Chapter 4

Light and Color Capture

James Hays, Brown University

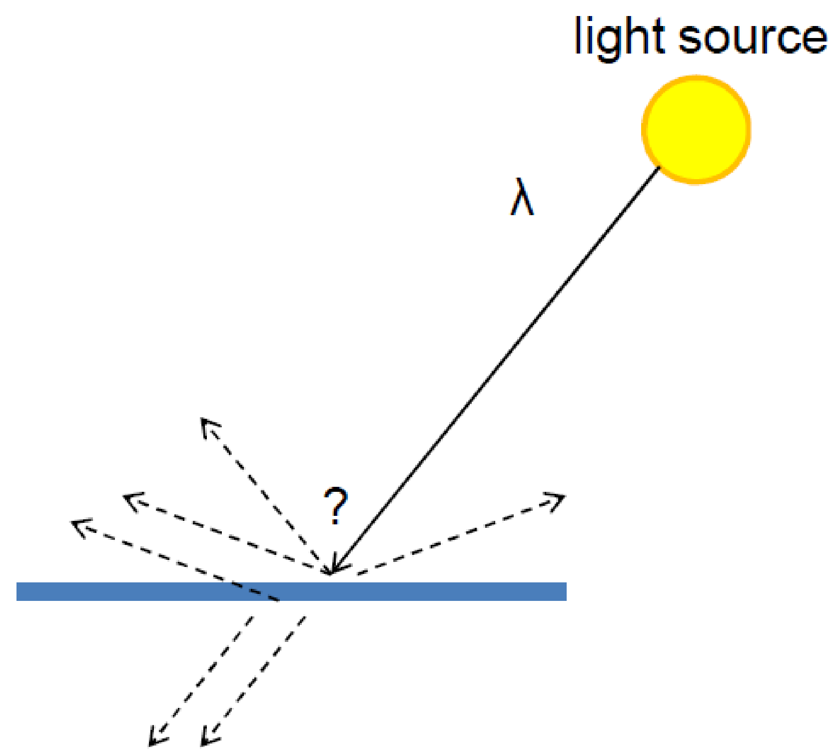
Contents

- **Review of lighting**
  - **Color, Reflection, and absorption**

- **What is a pixel? How is an image represented?**
  - **Color spaces**

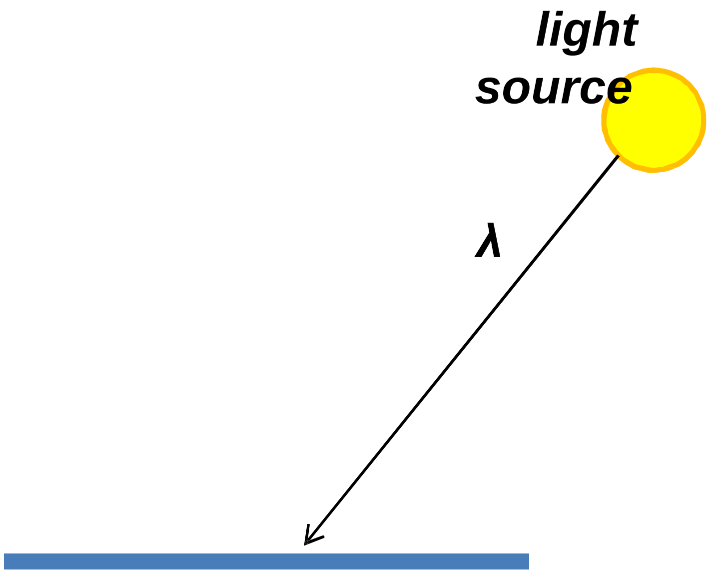
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



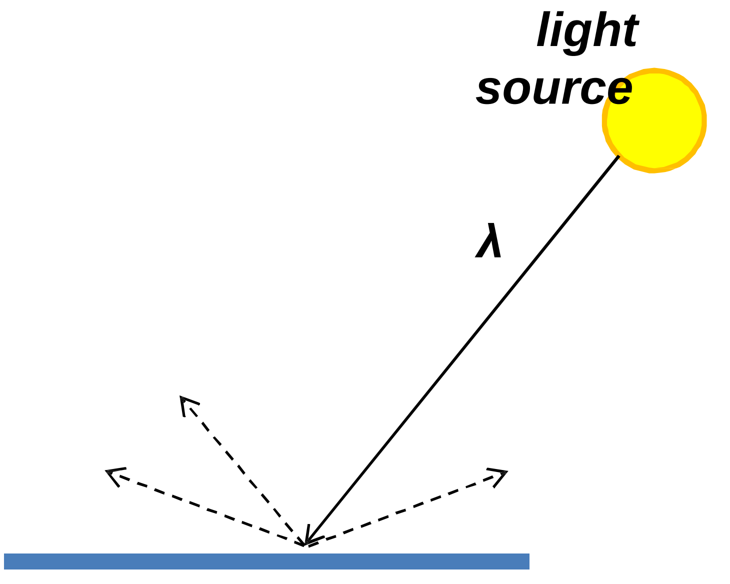
A photon's life choices

- **Absorption**
- *Diffusion*
- *Reflection*
- *Transparency*
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- *Phosphorescence*
- *Interreflection*



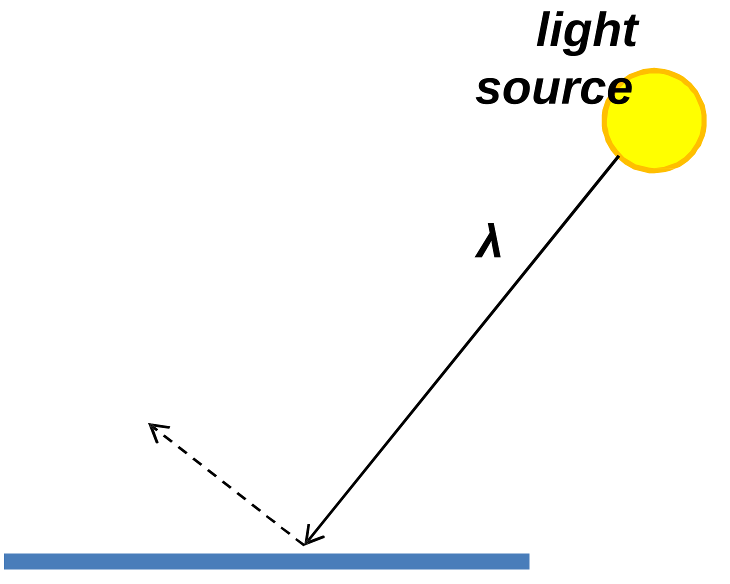
A photon's life choices

- *Absorption*
- **Diffuse Reflection**
- *Reflection*
- *Transparency*
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- *Phosphorescence*
- *Interreflection*



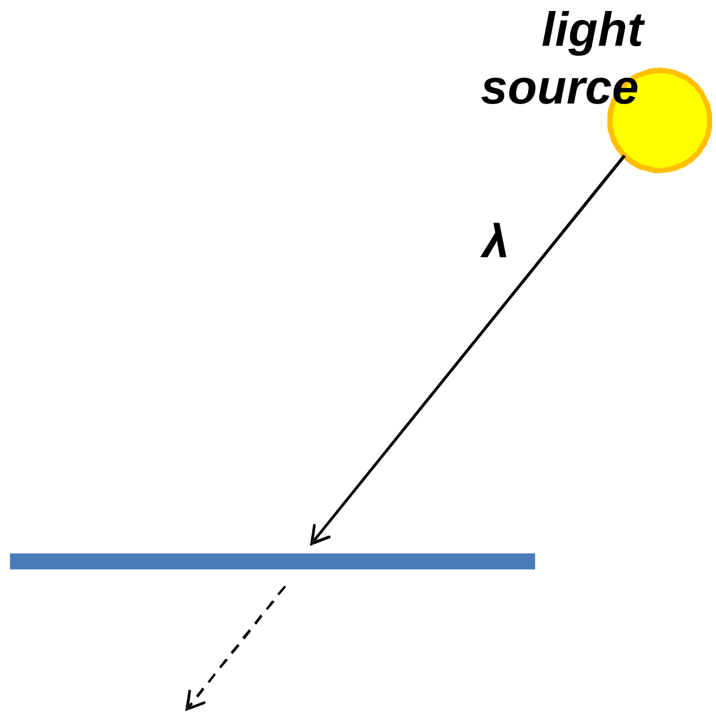
A photon's life choices

- *Absorption*
- *Diffusion*
- **Specular Reflection**
- *Transparency*
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- *Phosphorescence*
- *Interreflection*



A photon's life choices

- *Absorption*
- *Diffusion*
- *Reflection*
- **Transparency**
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- *Phosphorescence*
- *Interreflection*



A photon's life choices

- *Absorption*
- *Diffusion*
- *Reflection*
- *Transparency*
- **Refraction**
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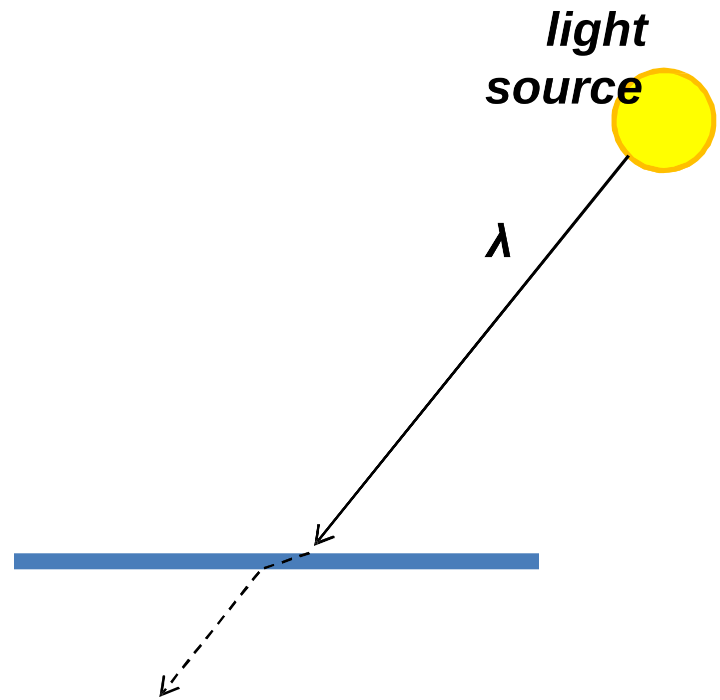

A photon's life choices

- *Absorption*
- *Diffusion*
- *Reflection*
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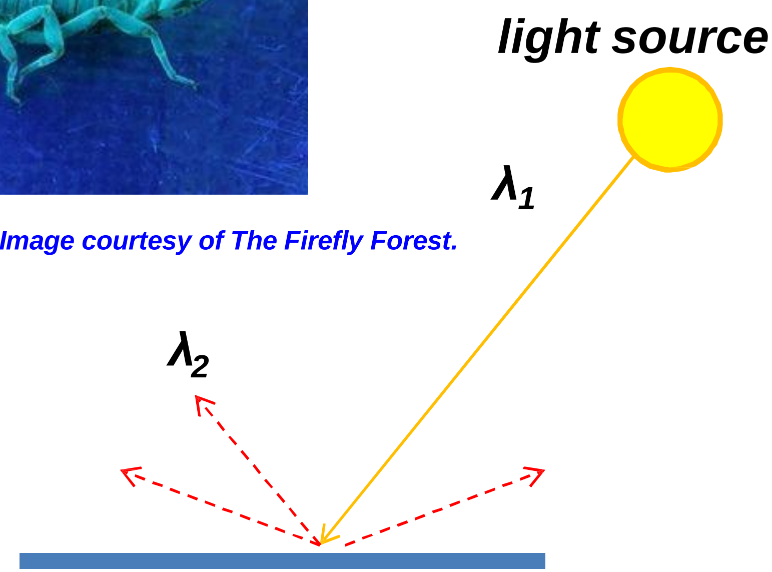
- **Fluorescence**
- *Subsurface scattering*
- *Phosphorescence*
- *Interreflection*

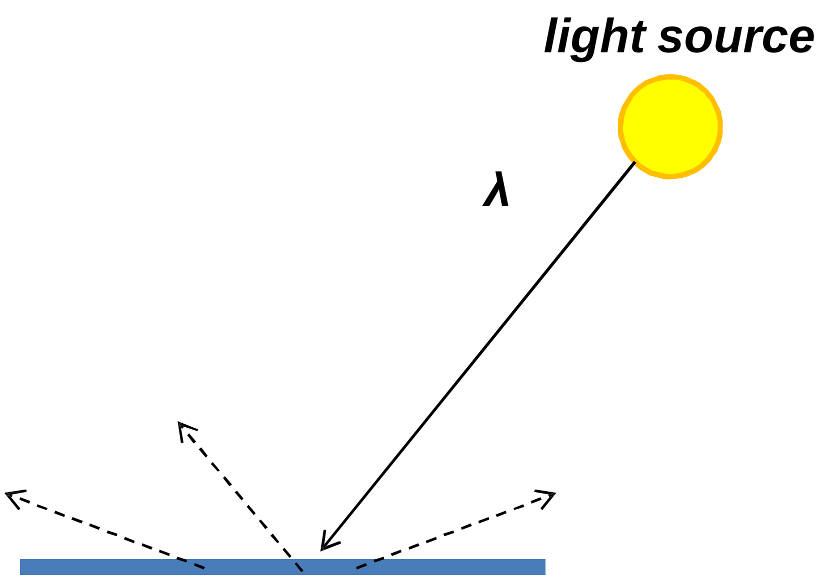
Fluorescent scorpion. Image courtesy of The Firefly Forest.



Fluorescence occurs when a substance absorbs radiation of one wavelength, and immediately emits radiation of a different wavelength.

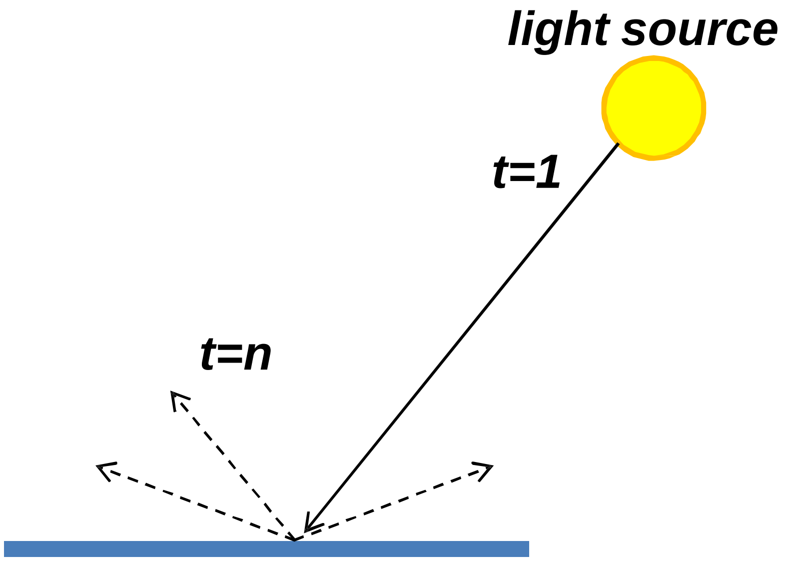
A photon's life choices

- *Absorption*
- *Diffusion*
- *Reflection*
- *Transparency*
- *Refraction*
- *Fluorescence*
- **Subsurface scattering**
- *Phosphorescence*
- *Interreflection*



A photon's life choices

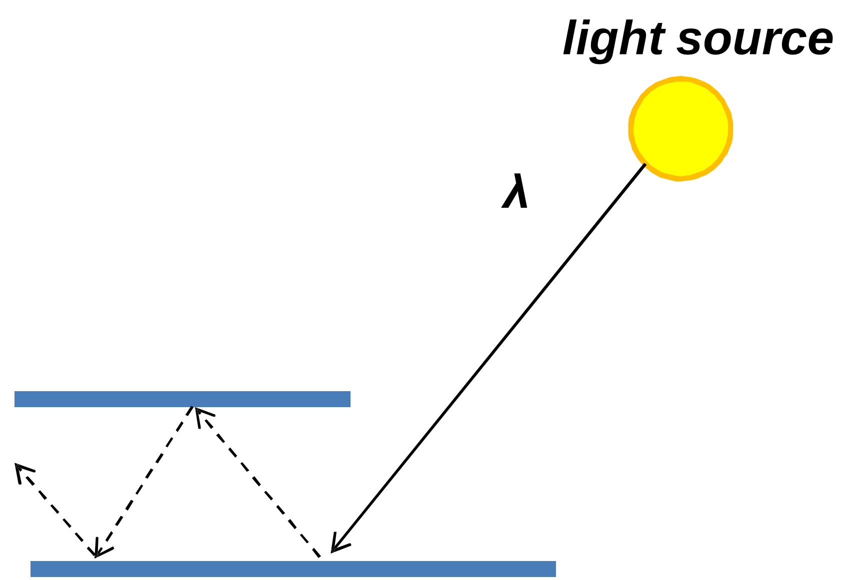
- *Absorption*
- *Diffusion*
- *Reflection*
- *Transparency*
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- **Phosphorescence**
- *Interreflection*



Phosphorescence is a related type of photoluminescence in which absorbed radiation is re-emitted more slowly, so phosphorescent objects can still glow for periods up to several hours after the source of incident radiation is removed.

A photon's life choices

- *Absorption*
- *Diffusion*
- *Reflection*
- *Transparency*
- *Refraction*
- *Fluorescence*
- *Subsurface scattering*
- *Phosphorescence*
- **Interreflection**



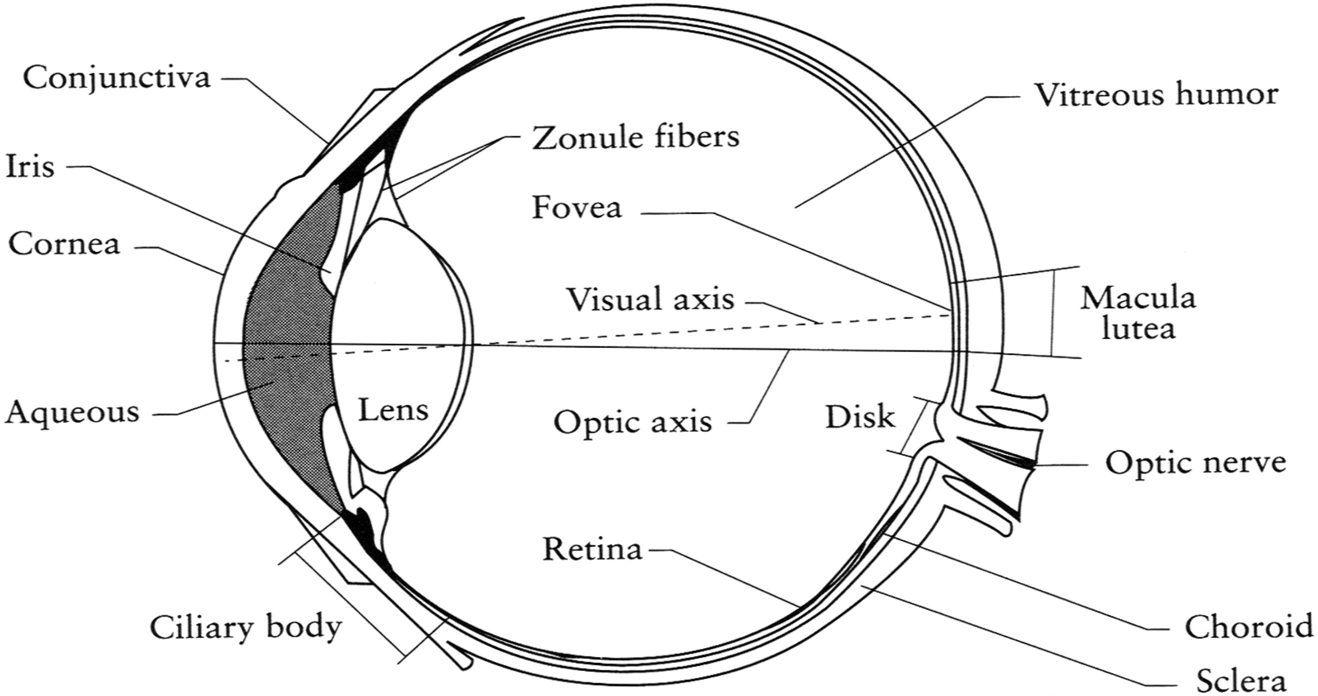
(Specular Interreflection)

The Eye

- ***Your eyes work a lot like a camera. The lens of a camera focuses light onto the film inside. The cornea and lens in the front of the eye focus light onto the back, where light-sensitive tissue called the retina is located. When the retina receives an image, it sends a signal through the optic nerve to the brain for the image to be developed.***

- ***http://www.healthline.com/vpvideo/vision***

The Eye

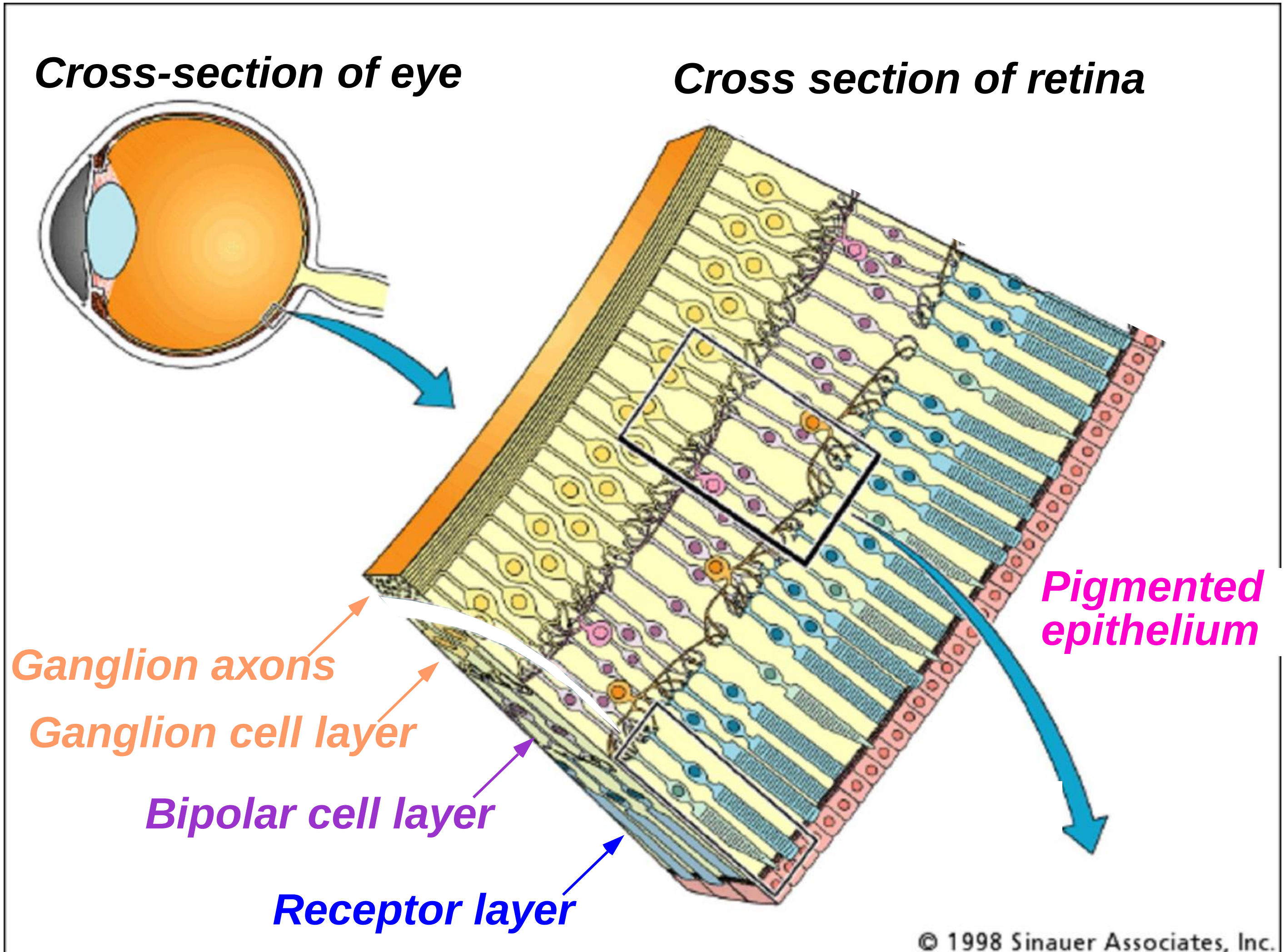


The human eye is a camera!

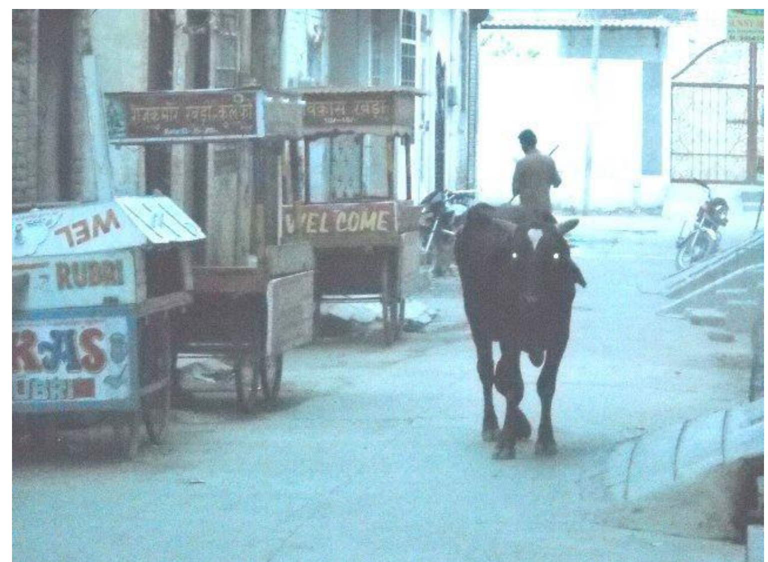
- ***Iris** - colored annulus with radial muscles*
- ***Pupil** - the hole (aperture) whose size is controlled by the iris*
- ***What's the "film"?***
  - ***photoreceptor cells (rods and cones) in the retina***

Slide by Steve Seitz

The Retina


Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.

What humans don’t have: tapetum lucidum



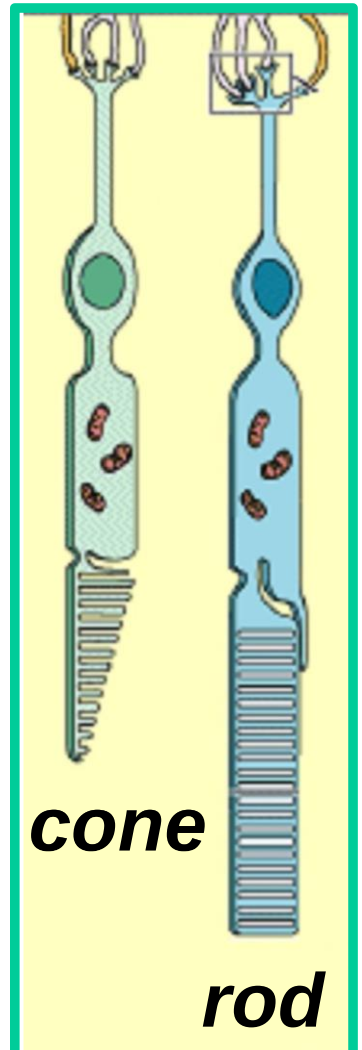
Two types of light-sensitive receptors

Cones

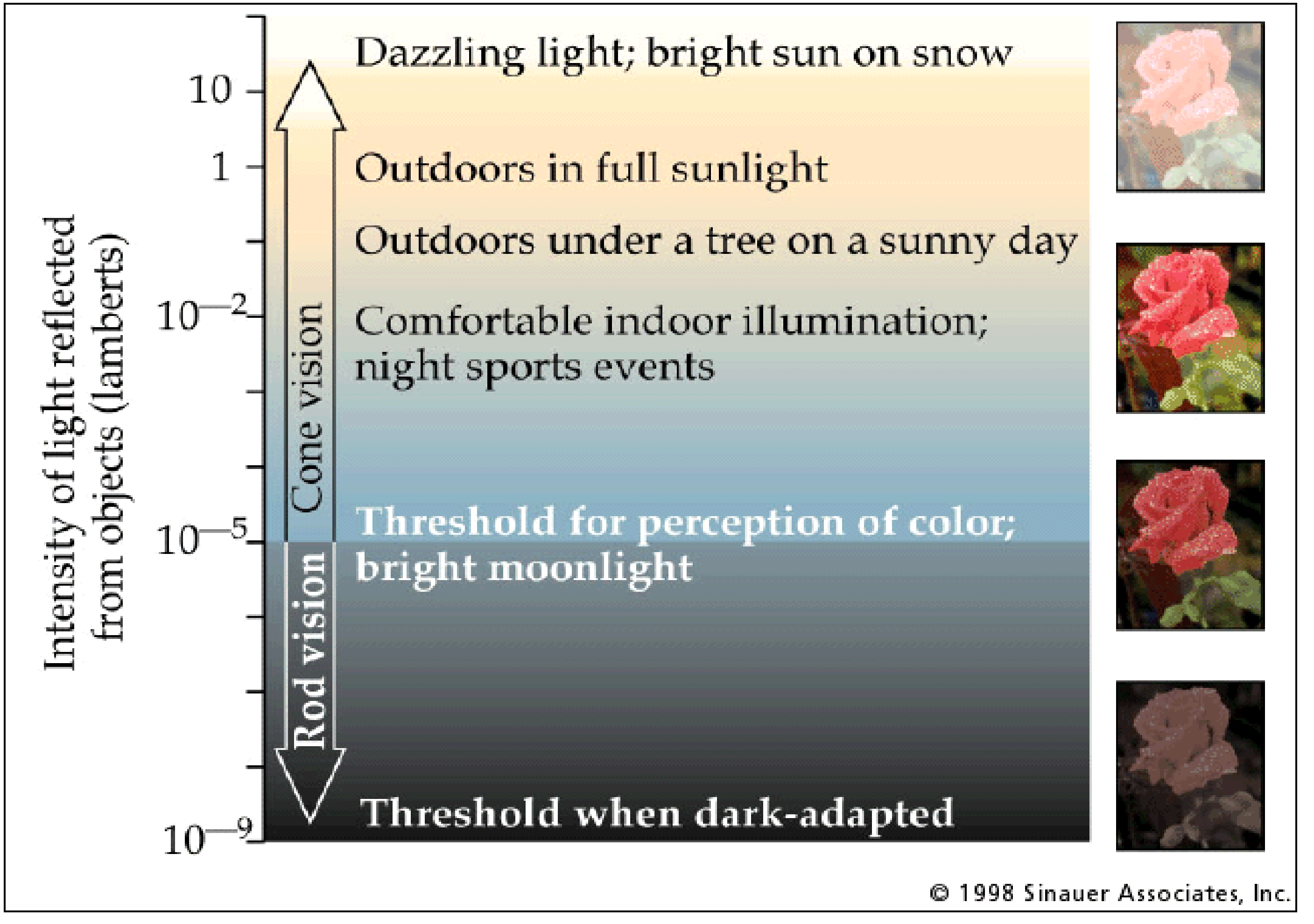
cone-shaped
less sensitive
operate in high light
color vision

Rods

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

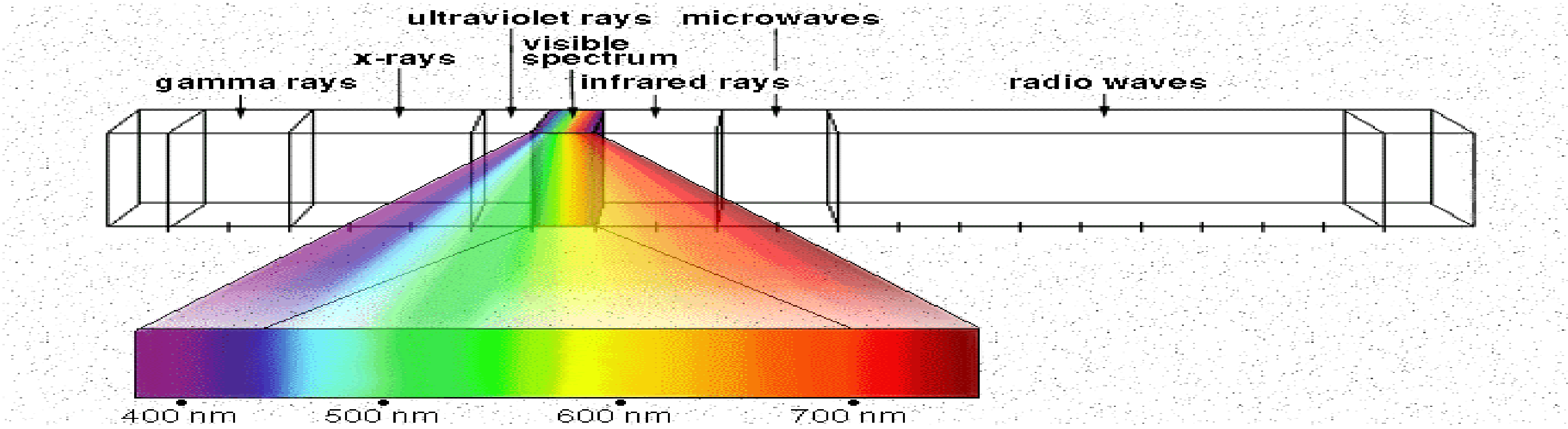


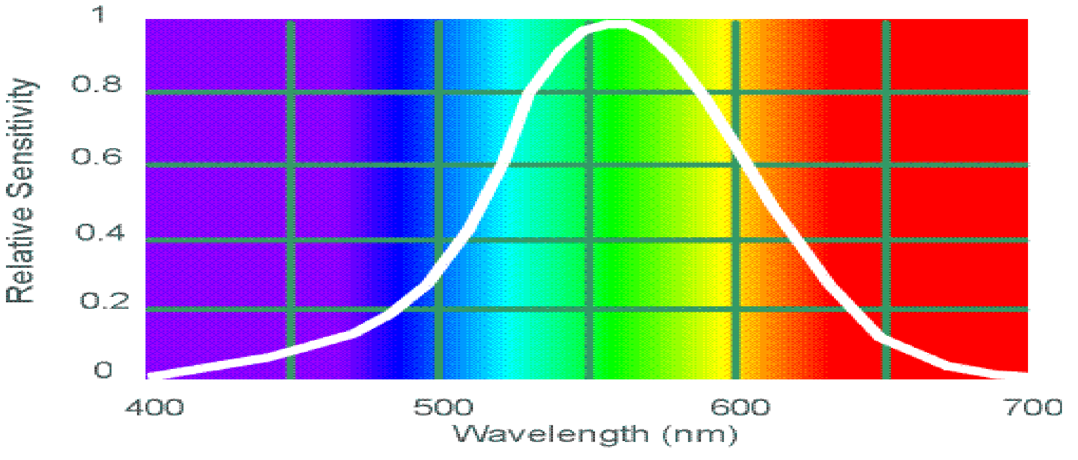
Rod / Cone sensitivity



The famous sock-matching problem…

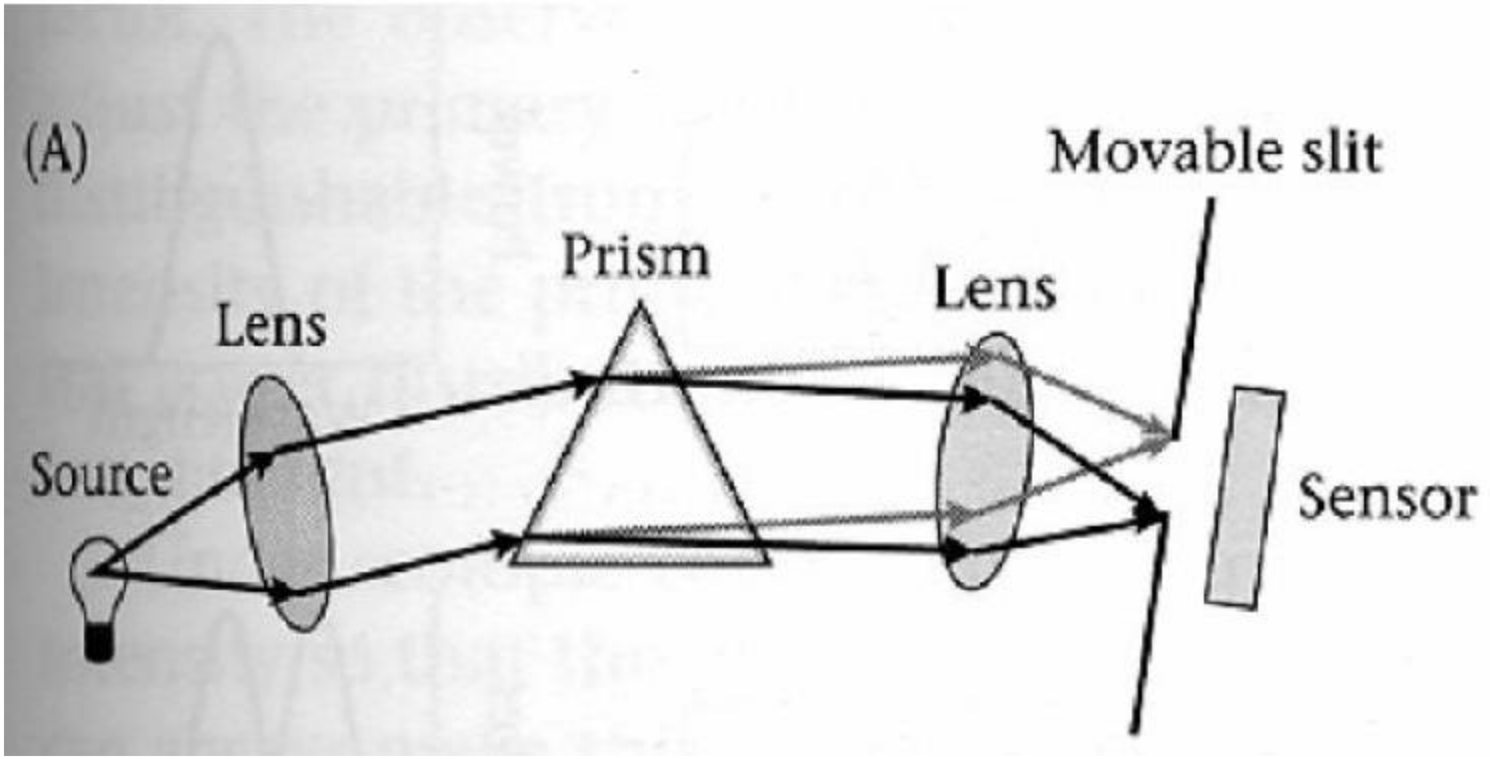
Electromagnetic Spectrum





Human Luminance Sensitivity Function

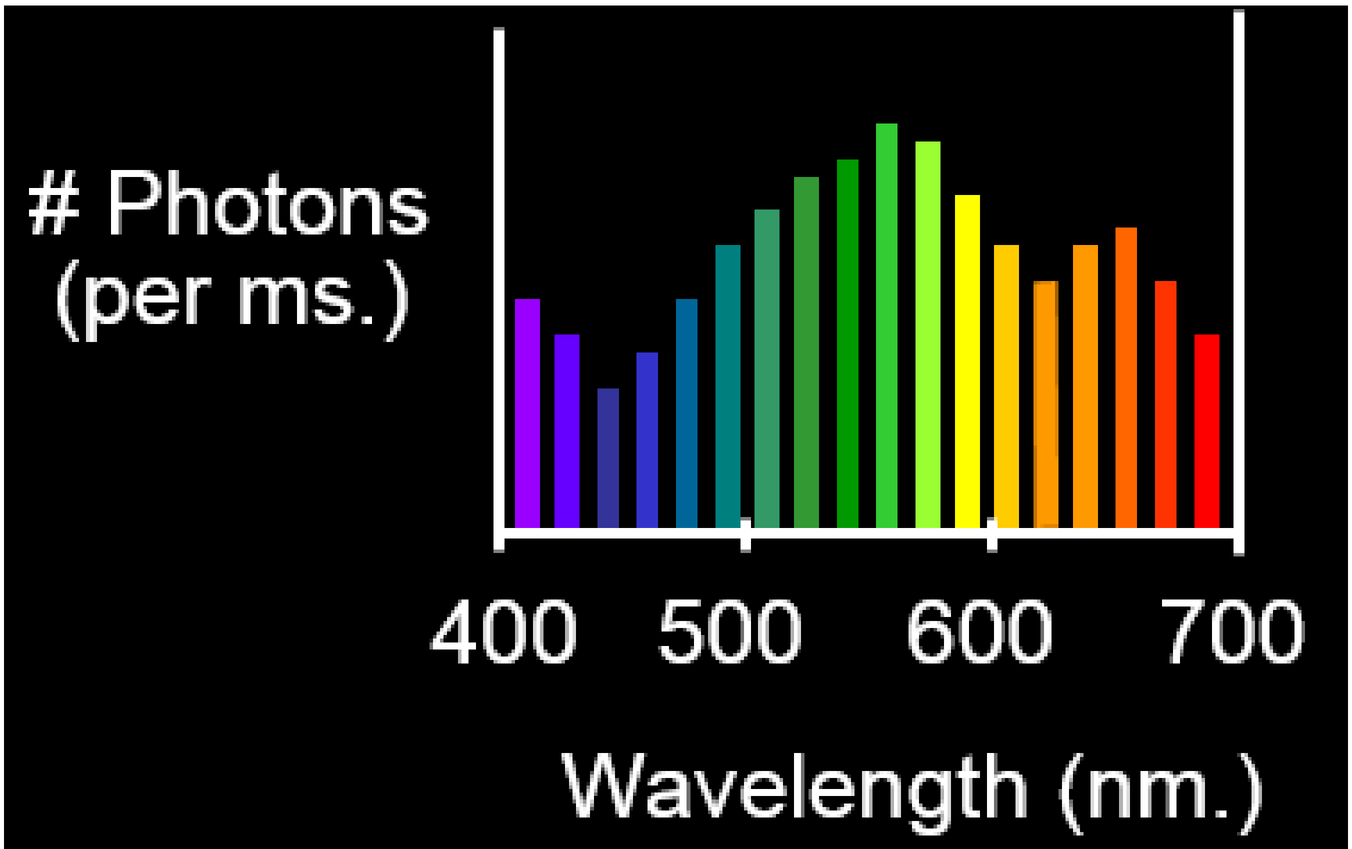
Measuring spectra



Spectroradiometer:* *separate input light into its different wavelengths, and measure the energy at each.

The Physics of Light

Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



The Physics of Light

Some examples of the reflectance spectra of surfaces



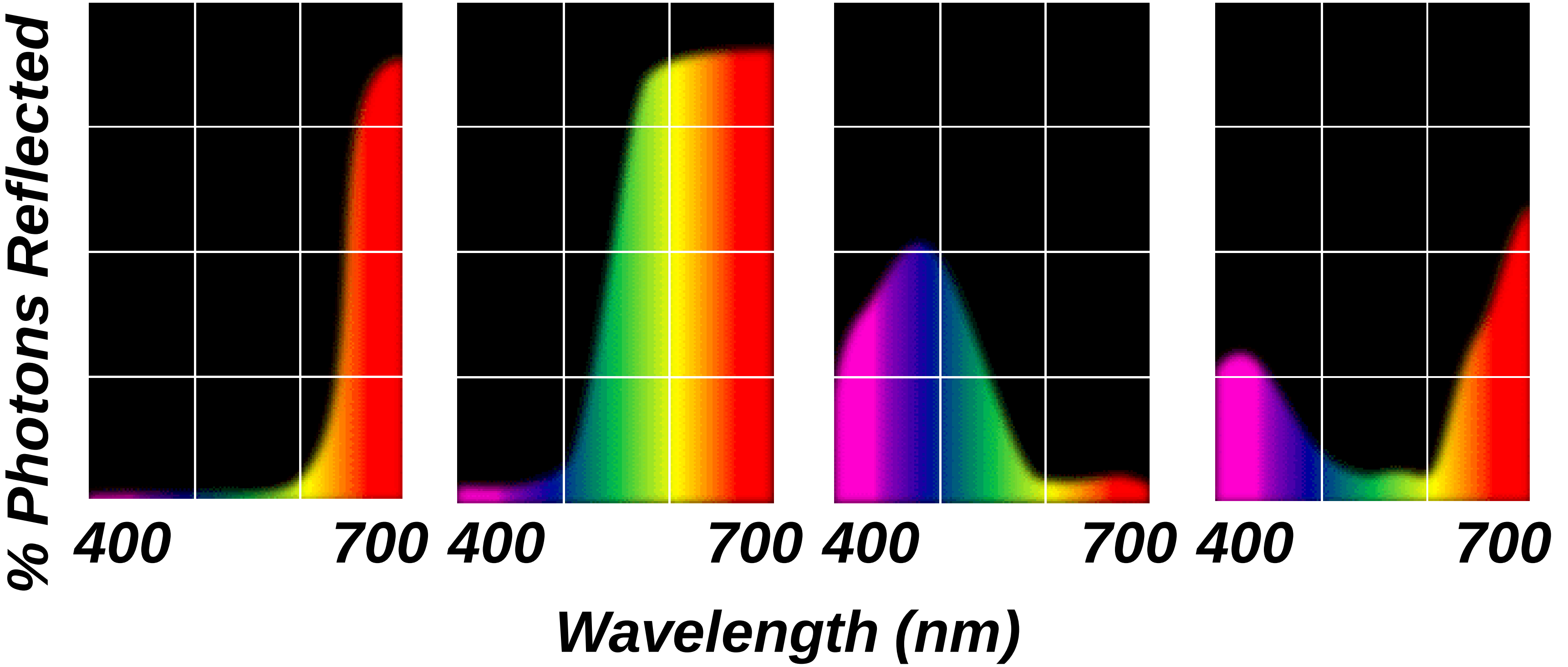
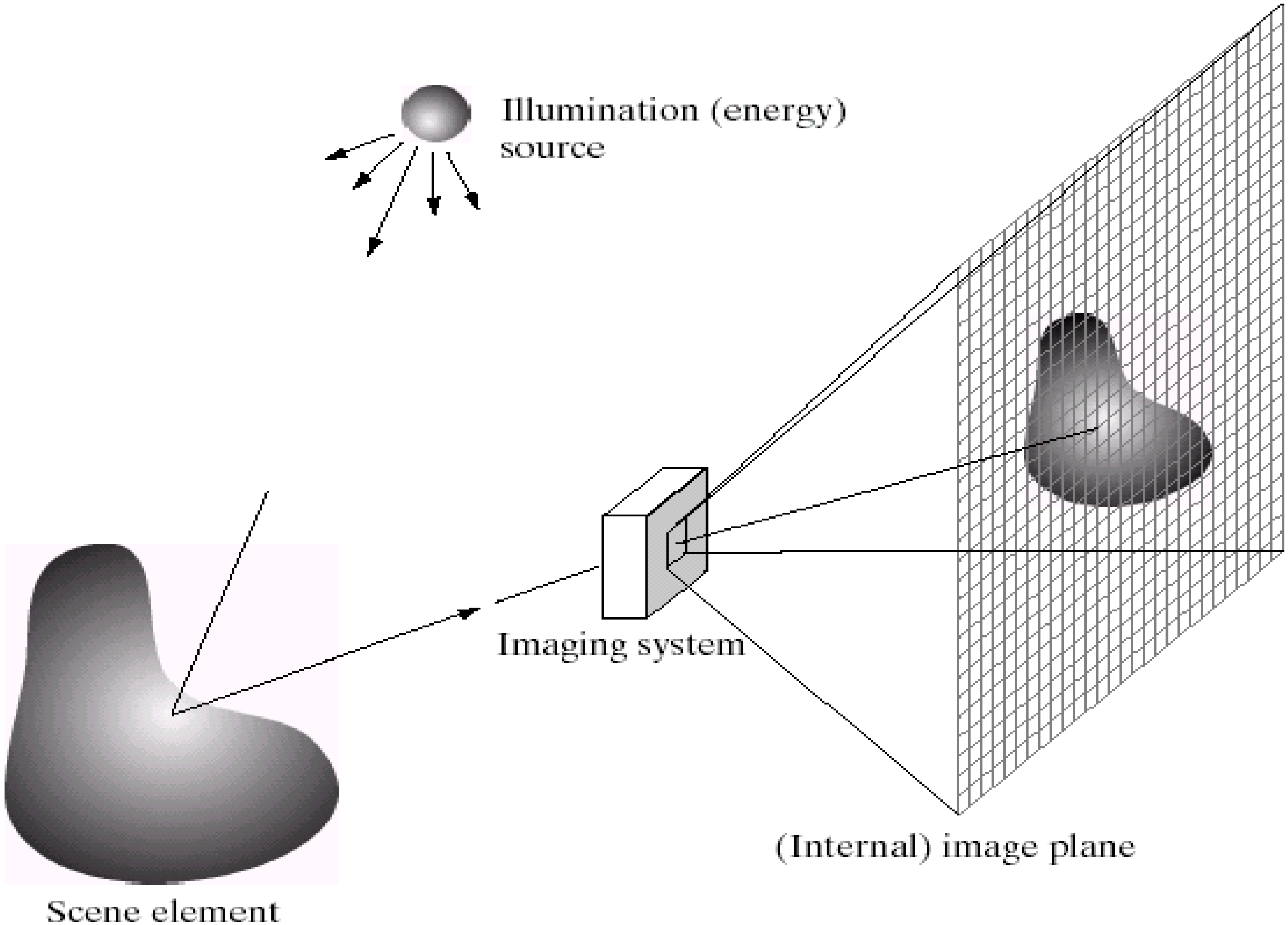



Image Formation



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***
- ***Two common types: Charge Coupled Device (CCD) and CMOS***
- ***http://electronics.howstuffworks.com/digital-camera.htm***

Slide by Steve Seitz

Sensor Array

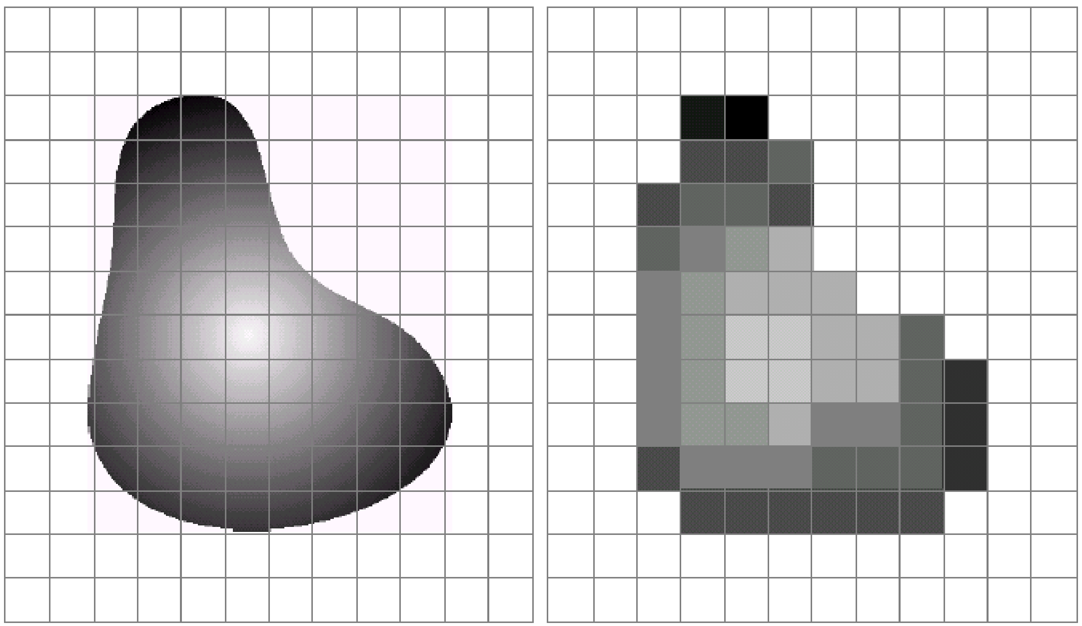
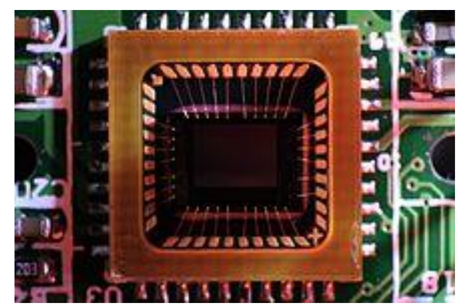
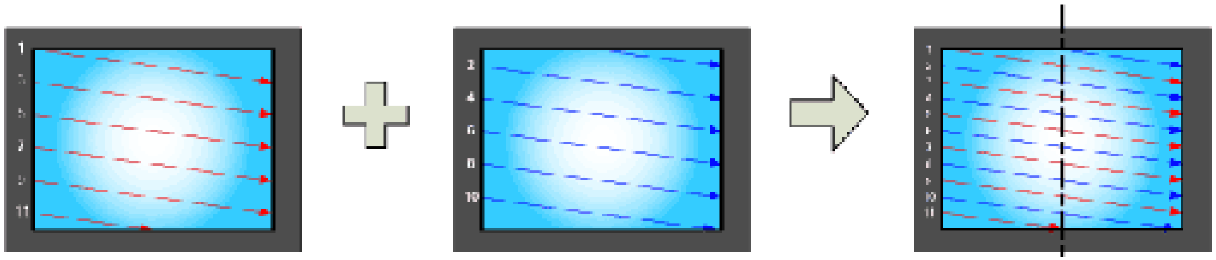

a b

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


CMOS sensor


CCD sensor

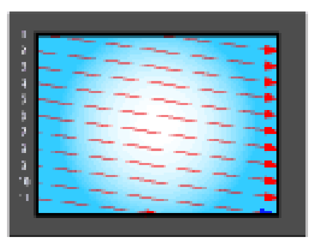
Interlace vs. progressive scan



1st field: Odd field

2nd field: Even field

One complete frame using interlaced scanning



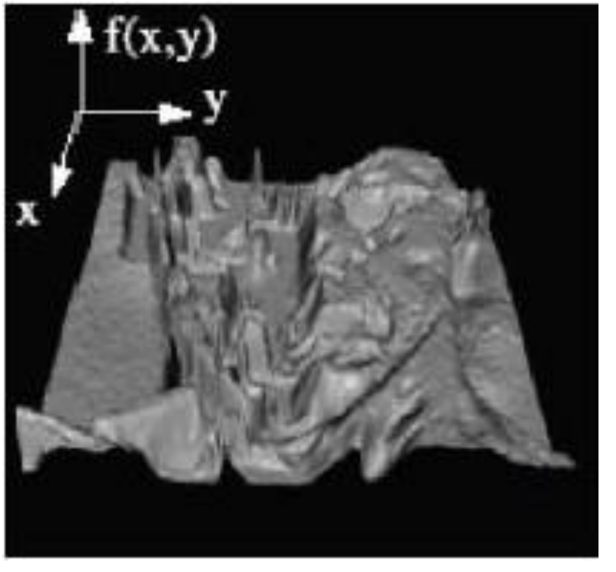
One complete frame using progressive scanning

http://www.axis.com/products/video/camera/progressive_scan.htm

Slide by Steve Seitz

What is an image?

- *Ideally, we think of an image as a 2-dimensional light intensity function, f(x,y), where x and y are spatial coordinates, and f at (x,y) is related to the brightness or color of the image at that point.*
- *In practice, most images are defined over a rectangle.*
- *Continous in amplitude ("continuous-tone")*
- *Continous in space: no pixels!*



Digital Images and Pixels

- ***A digital image is the representation of a continuous image $f(x,y)$ by a 2-d array of discrete samples $f[x,y]$. The amplitude of each sample is quantized to be represented by a finite number of bits.***
- ***Each element of the 2-d array of samples is called a pixel or pel (from "picture element")***
- ***Think of pixels as point samples, without extent.***

Image Resolution

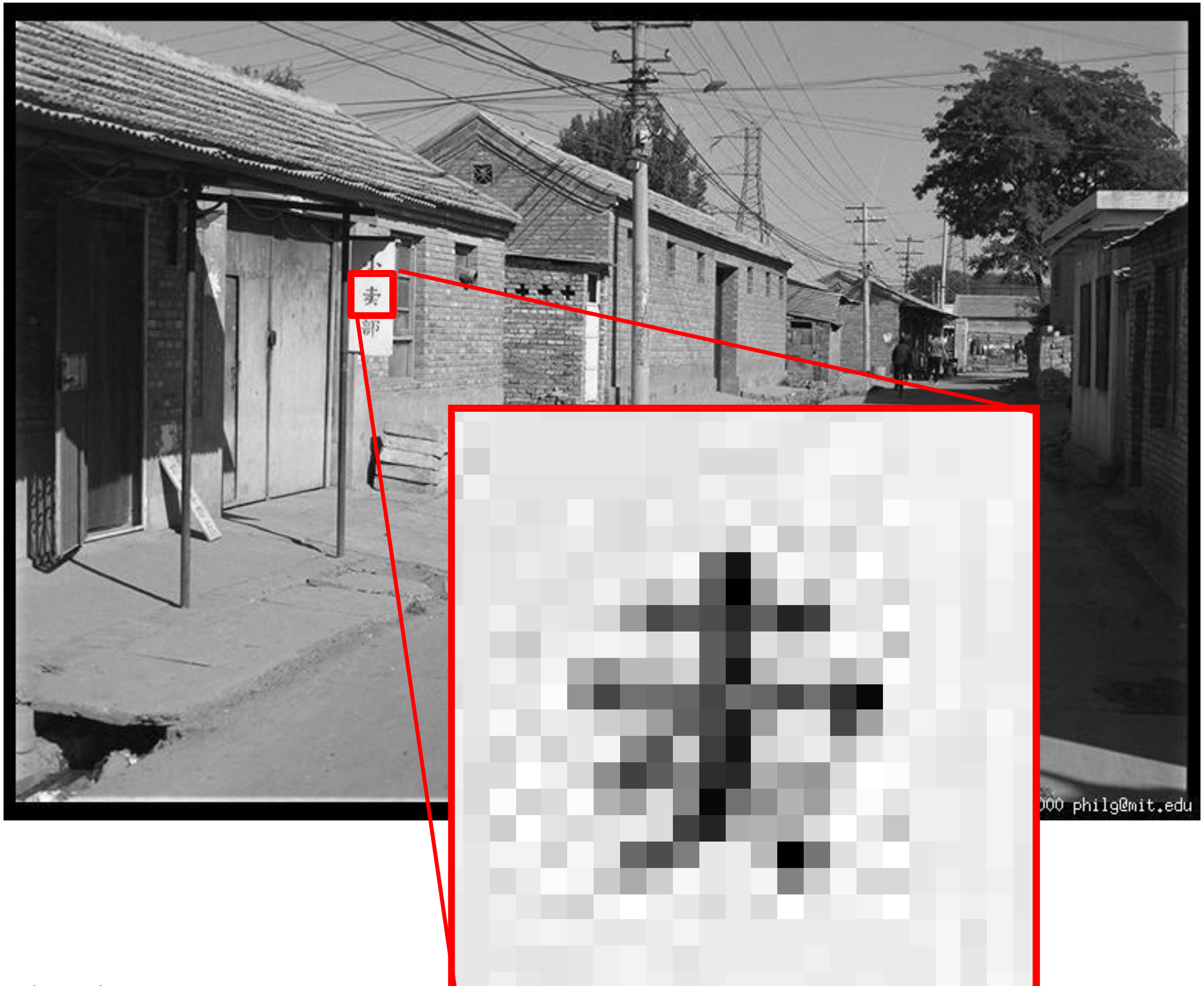
200x200 *100x100* *50x50* *25x25*

These images were produced by simply picking every n-th sample horizontally and vertically and replicating that value nxn times.

We can do better

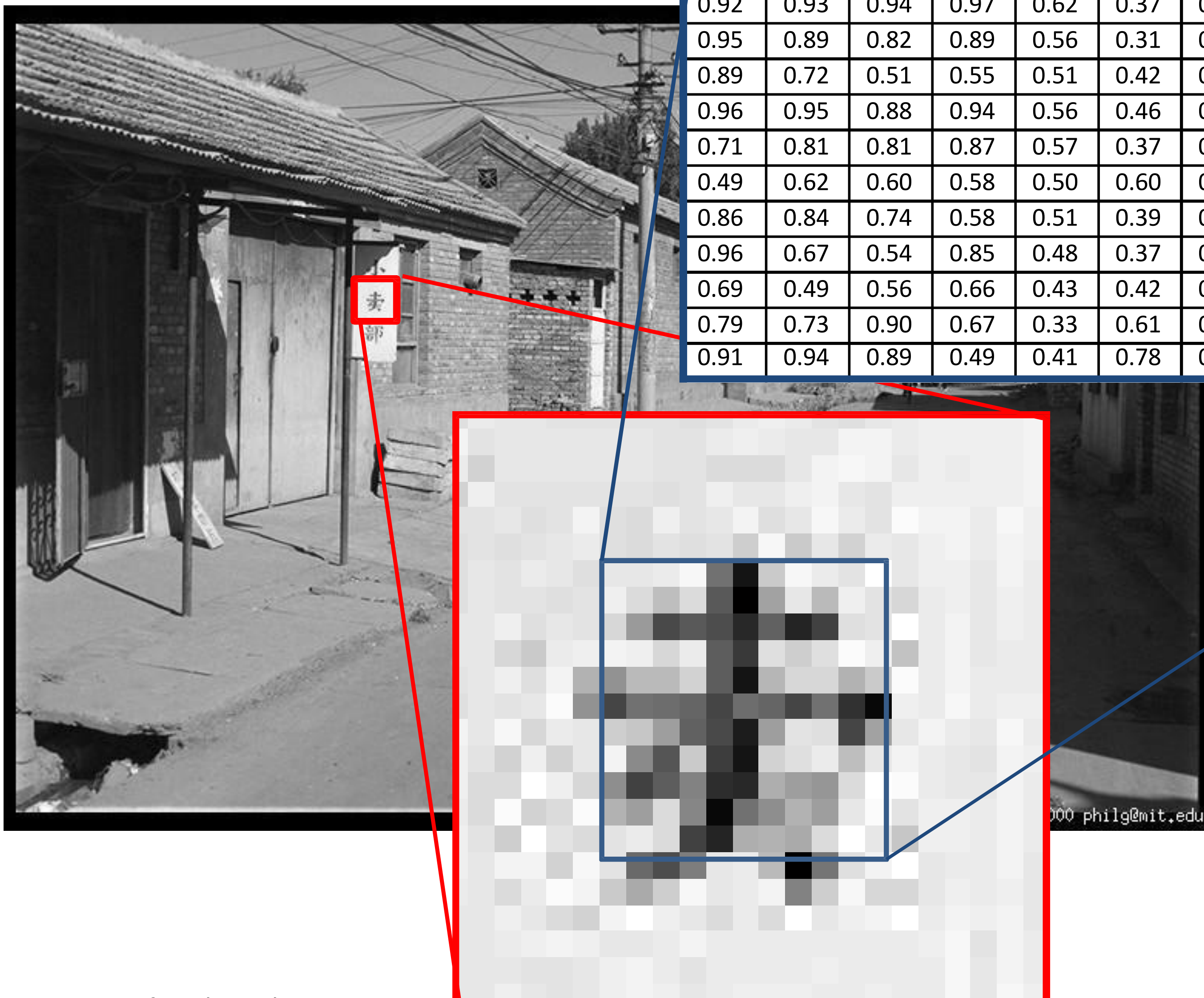
- ***Pre-filtering before subsampling to avoid aliasing***
- ***Smooth interpolation***

The raster image (pixel matrix)

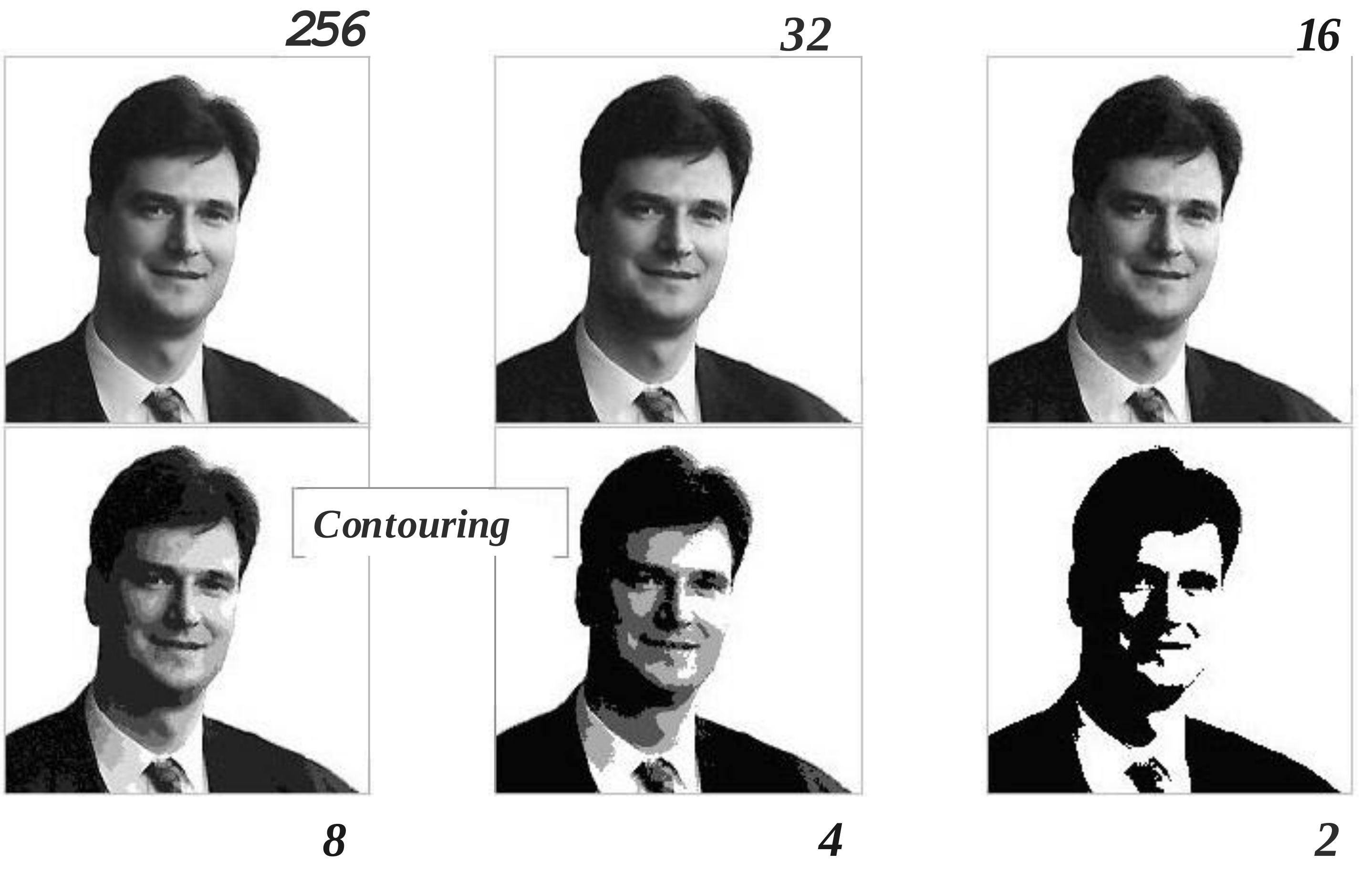


The raster image (pixel matrix)

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



Different numbers of gray levels



Color Components

Monochrome image

$R[x,y] = G[x,y] = B[x,y]$

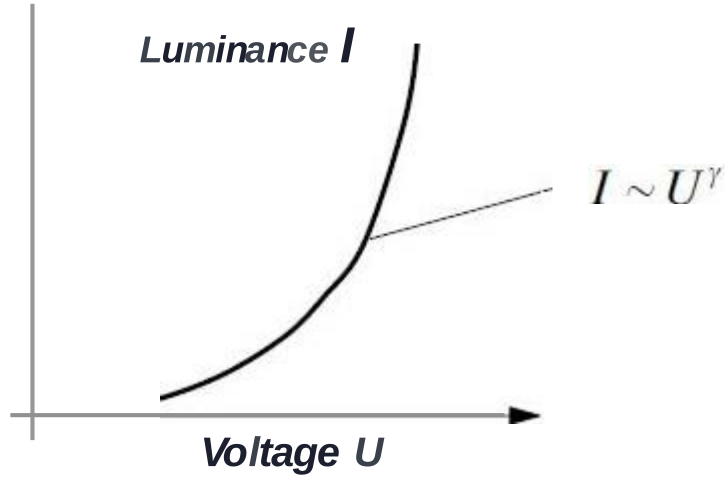
Red
R[x,y]

Green
G[x,y]

Blue
B[x,y]

Gamma characteristic

- *Cathode ray tubes (CRTs) are nonlinear*

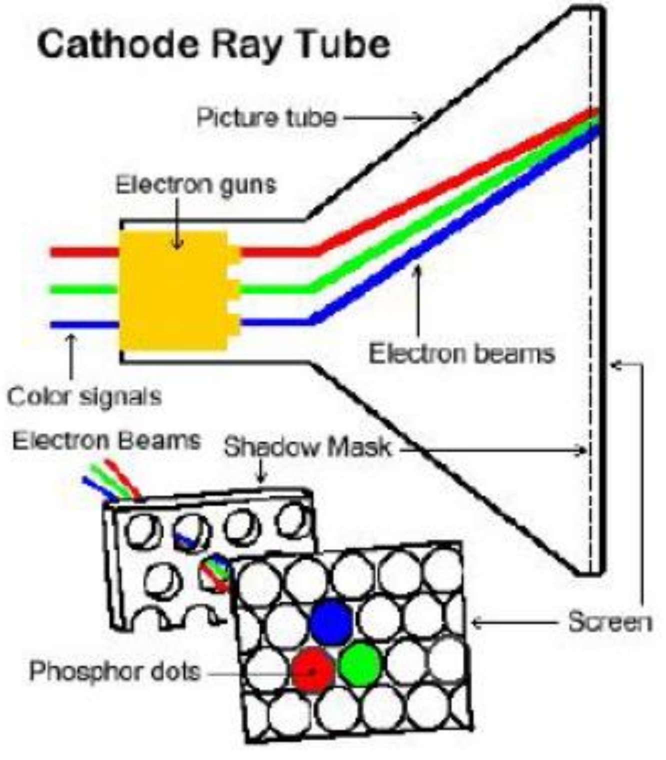


$y = 2.0 \ldots 2.3$

- *Cameras contain y-predistortion circuit*

$$U \sim I^{1/\gamma}$$

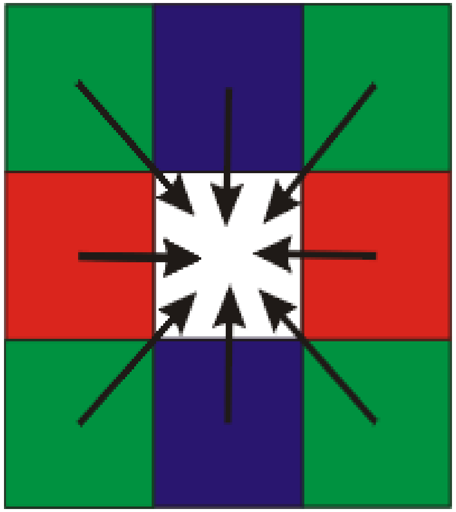
Examples of additive color systems

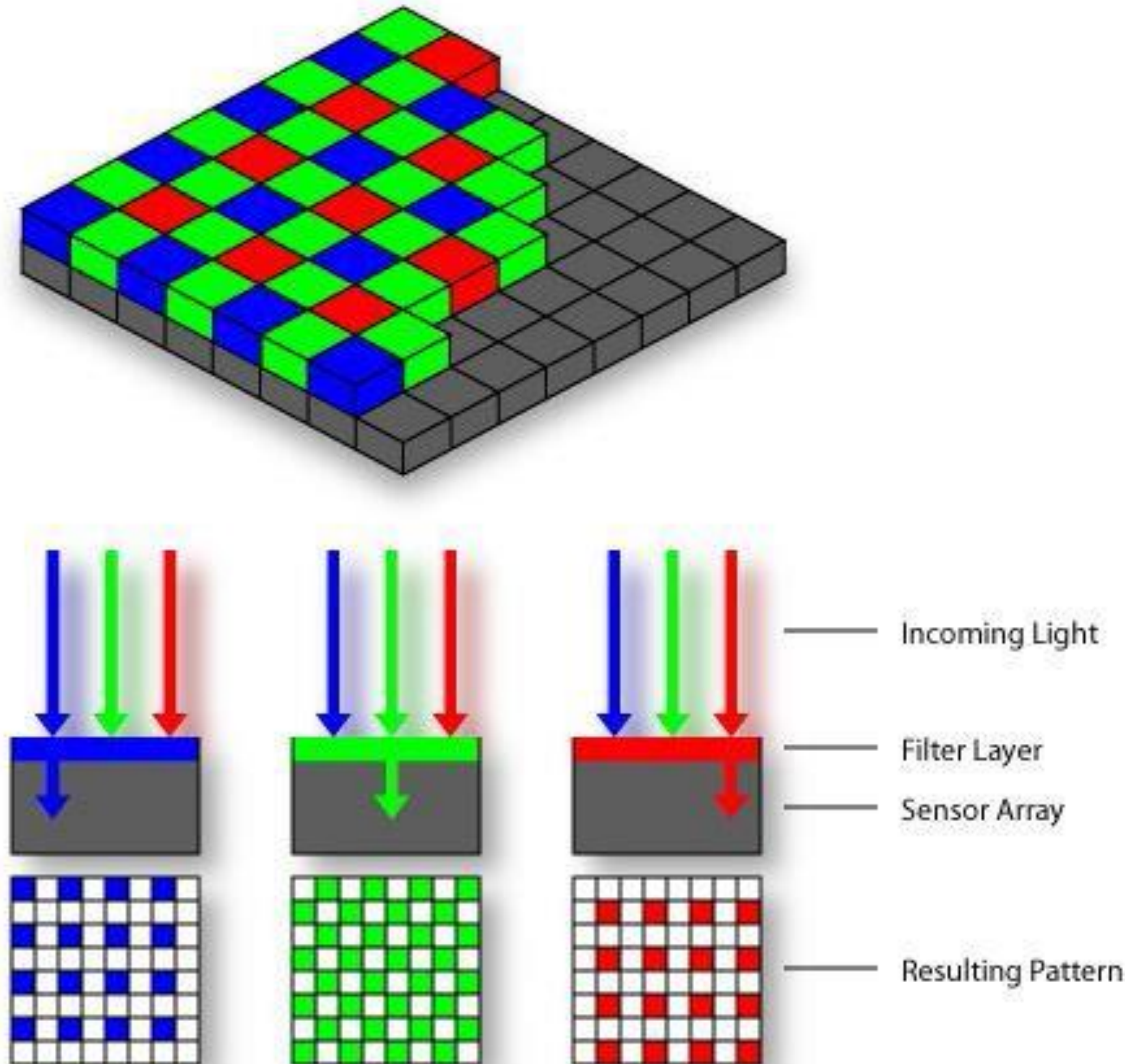


CRT phosphors

Multiple projectors

Color Images: Bayer Grid

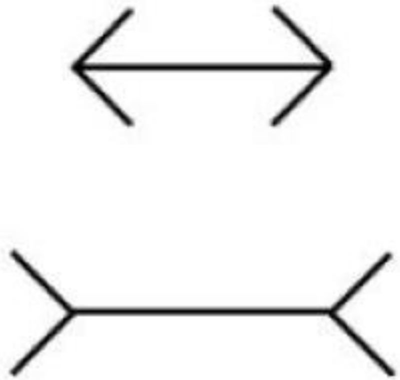




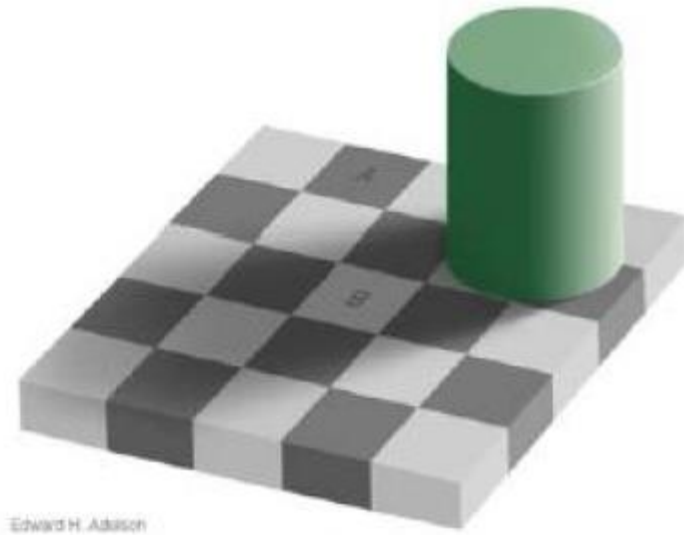
Estimate RGB at ‘G’ cells from neighboring values

http://en.wikipedia.org/wiki/Bayer_filter

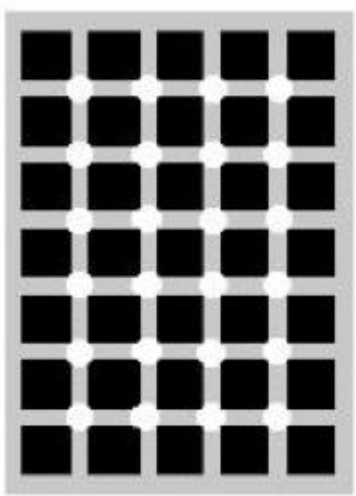
Some common optical illusions



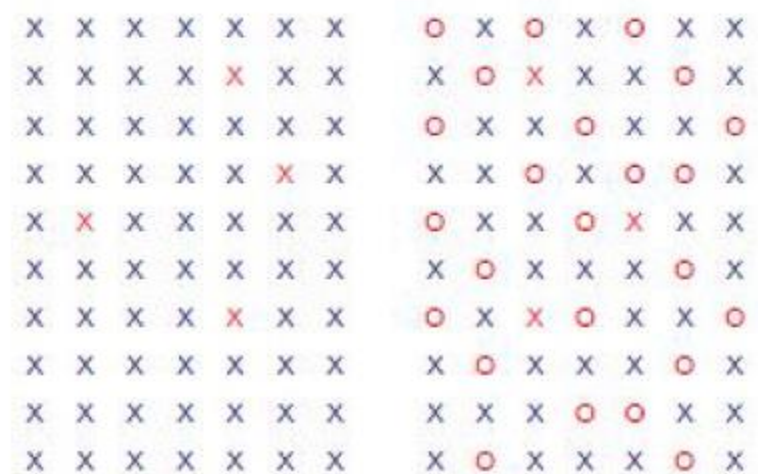
(a)



(b)



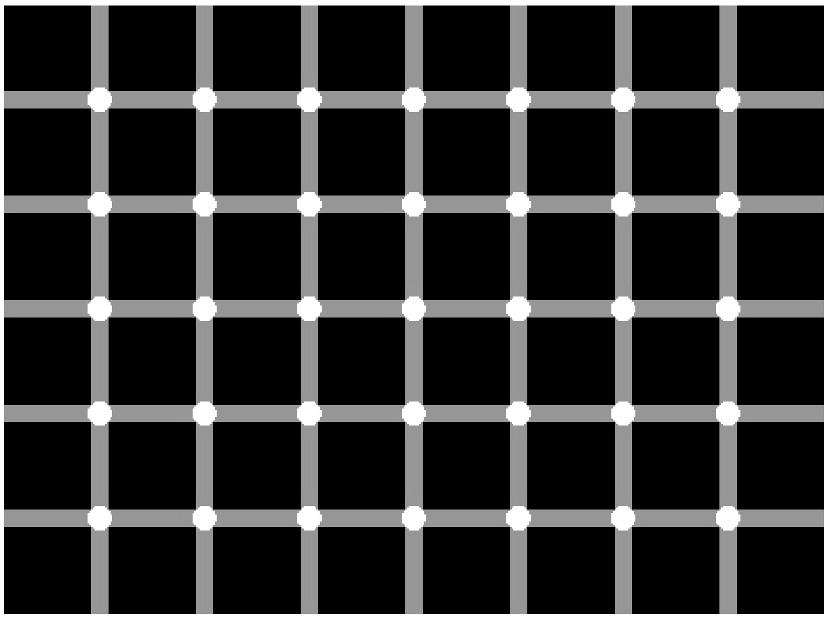
(c)



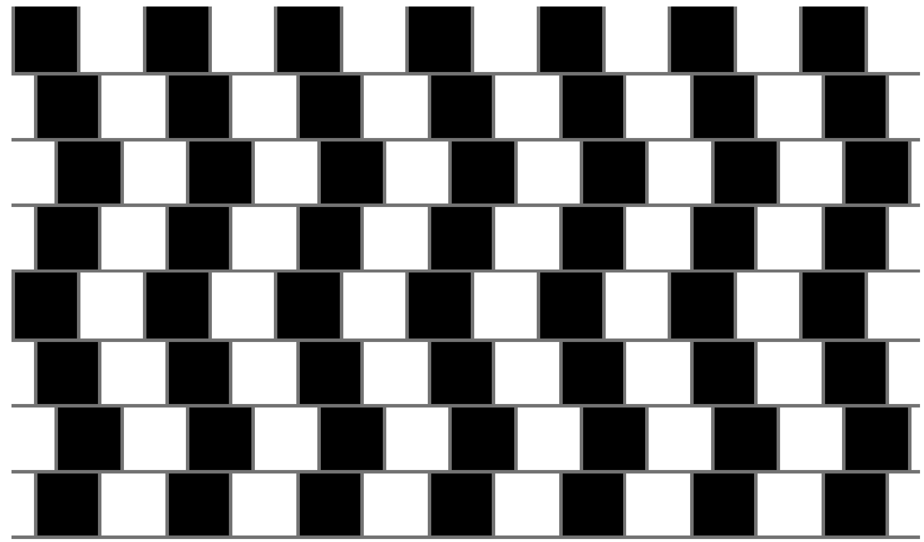
(d)

Optical illusions

Try to count the number of black dots on the image below

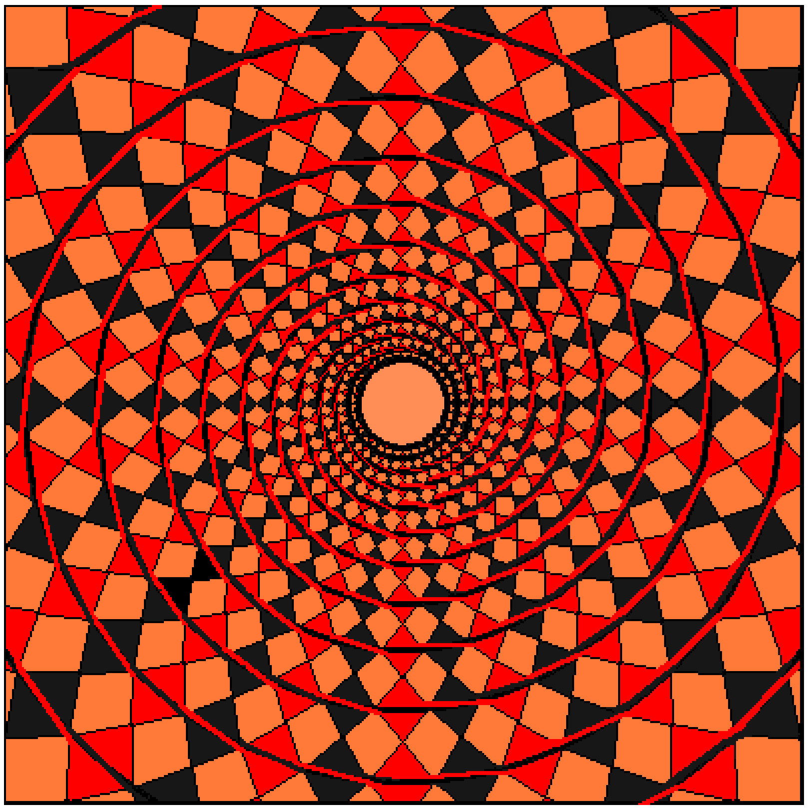


Are the lines below straight or are they curved?

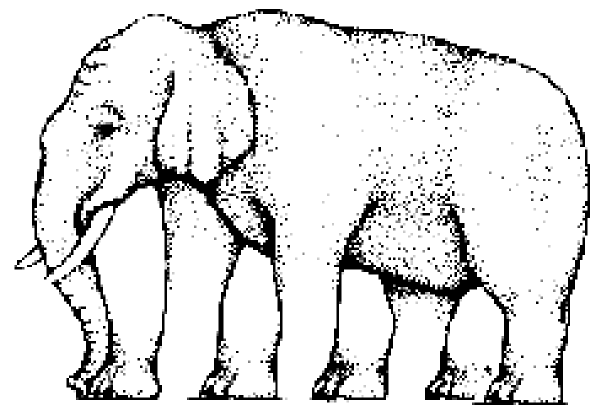


Optical illusions

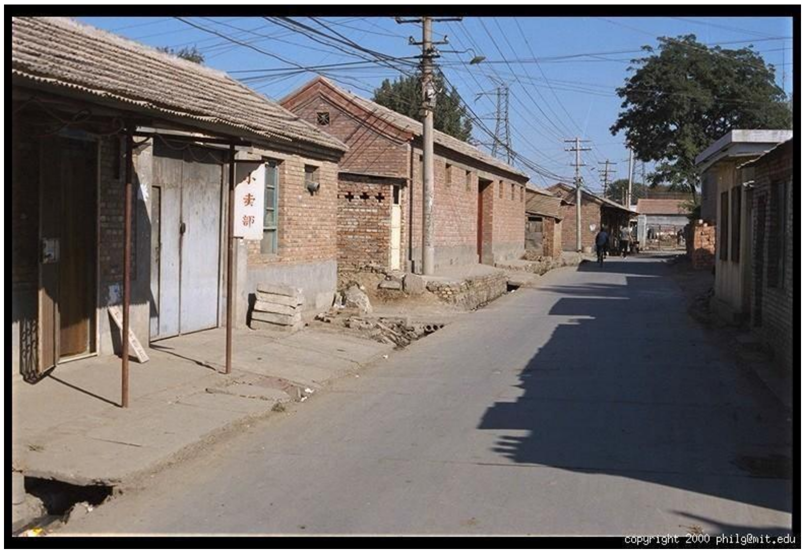
It's a spiral, right?



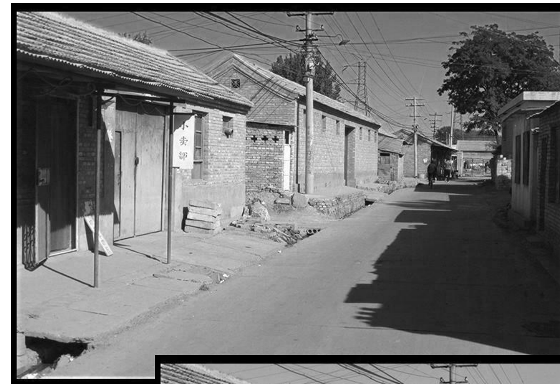
How many legs does this elephant have?



Color Image



R



G

B

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*

column

row

R

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

G

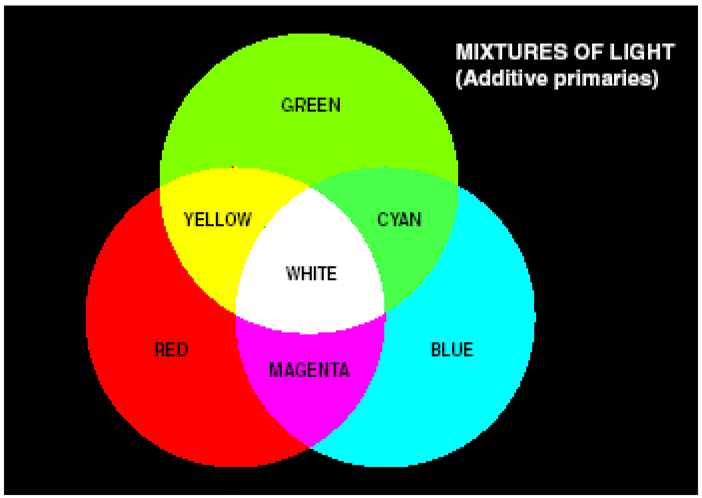
									0.92	0.99
									0.95	0.91
									0.91	0.92
									0.97	0.95
									0.79	0.85
									0.45	0.33
									0.49	0.74
									0.82	0.93
									0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

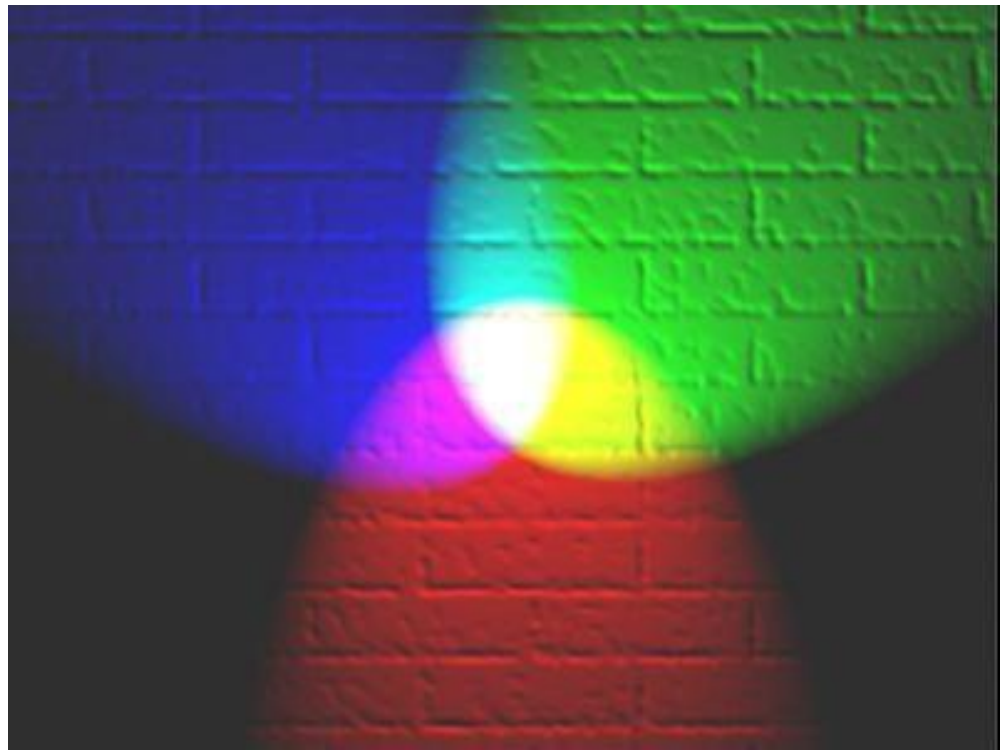
B

									0.92	0.99
									0.95	0.91
									0.91	0.92
									0.97	0.95
									0.79	0.85
									0.45	0.33
									0.49	0.74
									0.82	0.93
									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

Color spaces

- ***How can we represent color?***

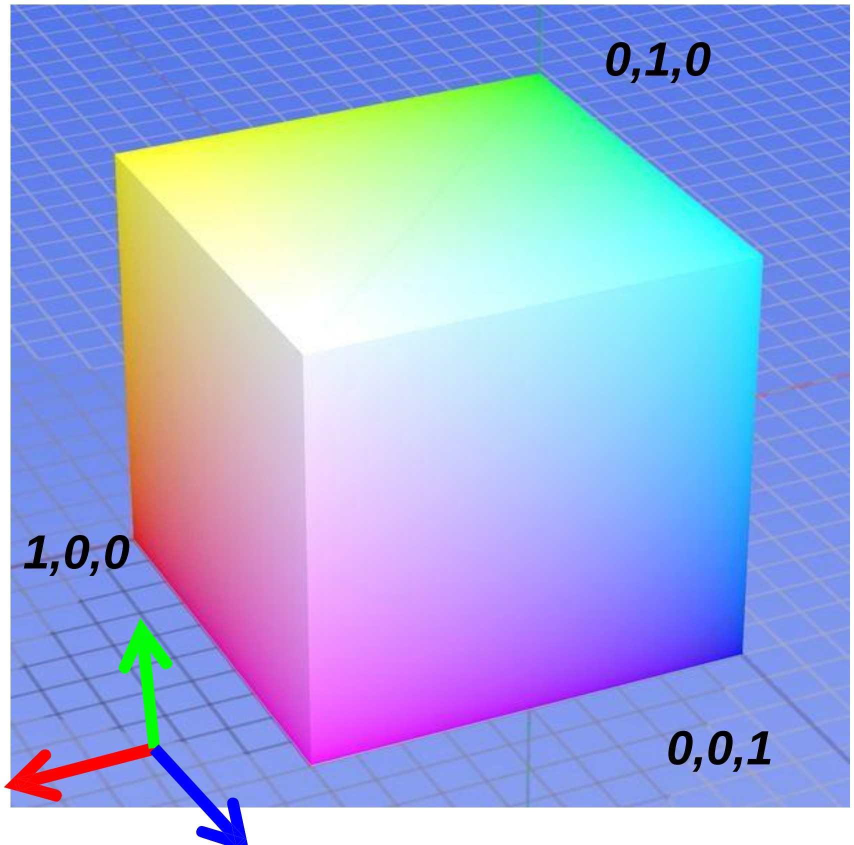


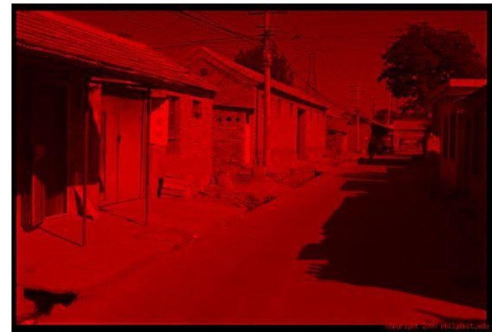


http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Color spaces: RGB

Default color space





R
(G=0,B=0)

G
(R=0,B=0)

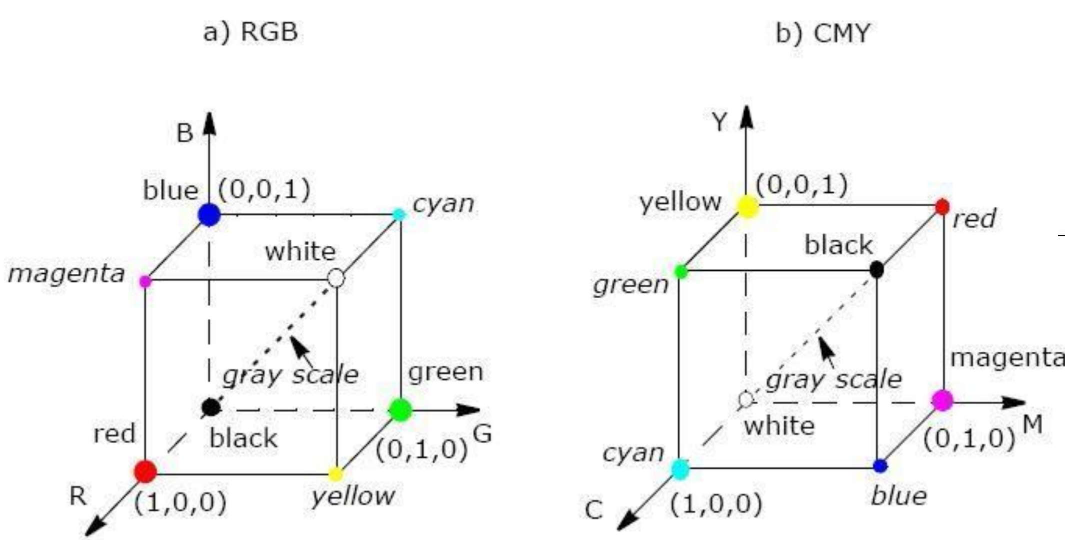
B
(R=0,G=0)

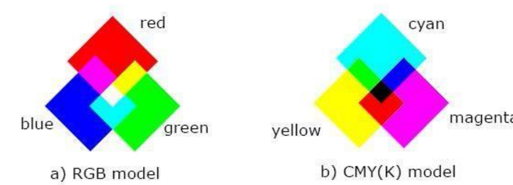
Some drawbacks

- ***Strongly correlated channels***
- ***Non-perceptual***

Color spaces: RGB and CMY Models

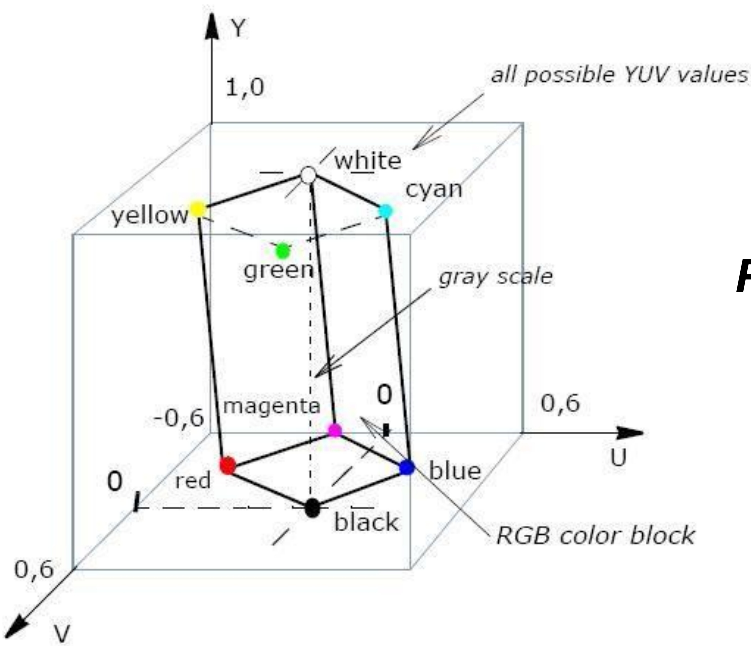
- **RGB color model is used in computer graphics**
- **Magenta (red plus blue), Cyan (green plus blue), and Yellow (red plus green)**
- **The CMY color model is a subset of the RGB model and is primarily used in color print production**



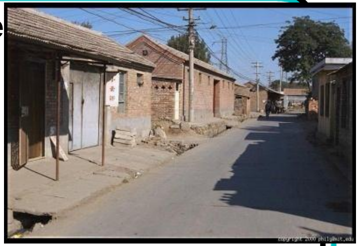


YUV Color Model

- **The YUV color model is the basic color model used in analogue color TV broadcasting.**
- **It comprises the *luminance* (Y) and two color difference (U, V) components. The luminance can be computed as a weighted sum of red, green and blue components; the color difference, or *chrominance*, components are formed by subtracting luminance from blue and from red.**



RGB Colors Cube in the YUV Color Space



Color spaces: YCbCr

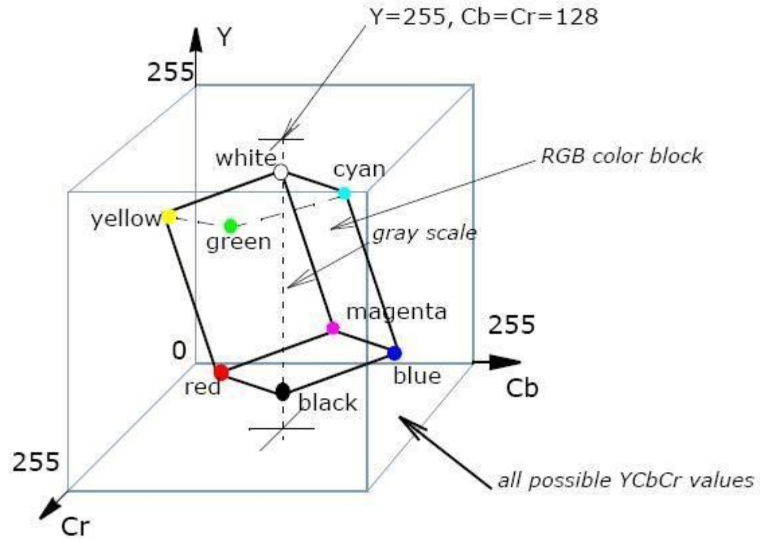
- ***Fast to compute, good for compression. The YCbCr color space is used for component digital video and was developed as part of the ITU-R BT.601***
- ***Recommendation. YCbCr is a scaled and offset version of the YUV color space.***

rgbmap = ycbcr2rgb(ycbcrmap)
RGB = ycbcr2rgb(YCBCR)

Y
(Cb=0.5,Cr=0.5)

Cb
(Y=0.5,Cr=0.5)

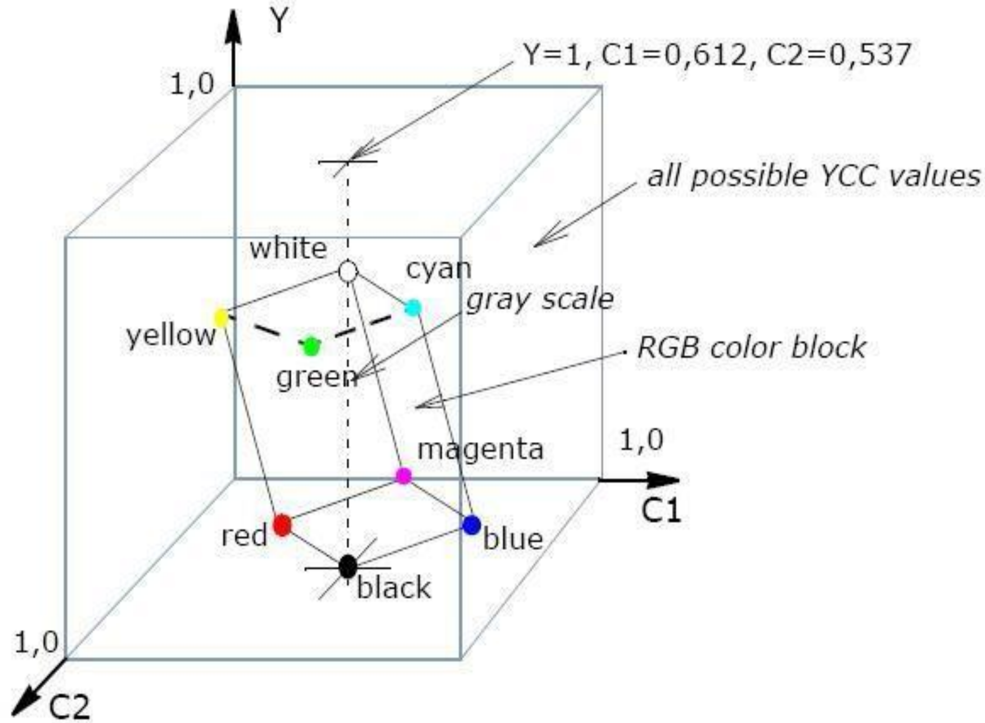
Cr
(Y=0.5,Cb=05)



RGB Colors Cube in the YCbCr Space

PhotoYCC Color Model

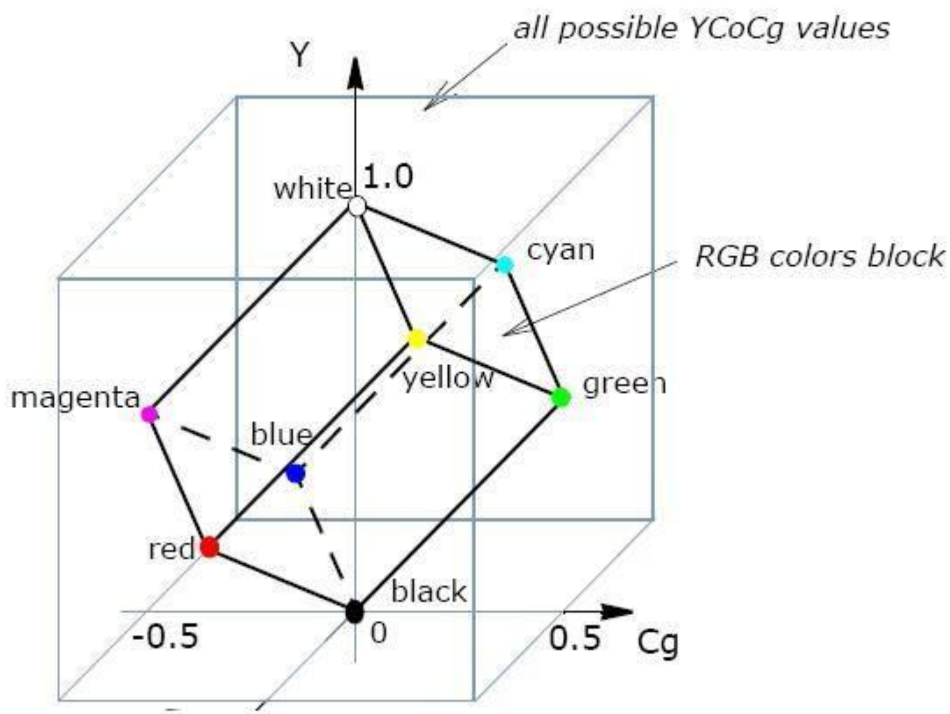
- ***The Kodak* PhotoYCC* was developed for encoding Photo CD* image data.***



RGB Colors in the YCC Color Space

YCoCg Color Models

- ***The YCoCg color model was developed to increase the effectiveness of the image compression***

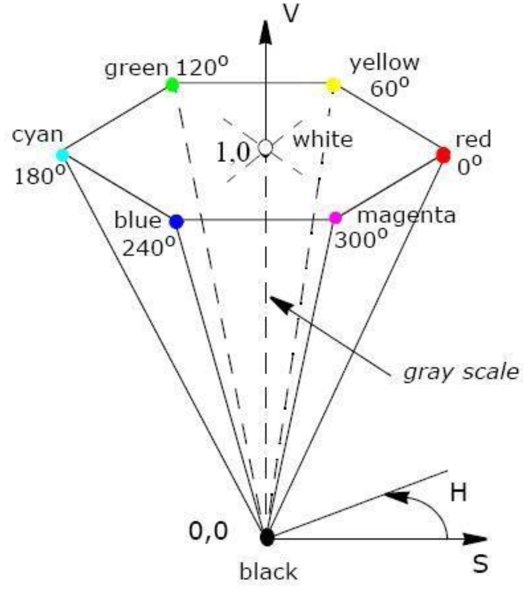


RGB Color Cube in the YCoCg Color Space

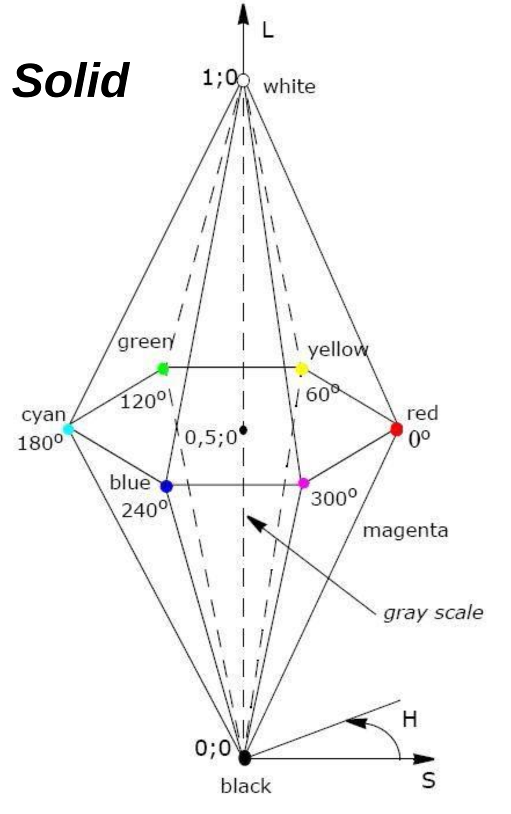
HSV, and HLS Color Models

- ***The HLS (hue, lightness, saturation) and HSV (hue, saturation, value) color models were developed to be more "intuitive" in manipulating with color and were designed to approximate the way humans perceive and interpret color.***

HSV Solid



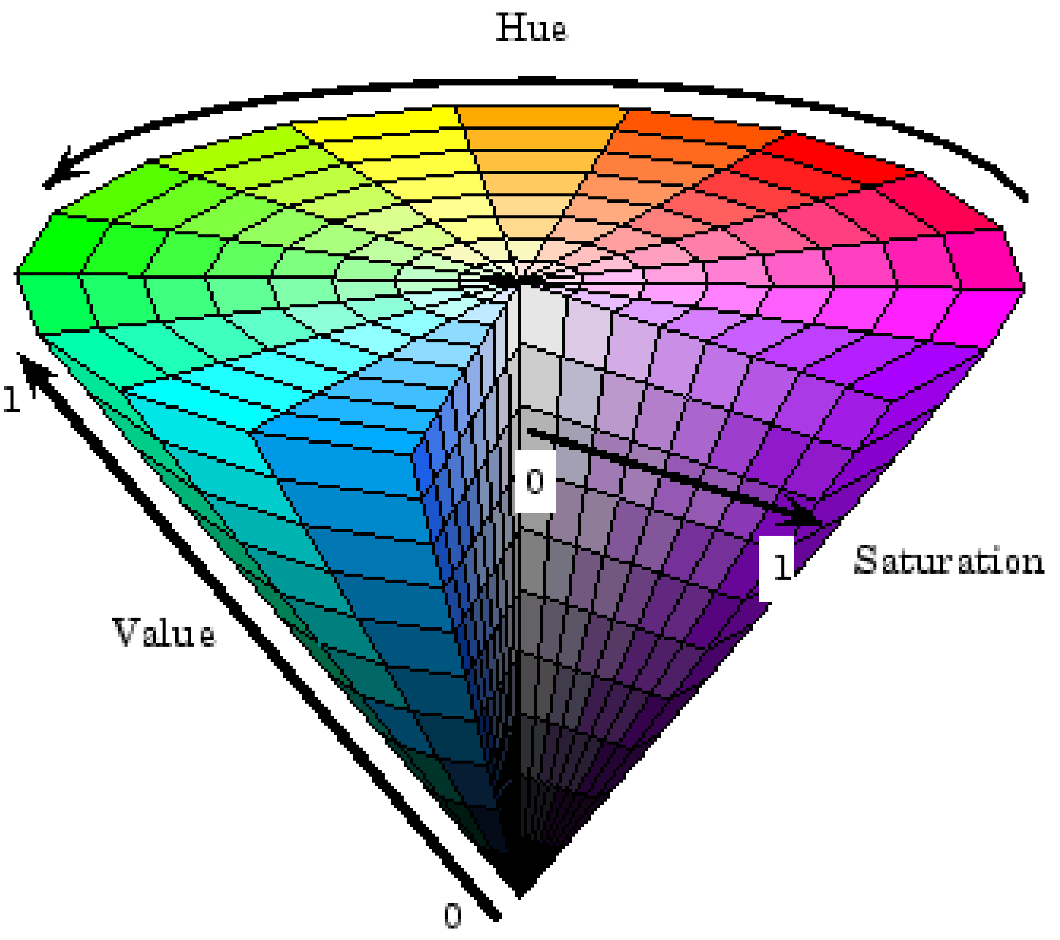
HLS Solid

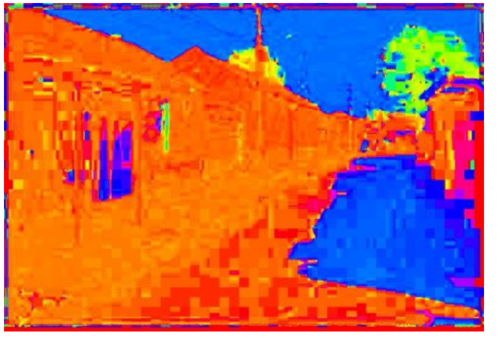


Color spaces: HSV

Matlab: `hsv2rgb`, `rgb2hsv`

Intuitive color space





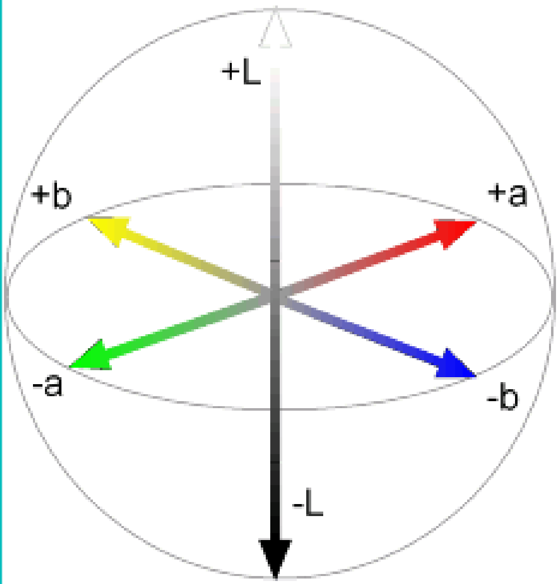
H
(S=1,V=1)

S
(H=1,V=1)

V
(H=1,S=0)

Color spaces: L*a*b*

“Perceptually uniform” color space*



L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

- ***Color of foods is usually measured in units L*a*b* which is an international standard for color measurements, adopted by the CIE (Commission Internationale d'Eclairage).***

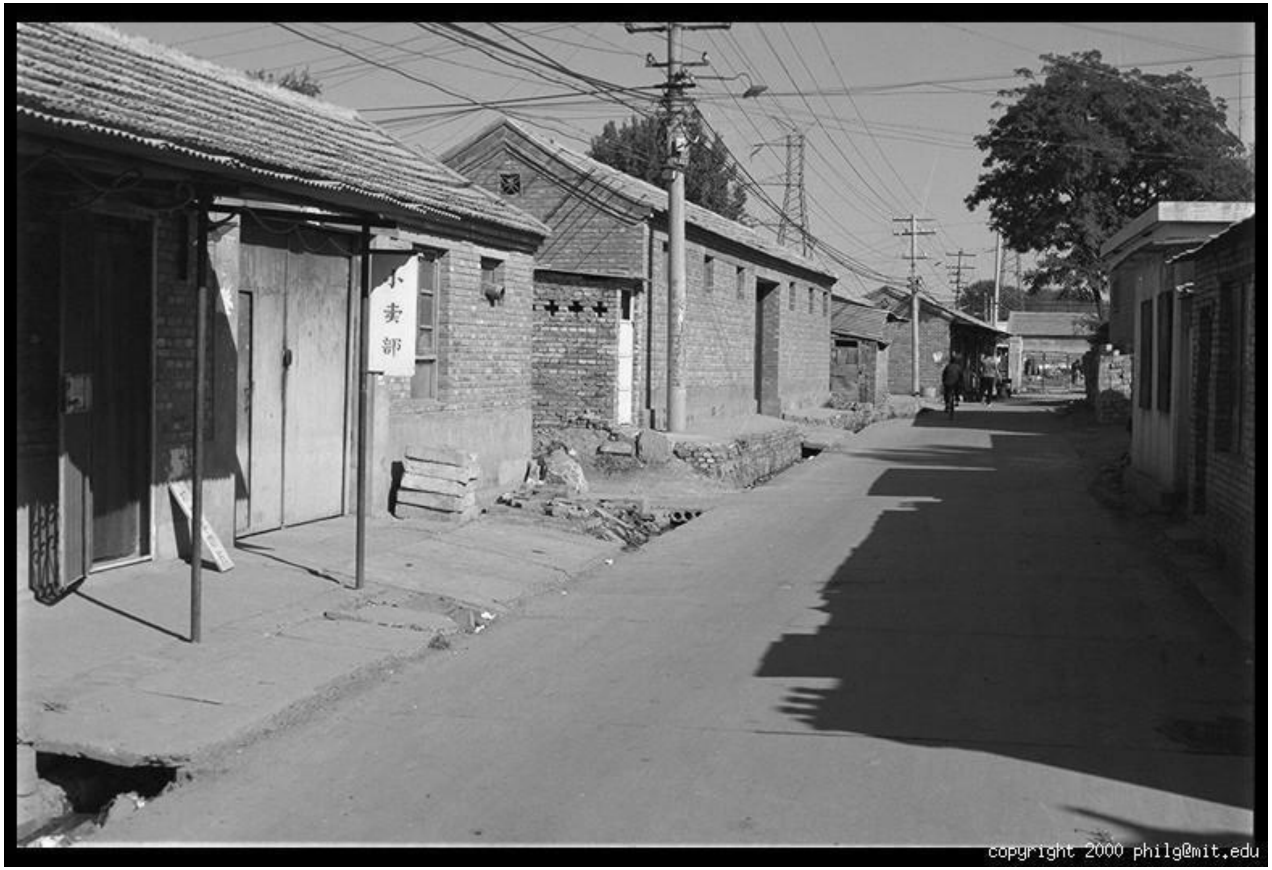
- ***The lightness ranges between 0 and 100 while chromatic parameters (a, b) range between -120 and 120.***

If you had to choose, would you rather go without luminance or chrominance?

Most information in intensity

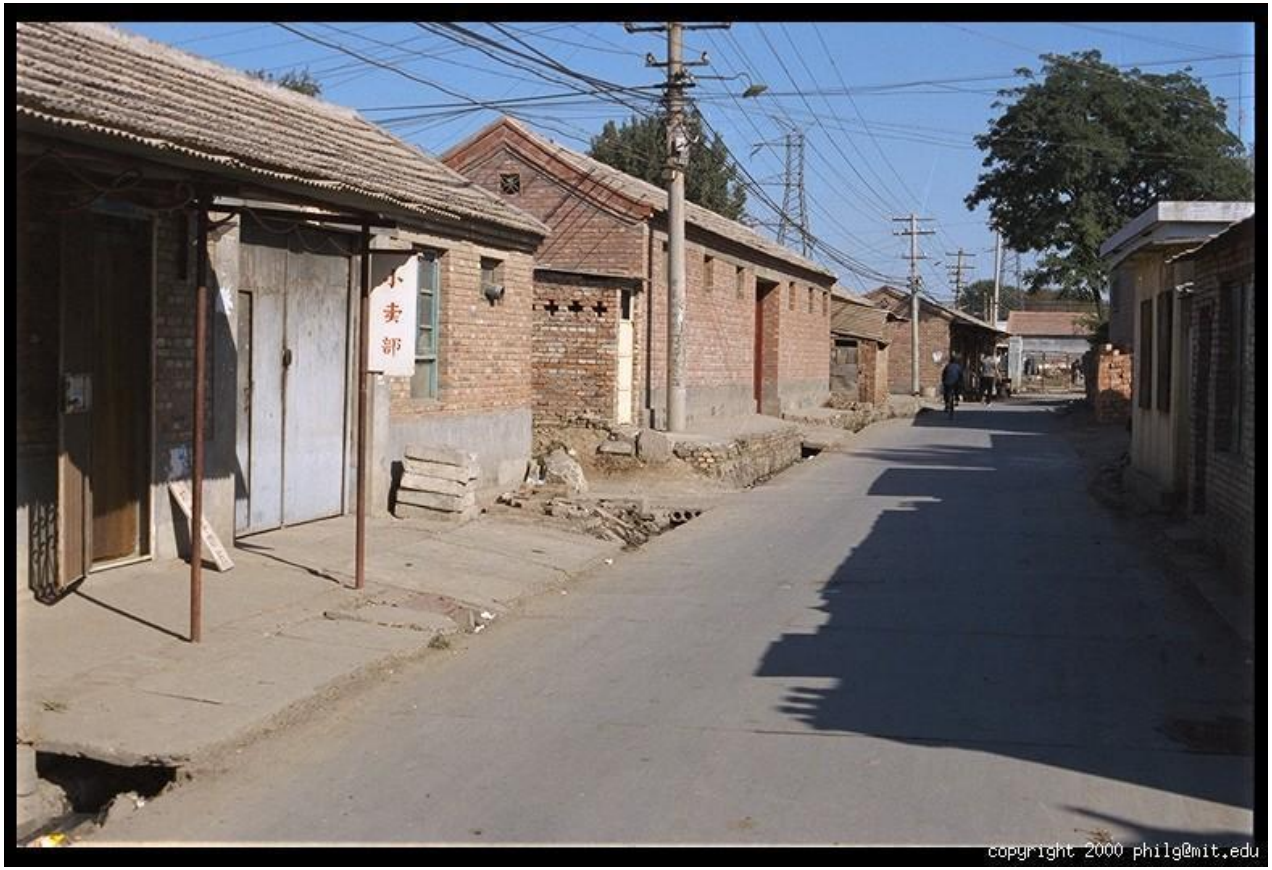
Only color shown – constant intensity

Most information in intensity



Only intensity shown – constant color

Most information in intensity



Original image