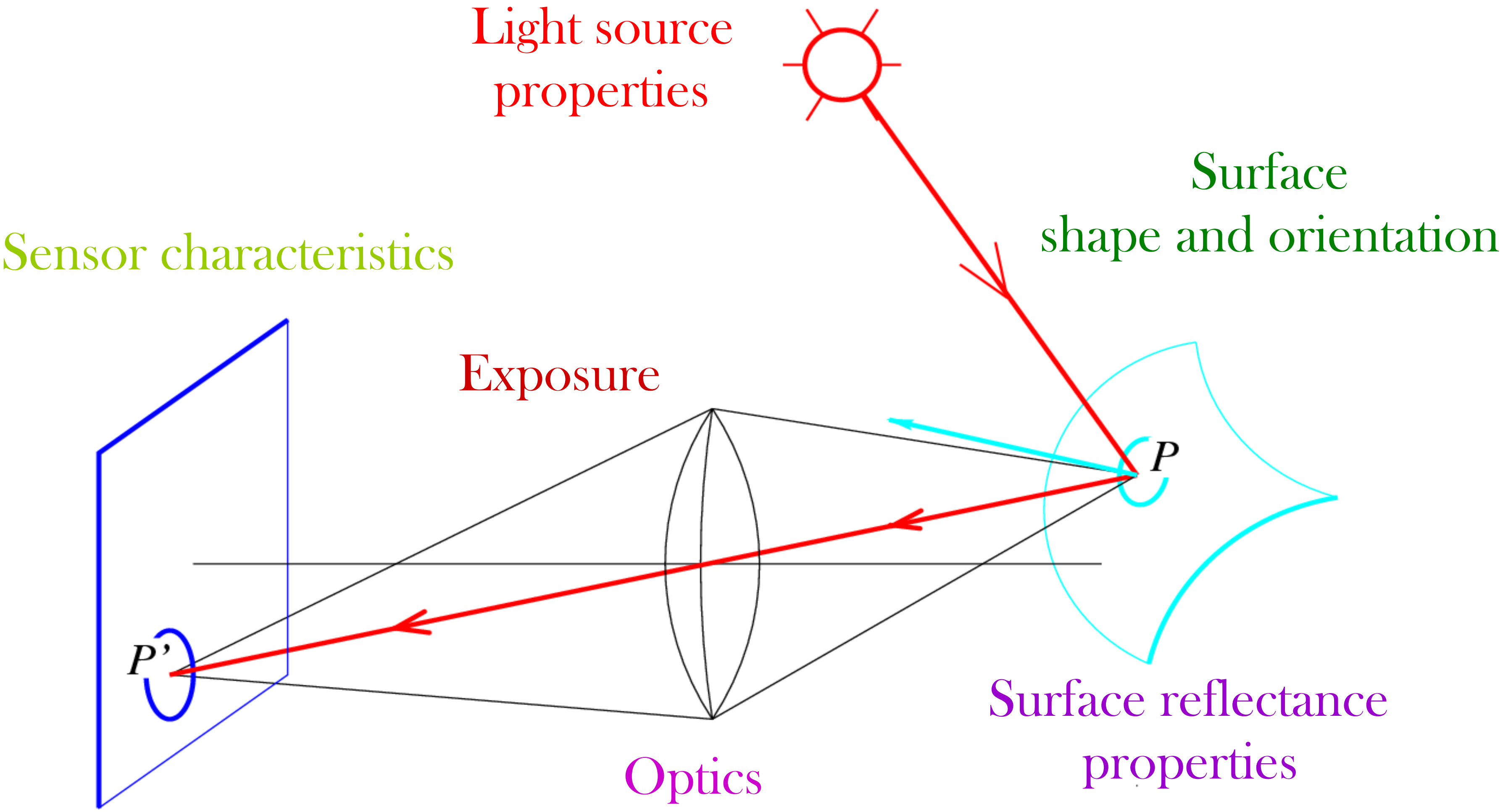
BBM 413 Fundamentals of Image Processing

Erkut Erdem
Dept. of Computer Engineering
Hacettepe University

Color Perception and Color Spaces

Review - image formation

- What determines the brightness of an image pixel?



Slide credit: L. Fei-Fei

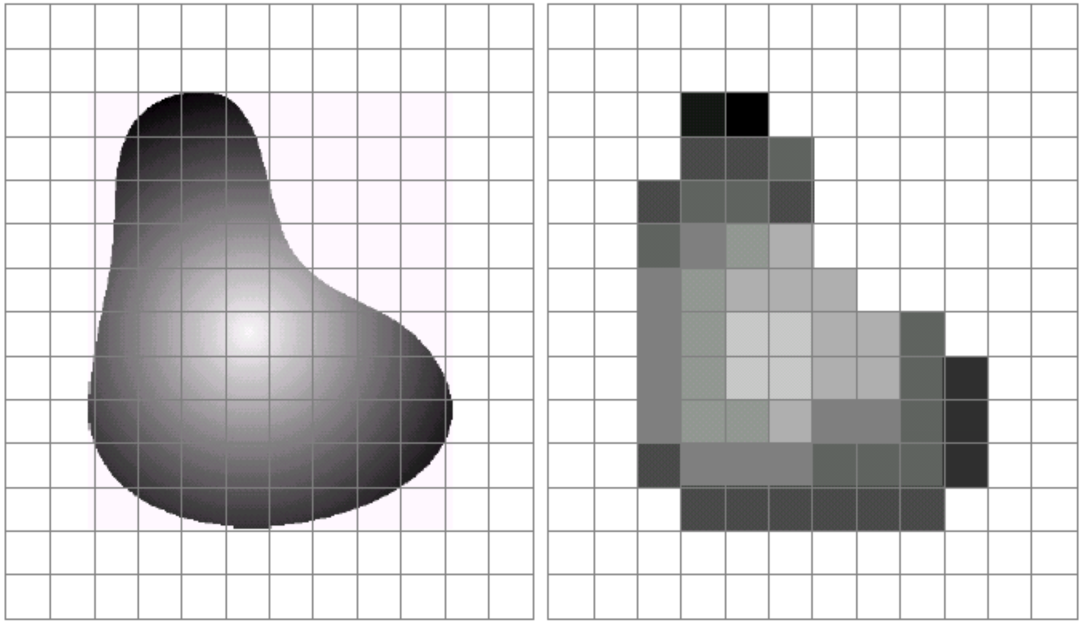
Review - digital camera

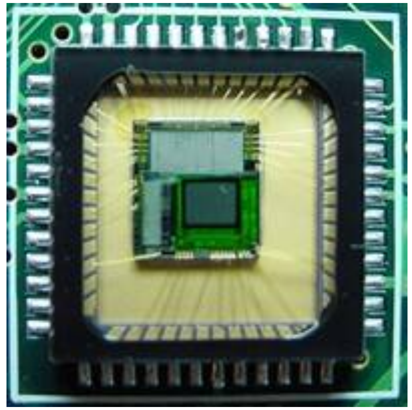
A digital camera replaces film with a sensor array

- Each cell in the array is light-sensitive diode that converts photons to electrons
- http://electronics.howstuffworks.com/digital-camera.htm

Slide credit: S. Seitz

Review – digital images





a b

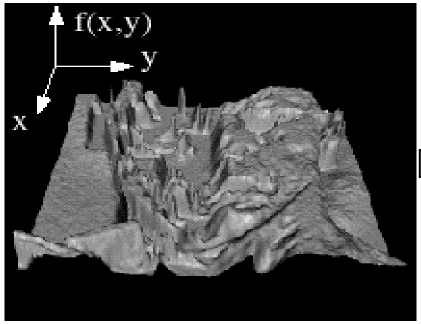
FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.

Slide credit: D. Hoiem

Review - digital images

- <u>Sample</u> the 2D space on a regular grid
- <u>Quantize</u> each sample (round to nearest integer)

- Image thus represented as a matrix of integer values.

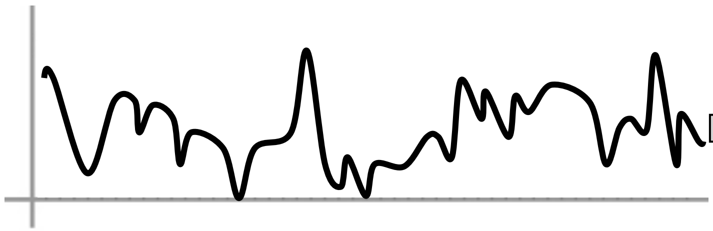


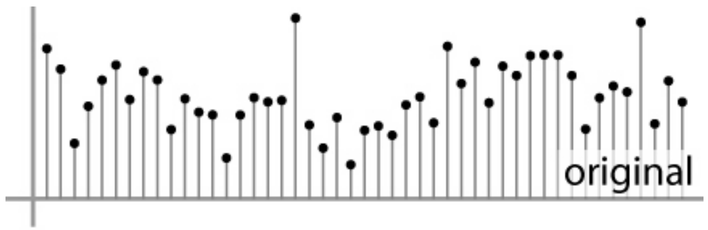
j

i

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

2D



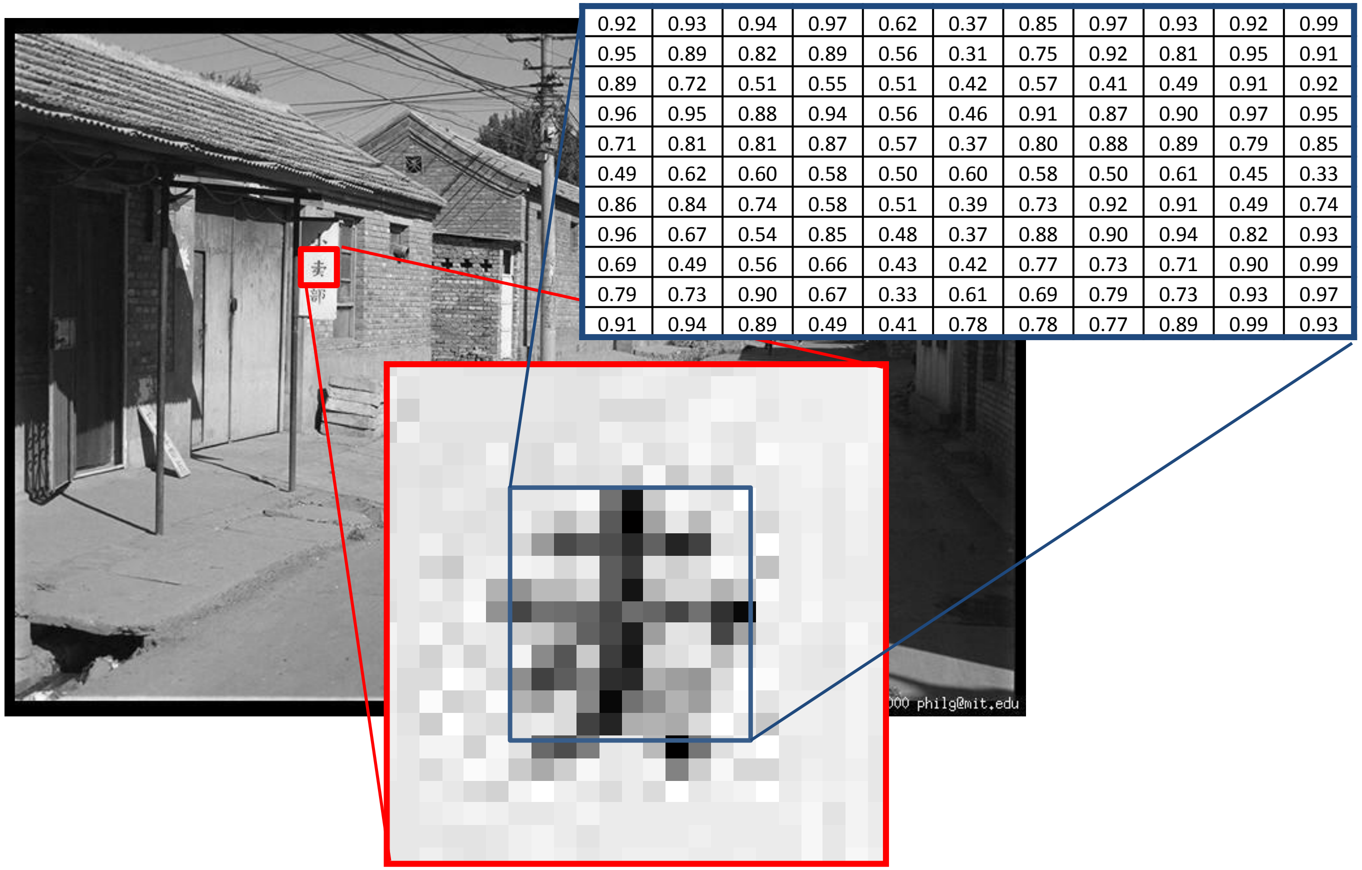


1D

Slide credit: K. Grauman, S. Seitz

Review – image representation

- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Slide credit: M. J. Black

Outline

- Perception of color and light
- Color spaces

Why does a visual system need color?

http://www.hobbylinc.com/gr/pll/pll5019.jpg

Slide credit: W. Freeman

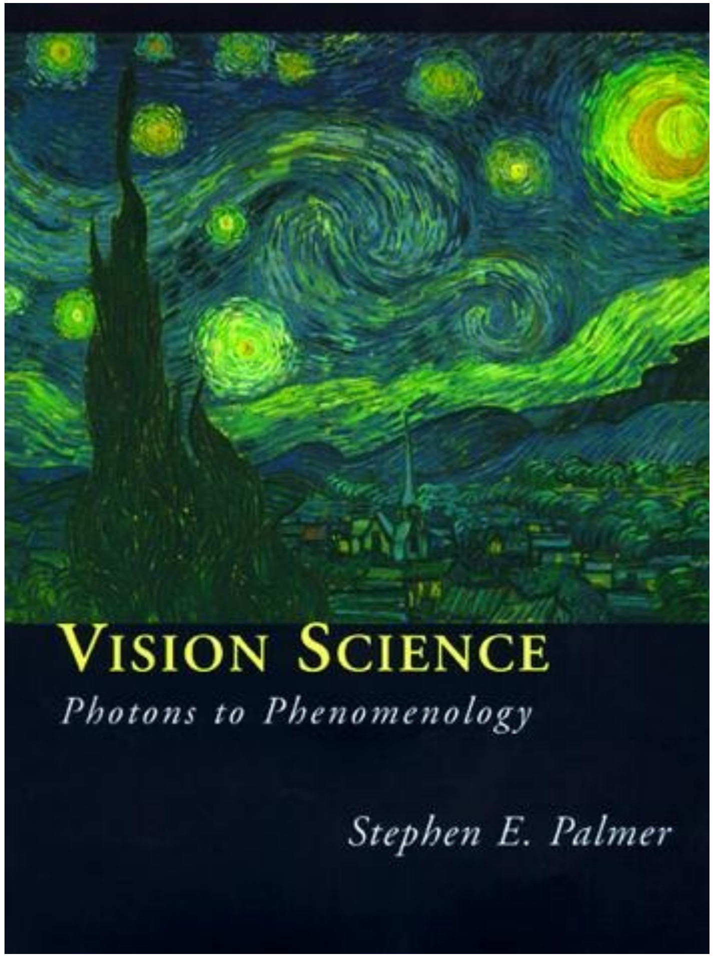
Why does a visual system need color? (an incomplete list…)

- To tell what food is edible.
- To distinguish material changes from shading changes.
- To group parts of one object together in a scene.
- To find people's skin.
- Check whether a person's appearance looks normal/healthy.

Slide credit: W. Freeman

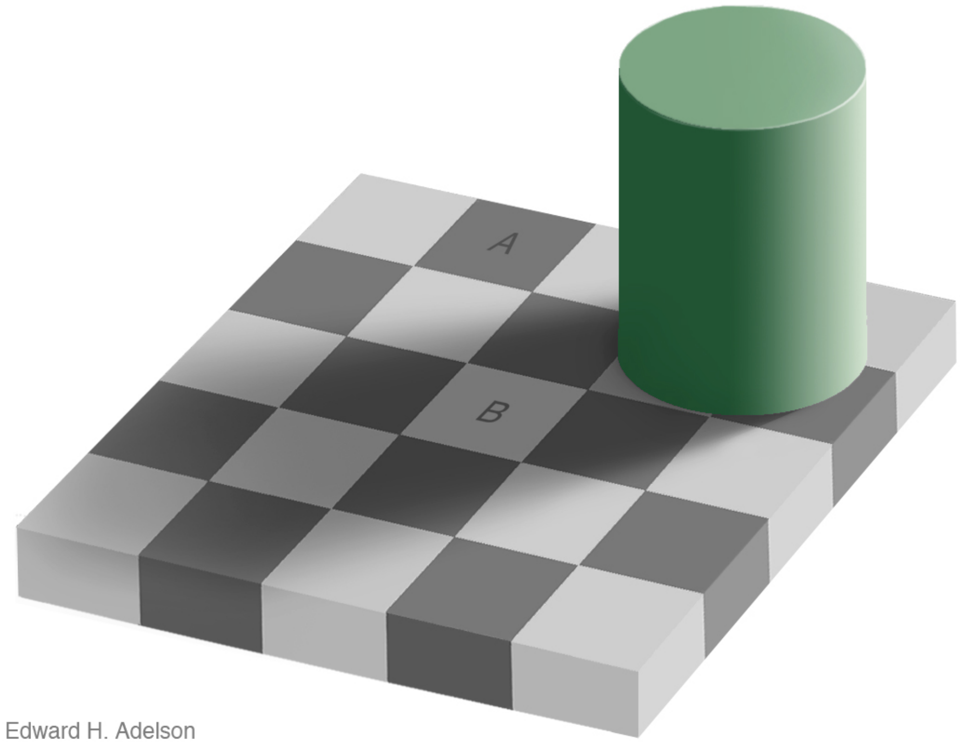
What is color?

- Color is the result of interaction between physical light in the environment and our visual system
- Color is a psychological property of our visual experiences when we look at objects and lights, *not* a physical property of those objects or lights (S. Palmer, *Vision Science: Photons to Phenomenology*)



Slide credit: A. Efros

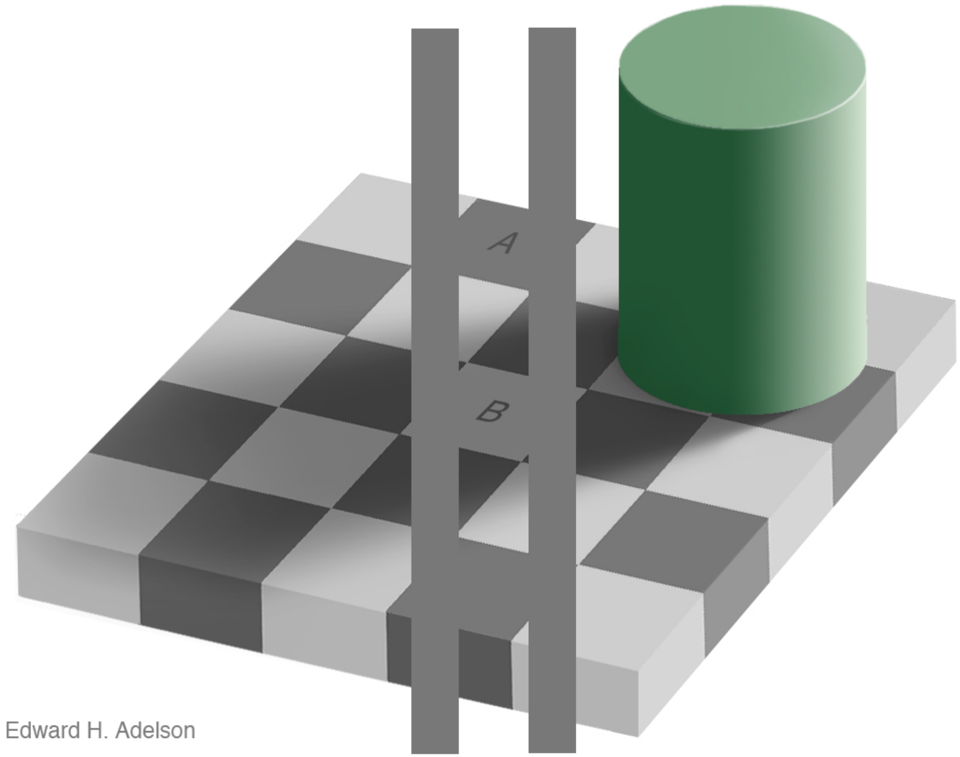
Brightness perception



Edward Adelson

http://web.mit.edu/persci/people/adelson/illusions_demos.html

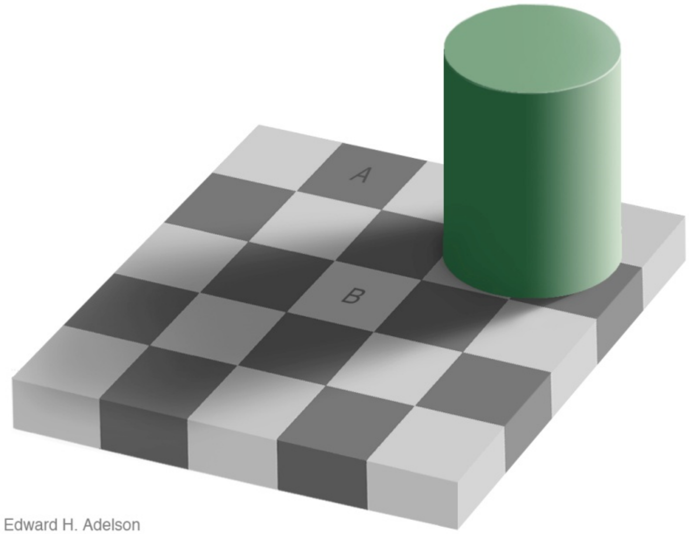
Brightness perception

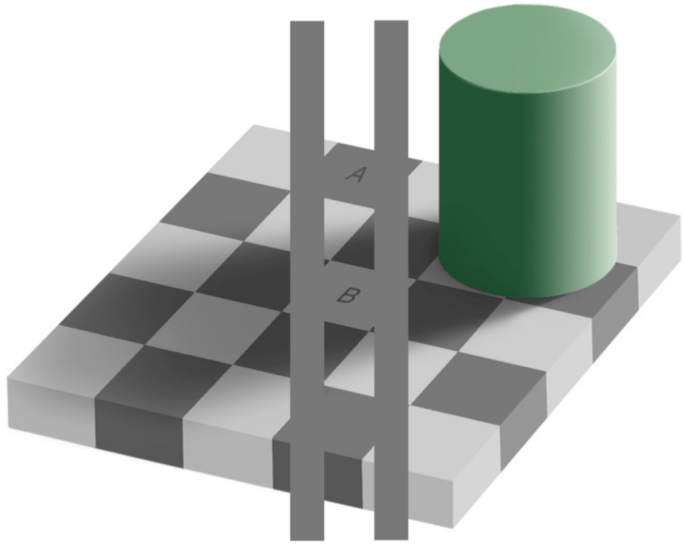


Edward Adelson

http://web.mit.edu/persci/people/adelson/
illusions_demos.html

Brightness perception



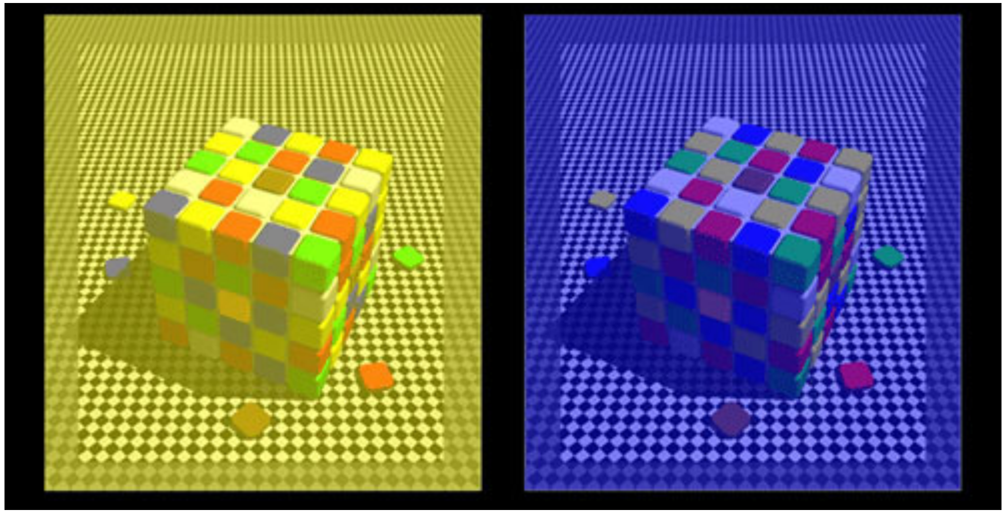


Edward Adelson

http://web.mit.edu/persci/people/adelson/illusions_demos.html

Brightness perception

Color perception

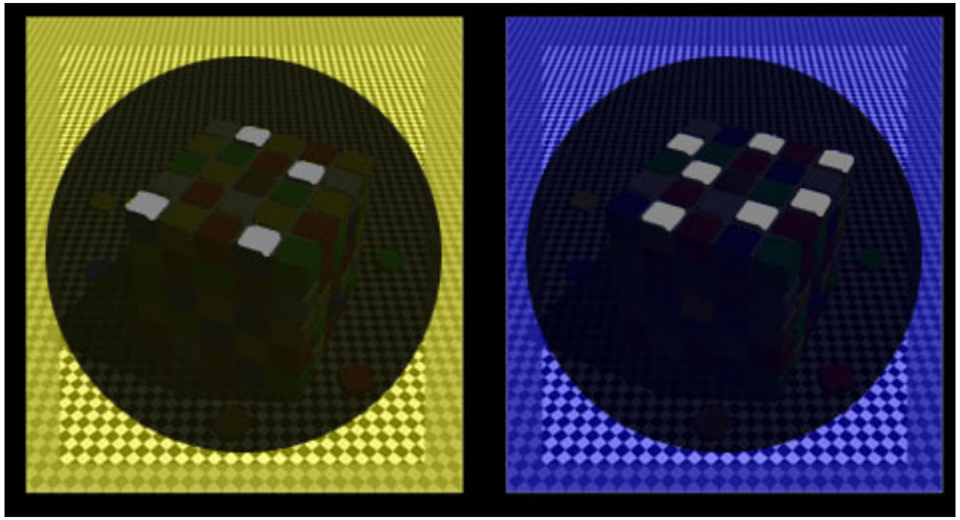


Look at blue squares

Look at yellow squares

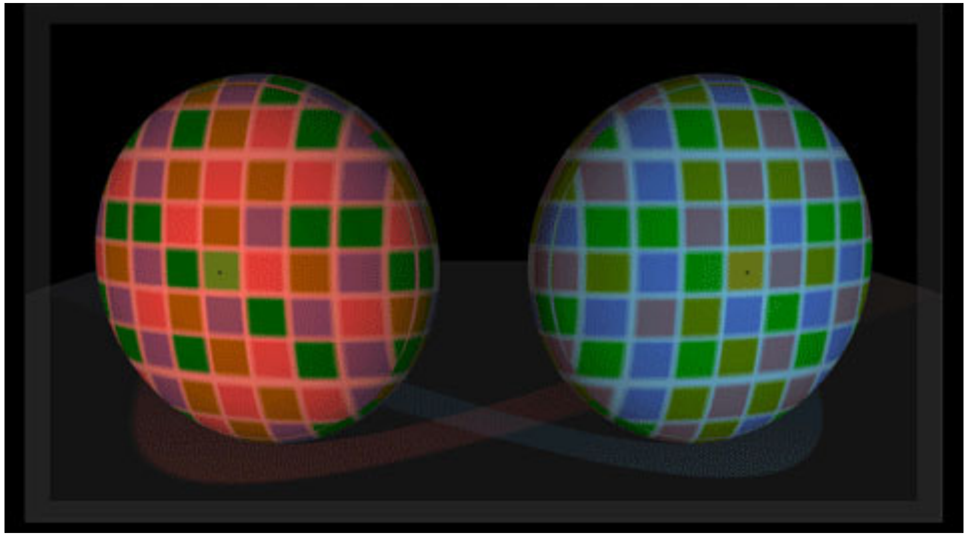
http://www.lottolab.org/articles/illusionsoflight.asp

Color perception



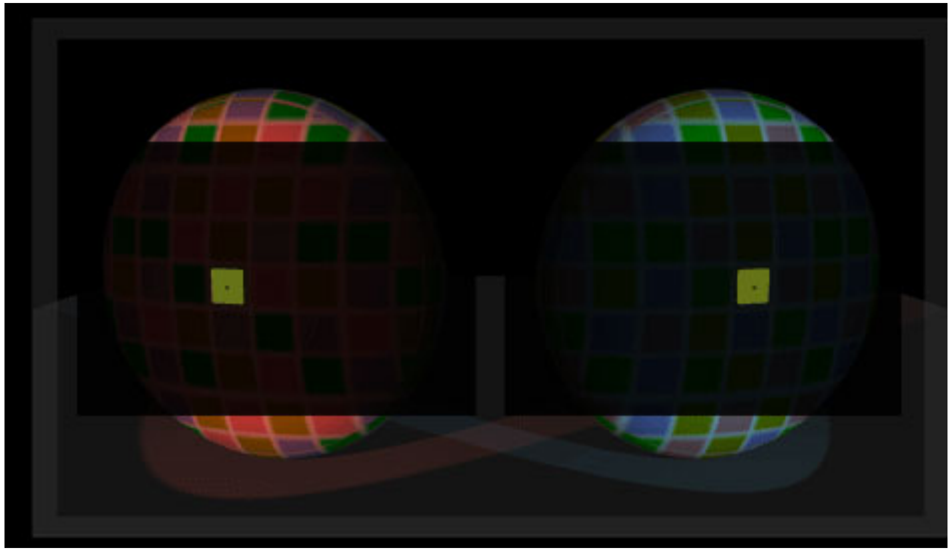
http://www.lottolab.org/articles/illusionsoflight.asp

Color perception



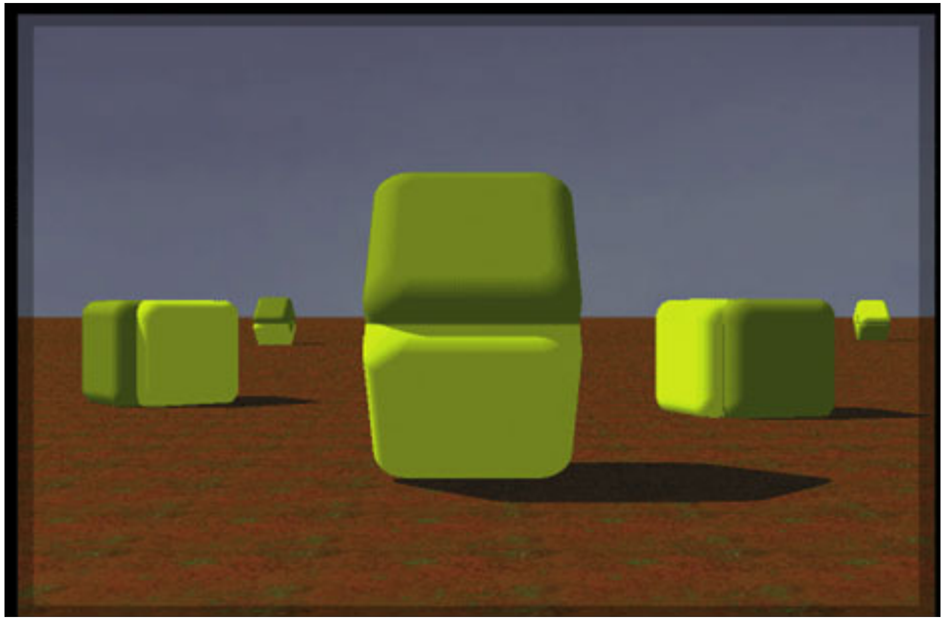
http://www.lottolab.org/articles/illusionsoflight.asp

Color perception



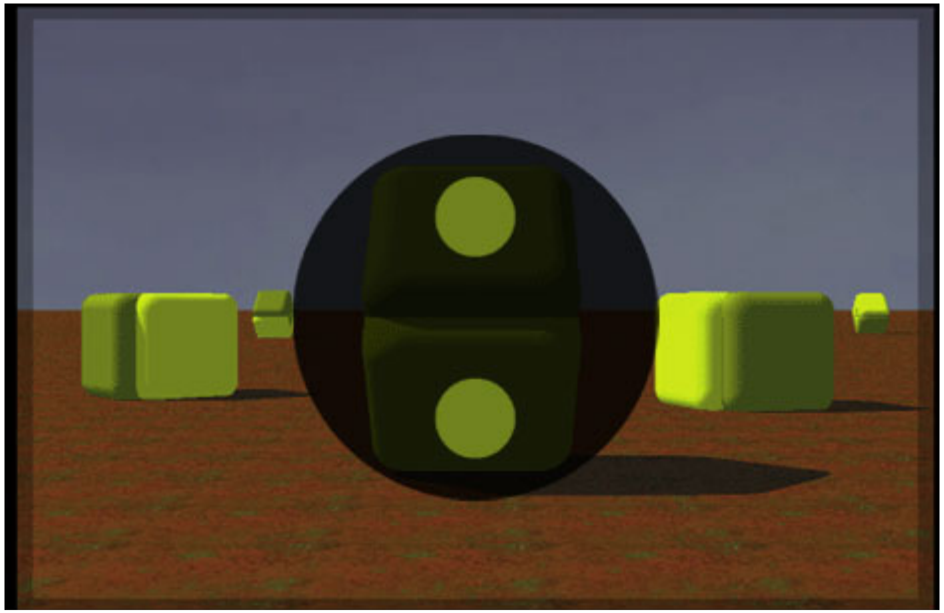
http://www.lottolab.org/articles/illusionsoflight.asp

Color perception



http://www.lottolab.org/articles/illusionsoflight.asp

Color perception



http://www.lottolab.org/articles/illusionsoflight.asp

Reading Assignment #2

- Watch Beau Lotto's TED talk on "Optical illusions show how we see" [link available on course webpage]
- Prepare a 1-page summary of the talk
- Due on 8th of November

TED Ideas worth spreading

Color and light

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch

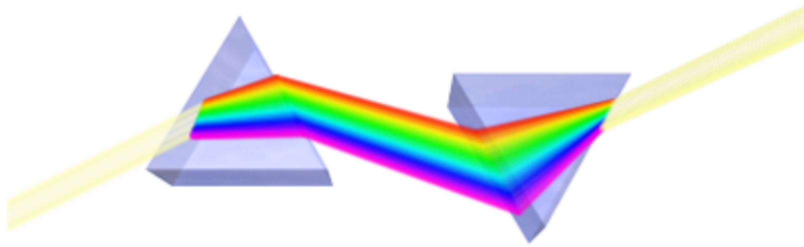
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

- Color is a phenomenon of human perception; it is **not** a universal property of light

Slide credit: K. Grauman, S. Marschner

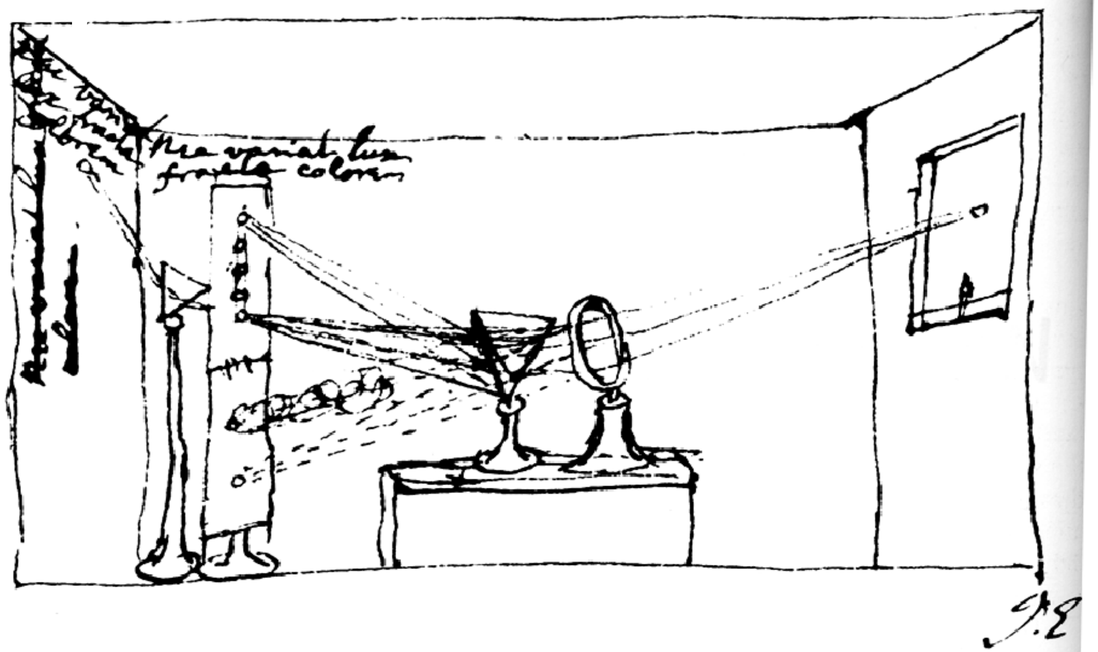
Color

White light: composed of about equal energy in all wavelengths of the visible spectrum



Newton 1665

Color



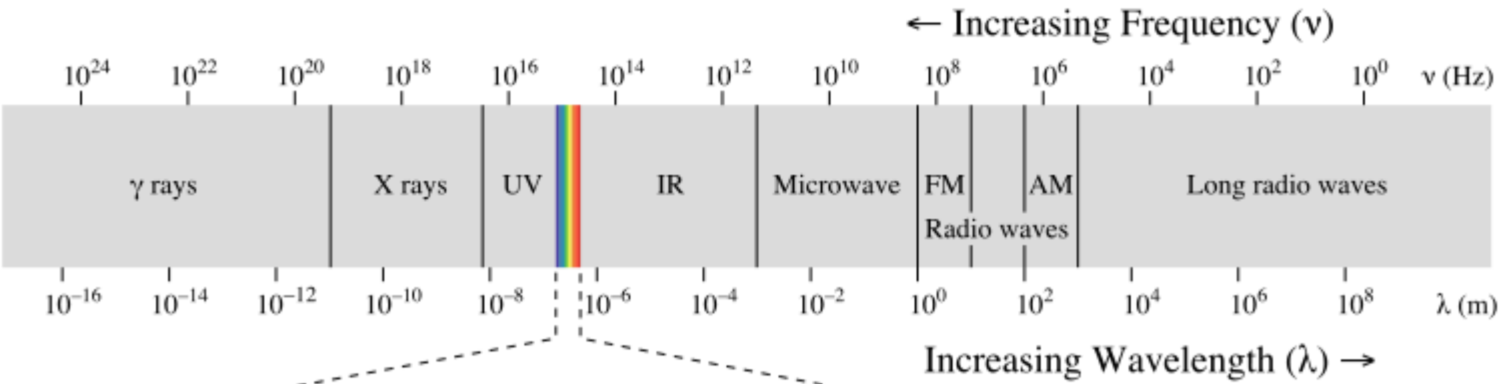
4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

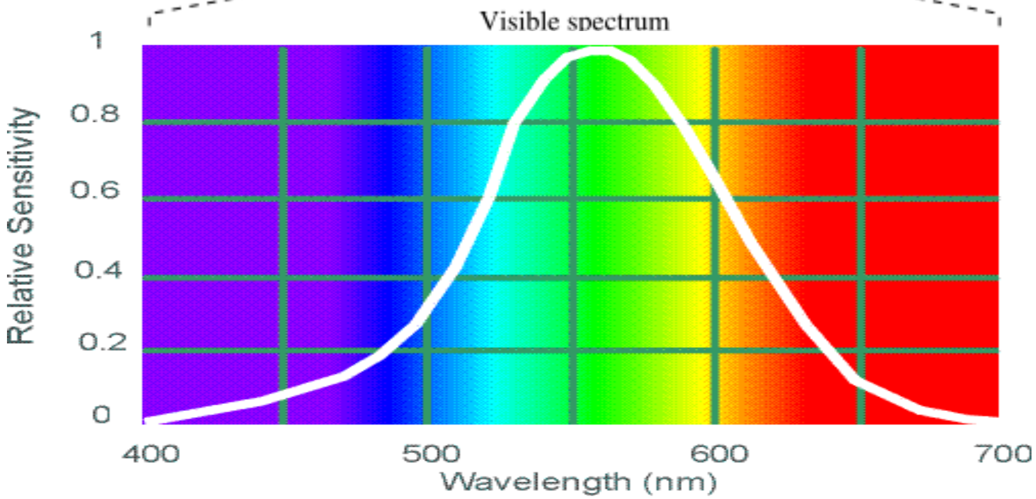
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Slide credit: B. Freeman, A. Torralba, K. Grauman

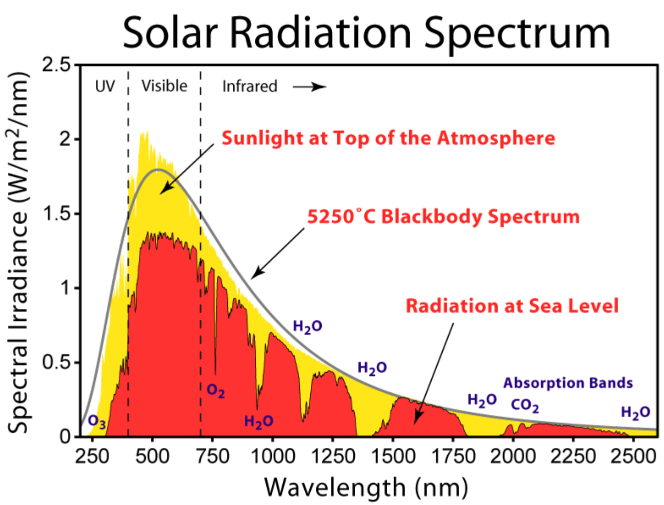
Electromagnetic spectrum

- Light is electromagnetic radiation
  - exists as oscillations of different frequency (or, wavelength)





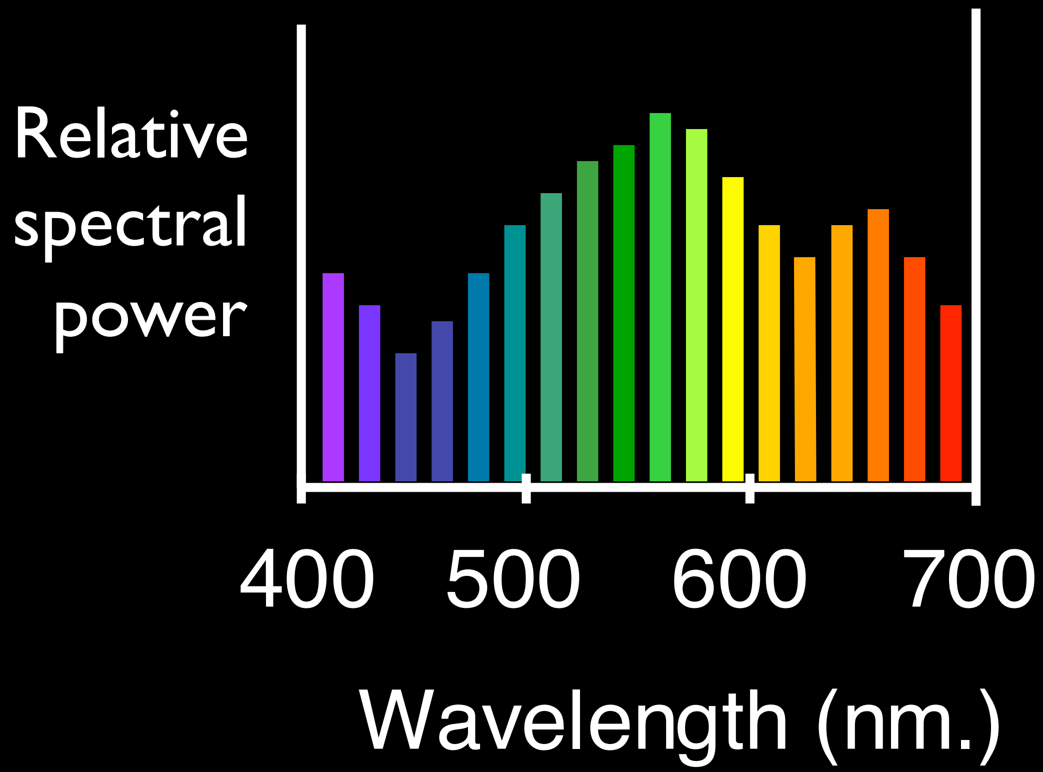
Human Luminance Sensitivity Function



Slide credit: A. Efros

The Physics of light

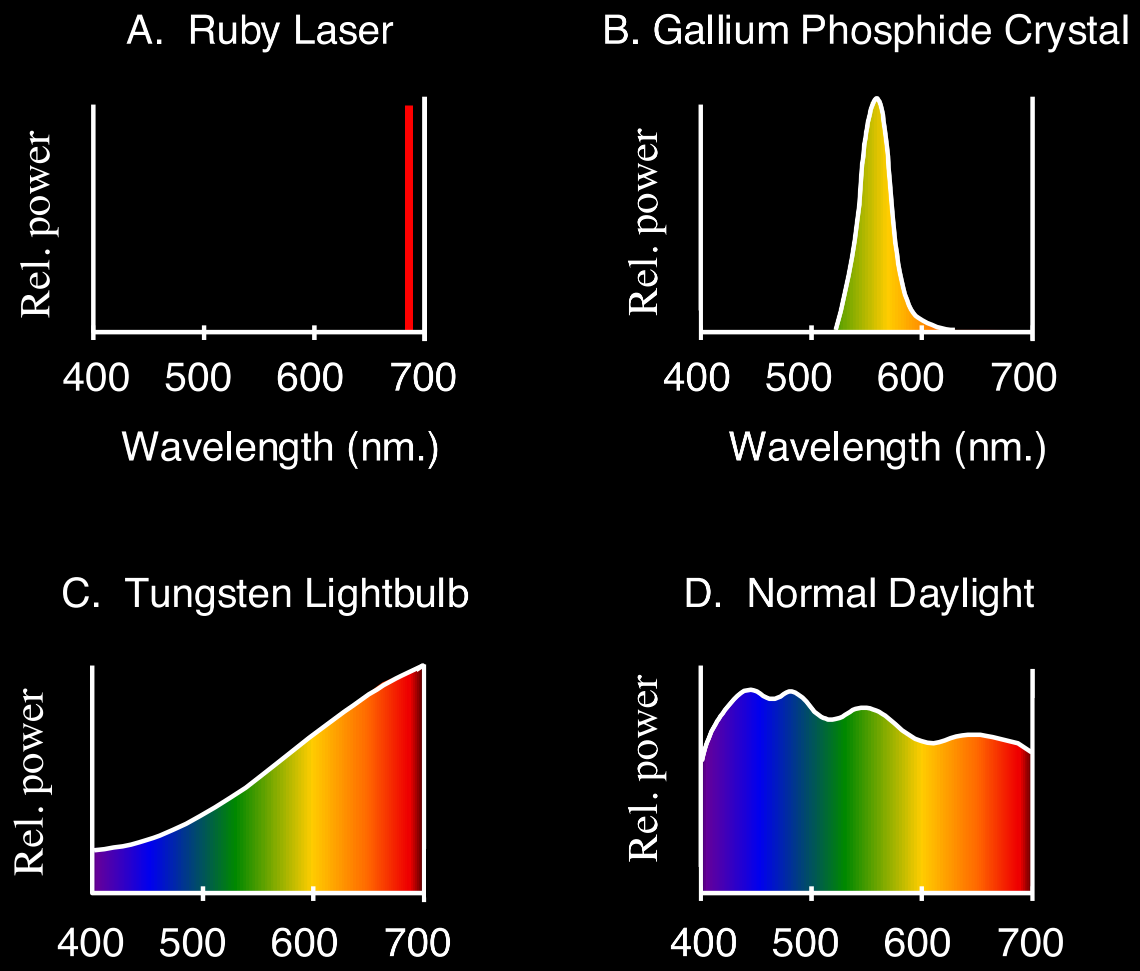
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



Slide credit: A. Efros

The Physics of light

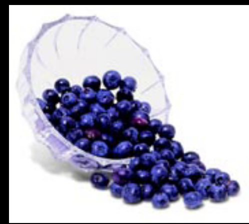
Some examples of the spectra of light sources

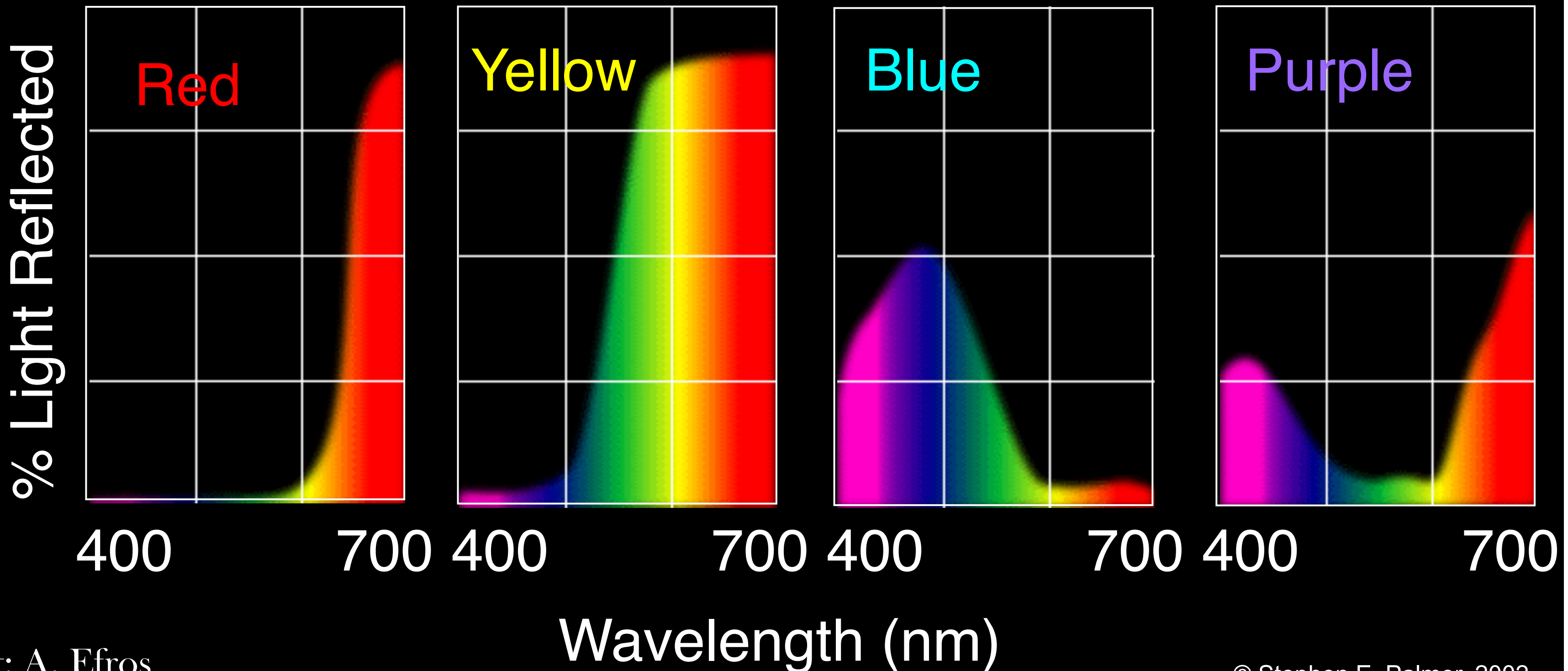


Slide credit: A. Efros

The Physics of light

Some examples of the reflectance spectra of surfaces

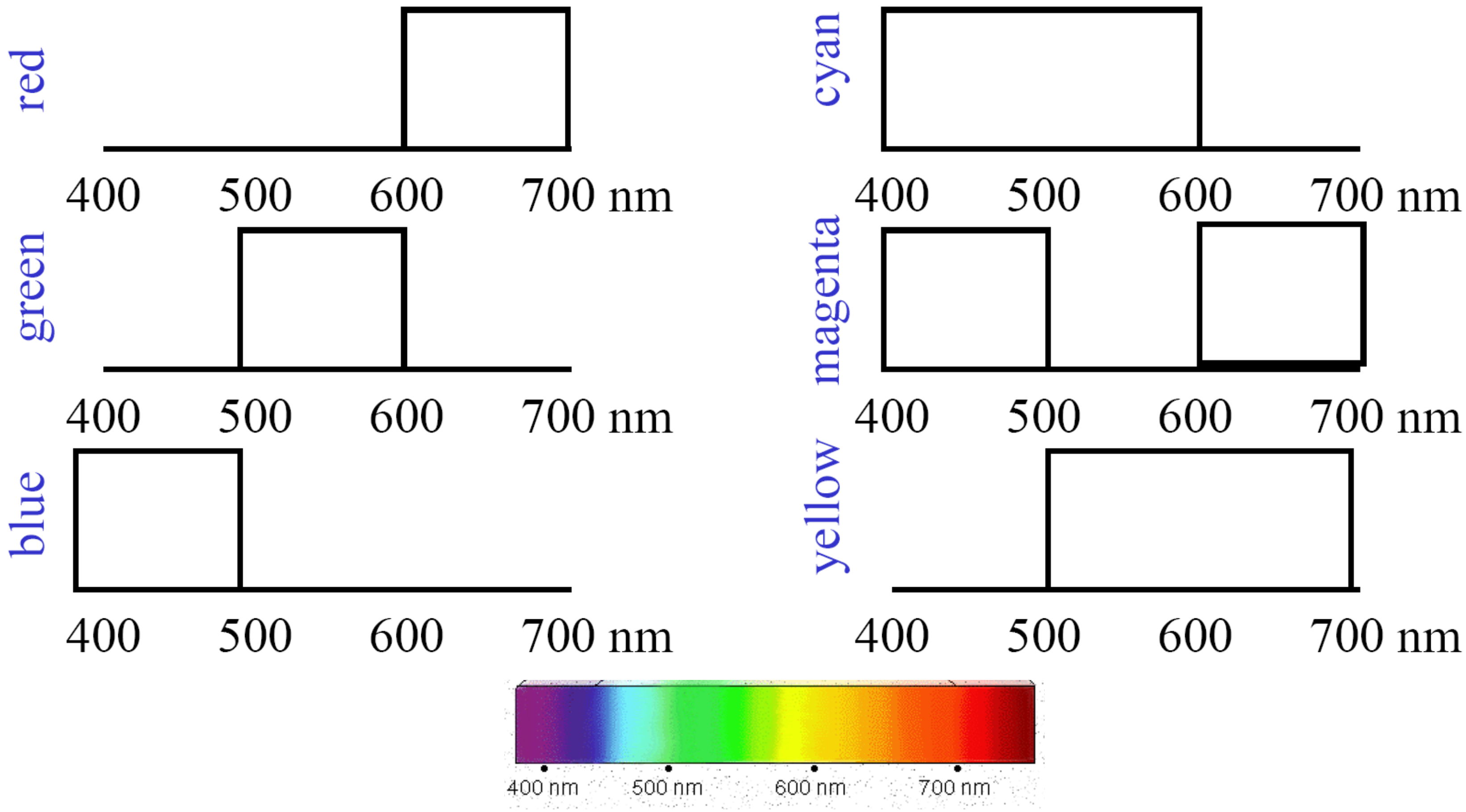




Slide credit: A. Efros

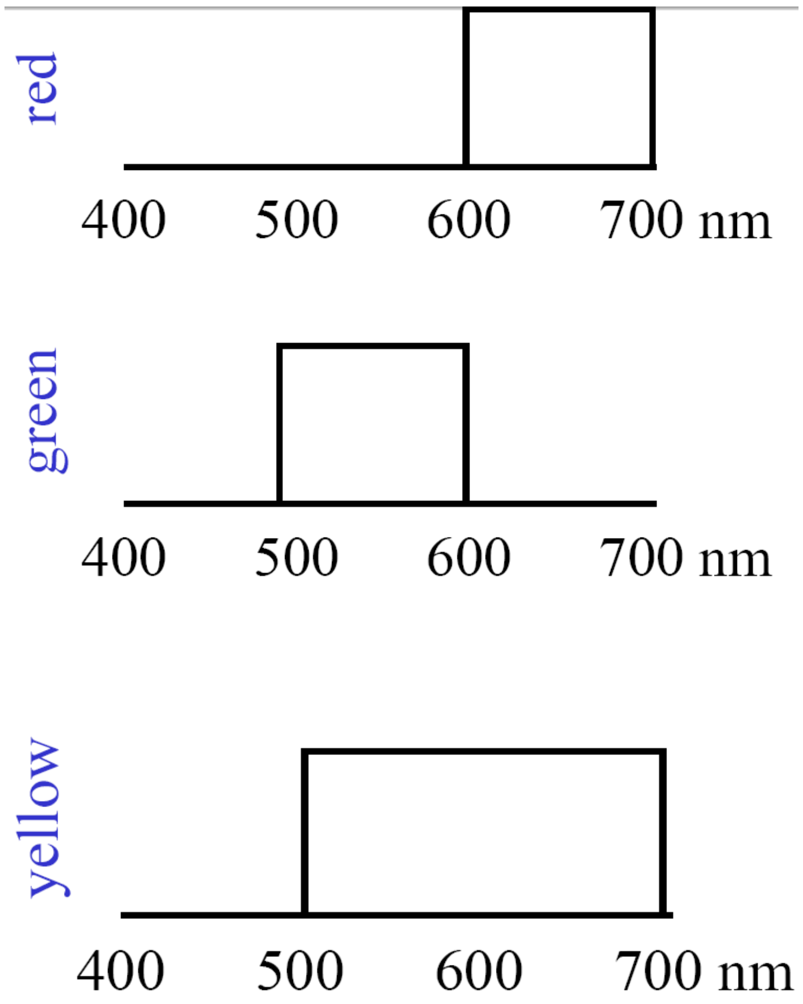
Color mixing

Cartoon spectra for color names:

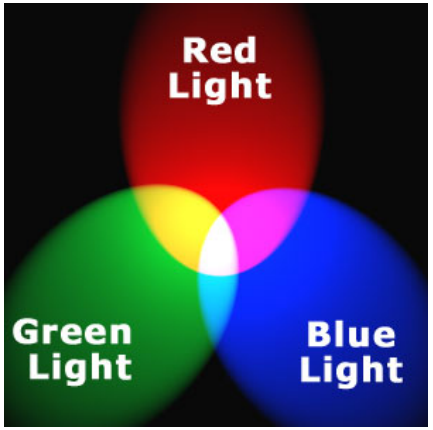


Credit: W. Freeman

Additive color mixing



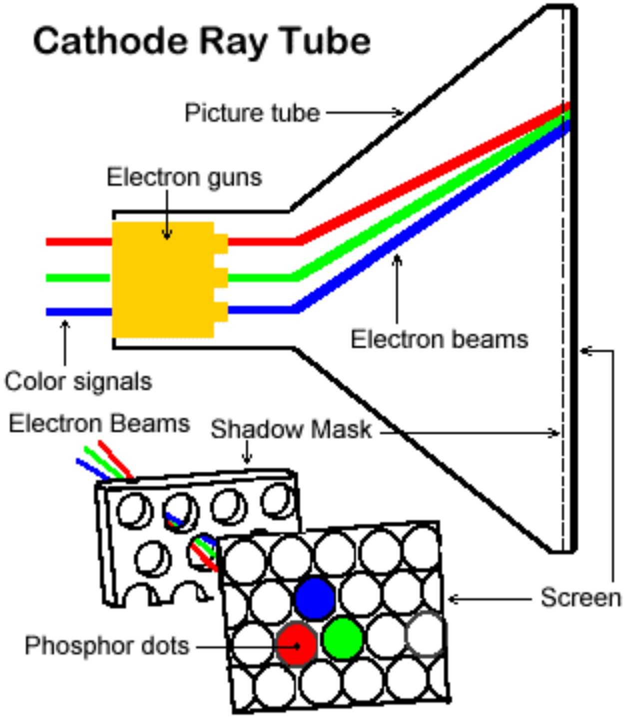
Colors combine by *adding* color spectra



Light *adds* to black.

Credit: W. Freeman

Examples of additive color systems



CRT phosphors

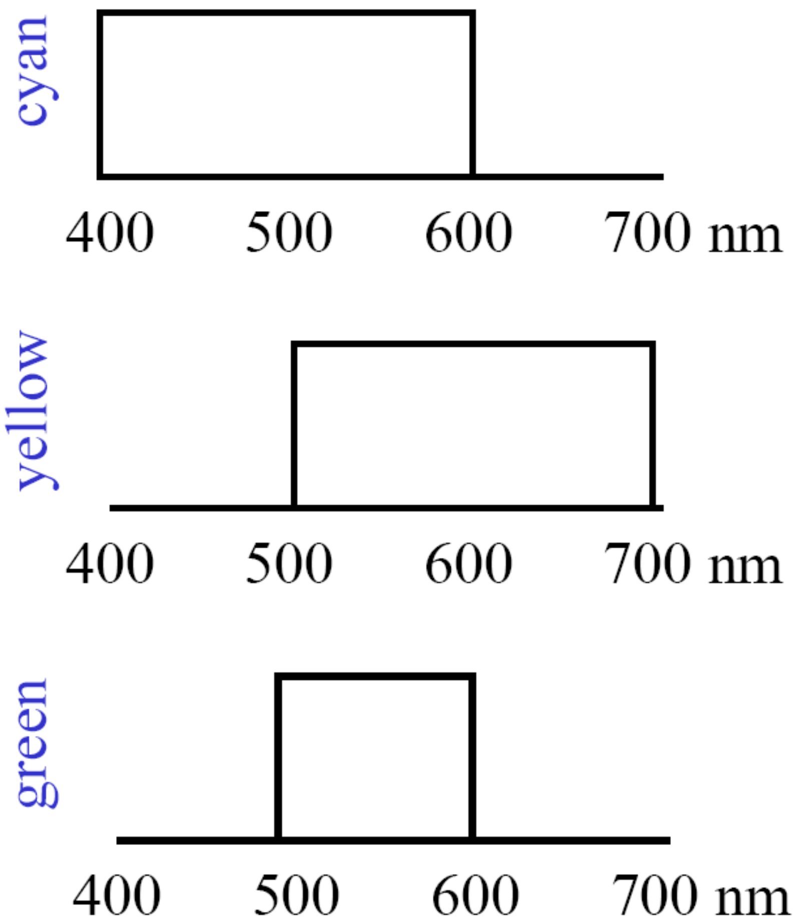
multiple projectors

http://www.jegsworks.com

http://www.crtprojectors.co.uk/

Slide credit: K. Grauman

Subtractive color mixing



Colors combine by *multiplying* color spectra.

Pigments *remove* color from incident light (white).

Credit: W. Freeman

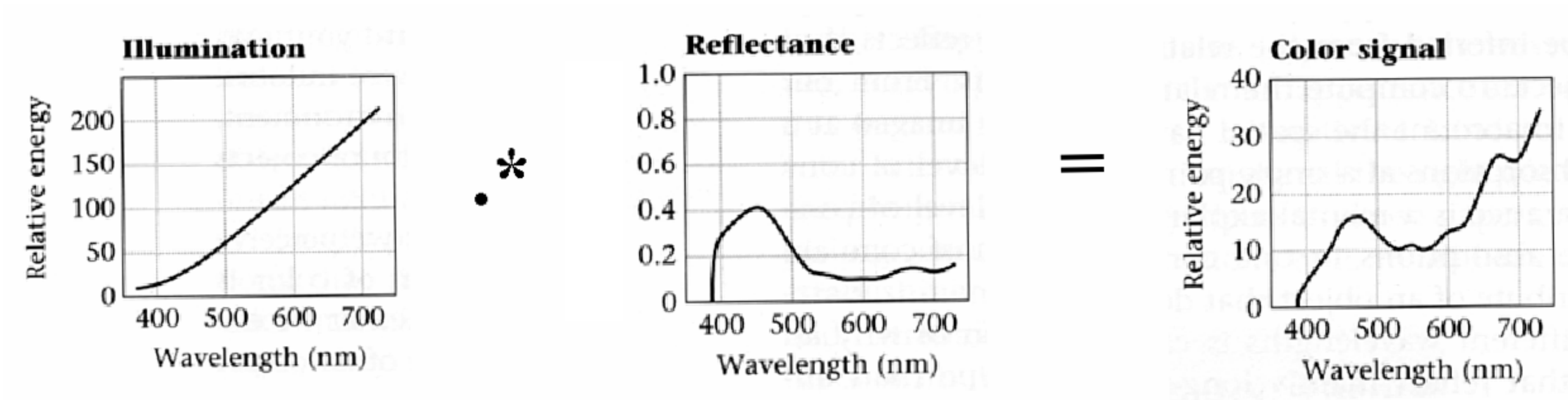
Examples of subtractive color systems

- Printing on paper
- Crayons
- Photographic film

Slide credit: K. Grauman

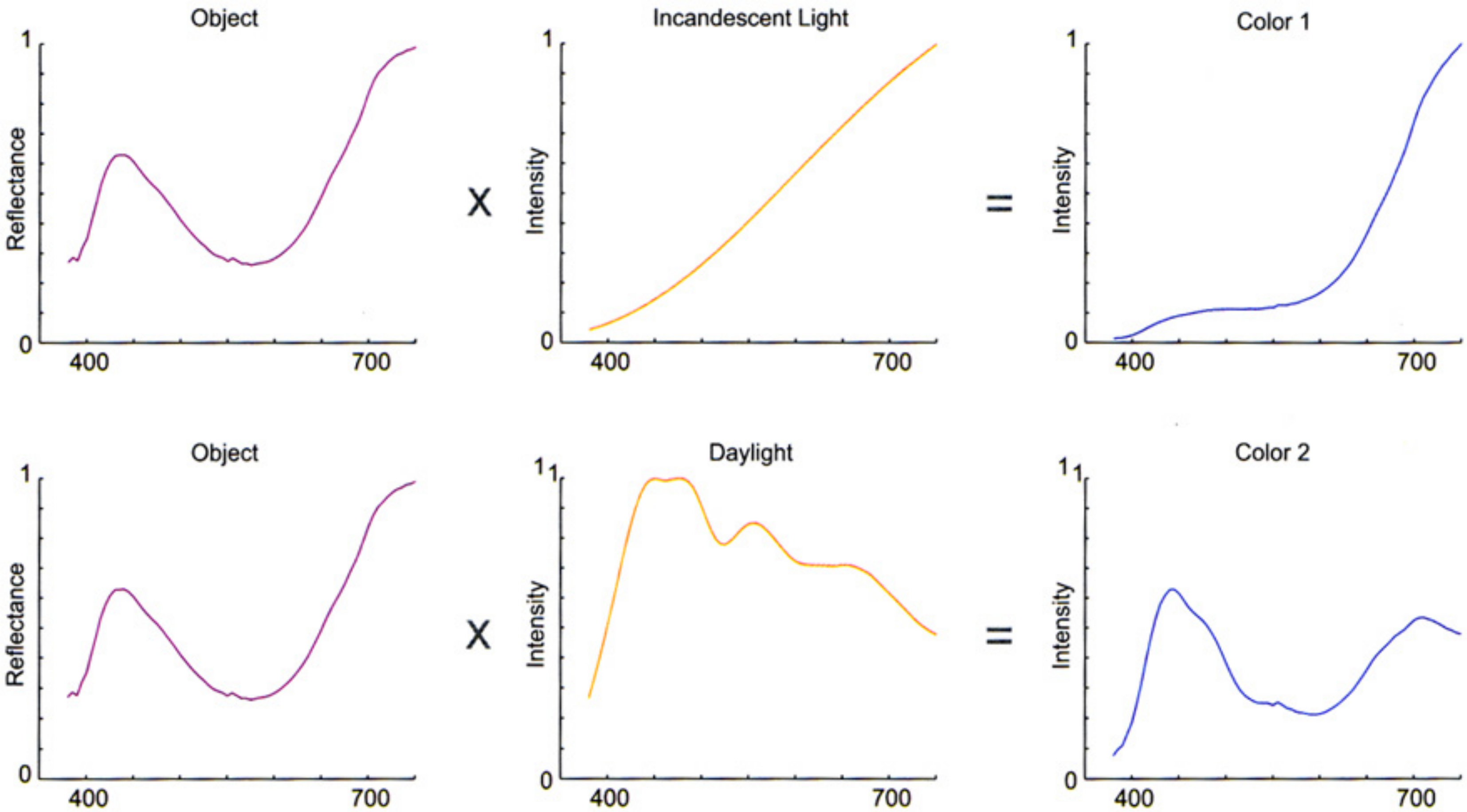
Interaction of light and surfaces

- Reflected color is the result of interaction of light source spectrum with surface reflectance



Slide credit: A. Efros

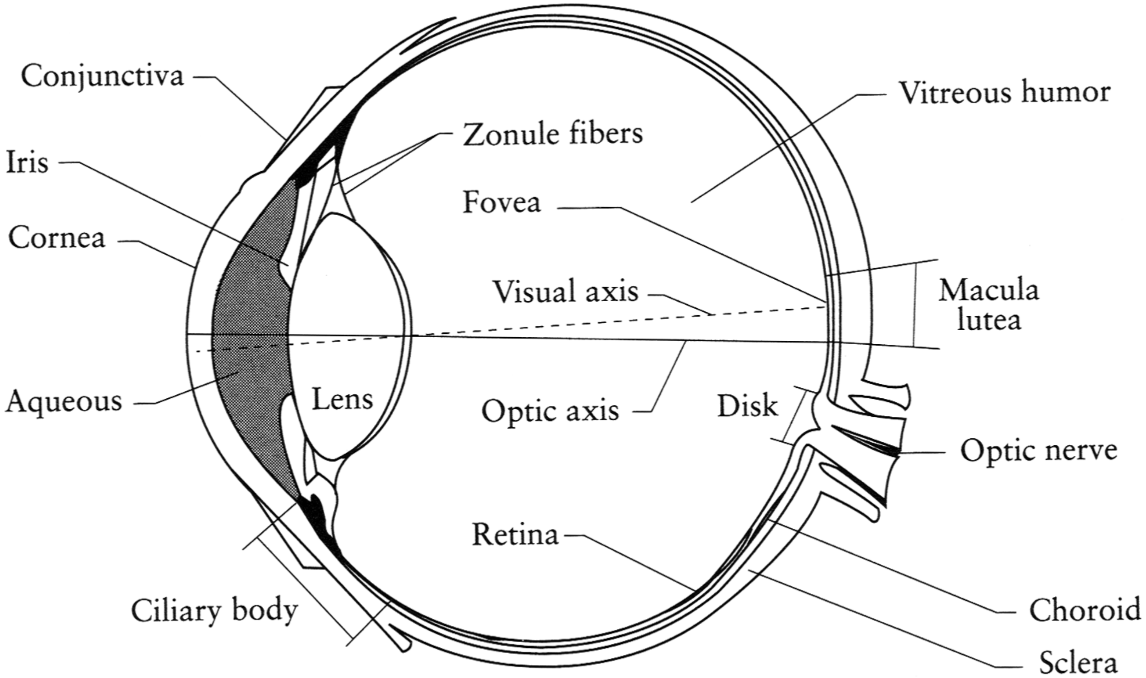
Reflection from colored surface



[Stone 2003]

Slide credit: S. Marschner

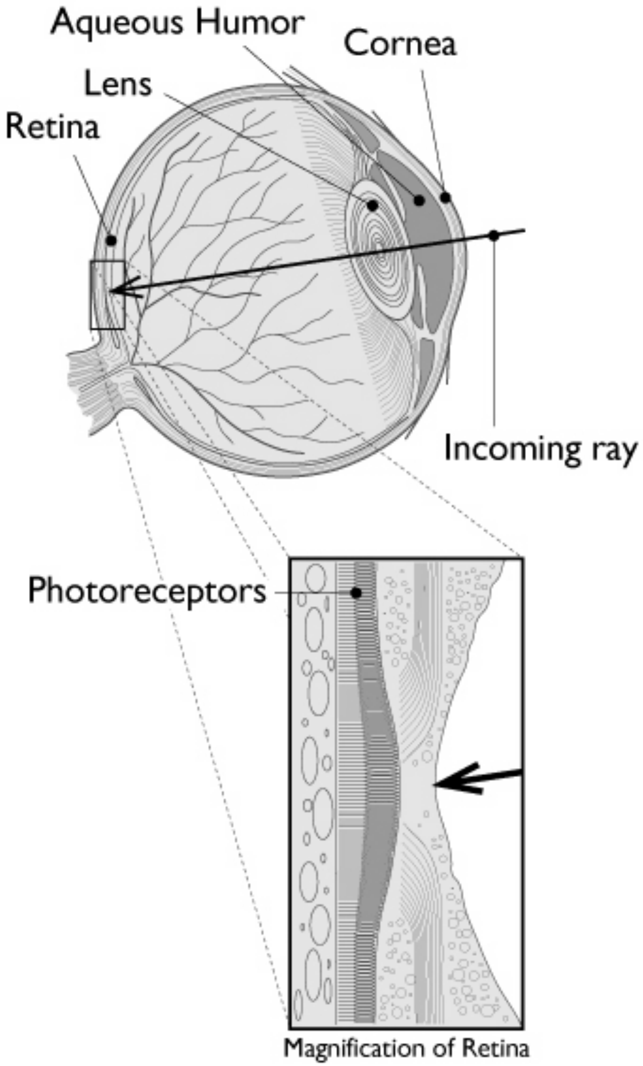
The Eye



- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- **Retina** - photoreceptor cells

Slide credit: S. Seitz

The eye as a measurement device

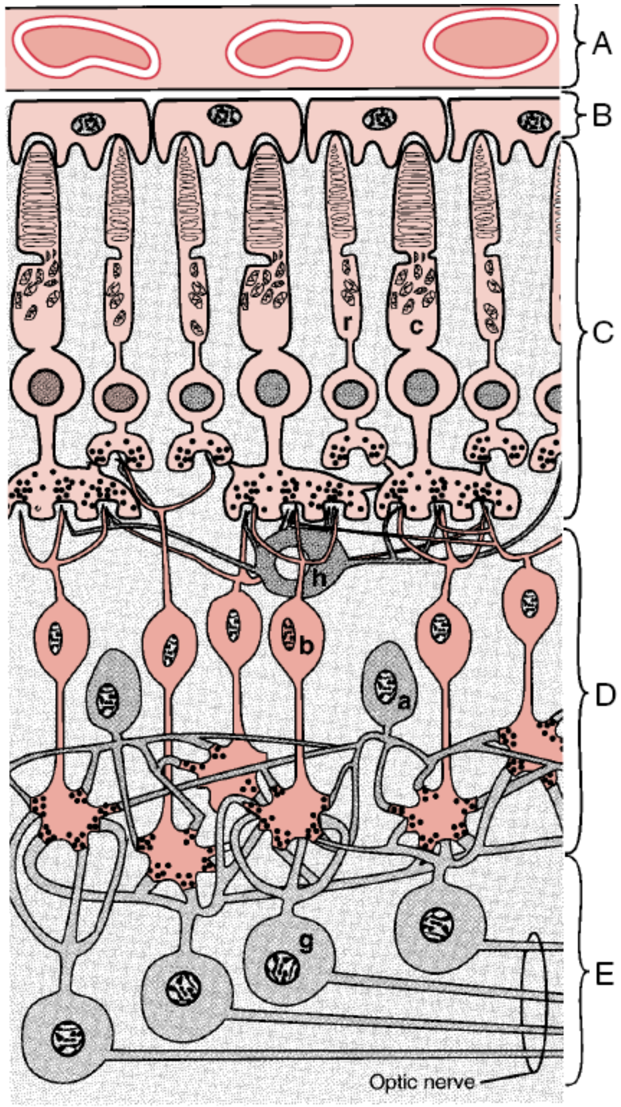


[Greger et al. 1995]

- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera
- Light is measured by the *photoreceptors* in the retina
  - they respond to visible light
  - different types respond to different wavelengths
- **The human eye is a camera!**

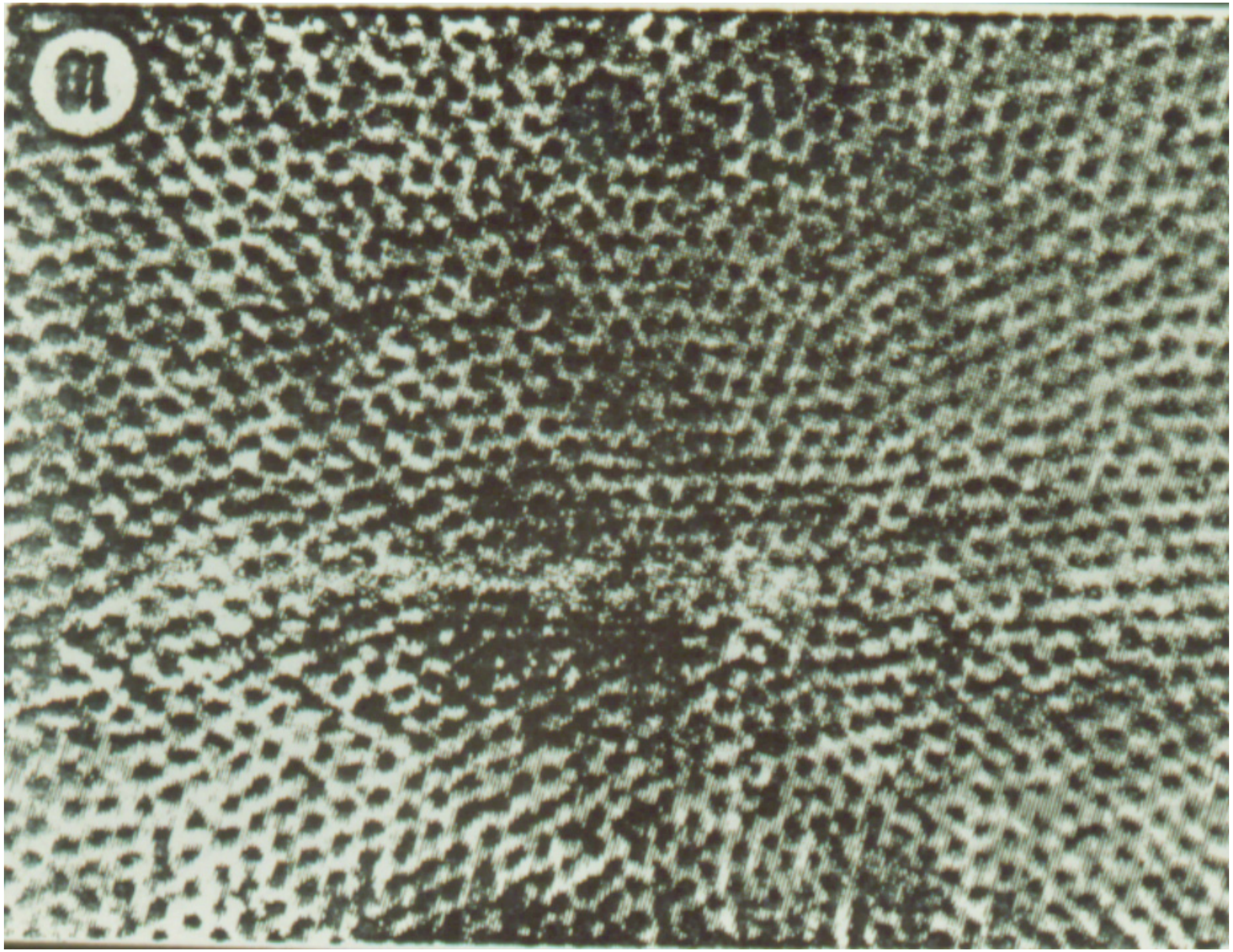
Slide credit: S. Marschner

Layers of the retina



Slide credit: S. Ullman

Receptors Density - Fovea



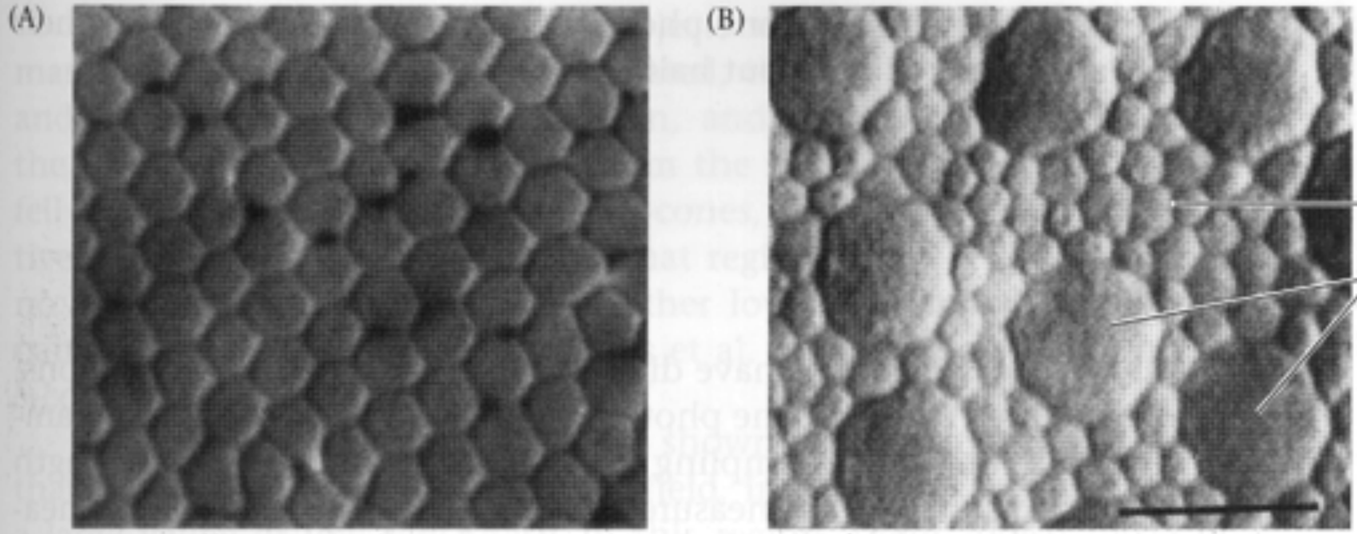
Slide credit: S. Ullman

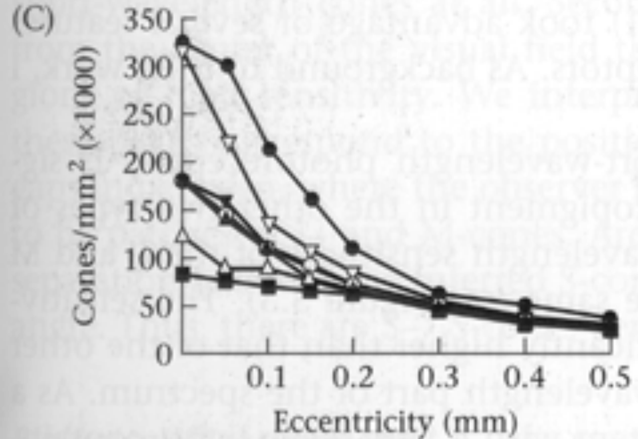
Receptors Density - Fovea

64	66	76	85	99	100	101	101	106	112	117	118	105	77	57	50	51	43	52	55	62
65	69	76	84	97	89	93	107	121	121	121	122	125	101	71	43	45	41	52	52	68
66	72	78	83	91	86	91	102	108	104	106	113	136	118	86	43	49	47	60	55	64
73	79	83	85	94	93	90	83	79	79	85	92	124	124	108	62	58	43	57	57	64
78	84	86	86	69	71	68	68	86	108	115	109	117	135	139	93	73	37	49	58	70
75	75	73	77	75	80	62	84	90	94	98	102	102	110	114	100	80	58	51	51	51
77	72	73	83	84	91	80	77	71	70	73	80	80	87	99	103	93	67	53	50	51
74	66	69	88	98	101	95	65	56	55	55	60	64	70	93	114	112	82	56	47	53
64	59	66	86	108	103	98	54	52	57	54	54	67	77	103	124	125	96	64	46	53
56	57	66	83	112	108	104	59	55	60	59	60	78	94	115	125	121	98	68	43	46
56	58	66	80	114	121	117	85	71	67	69	76	87	101	116	117	112	94	68	43	46
61	57	61	77	111	125	119	114	98	87	87	94	97	102	111	113	108	90	65	43	44
63	52	54	73	103	117	107	126	119	108	103	104	106	103	108	115	112	91	65	48	42
66	63	58	63	94	115	120	108	102	104	106	108	105	108	107	105	105	97	72	47	41
68	65	58	61	86	108	115	106	102	103	103	104	98	99	97	97	103	101	81	57	43
72	68	62	64	78	102	111	105	101	101	101	103	99	98	96	97	104	104	86	63	48
74	71	64	64	69	93	104	99	94	93	96	101	99	101	102	103	108	106	90	69	53

Slide credit: S. Ullman

Human Photoreceptors



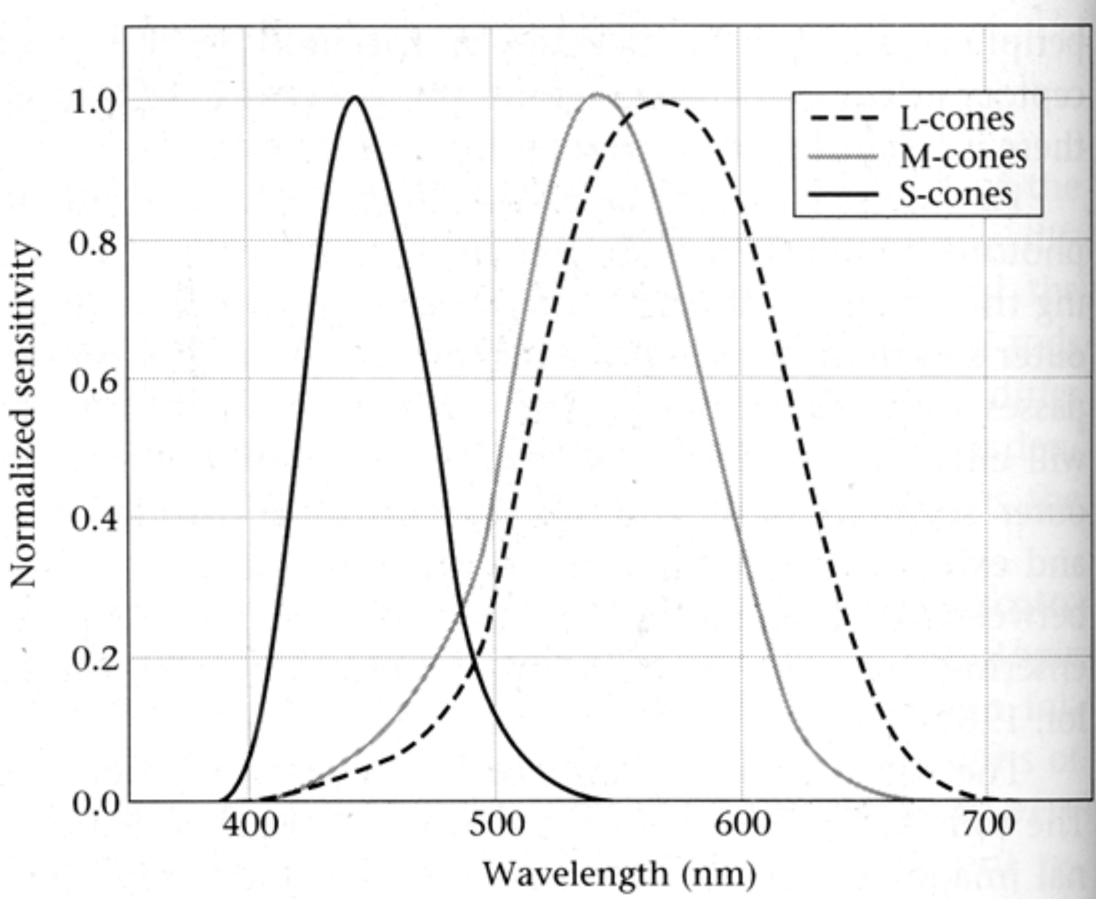


3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the spaces. (C) Cone density plotted as a function of distance from the center of the fovea for seven human retinas; cone density decreases with distance from the fovea. Source: Curcio et al., 1990.

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

Slide Credit: B. Freeman and A. Torralba

Human eye photoreceptor spectral sensitivities



3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

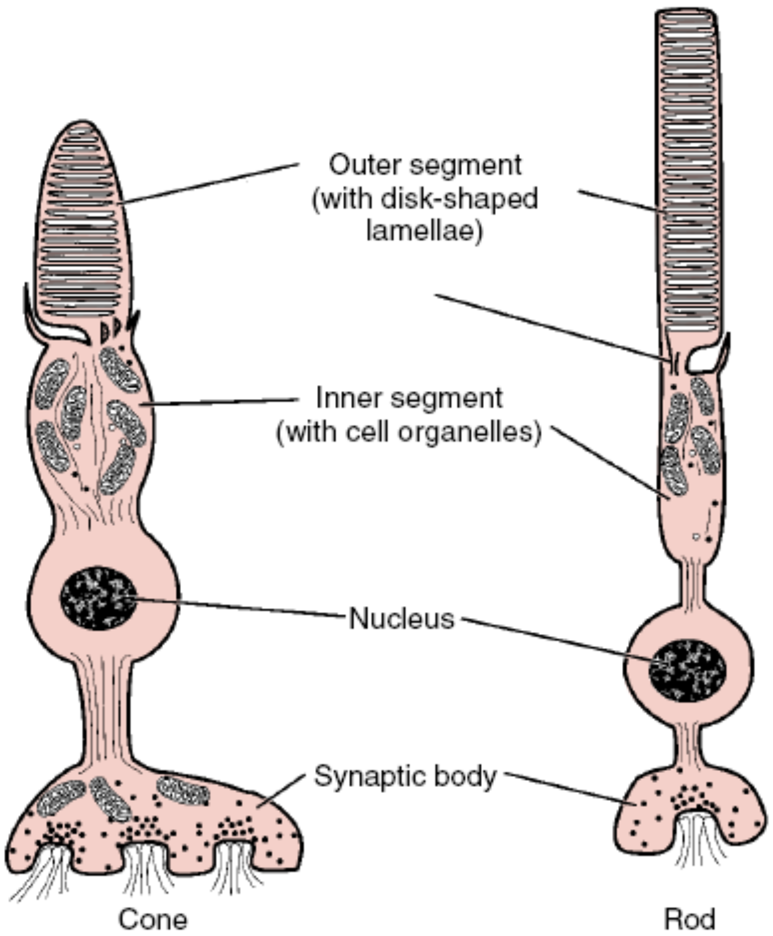
Images: Foundations of Vision,
by Brian Wandell, Sinauer Assoc., 1995

Slide Credit: B. Freeman and A. Torralba

Two types of light-sensitive receptors

Cones

cone-shaped
less sensitive
operate in high light
color vision



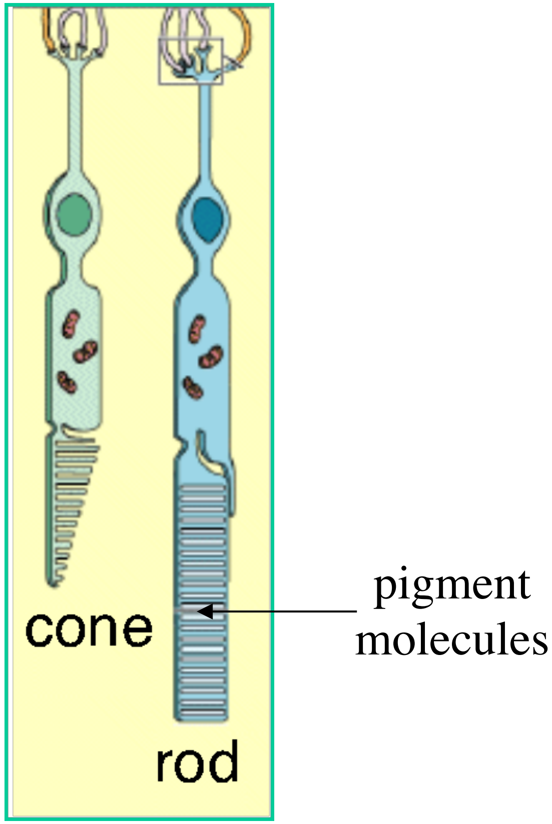
Images by Shimon Ullman

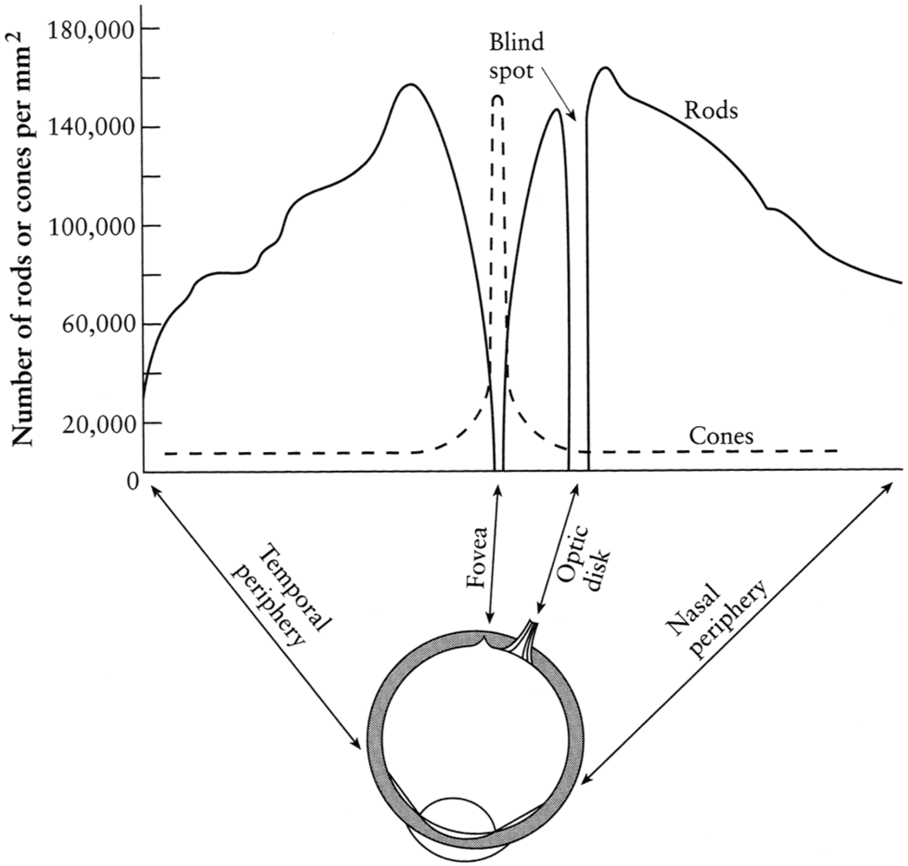
Rods

rod-shaped
highly sensitive
operate at night
gray-scale vision

Slide credit: A. Efros

Rods and cones





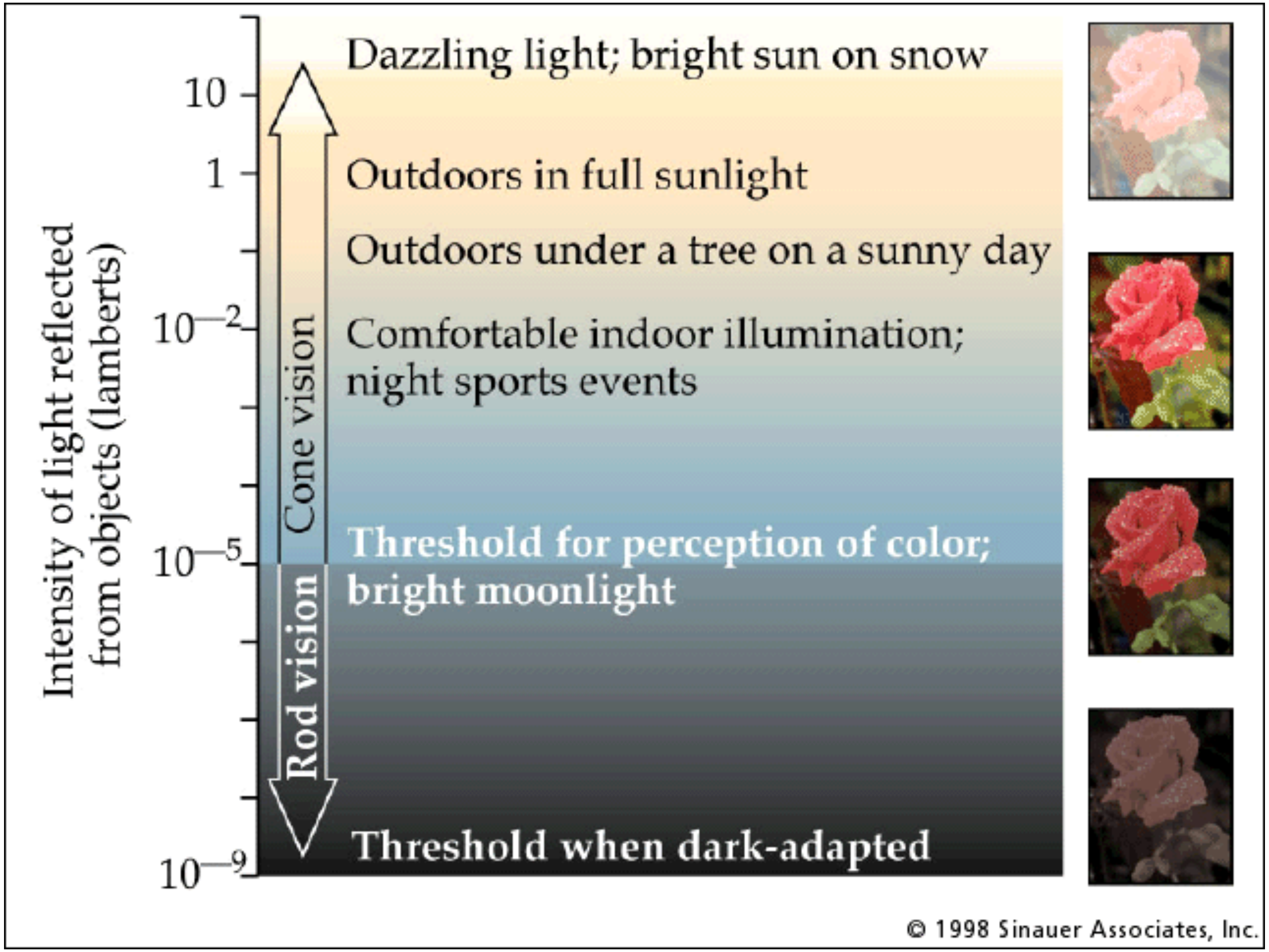
Rods are responsible for intensity, cones for color perception

Rods and cones are non-uniformly distributed on the retina

- Fovea - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods)

Slide credit: S. Seitz

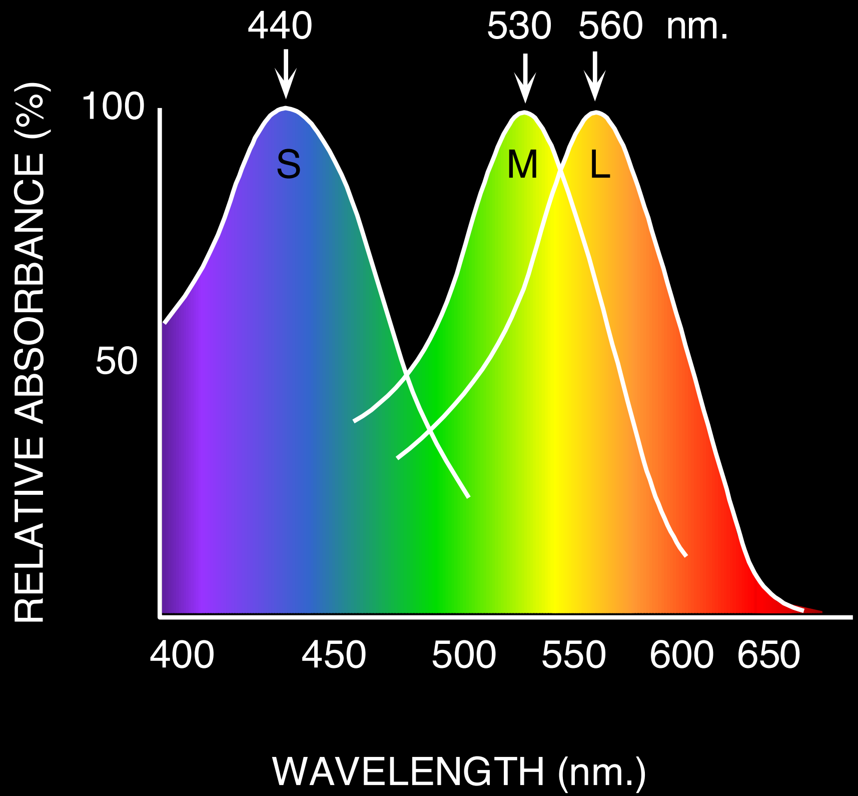
Rod / Cone sensitivity

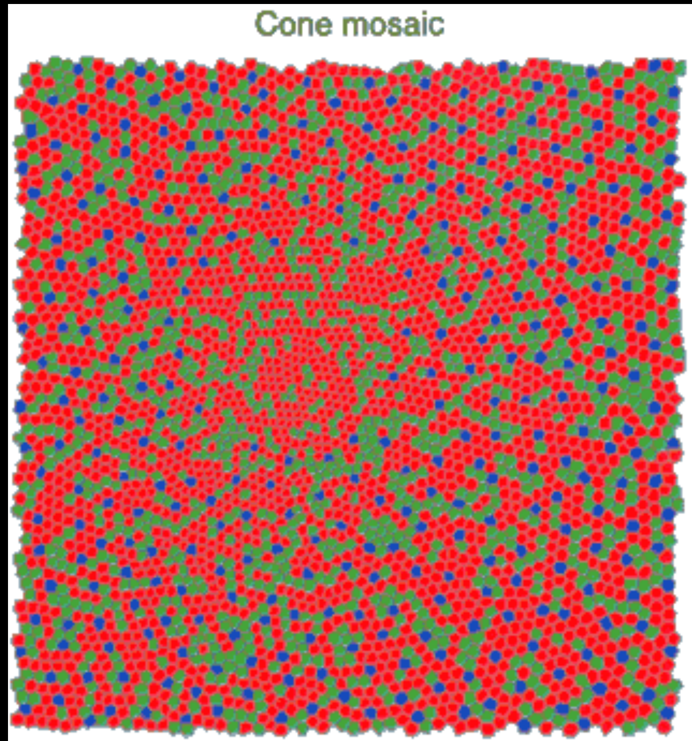


Slide credit: A. Efros

Physiology of Color Vision

Three kinds of cones:

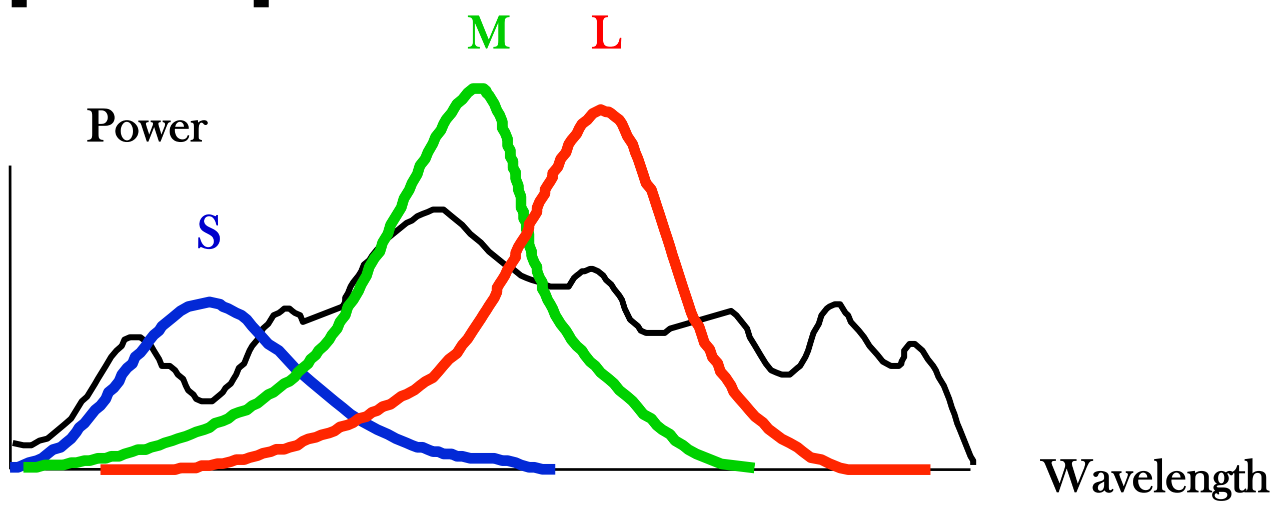




- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

Slide credit: A. Efros

Color perception



Rods and cones act as filters on the spectrum

- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

Q: How can we represent an entire spectrum with 3 numbers?

A: We can't! Most of the information is lost.

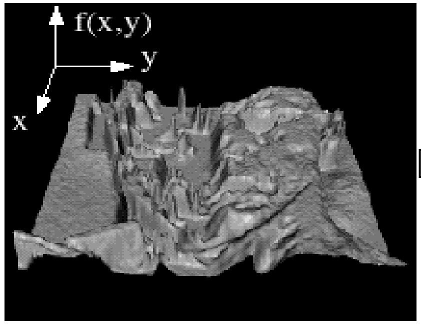
- As a result, two different spectra may appear indistinguishable

Slide credit: S. Seitz

Digital images

- Sample the 2D space on a regular grid
- Quantize each sample (round to nearest integer)

- Image thus represented as a matrix of integer values.

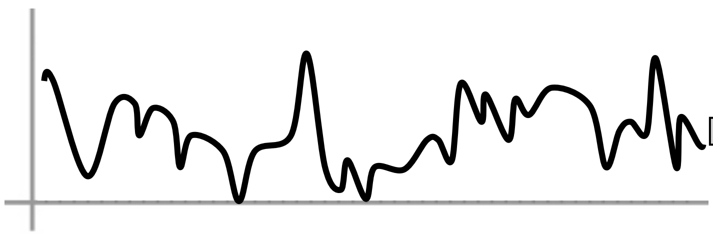


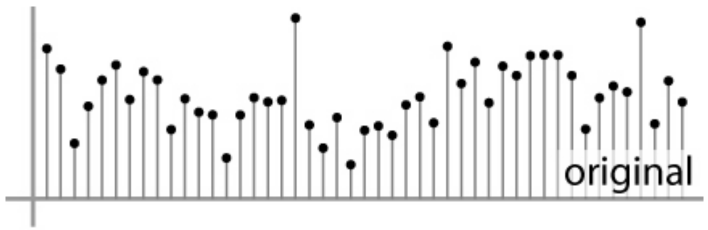
j

i

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

2D

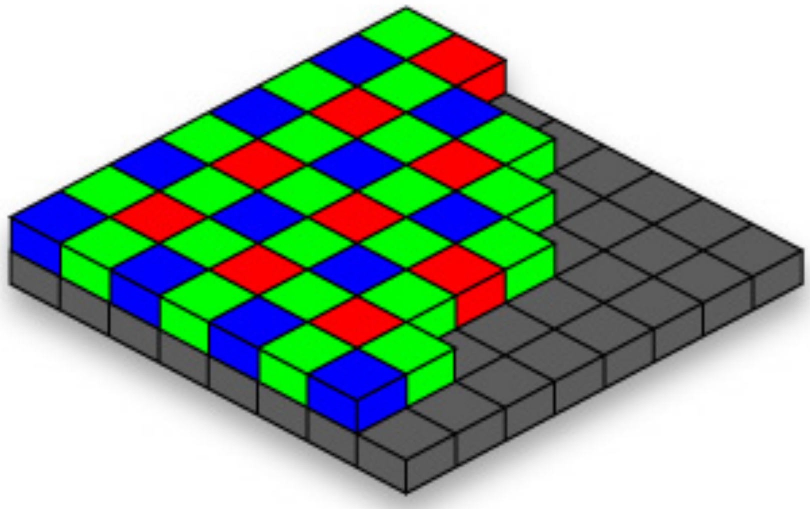




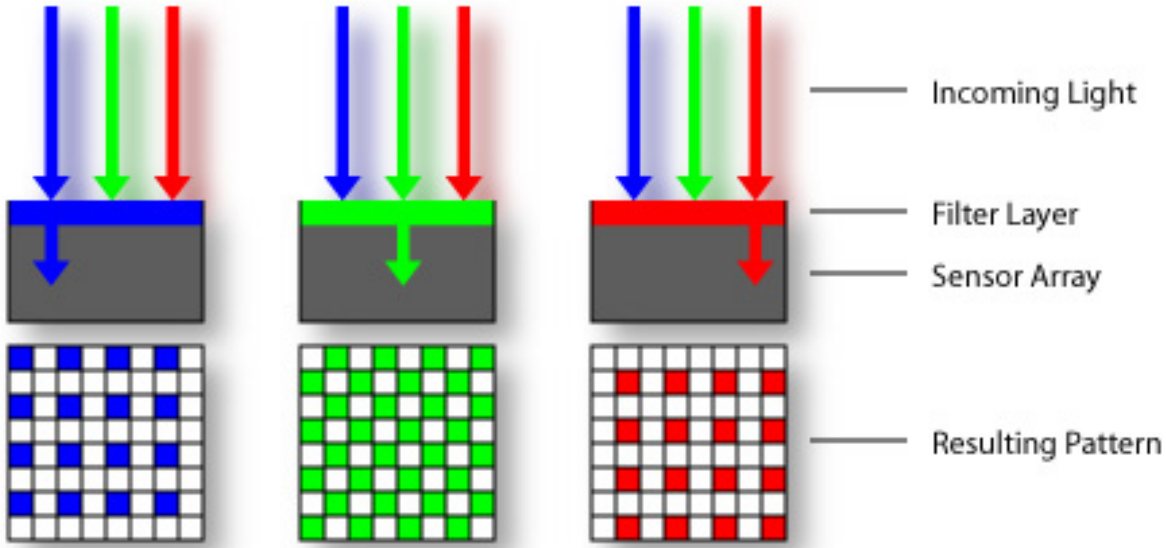
1D

Slide credit: K. Grauman, S. Seitz

Color Images: Bayer Grid



- Estimate RGB at ‘G’ cells from neighboring values

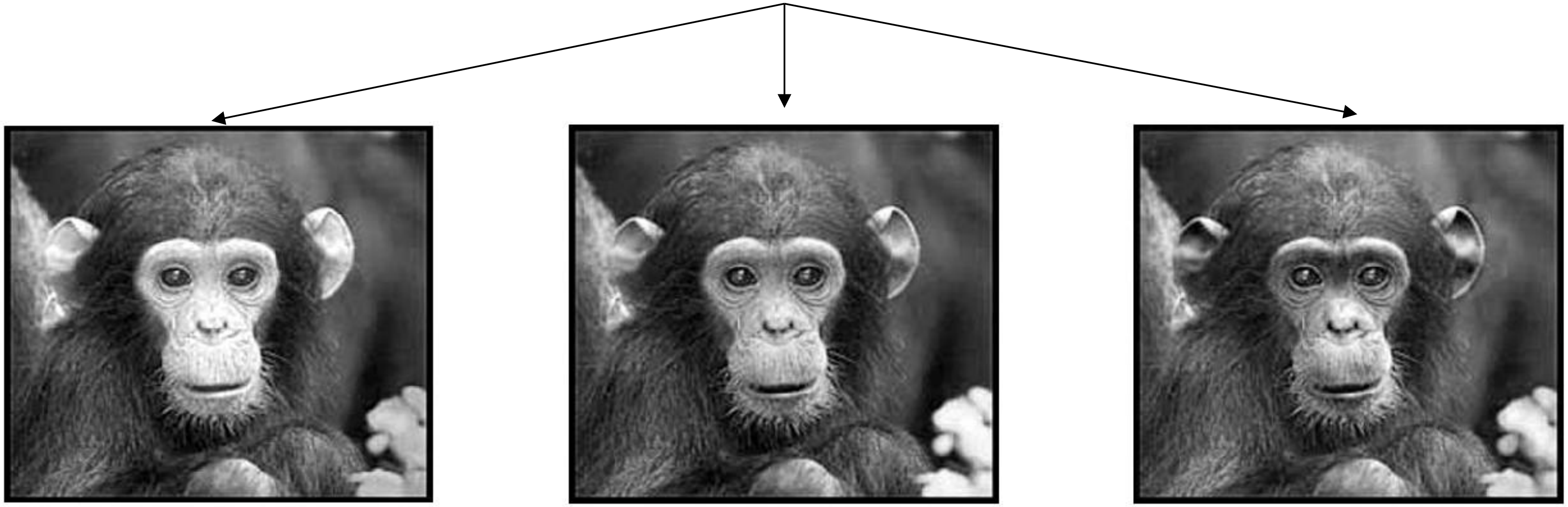


http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Slide credit: S. Seitz

Digital color images

Color images, RGB color space

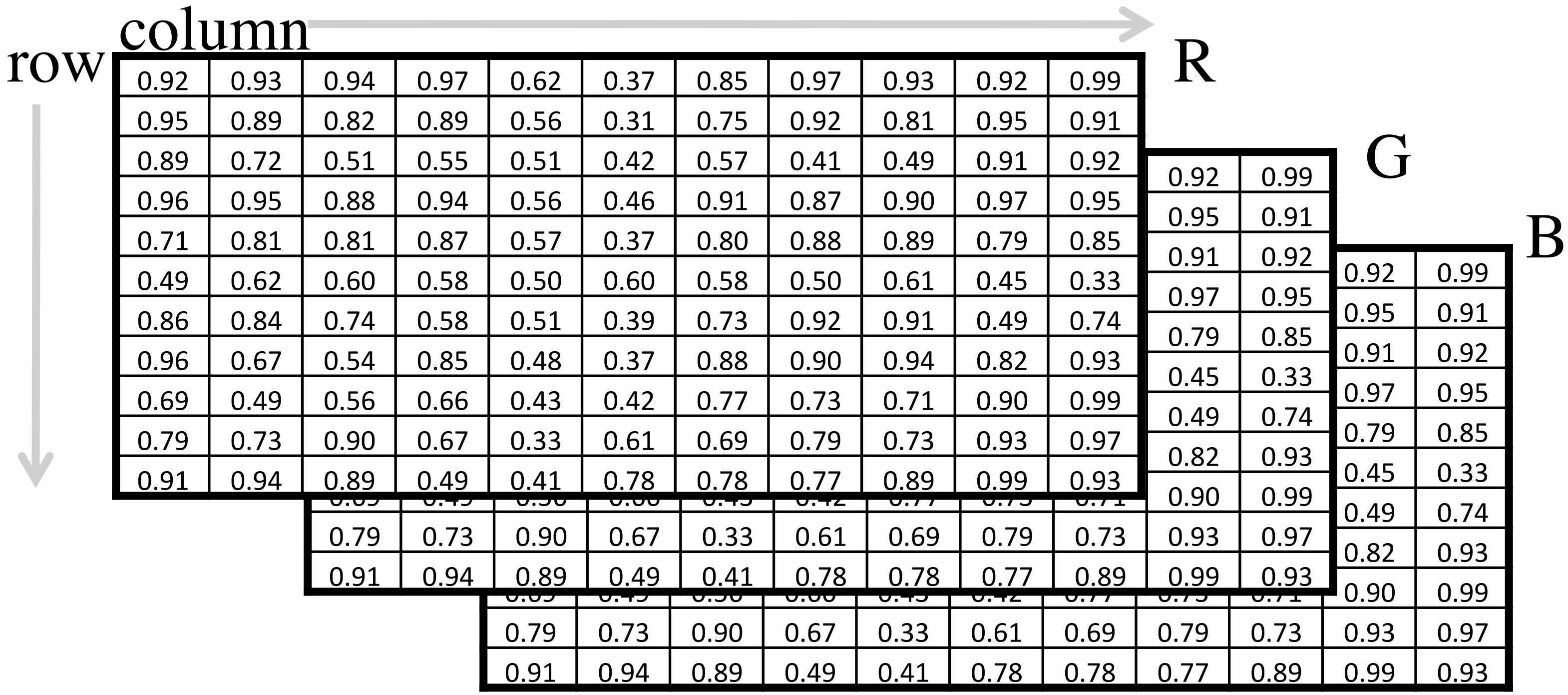


R G B

Slide credit: K. Grauman

Images in Matlab

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - `im(1,1,1)` = top-left pixel value in R-channel
  - `im(y,x,b)` = y pixels down, x pixels to right in the bth channel
  - `im(N,M,3)` = bottom-right pixel in B-channel
- `imread(filename)` returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with im2double



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Slide credit: D. Hoiem

Color spaces

- How can we represent color?

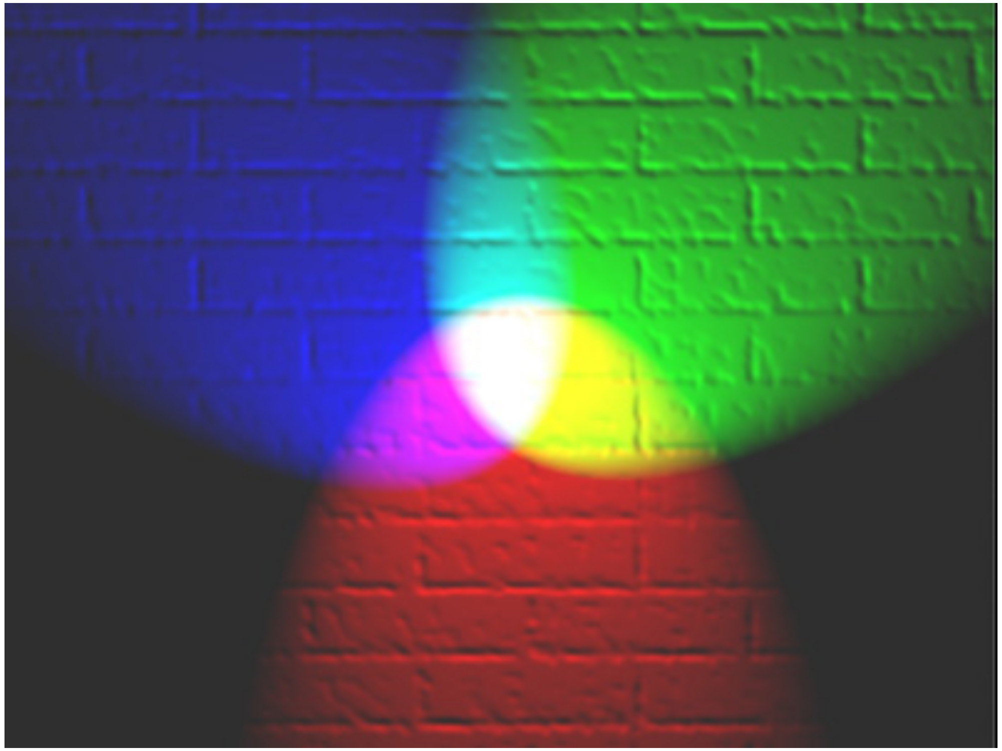
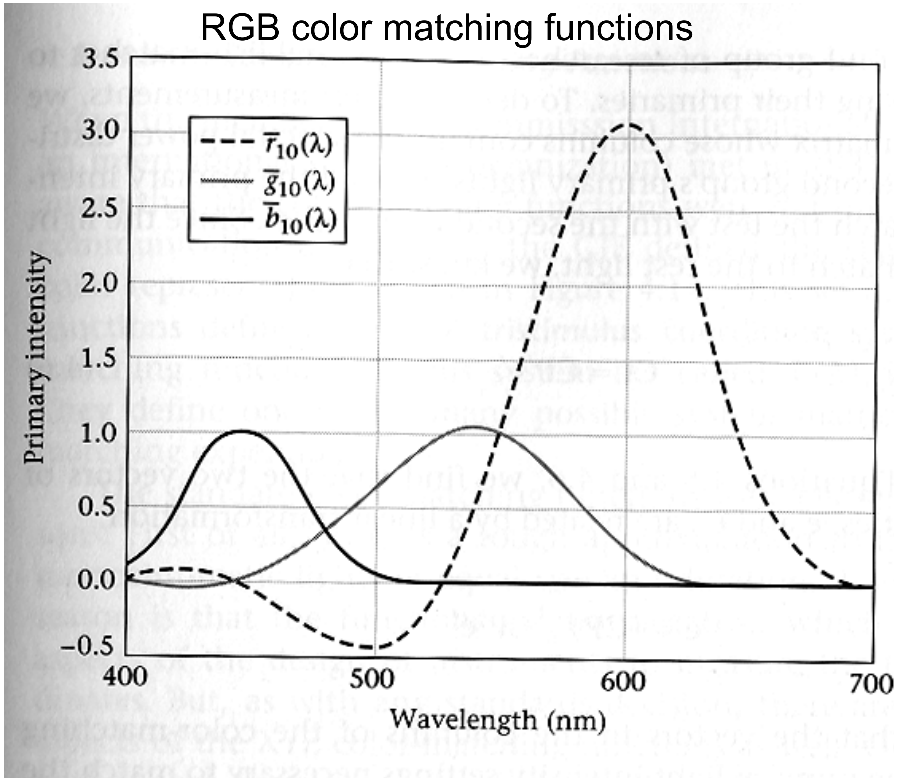


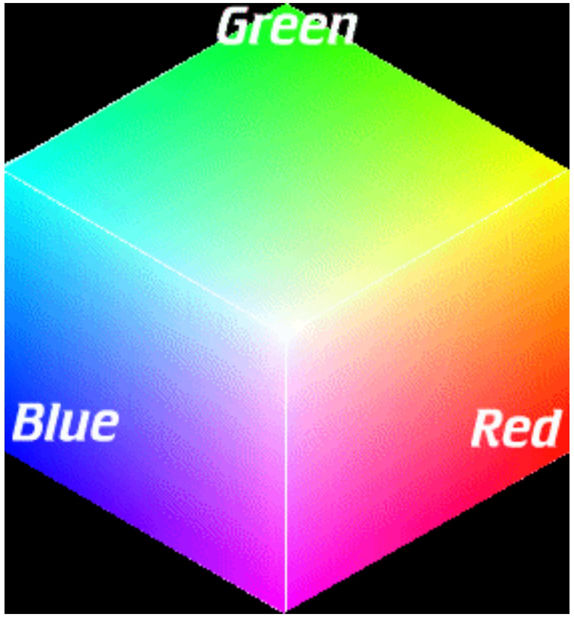
Image from http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Slide credit: D. Hoiem

Color spaces: RGB

- Single wavelength primaries
- makes a particular monitor RGB standard
- Good for devices (e.g., phosphors for monitor), but not for perception

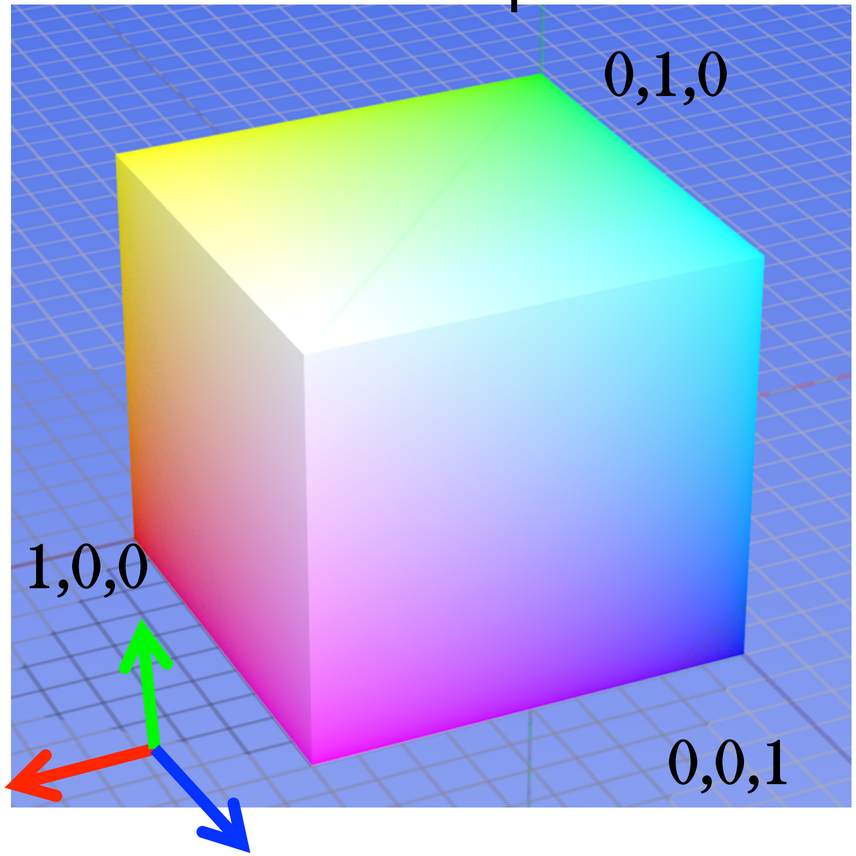




Slide credit: K. Grauman, S. Marschner

Color spaces: RGB

Default color space



R
(G=0,B=0)

G
(R=0,B=0)

B
(R=0,G=0)

Some drawbacks

- Strongly correlated channels
- Non-perceptual

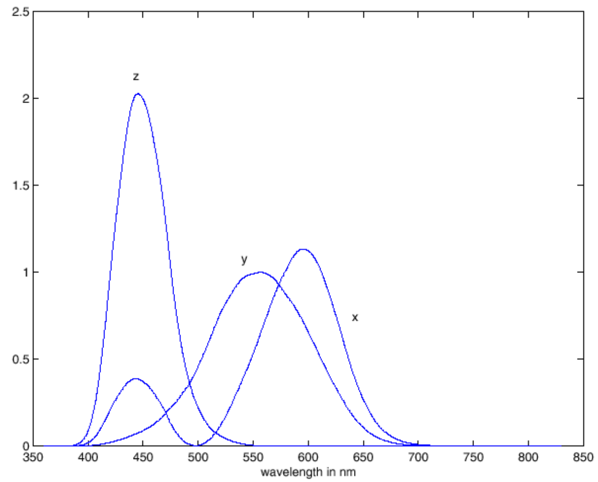
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

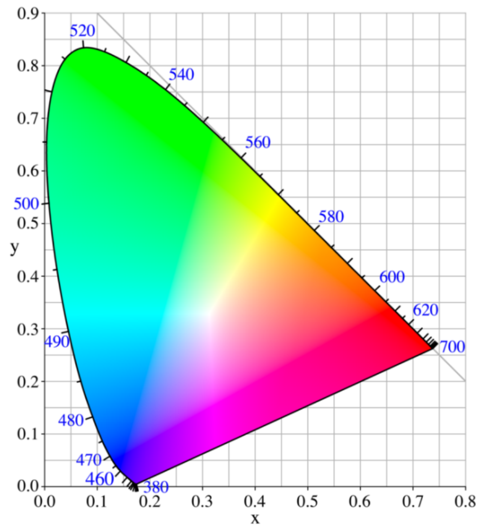
Slide credit: D. Hoiem

Color spaces: CIE XYZ

- Standardized by CIE (*Commission Internationale de l'Eclairage*, the standards organization for color science)
- Based on three "imaginary" primaries **X**, **Y**, and **Z**
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: **X**, **Z** have zero luminance, so *Y* tells you the luminance by itself

CIE XYZ Color matching functions





Slide credit: K. Grauman, S. Marschner

Color spaces: CIE XYZ

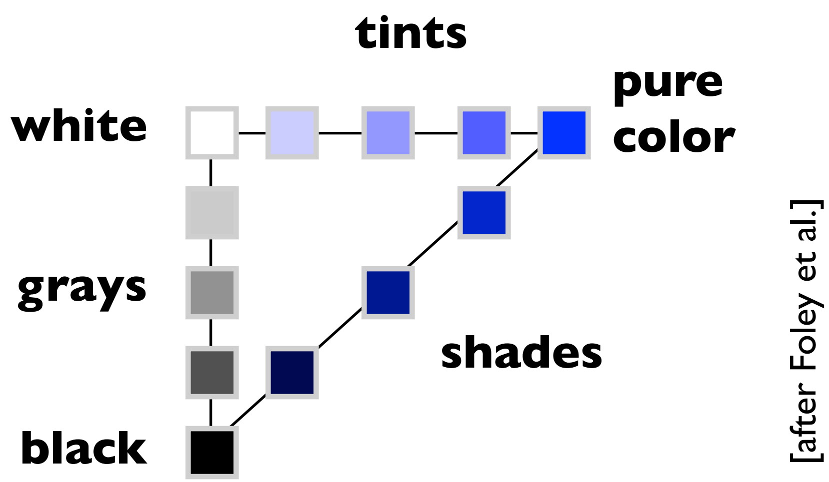
- Standardized by CIE (*Commission Internationale de l'Eclairage*, the standards organization for color science)
- Based on three "imaginary" primaries **X**, **Y**, and **Z**
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: **X**, **Z** have zero luminance, so *Y* tells you the luminance by itself

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Slide credit: K. Grauman, S. Marschner

Perceptually organized color spaces

- Artists often refer to colors as *tints*, *shades*, and *tones* of pure pigments
  - tint: mixture with white
  - shade: mixture with black
  - tones: mixture with black and white
  - gray: no color at all (aka. neutral)



- This seems intuitive
  - tints and shades are inherently related to the pure color
    - "same" color but lighter, darker, paler, etc.

Slide credit: S. Marschner

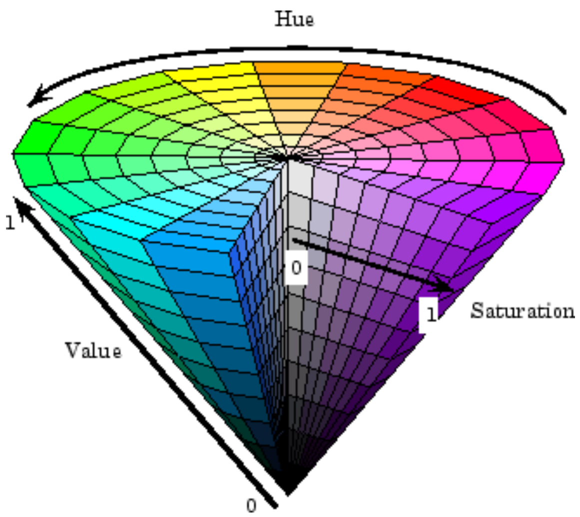
Perceptual dimensions of color

- Hue
  - the “kind” of color, regardless of attributes
  - colorimetric correlate: dominant wavelength
  - artist’s correlate: the chosen pigment color
- Saturation
  - the “colorfulness”
  - colorimetric correlate: purity
  - artist’s correlate: fraction of paint from the colored tube
- Lightness (or value)
  - the overall amount of light
  - colorimetric correlate: luminance
  - artist’s correlate: tints are lighter, shades are darker

Slide credit: S. Marschner

Color spaces: HSV

- **H**ue, **S**aturation, **V**alue
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- Matlab: `hsv2rgb`, `rgb2hsv`.



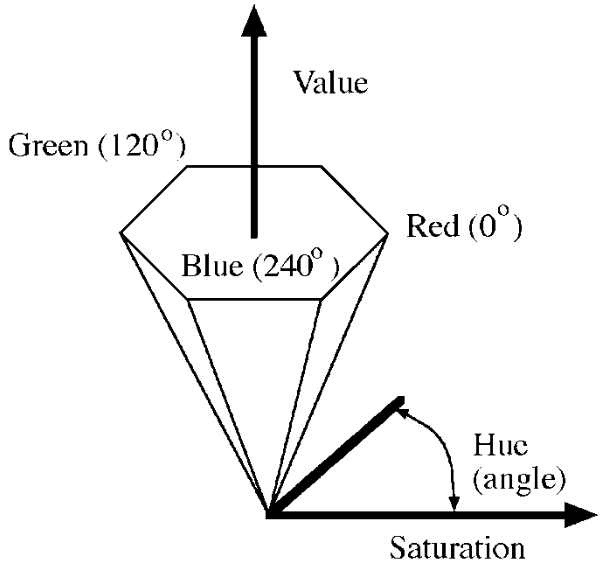
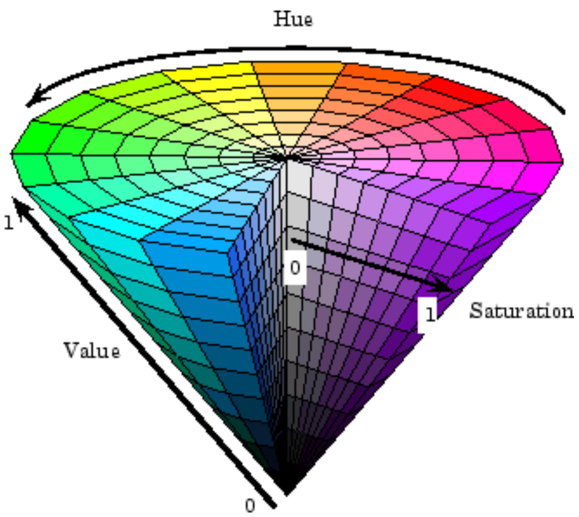


Image from mathworks.com

Slide credit: K. Grauman

Color spaces: HSV

- **H**ue, **S**aturation, **V**alue
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- Matlab: `hsv2rgb`, `rgb2hsv`.



$$H = \begin{cases} \left(\dfrac{G' - B'}{MAX - MIN}\right)/6, & \text{if } R' = MAX \\ \left(2 + \dfrac{B' - R'}{MAX - MIN}\right)/6, & \text{if } G' = MAX \\ \left(4 + \dfrac{R' - G'}{MAX - MIN}\right)/6, & \text{if } B' = MAX \end{cases}$$

$$S = \frac{MAX - MIN}{MAX}$$

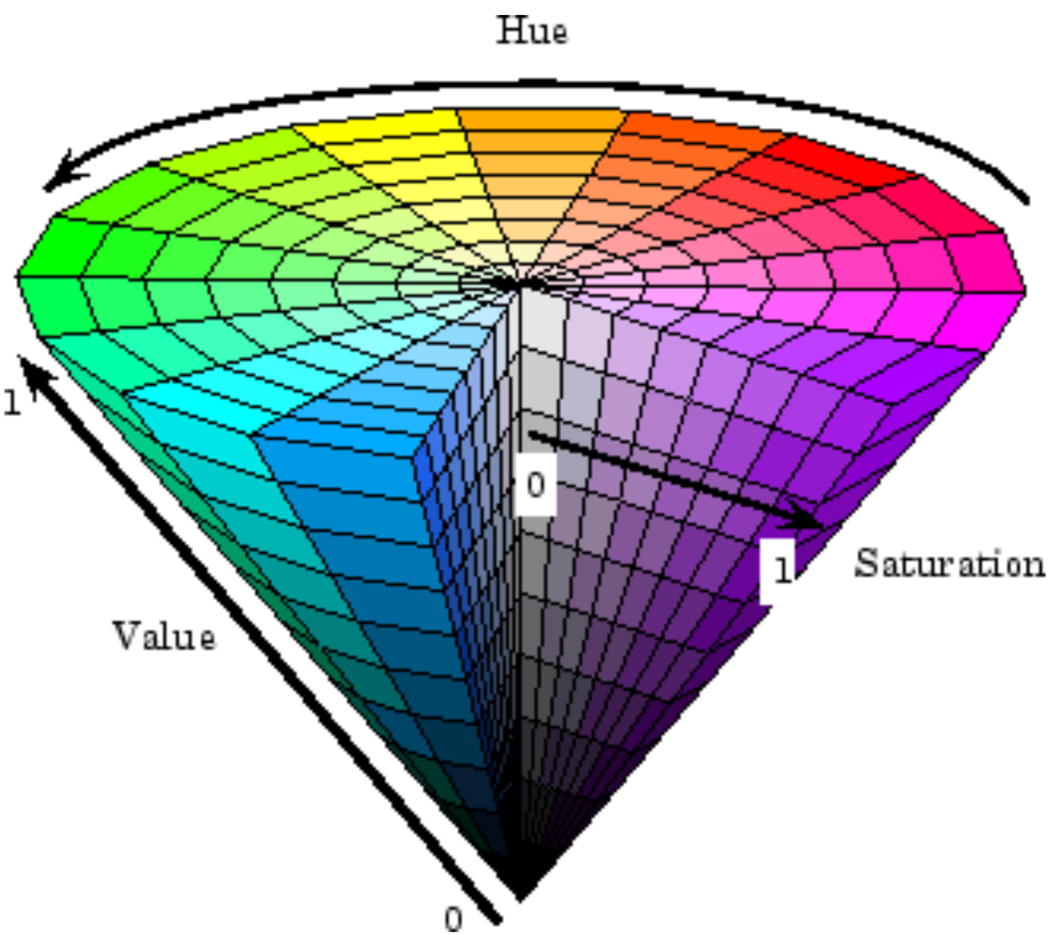
$$V = MAX$$

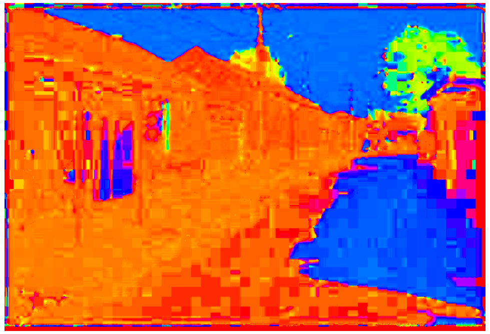
Image from mathworks.com

Slide credit: K. Grauman

Color spaces: HSV

Intuitive color space

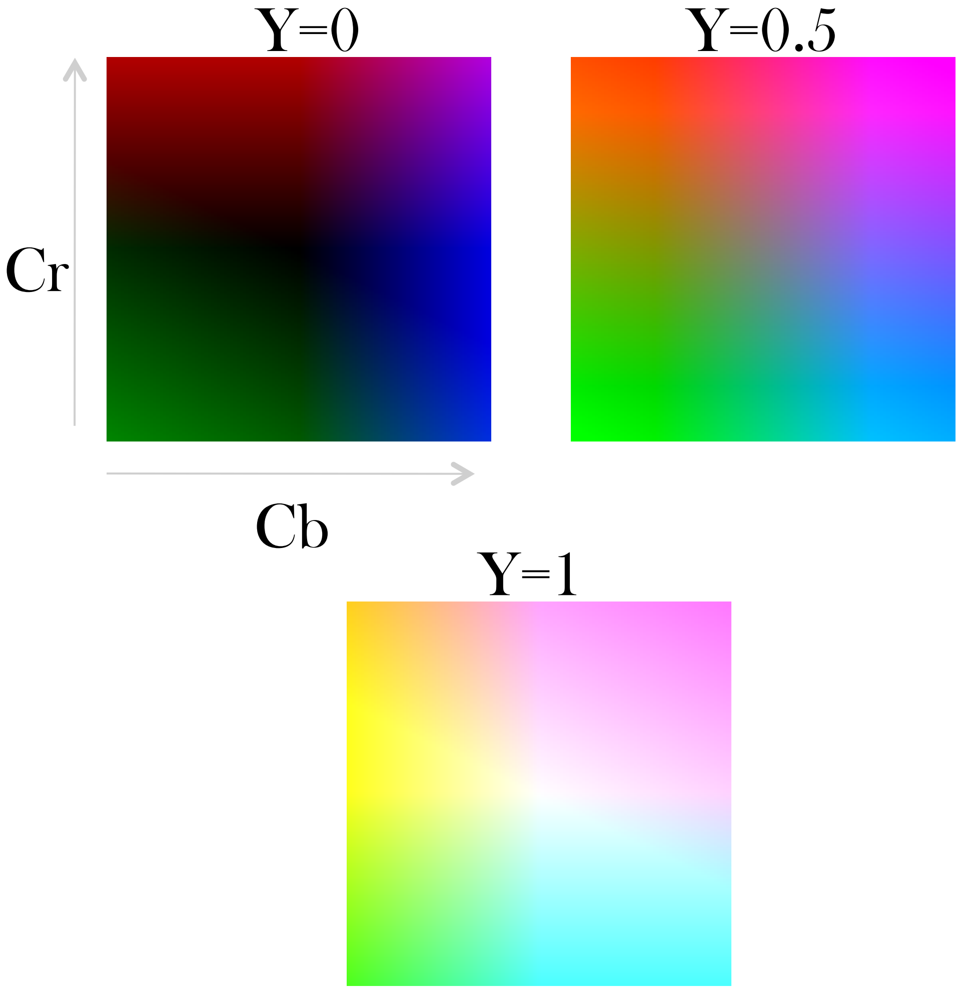


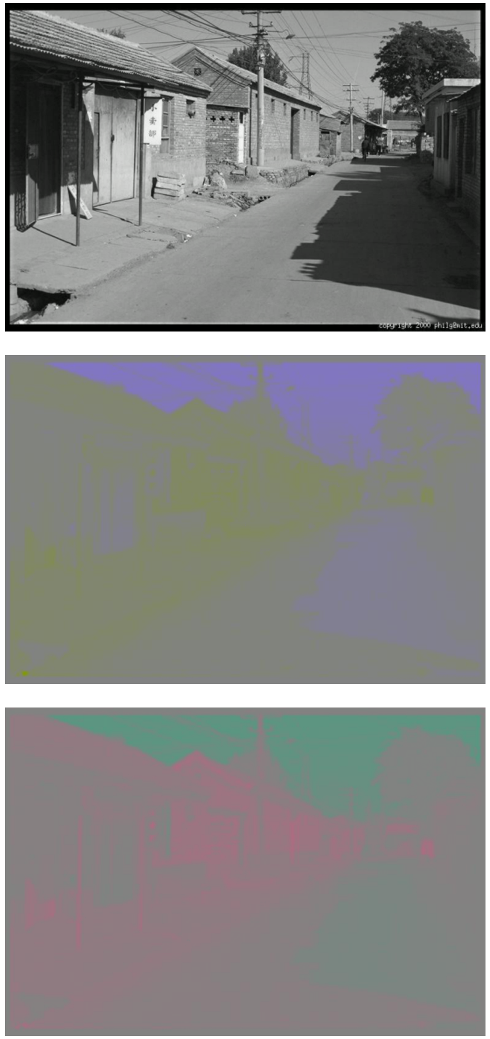


Slide credit: D. Hoiem

Color spaces: YCbCr

Fast to compute, good for compression, used by TV





Y
(Cb=0.5,Cr=0.5)

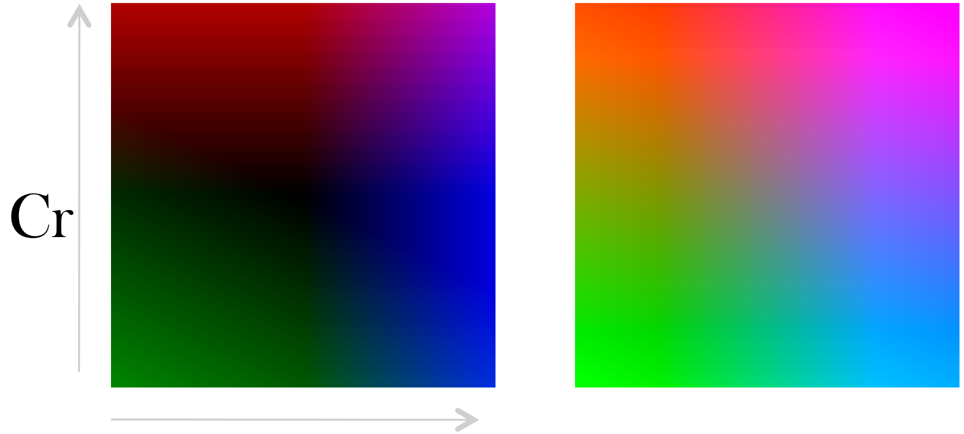
Cb
(Y=0.5,Cr=0.5)

Cr
(Y=0.5,Cb=05)

Slide credit: D. Hoiem

Color spaces: YCbCr

Fast to compute, good for compression, used by TV



Y=1

Y

(Cb=0.5,Cr=0.5)

Cb

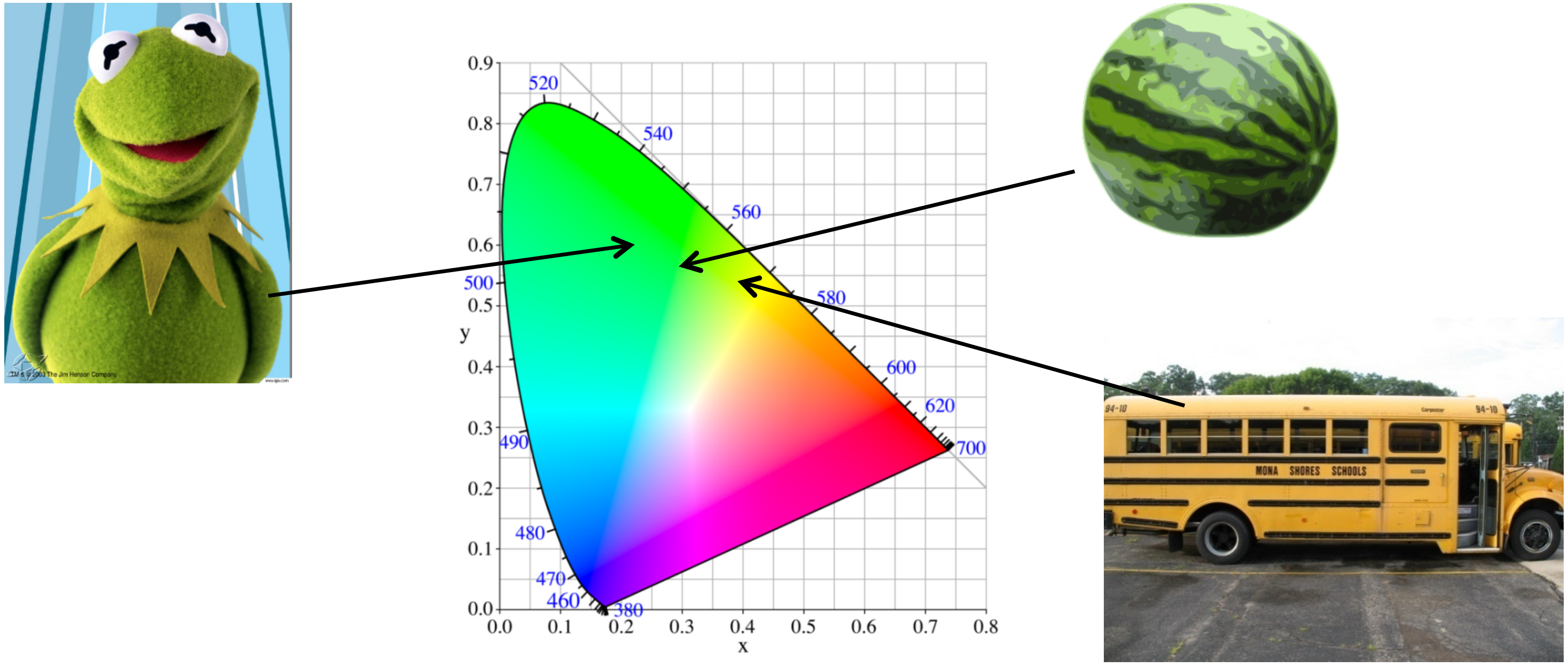
(Y=0.5,Cr=0.5)

$$\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 0 \\ 128 \\ 128 \end{bmatrix}$$

Slide credit: D. Hoiem

Distances in color space

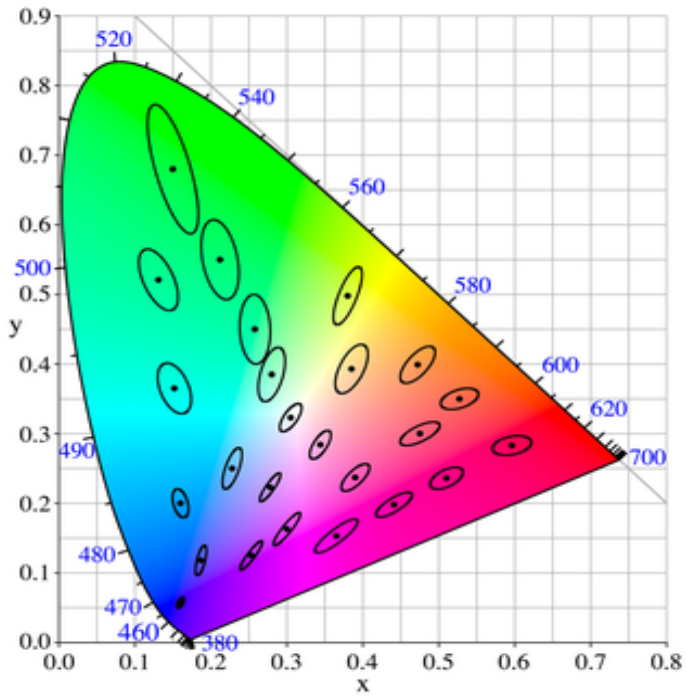
- Are distances between points in a color space perceptually meaningful?



Slide credit: K. Grauman

Distances in color space

- Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color "distance".



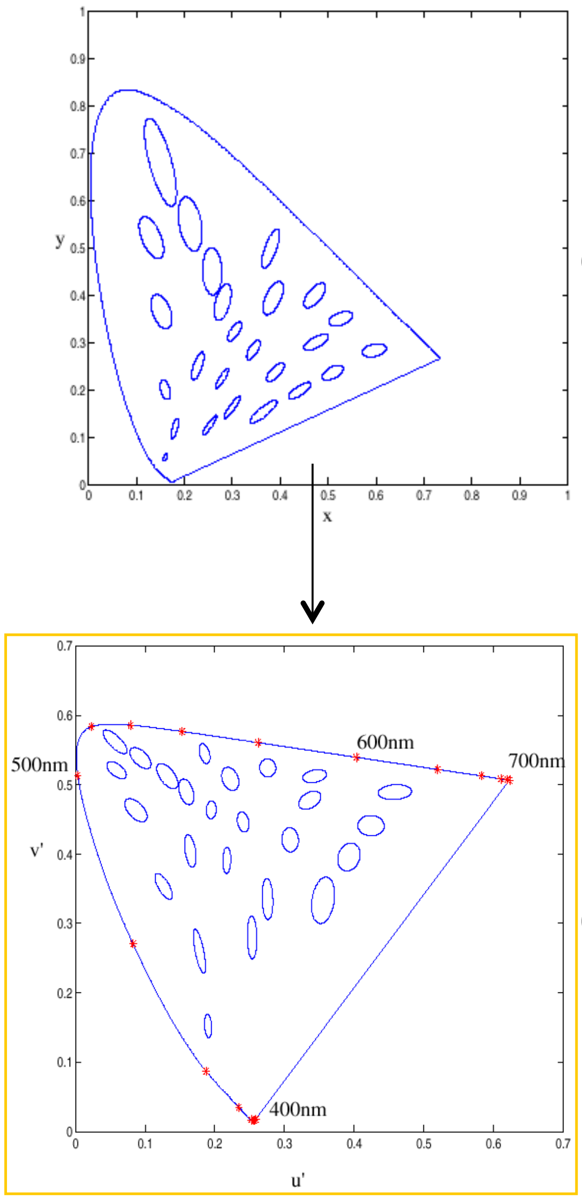
McAdam ellipses:
Just noticeable differences in color

Slide credit: K. Grauman

Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles → distances more perceptually meaningful.

- Examples:
  - CIE u'v'
  - CIE Lab



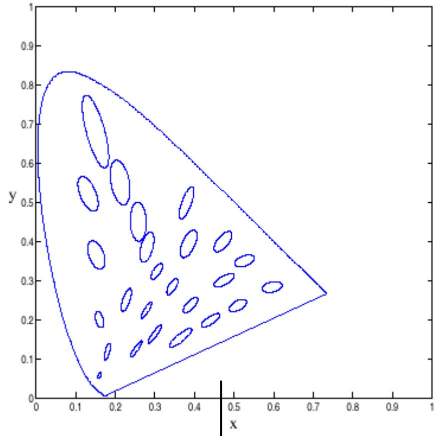
CIE XYZ

CIE u' v'

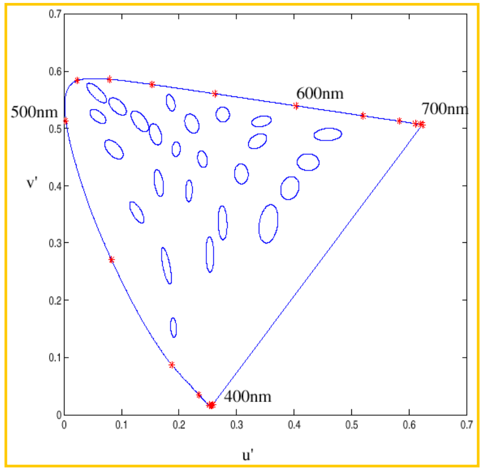
Slide credit: K. Grauman

Perceptually uniform spaces

- Two major spaces standardized by CIE
  - designed so that equal differences in coordinates produce equally visible differences in color
  - by remapping color space so that just-noticeable differences are contained by circles→ distances more perceptually meaningful.
  - LUV: earlier, simpler space; *L**, *u**, *v**
  - LAB: more complex but more uniform: *L**, *a**, *b**
  - both separate luminance from chromaticity
  - including a gamma-like nonlinear component is important



CIE XYZ

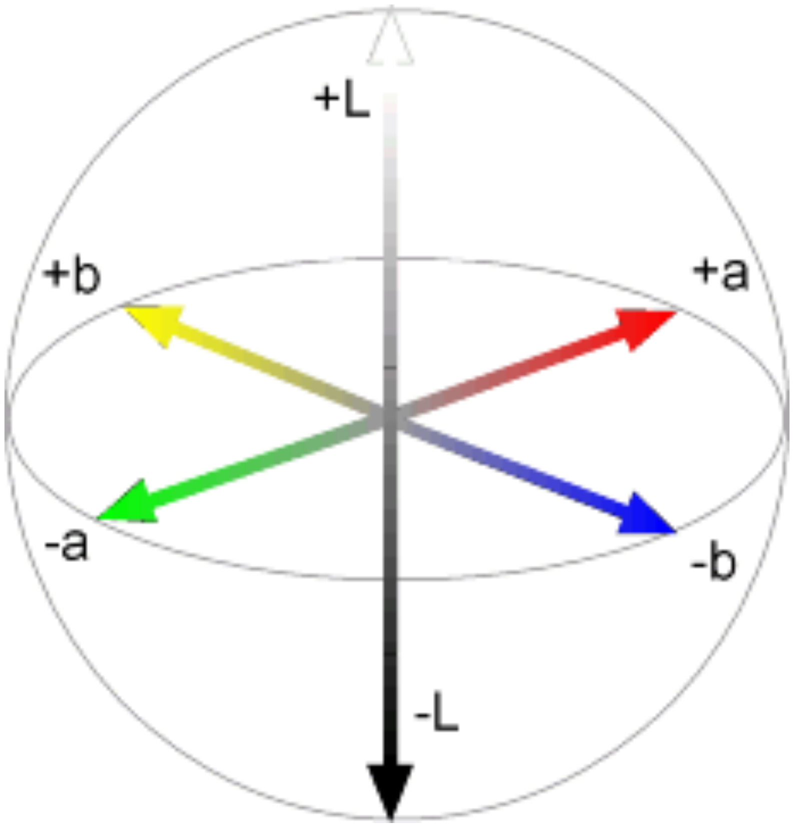


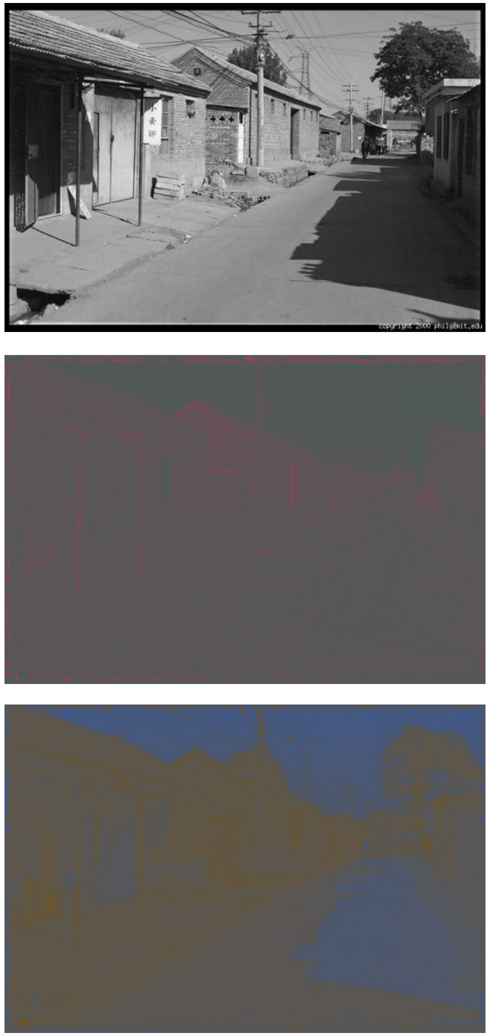
CIE u’ v’

Slide credit: K. Grauman, S. Marschner

Color spaces: L*a*b*

"Perceptually uniform"* color space





L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

Slide credit: D. Hoiem

Color spaces: L*a*b*

"Perceptually uniform"* color space

$$L^* = 116 f\left(\frac{Y}{Y_n}\right)$$

$$f(t) = \begin{cases} t^{1/3} & t > \delta^3 \\ t/(3\delta^2) + 2\delta/3 & \text{else,} \end{cases}$$

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

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

(X_n, Y_n, Z_n): measured white point

L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

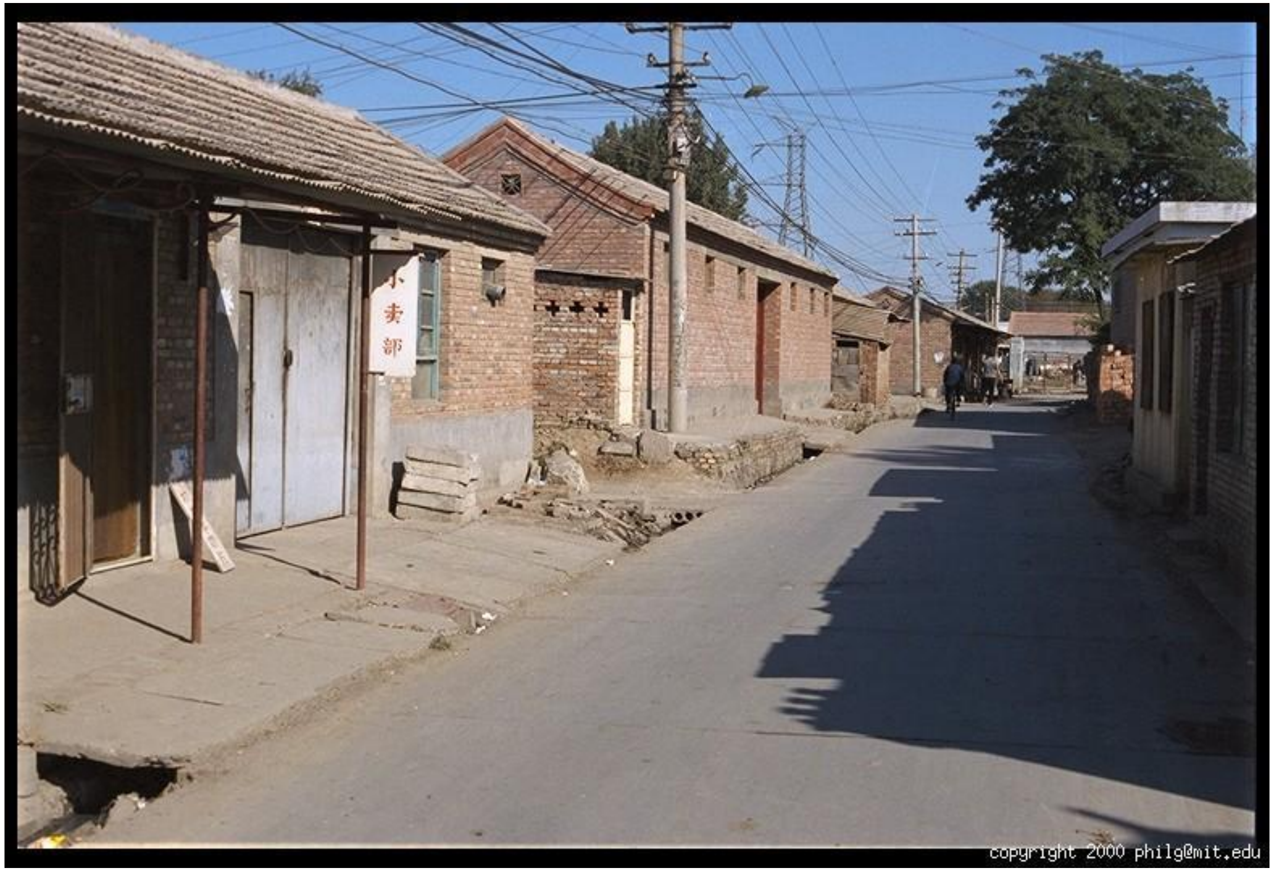
Slide credit: D. Hoiem

Most information in intensity

Only intensity shown – constant color

Slide credit: D. Hoiem

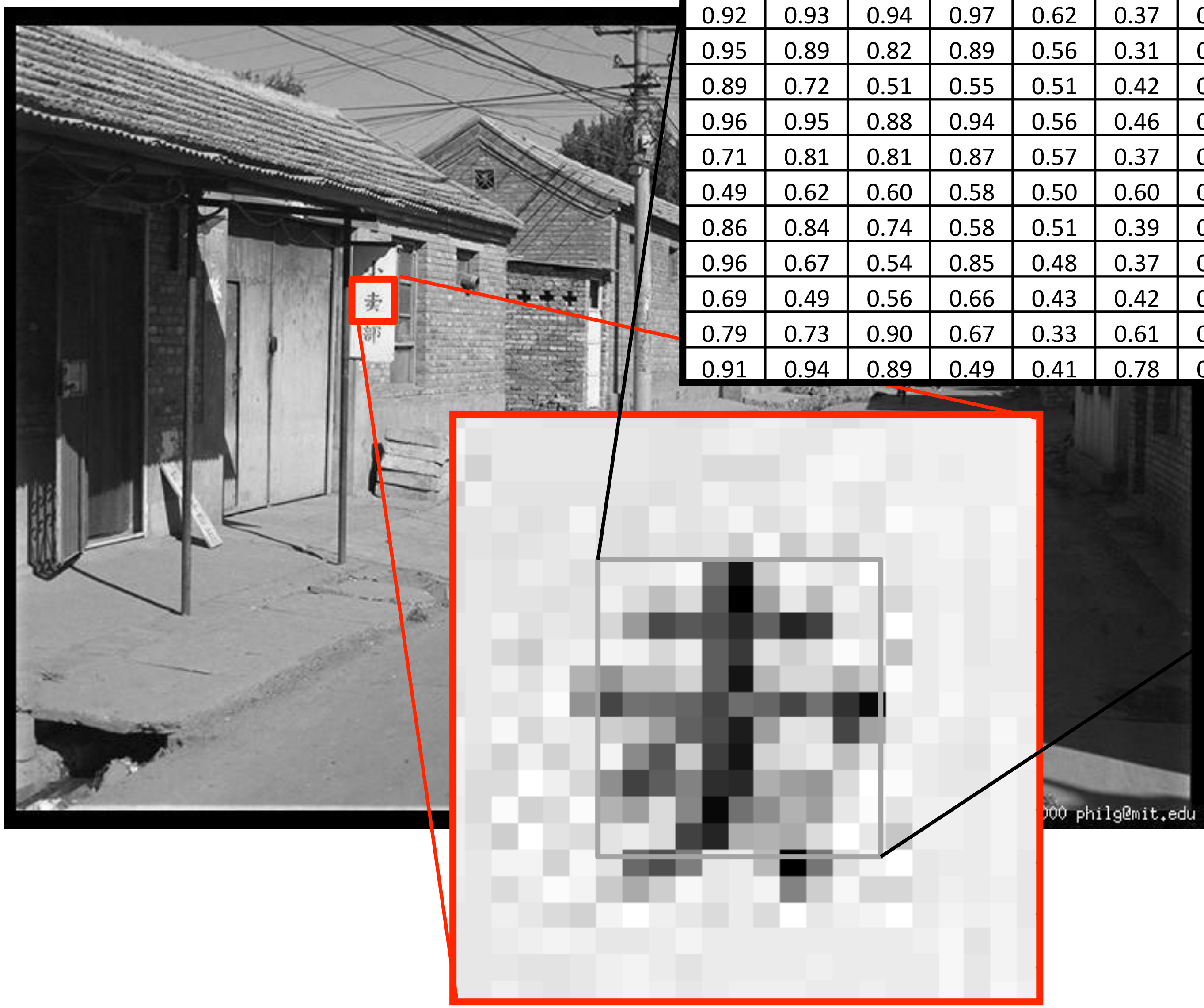
Most information in intensity



Original image

Slide credit: D. Hoiem

Back to grayscale intensity



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

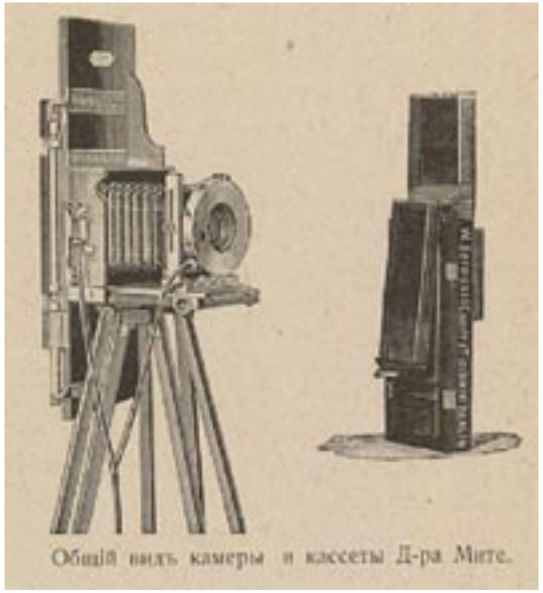
Slide credit: D. Hoiem

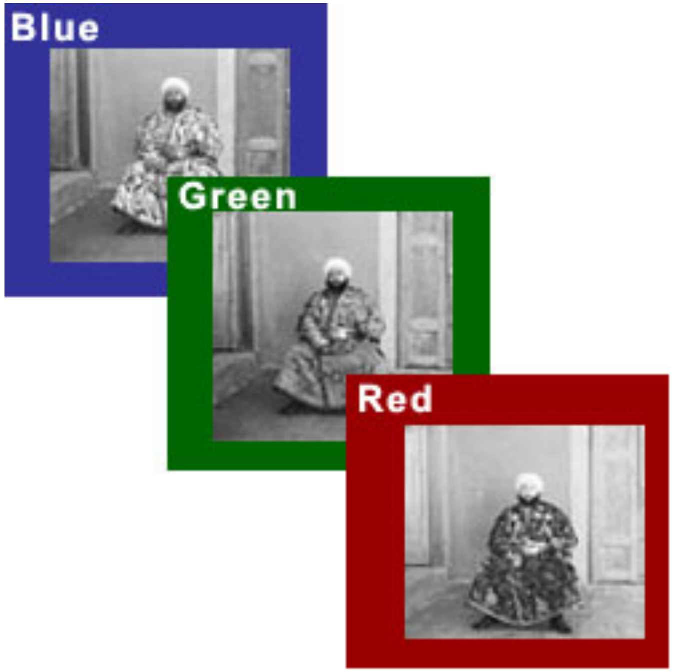
Your first programming assignment

- Colorizing the Prokudin-Gorskii photo collection
- A Matlab warm-up exercise
- Main steps:
  1. Divide the input image into three equal parts corresponding to RGB channels.
  2. Align the second and the third parts (G and R channels) to the first one (B channel).

Prokudin-Gorskii's Russia in Color

- Russia circa 1900
- One camera, move the film with filters to get 3 exposures





Images from: http://www.loc.gov/exhibits/empire/

Slide credit: F. Durand

Prokudin-Gorskii's Russia in Color

- Digital restoration

Slide credit: F. Durand

Emir Seyyid Mir Mohammed Alim Khan, the Emir of Bukhara, ca. 1910.

Self-portrait on the Karolitskhali River, ca. 1910.

A metal truss bridge on stone piers, part of the Trans-Siberian Railway, crossing the Kama River near Perm, Ural Mountains Region, ca. 1910.


On the Sim River, a shepherd boy, ca. 1910.

Peasants harvesting hay in 1909. From the album "Views along the Mariinskii Canal and river system, Russian Empire", ca. 1910.