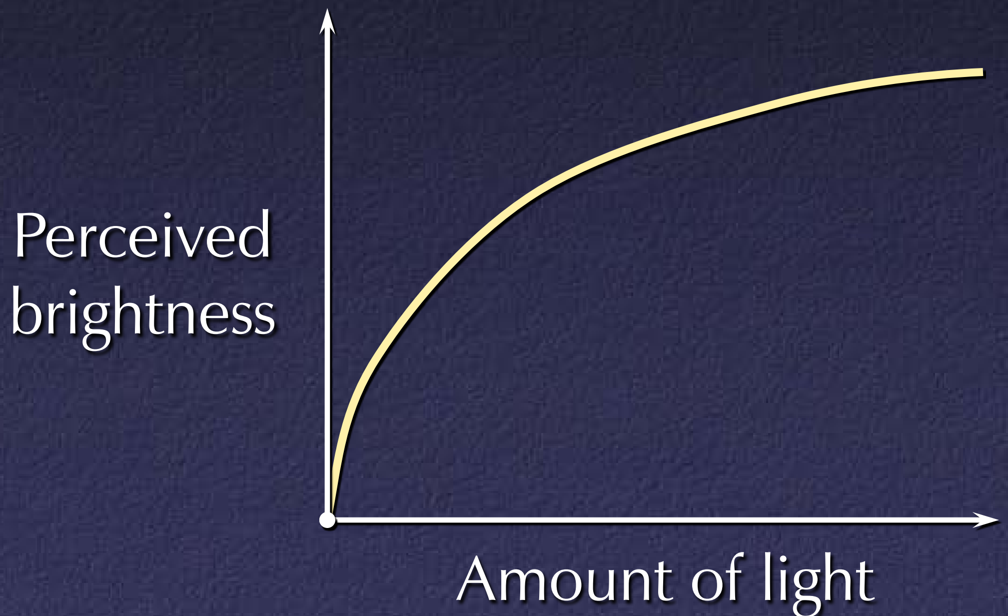
Light and Color

Problems

- How do cameras measure light and color?
  - Radiometry
- How do humans perceive light and color?
  - Photometry
- How do computers represent light and color?
- How do monitors display light and color?

Intensity

- Perception of intensity is nonlinear

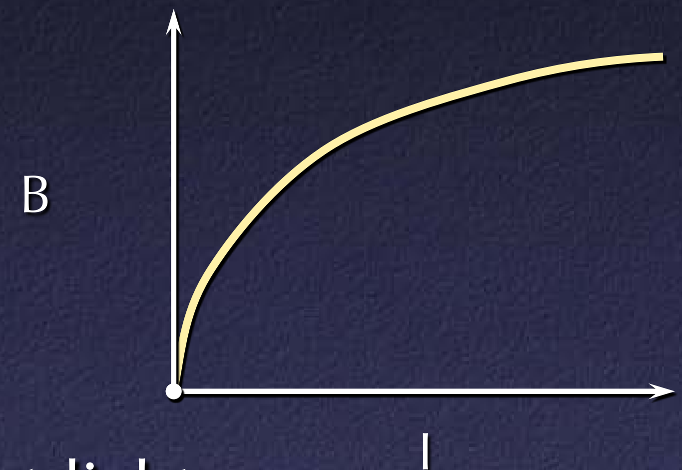


Modeling Nonlinear Intensity Response

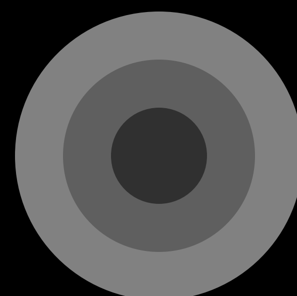
- Brightness (*B*) usually modeled as a logarithm or power law of intensity (*I*)

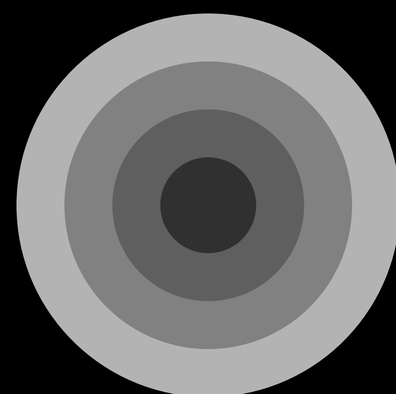
$$B = k \log I$$

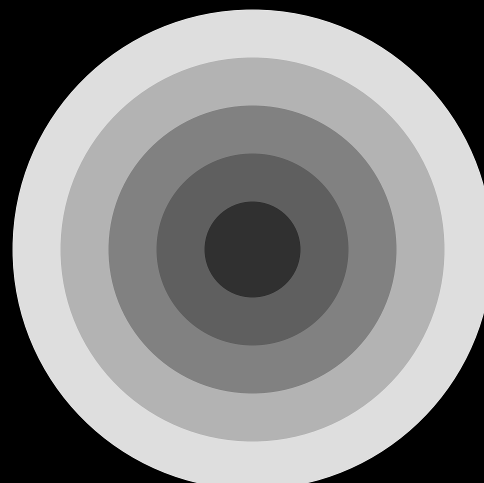
$$B = I^{1/3}$$

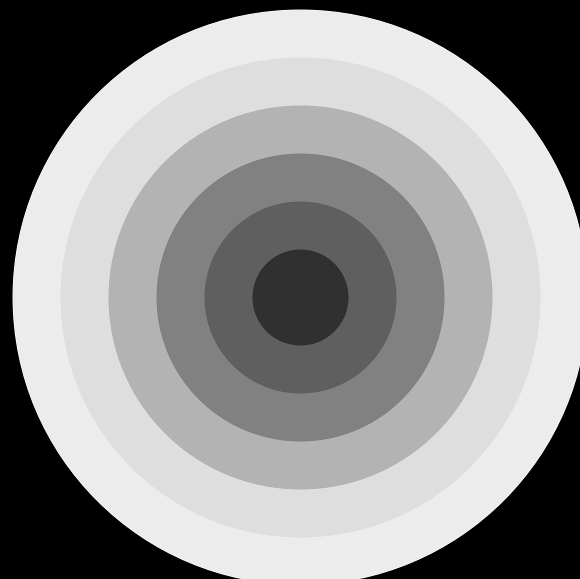


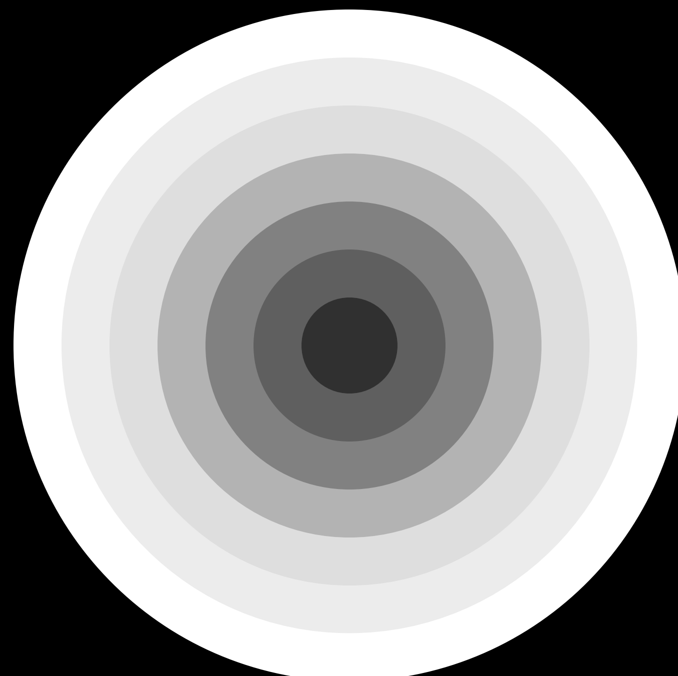
- Exact curve varies with ambient light, adaptation of eye



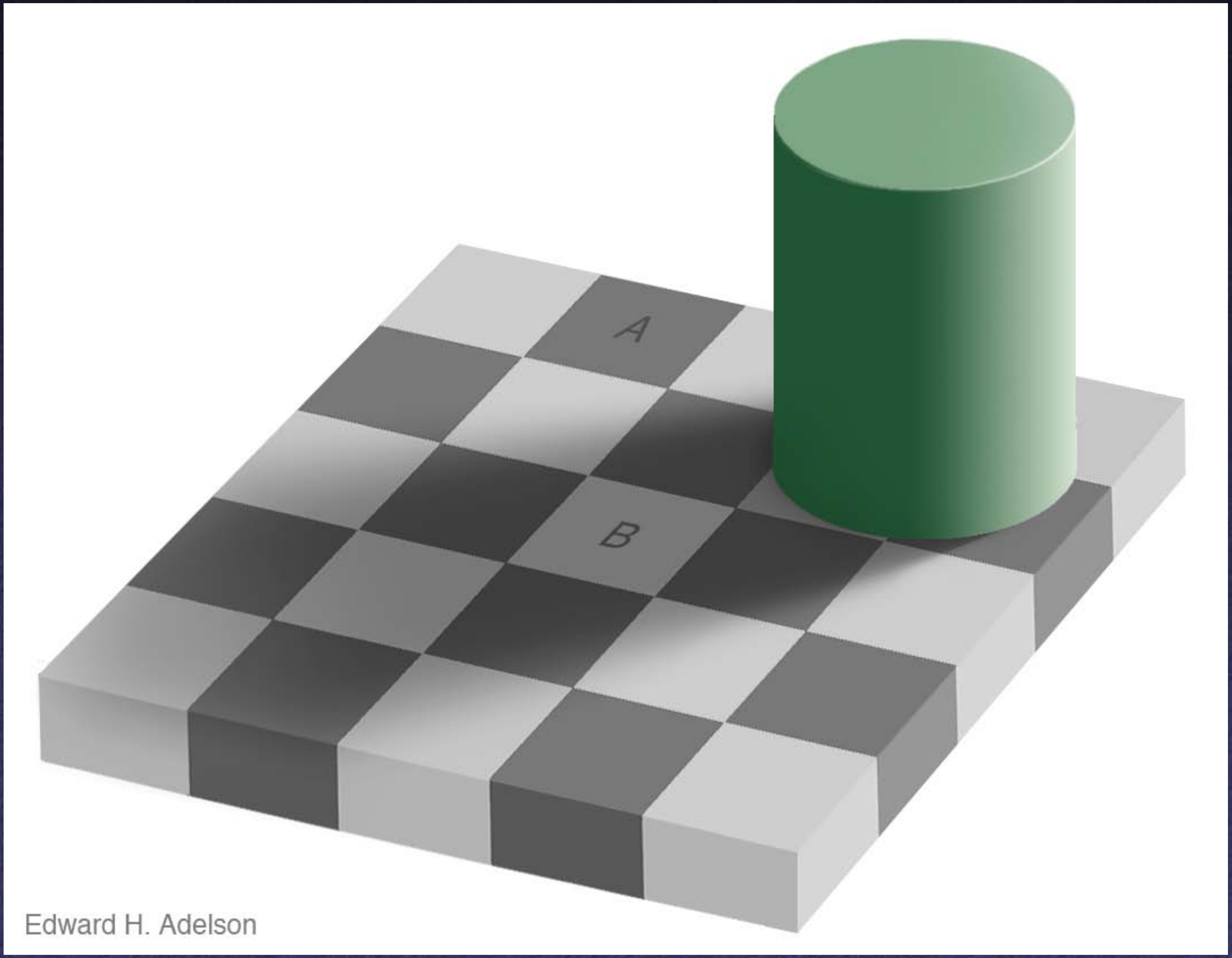




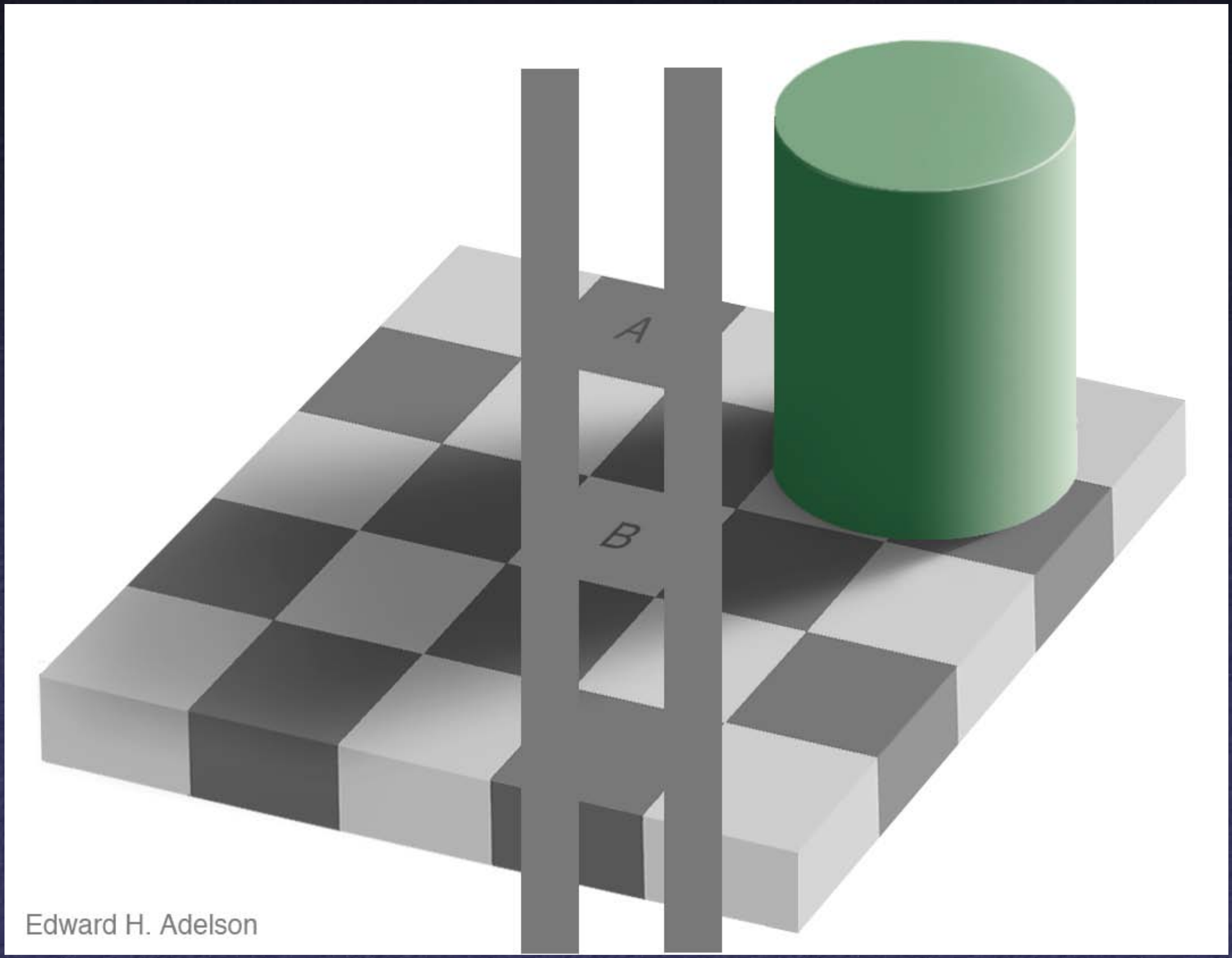




Adelson's Checker Illusion



Adelson's Checker Illusion



CRT Response

- Power law for Intensity (*I*) vs. applied voltage (*V*)

$$I = V^{\gamma}$$

$$\gamma = 2.5$$

- Other displays (e.g. LCDs) contain electronics to emulate this law

Digression: Monitor Knobs

- "Brightness" knob is offset
- "Contrast" knob is scale

$$I = contrast \cdot (V + brightness)^{\gamma}$$

- Yes, the names *are* misleading…

Cameras

- Original cameras based on Vidicon obey power law for Voltage (V) vs. Intensity (I):

$$V = I^{\gamma}$$

$$\gamma = 0.45$$

- Vidicon + CRT = almost linear!

CCD Cameras

- Camera gamma codified in NTSC standard
- CCDs have linear response to incident light
- Electronics to apply required power law
- So, pictures from most cameras (including digital still cameras) will have $\gamma = 0.45$

Consequences for Vision

- Output of most cameras is not linear
- Know what it is! (Sometimes system automagically applies “gamma correction”)
- Necessary to correct raw pixel values for:
  - Reflectance measurements
  - Shape from shading
  - Photometric stereo
  - Recognition under variable lighting

Consequences for Vision

- What about e.g. edge detection?
  - Often want "perceptually significant" edges
  - Standard nonlinear signal close to (inverse of) human response
  - Using nonlinear signal often the "right thing"

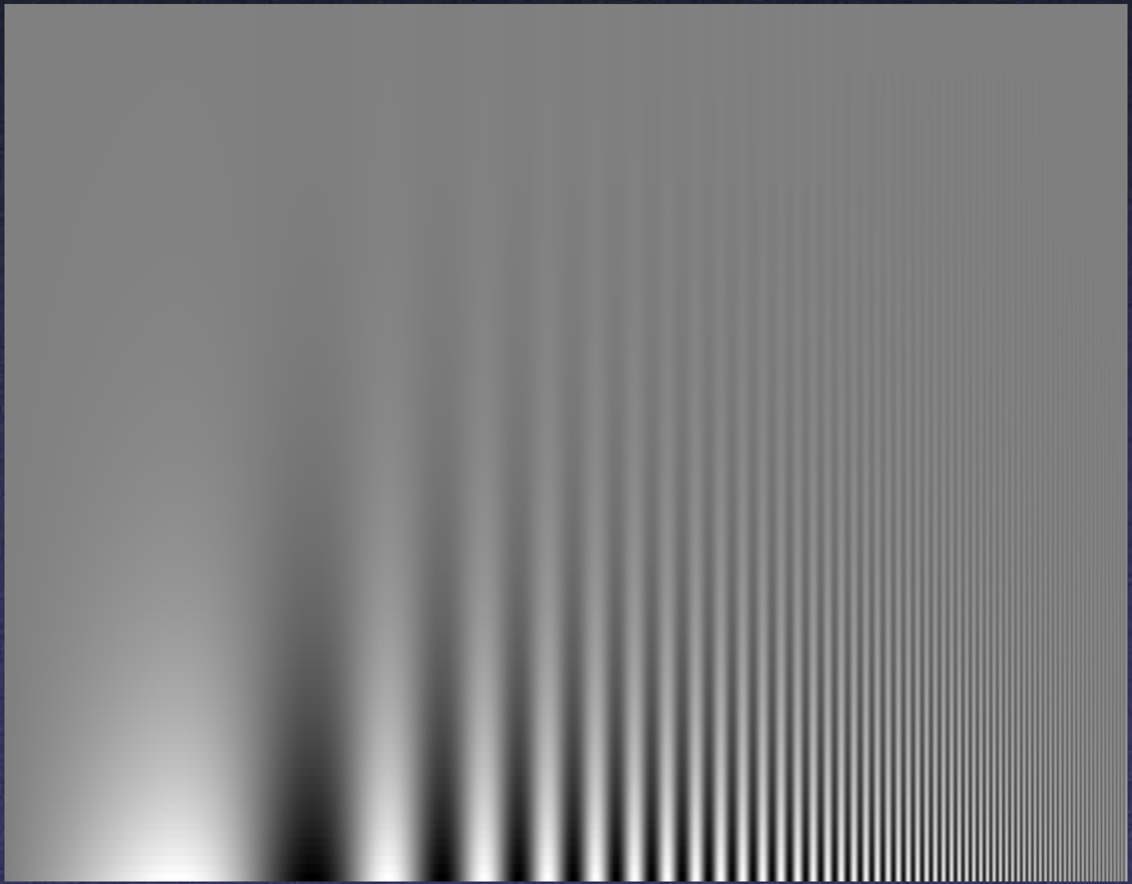
Contrast Sensitivity

Contrast Sensitivity

- Contrast sensitivity for humans about 1%
- 8-bit image (barely) adequate if using perceptual (nonlinear) mapping
- Frequency dependent: contrast sensitivity lower for high and very low frequencies

Contrast Sensitivity

- Campbell-Robson contrast sensitivity chart



Bits per Pixel – Scanned Pictures

8 bits / pixel / color

6 bits / pixel / color

Marc Levoy / Hanna-Barbera

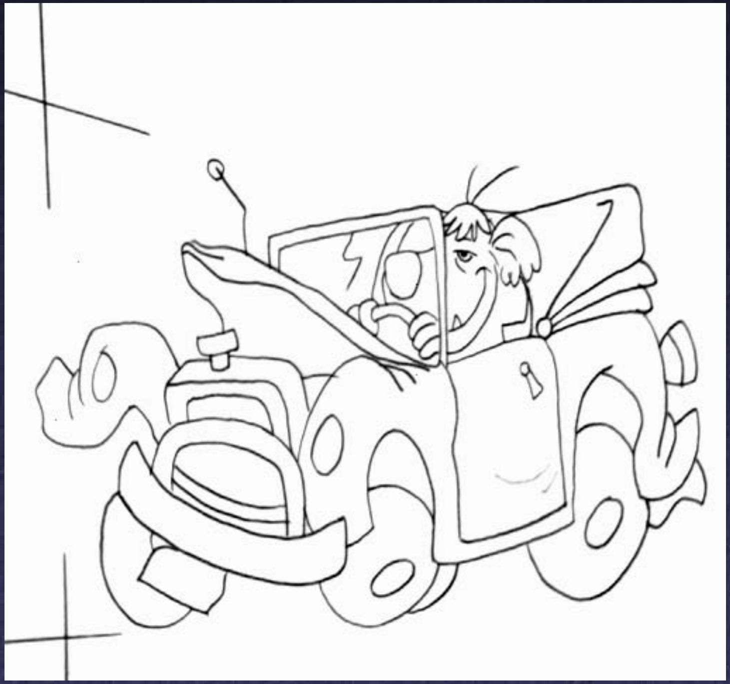
Bits per Pixel – Scanned Pictures (cont.)

5 bits / pixel / color

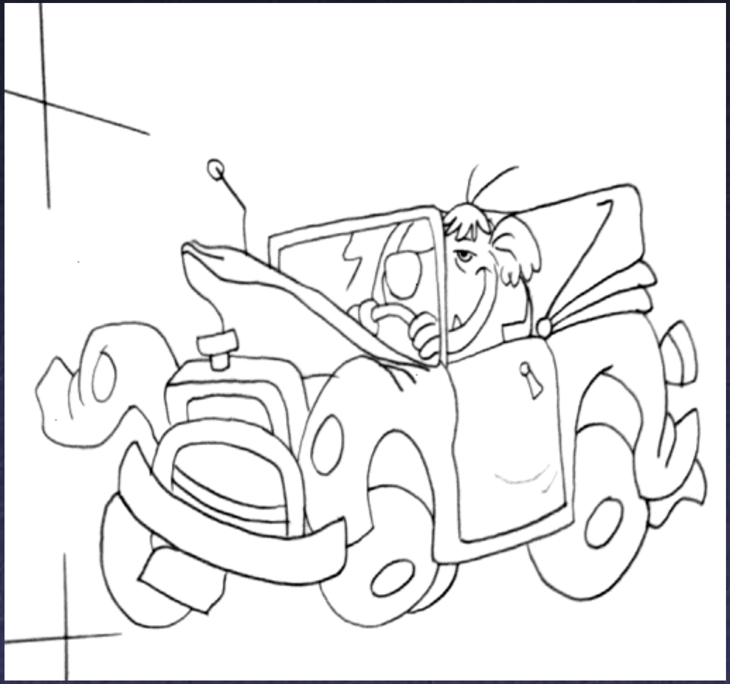
4 bits / pixel / color

Marc Levoy / Hanna-Barbera

Bits per Pixel – Line Drawings



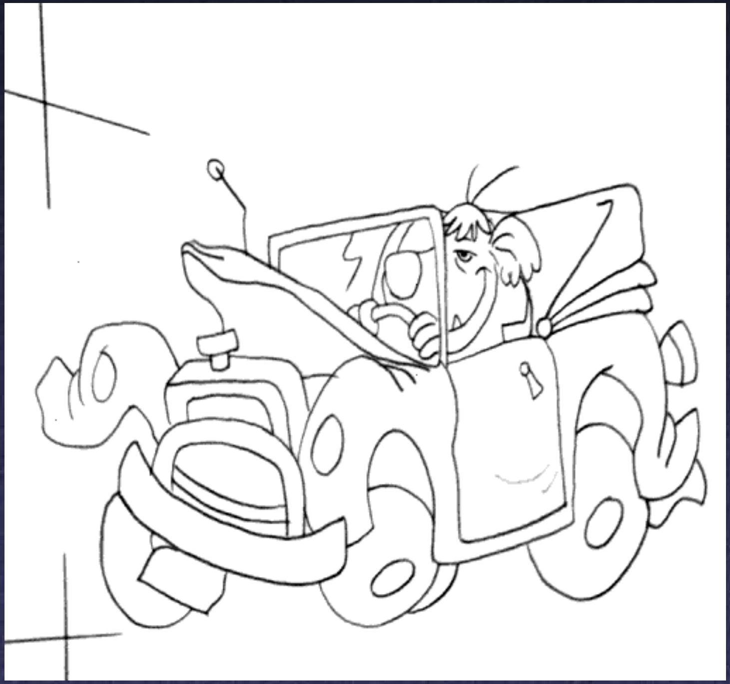
8 bits / pixel / color



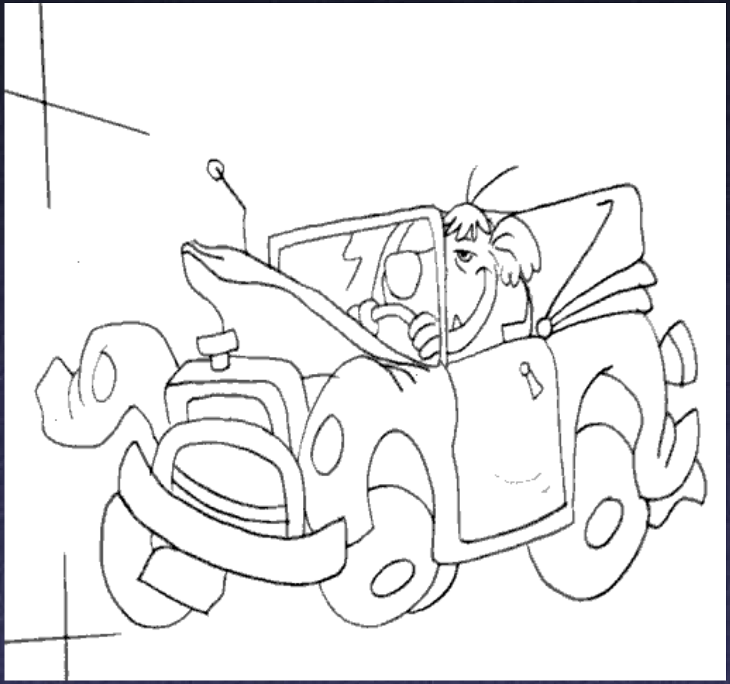
4 bits / pixel / color

Marc Levoy / Hanna-Barbera

Bits per Pixel – Line Drawings (cont.)

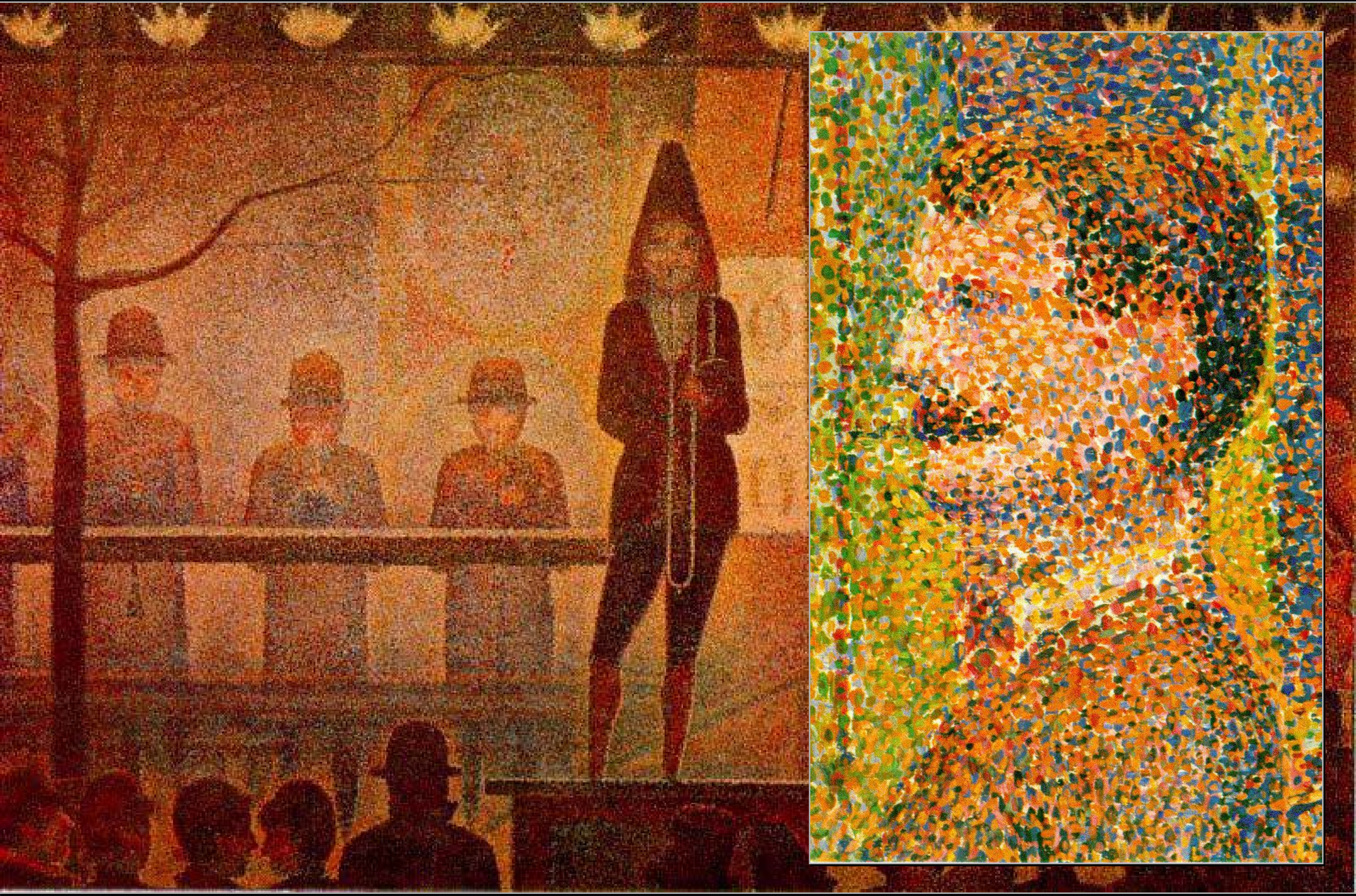


3 bits / pixel / color



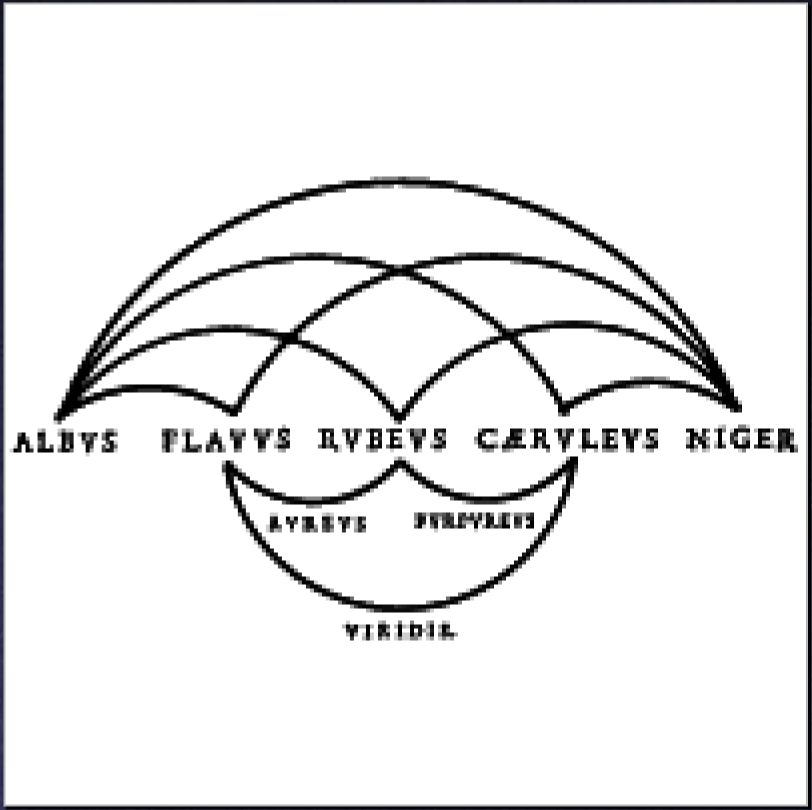
2 bits / pixel / color

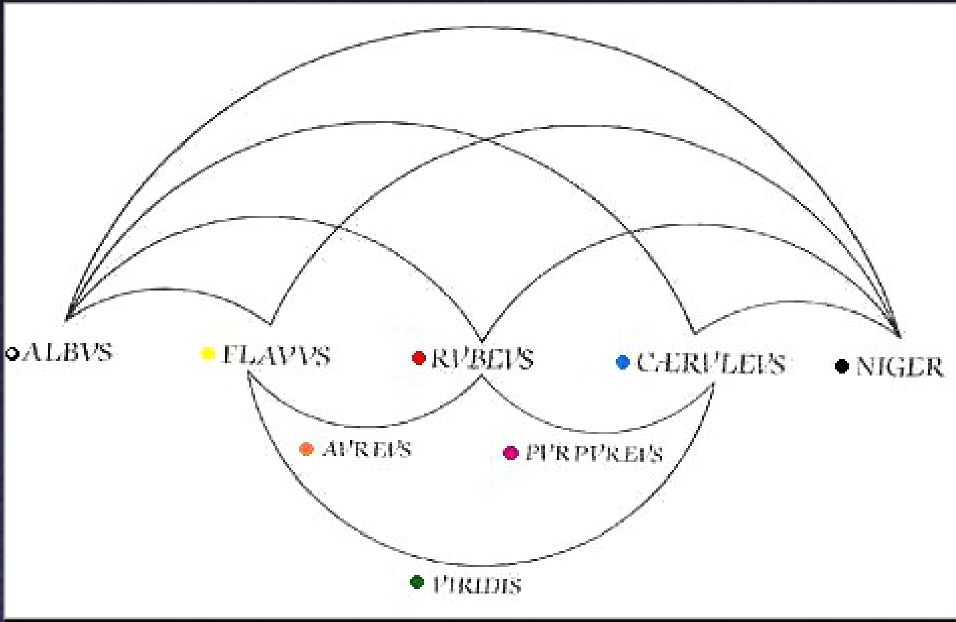
Marc Levoy / Hanna-Barbera



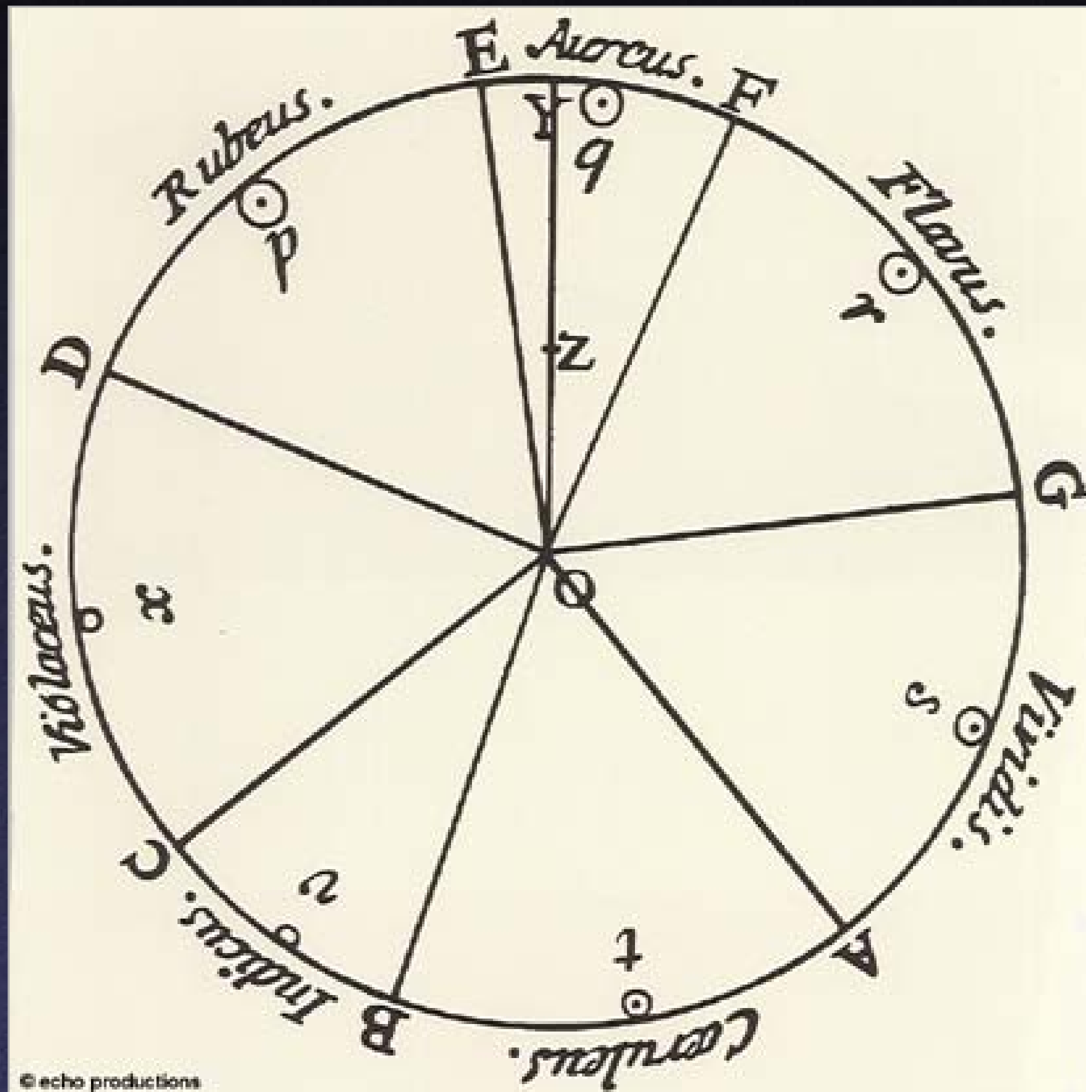
Seurat: *The Side Show*, 1888

Color

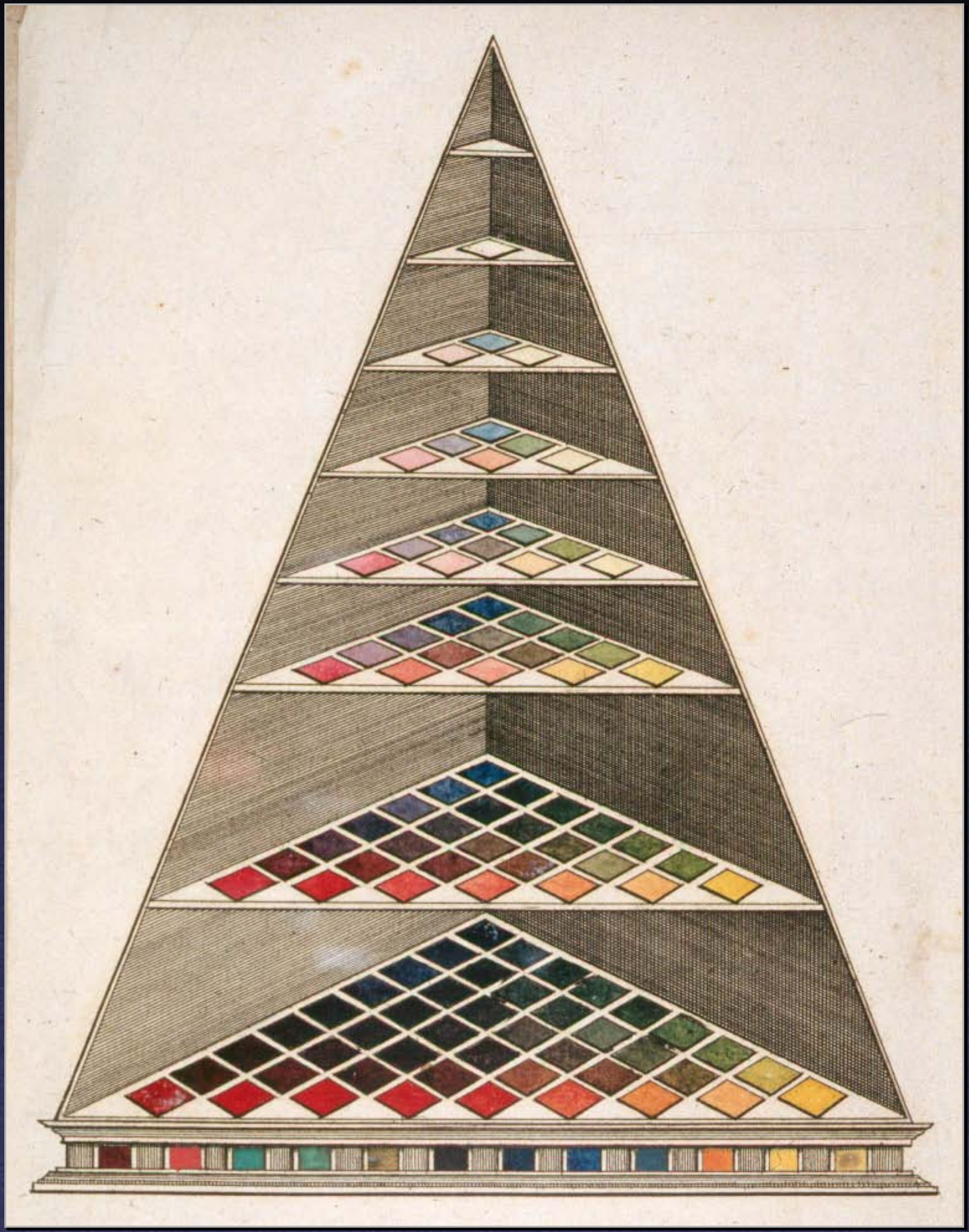




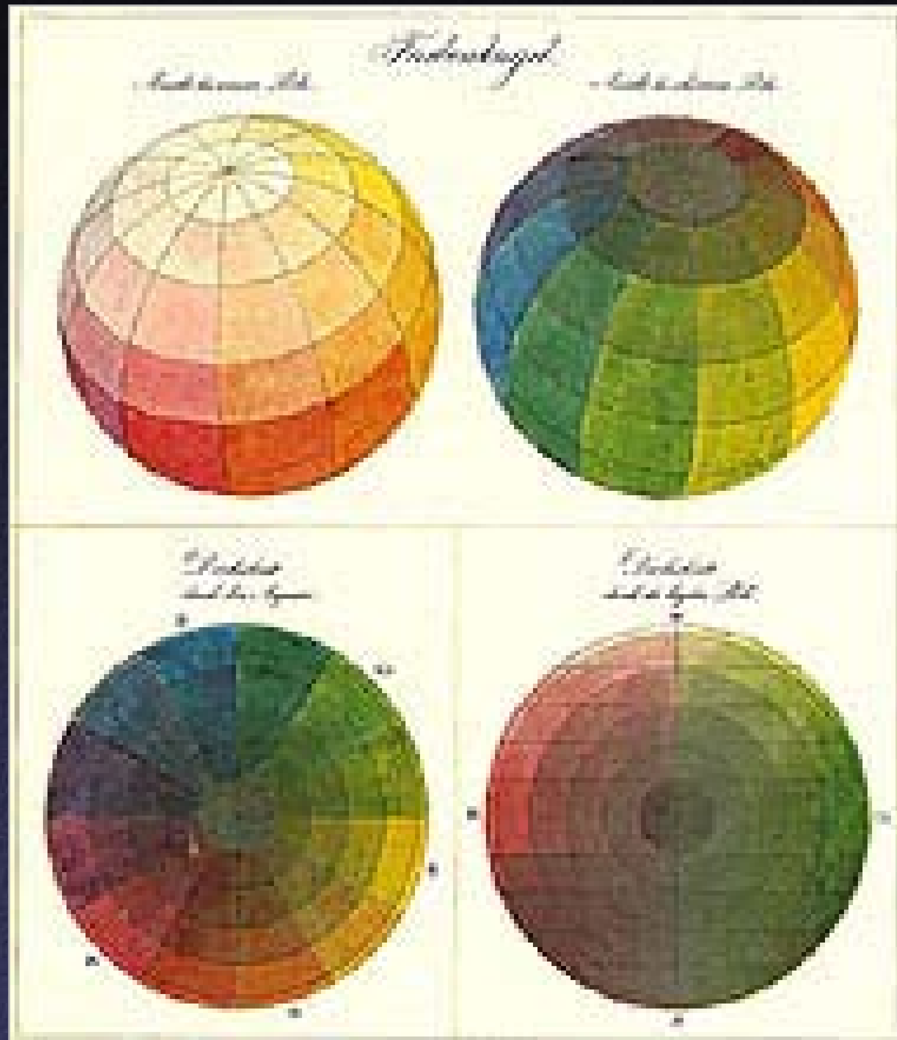
Aguilonius, 1613



Newton: color circle from *Optiks*, 1704



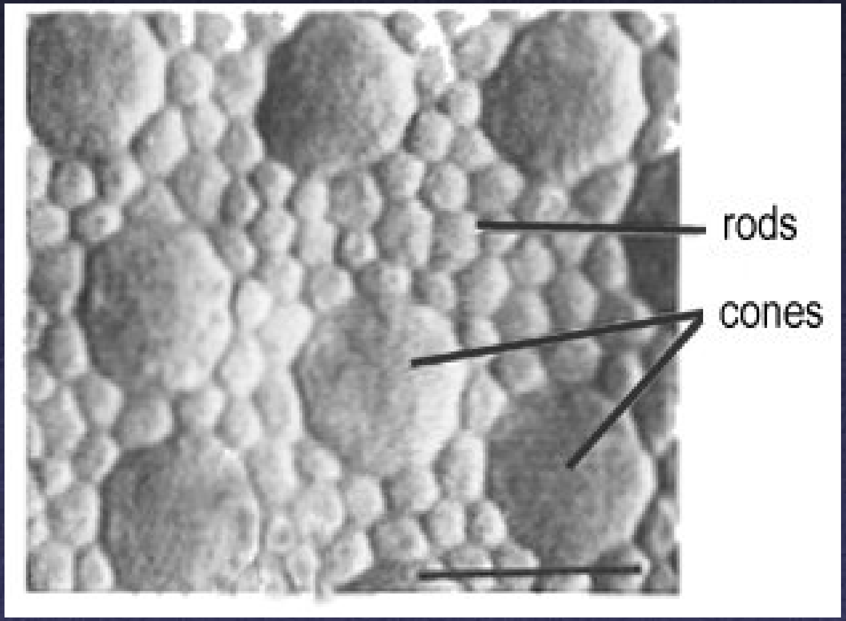
Johann Lambert: *Color pyramid*, 1772



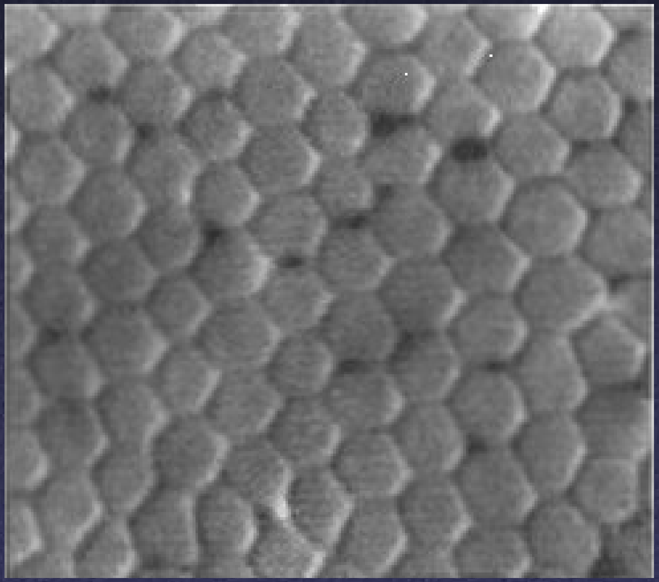
Runge: *Colour Sphere*, 1809

Modern Understanding of Color

- Two types of receptors: rods and cones



Rods and cones



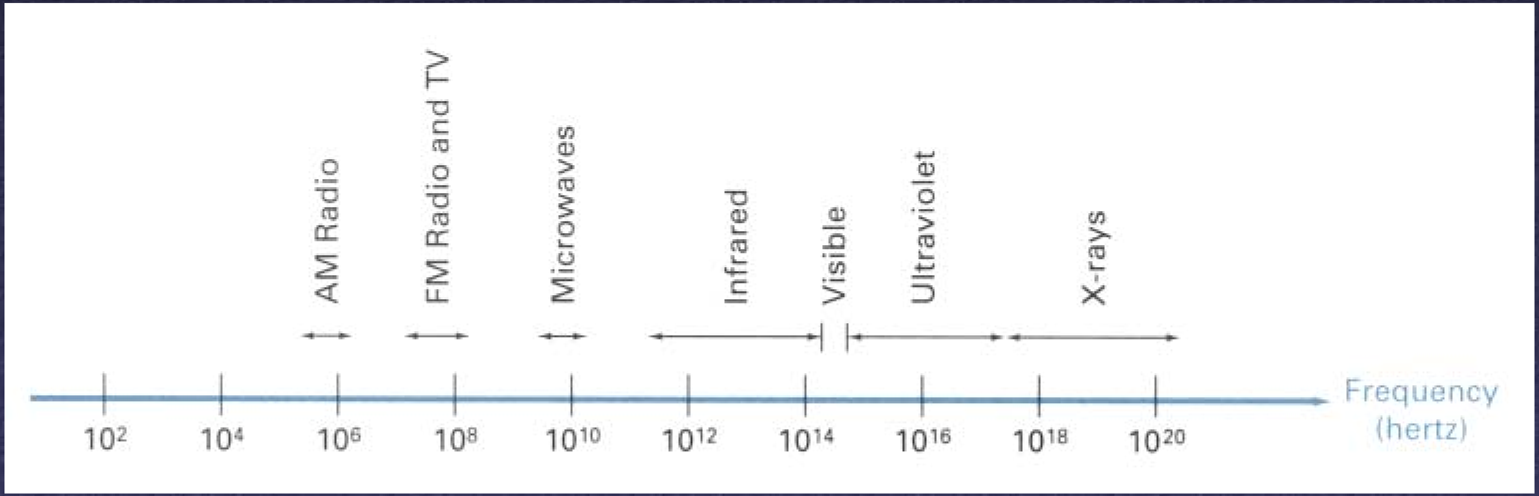
Cones in fovea

Rods and Cones

- Rods
  - More sensitive in low light: “scotopic” vision
  - More dense near periphery
- Cones
  - Only function with higher light levels: “photopic” vision
  - Densely packed at center of eye: fovea
  - Different types of cones $\rightarrow$ color vision

Electromagnetic Spectrum

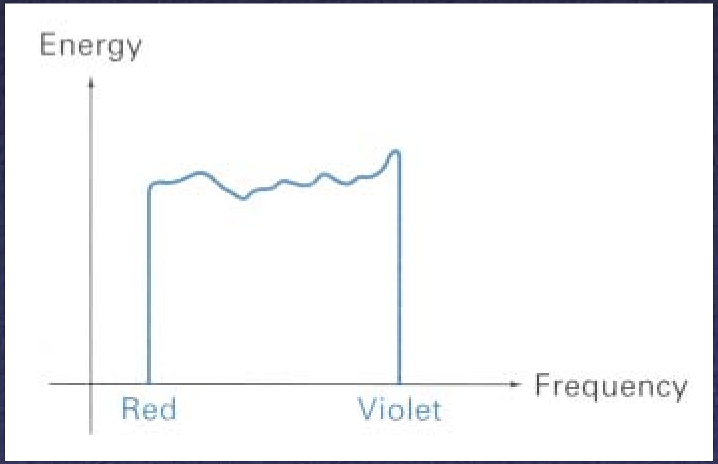
- Visible light frequencies range between …
  - Red = 4.3×10^{14} hertz (700nm)
  - Violet = 7.5×10^{14} hertz (400nm)



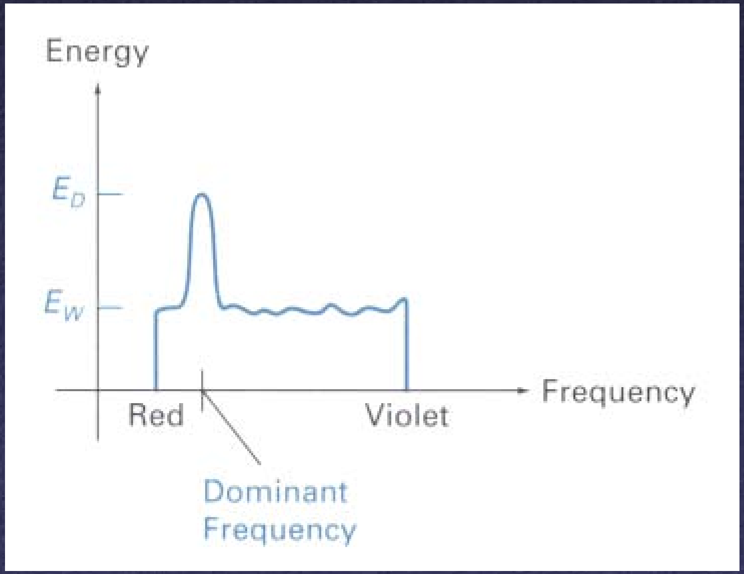
Figures 15.1 from H&B

Visible Light

- Color may be characterized by …
  - Hue = dominant frequency (highest peak)
  - Saturation = excitation purity (ratio of highest to rest)
  - Lightness = luminance (area under curve)



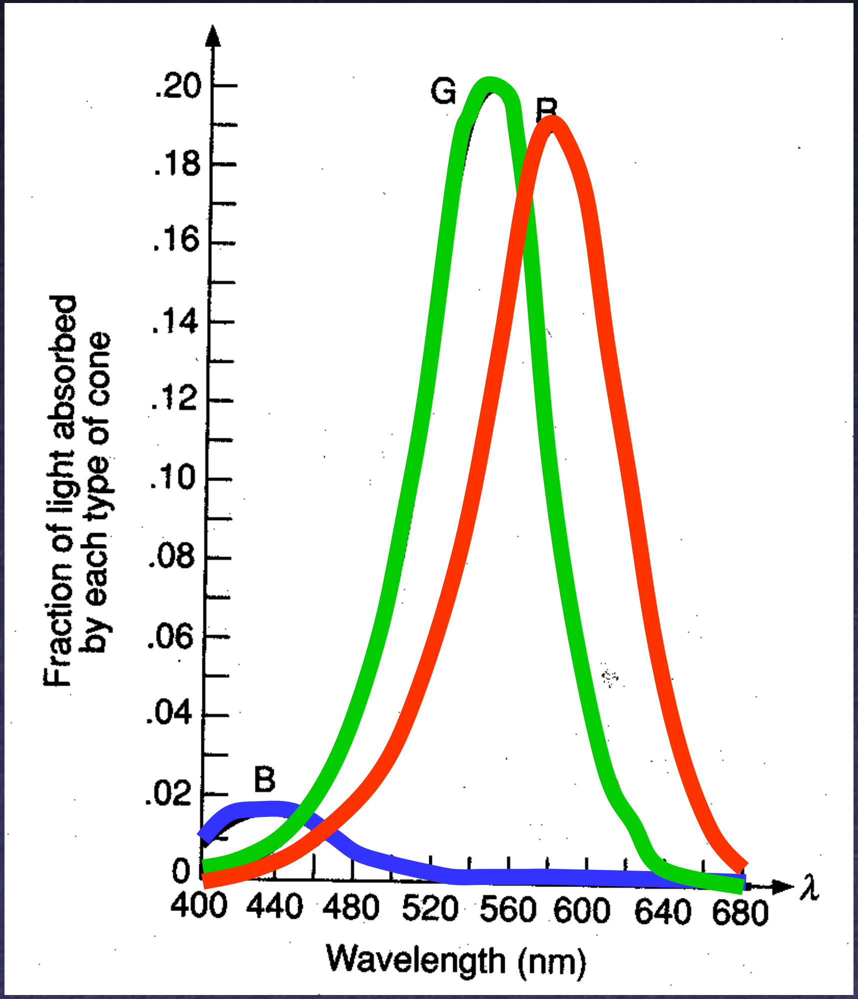
White Light



Orange Light

Figures 15.3-4 from H&B

Color Perception



Spectral-response functions of the three types of cones.

Tristimulus theory of color

Figure 13.18 from FvDFH

Tristimulus Color

- Any distribution of light can be summarized by its effect on 3 types of cones
- Therefore, human perception of color is a 3-dimensional space
- Metamerism: different spectra, same response
- Color blindness: fewer than 3 types of cones
  - Most commonly L cone = M cone

Color Models

- RGB
- XYZ
- CMY
- HSV
- …etc

Color Models

- Different ways of parameterizing 3D space
- RGB
  - Official standard:
    R = 645.16 nm, G = 526.32 nm, B = 444.44 nm
  - Most monitors are some approximation to this

Color CRT

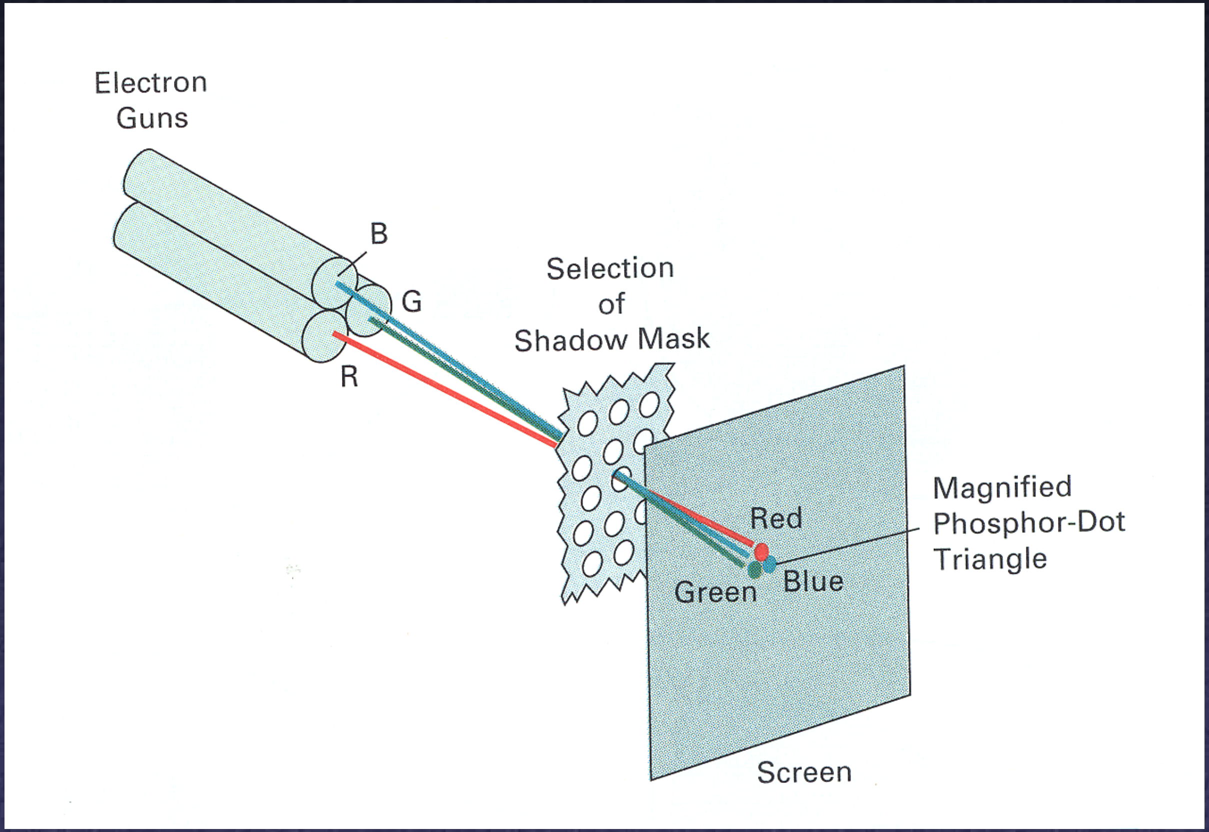
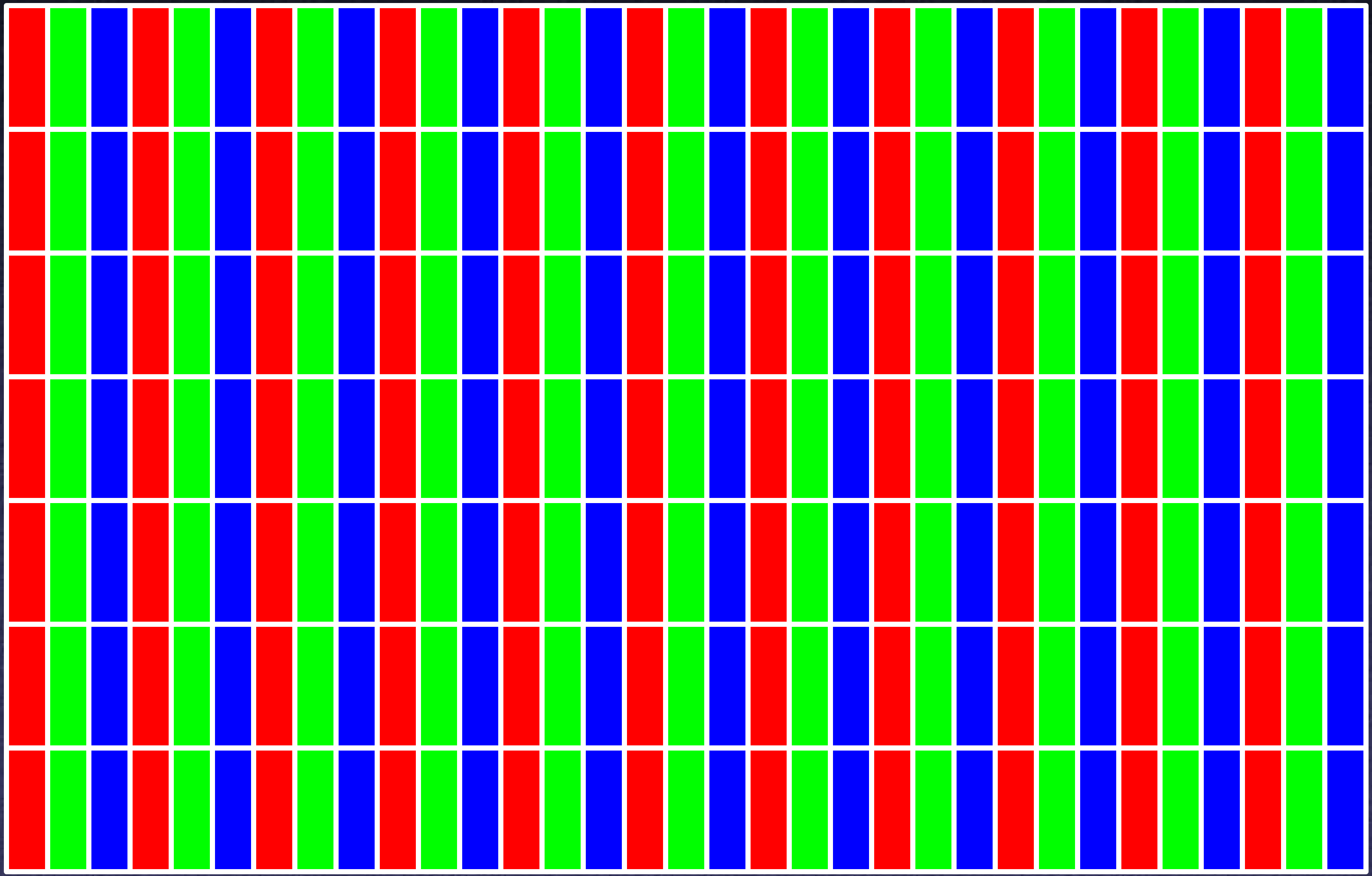
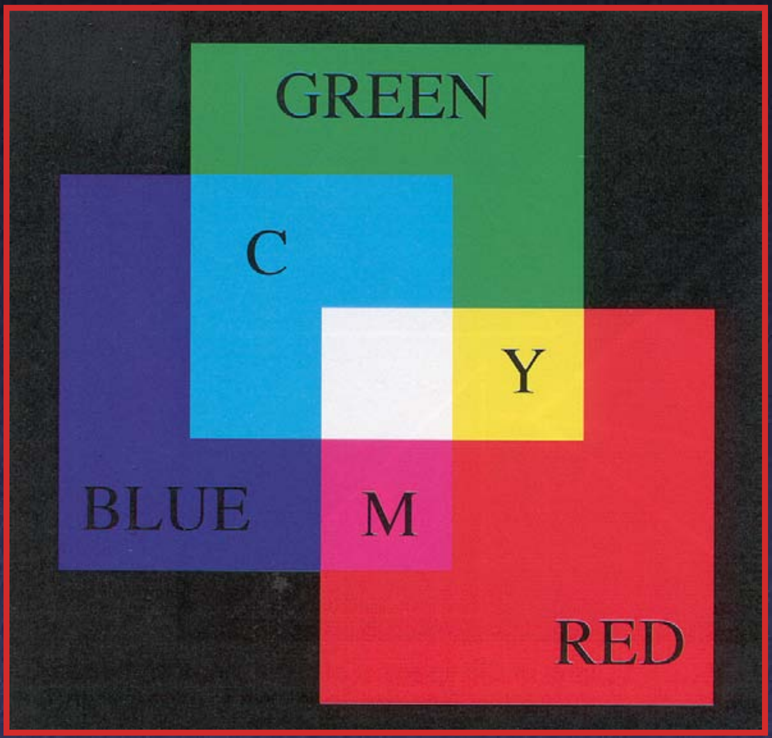


Figure 2.8 from H&B

Color LCD



RGB Color Model

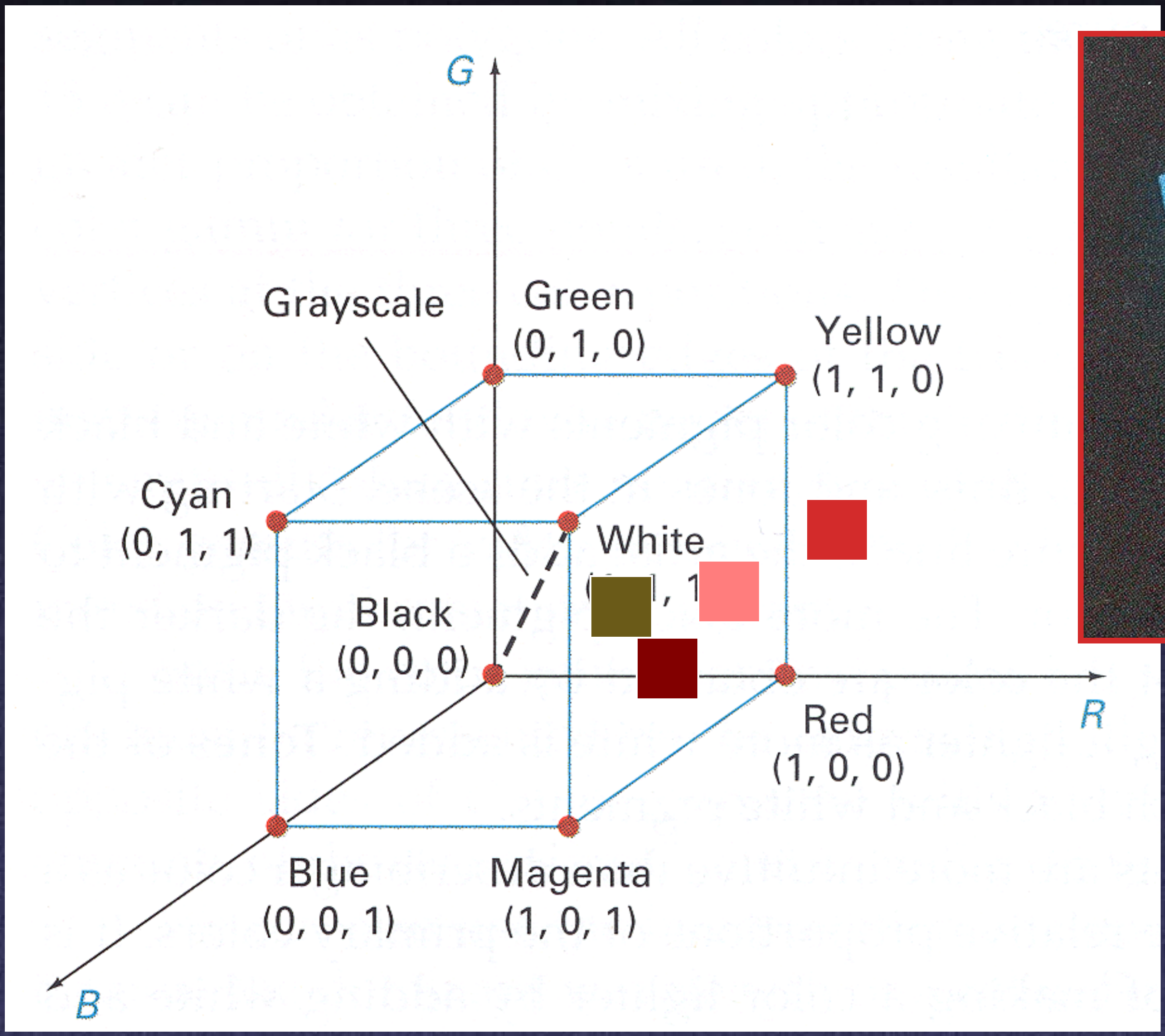


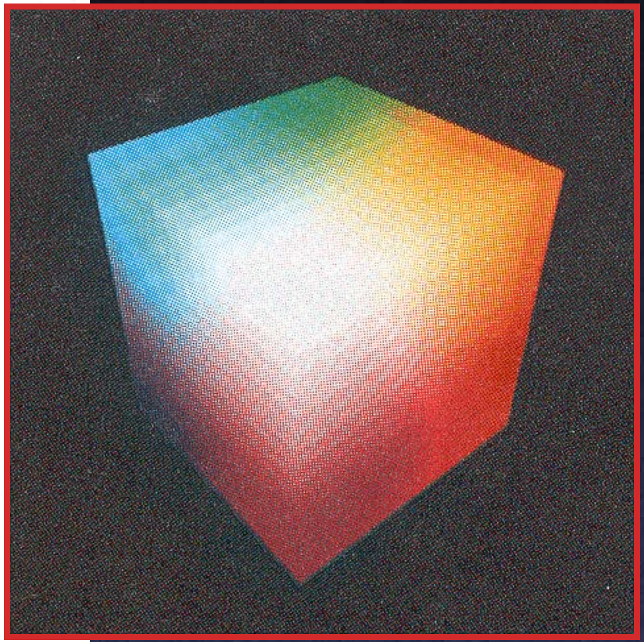
Colors are additive

Plate II.3 from FvDFH

R	G	B	Color
0.0	0.0	0.0	Black
1.0	0.0	0.0	Red
0.0	1.0	0.0	Green
0.0	0.0	1.0	Blue
1.0	1.0	0.0	Yellow
1.0	0.0	1.0	Magenta
0.0	1.0	1.0	Cyan
1.0	1.0	1.0	White
0.5	0.0	0.0	?
1.0	0.5	0.5	?
1.0	0.5	0.0	?
0.5	0.3	0.1	?

RGB Color Cube





Figures 15.11&15.12 from H&B

RGB Spectral Colors

Amounts of RGB primaries needed to display spectral colors

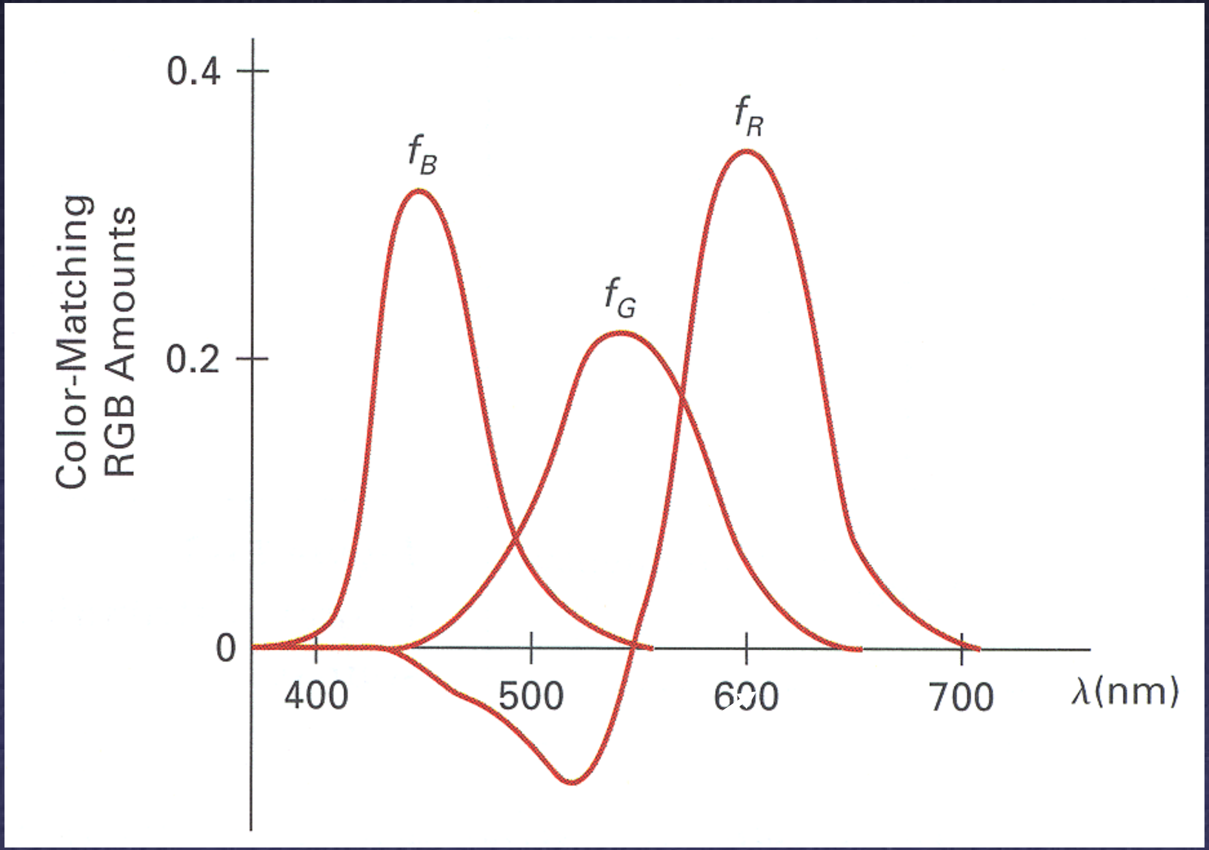


Figure 15.5 from H&B

XYZ Color Model (CIE)

Amounts of CIE primaries needed to display spectral colors

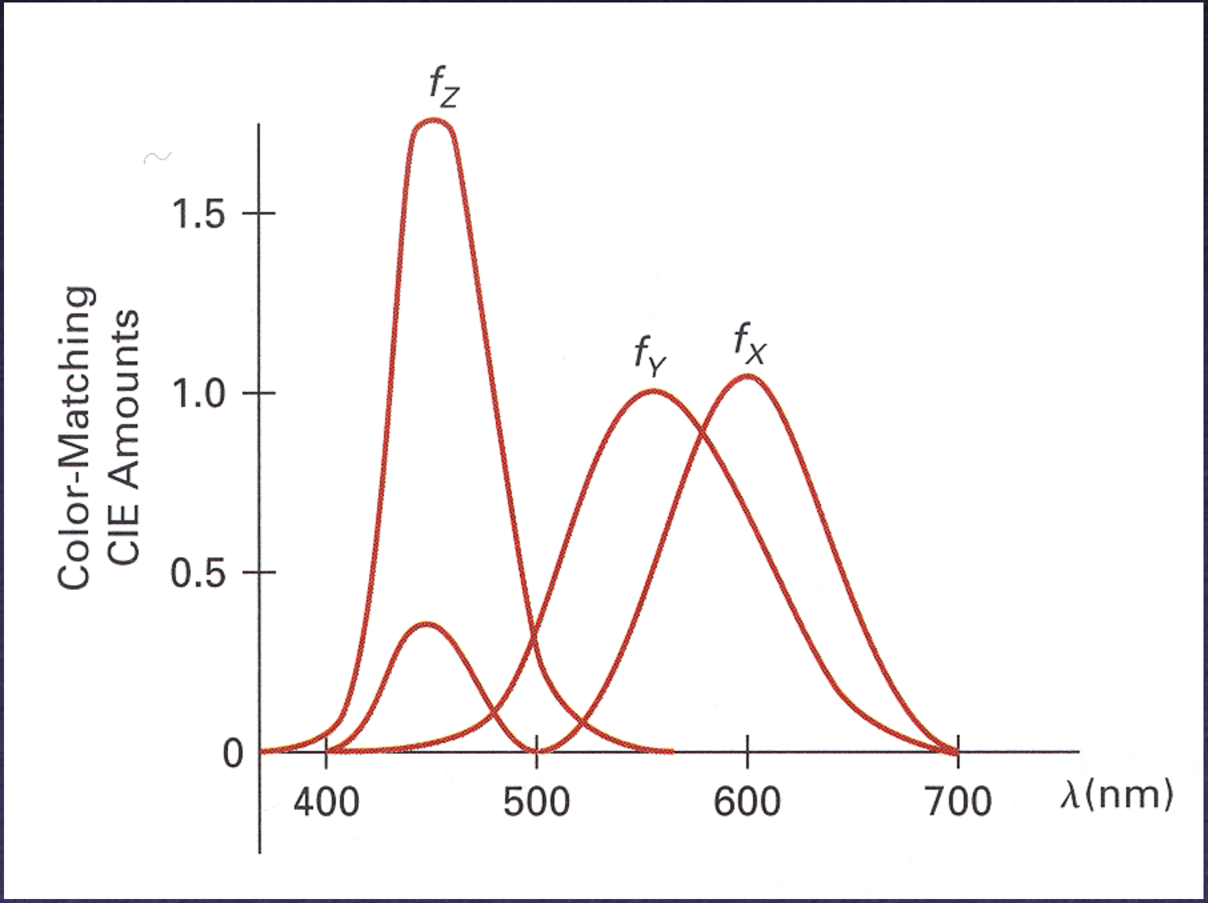
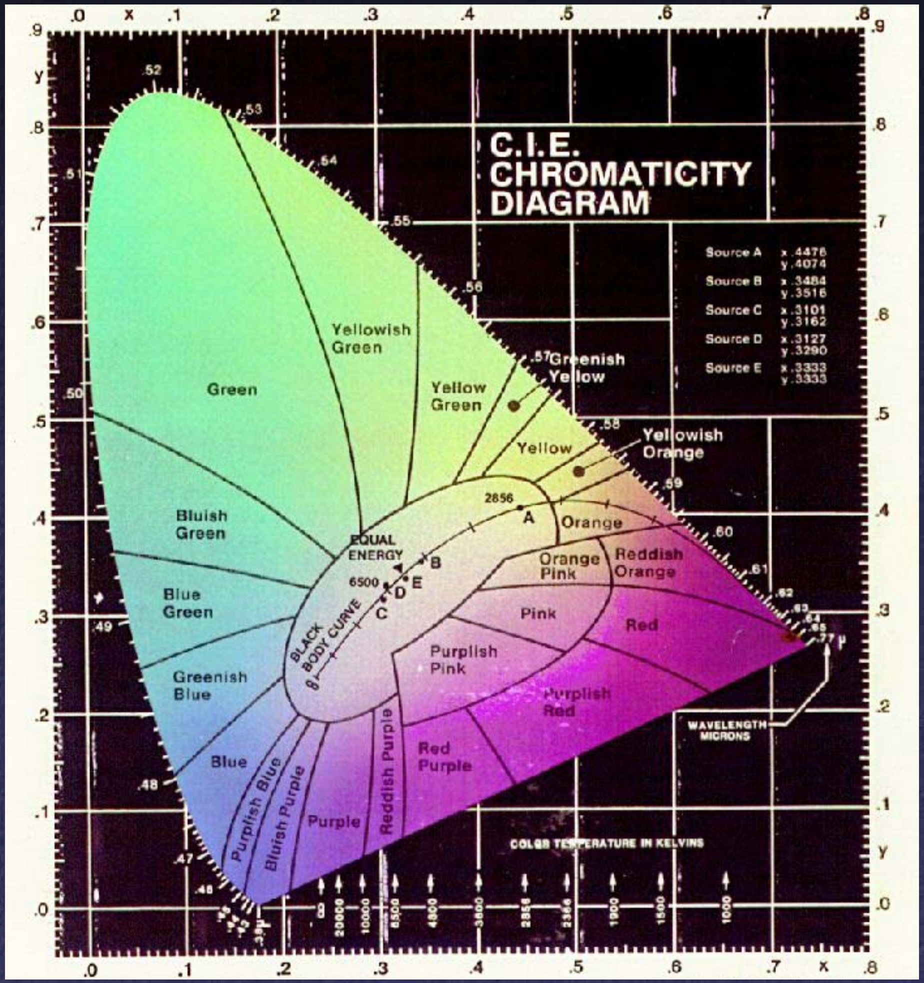


Figure 15.6 from H&B

XYZ Colorspace

- RGB can't represent all pure wavelengths with positive values
  - Saturated greens would require negative red
- XYZ colorspace is a linear transform of RGB so that all pure wavelengths have positive values

CIE Chromaticity Diagram



CIE Chromaticity Diagram

Normalized amounts of X and Y for colors in visible spectrum

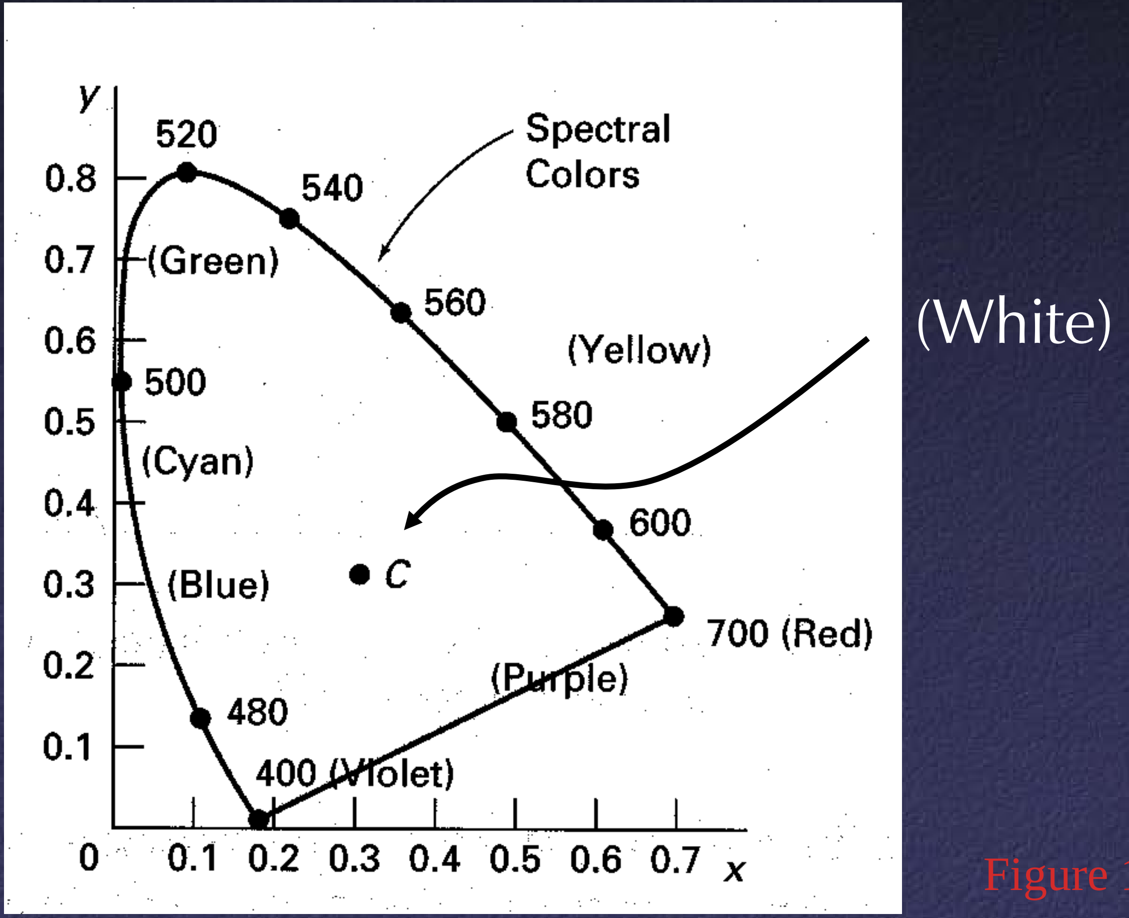
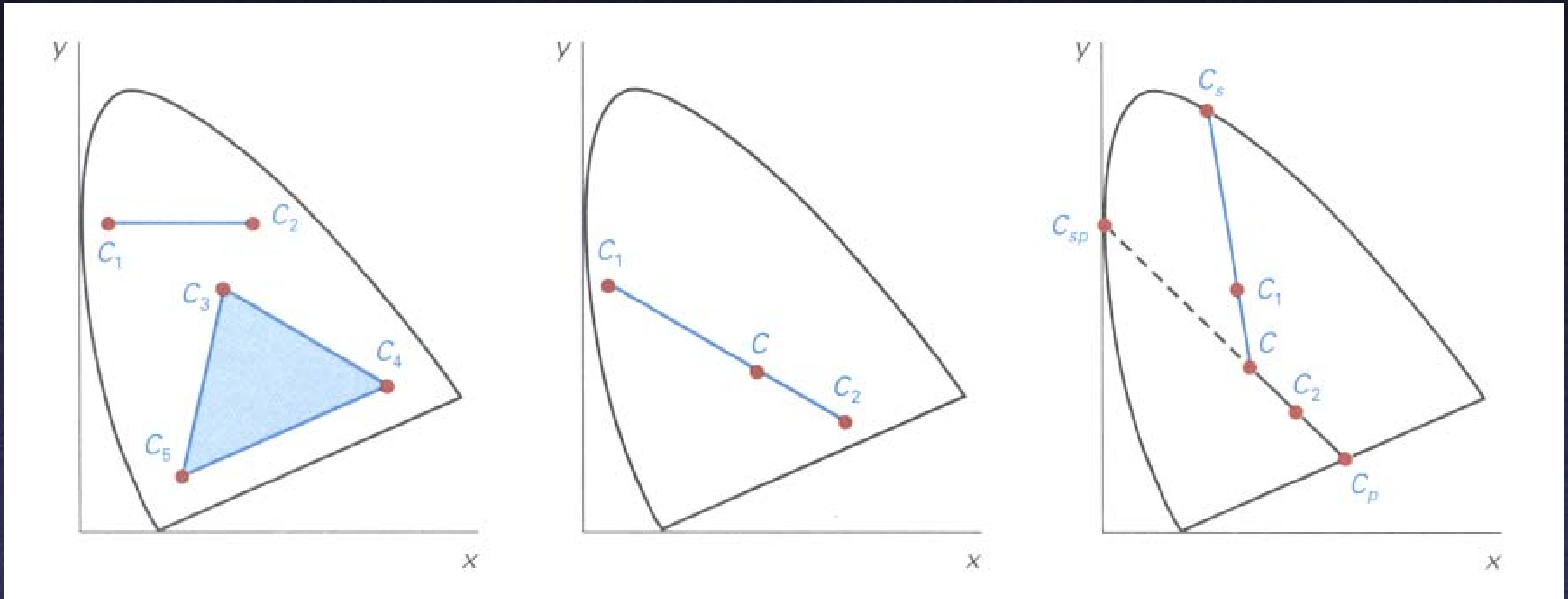


Figure 15.7 from H&B

CIE Chromaticity Diagram



Compare Color Gamuts

Identify Complementary Colors

Determine Dominant Wavelength and Purity

Figures 15.8-10 from H&B

RGB Color Gamut

Color gamut for a typical RGB computer monitor

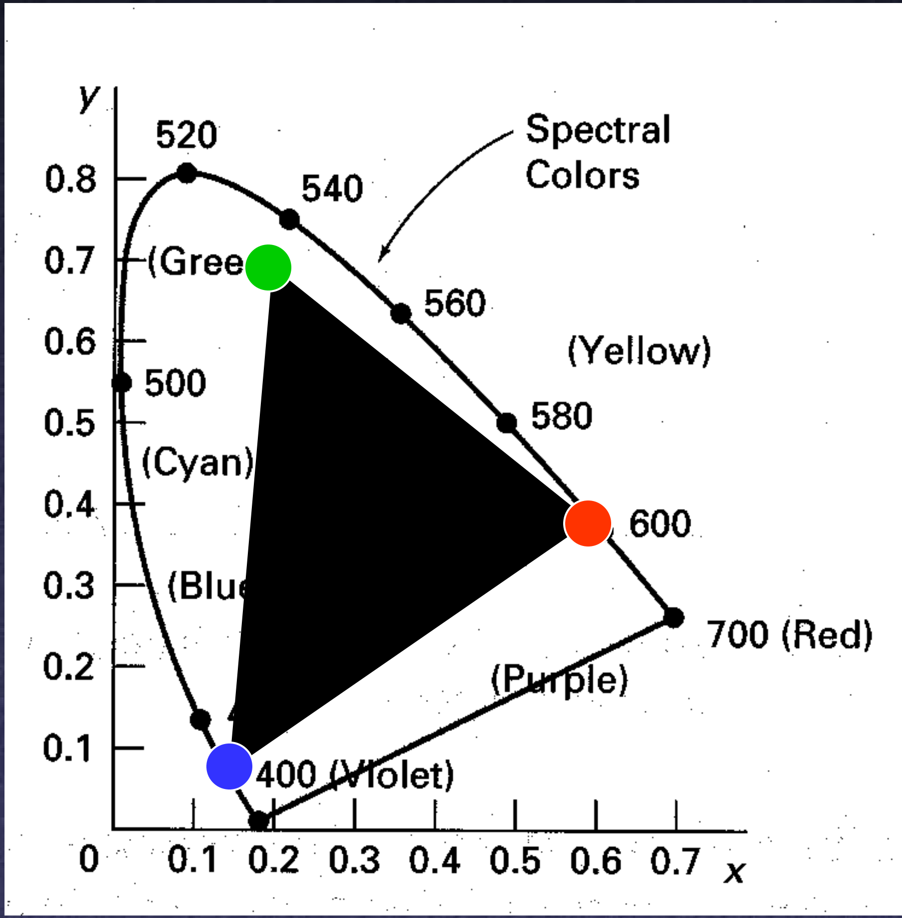
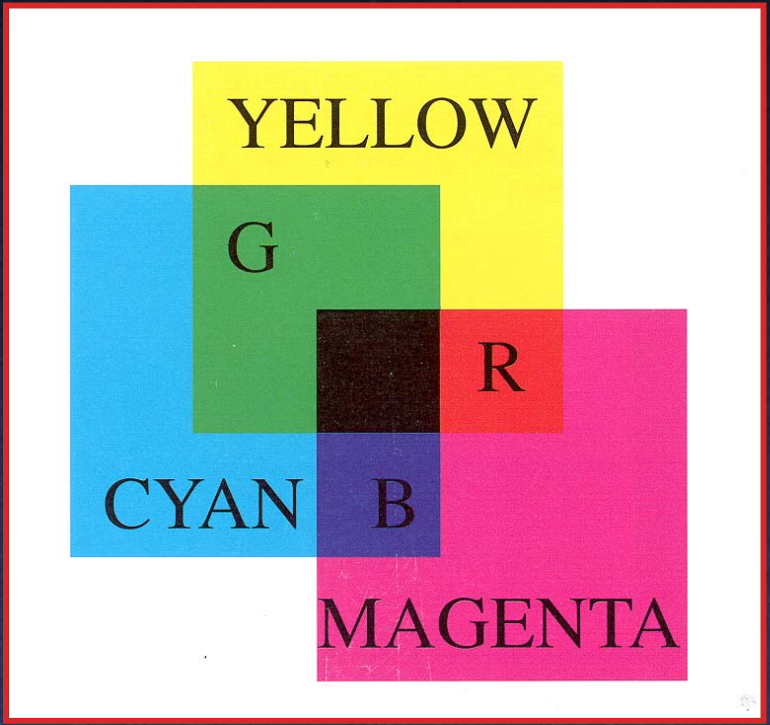


Figure 15.13 from H&B

CMY Color Model



Colors are subtractive

C	M	Y	Color
0.0	0.0	0.0	White
1.0	0.0	0.0	Cyan
0.0	1.0	0.0	Magenta
0.0	0.0	1.0	Yellow
1.0	1.0	0.0	Blue
1.0	0.0	1.0	Green
0.0	1.0	1.0	Red
1.0	1.0	1.0	Black
0.5	0.0	0.0	
1.0	0.5	0.5	
1.0	0.5	0.0	

Plate II.7 from FvDFH

CMY Color Cube

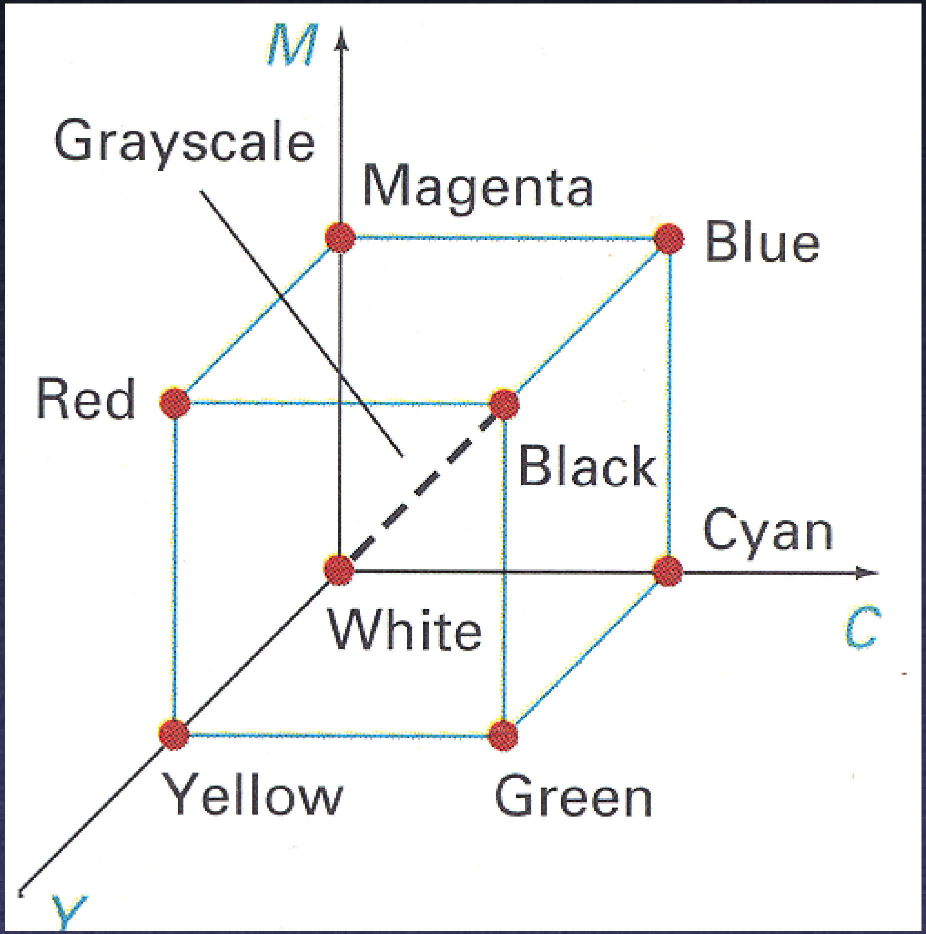
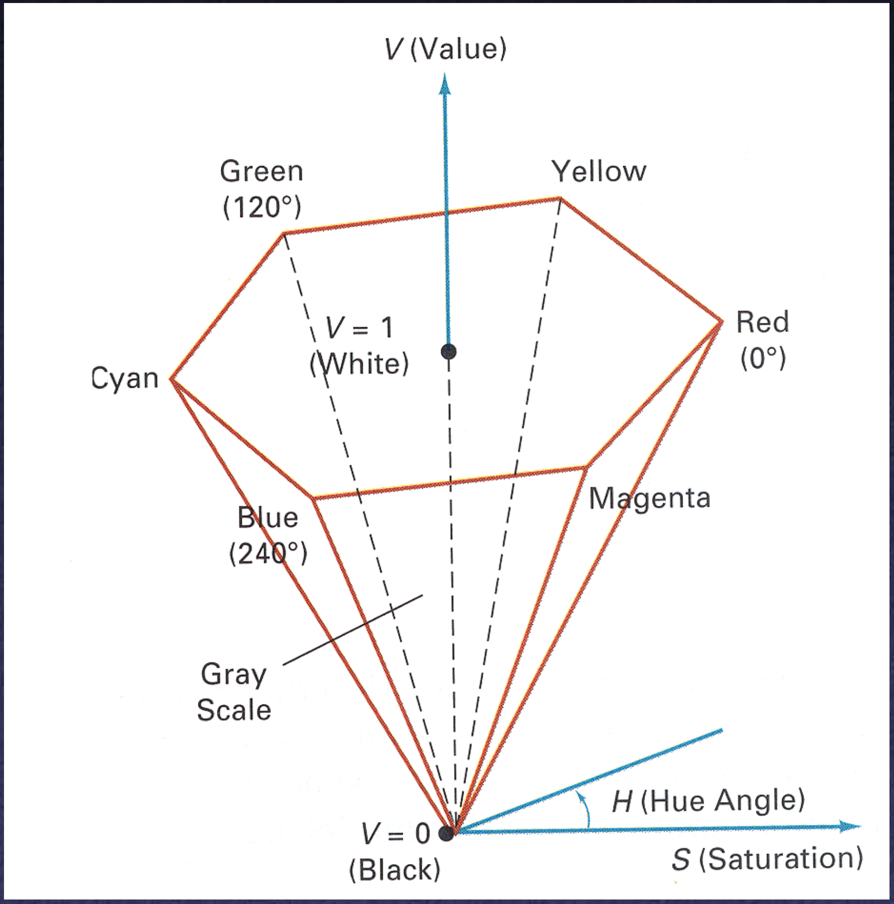


Figure 15.14 from H&B

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	

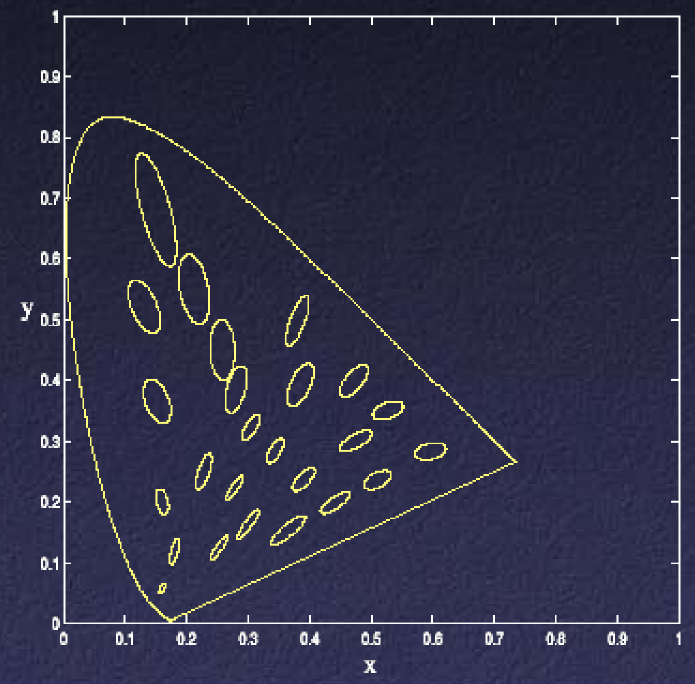
Figure 15.16&15.17 from H&B

Colorspaces for Television

- Differences in brightness more important than differences in color
- YC_rC_b, YUV, YIQ colorspaces = linear transforms of RGB
  - Lightness: $Y = 0.299R + 0.587G + 0.114B$
  - Other color components typically allocated less bandwidth than Y

Perceptually-Uniform Colorspaces

- Most colorspaces not perceptually uniform
- MacAdam ellipses: color within each ellipse appears constant (shown here 10X size)

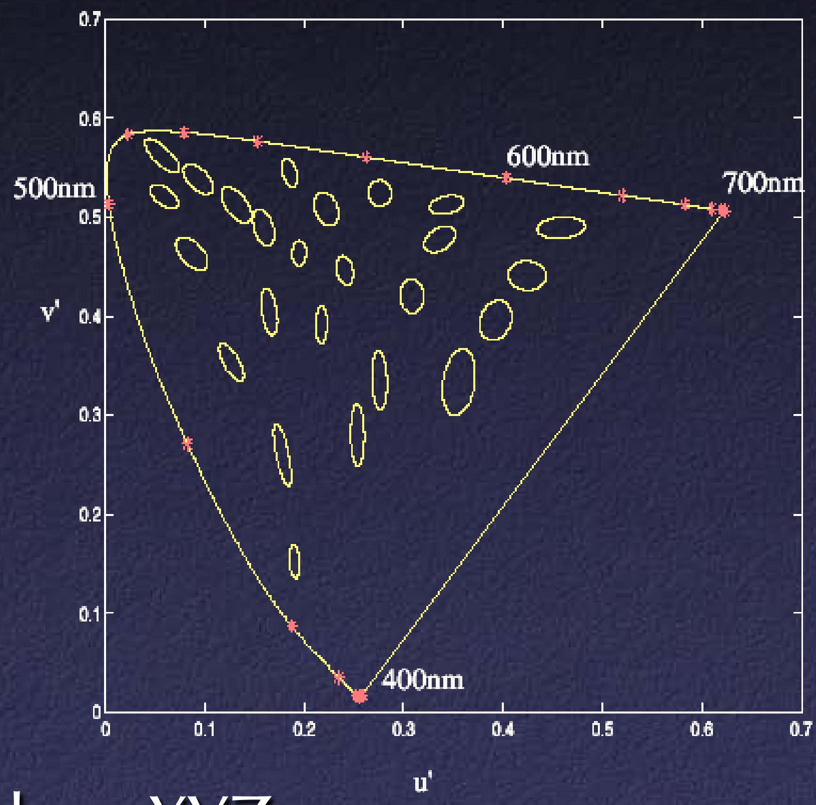


Perceptually-Uniform Colorspaces

- u′v′ space

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$



- Not perfect, but better than XYZ

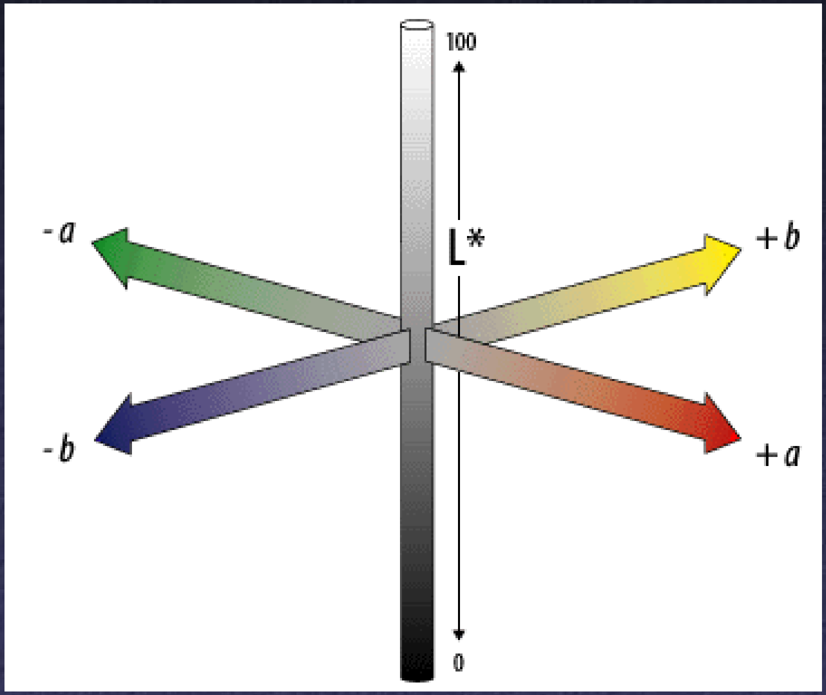
L*a*b* Color Space

- Another choice: L*a*b*

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

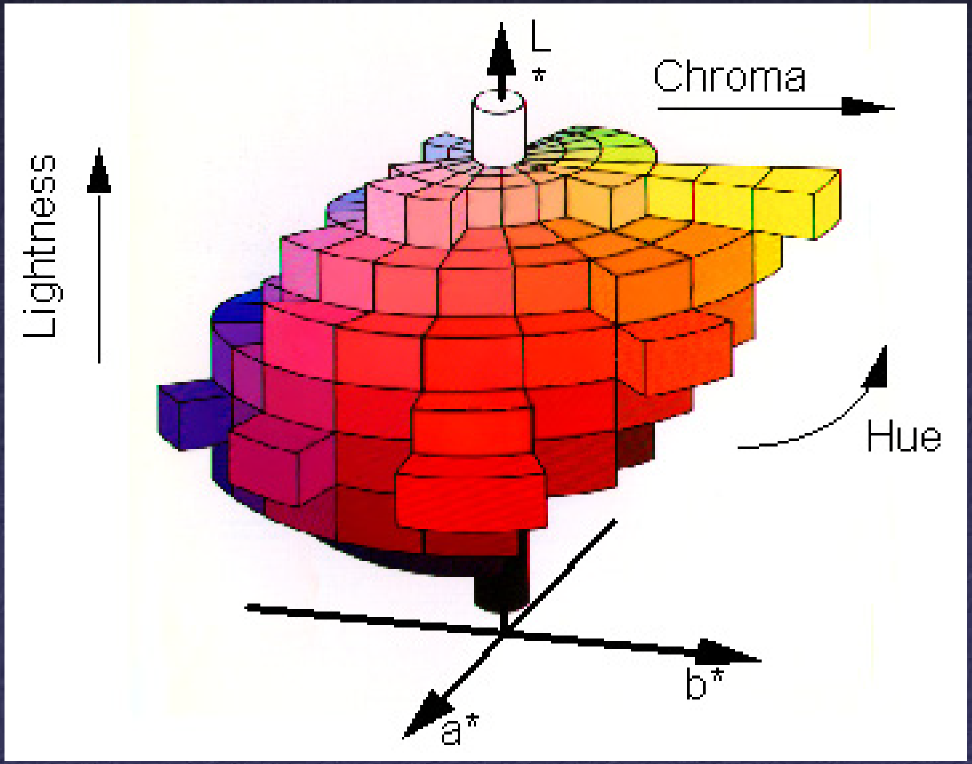
$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

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



L*a*b* Color Space

- Often used for color comparison when "perceptual" differences matter



Summary

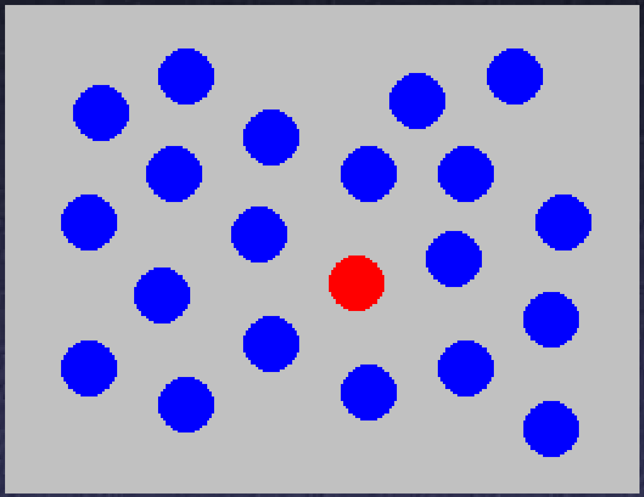
- Perception and representation of
  - Intensity, frequency, color
- Color
  - Tristimulus theory of color
  - CIE Chromaticity Diagram
  - Different color models

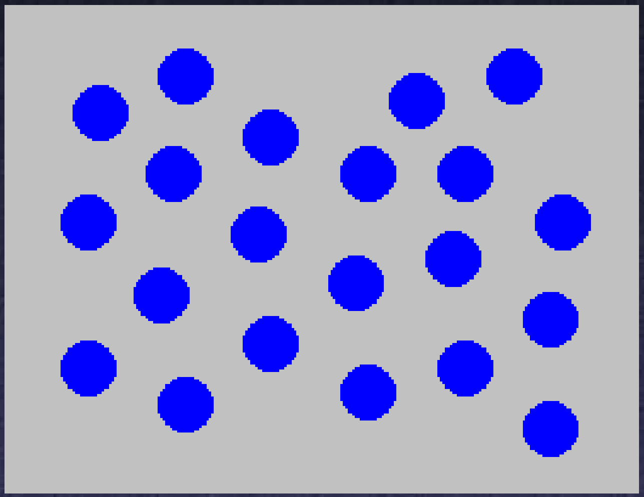
Preattentive Processing

- Some properties are processed preattentively (without need for focusing attention).
- Important for art, design of visualizations
  - what can be perceived immediately
  - what properties are good discriminators
  - what can mislead viewers

Preattentive processing sildes from Healey
http://www.csc.ncsu.edu/faculty/healey/PP/PP.html

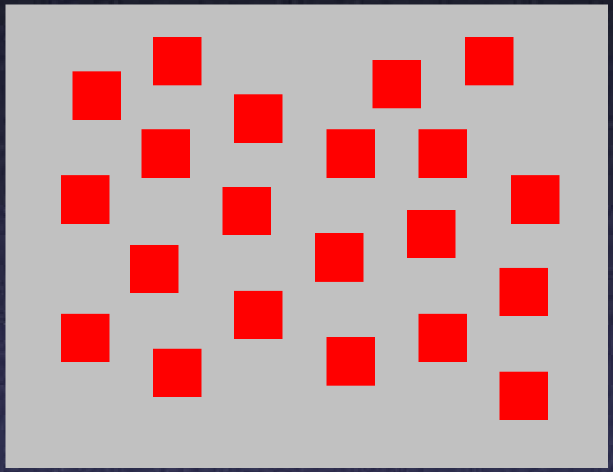
Example: Color Selection

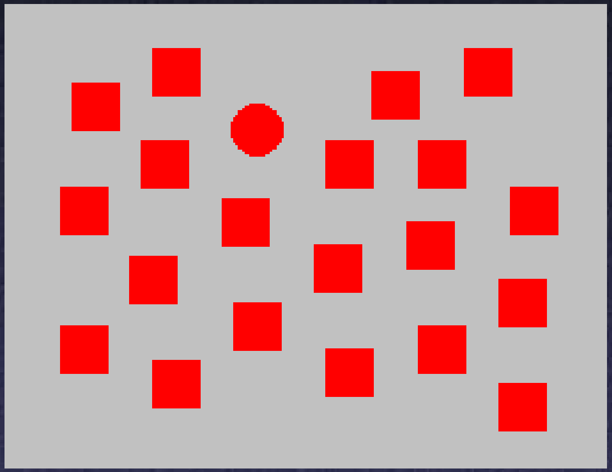




Viewer can rapidly and accurately determine whether the target (red circle) is present or absent. Difference detected in color.

Example: Shape Selection



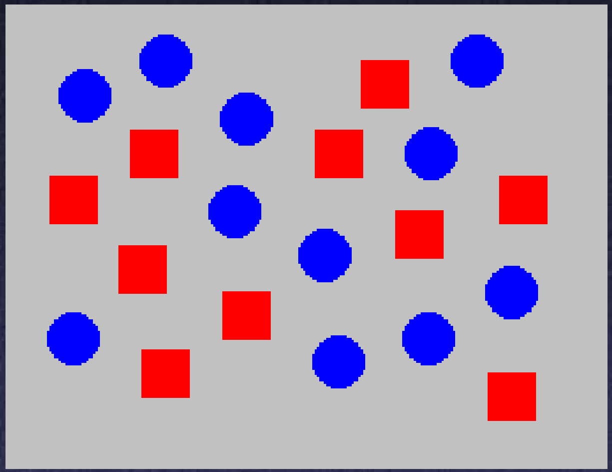


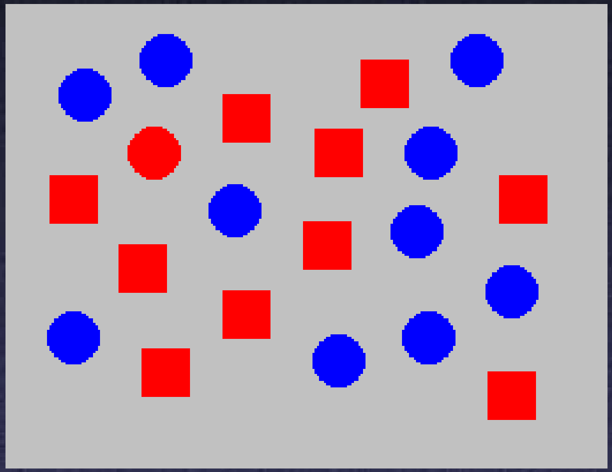
Viewer can rapidly and accurately determine whether the target (red circle) is present or absent. Difference detected in form (curvature)

Pre-attentive Processing

- < 200–250 ms qualifies as pre-attentive
  - eye movements take at least 200ms
  - yet certain processing can be done very quickly, implying low-level processing in parallel
- If a decision takes a fixed amount of time regardless of the number of distractors, it is considered to be preattentive

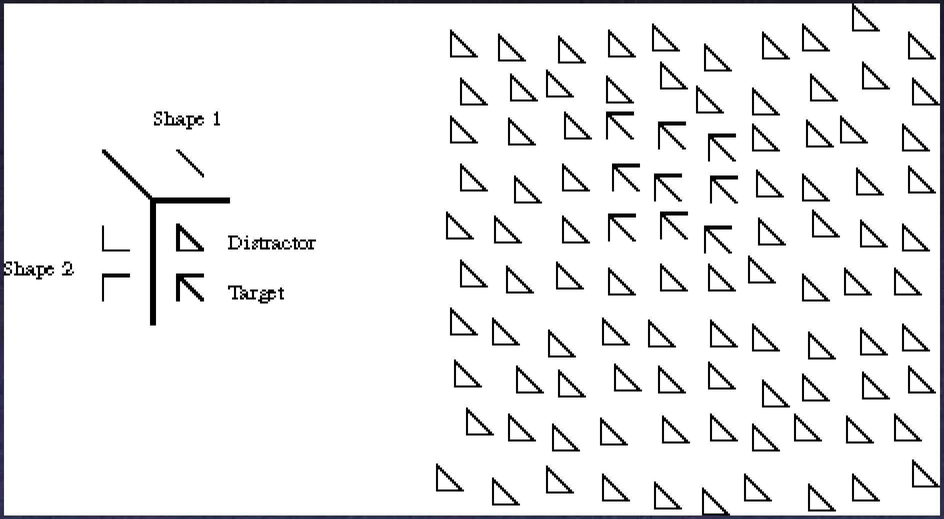
Example: Conjunction of Features





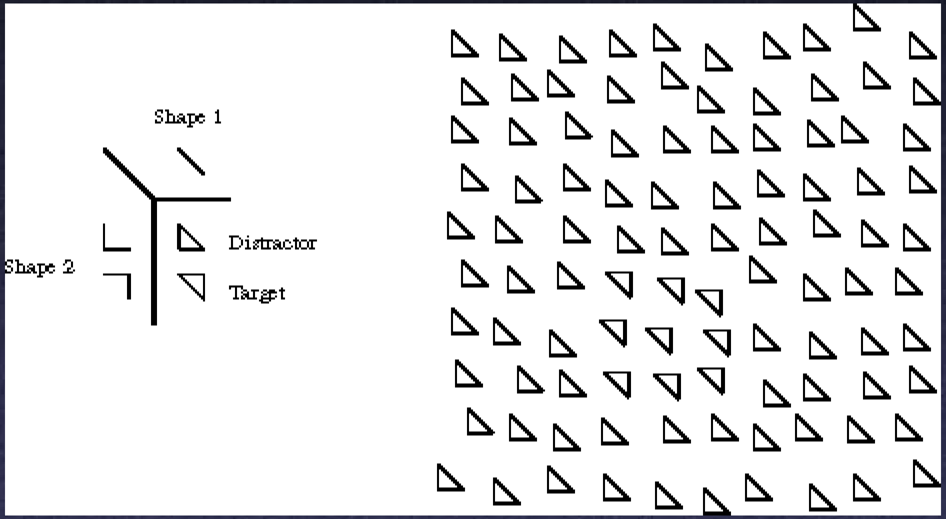
Viewer *cannot* rapidly and accurately determine whether the target (red circle) is present or absent when target has two or more features, each of which are present in the distractors. Viewer must search sequentially.

Example: Emergent Features



Target has a unique feature with respect to distractors (open sides) and so the group can be detected preattentively.

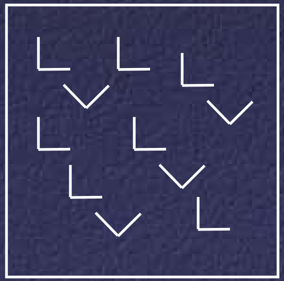
Example: Emergent Features

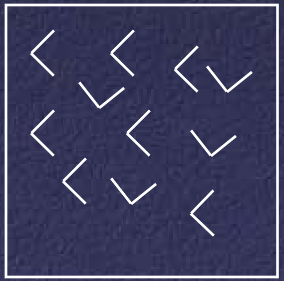


Target does not have a unique feature with respect to distractors and so the group cannot be detected preattentively.

Asymmetric and Graded Preattentive Properties

- Some properties are asymmetric
  - a sloped line among vertical lines is preattentive
  - a vertical line among sloped ones is not
- Some properties have a gradation
  - some more easily discriminated among than others





SUBJECT PUNCHED QUICKLY OXIDIZED TCEJBUS DEHCNUP YLKCIUQ DEZIDIXO
CERTAIN QUICKLY PUNCHED METHODS NIATREC YLKCIUQ DEHCNUP SDOHTEM
SCIENCE ENGLISH RECORDS COLUMNS ECNEICS HSILGNE SDROCER SNMULOC
GOVERNS PRECISE EXAMPLE MERCURY SNREVOG ESICERP ELPMAXE YRUCREM
CERTAIN QUICKLY PUNCHED METHODS NIATREC YLKCIUQ DEHCNUP SDOHTEM
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Text NOT Preattentive

SUBJECT PUNCHED QUICKLY OXIDIZED TCEJBUS DEHCNUP YLKCIUQ DEZIDIXO
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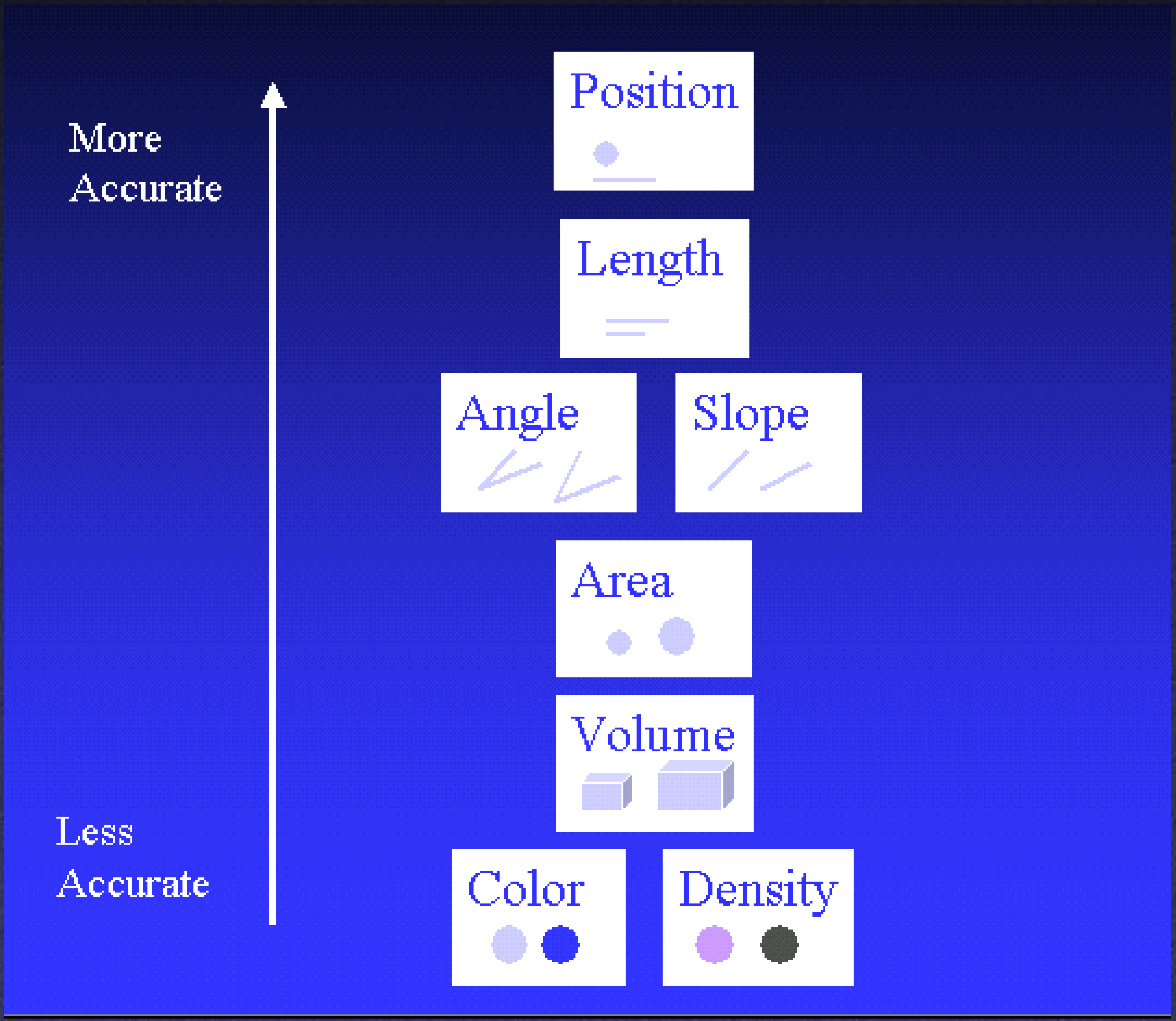
Preattentive Visual Properties [Healey 97]

length	Triesman & Gormican [1988]
width	Julesz [1985]
size	Triesman & Gelade [1980]
curvature	Triesman & Gormican [1988]
number	Julesz [1985]; Trick & Pylyshyn [1994]
terminators	Julesz & Bergen [1983]
intersection	Julesz & Bergen [1983]
closure	Enns [1986]; Triesman & Souther [1985]
colour (hue)	Nagy & Sanchez [1990, 1992]; D'Zmura [1991] Kawai et al. [1995]; Bauer et al. [1996]
intensity	Beck et al. [1983]; Triesman & Gormican [1988]
flicker	Julesz [1971]
direction of motion	Nakayama & Silverman [1986]; Driver & McLeod [1992]
binocular lustre	Wolfe & Franzel [1988]
stereoscopic depth	Nakayama & Silverman [1986]
3-D depth cues	Enns [1990]
lighting direction	Enns [1990]

Accuracy Ranking of Quantitative Perceptual Tasks
Estimated; only pairwise comparisons have been validated
[Mackinlay 88 from Cleveland & McGill]

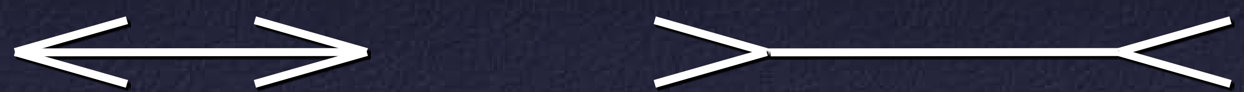


Visual Illusions

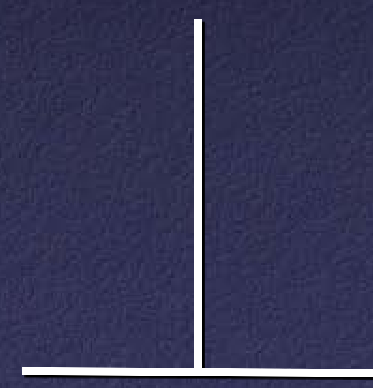
- People don’t perceive length, area, angle, brightness they way they “should”
- Some illusions have been reclassified as systematic perceptual errors
  - e.g., brightness contrasts (grey square on white background vs. on black background)
  - partly due to increase in our understanding of the relevant parts of the visual system
- Nevertheless, the visual system does some really unexpected things

Illusions of Linear Extent

- Mueller-Lyon (off by 25-30%)

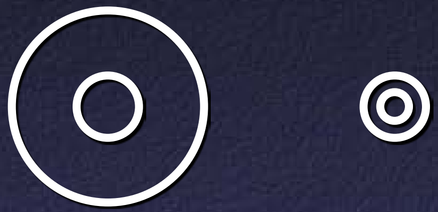


- Horizontal-Vertical



Illusions of Area

- Delboeuf Illusion



- Height of 4-story building overestimated by approximately 25%