Computer Vision

3. Color

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Outline

- Color sources and reflectance
- Color perception
- Color representation
- Surface color from images

Textbook:

• David A. Forsyth and Jean Ponce, Computer Vision: A Modern Approach, Prentice Hall, New Jersey, (1st Ed. 2003, 2nd Ed. 2012).

Some contents are from the reference lecture notes:

• Prof. D.A. Forsyth, Computer Vision, UIUC.

• Prof. J. Rehg, Computer Vision, Georgia Inst. of Tech.

• Prof. D. Lowe, Computer Vision, UBC, CA.

• Prof. T. Darrell, Computer Vision and Applications, MIT.

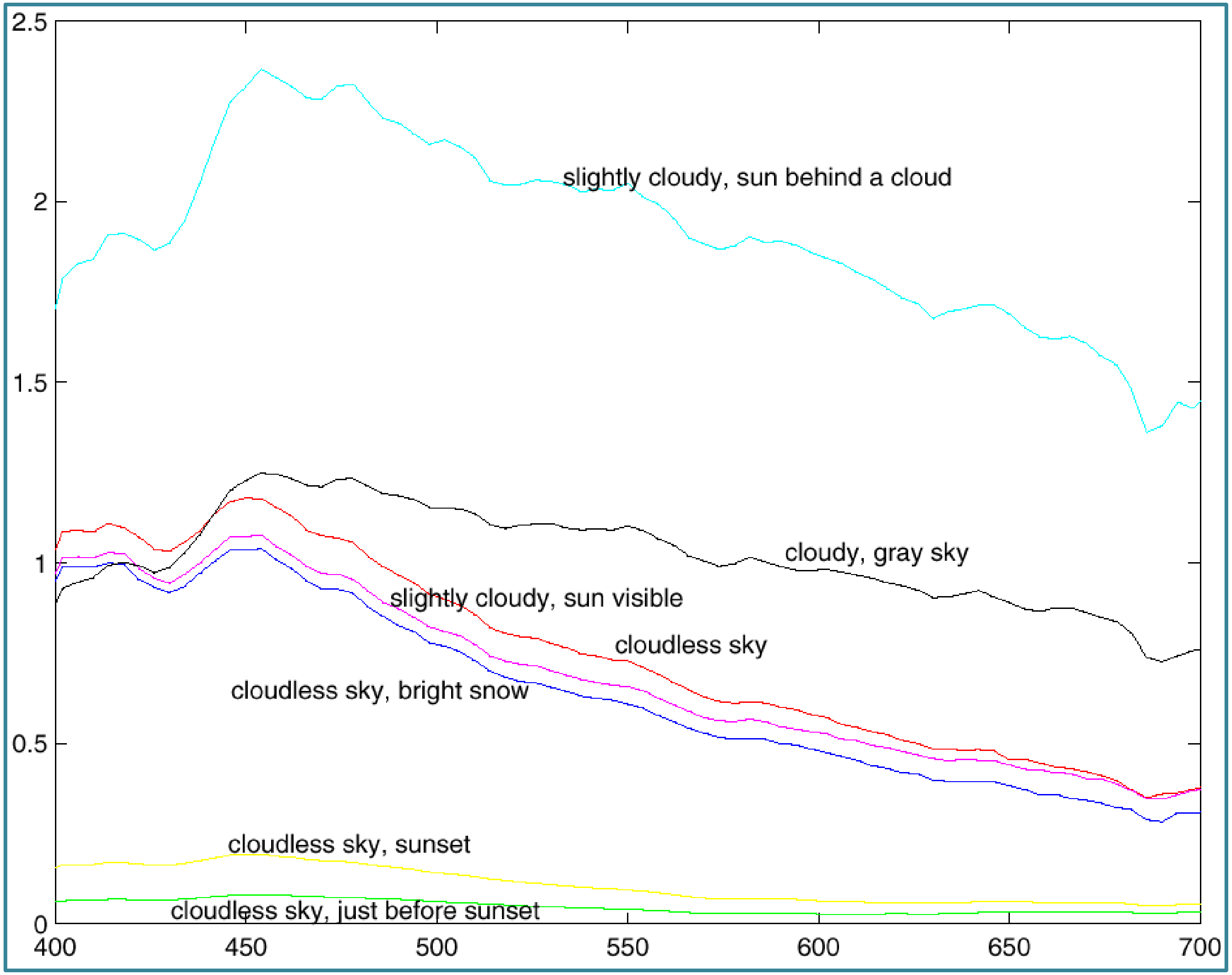
•Hearn and Baker, Computer Graphics, 3rd Ed., Prentice Hall

• E.Angel, Interactive Computer Graphics, 4th Ed., Addison Wesley

What’s color?

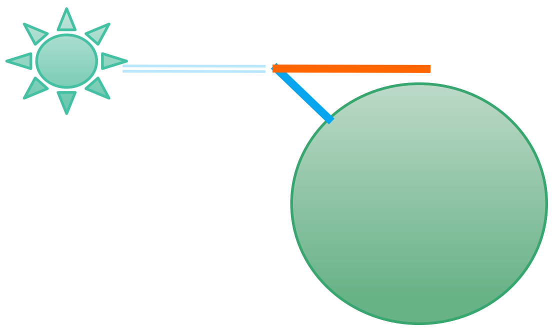
- Light is produced in different amounts at different wavelengths by each light source.
- Light is differentially reflected at each wavelength, which gives objects their natural colors.
- The sensation of color is determined by the human visual system, based on the product of light and reflectance (or transmission).

Illumination of sky



Why the sky is blue?

- Light of a long wavelength can travel much farther before scattered.



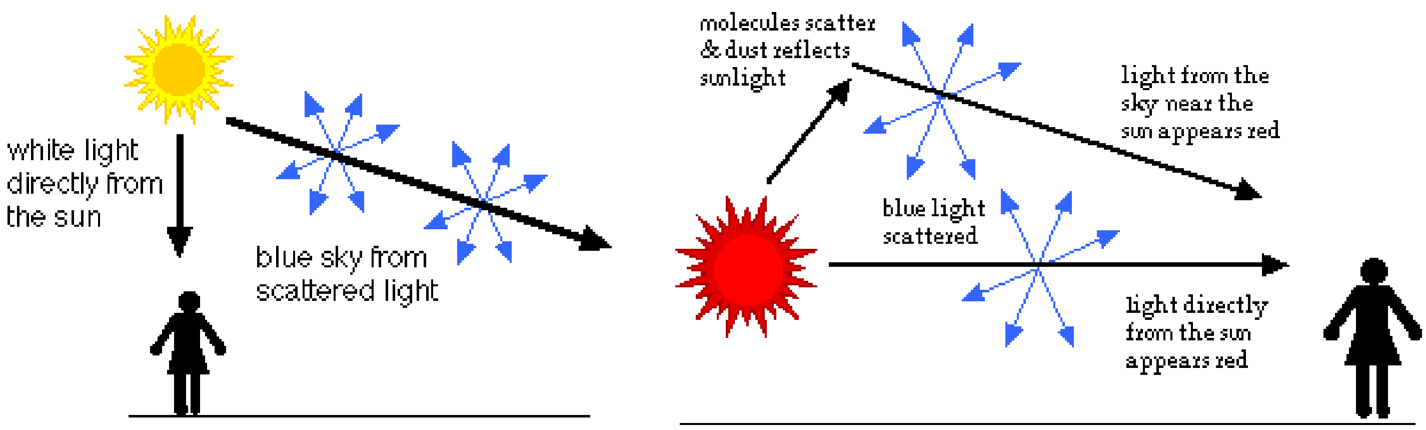
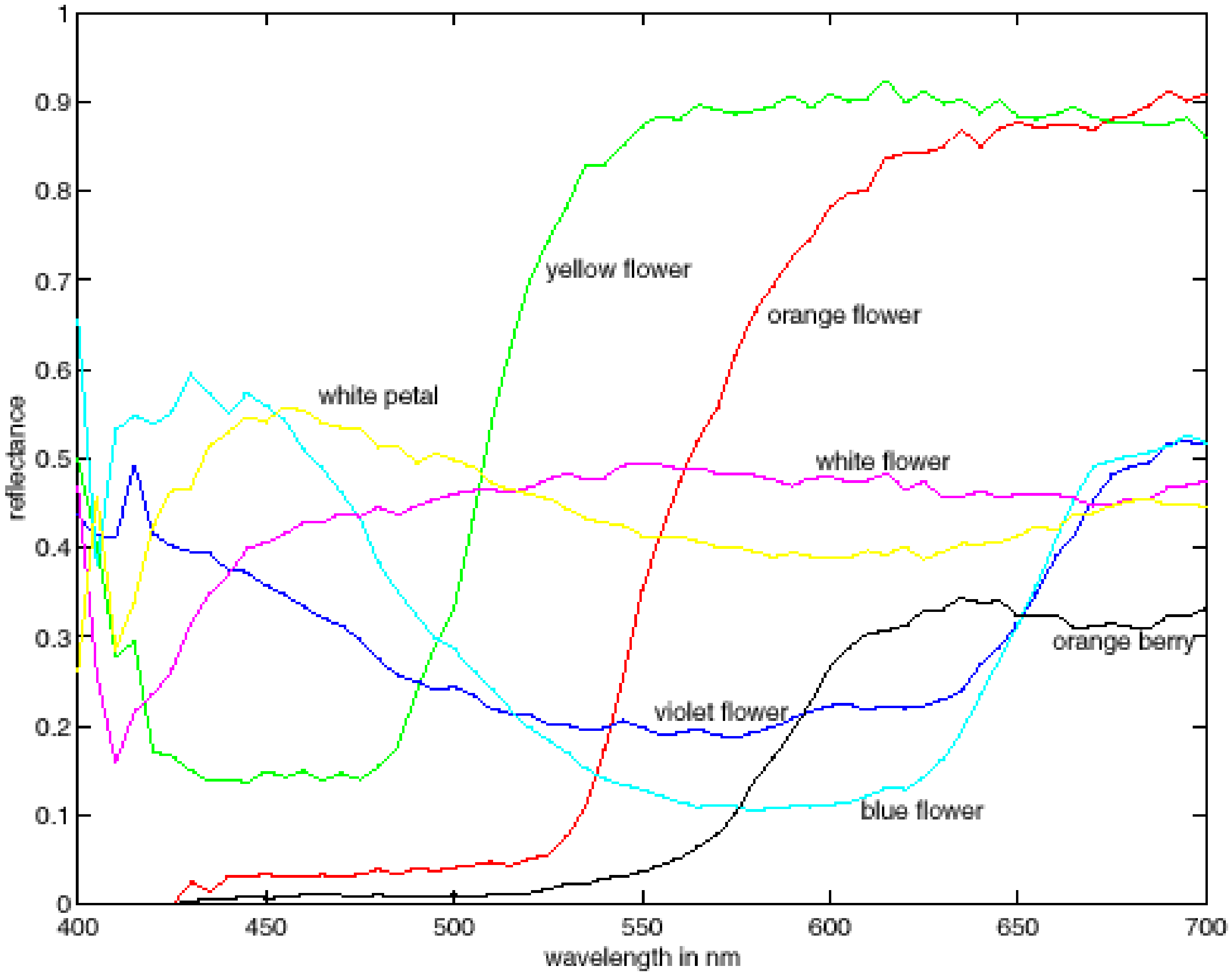
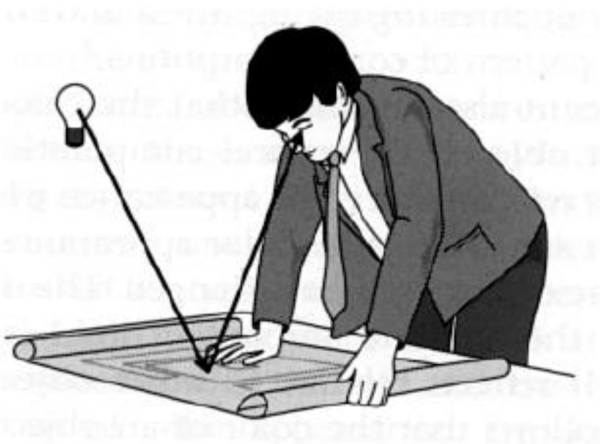


Figure from http://www.sciencemadesimple.com/sky_blue.html

Spectral albedo

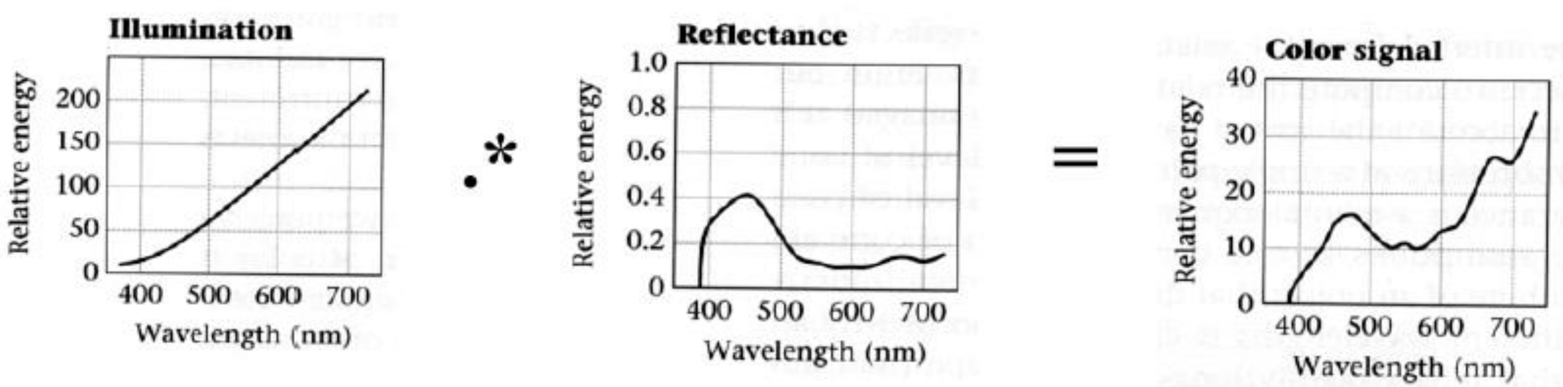


Bidirectional reflectance distribution function



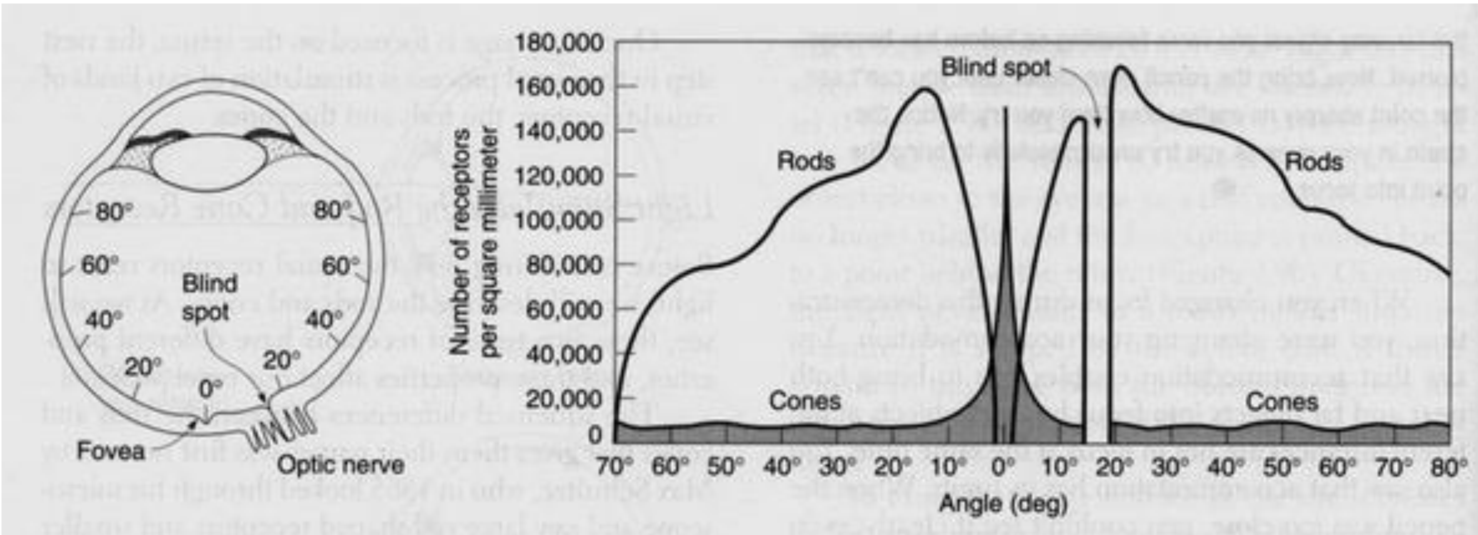
Often are more interested in relative spectral composition than in overall intensity, so the spectral BRDF computation simplifies a wavelength-by-wavelength multiplication of relative energies.

Why do we usually use RGB?



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

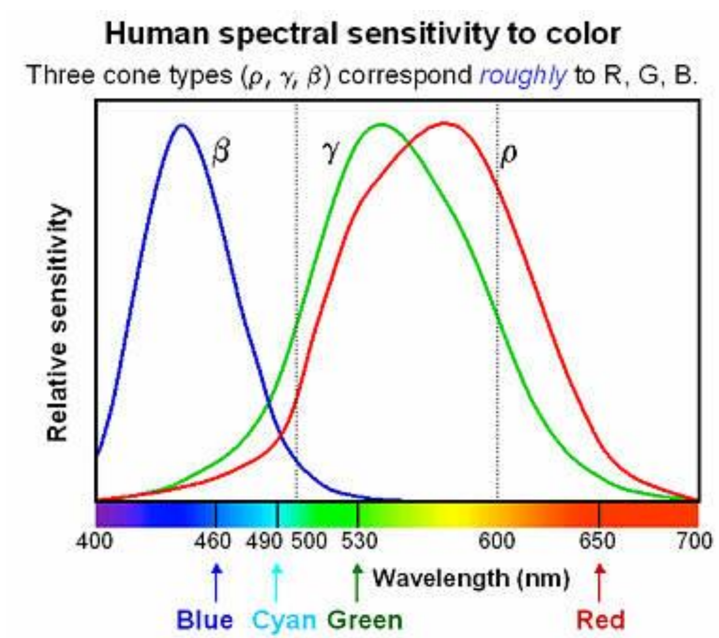
Retina



- Center of retina has most of the cones →
  - allows for high acuity of objects focused at center
- Edge of retina is dominated by rods →
  - allows detecting motion of threats in periphery

Color perception via cones

- "Photopigments" used to sense color
- 3 types: blue, green, "red" (really yellow) (or S, M, L cones)
  - each sensitive to different bands of spectrum
  - ratio of neural activity of the 3 $\rightarrow$ color
    - other colors are perceived by combining stimulation

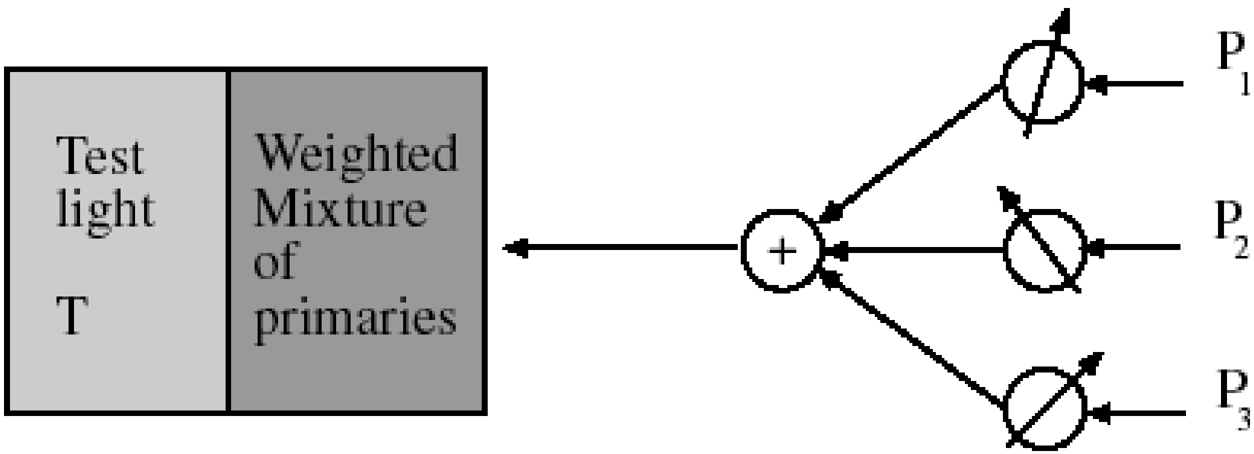


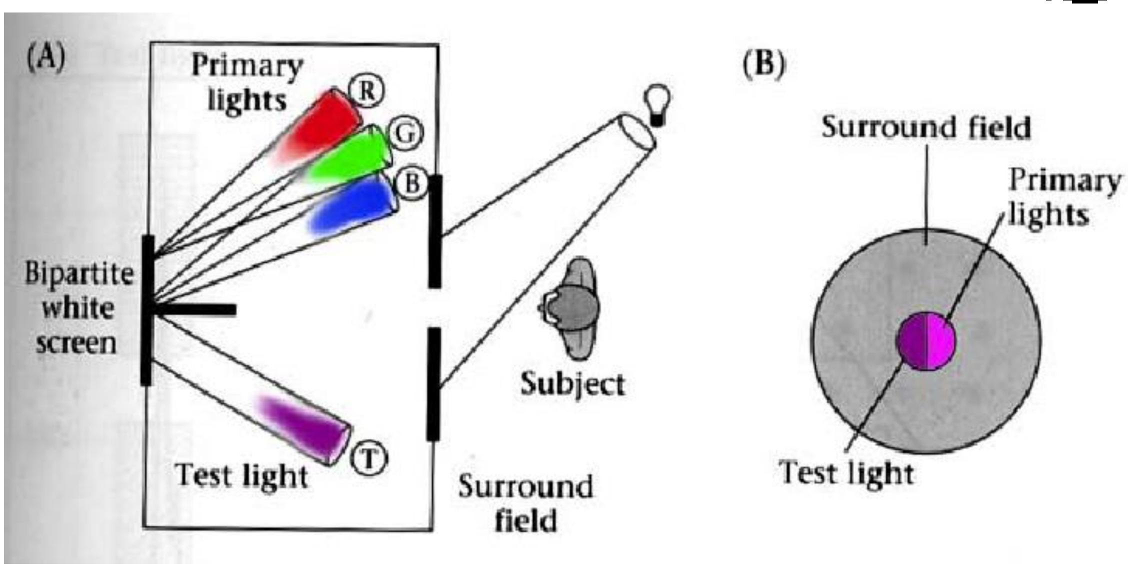
http://www.normankoren.com

Distribution of photopigments

- Not distributed evenly
  - mainly reds (64%) & very few blues (4%) →
    - insensitivity to short wavelengths
      - cyan to deep-blue
- Center of retina (high acuity) has no blue cones →
  - disappearance of small blue objects you fixate on

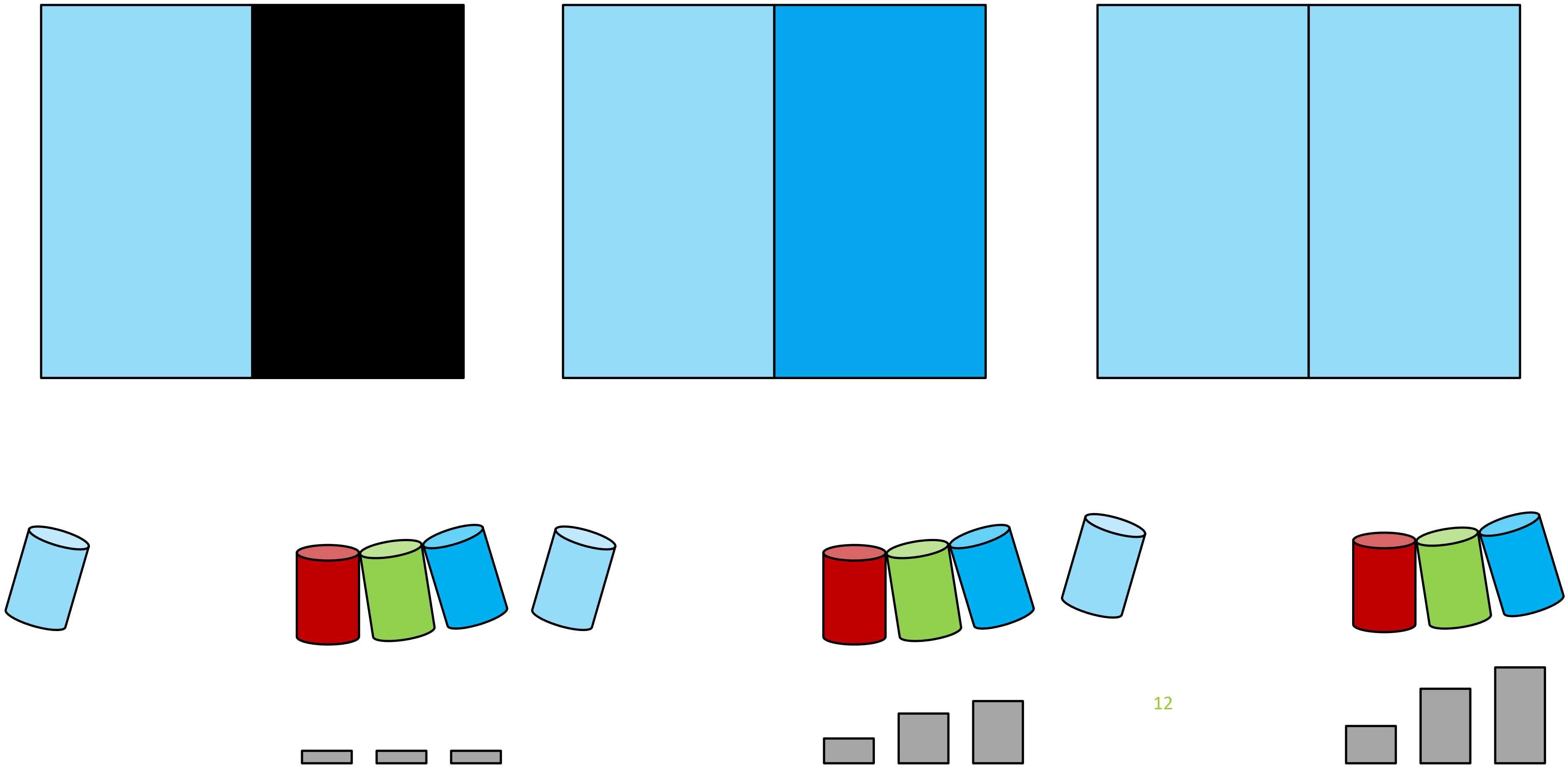
Color match experiments





Color matching experiments imply that 3 primaries are enough for most people.

Color matching experiment



Trichromacy

- Experimental facts:
  - Three primaries will work for most people if we allow subtractive matching
  - Exceptional people can match with two or only one .
  - Some elderly people may choose weights that differ from the norm.
  - Most people make the same matches.

- Color matching experiments imply that three good primaries are sufficient.

Color space

- Use color matching functions to define a coordinate system for color.
- Each color can be assigned a triple of coordinates with respect to some color space (e.g. RGB).
- Devices (monitors, printers, projectors) and computers can communicate colors precisely.

RGB color space

- Primaries are monochromatic 645.2nm, 526.3nm, 444.4nm.
- Color matching functions have negative parts
- Some colors can be matched with subtraction.

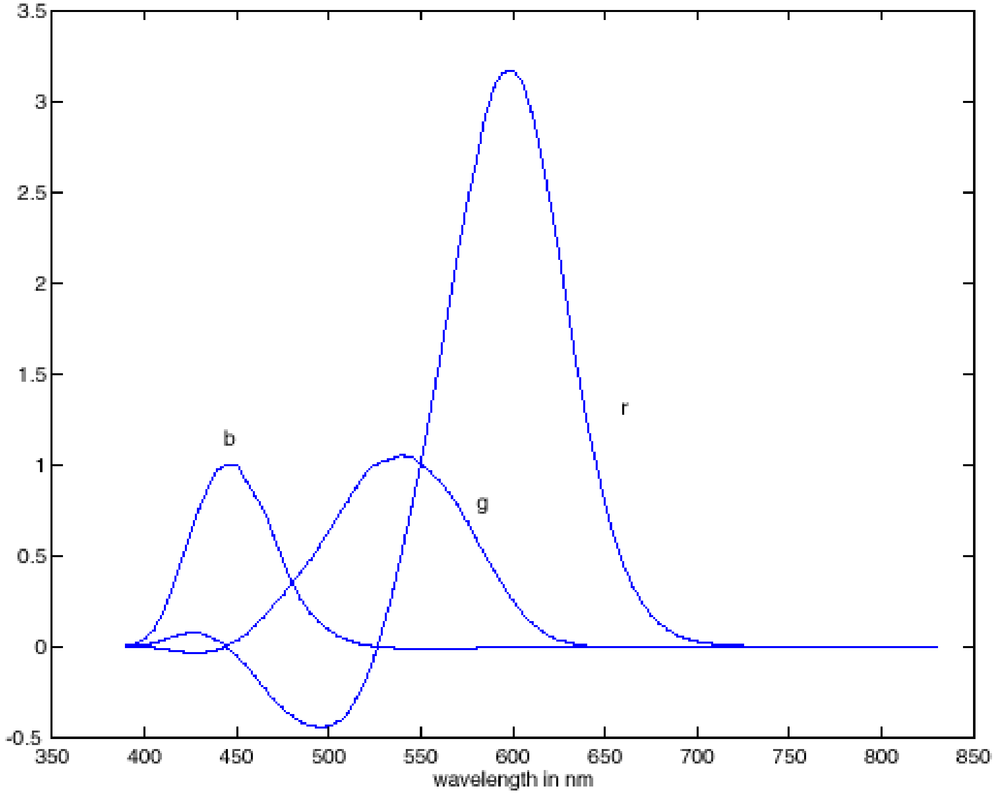
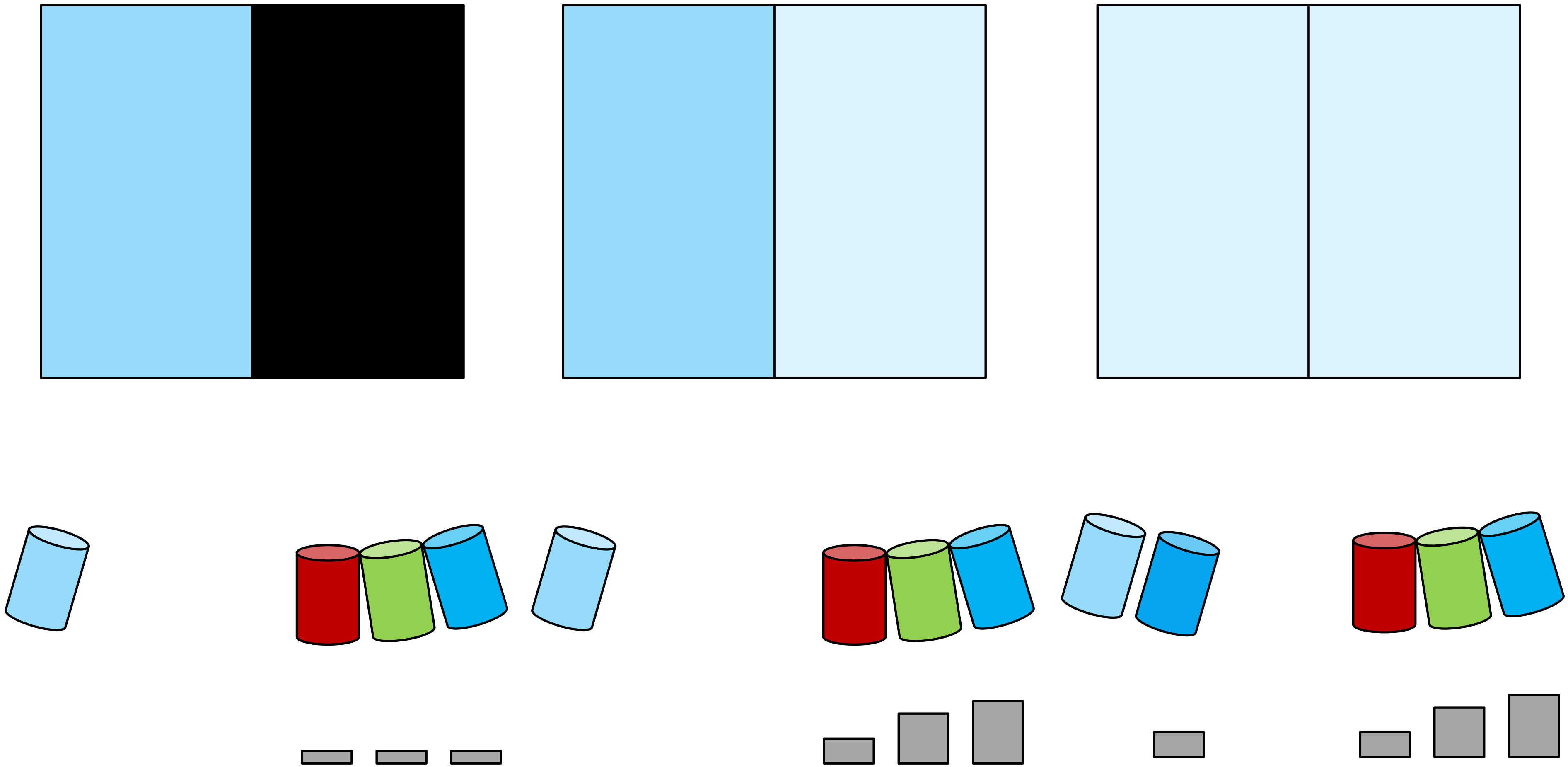


Figure courtesy of D. Forsyth

Color matching experiment

What's the negative color?



CIE XYZ color space

- CIE XYZ: color matching functions are positive everywhere, but primaries are imaginary.
- Usually draw x, y, as
  $x = X/(X+Y+Z)$
  $y = Y/(X+Y+Z)$
- The overall brightness is ignored.

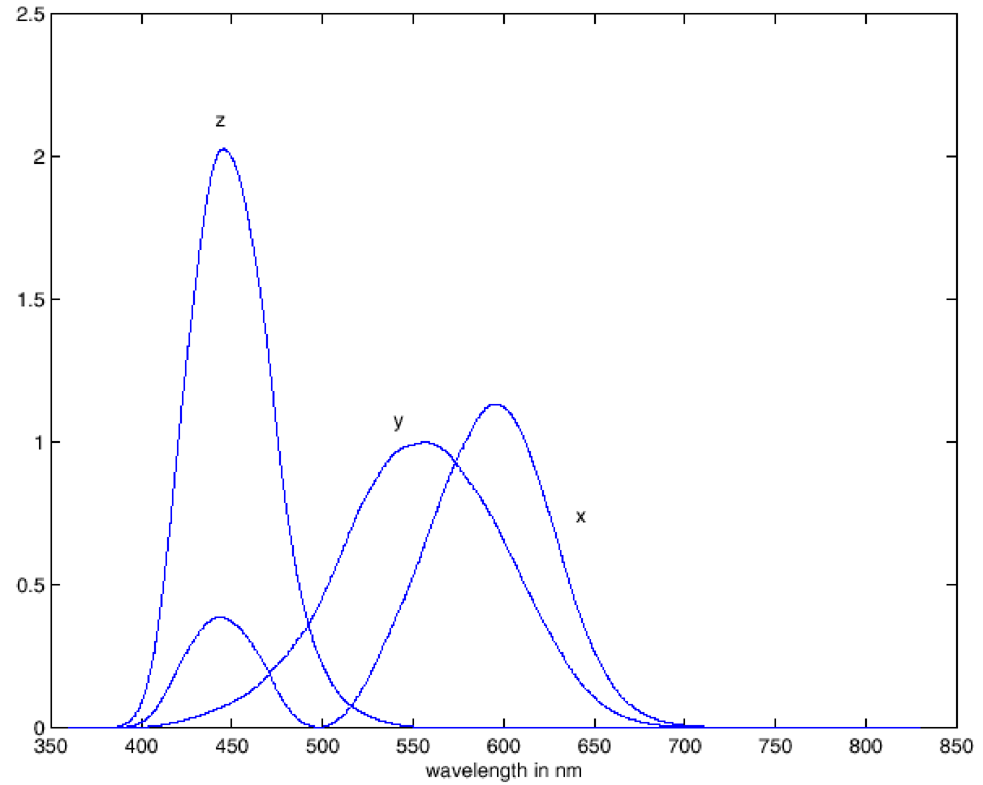
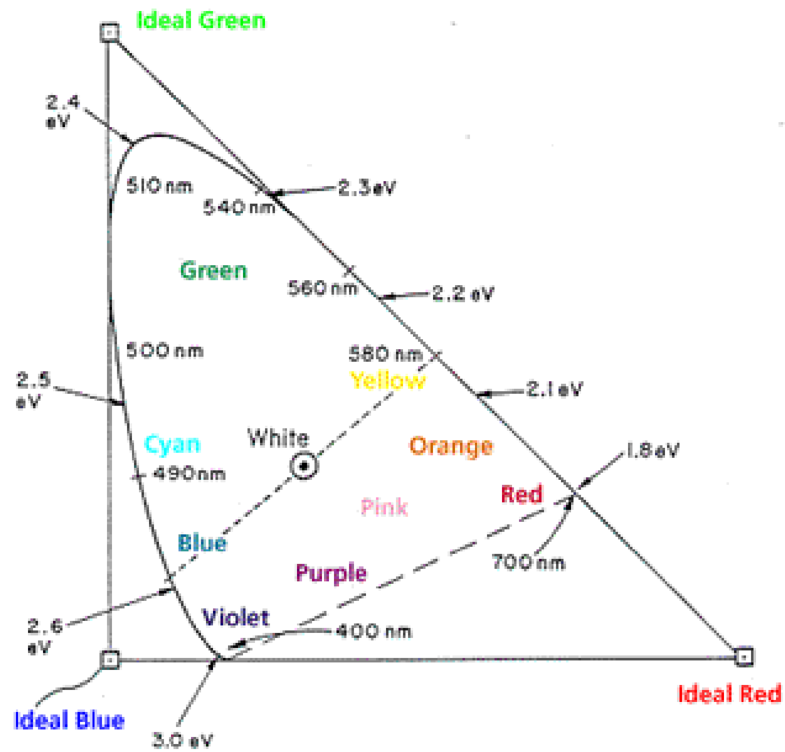


Figure courtesy of D. Forsyth

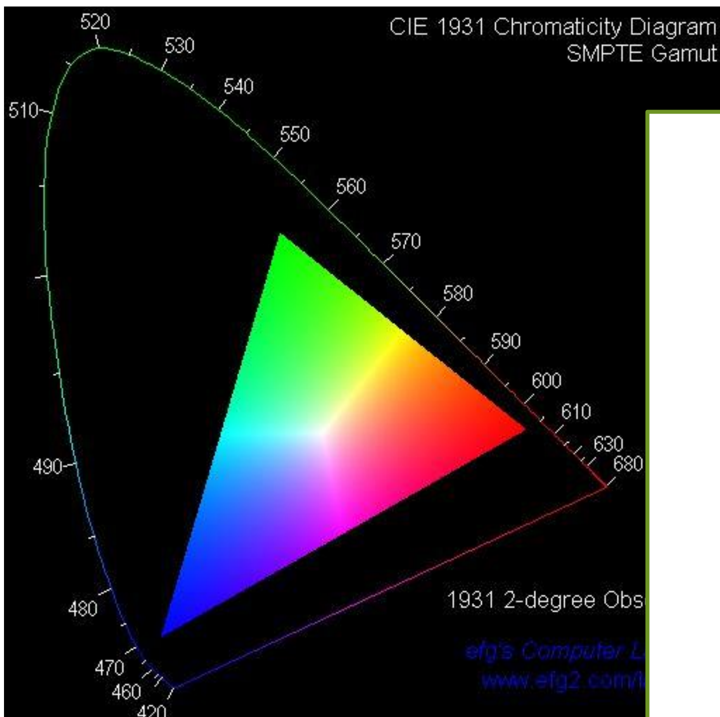
CIE xy Color space

- White is in the center, with saturation increasing towards the boundary
  - Mixing two colored lights creates colors on a straight line
  - Mixing 3 colors creates colors within a triangle
- There are sets of (x, y) coordinates that don't represent real colors, because the primaries are not real lights.



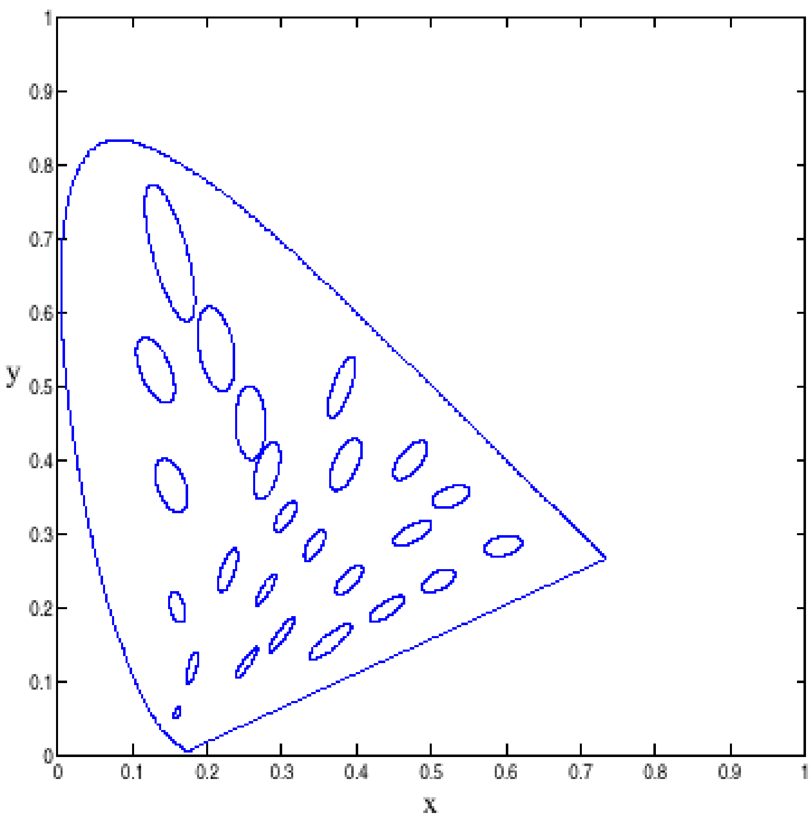
Color display

- The colors that can be displayed on a typical computer monitor (phosphor limitations keep the space quite small)

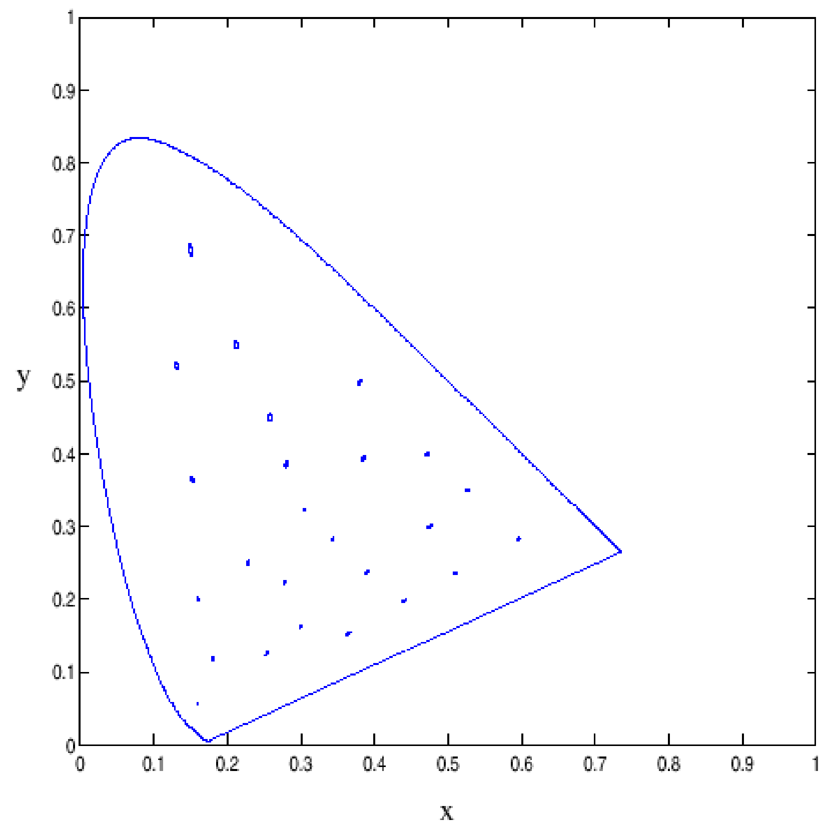


Uniform color spaces

- MacAdam ellipses demonstrate that differences in x,y coordinates are a poor guide to differences in color



10 times of the actual size



Actual size

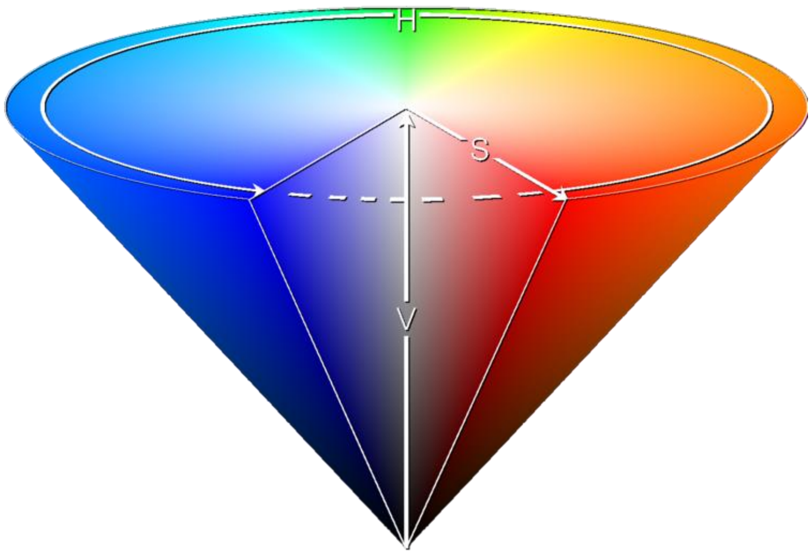
Figures courtesy of D. Forsyth

HSV color space

- Hue
  - property of the wavelengths of light (i.e., “color”)
- Lightness (or value)
  - how much light appears to be reflected from a surface
  - some hues are inherently lighter or darker
- Saturation
  - purity of the hue
    - e.g., red is more saturated than pink
  - color is mixture of pure hue & achromatic color
    - portion of pure hue is the degree of saturation

HSV color space (cont.)

Hue, Saturation, Value model (HSV)



https://en.wikipedia.org/wiki/HSL_and_HSV

HSV color space (cont.)

$H \in [0 .. 360]$; $S, V, R, G, B \in [0, 1]$

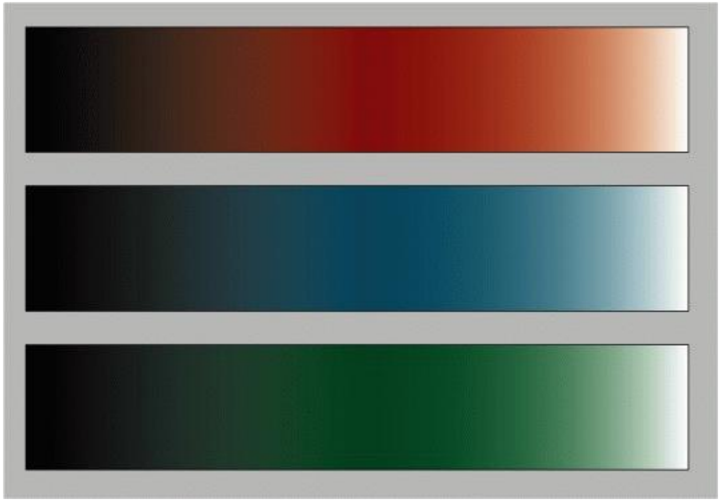
$MAX = \max(R, G, B)$; $MIN = \min(R, G, B)$

$$H = \begin{cases} \text{undefined}, & \text{if } MAX = MIN \\ 60 \times \frac{G-B}{MAX-MIN} + 0, & \text{if } MAX = R \\ & \text{and } G \geq B \\ 60 \times \frac{G-B}{MAX-MIN} + 360, & \text{if } MAX = R \\ & \text{and } G < B \\ 60 \times \frac{B-R}{MAX-MIN} + 120, & \text{if } MAX = G \\ 60 \times \frac{R-G}{MAX-MIN} + 240, & \text{if } MAX = B \end{cases}$$

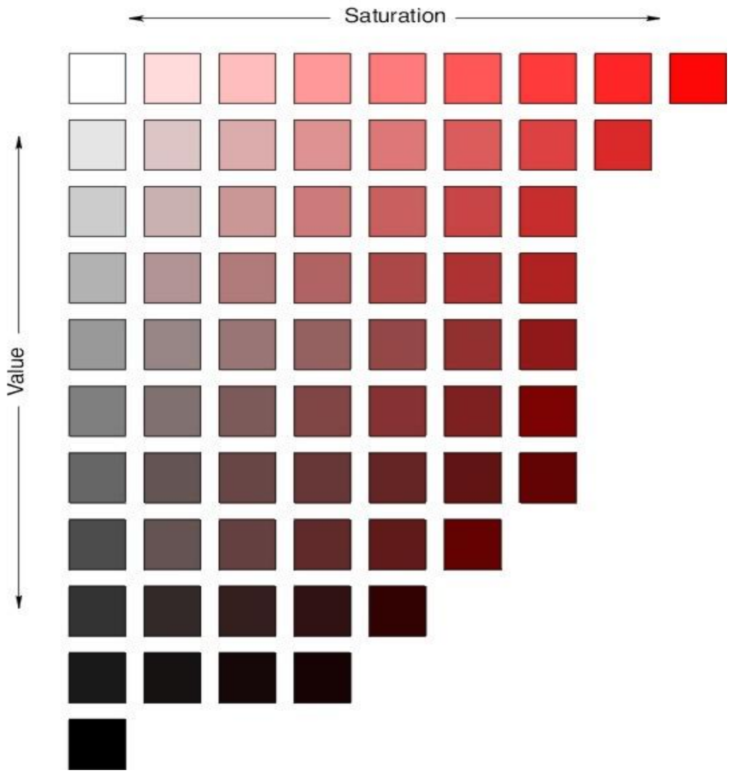
$$S = \begin{cases} 0, & \text{if } MAX = 0 \\ 1 - \frac{MIN}{MAX}, & \text{otherwise} \end{cases}$$

$$V = MAX$$

HSV color space (cont.)



lightness



Saturation

http://www2.ncsu.edu/scivis/lessons/colormodels/color_models2.html#saturation.

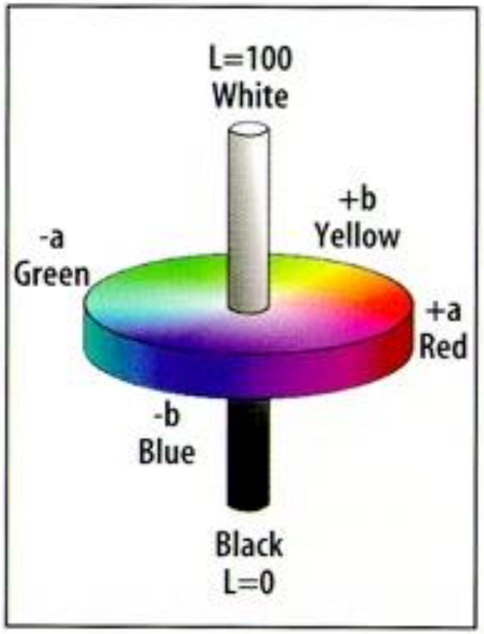
LAB color space

- CIE LAB is the most popular uniform color space.

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$



Lab model

http://www.cs.sfu.ca/CC/365/mark/material/notes/Chap3/Chap3.3/Chap3.3.html

Images of real objects

- Assume that reflections are mainly due to diffuse and specular components.

- Diffuse components
  - Color of reflected light depends on both illuminant and surface.
- Specular components
  - Specularities often saturate the camera film.
  - Specularities on dielectric (non-metalic) objects mainly take the color of the light.

Distribution of reflected lights

- T the saturate diffuse components.
- S the saturate specular components.

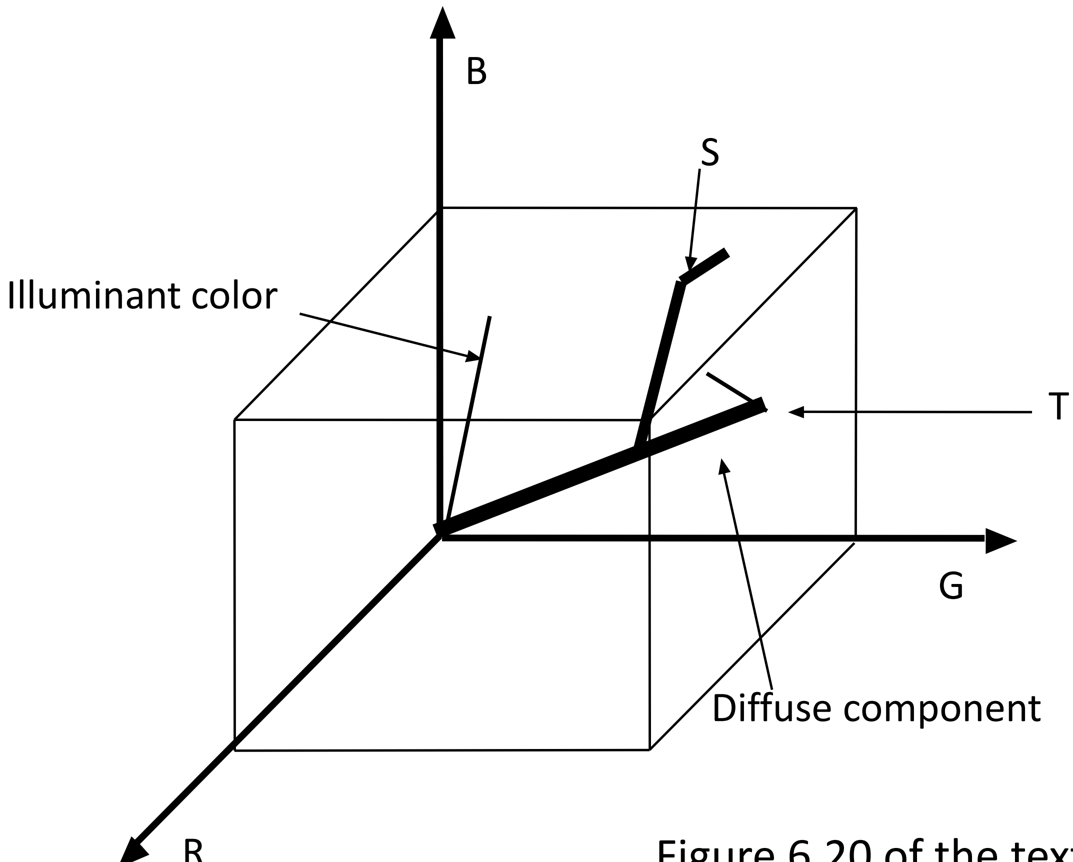


Figure 6.20 of the textbook

Distribution of reflected lights (cont.)

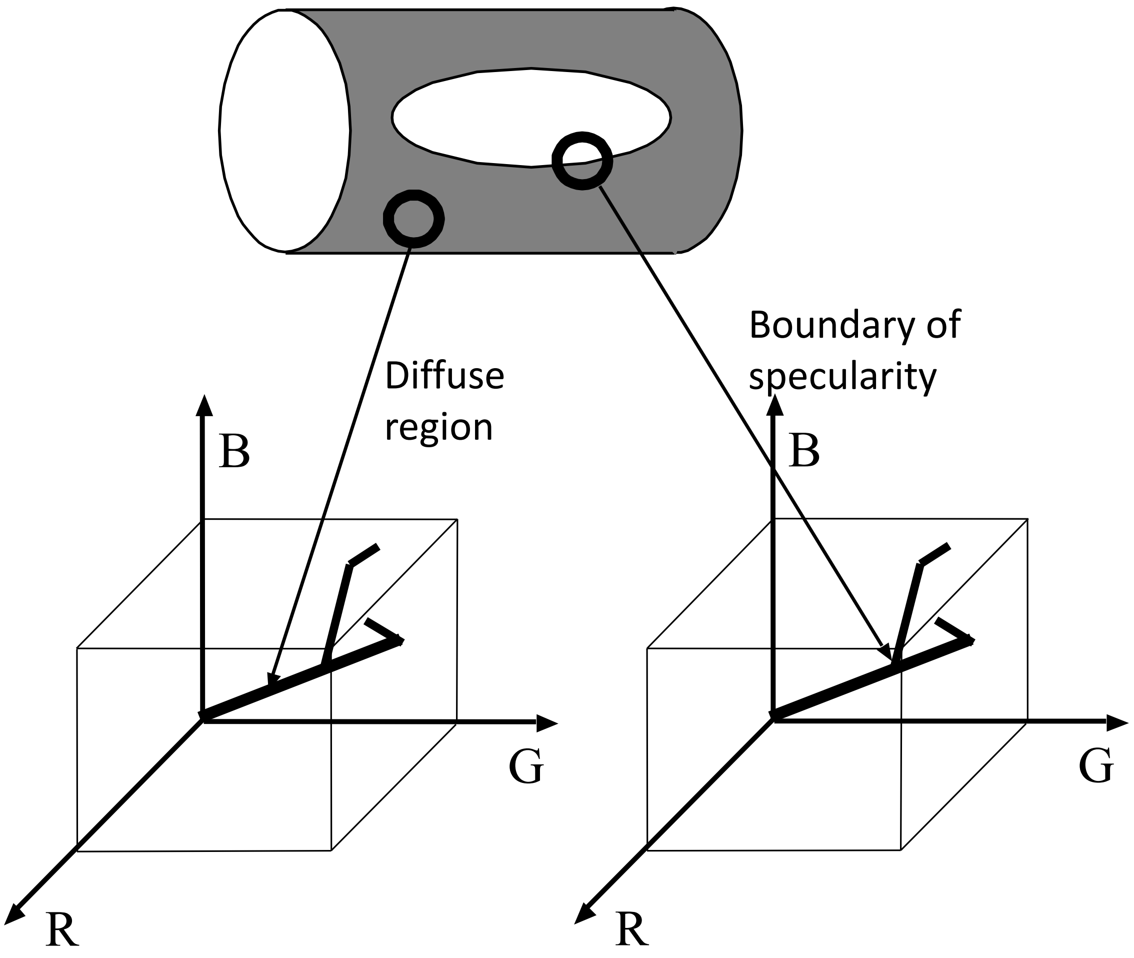


Figure 6.21 of the textbook

Human color constancy

- Color constancy: hue and saturation
- Lightness constancy: gray-level
- Humans can perceive
  - Color that a surface would have under white light (surface color)
  - Color of reflected light (separate surface color from measured color)
  - Color of illuminant (limited)

A simple model of lightness constancy

- Assumptions:
  - Linear camera response
  - Nearly planar frontal scene
  - Lambertian reflectance

k_c: Camera gain
I: illumination (reflection of light on surface)
ρ: albedo (material color)

$$C(x) = k_c I(x) \rho(x)$$

- Camera model: $\boxed{\log C(x) = \log k_c + \log I(x) + \log \rho(x)}$

- Modeling assumptions for scene
  - Piecewise constant albedo
  - Slowly-varying Illumination

1-D lightness

p can be regarded as C/k_c

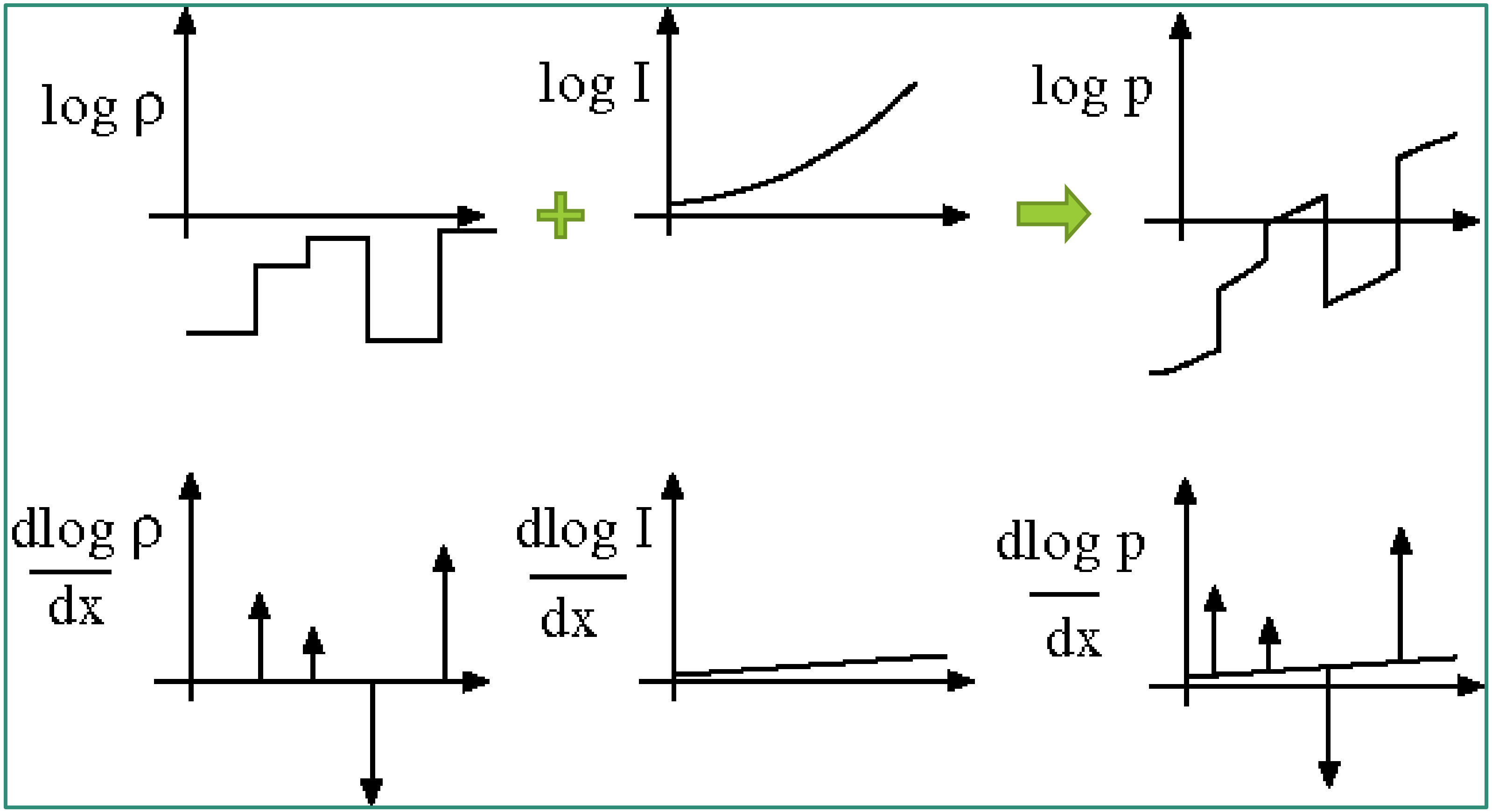
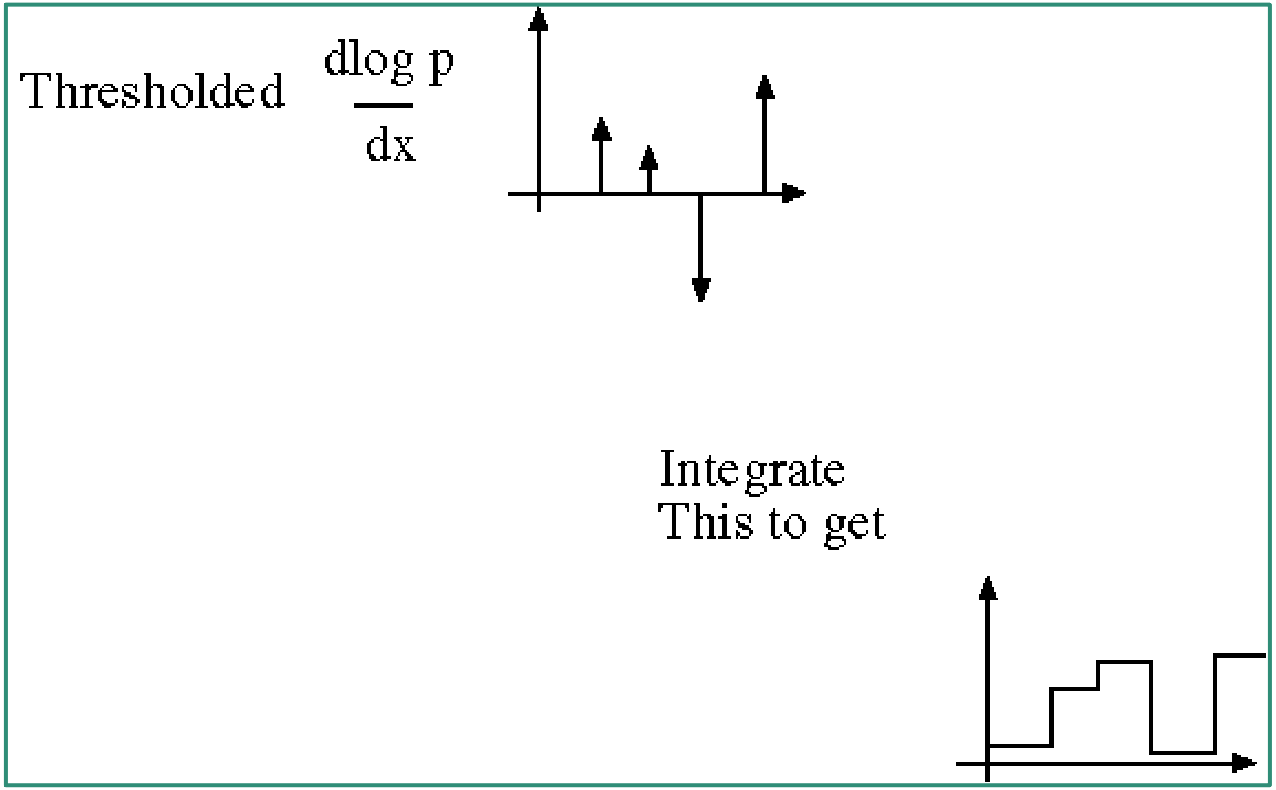


Figure 6.23 of the textbook

1-D lightness

- Assume that albedo changes during occlusion.
  - Derivative of log ρ are either zero or large.



Extending to 2D

- Spatial issues
  - Integration becomes much harder
  - Using minimization.

- Recover of absolute reference
  - Brightest patch is white
  - Average reflectance across scene is known
  - Gamut(collection of all colors) is known
  - Known reference (e.g. skin color)