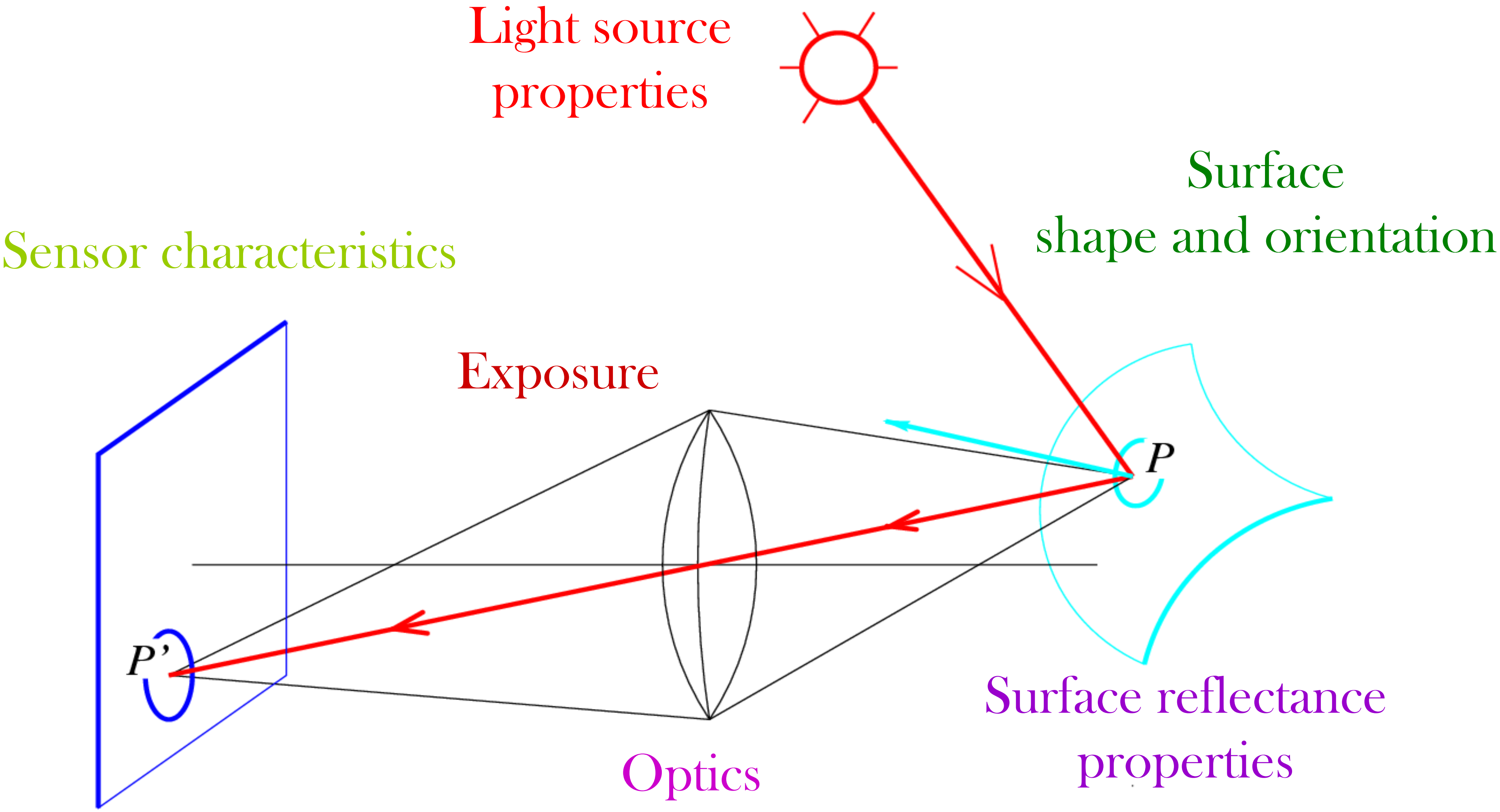
Image Processing

Burcu KIR SAVAŞ, PhD.

Image types and color

image formation

- What determines the brightness of an image pixel?



Slide credit: L. Fei-Fei

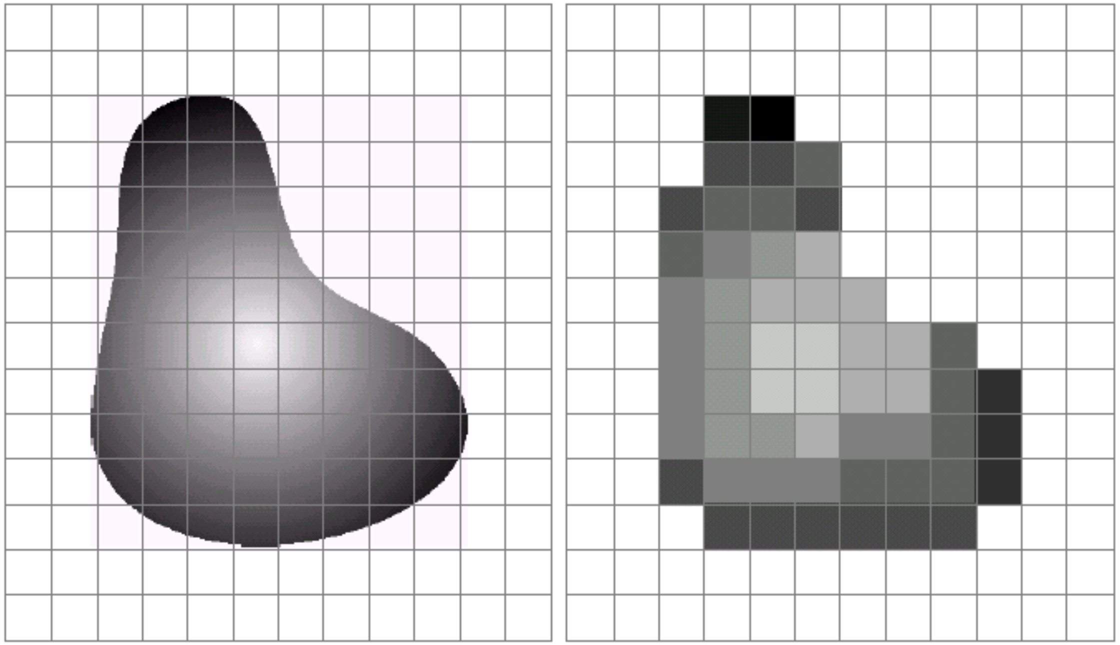
digital camera

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

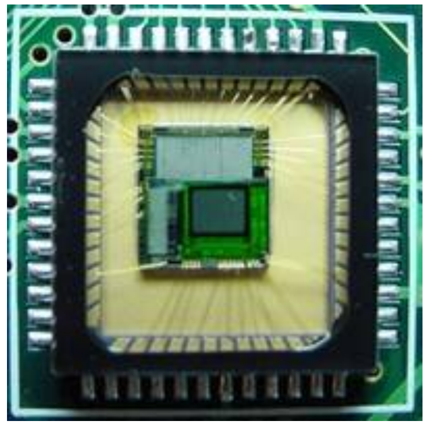
Slide credit: S. Seitz

digital images



a b

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

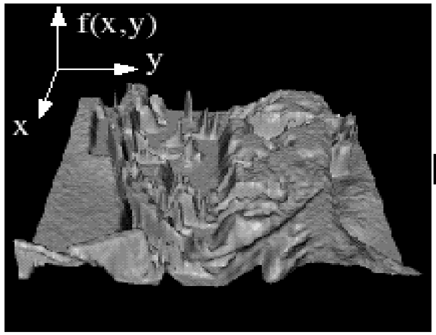


Slide credit: D. Hoiem

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.

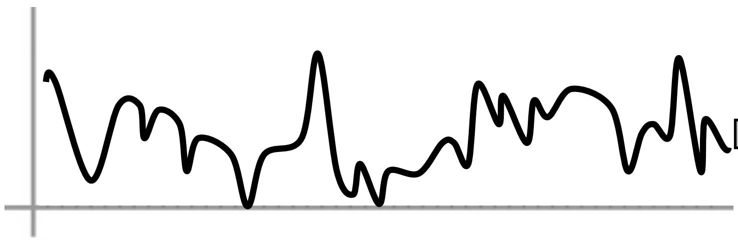


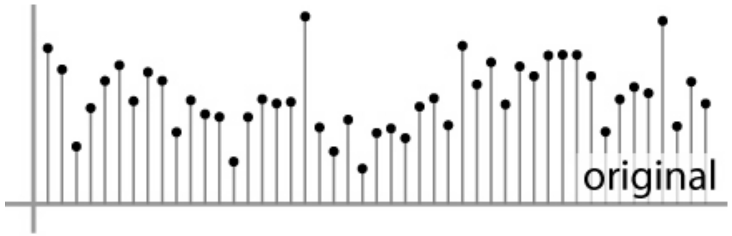
j

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



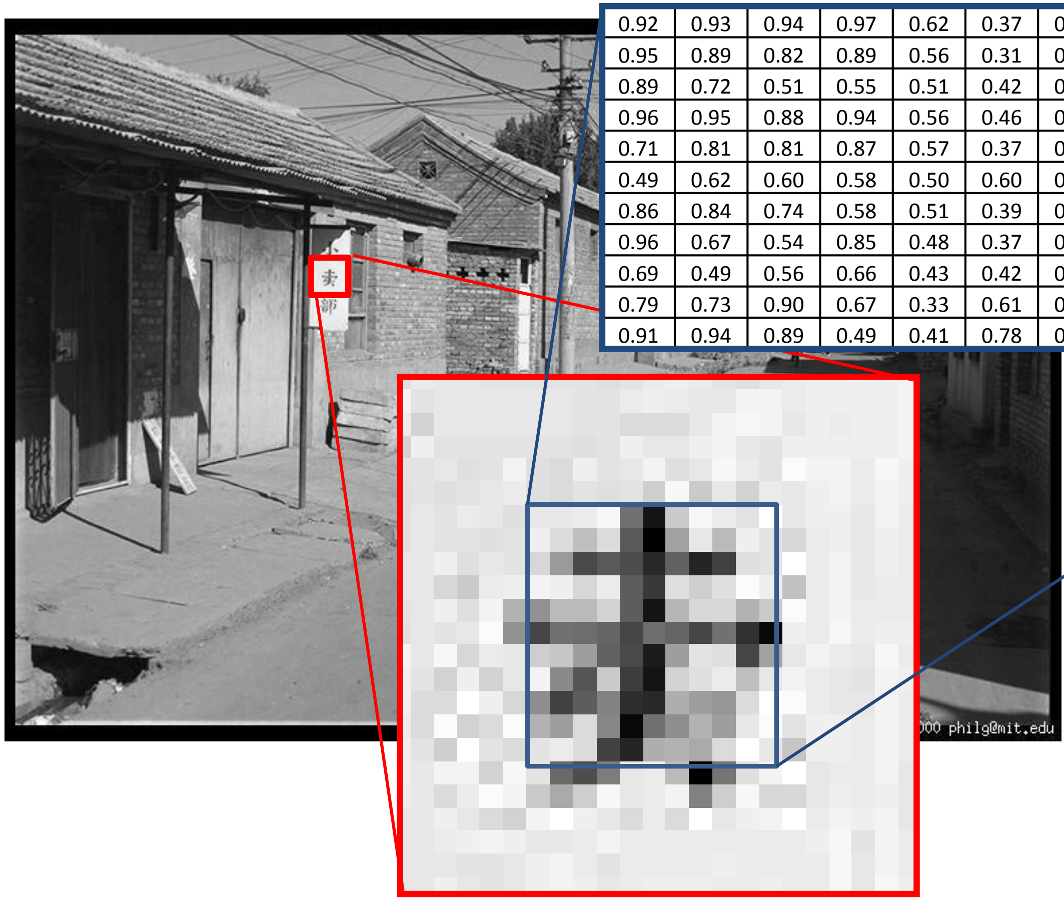


1D

Slide credit: K. Grauman, S. Seitz

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

TODAY

- Perception of color and light
- Color spaces

Why does a visual system need color?

Why does a visual system need color?

- To tell food and mates.
- To distinguish material changes from shading changes.
- To group parts of one object together in a scene.
- A person's appearance looks normal/healthy.

Slide credit: W. Freeman

What is color?

- Colour, also spelled, 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*)

Colour wheel

RYB colour model

#thedress

- What is the color of the dress?

- blue and black
- white and gold
- blue and brown

- What #thedress tell about our color perception?

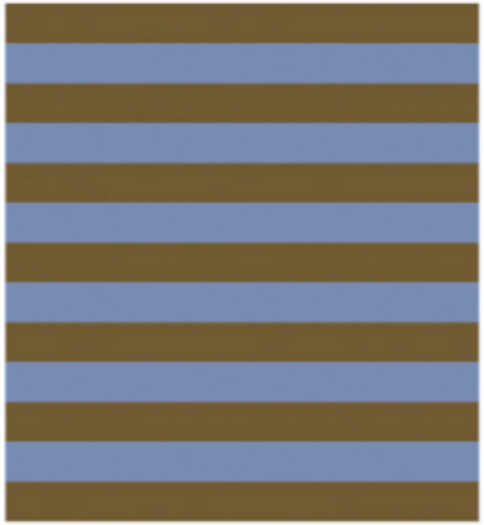
#thedress

- Let's take averages

two pieces of the dress | averages | basic pattern

#thedress

- The dress in the photograph



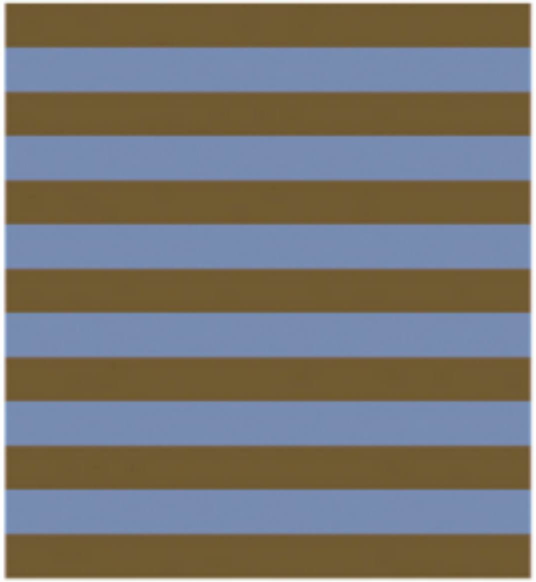
#thedress

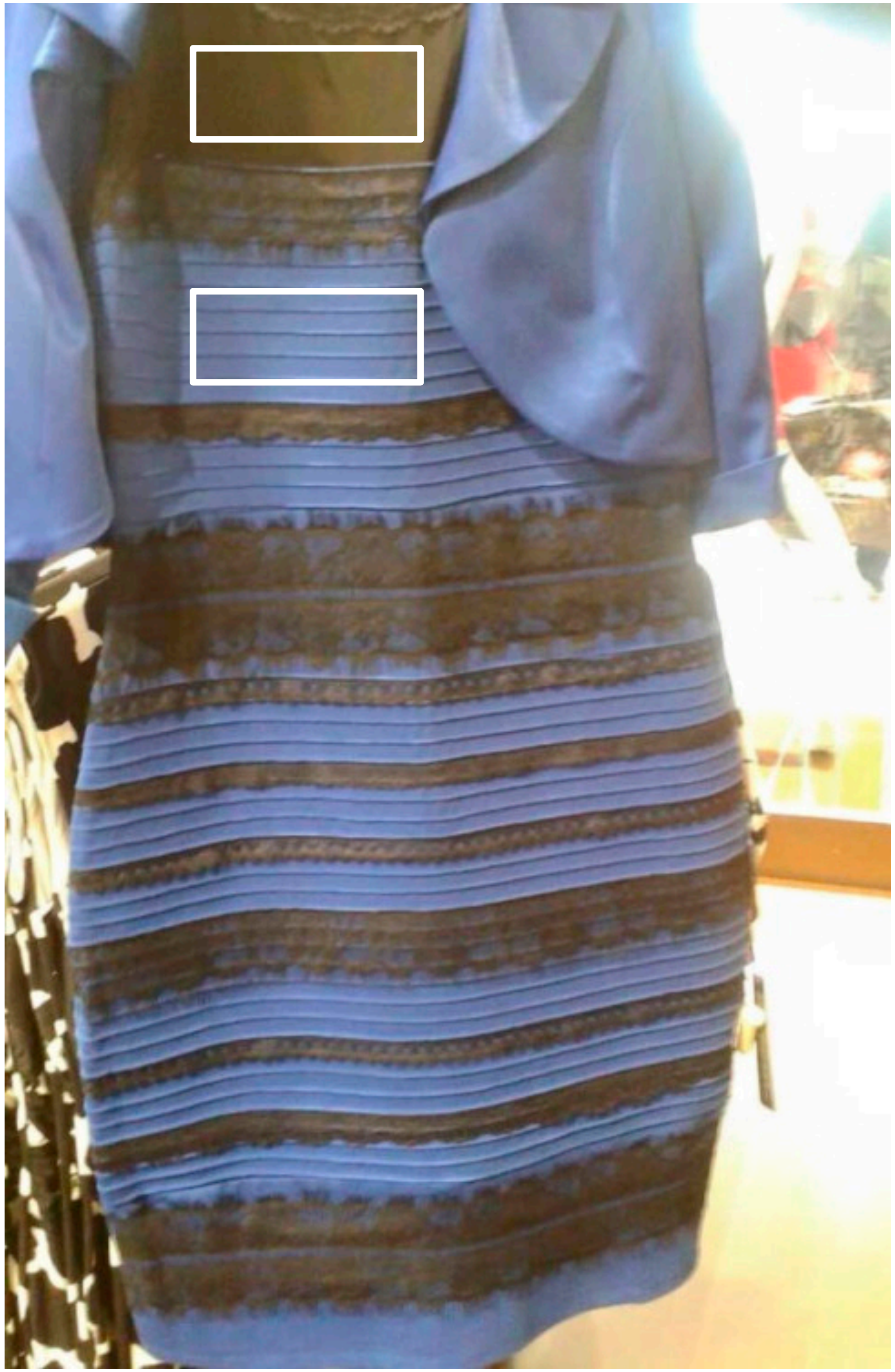
- Consider the dress is in shadow.

- Your brain remove the blue cast, and perceive it as white and gold.

#thedress

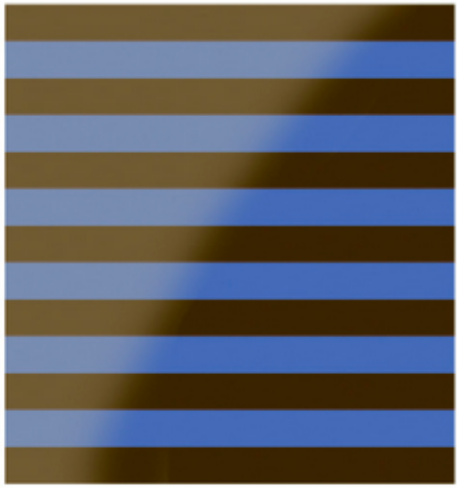
- The dress in the photograph





#thedress

- Consider the dress is in bright light.



- Your brain perceive the dress as a darker blue and black

#thedress

- Answer:

- The dress is actually blue and black.

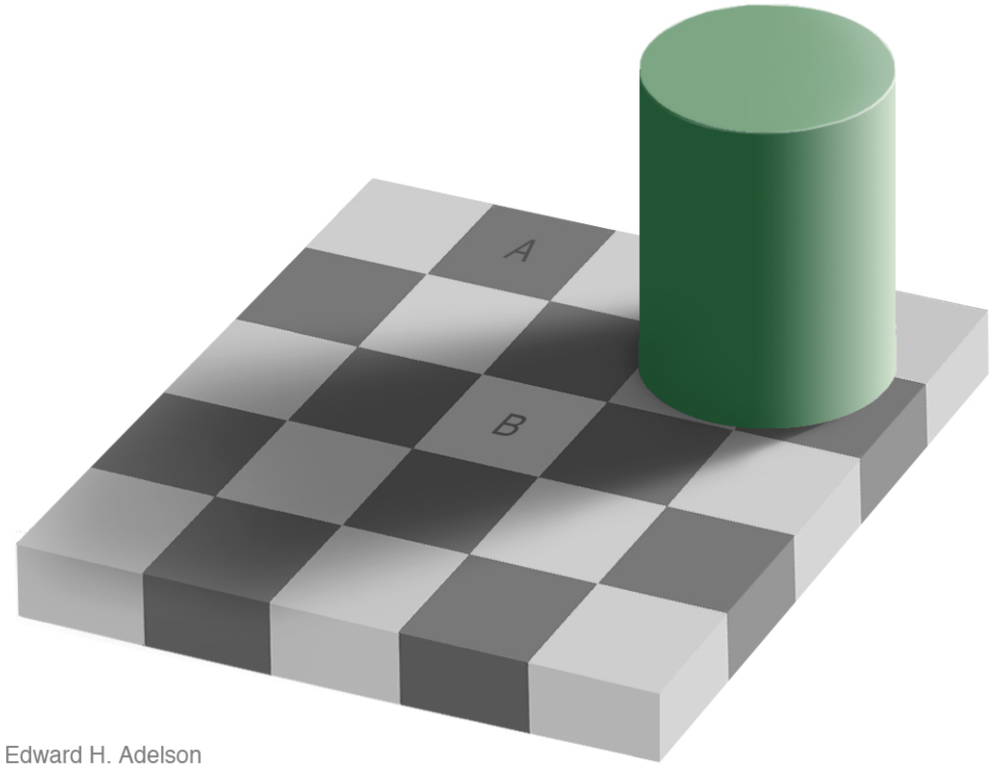
Brightness perception

Consider two pieces of paper, one black and one white.

Let's say we were outside in bright sunlight (instead of being in this dingy lecture hall).

What color do you imagine they would look like?

Still black and white.

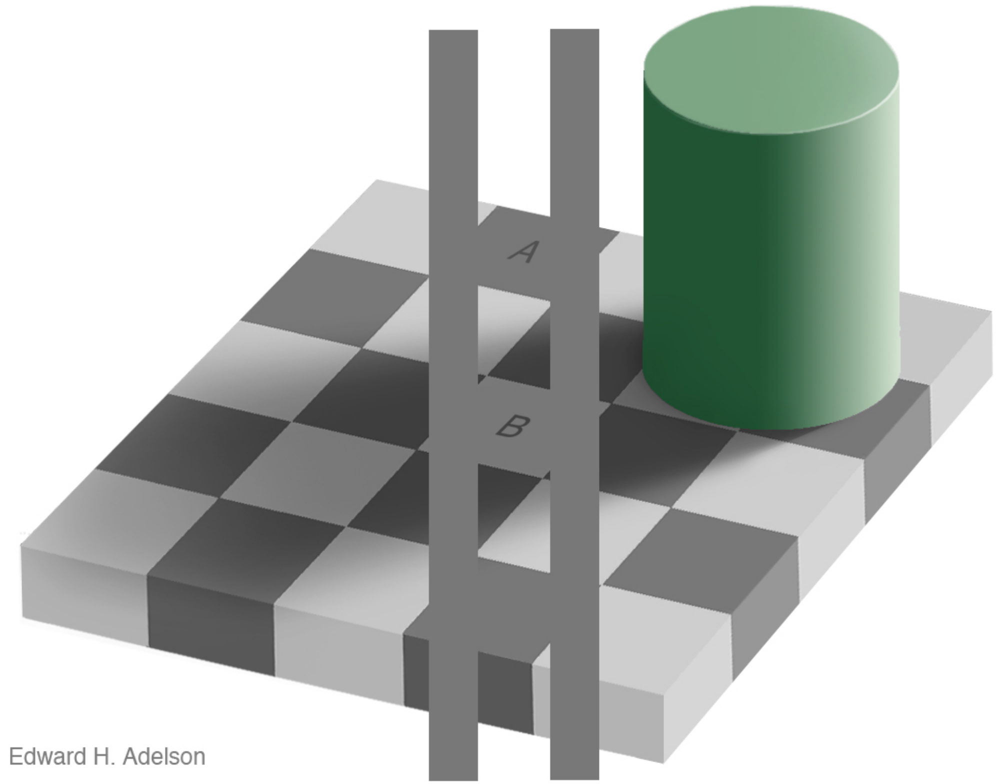


Edward Adelson

Brightness perception

The image of the black paper outdoors is actually more intense than the image of white paper indoors.

Why does the black paper outdoors still look black even though it is physically more intense?



Edward Adelson

Brightness perception

Land's Experiment (1959)

- Cover all patches except a blue rectangle
- Make it look gray by changing illumination
- Uncover the other patches

Color Constancy

We filter out illumination variations

Slide credit: S. Narasimhan

Land’s Experiment (1959)

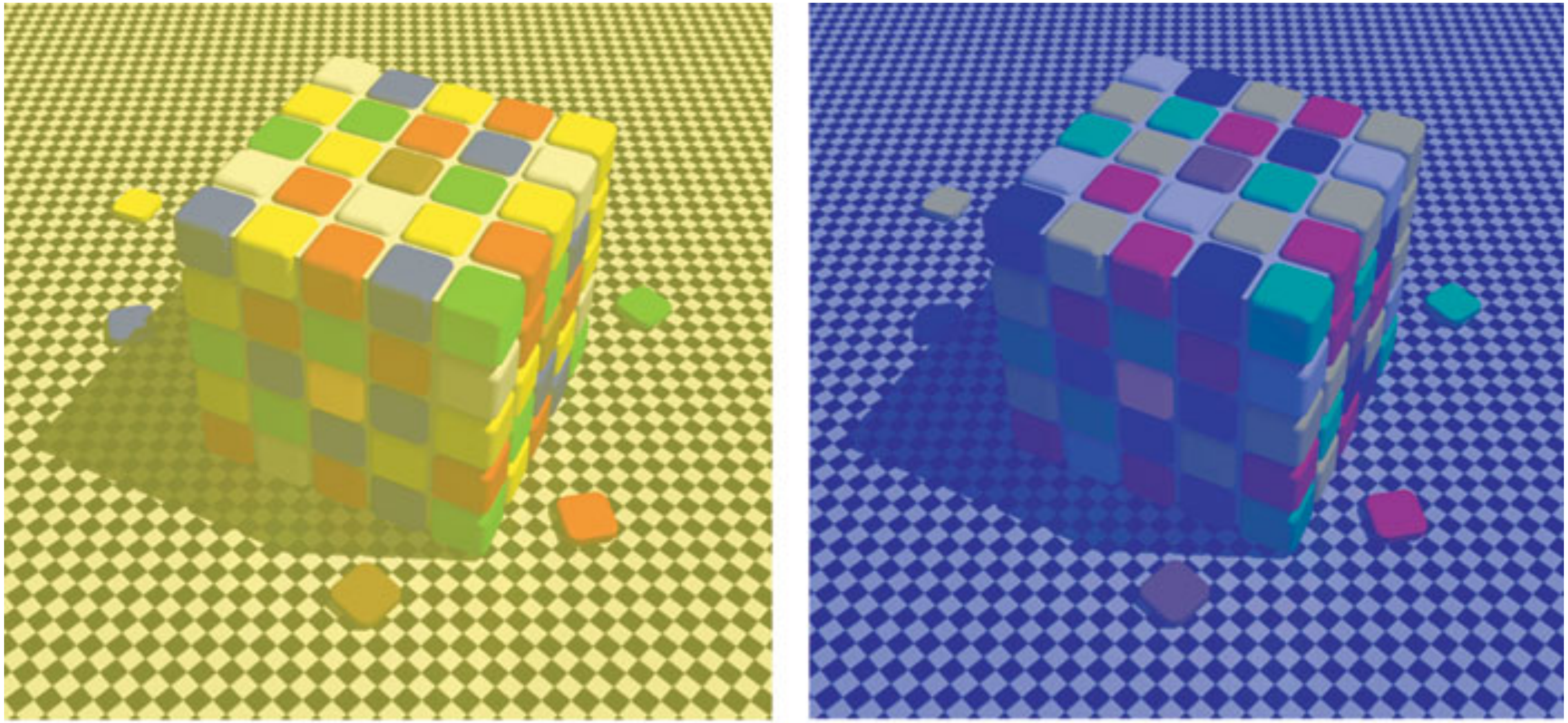
- Cover all patches except a blue rectangle
- Make it look gray by changing illumination
- Uncover the other patches

Color Constancy

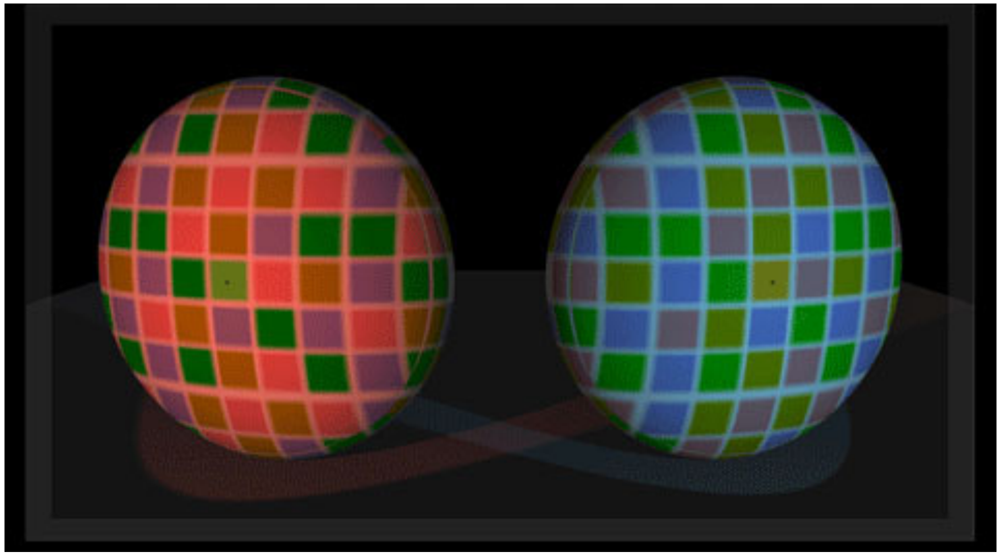
We filter out illumination variations

Slide credit: S. Narasimhan

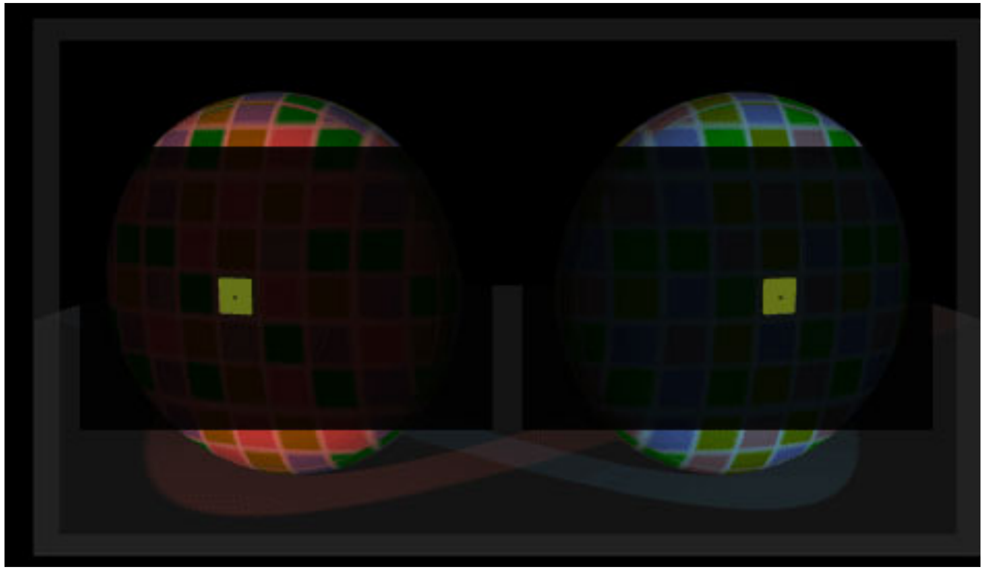
Color Cube Illusion



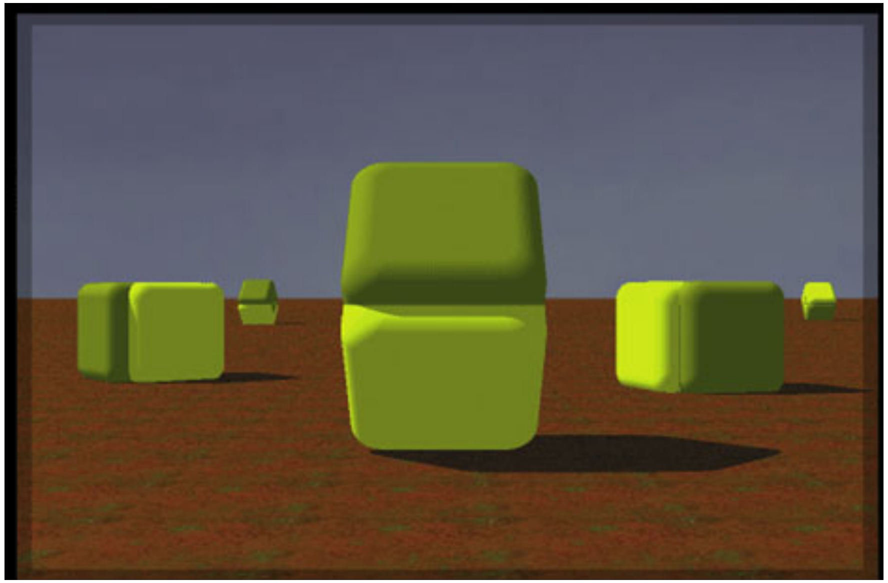
Color perception



Color perception



Color perception



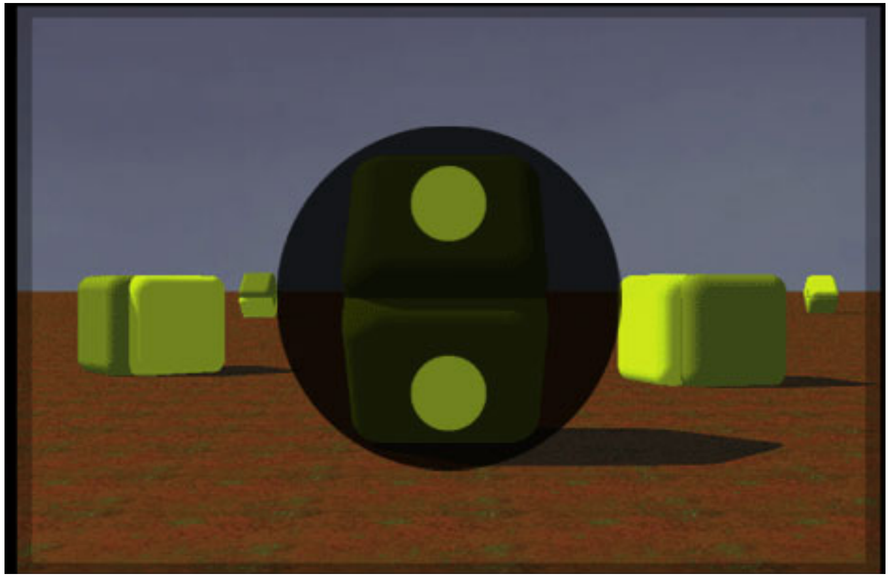
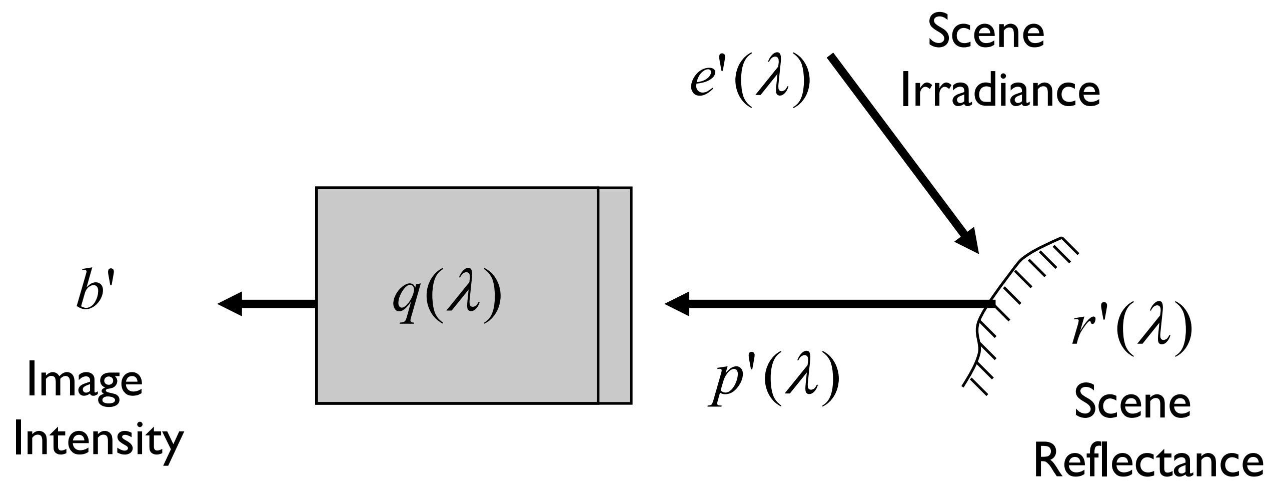


Image Brightness (Intensity)



• Monochromatic Light : $(\lambda = \lambda_i)$

$$b'(x, y) = r'(x, y)\, e'(x, y) \qquad\qquad q(\lambda_i) = 1$$

NOTE: The analysis can be applied to COLORED LIGHT using FILTERS

Slide credit: S. Narasimhan

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

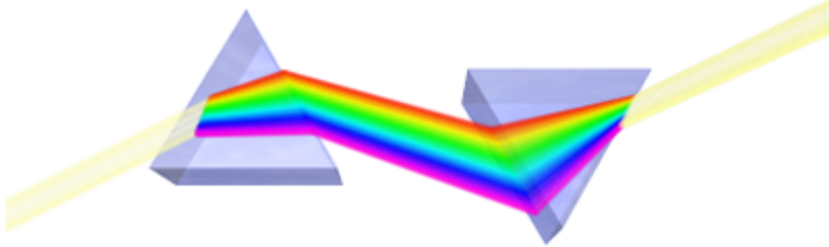
- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

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

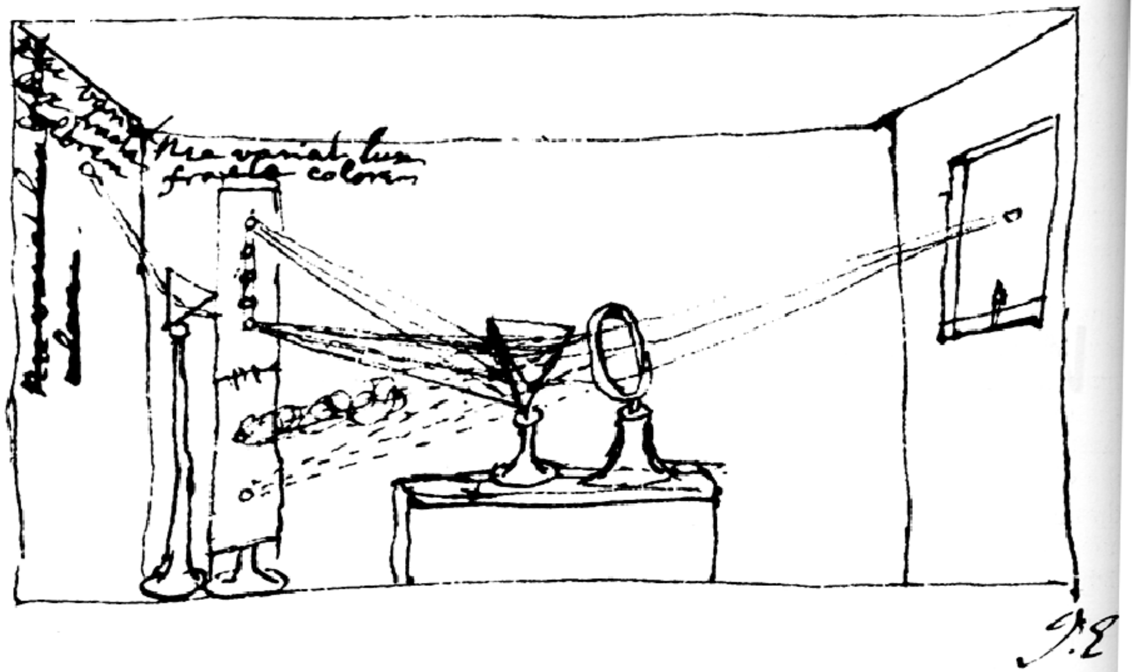
Slide credit: K. Grauman, S. Marschner

Color

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



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.

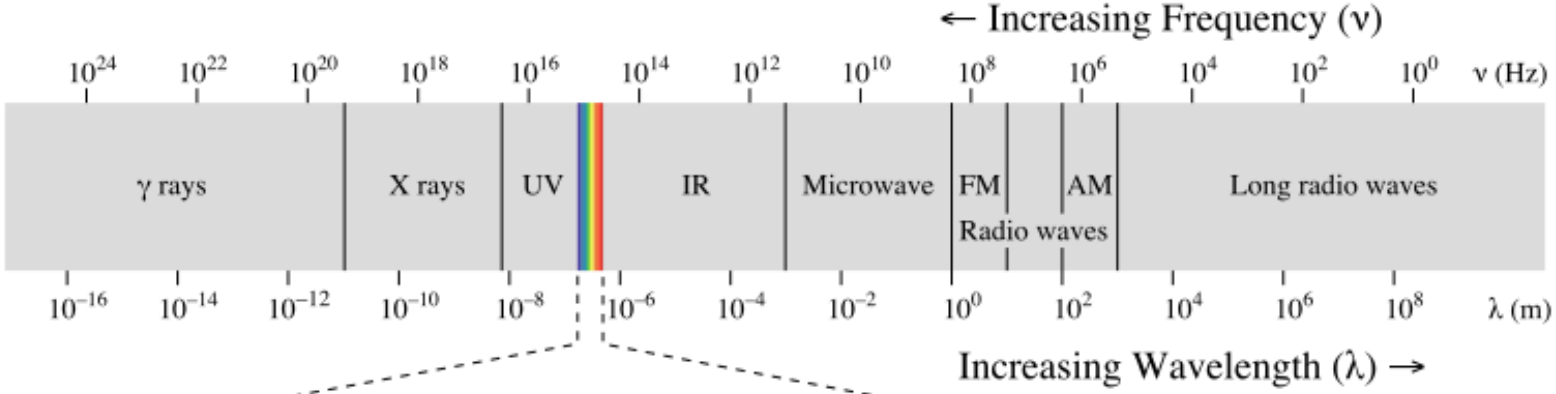
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

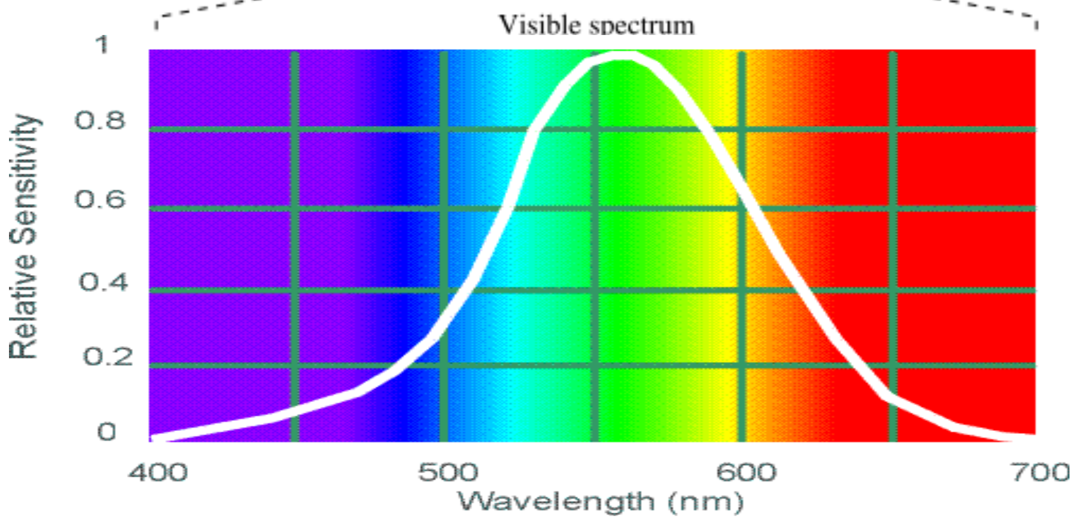
Newton 1665

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

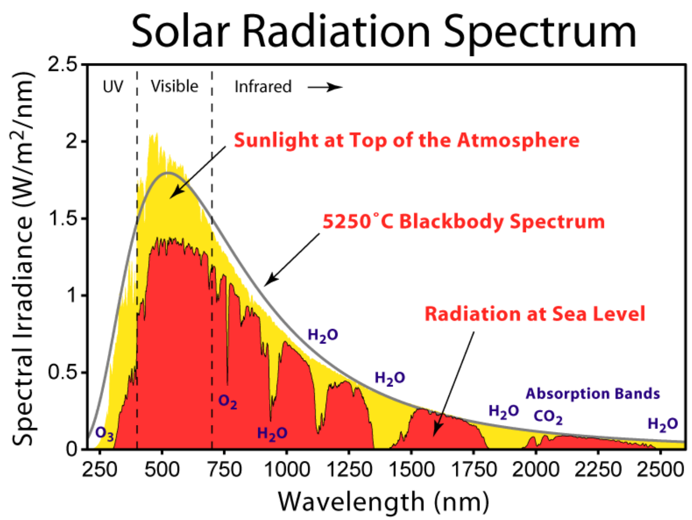
Electromagnetic spectrum

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





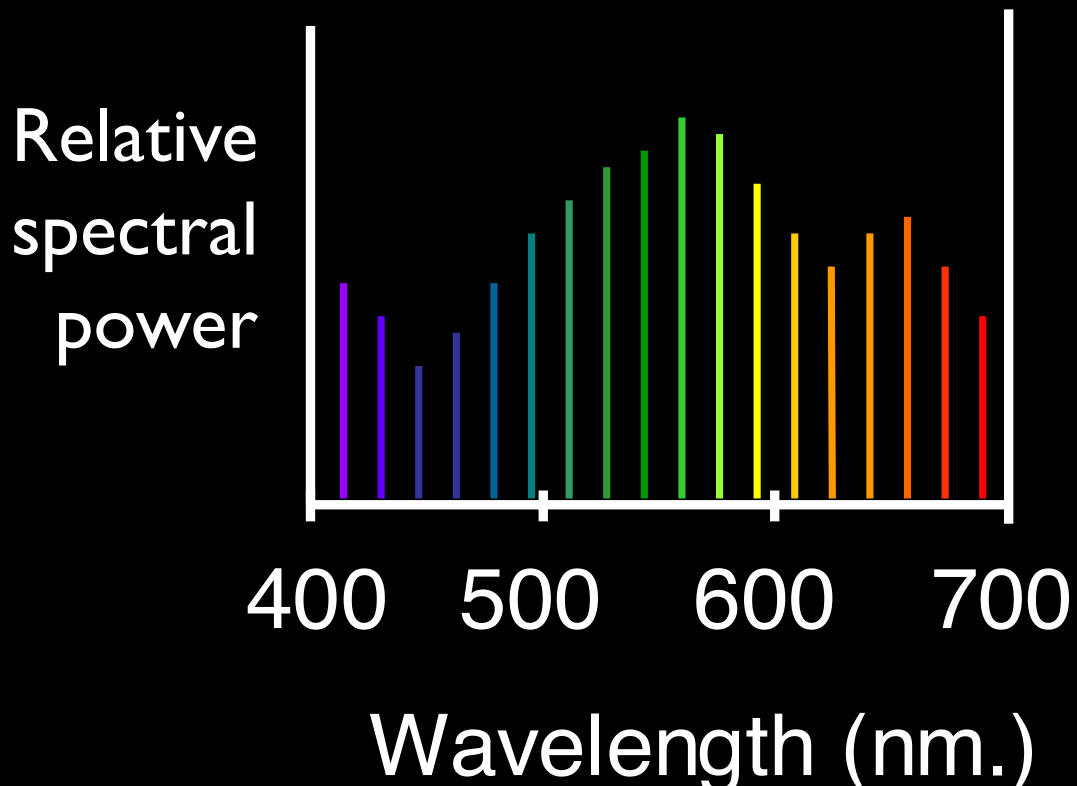
Human Luminance Sensitivity Function



Slide credit: A. Efros

The Physics of light

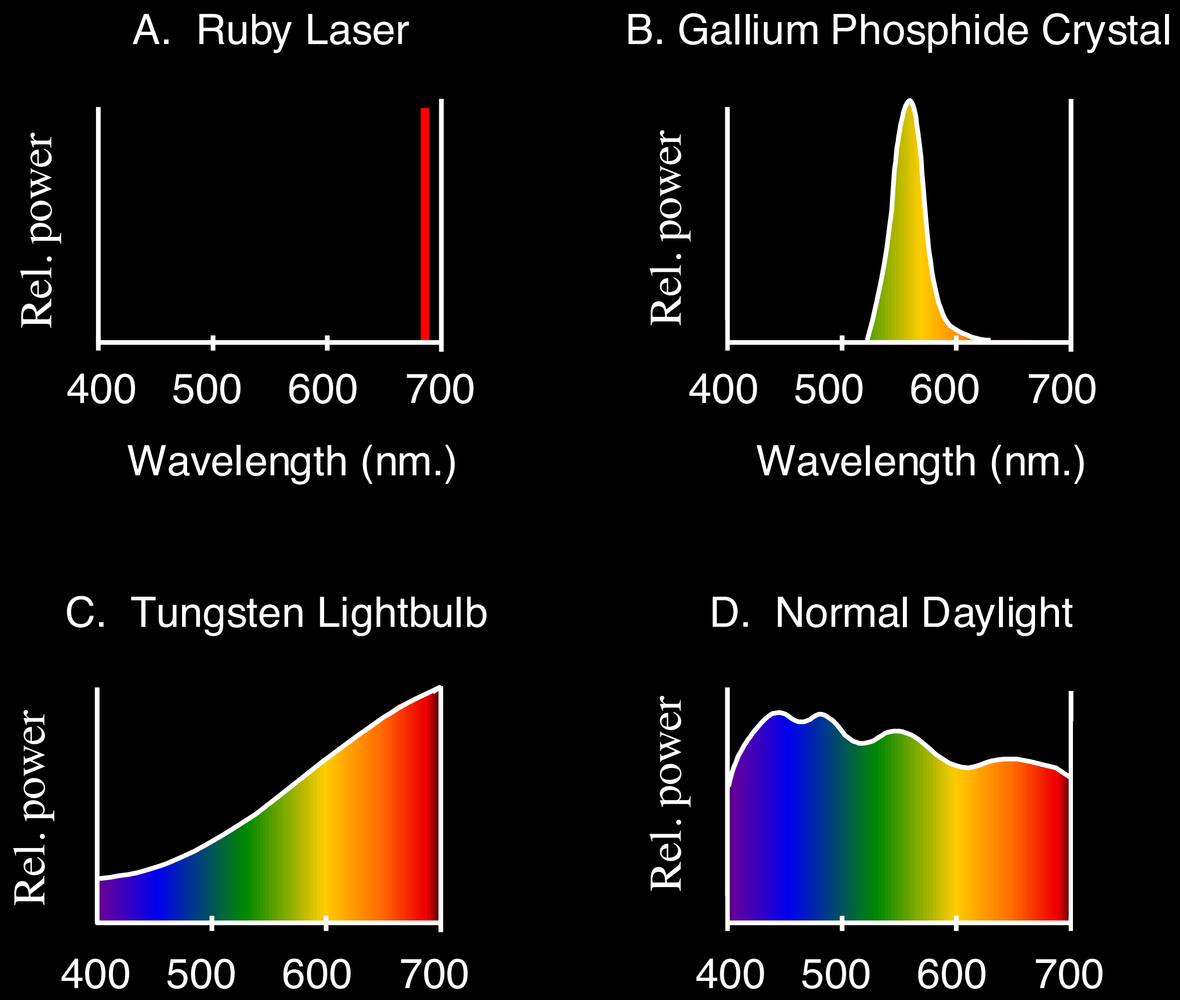
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (per time unit) at each wavelength 400 - 700 nm.



Slide credit: A. Efros

The Physics of light

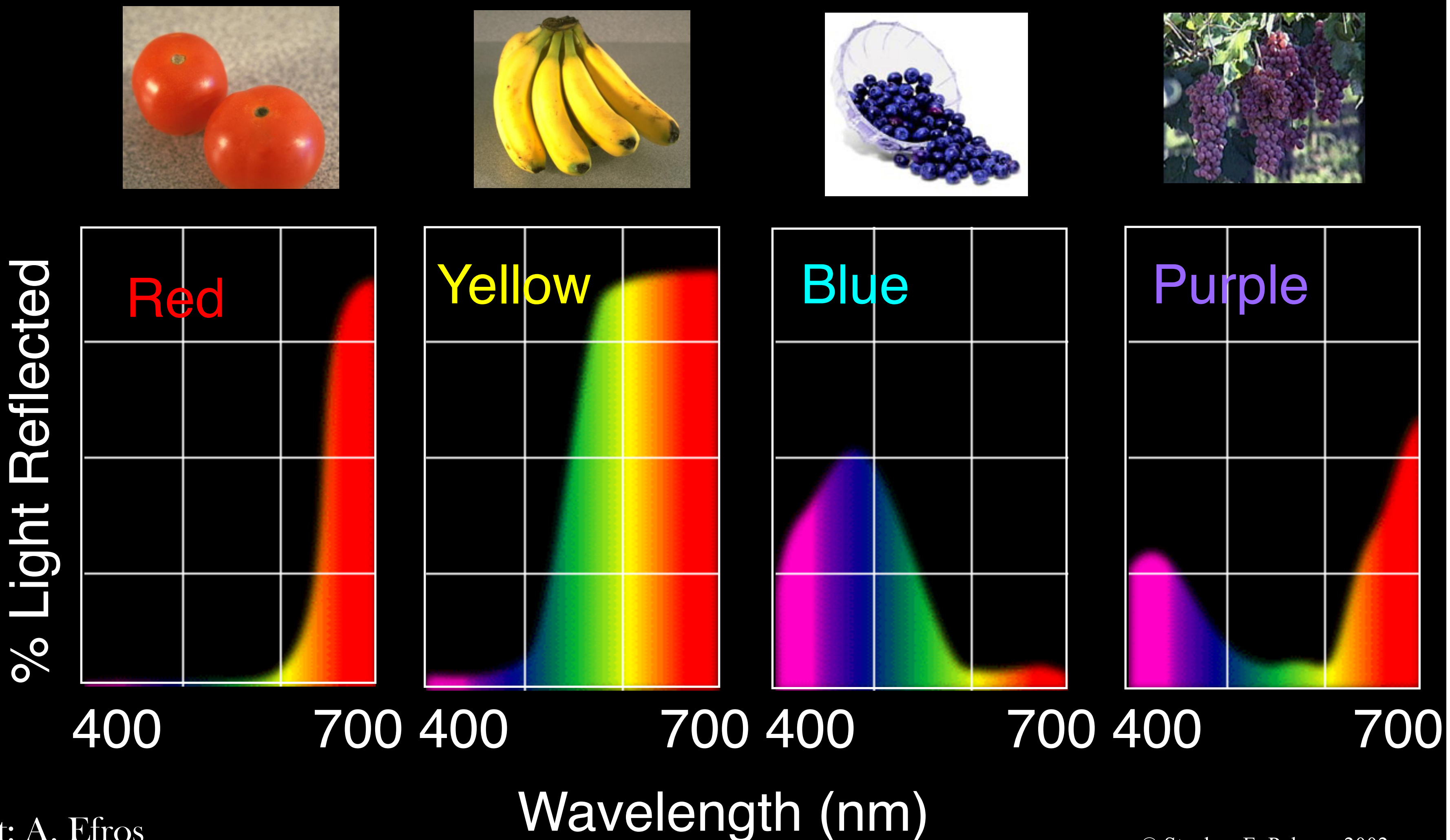
Some examples of the spectra of light sources



Slide credit: A. Efros

The Physics of light

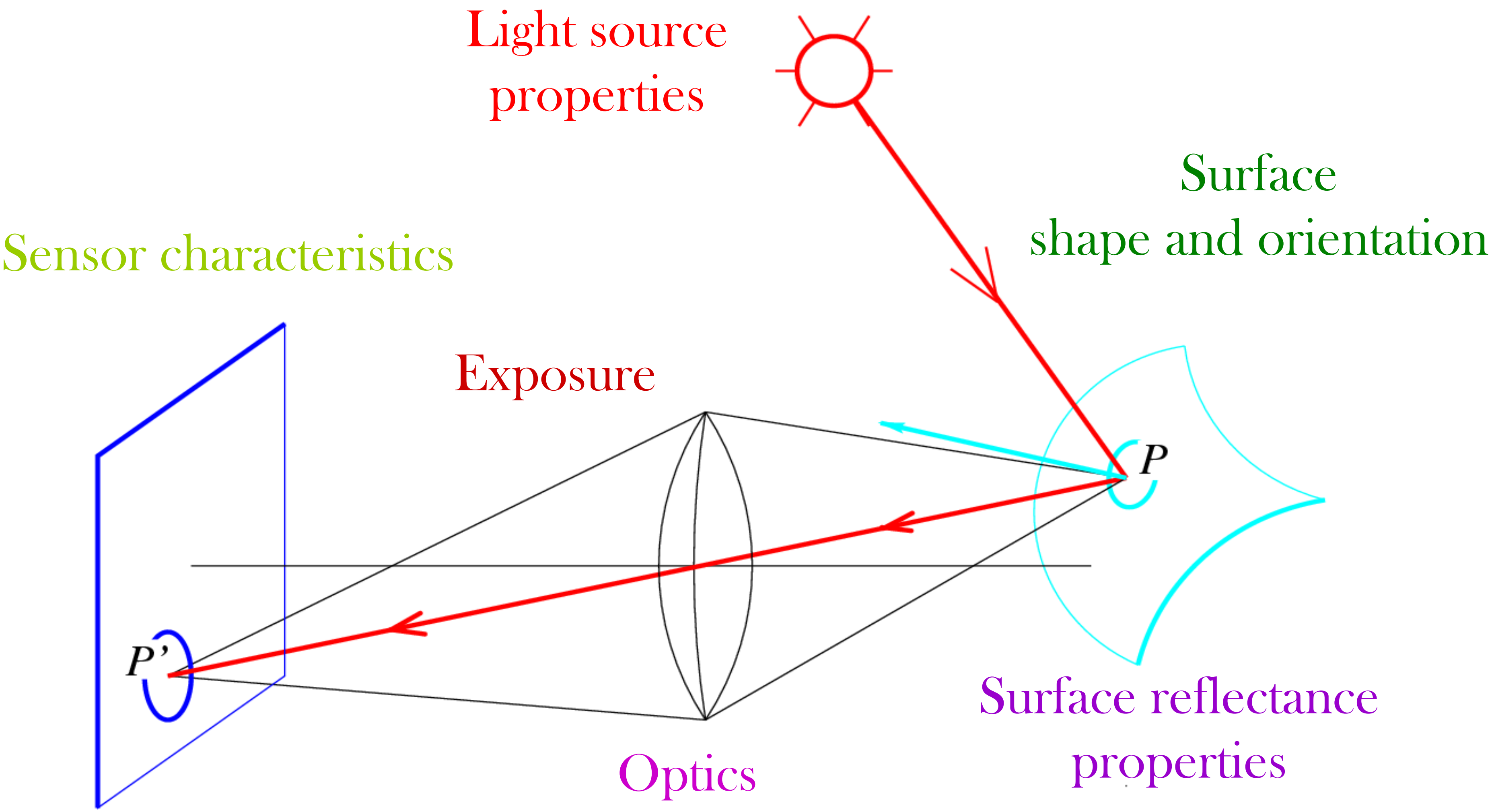
Some examples of the reflectance spectra of surfaces



Slide credit: A. Efros

Image formation

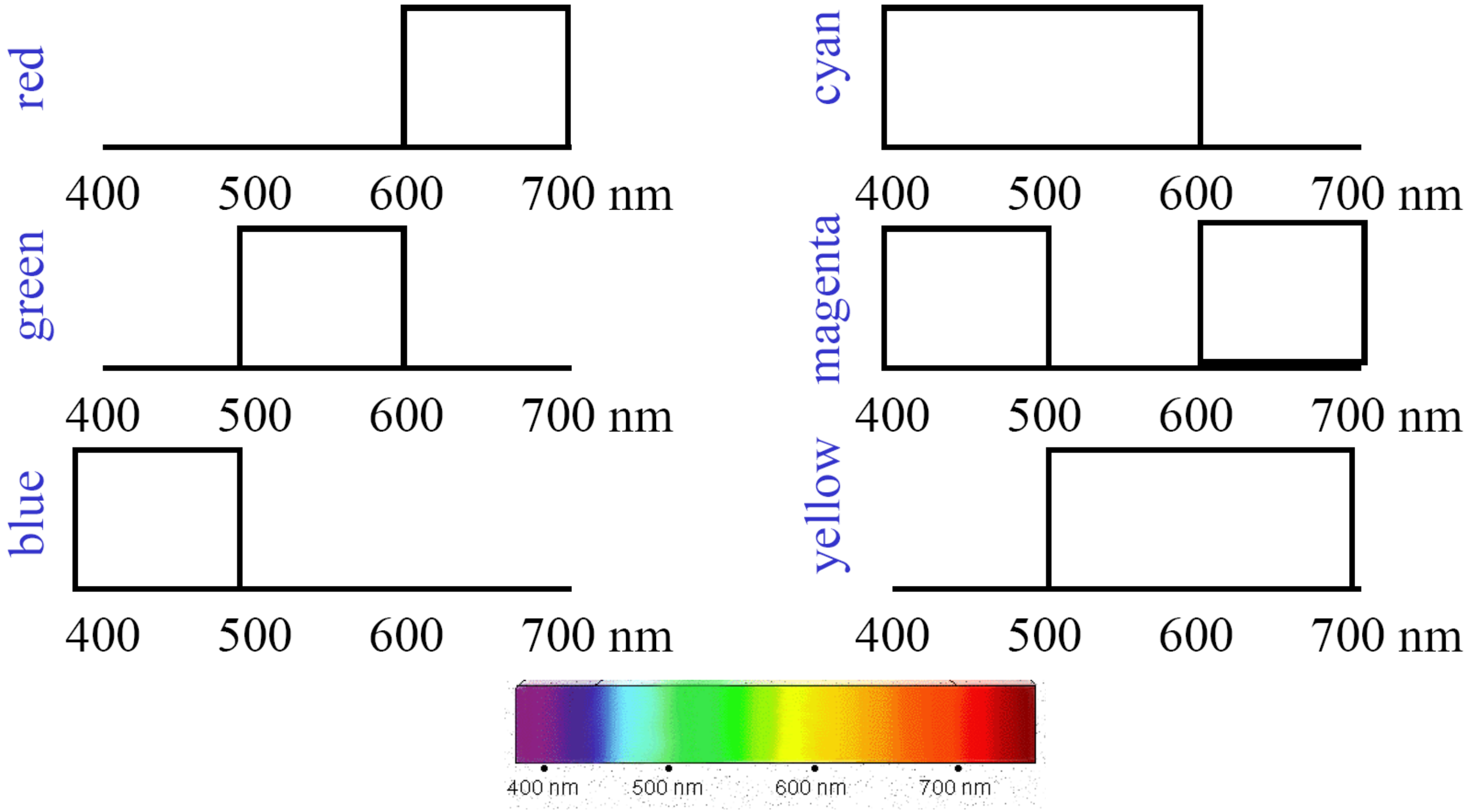
- What determines the brightness of an image pixel?



Slide credit: L. Fei-Fei

Color mixing

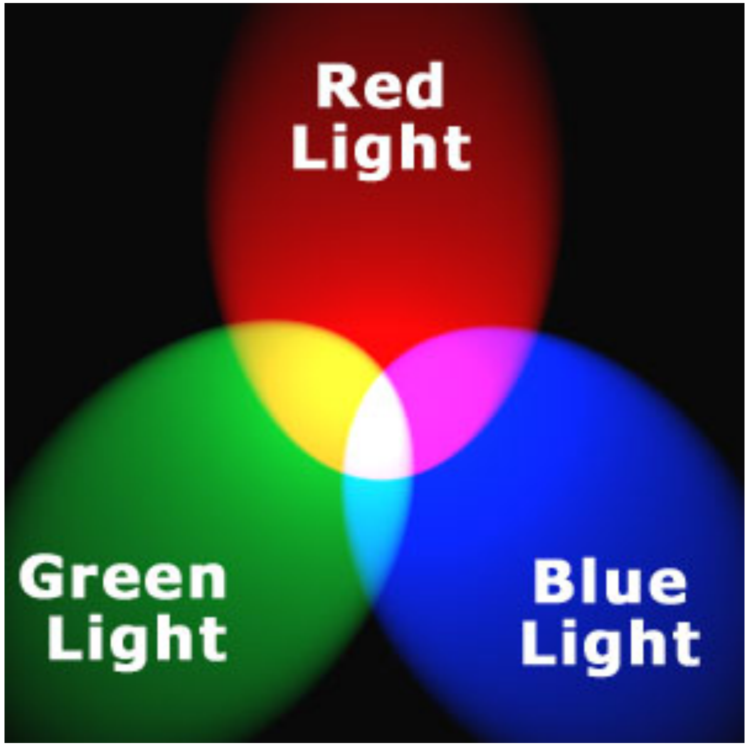
Cartoon spectra for color names:



Credit: W. Freeman

Additive color mixing

Colors combine by *adding* color spectra
Mixing the three primaries or a secondary with its opposite primary color produces white light.

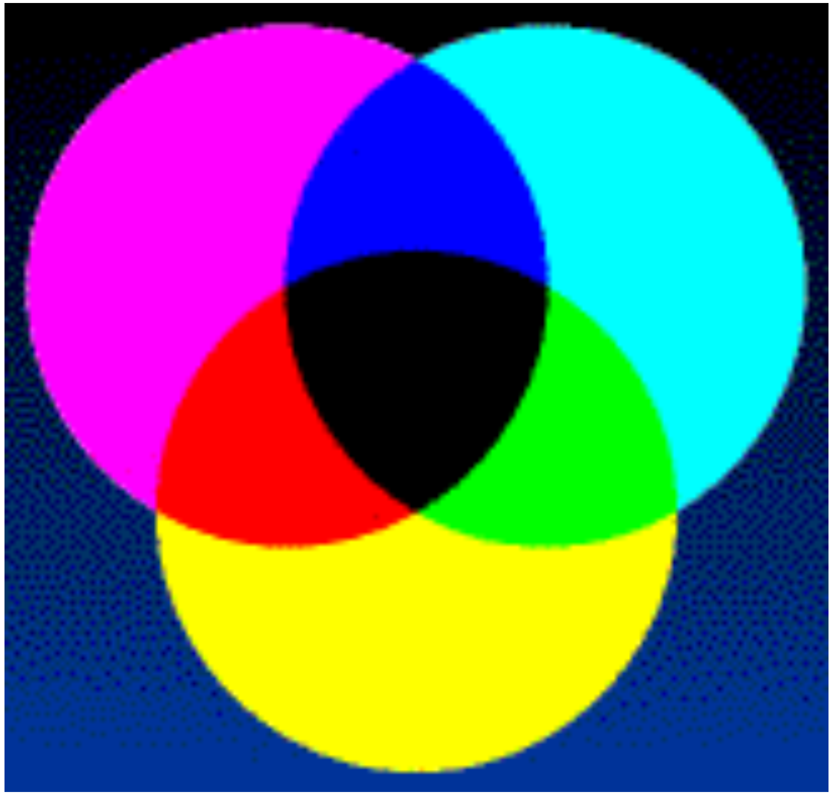


Light *adds* to black.

Credit: W. Freeman

Subtractive color mixing

Colors combine by *multiplying* color spectra.

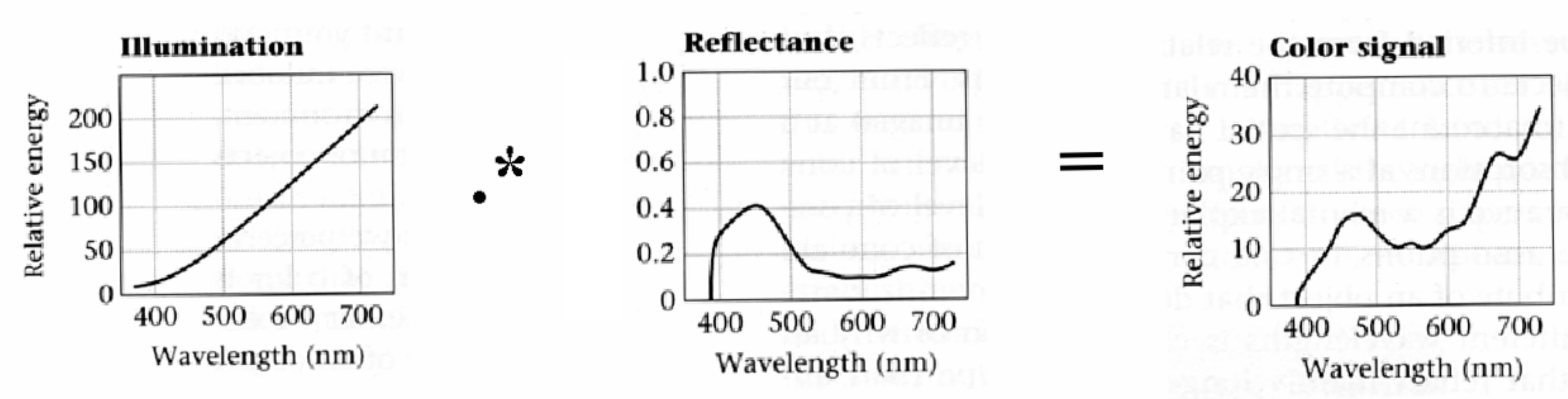


Pigments *remove* color from incident light (white).

Credit: W. Freeman

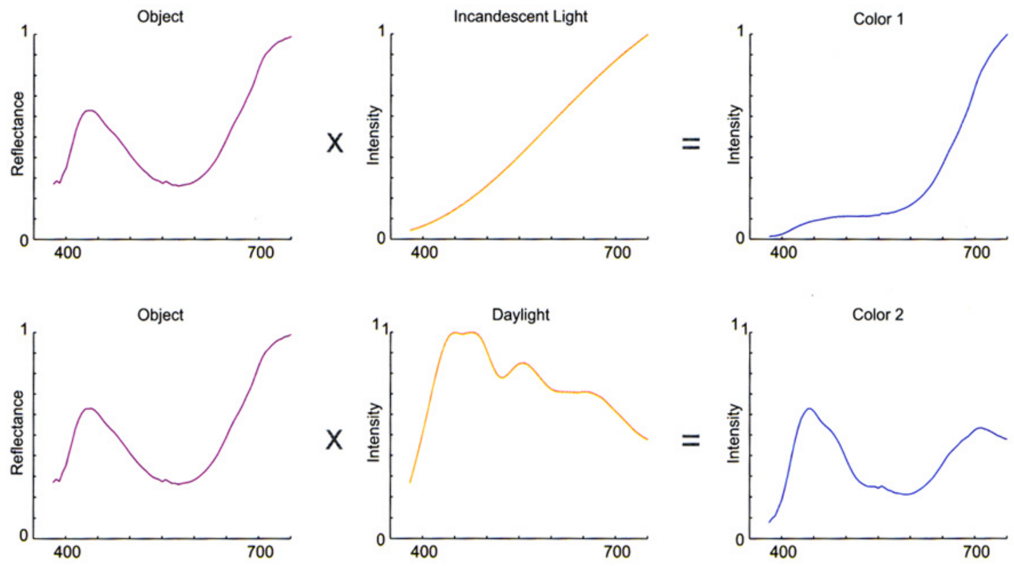
Interaction of light and surfaces

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

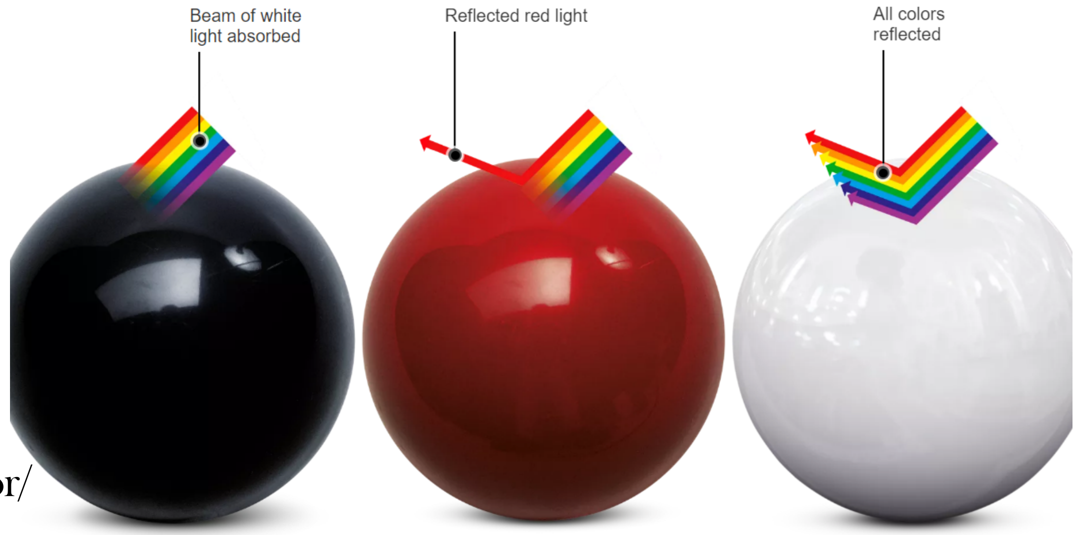


Slide credit: A. Efros

Reflection from colored surface



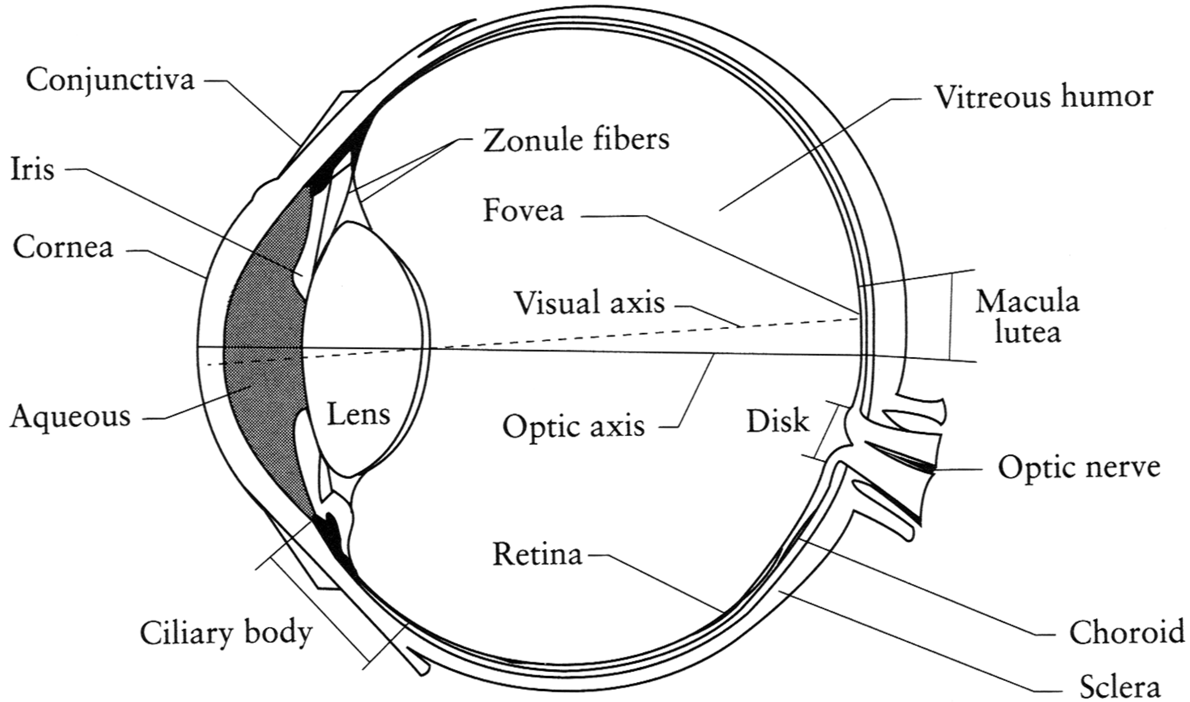
[Stone 2003]



Slide credit: S. Marschner

https://www.dkfindout.com/us/science/light/seeing-color/

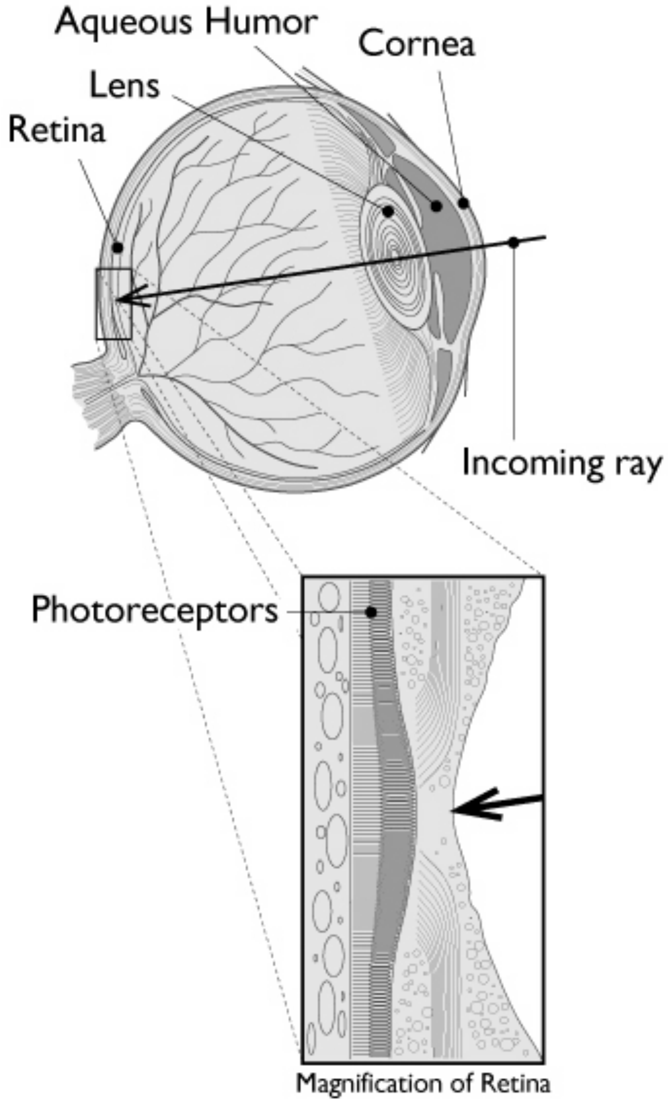
The Eye



- **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]

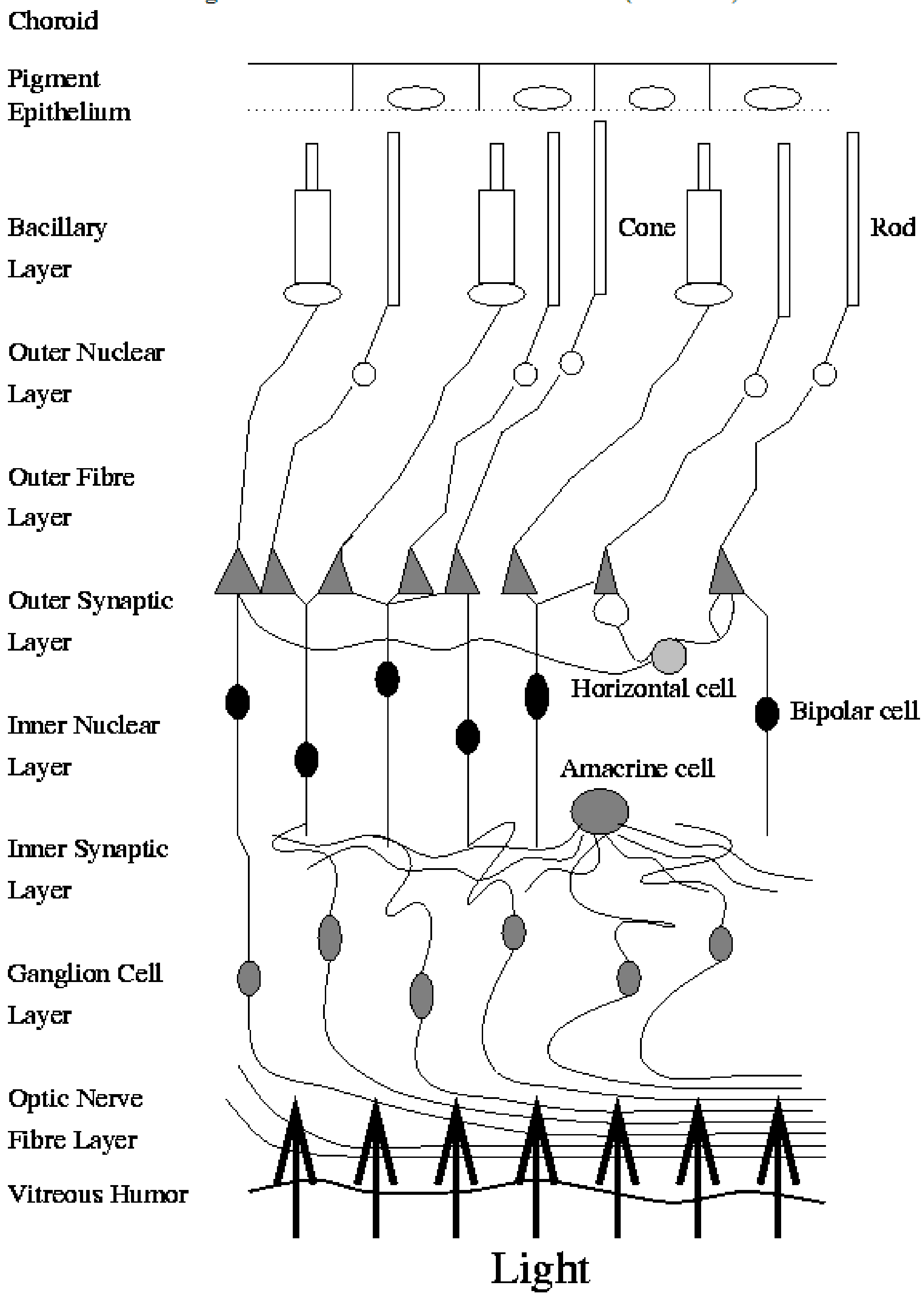
- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera
- Light is measured by the *photoreceptors* in the retina
  - they respond to visible light
  - different types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

- **The human eye is a camera!**

Slide credit: S. Marschner

Layers of the retina

Figure: Schematic of a cross section of the retina (after Nalwa).



Slide credit: S. Ullman

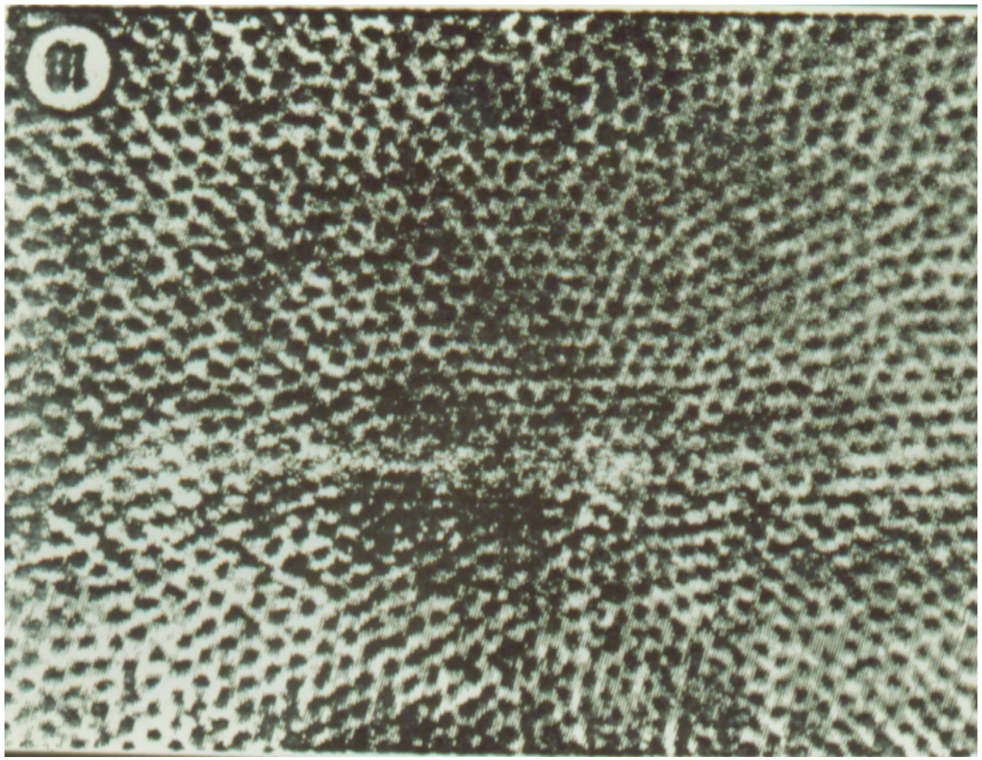
Eye Movements

- Saccades
  - Can be consciously controlled. Related to perceptual attention.
  - 200ms to initiation, 20 to 200ms to carry out. Large amplitude.
- Microsaccades
  - Involuntary. Smaller amplitude. Especially evident during prolonged fixation. Function debated.
- Smooth pursuit – tracking an object

Slide credit: J. Hays

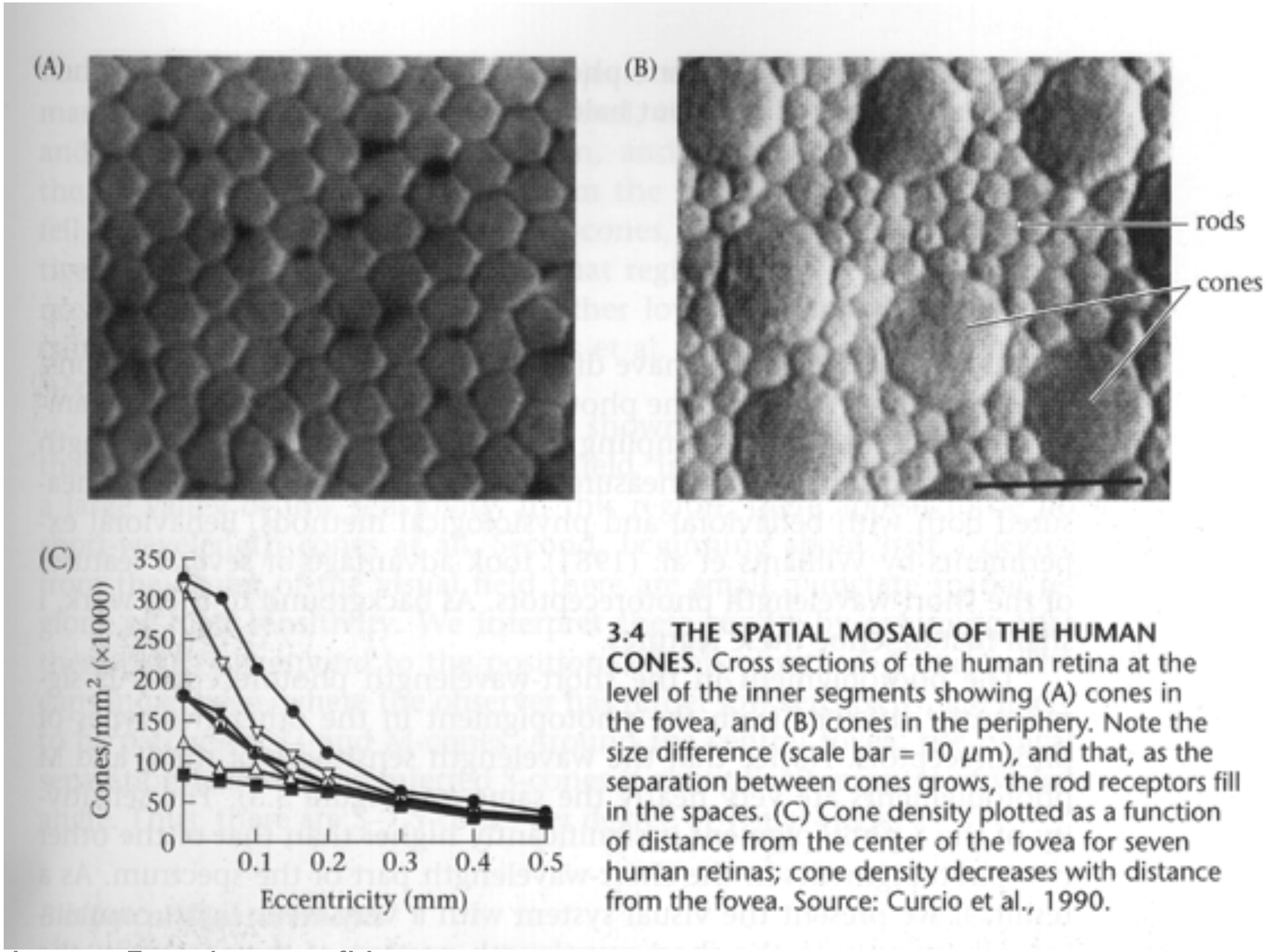
Receptors Density - Fovea

The fovea itself is the central portion of the macula, which is responsible for central vision. A large proportion of the striate cortex is devoted to processing information from the fovea.



Slide credit: S. Ullman

Human Photoreceptors



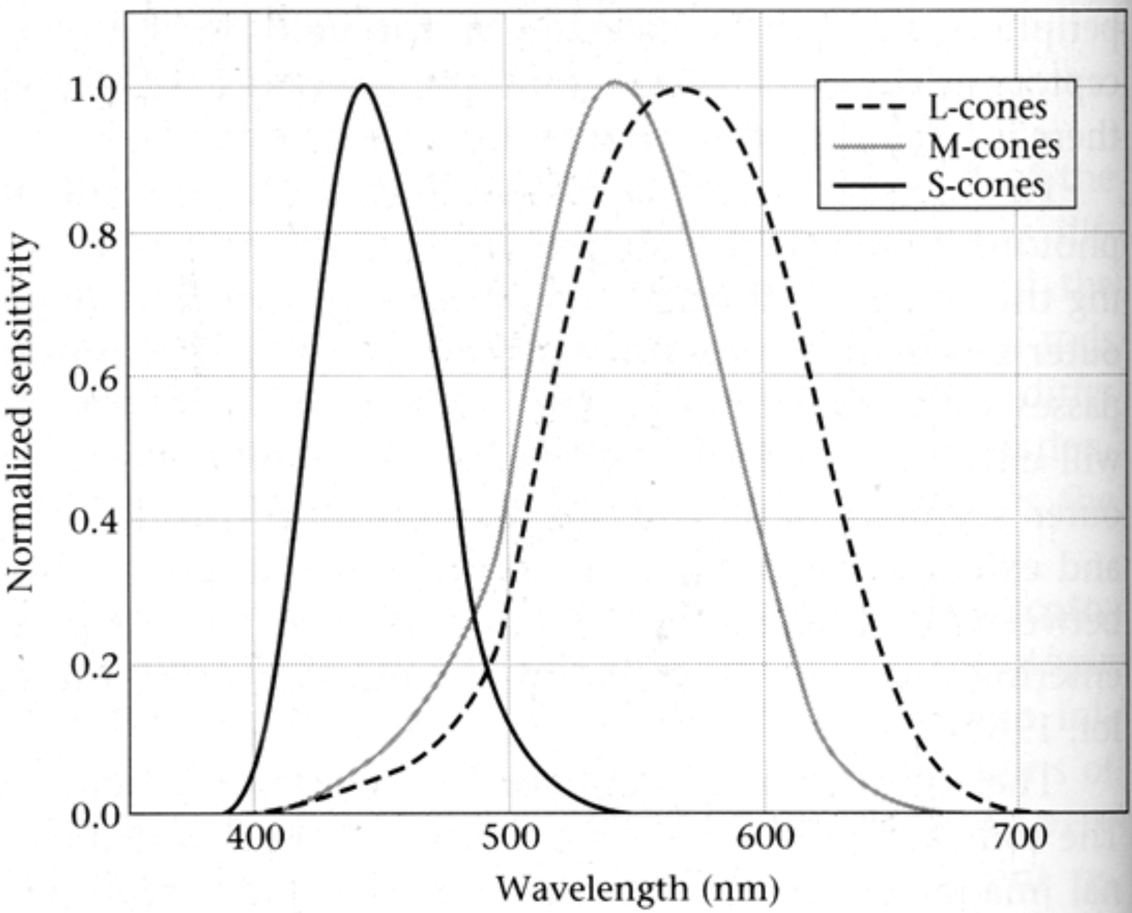
3.4 THE SPATIAL MOSAIC OF THE HUMAN CONES. Cross sections of the human retina at the level of the inner segments showing (A) cones in the fovea, and (B) cones in the periphery. Note the size difference (scale bar = 10 μm), and that, as the separation between cones grows, the rod receptors fill in the 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

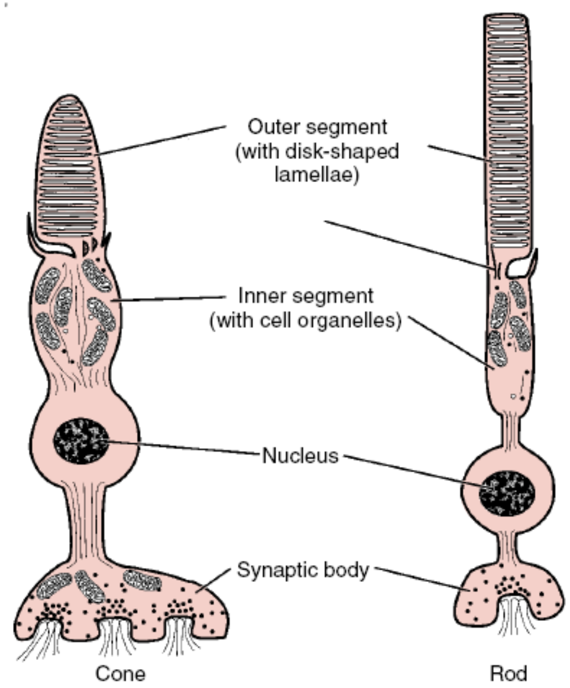
Two types of light-sensitive receptors

Cones cone-shaped less sensitive

operate in high light color vision

Rods rod-shaped highly sensitive

operate at night gray-scale vision



Rods are responsible for intensity, cones for color perception

Rods and cones are <u>non-uniformly</u> distributed on the retina

Images by Shimon Ullman

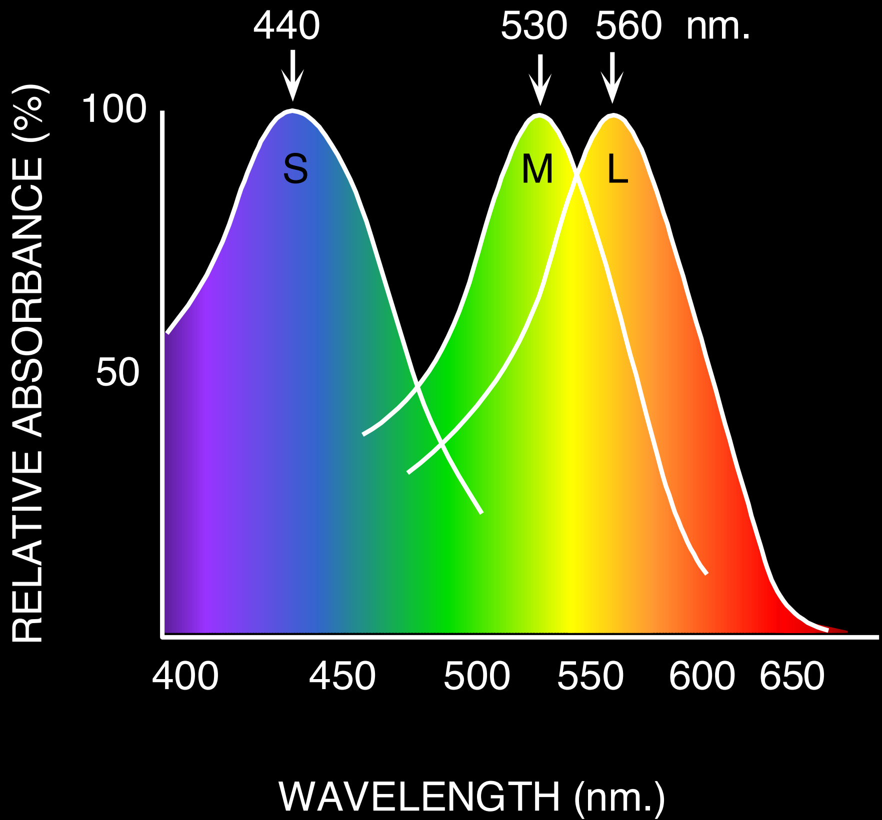
Slide credit: A. Efros

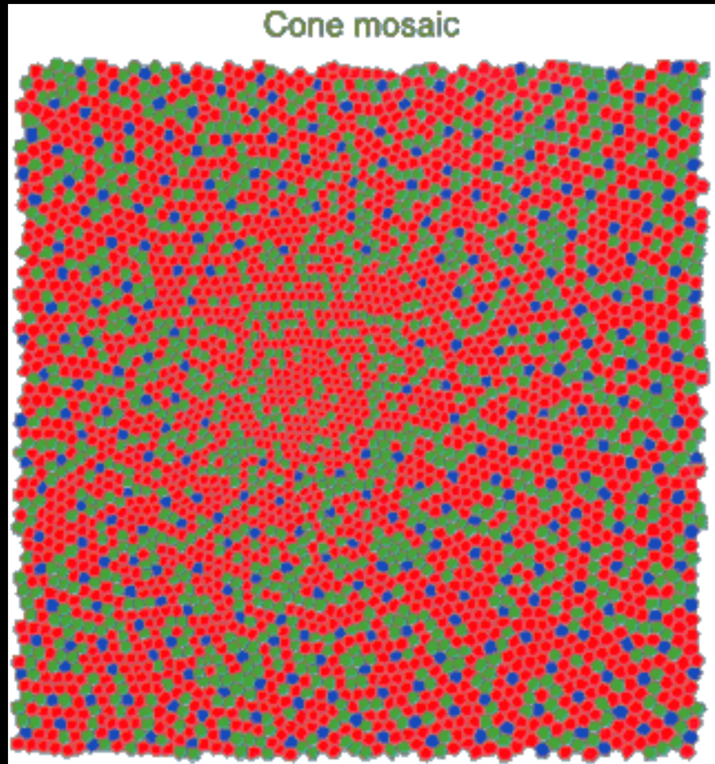
Rod / Cone sensitivity

Properties of Rod and Cone Systems		
Rods	**Cones**	**Comment**
More photopigment	Less photopigment	
Slow response: long integration time	Fast response: short integration time	Temporal integration
High amplification	Less amplification	Single quantum detection in rods (Hecht, Schlaer & Pirenne)
Saturating Response (by 6% bleached)	Non-saturating response (except S-cones)	The rods' response saturates when only a small amount of the pigment is bleached (the absorption of a photon by a pigment molecule is known as bleaching the pigment).
Not directionally selective	Directionally selective	Stiles-Crawford effect (see later this chapter)
Highly convergent retinal pathways	Less convergent retinal pathways	Spatial integration
High sensitivity	Lower absolute sensitivity	
Low acuity	High acuity	Results from degree of spatial integration
Achromatic: one type of pigment	Chromatic: three types of pigment	Color vision results from comparisons between cone responses

Physiology of Color Vision

Three kinds of cones:

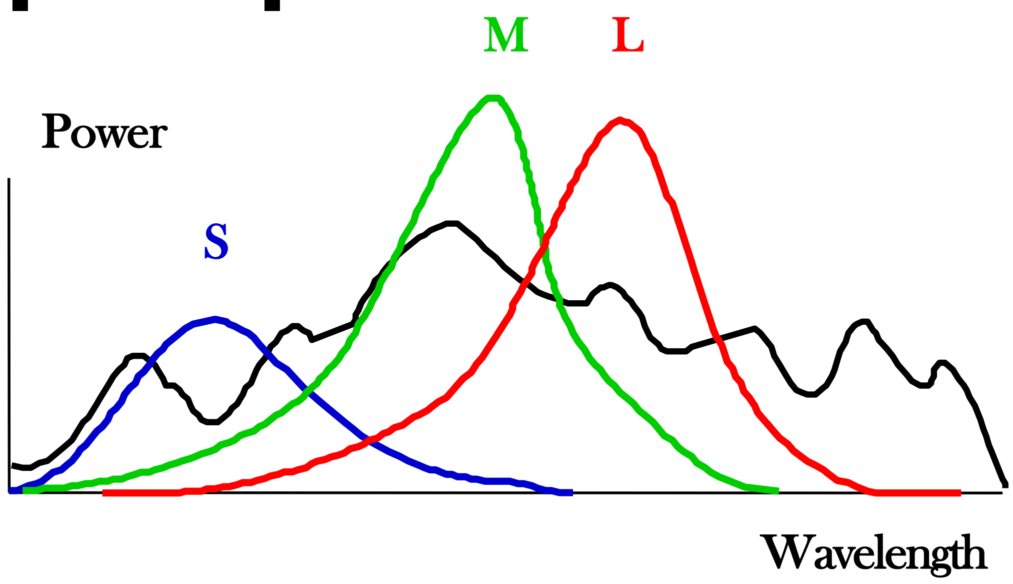




- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea

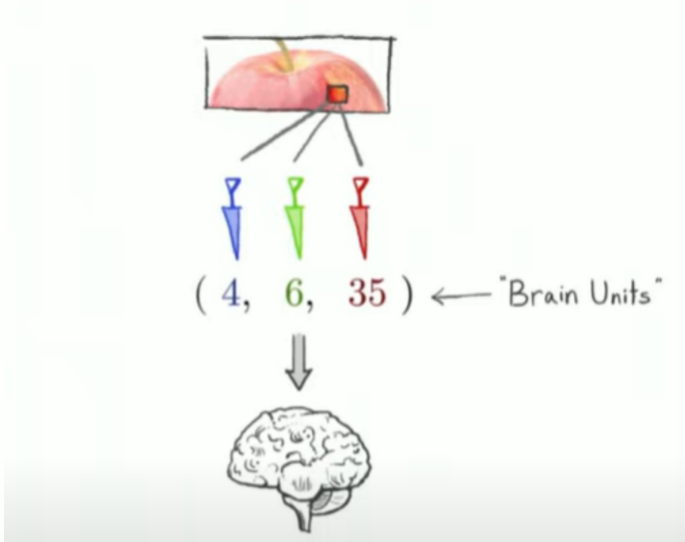
Slide credit: A. Efros

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



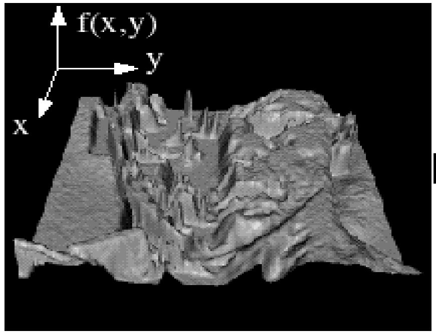
Q: How can we represent an entire spectrum with 3 numbers?A: We can't! Most of the information is lost.

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.

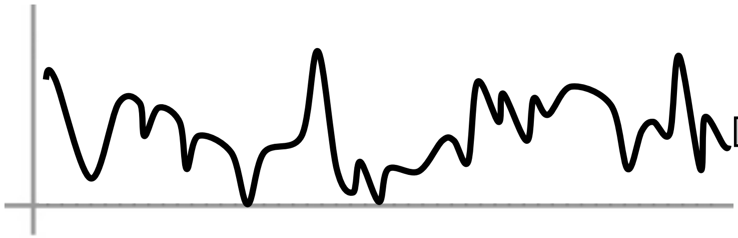


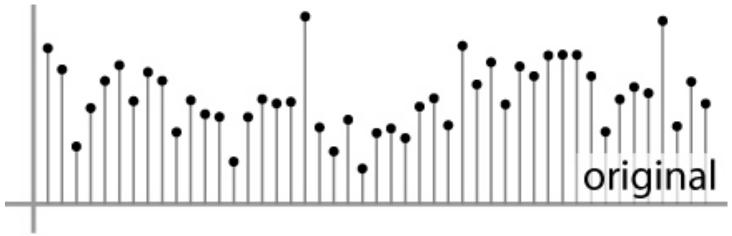
j

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

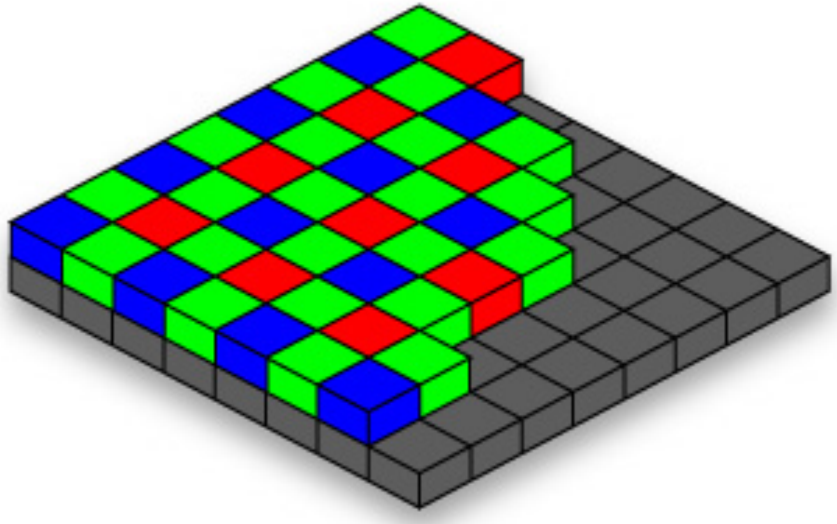


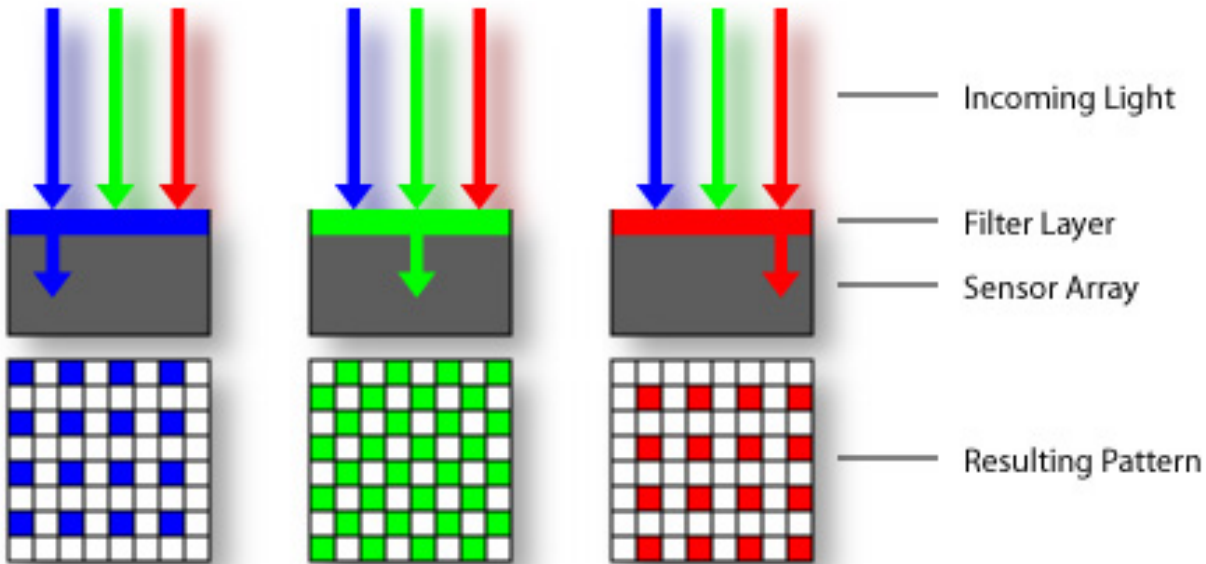


1D

Slide credit: K. Grauman, S. Seitz

Color Images: Bayer Grid





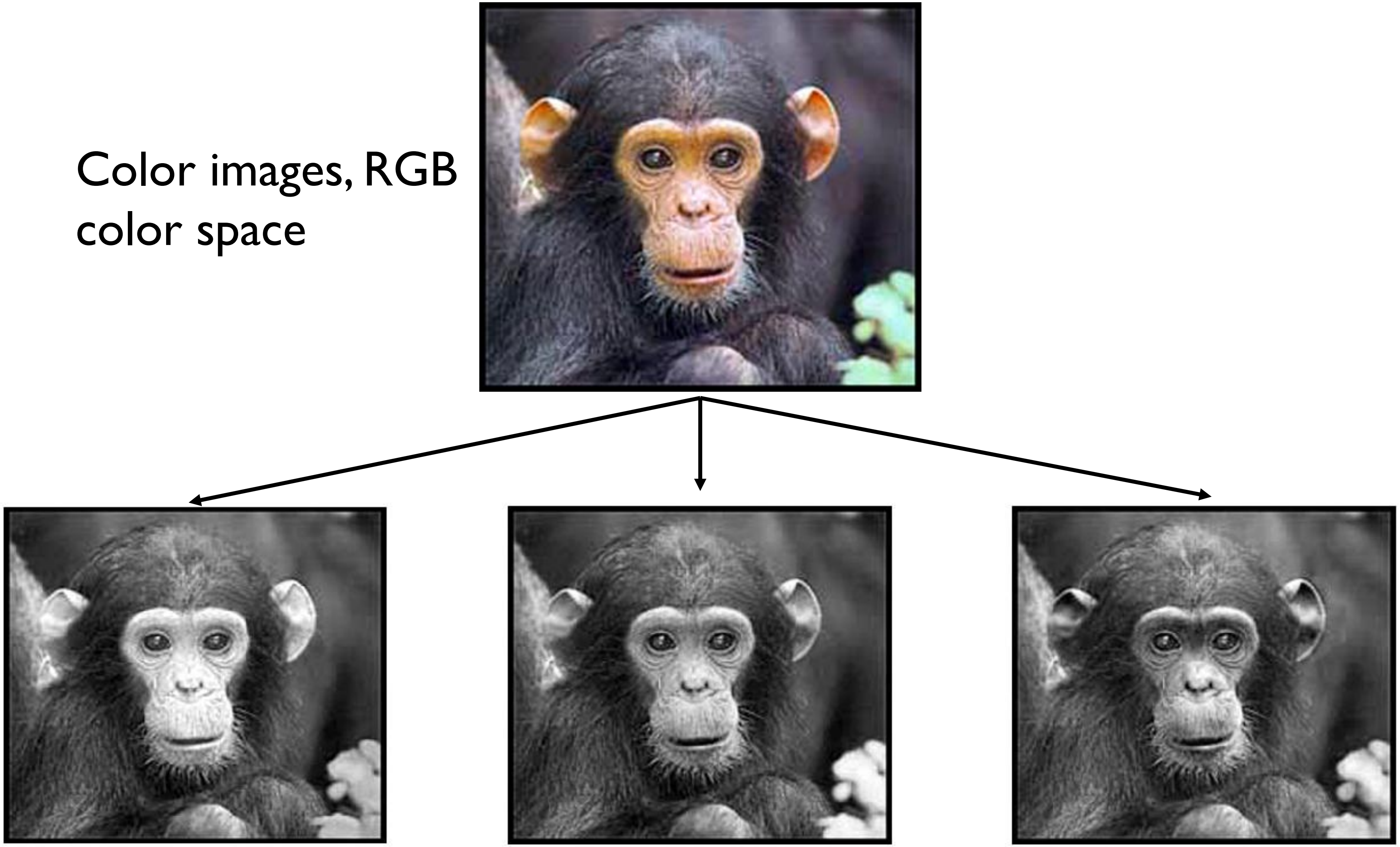
- Estimate RGB at 'G' cells from neighboring values

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

Slide credit: S. Seitz

Digital color images

Color images, RGB color space

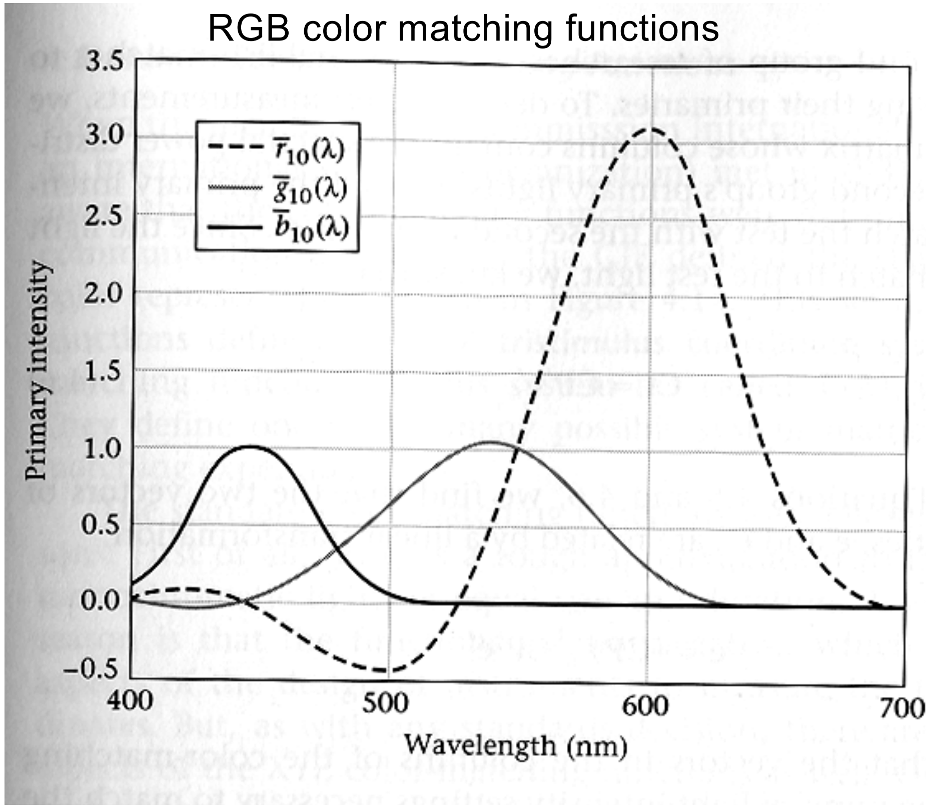


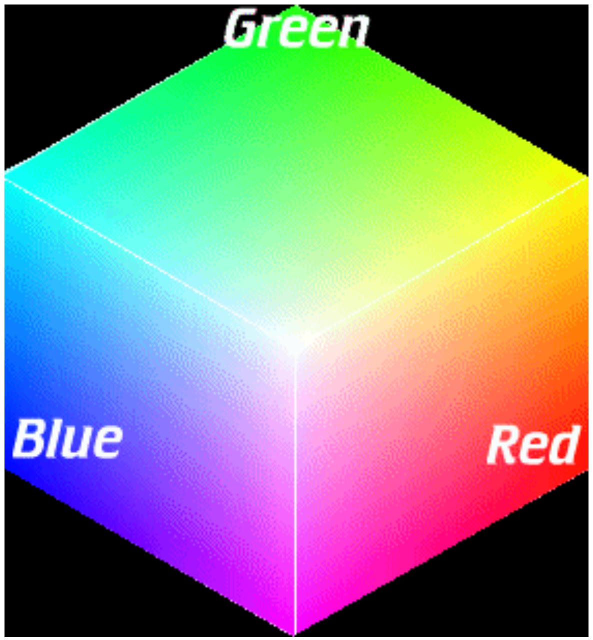
R G B

Slide credit: K. Grauman

Color spaces: RGB

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

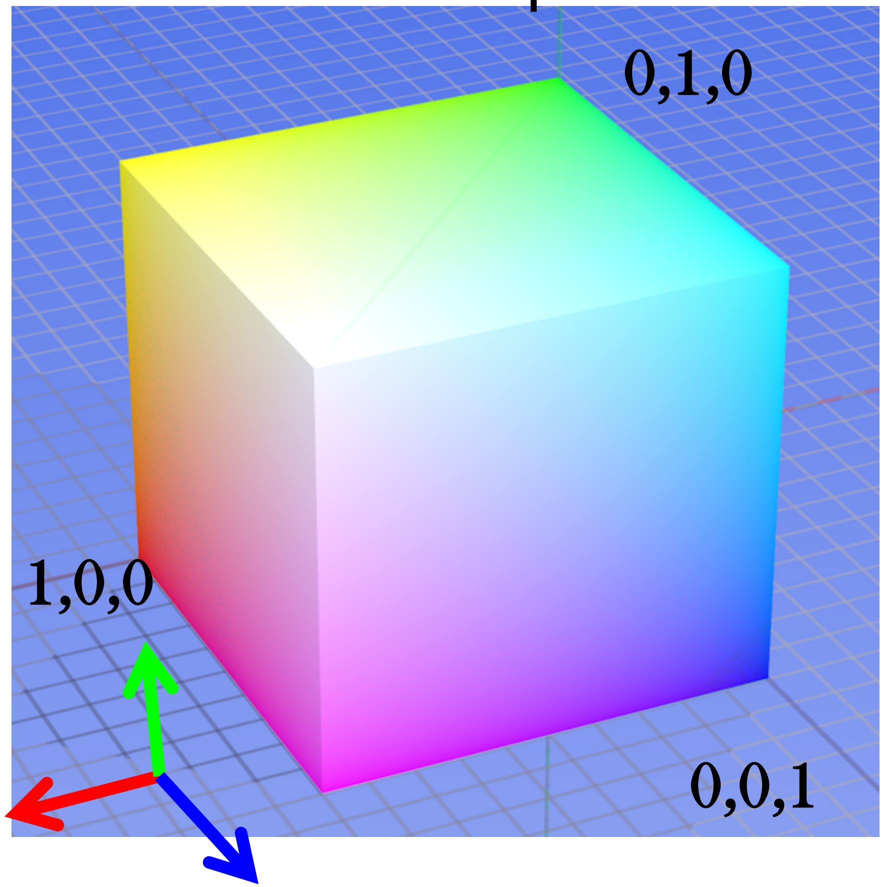




Slide credit: K. Grauman, S. Marschner

Color spaces: RGB

Default color space



R
(G=0,B=0)

G
(R=0,B=0)

B
(R=0,G=0)

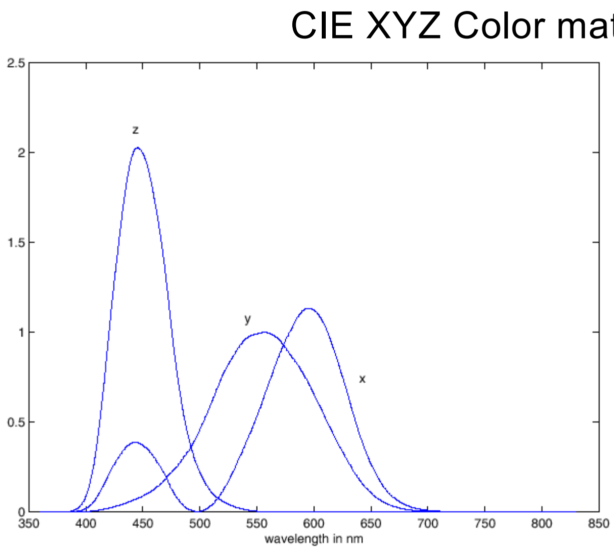
Some drawbacks
- Strongly correlated channels
- Non-perceptual

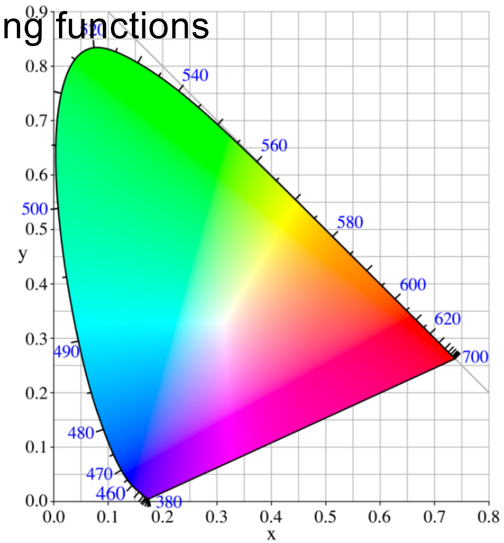
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

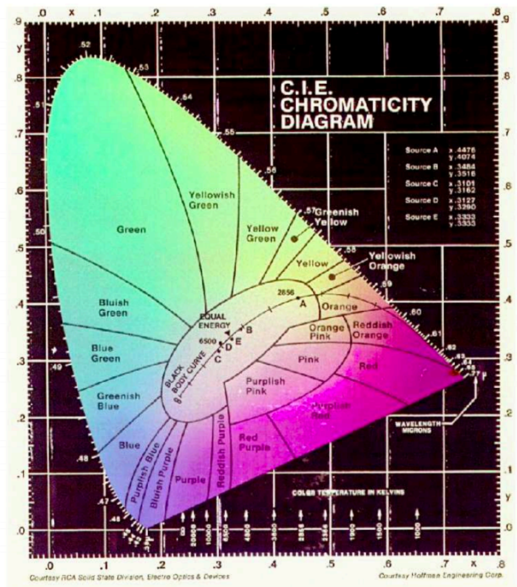
Slide credit: D. Hoiem

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







Slide credit: K. Grauman, S. Marschner

Color spaces: CIE XYZ

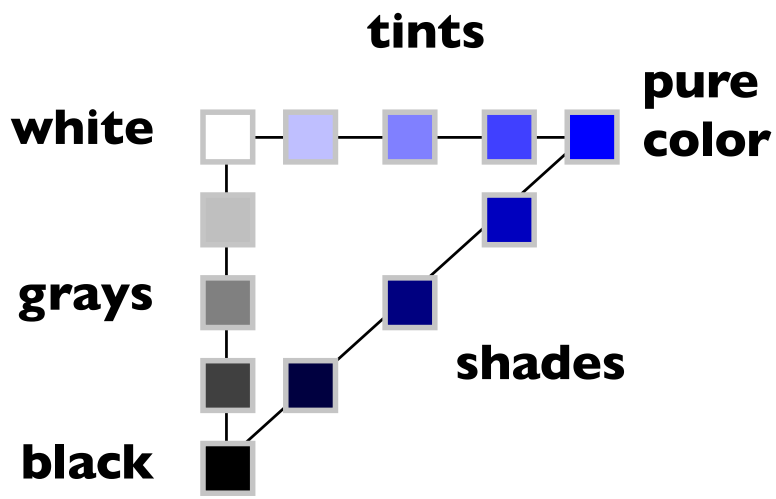
- Standardized by CIE (*Commission Internationale de l'Eclairage*, the standards organization for color science)
- Based on three "imaginary" primaries **X**, **Y**, and **Z**
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: **X**, **Z** have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



[after Foley et al.]

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

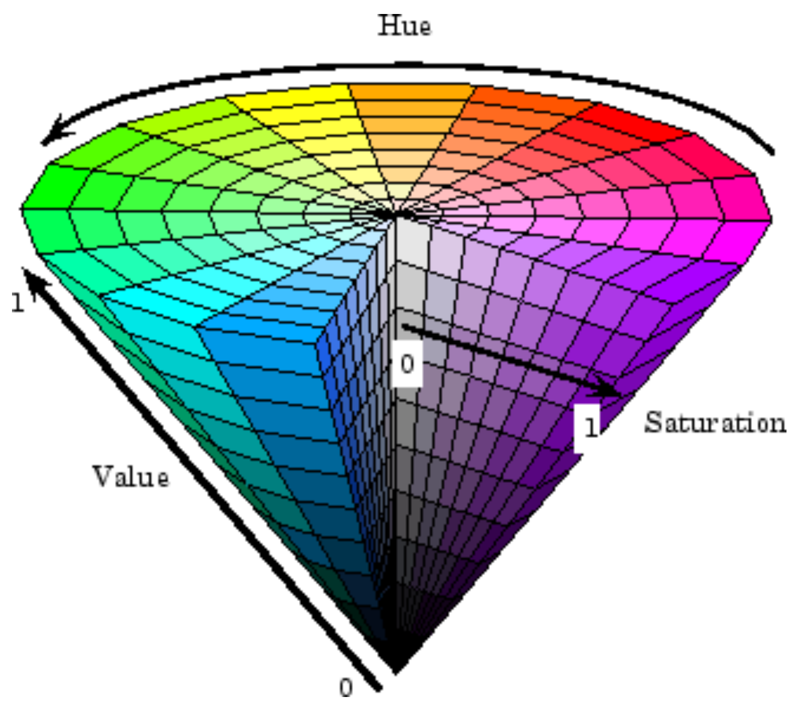
Perceptual dimensions of color

- 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



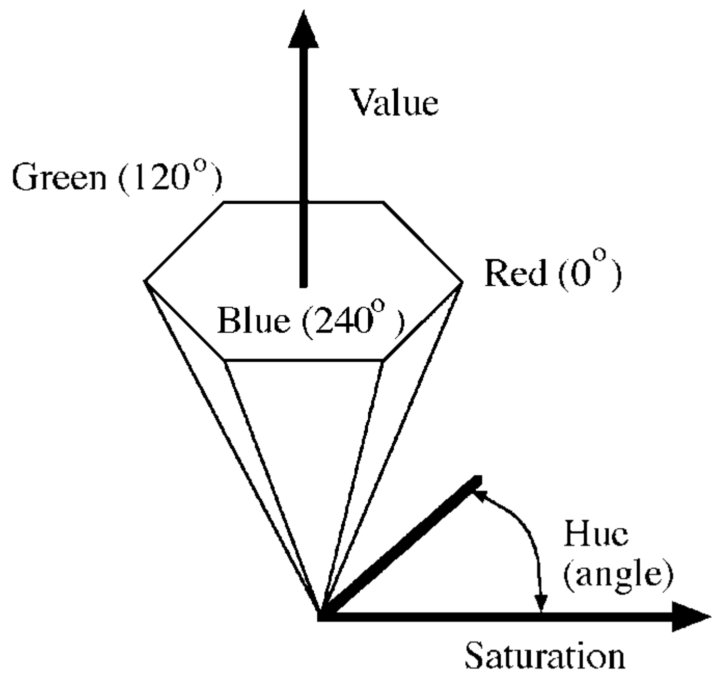
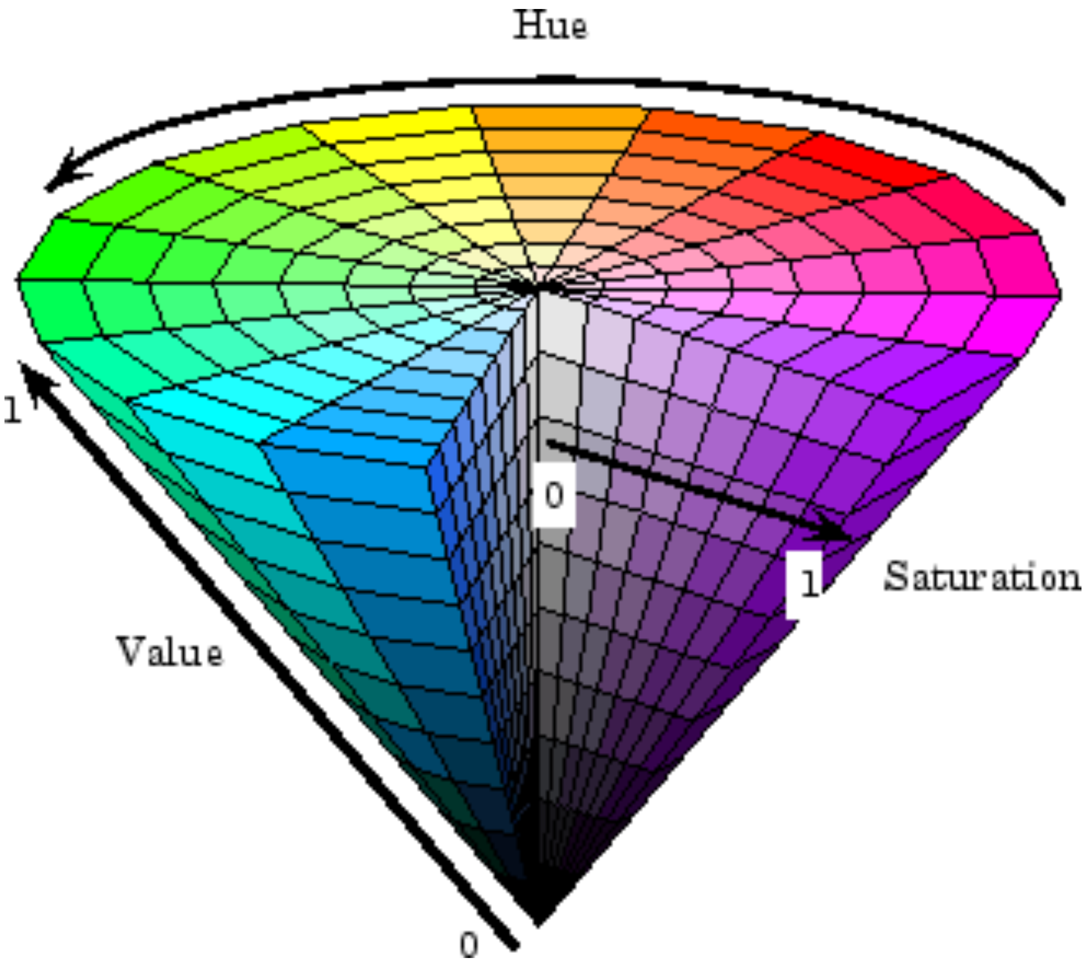


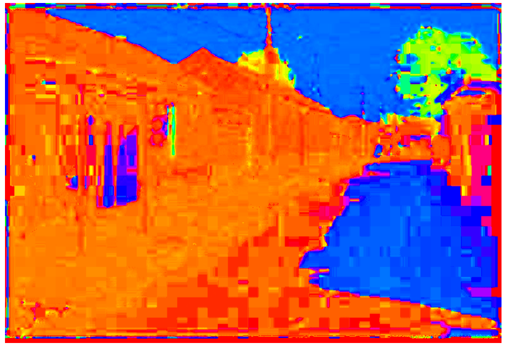
Image from mathworks.com

Slide credit: K. Grauman

Color spaces: HSV

Intuitive color space





H

(S=1,V=1)

S

(H=1,V=1)

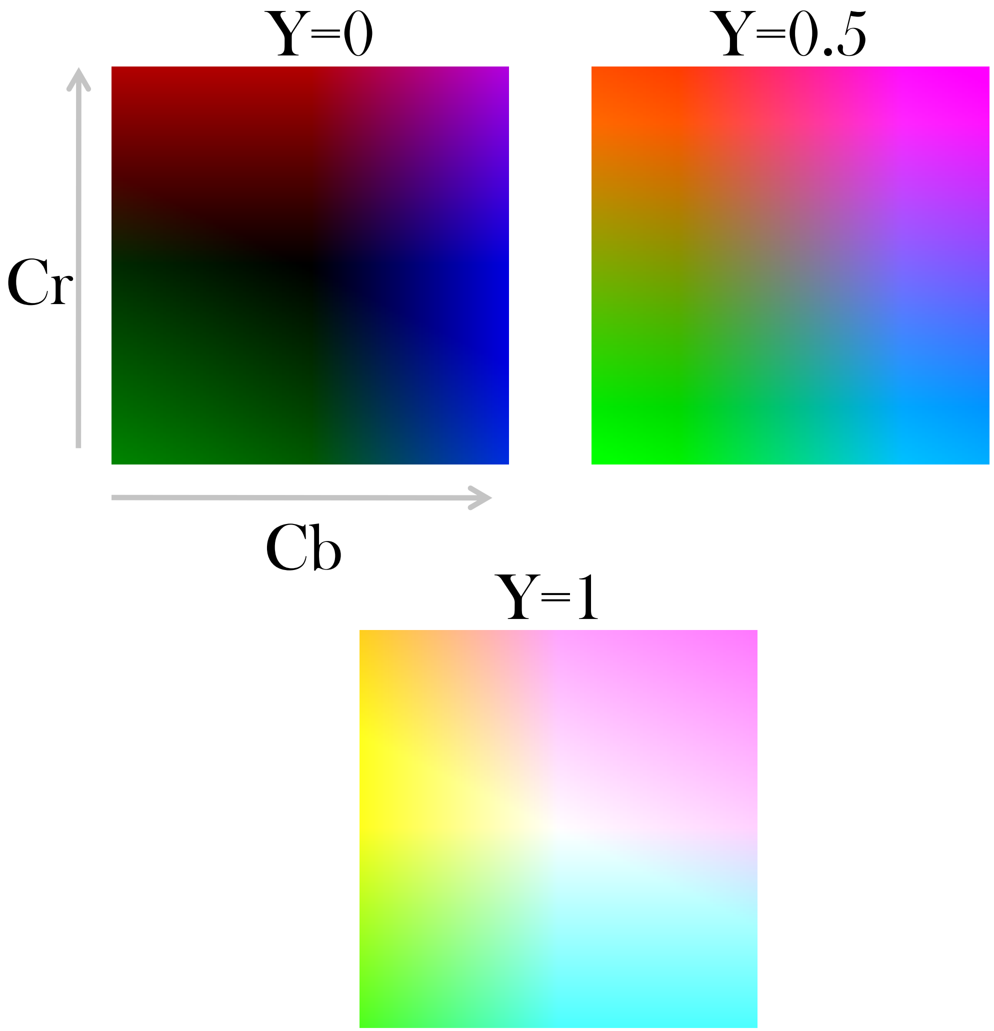
V

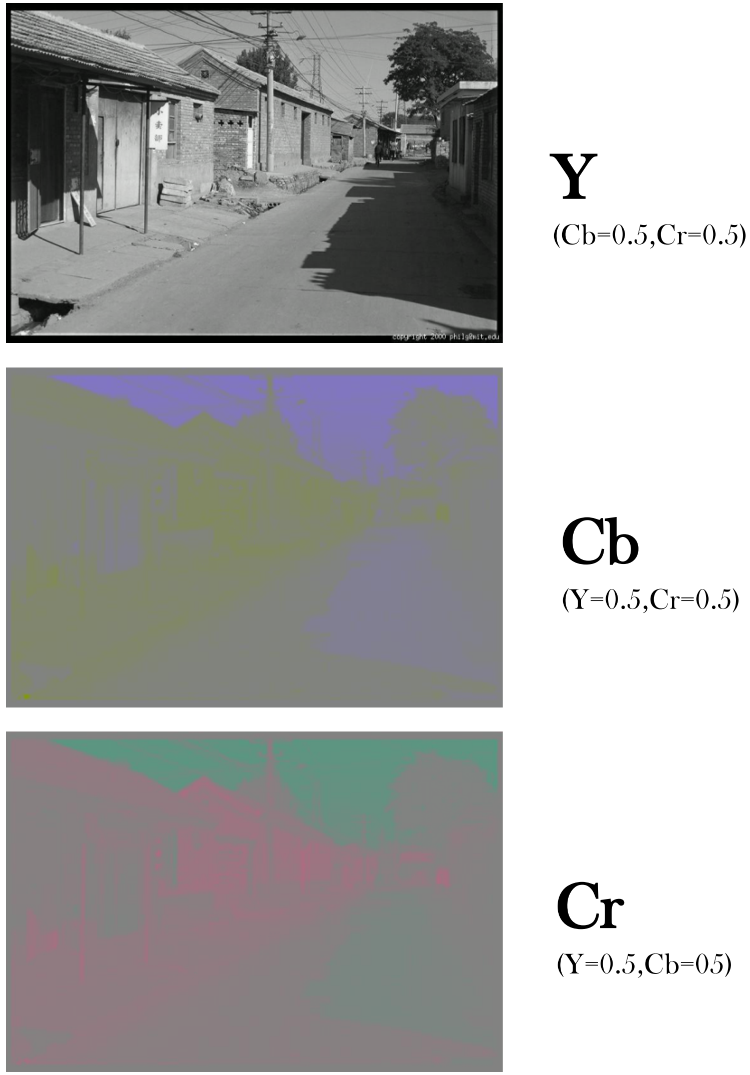
(H=1,S=0)

Slide credit: D. Hoiem

Color spaces: YCbCr

Fast to compute, good for compression, used by TV



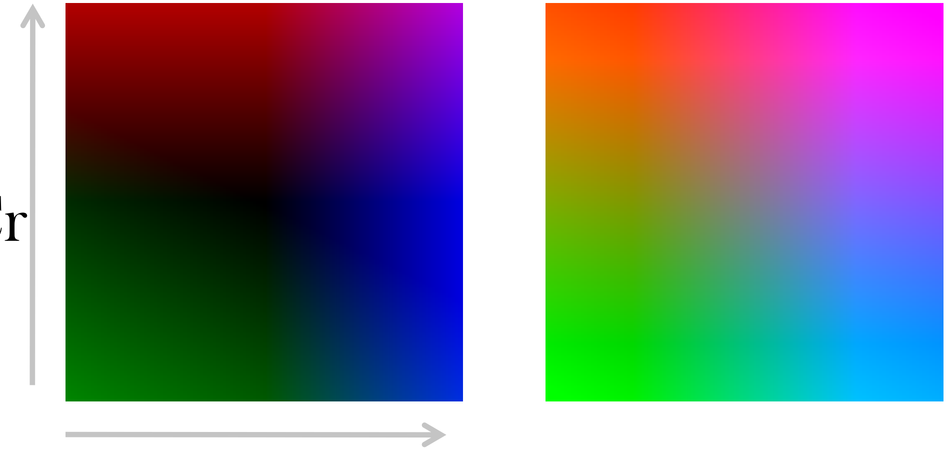


Slide credit: D. Hoiem

Color spaces: YCbCr

Fast to compute, good for compression, used by TV

Y=0 Y=0.5



Cr

Cb

Y

(Cb=0.5,Cr=0.5)

Cb

(Y=0.5,Cr=0.5)

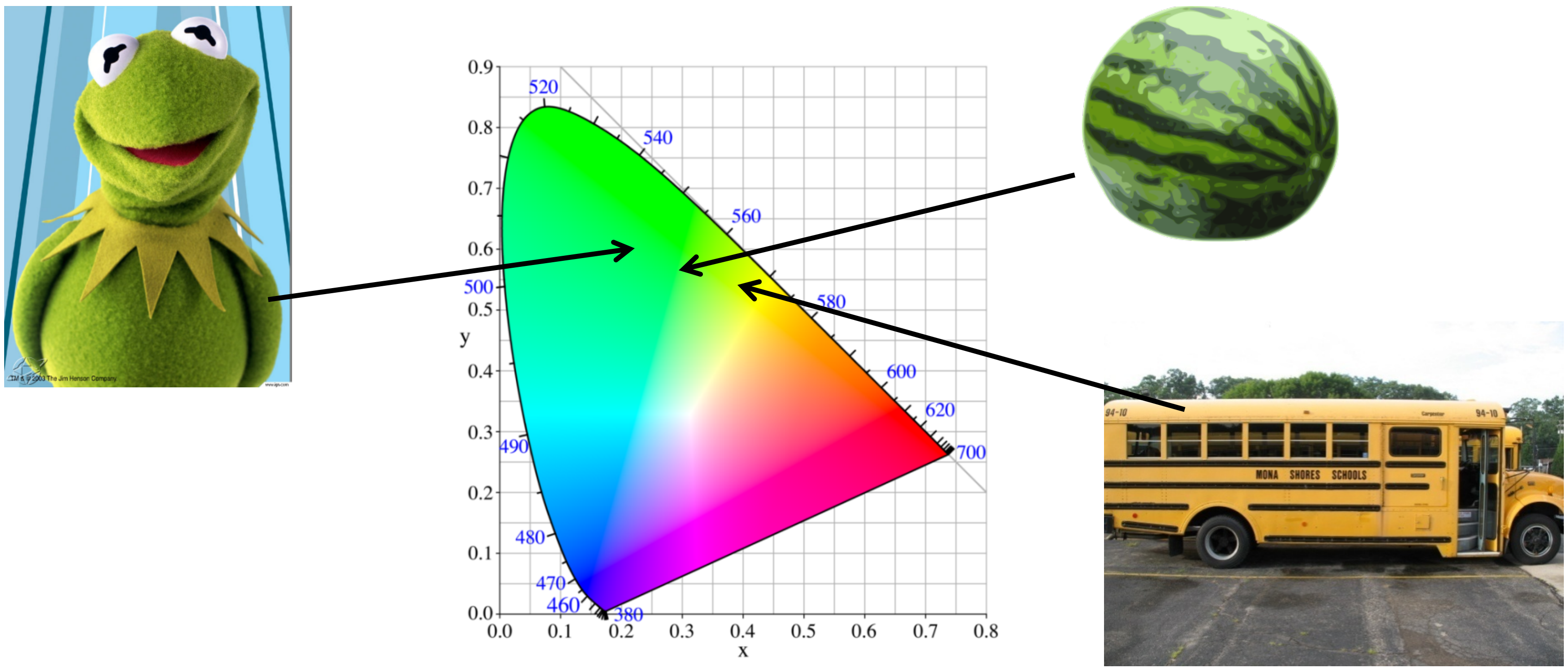
Y=1

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

Slide credit: D. Hoiem

Distances in color space

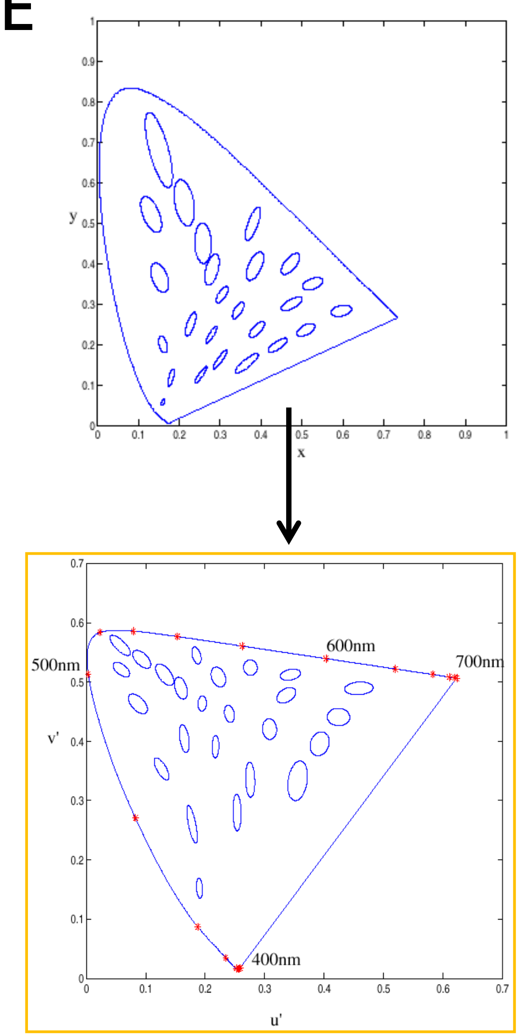
- Are distances between points in a color space perceptually meaningful?



Slide credit: K. Grauman

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



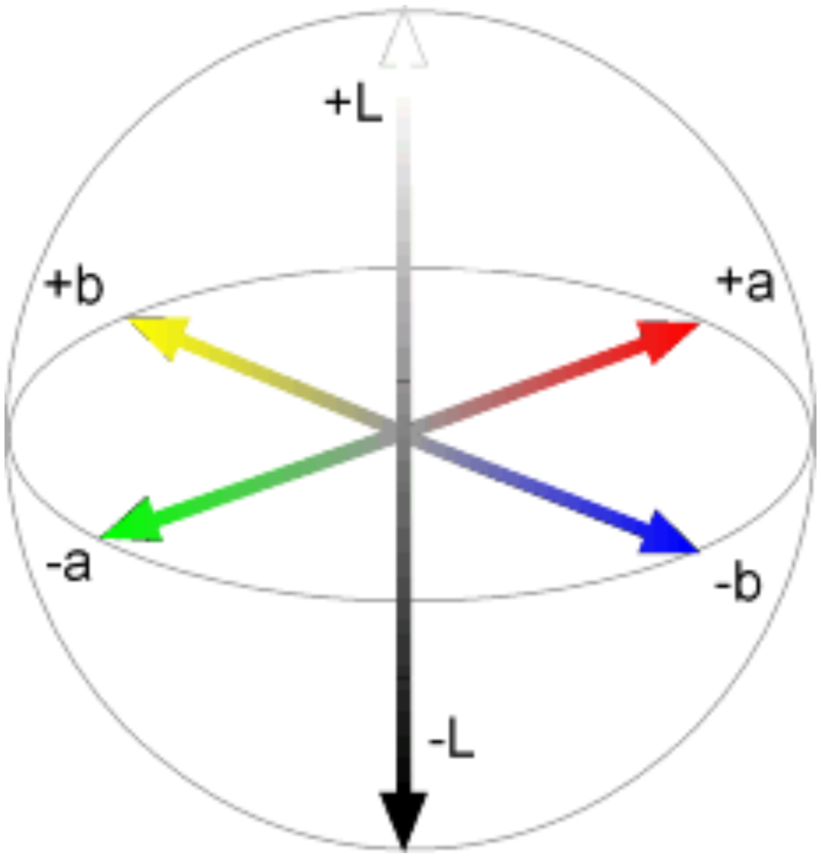
CIE XYZ

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)

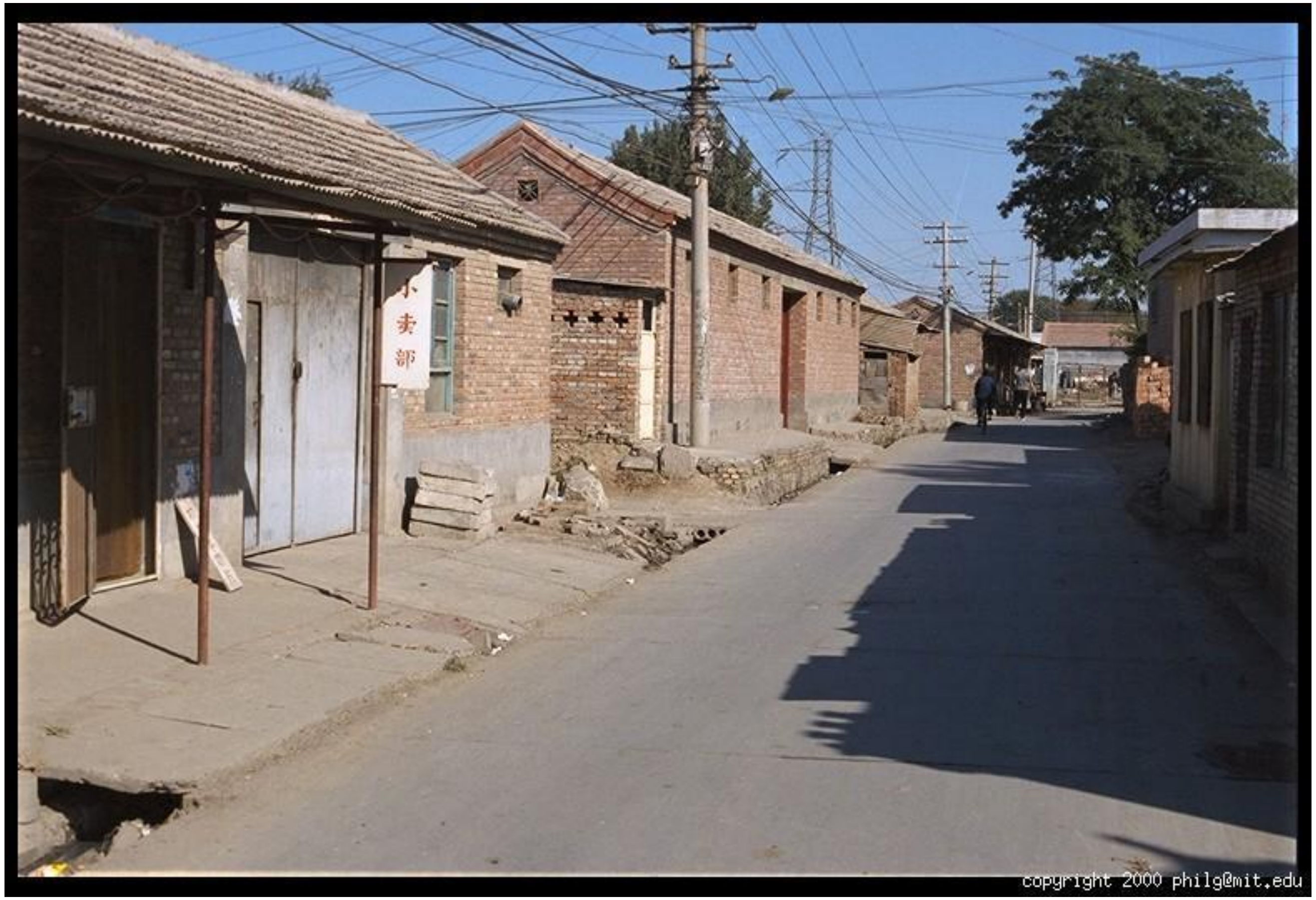
Slide credit: D. Hoiem

Most information in intensity

Only intensity shown – constant color

Slide credit: D. Hoiem

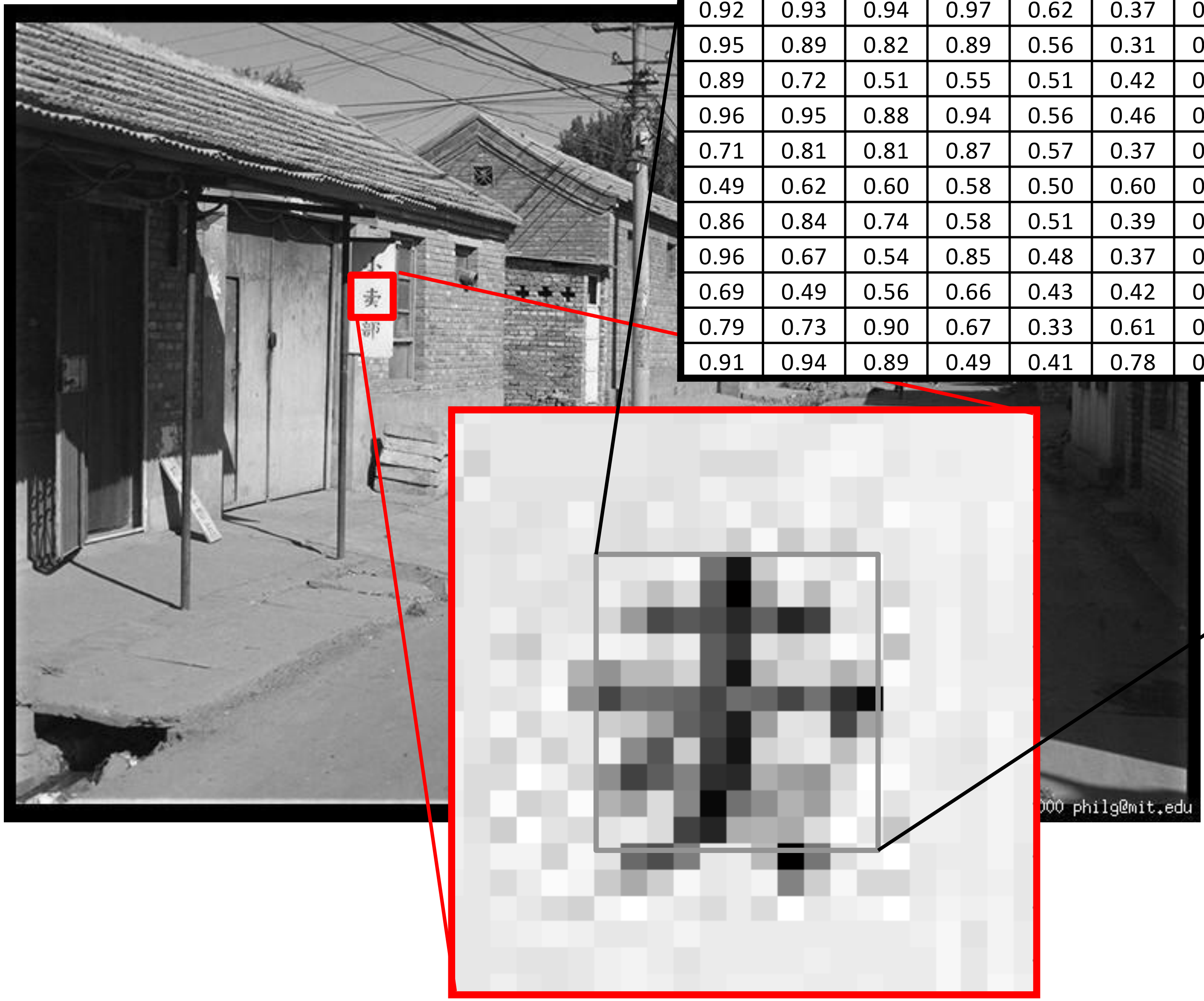
Most information in intensity



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

Today

- Perception of color and light
- Color spaces

Next week

- Point operations
- Histogram processing

Reading Assignment

- Watch Beau Lotto's TED talk on "Optical illusions show how we see"
- Prepare a 1-page summary of the talk
- Due on 4th of MAch

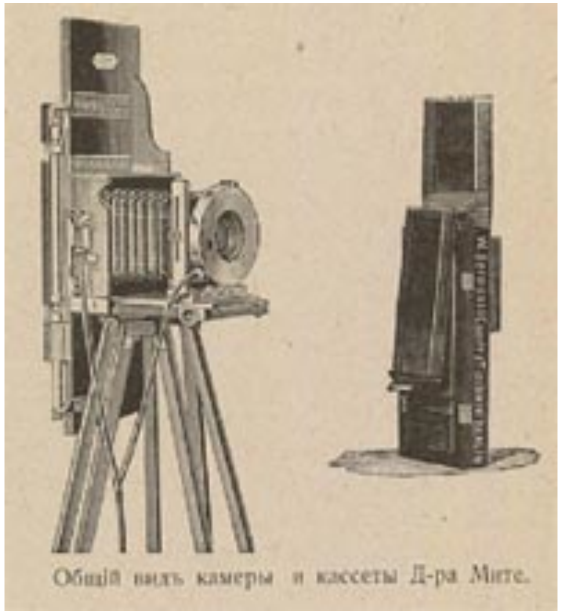
TED Ideas worth spreading

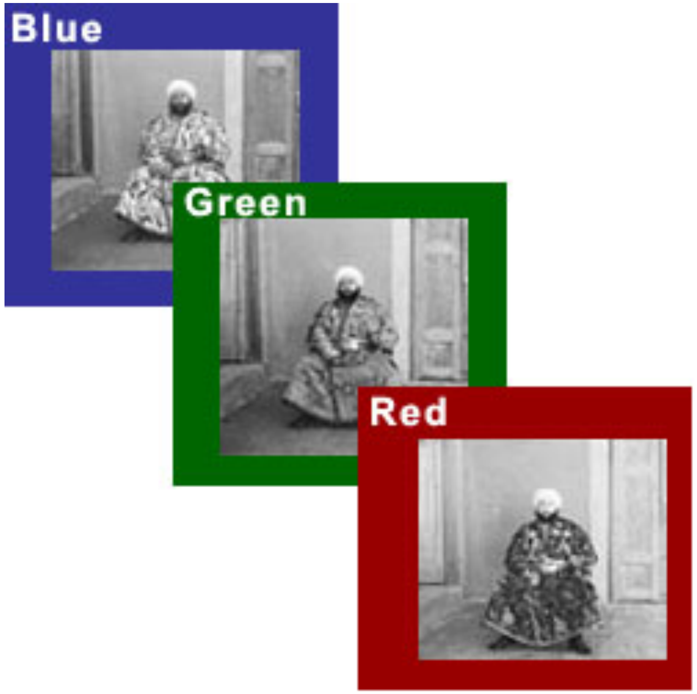
Programming assignment

- Colorizing the Prokudin-Gorskii photo collection
- A 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





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.