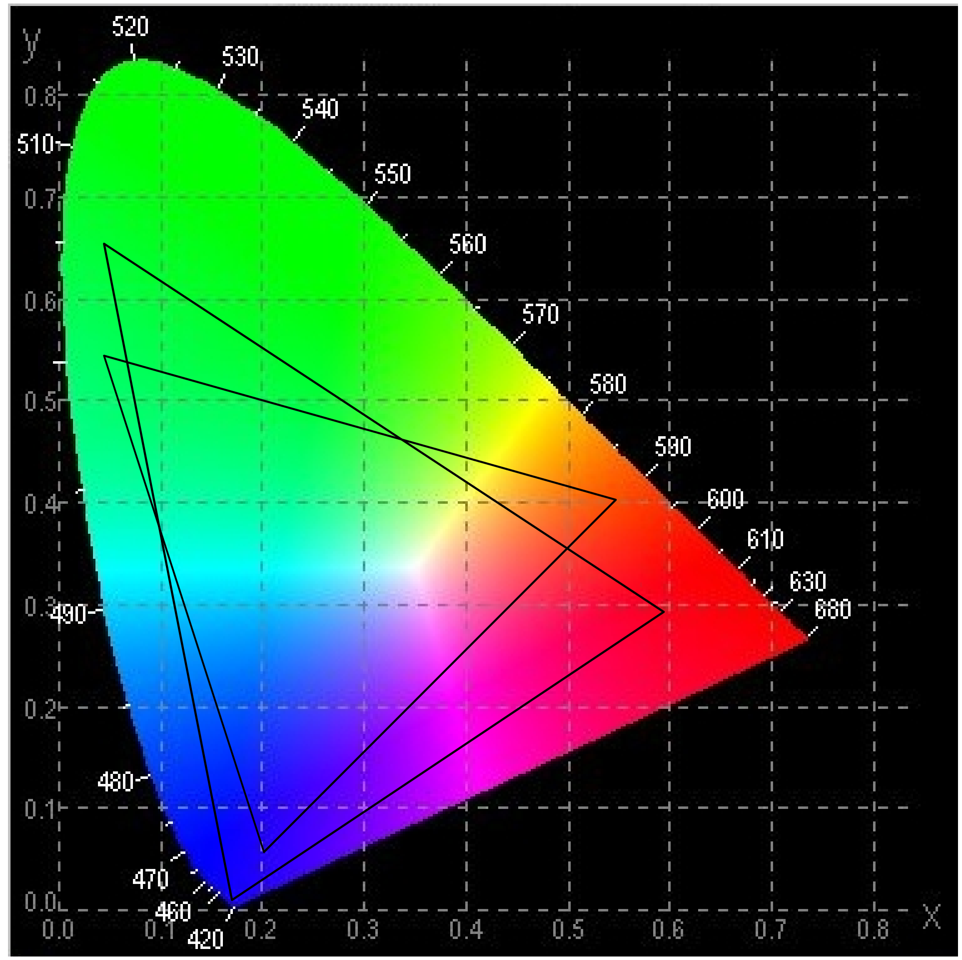
Chromaticity Chart

- What happens here?
  - Complimentary wavelength
  - When mixed generate achromatic color
- Purity (Saturation)
  - How far shifted towards the spectral color
  - Ratio of a/b
  - Purity =1 implies spectral color with maximum saturation

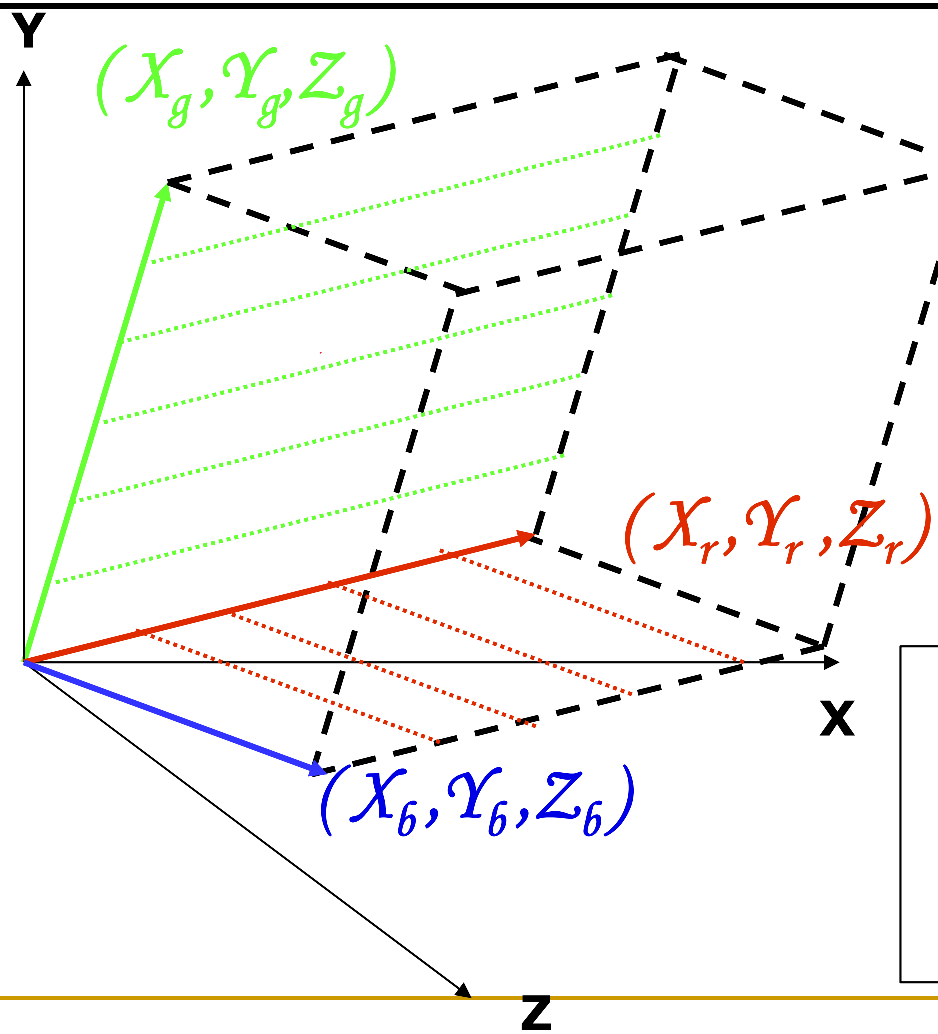


How to combine colors?

- Board Work
  - Using just XYZ
  - Using hue, saturation and brightness
- What happens when add two colors of same hue and saturation?

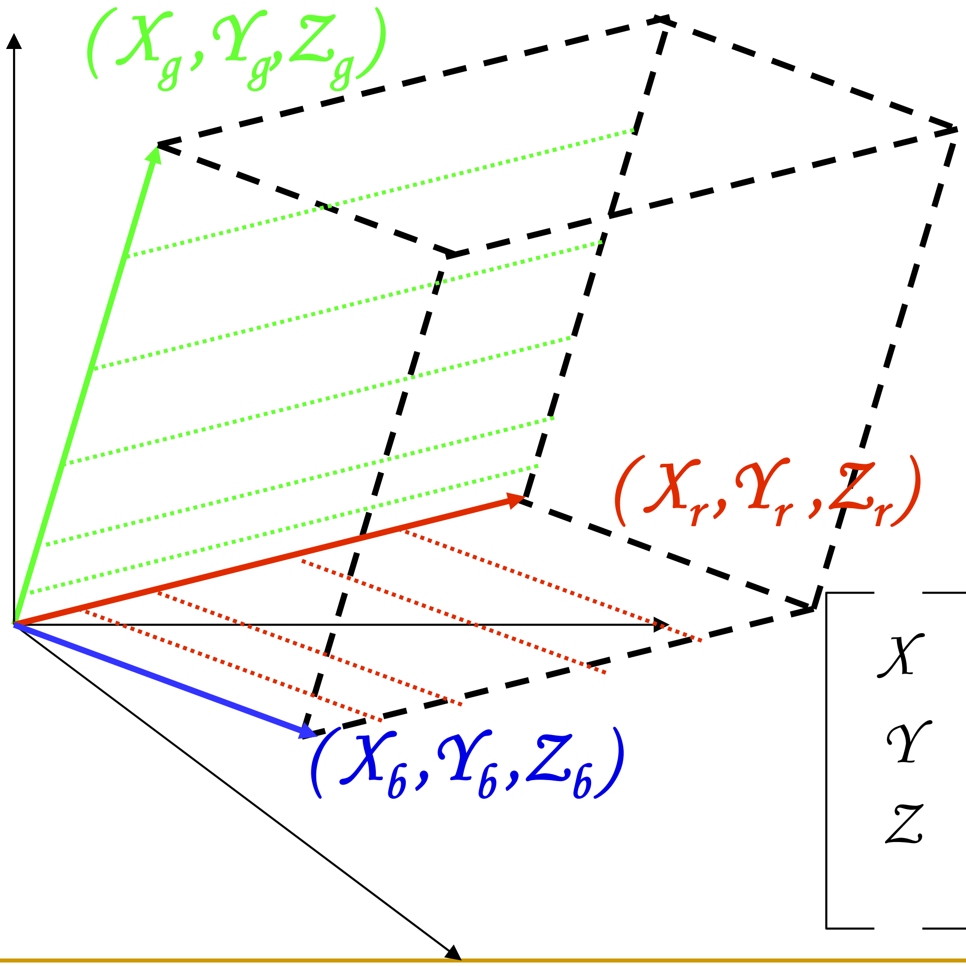


What is the RGB color?



$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} i_r \\ i_g \\ i_b \end{bmatrix}$$

What is gamma function?



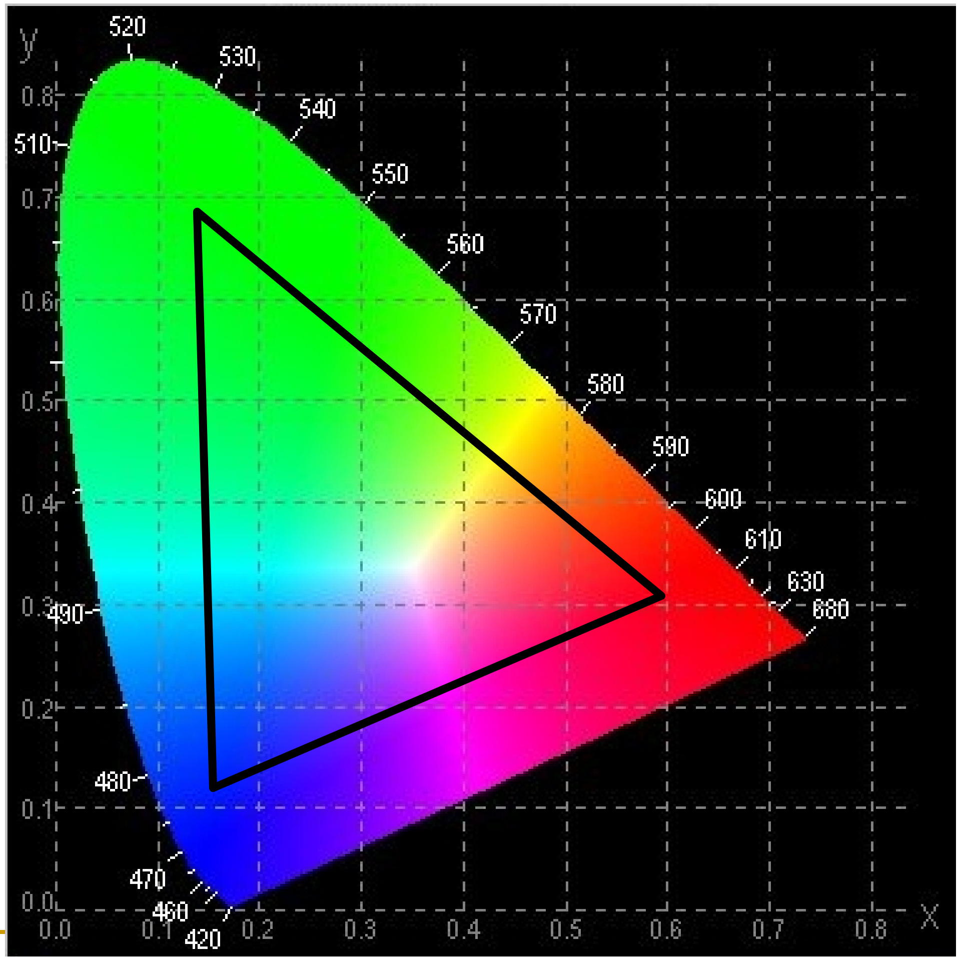
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} h_r(i_r) \\ h_g(i_g) \\ h_b(i_b) \end{bmatrix}$$

Color reproducibility

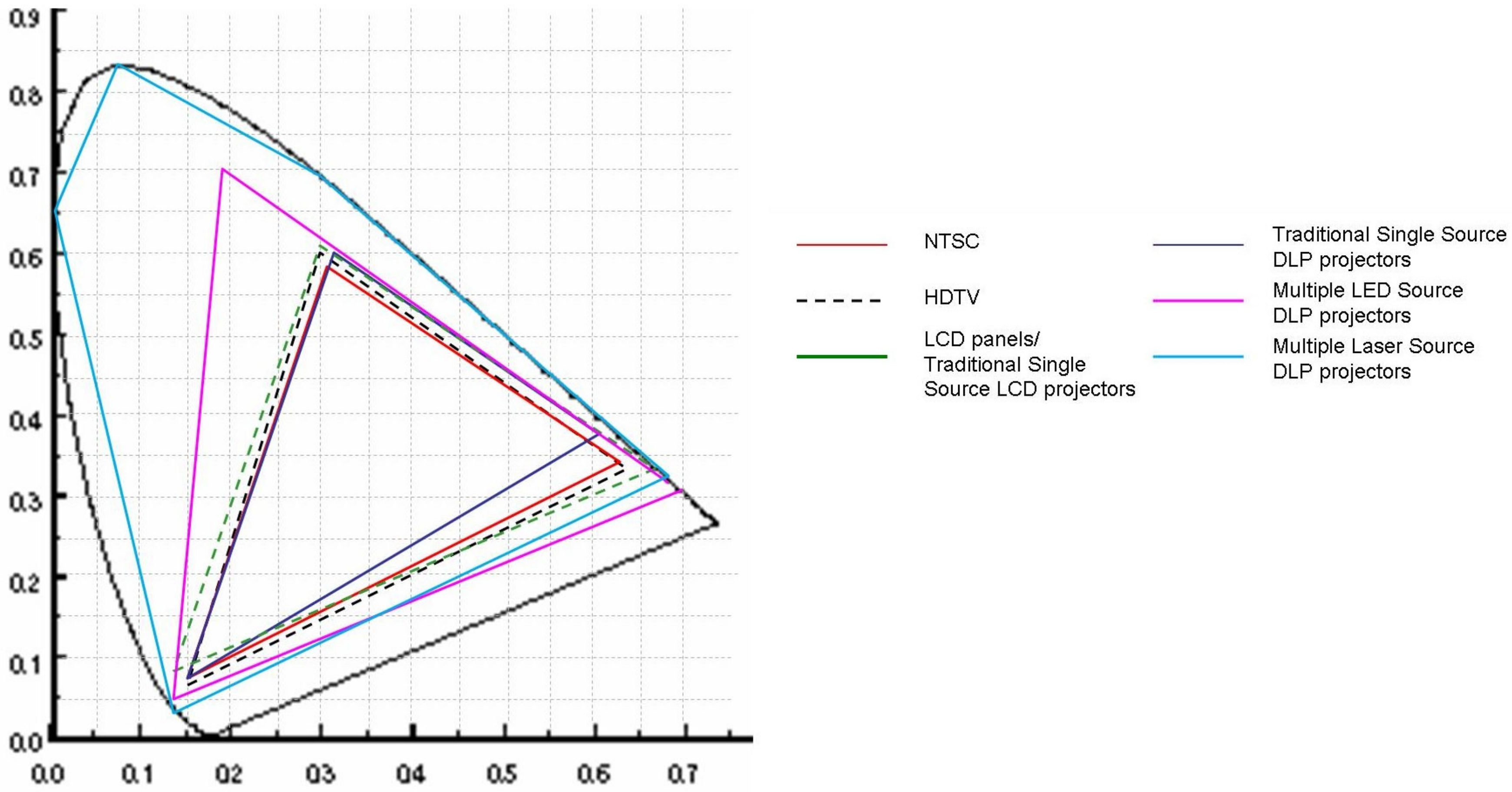
- Only a subset of the 3D CIE XYZ space called 3D color gamut
- Projection of the 3D color gamut on the same plane with normal (1,1,1)
  - Triangle
  - 2D color gamut
    - Cannot describe brightness range reproducibility

Specification Protocols

- Brightness or Luminance
- 2D gamut
  - Large if using more saturated primaries



Current standards and devices



Gamut Transformation

- Assume linear gamma
- $[X\ Y\ Z\ 1]^T = M\ [R\ G\ B\ 1]^T$
- Two devices
  - $[X\ Y\ Z\ 1]^T = M_1\ [R_1\ G_1\ B_1\ 1]^T$
  - $[X\ Y\ Z\ 1]^T = M_2\ [R_2\ G_2\ B_2\ 1]^T$
- $[R_2\ G_2\ B_2\ 1]^T = M_2^{-1}[X\ Y\ Z\ 1]$

$$= M_2^{-1}M_1[R_1\ G_1\ B_1\ 1]^T$$

Gamut Transformation

- How to get the matrix from the standard spec?
- Given (Y,x,y) or (I,x,y) for the three vectors, you can compute (X,Y,Z)
  - (x. Y/y, Y, (1-x-y). Y/y)
  - (x.I, y.I, (1-x-y).I)
- **Does not change the color**, finds the new coordinates when using the new basis

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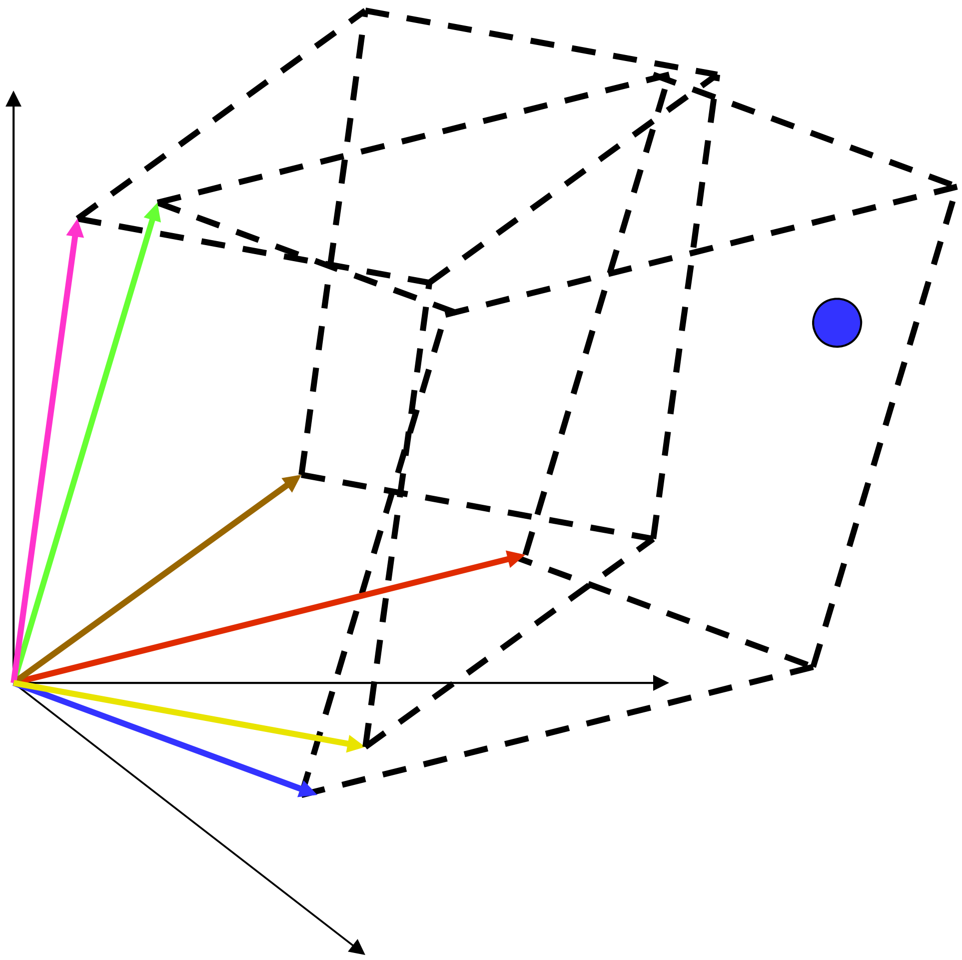
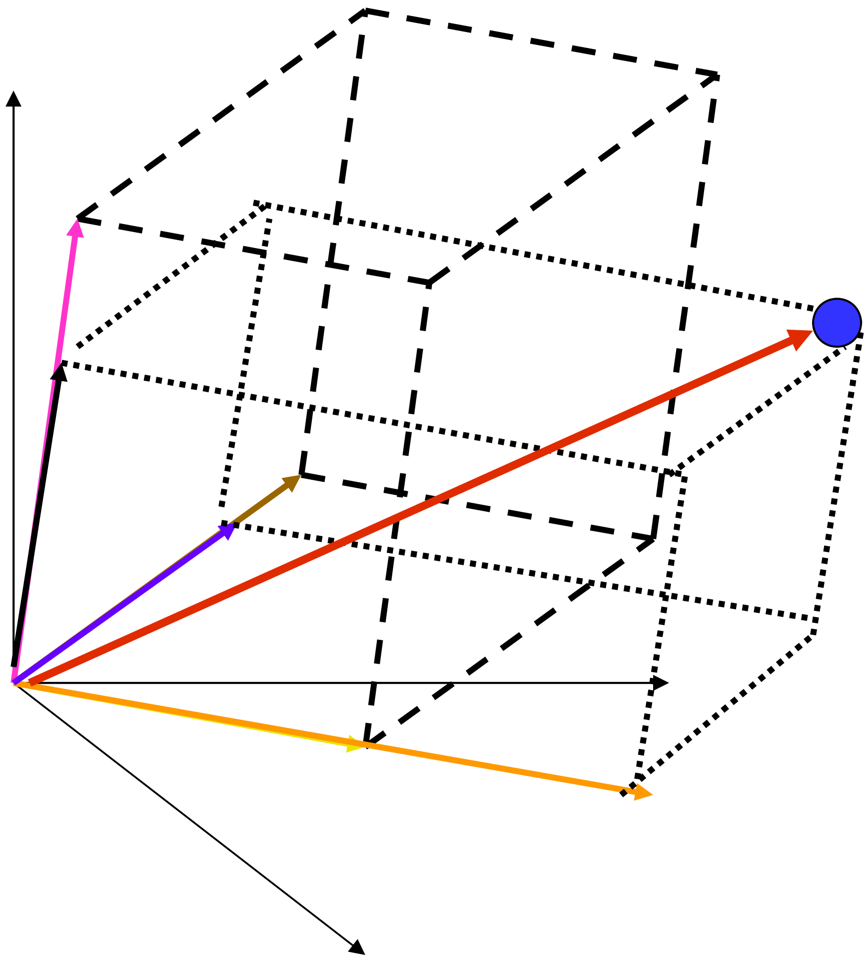
Problem



Problem: Out of Gamut colors



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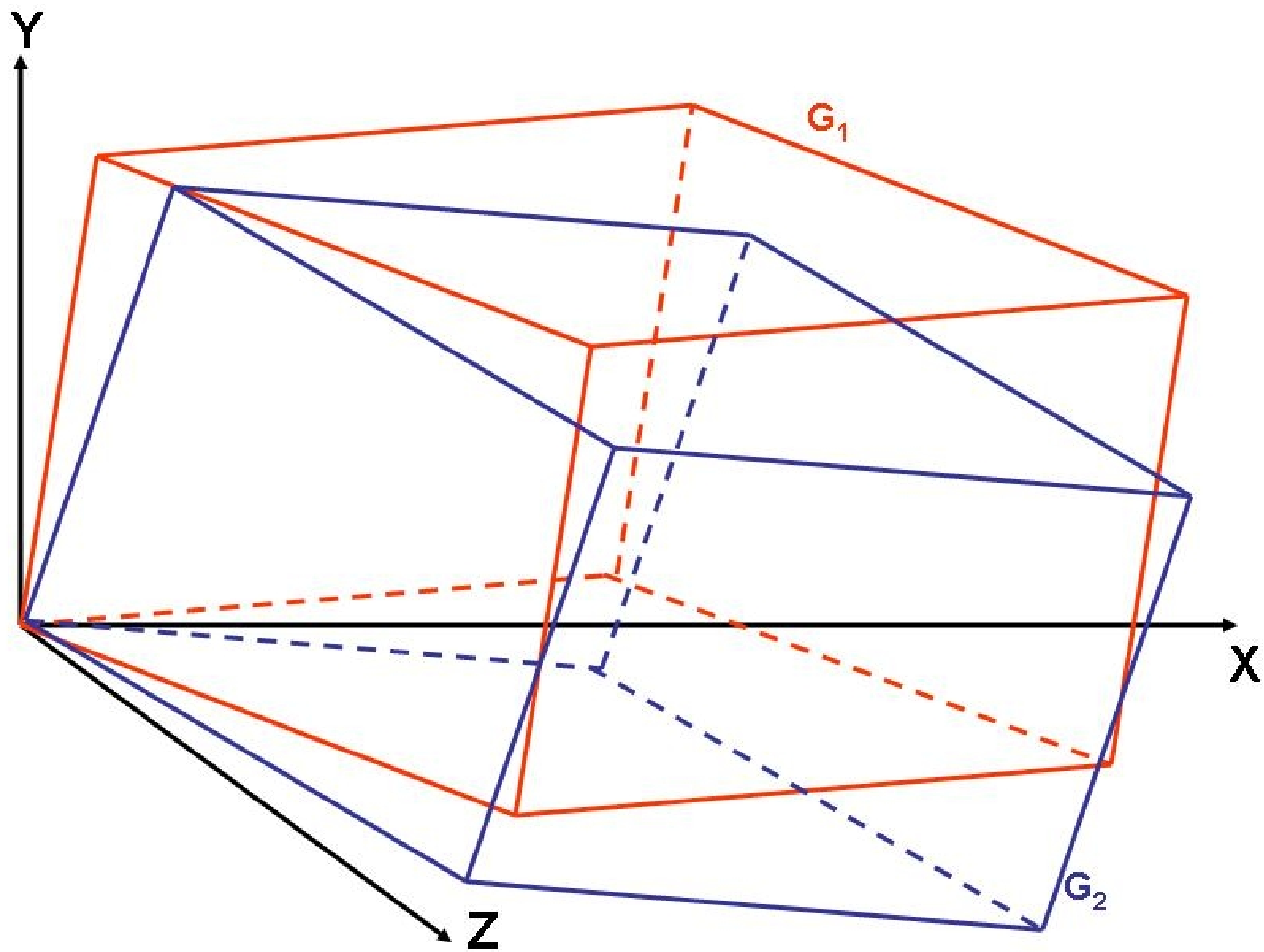
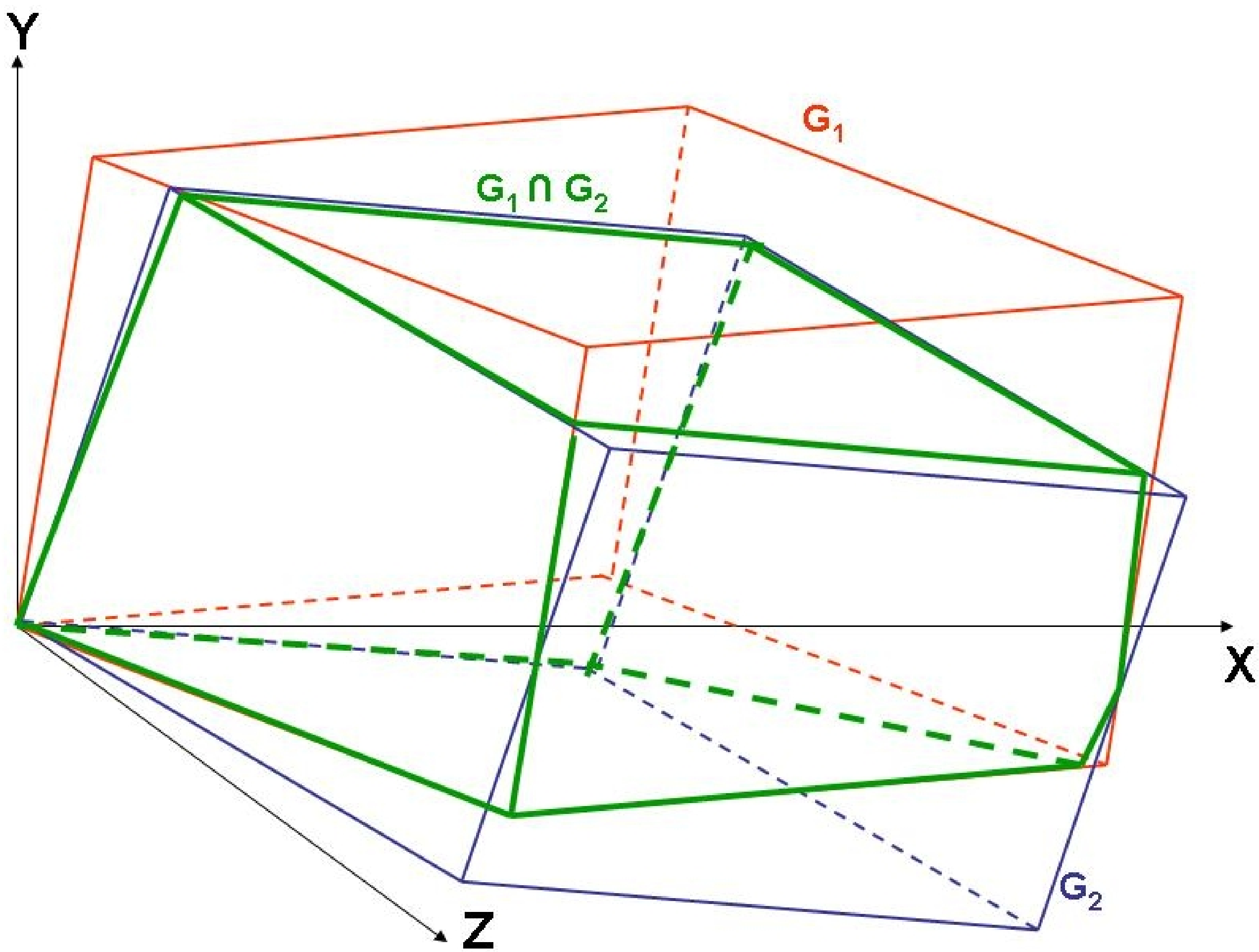
Gamut Matching

- Find a common color gamut defined by R_c, G_c, B_c
- Find the common function M_c
  - $[X\ Y\ Z\ 1]^T = M_c\ [R_c\ G_c\ B_c\ 1]^T$
- For any device i
  - $[R_i\ G_i\ B_i\ 1]^T = M_i^{-1} M_c\ [R_c\ G_c\ B_c\ 1]^T$

Two gamut

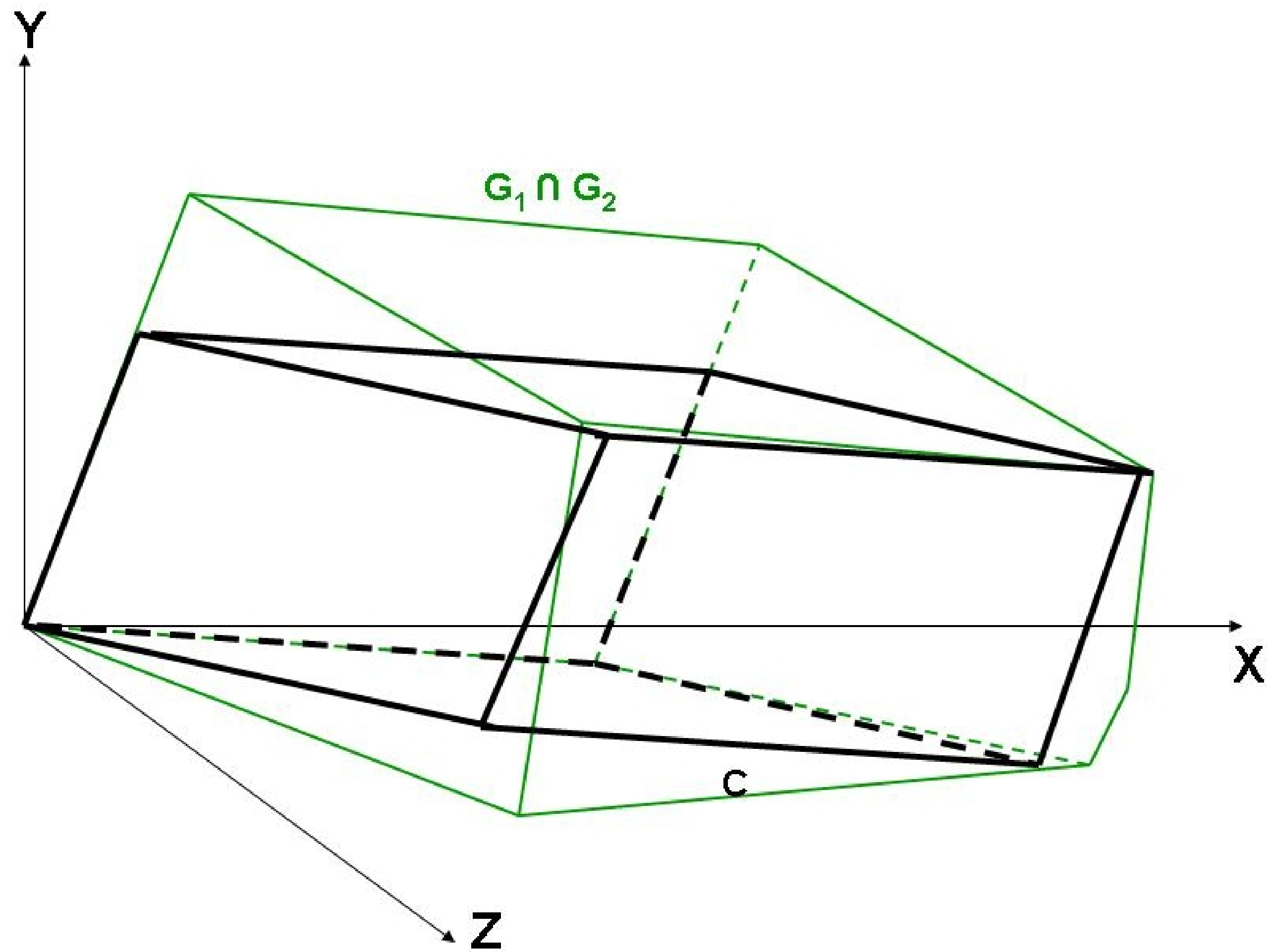


Find their intersection

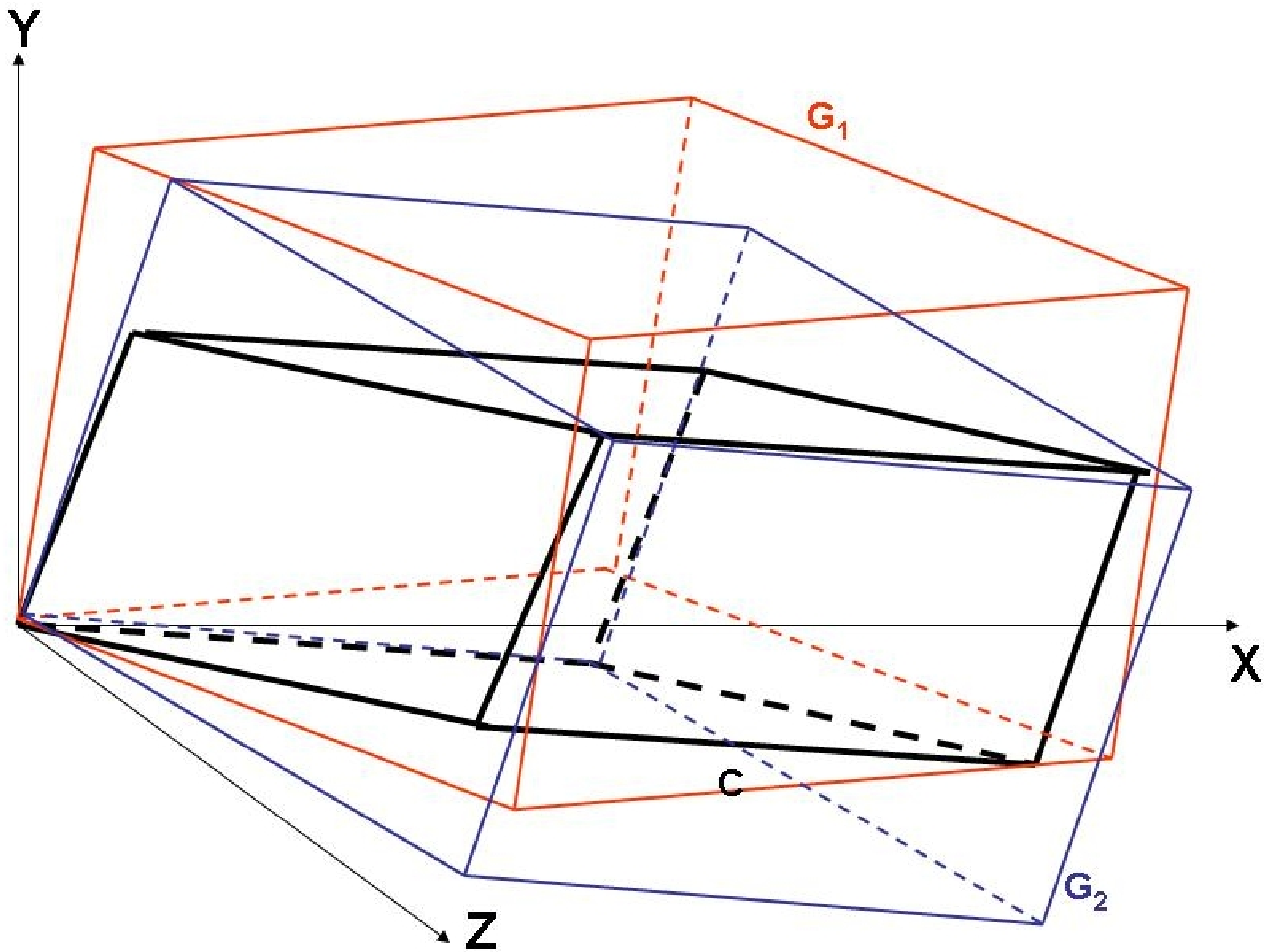


Need not be a parallelopipped

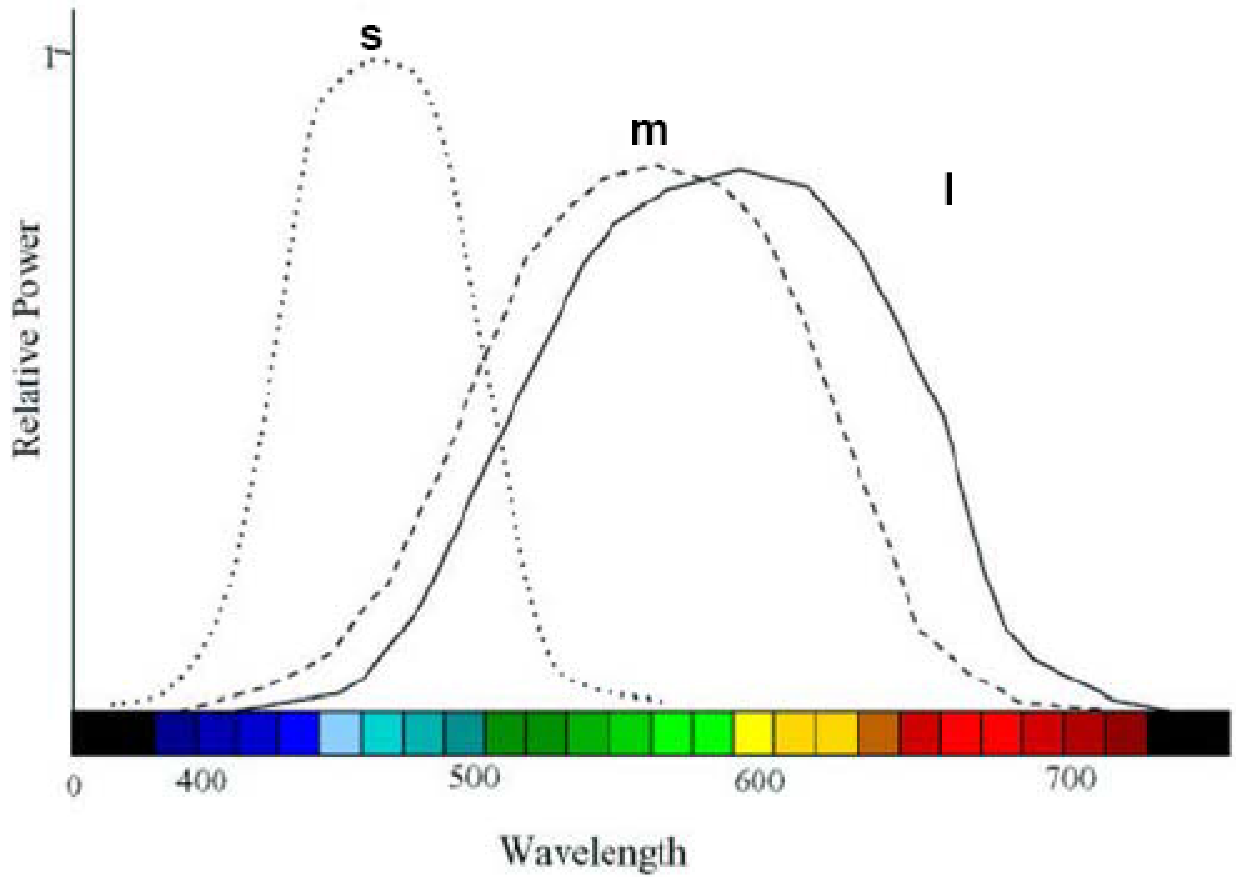
Find the common gamut



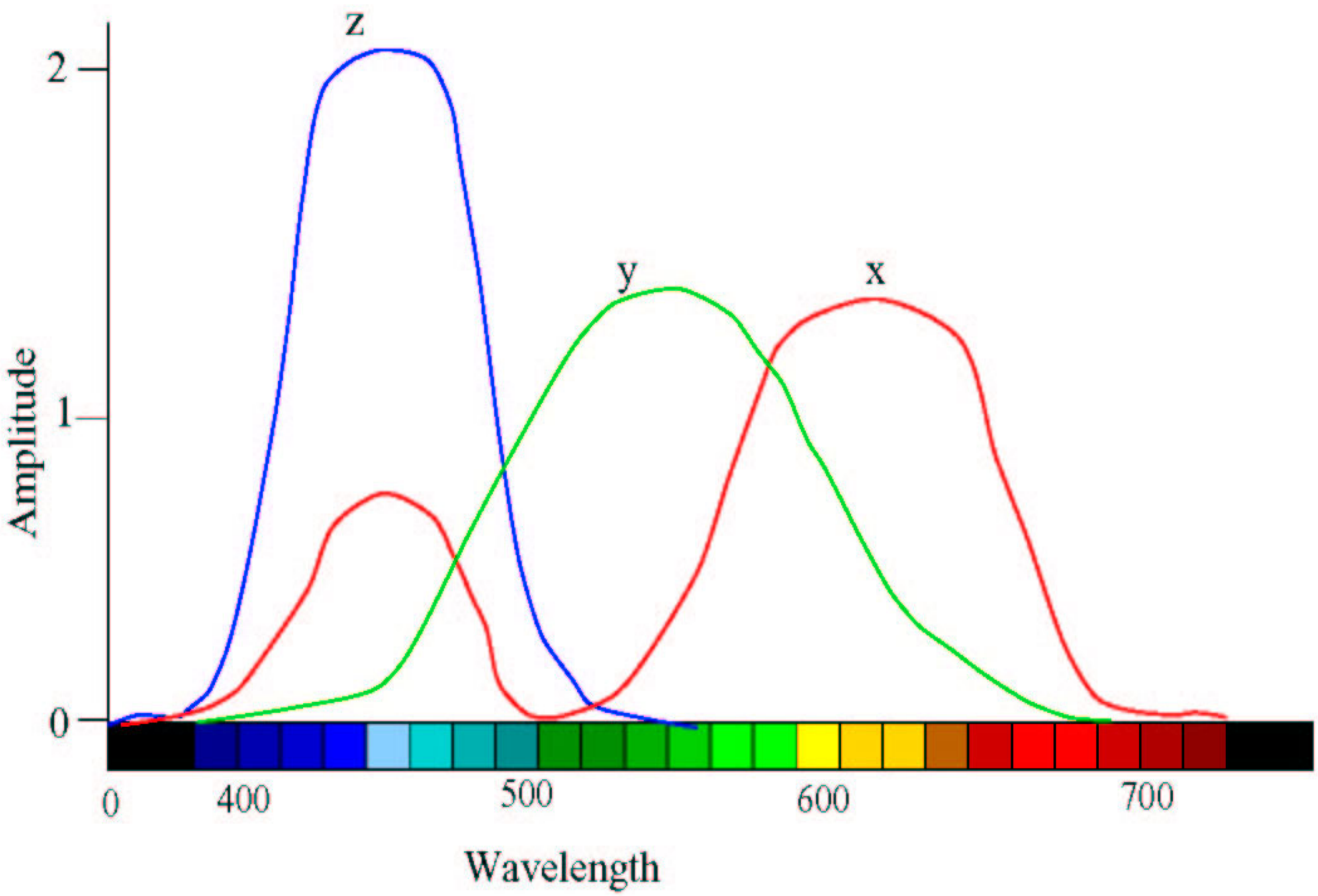
Find the mapping function



Human Visual Response (Later)



CIE Functions for Standard Observer



Human Visual Response

- Trichromatic Theory
  - Proposed by Thomas Young
  - Eye has three kinds of receptors
  - Produce psychologically similar sensations of red, green and blue

You have seen different sets of primaries

- Helmholtz color matching functions
- CIE Standard Observer functions
- Human visual cone functions
- Should all be the same but are not
  - Due to historical legacy
- Each can be transformed to other by a 3x3 linear transformation function

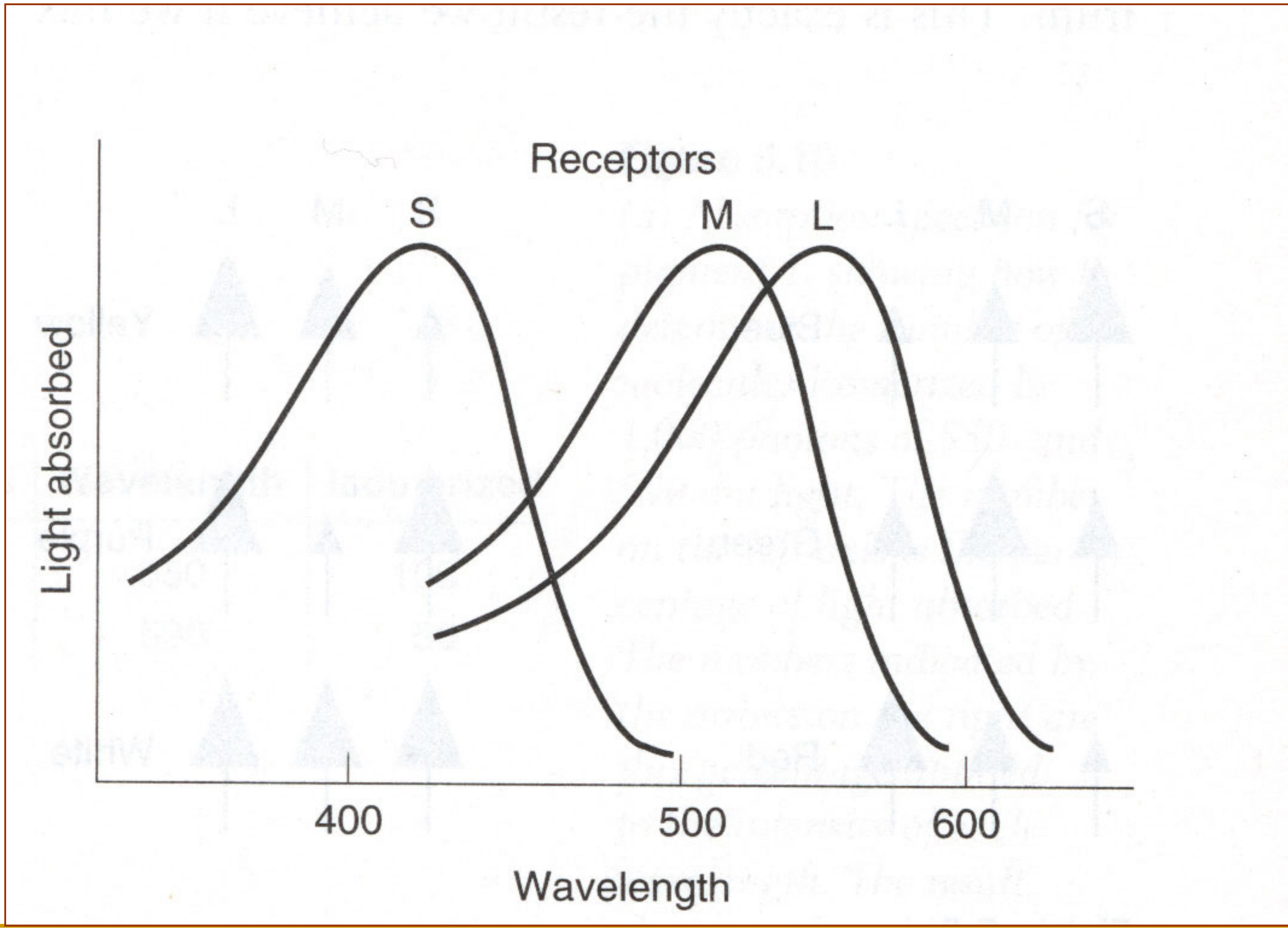
In the Eye

- All colors can be produced by mixing various proportions of three wavelengths
  - 420nm, 560nm and 640nm
  - Young Helmholtz theory of color vision
- Three types of receptors excited
  - Pattern of excitation depends on the color or the wavelength of the light

Physiological Explanation

- Three different types of cone
  - Different pigment with different absorption spectra
- Pigments have different amino acids in their opsins
  - Causes the different absorption spectra
- S, M, L
  - S and M are 44% similar, peaks 112nm apart
  - M and L are 96% similar, peaks 27nm apart

Response of Cones



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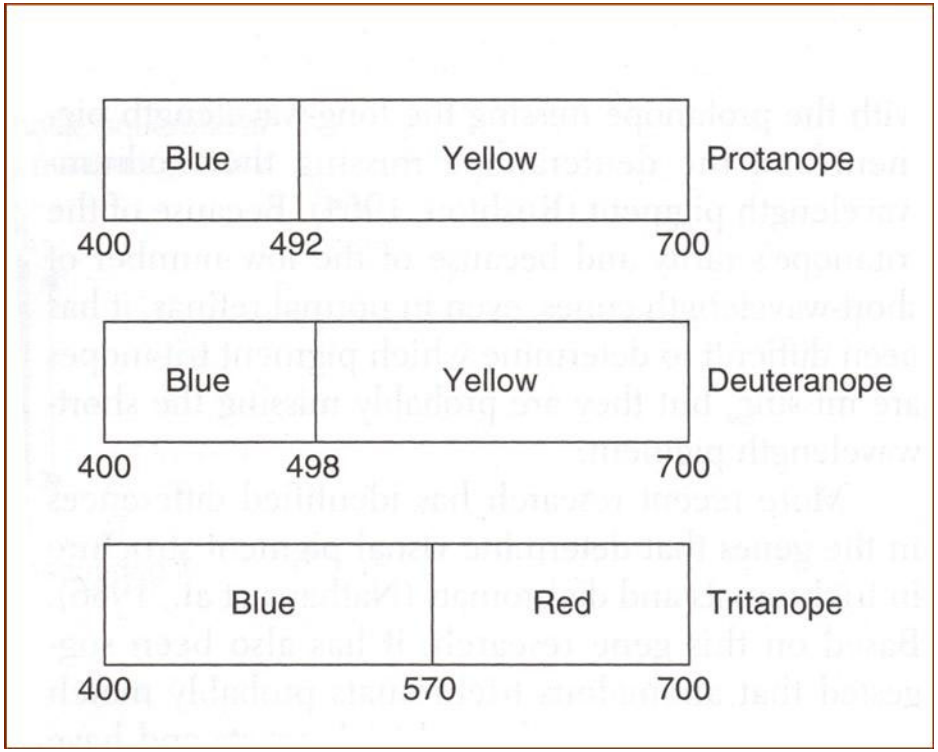
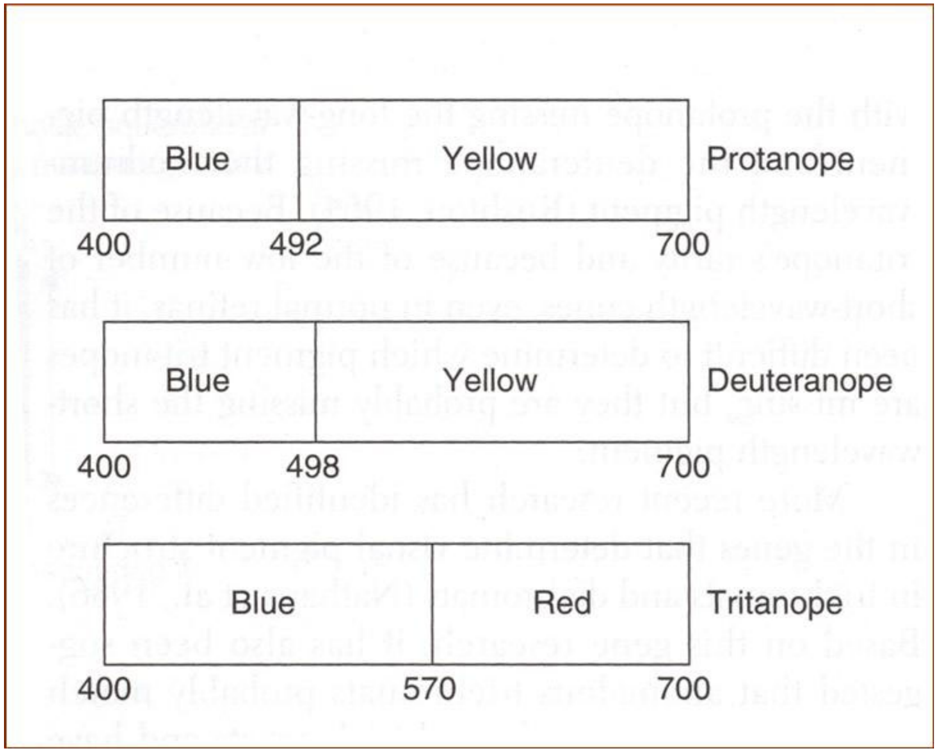
Color Deficiency

- Monochromat
- Dichrromat
- Color weakness
- Cerebral achromatopsia



Reasons

- Monochromat
  - No cones
- Dichrromat
  - No L, No M, and No S
- Color weakness
  - S,M and L of reduced sensitivity
- Cerebral achromatopsia
  - Cones are fine but problem in visual cortex



Dichromatism

- Why more males?
  - Resides in X chromosome
  - Both X’s need to have the defect in women
  - Can be passed on by women with one deficient X to the male offspring

Trichromatic Theory Cannot Explain

- Complementary afterimages
  - Red green complements
  - Blue yellow complements

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Trichromatic Theory Cannot Explain

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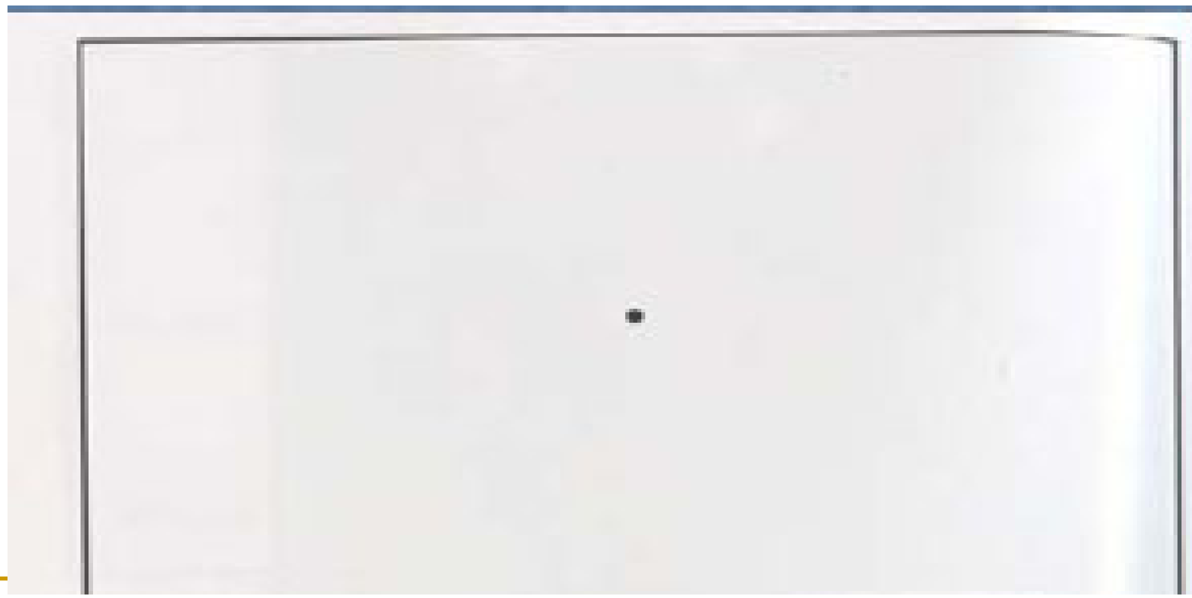
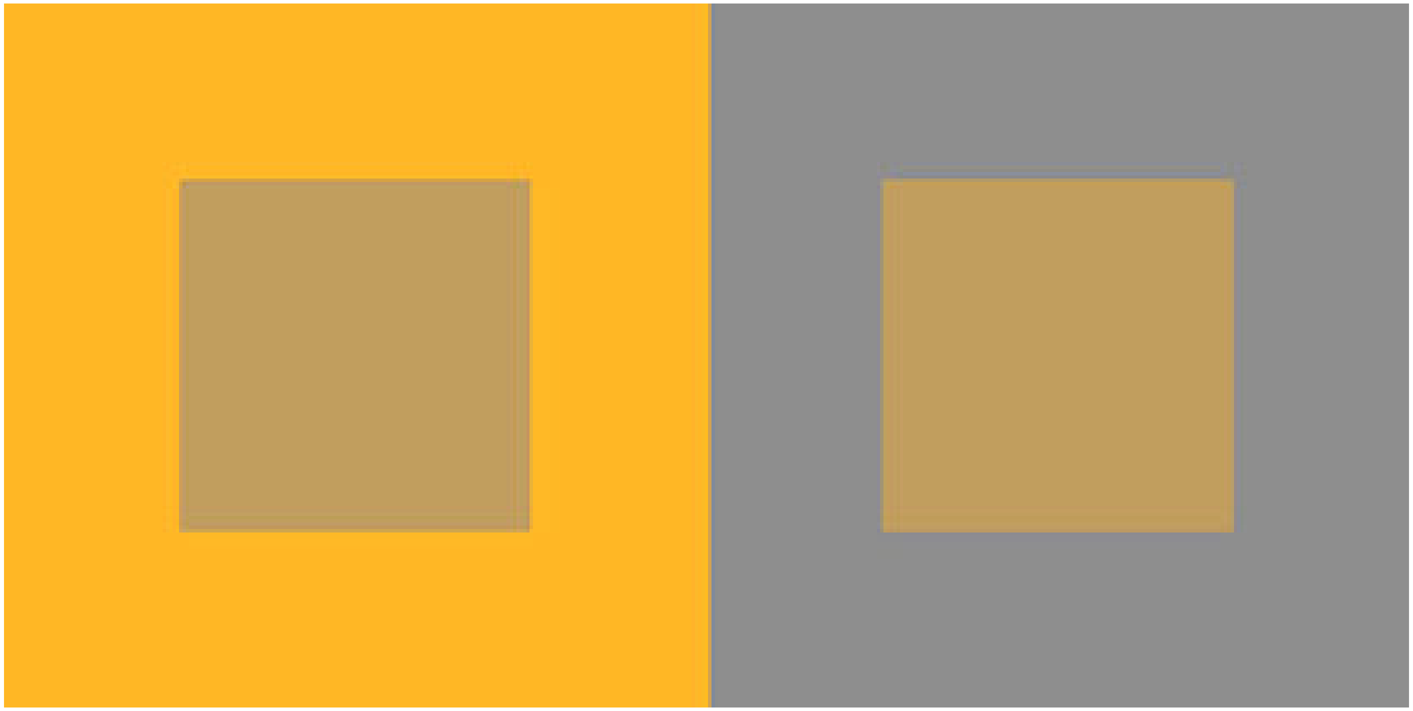


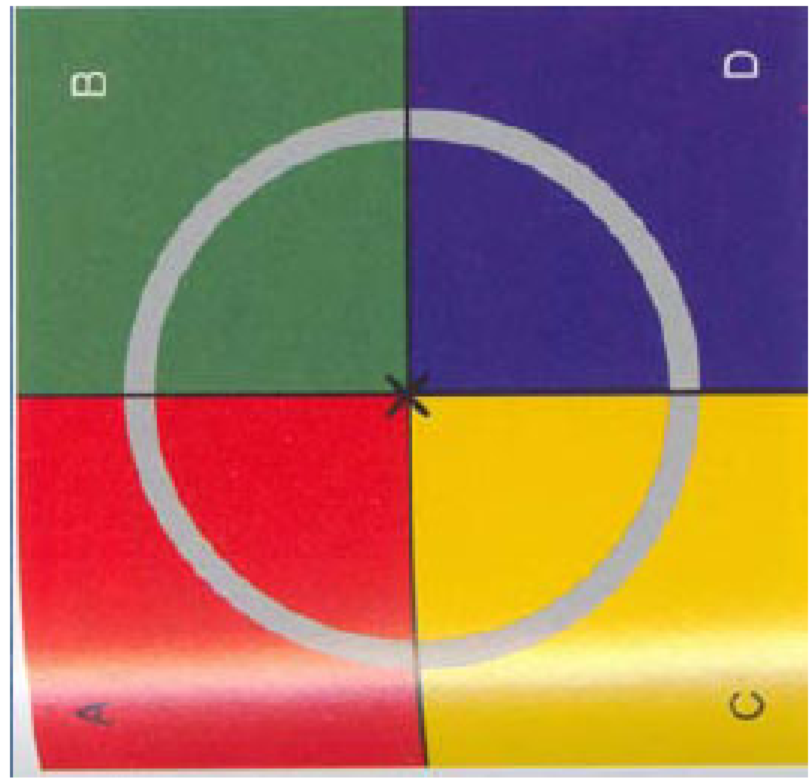
Trichromatic Theory Cannot Explain



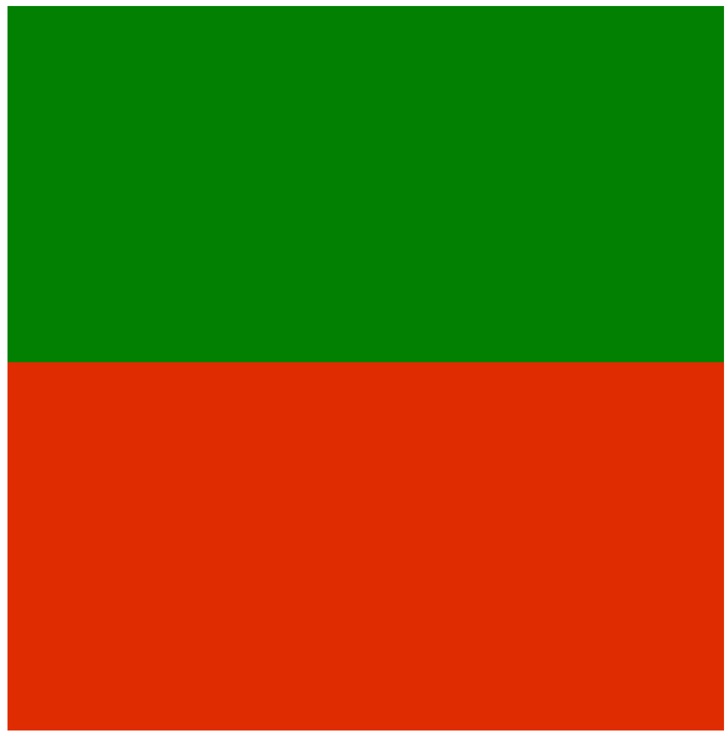
Trichromatic Theory Cannot Explain

Trichromatic Theory Cannot Explain

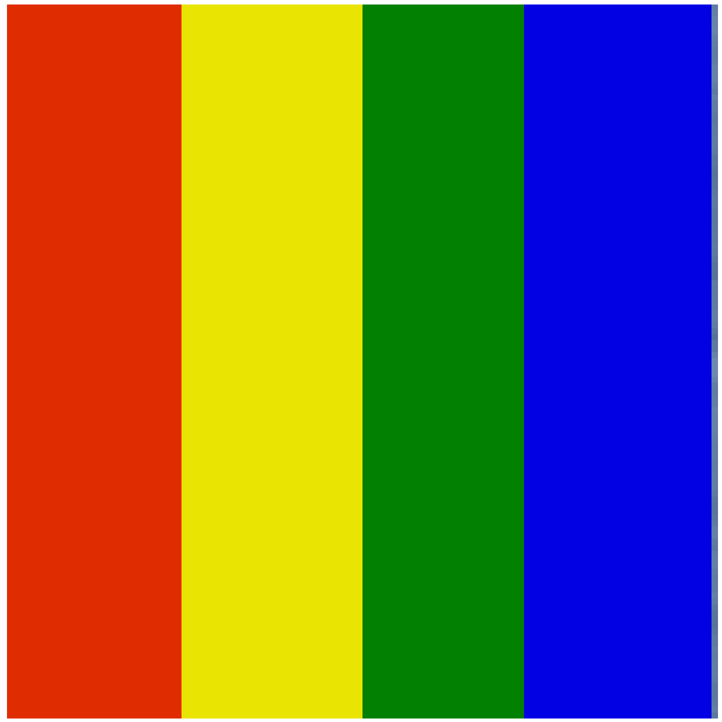
- Simultaneous color contrast
- Visualizing colors



Another experiment

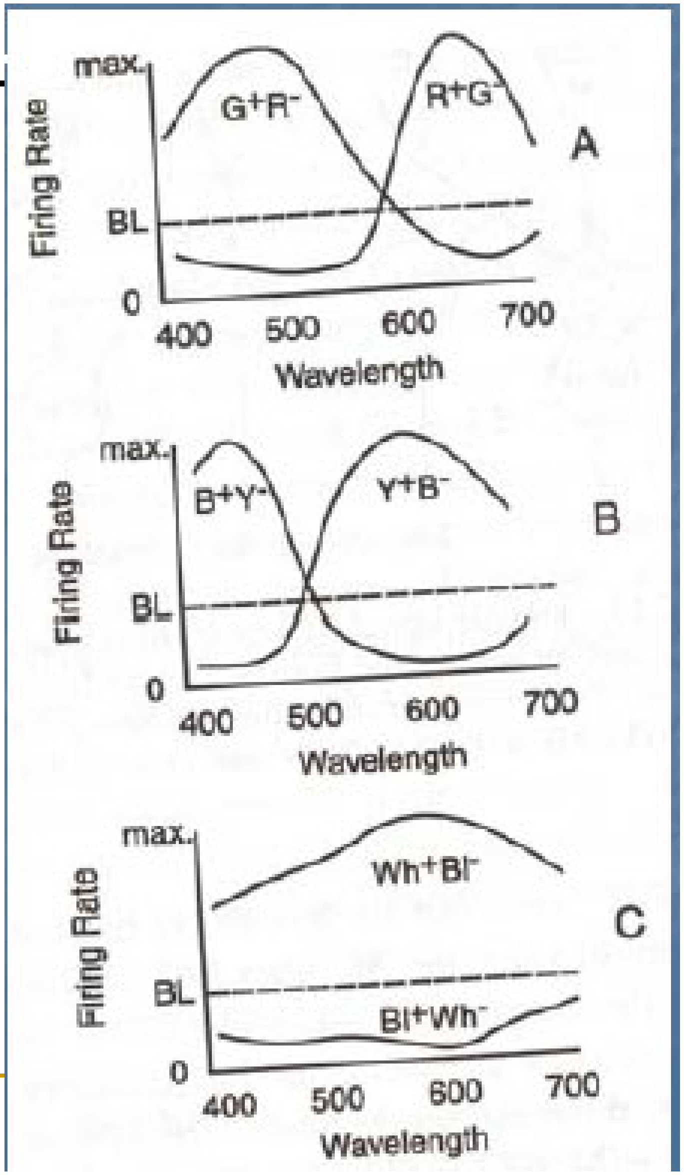


Another experiment



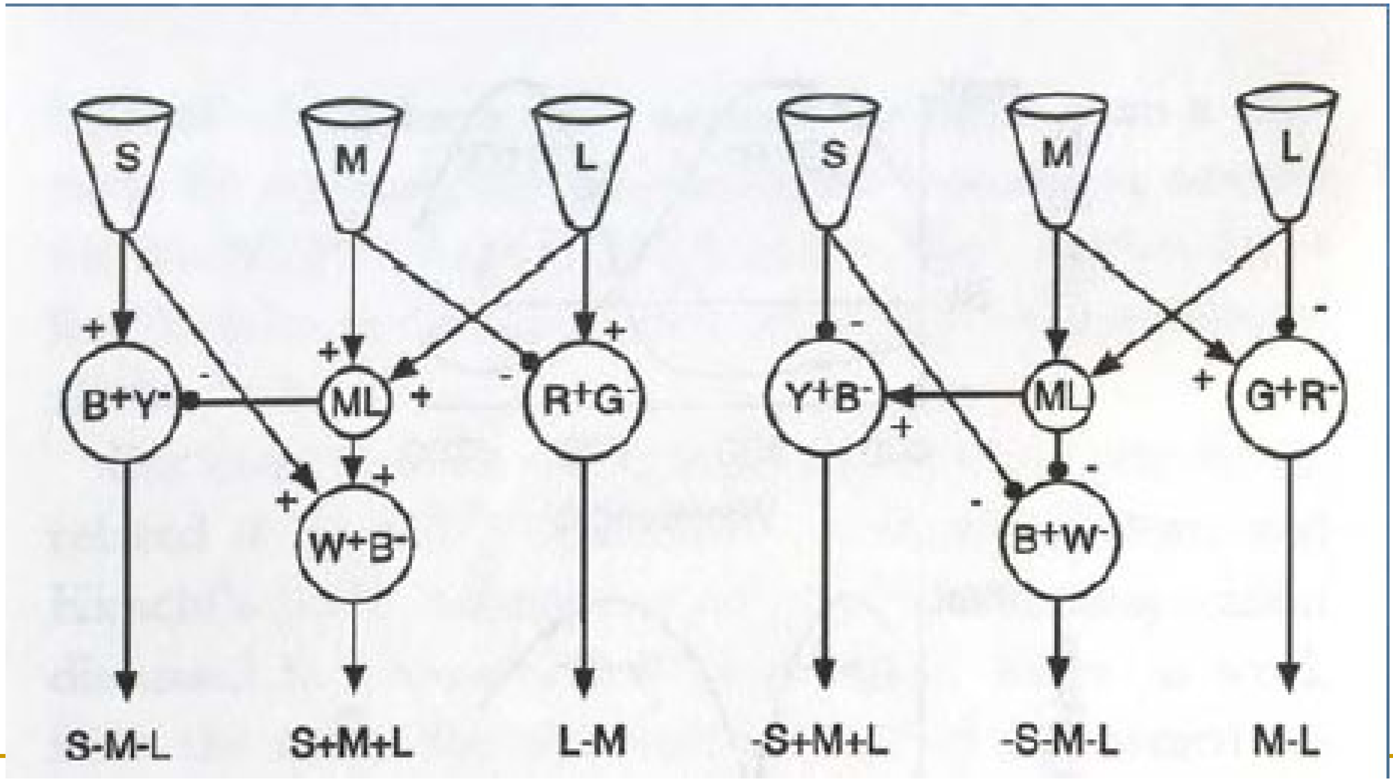
Opponent Theory

- Herring proposed three types of cell
- Long struggle between trichromatic and opponent theory
- In 1965, such cells were found in LGN (not in eye as proposed by Herring)

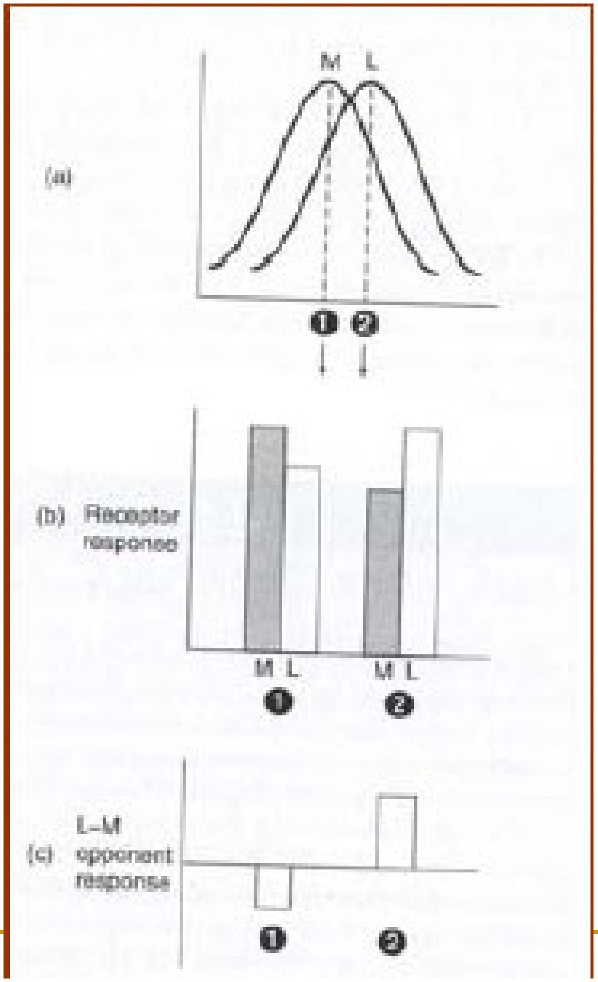


Opponent Theory

- How does signal from the S, M and L cells get processed by the opponent cells?



Why Opponent Theory?



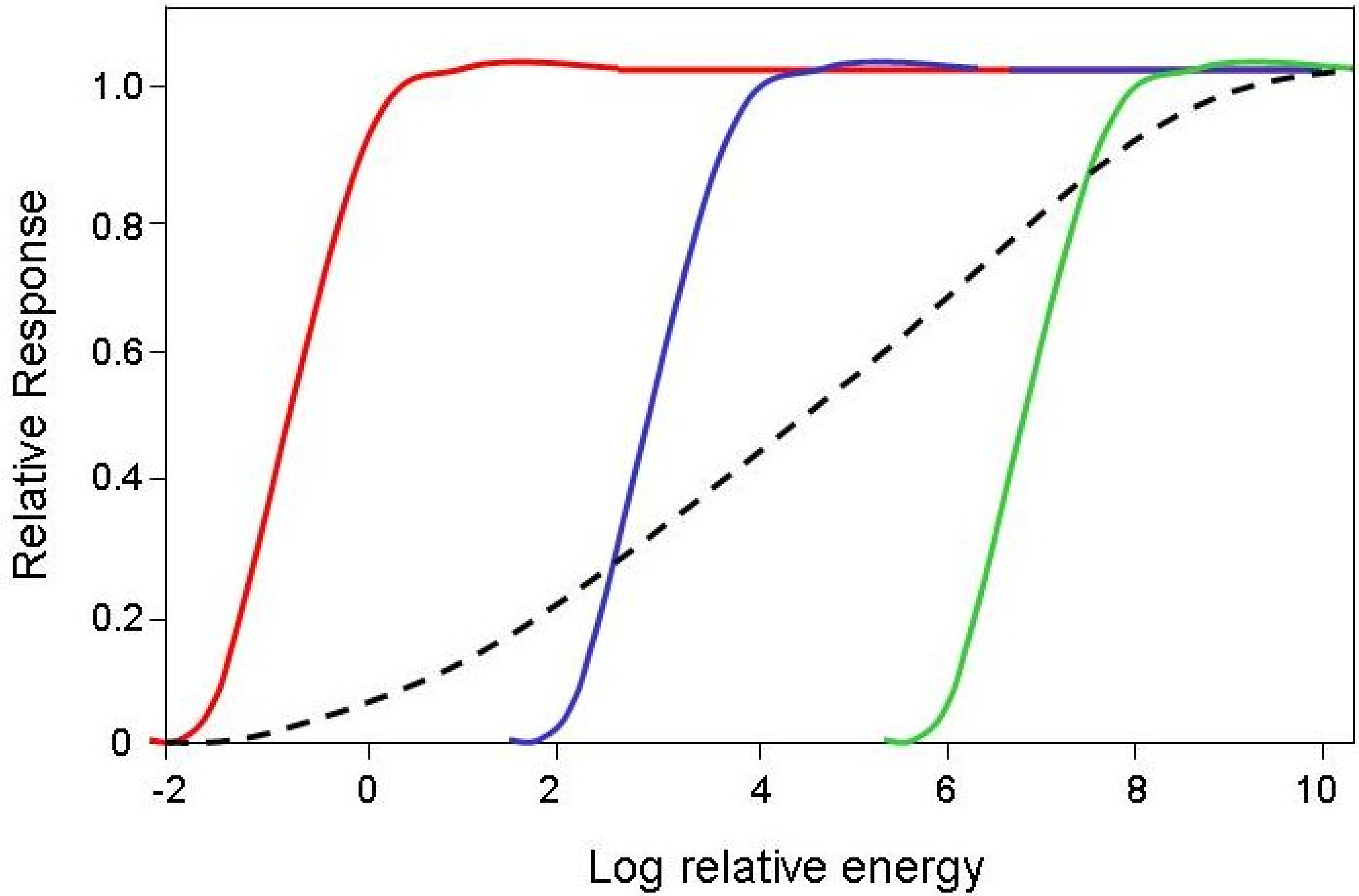
Why long gaze?

- Theory of Adaptation

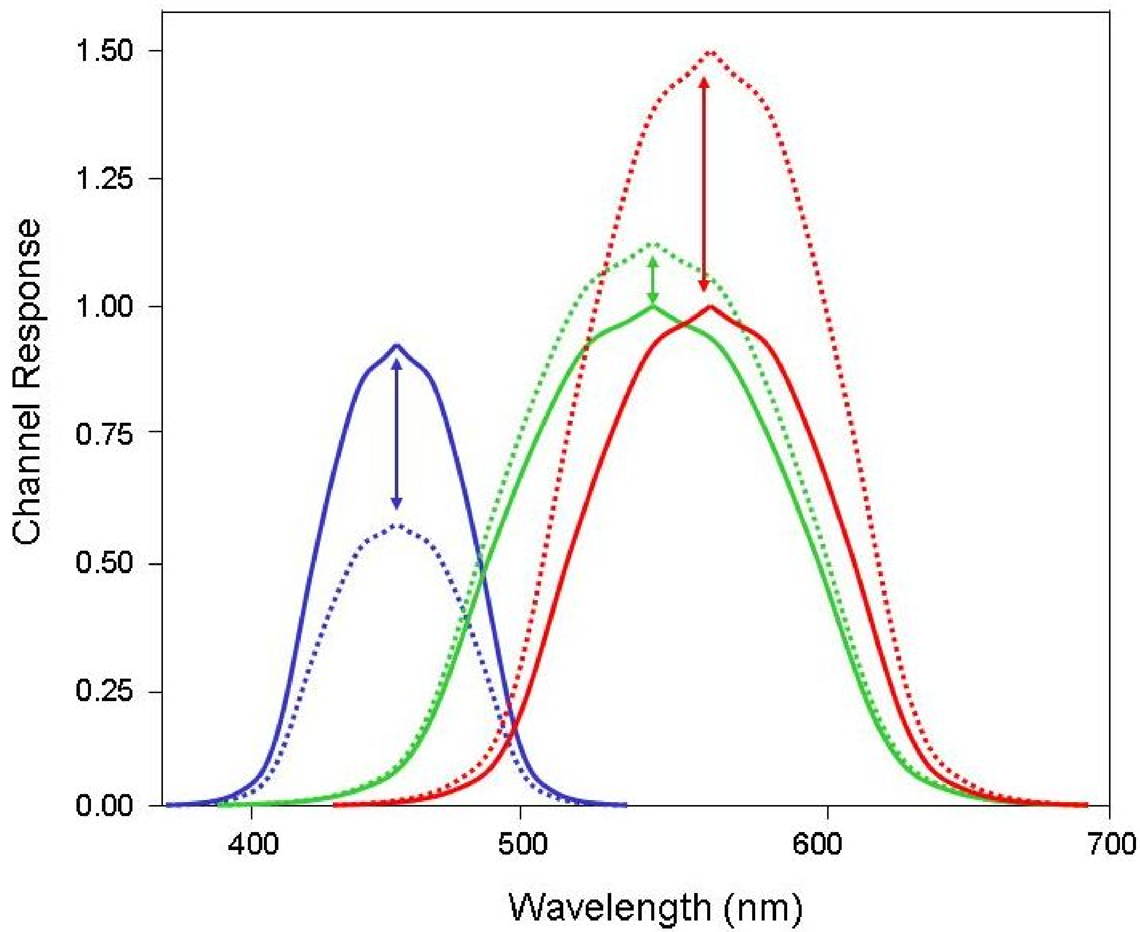
Light Adaptation

- Dark Adaptation
- Light Adaptation
  - Not symmetric (5 minutes, not 30 minutes)
  - Covers a very large dynamic range
    - 10 orders of magnitude
    - How?

Light Adaptation



Chromatic Adaptation (Cones)



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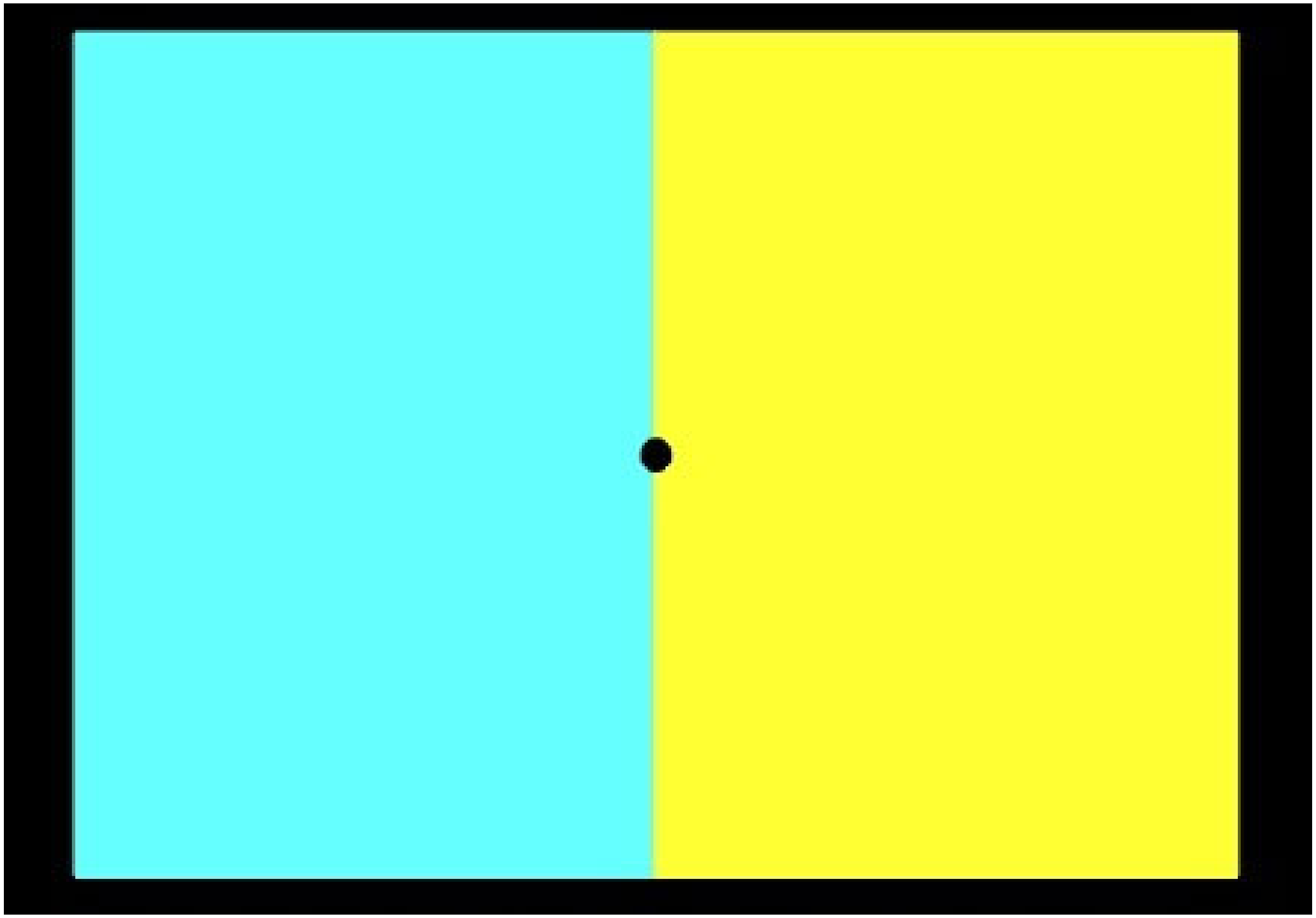
Example of chromatic adaptation

Example of chromatic adaptation



Example of chromatic adaptation

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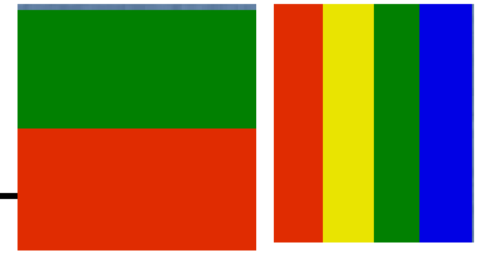
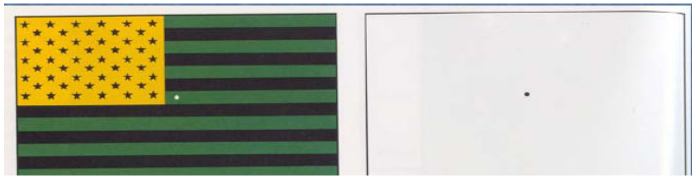
Adaptation



- Prolonged exposure to red
  - R+G- cells fire less strongly
  - G+R- cells fire more strongly
- Red looks less saturated
- Green looks more saturated
- Other colors have a greenish tint

Aftereffects



- Prolonged exposure to green
  - G+R- cells are fatigued
- When trying to view white
  - R+G- cells fire more strongly
  - Hence, red afterimage
- Similarly for blue yellow
- Still cannot explain simultaneous color contrast

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Lightness and Color Constancy

- Lightness remains relatively same even under varying illumination
- Color remains relatively same under vastly different illuminations

Lightness Constancy

- An achromatic surface appears to have same lightness irrespective of different illumination conditions
  - Indoor illumination: 100 photons
    - Black: 10 photons
    - White: 90 photons
  - Outdoor Illumination: 10,000 photons
    - Black: 1000 photons
    - Whiie: 9000 photons
- Black in outdoor is almost 900 times more than white in indoor
  - Still it is perceived as black

Simultaneous Color Contrast

- Double opponent cells in visual cortex
- Same as lateral inhibition