

COLOR

Introduction to Computer Vision
CSE 152
Lecture 6

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Announcements

- HW1 has been posted
- See links on web page for readings on color.

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Deviations from the lens model

Deviations from this ideal are **aberrations**

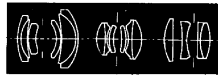
Two types

1. geometrical

- spherical aberration
- astigmatism
- distortion
- coma

2. chromatic

Aberrations are reduced by combining lenses



Compound lenses

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Lighting

- Special light sources
 - Point sources
 - Distant point sources
 - Strip sources
 - Area sources
- Common to think of lighting at infinity (a function on the sphere, a 2-D space)
- Completely arbitrary lighting can be represented as a function on the 4-D ray space (radiance)

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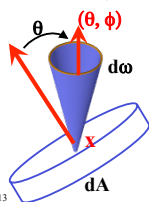
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Radiance

- Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle

$$L = \frac{P}{(dA \cos \theta) d\omega}$$

- Units: watts per square meter per steradian : $w/(m^2 sr^{-1})$



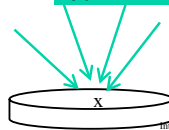
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Irradiance

- How much light is arriving at a surface?
- Irradiance -- power per unit area: W/cm^2
- Total power arriving at the surface is given by adding irradiance over all incoming angles

$$\int_{hemisphere} L(x, \theta, \phi) \cos \theta d\omega$$

$$= \int_0^{2\pi} \int_0^{\pi/2} L(x, \theta, \phi) \cos \theta \sin \theta d\theta d\phi$$



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Camera's sensor

- Measured pixel intensity is a function of irradiance integrated over
 - pixel's area
 - over a range of wavelengths
 - For some time

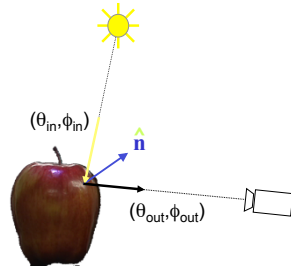
$$I = \int_t \int_\lambda \int_x \int_y E(x, y, \lambda, t) s(x, y) q(\lambda) dy dx d\lambda dt$$

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BRDF

- Bi-directional Reflectance Distribution Function
 $\rho(\theta_{in}, \phi_{in}; \theta_{out}, \phi_{out})$
- Function of
 - Incoming light direction:
 θ_{in}, ϕ_{in}
 - Outgoing light direction:
 θ_{out}, ϕ_{out}
- Ratio of incident irradiance to emitted radiance



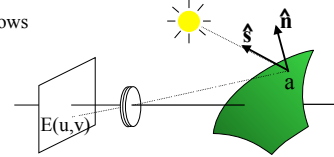
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Lambertian Surface

[Important: We'll use this a lot]

Without shadows



At image location (u,v) , the intensity of a pixel $x(u,v)$ is:

$$E(u,v) = [a(u,v) \hat{n}(u,v)] \cdot [s_0 \hat{s}]$$

where

- $a(u,v)$ is the albedo of the surface projecting to (u,v) .
- $\hat{n}(u,v)$ is the direction of the surface normal.
- s_0 is the light source intensity.
- $\hat{s}$ is the direction to the light source.

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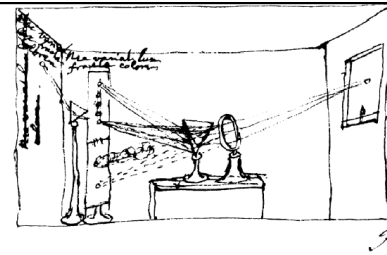
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The appearance of colors

- Color appearance is strongly affected by (at least):
 - Spectrum of lighting striking the retina
 - other nearby colors (space)
 - adaptation to previous views (time)
 - “state of mind”

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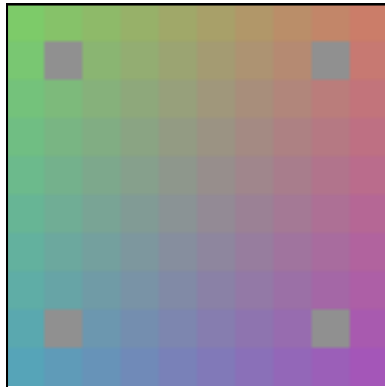
4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By recombining the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides



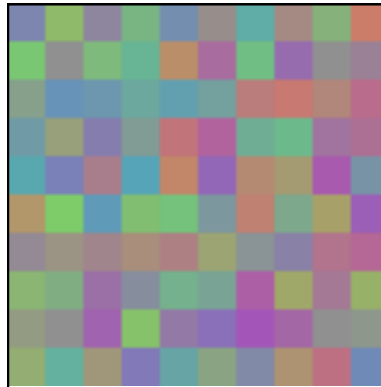
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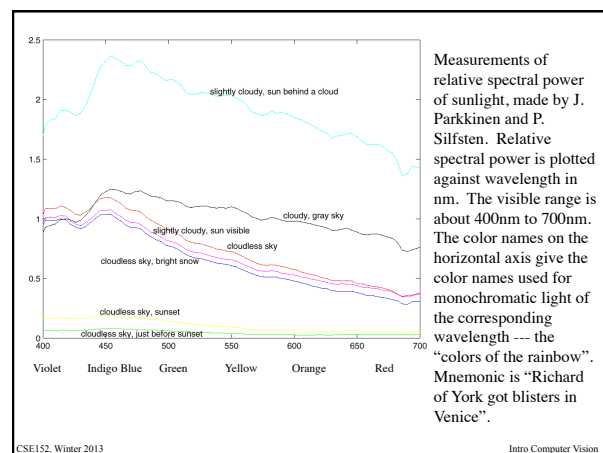
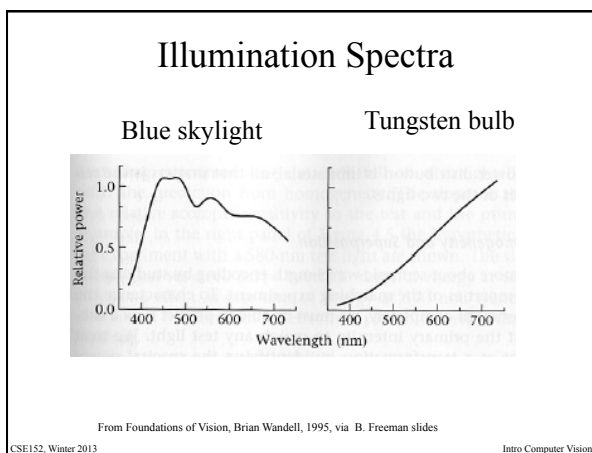
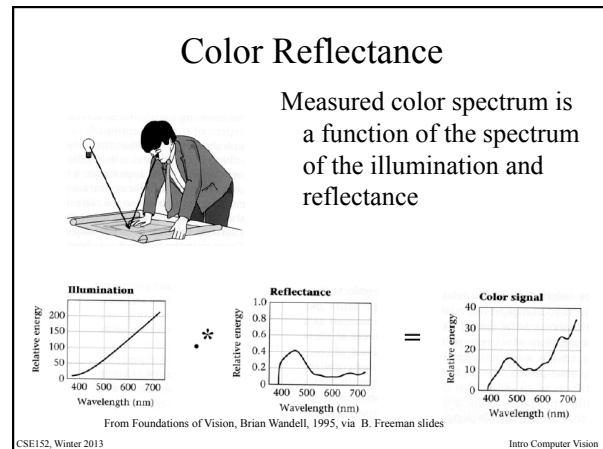
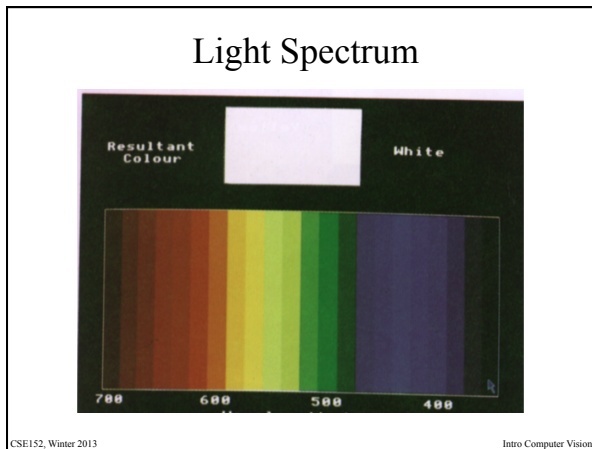
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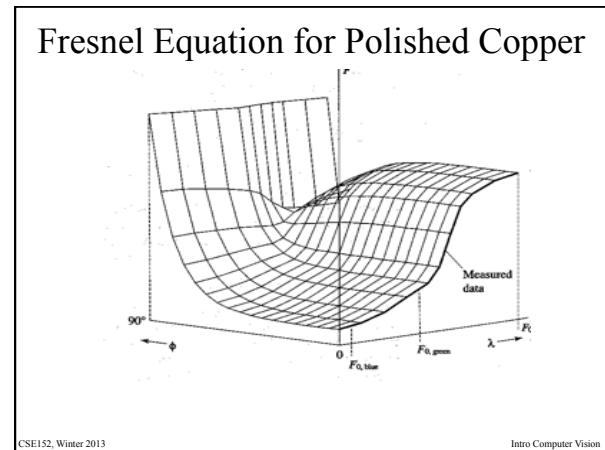
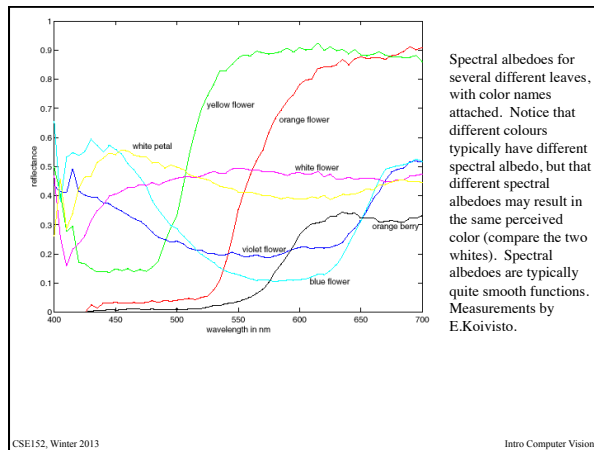
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Dielectrics (e.g., plastics)

Diffuse + specular component
Specularity is the color of the light source

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Color matching experiment

4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

Not on a computer Screen

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slide from T. Darral

Color matching experiment 1

Test Light

Primaries

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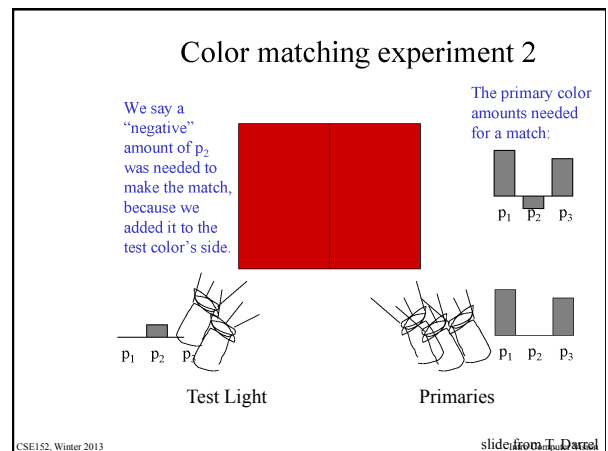
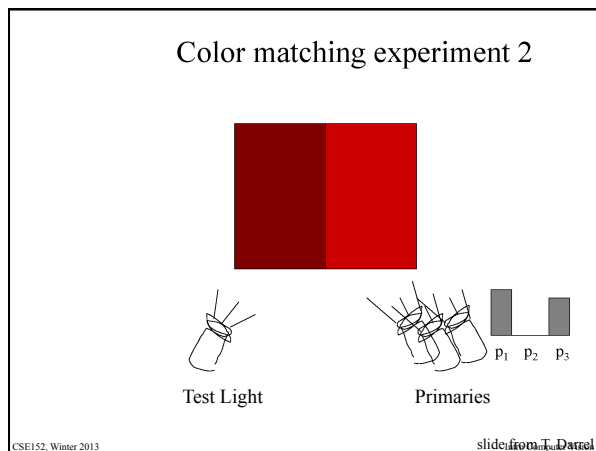
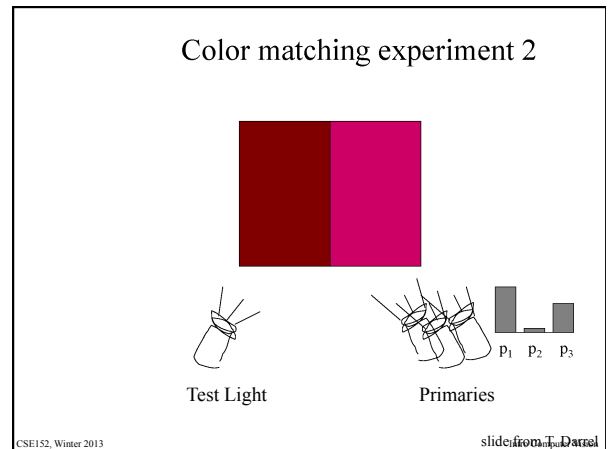
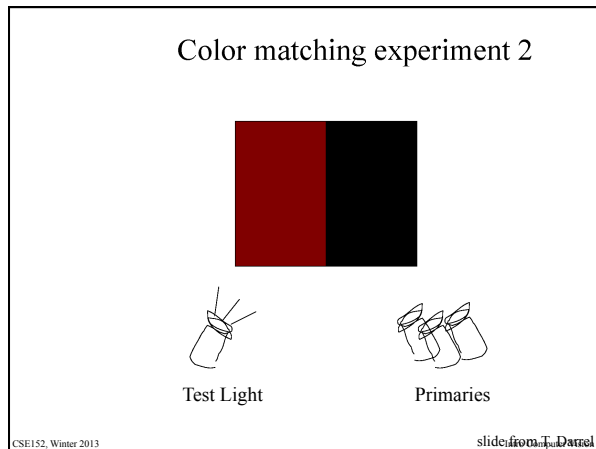
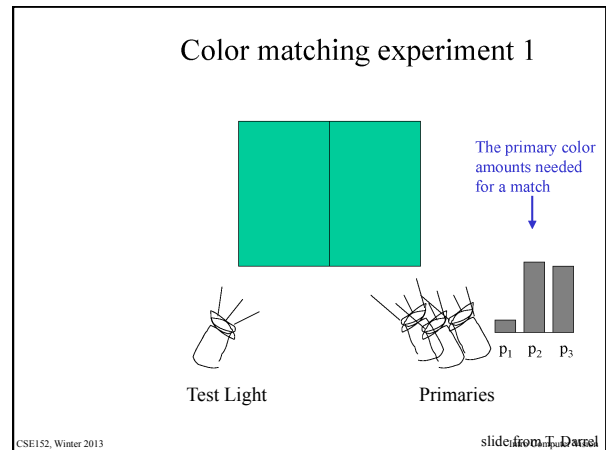
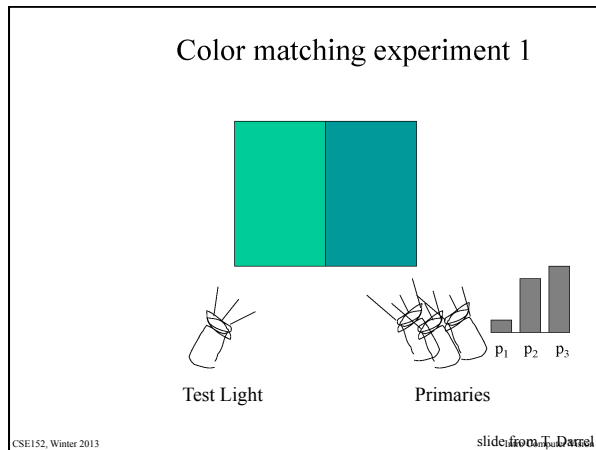
Color matching experiment 1

Test Light

Primaries

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slide from T. Darral



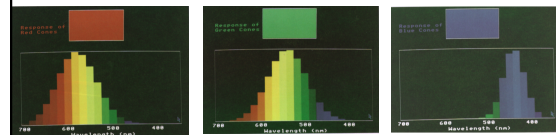
The principle of trichromacy

- Experimental facts:
 - Three primaries will work for most people if we allow subtractive matching
 - Exceptional people can match with two or only one primary.
 - This could be caused by a variety of deficiencies.
 - Most people make the same matches.
 - There are some anomalous trichromats, who use three primaries but make different combinations to match.

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Color receptors



"Red" cone

"Green" cone

"Blue" cone

Response of k'th cone =
$$\int \rho_k(\lambda) E(\lambda) d\lambda$$

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Color Cameras

Eye:

Three types of Cones

Cameras:

1. Prism (with 3 sensors)
 2. Filter mosaic
 3. Filter wheel
- ... and X3

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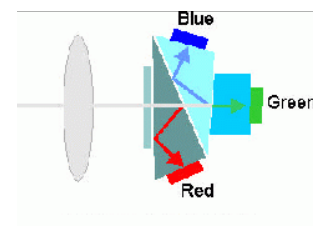
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Prism color camera

Separate light in 3 beams using dichroic prism

Requires 3 sensors & precise alignment

Good color separation

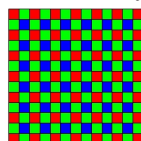
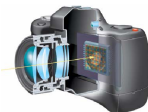


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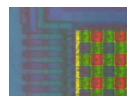
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Filter mosaic

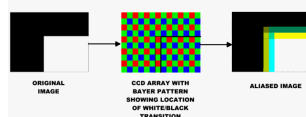
Coat filter directly on sensor



Bayer filter



Demosaicing (obtain full colour & full resolution image)



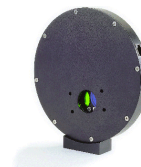
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Filter wheel

Rotate multiple filters in front of lens

Allows more than 3 color bands

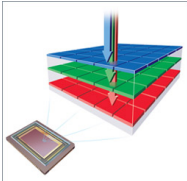


Only suitable for static scenes

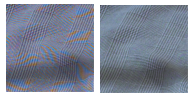
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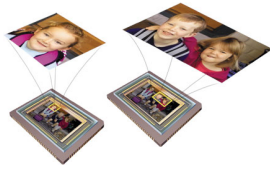
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color CMOS sensor Foveon's X3

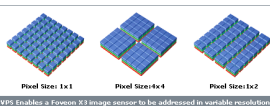


better image quality





smarter pixels

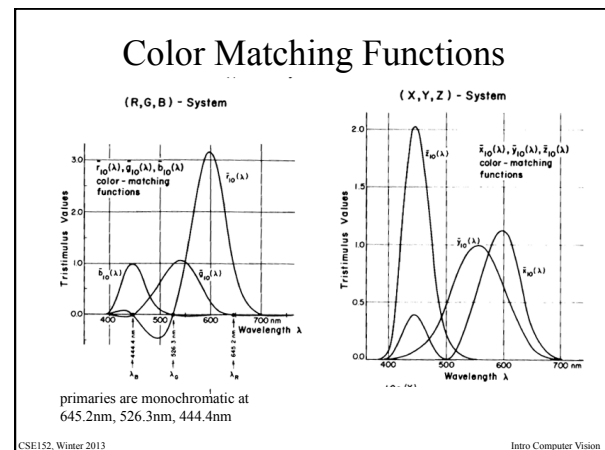


Pixel Size: 1x1 Pixel Size: 4x4 Pixel Size: 2x2

VPI enables a Foveon's X3 image sensor to be addressed in variable resolutions

Acquired by Sigma in 2008,

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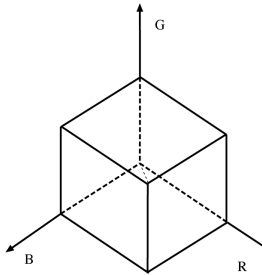


Color spaces

- Linear color spaces describe colors as linear combinations of primaries
- Choice of primaries=choice of color matching functions=choice of color space
- Color matching functions, hence color descriptions, are all within linear transformations
- RGB: primaries are monochromatic, energies are 645.2nm, 526.3nm, 444.4nm. Color matching functions have negative parts -> some colors can be matched only subtractively.
- CIE XYZ: Color matching functions are positive everywhere, but primaries are imaginary. Usually draw x, y, where $x=X/(X+Y+Z)$ and $y=Y/(X+Y+Z)$

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RGB Color Cube



- Block of colours for (r, g, b) in the range (0-1).
- Convenient to have an upper bound on coefficient of each primary.
- In practice:
 - primaries given by monitor phosphors, led filters, etc.
 - (phosphors are the materials on the face of the monitor screen that glow when struck by electrons)

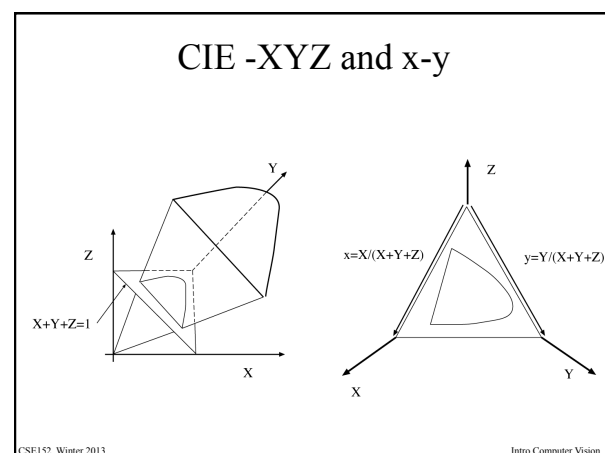
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YIQ Model

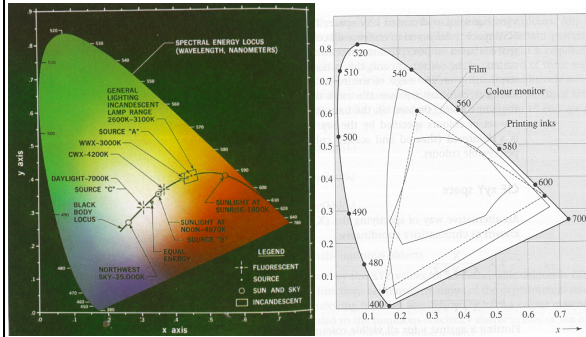
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.532 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Used by NTSC TV standard
- Separates Hue & Saturation (I,Q) from Luminance (Y)

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CIE xyY (Chromaticity Space)



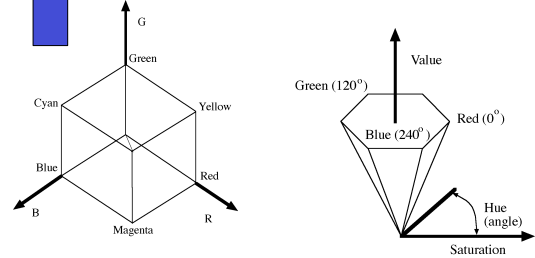
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HSV Hexcone

Hue, Saturation, Value

AKA: Hue, Saturation, Intensity (HIS)

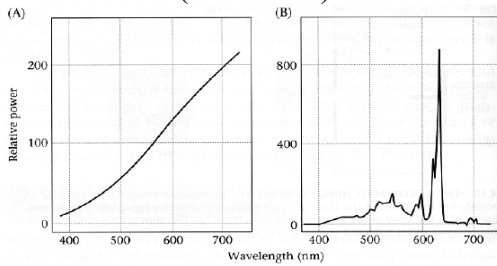


Hexagon arises from projection of cube onto plane orthogonal to $(R,G,B) = (1,1,1)$

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Metameric Lights (Metamers)



4.11 METAMERIC LIGHTS. Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.

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