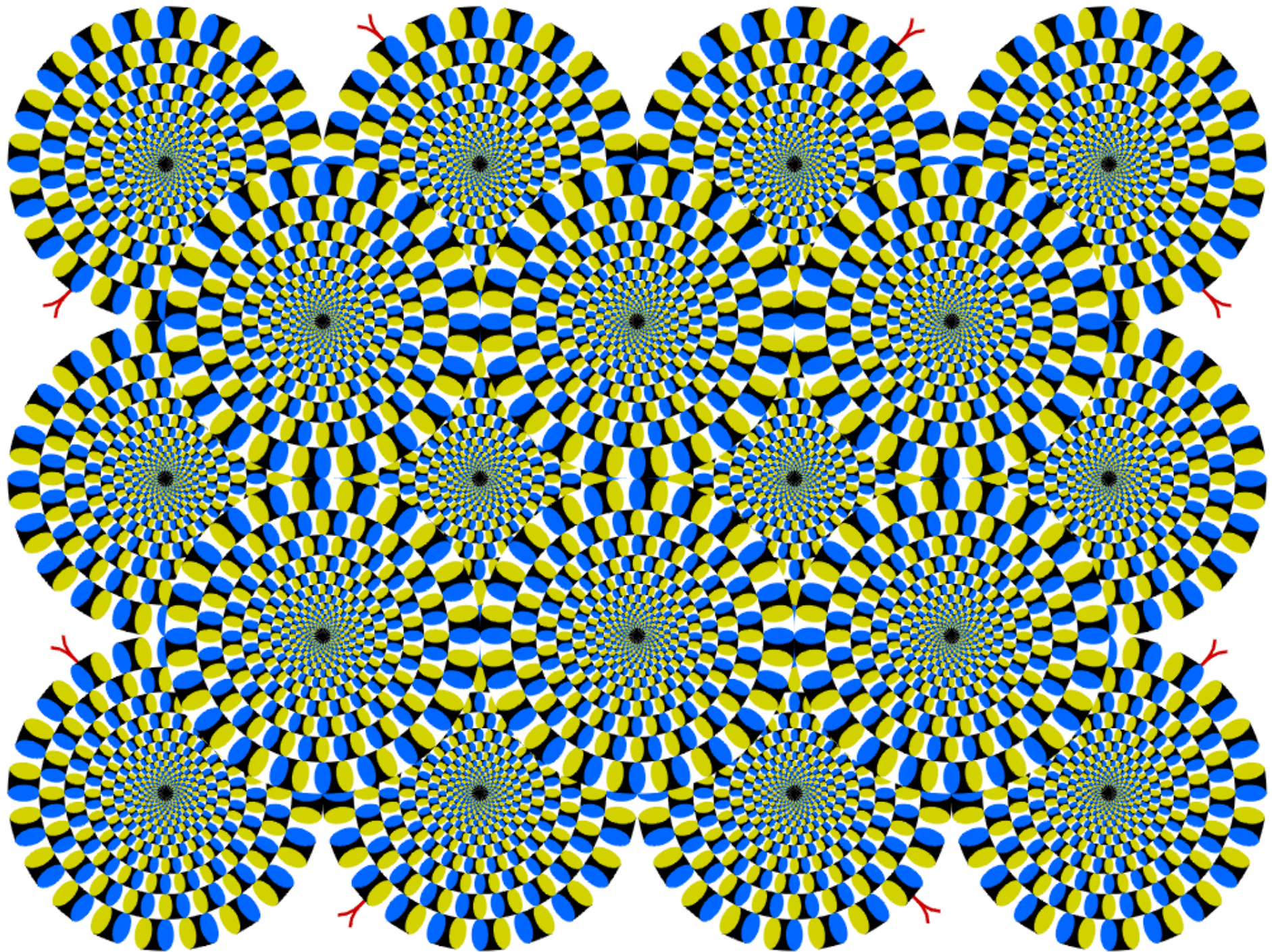
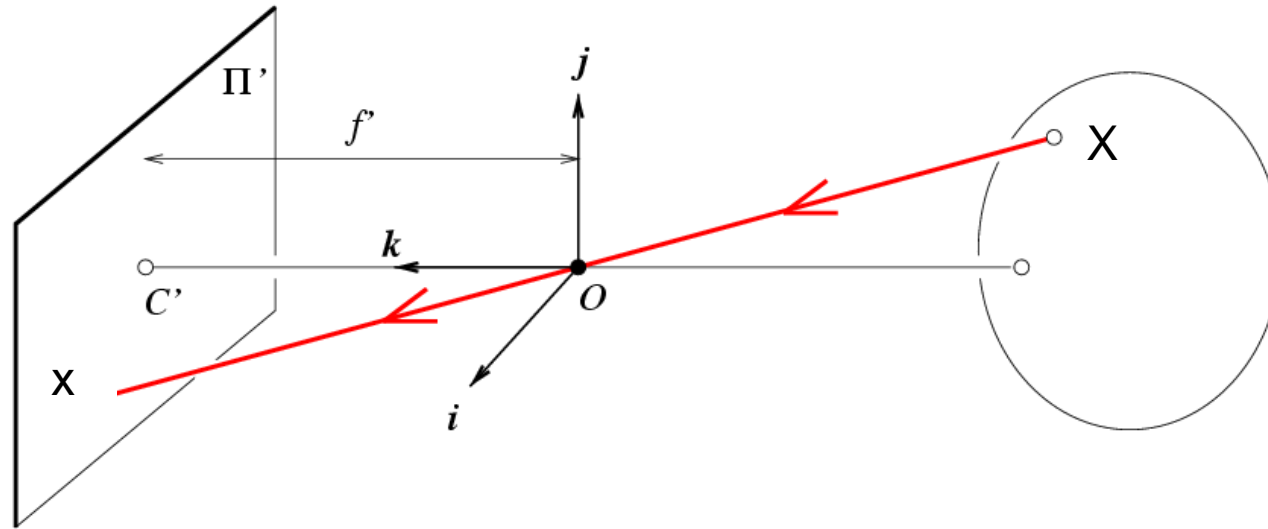


Moti



Recap: projection



$$\mathbf{x} = \mathbf{K}[\mathbf{R} \quad \mathbf{t}] \mathbf{X}$$



$$w \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & s & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

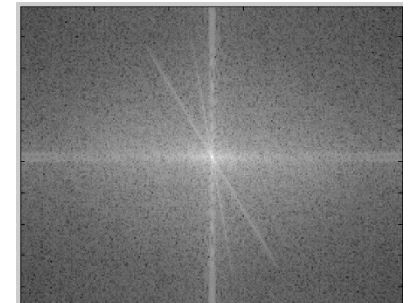
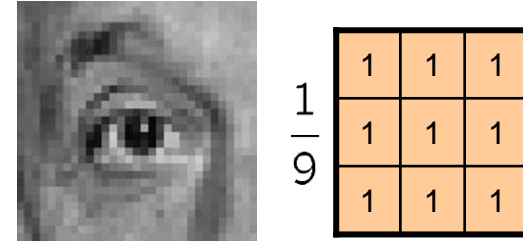
Relating multiple views



Figure Credit: Bundler: Structure from Motion (SfM) for Unordered Image Collections

Recap of Filtering

- Linear filtering is dot product at each position
 - Not a matrix multiplication
 - Can smooth, sharpen, translate (among many other uses)
- We can use the Fourier transform to represent images in the frequency domain.
 - Filtering in the spatial domain is multiplication in the frequency domain.



This lecture

- Image Formation
- Biological Vision
- Light and Color

From the 3D to 2D

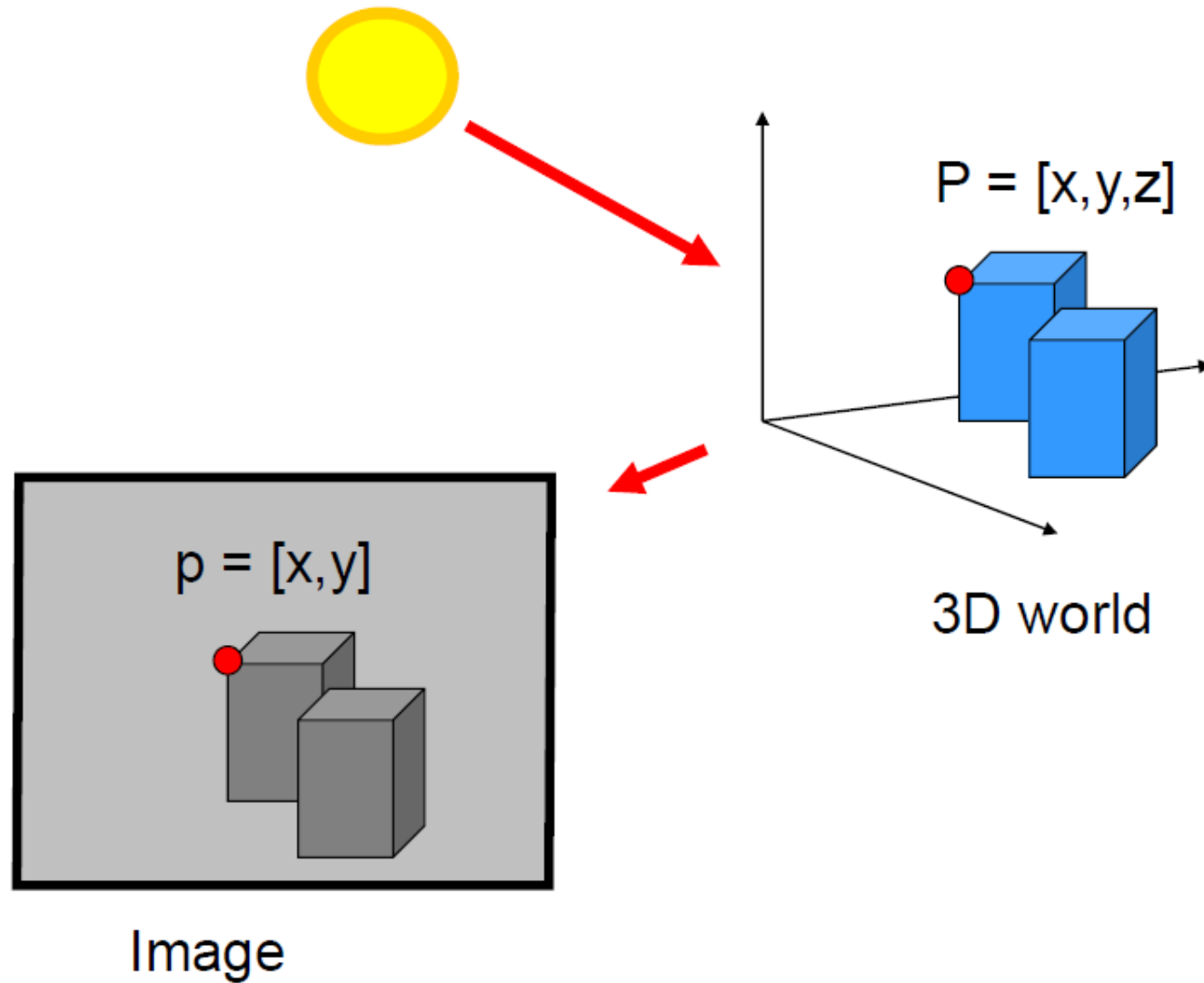
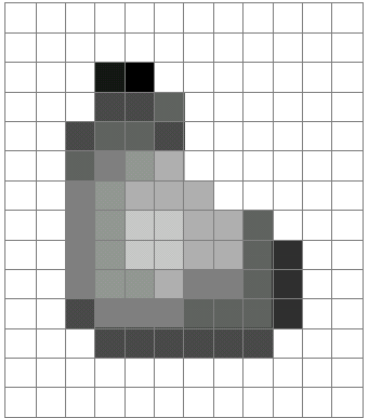
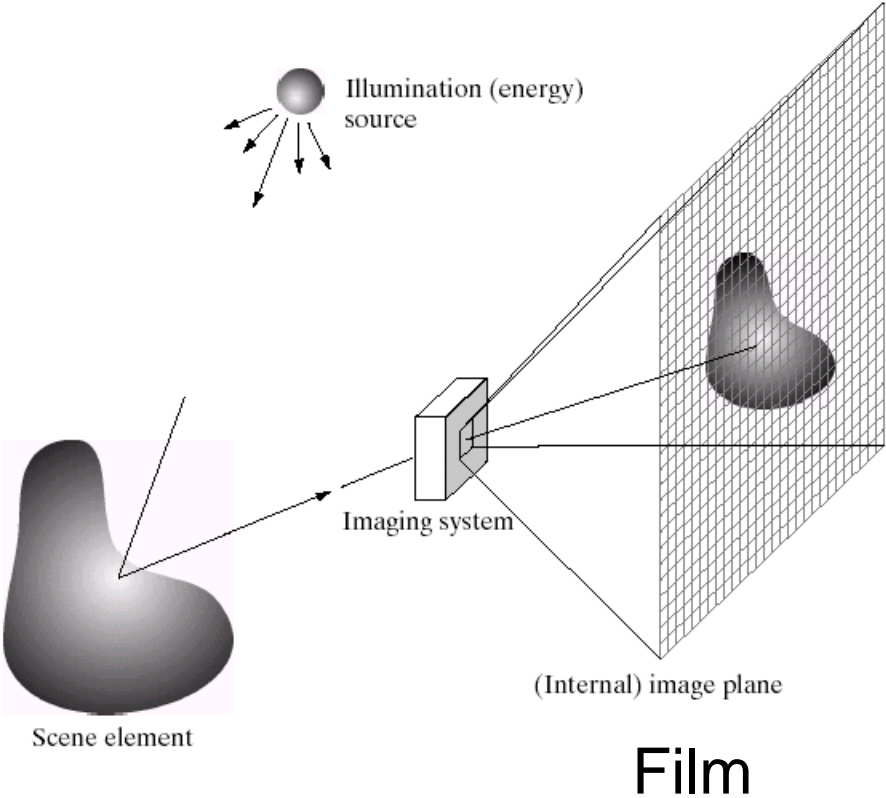
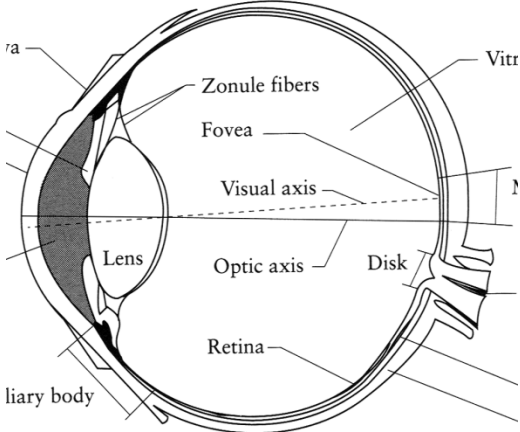


Image Formation



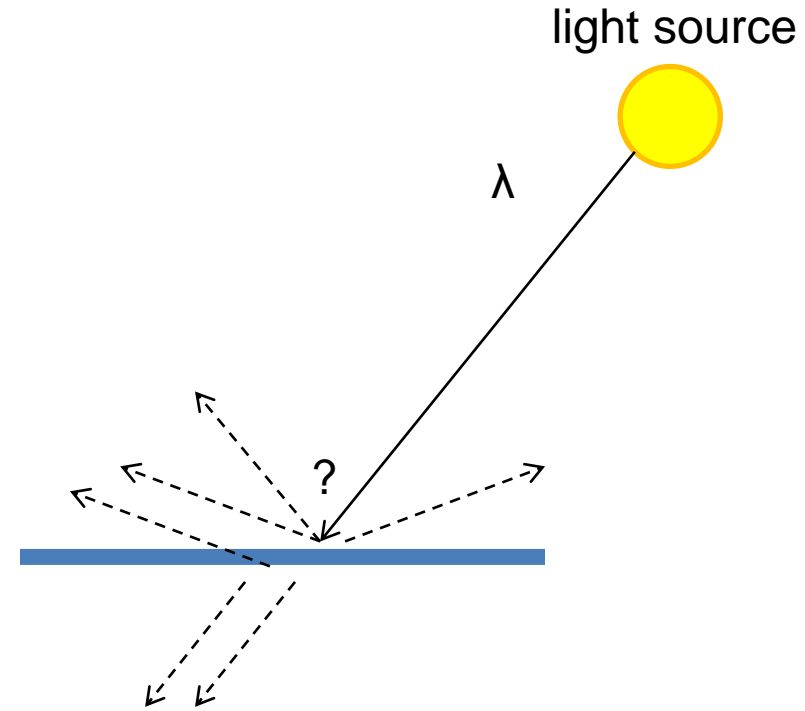
Digital Camera



The Eye

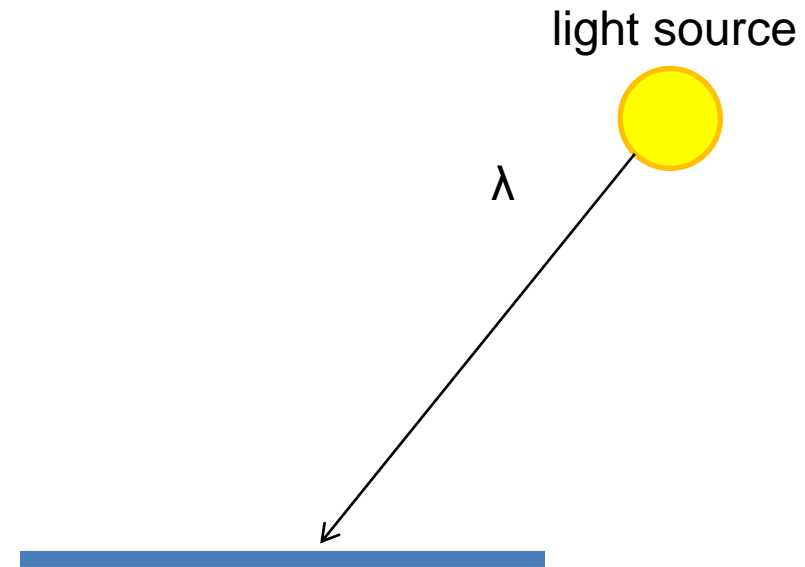
A photon's life choices

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



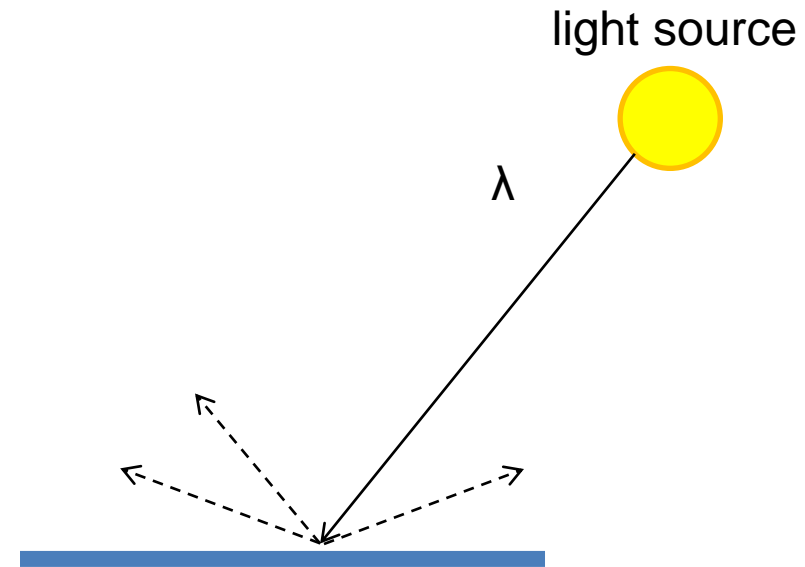
A photon's life choices

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



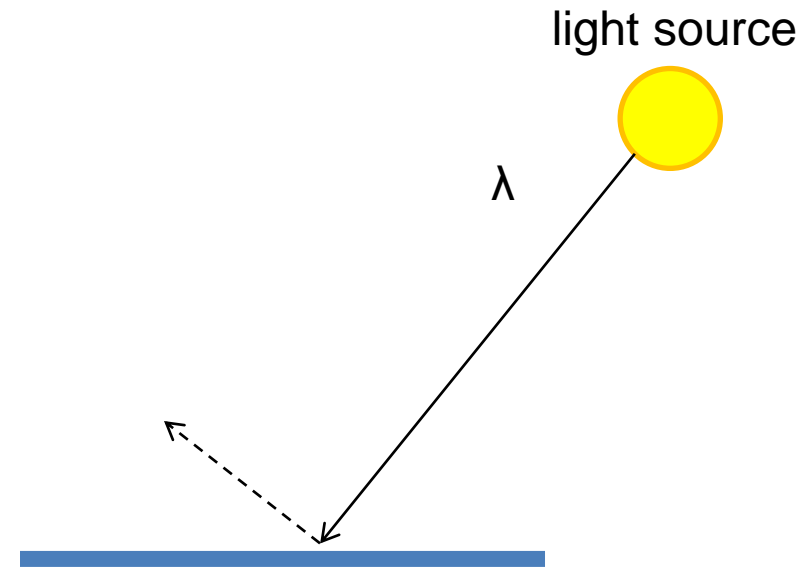
A photon's life choices

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



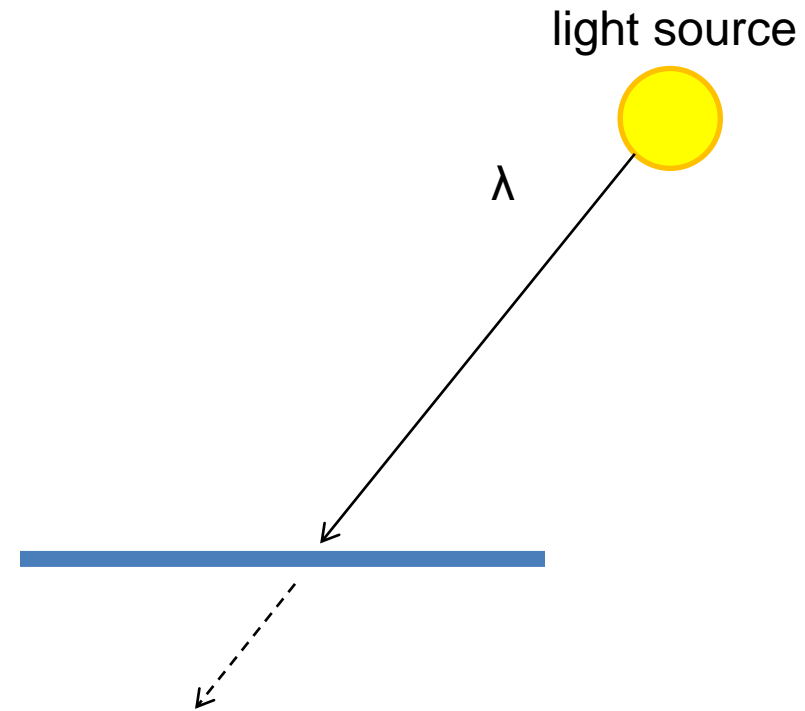
A photon's life choices

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



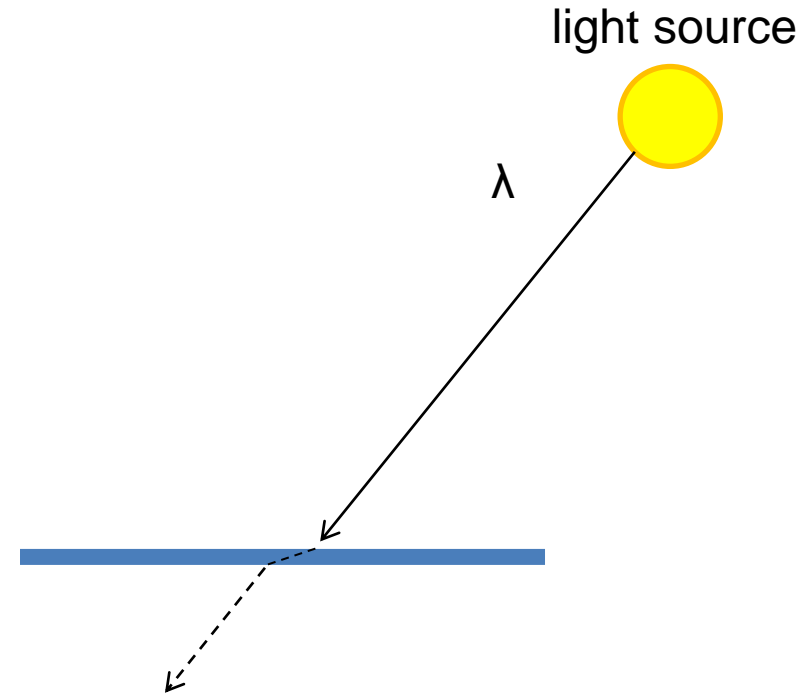
A photon's life choices

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



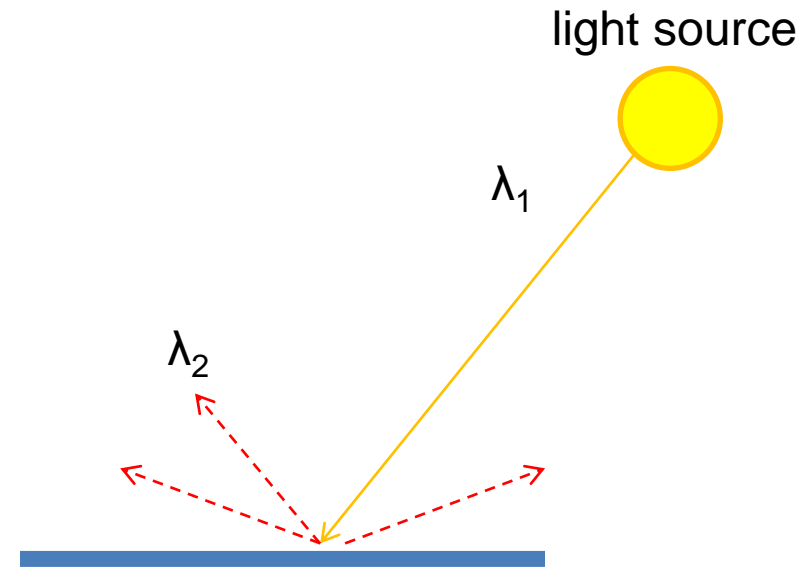
A photon's life choices

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



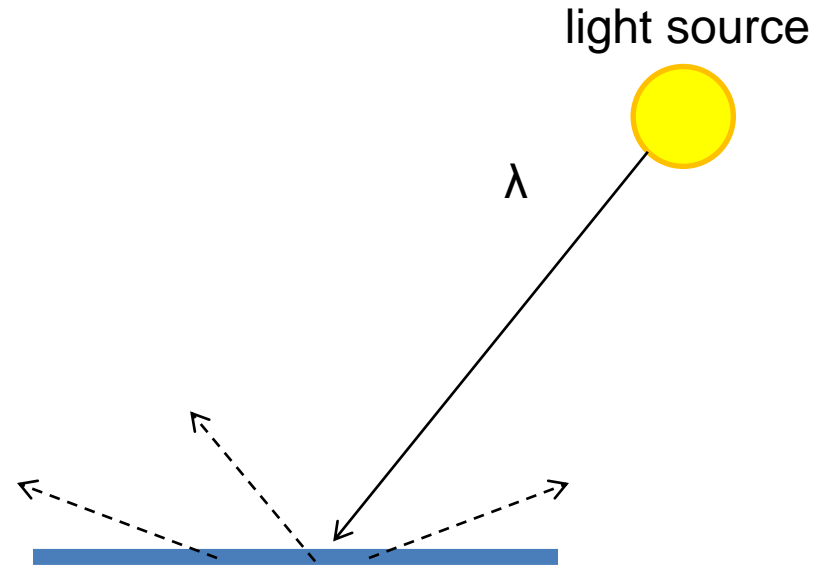
A photon's life choices

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



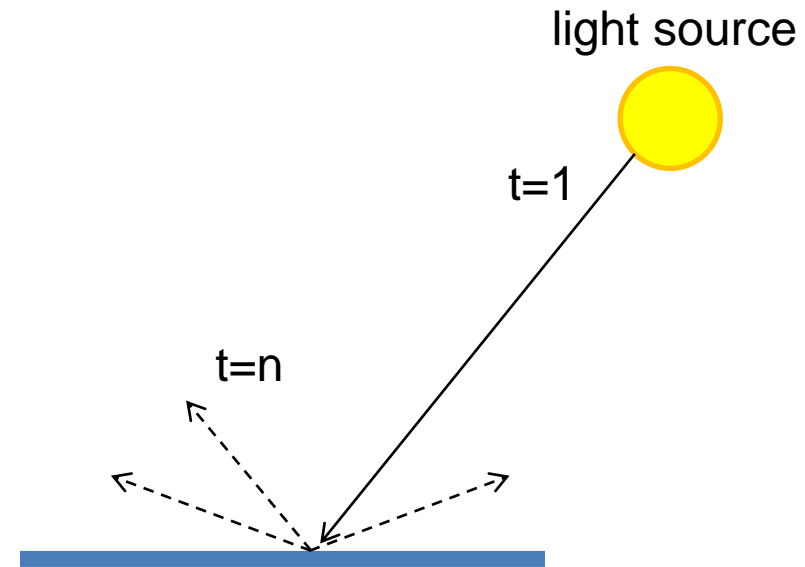
A photon's life choices

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



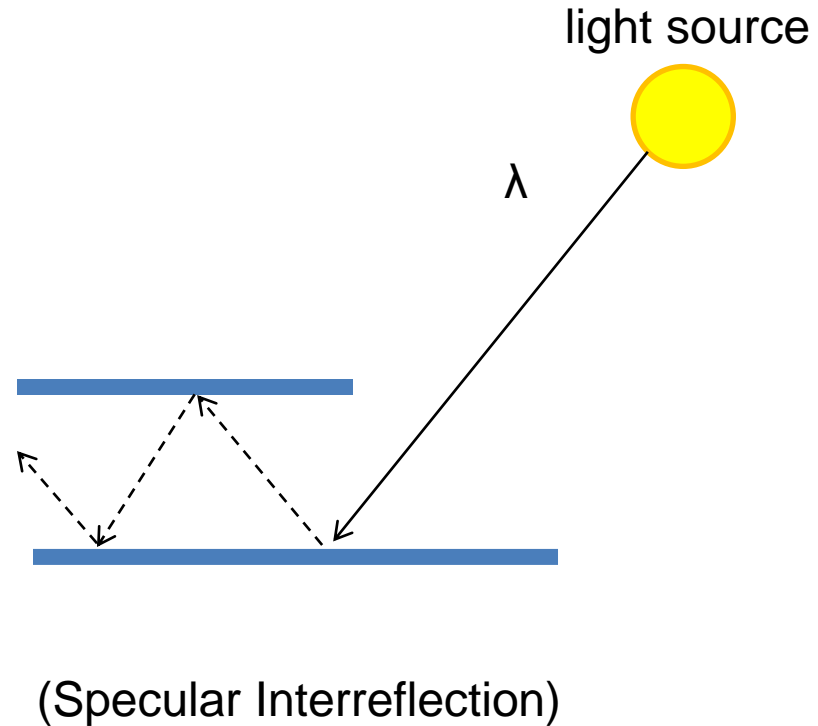
A photon's life choices

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



A photon's life choices

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



Lambertian Reflectance

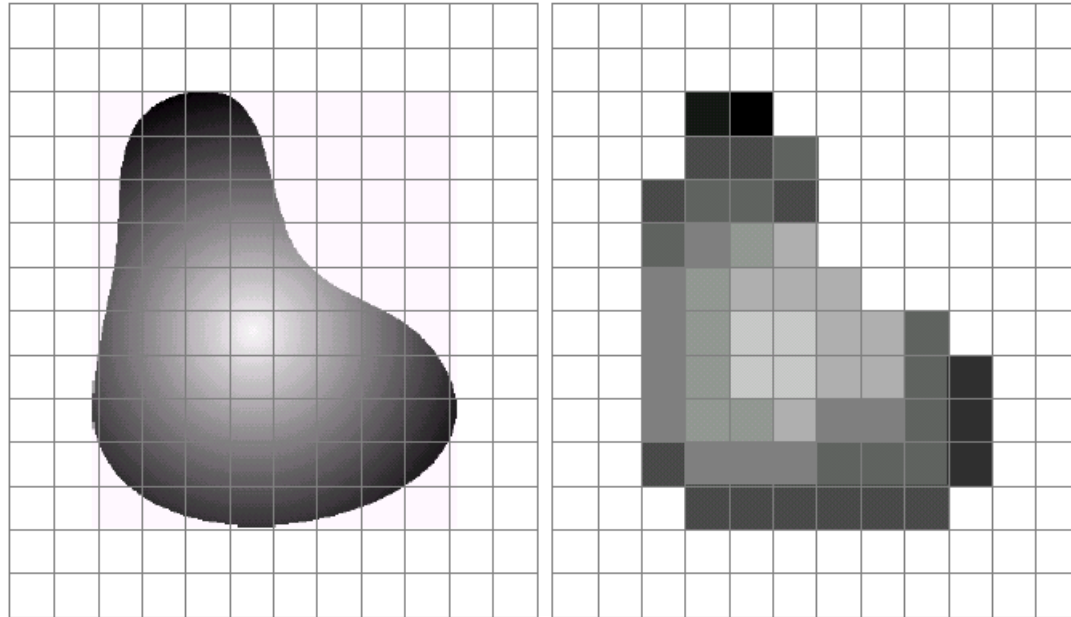
- In computer vision, the complexity of light transport is mostly ignored.
- Surfaces are often assumed to be ideal diffuse reflectors with no dependence on viewing direction.

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)
 - CMOS
 - <http://electronics.howstuffworks.com/digital-camera.htm>

Sensor Array



a b

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



CMOS sensor

Sampling and Quantization

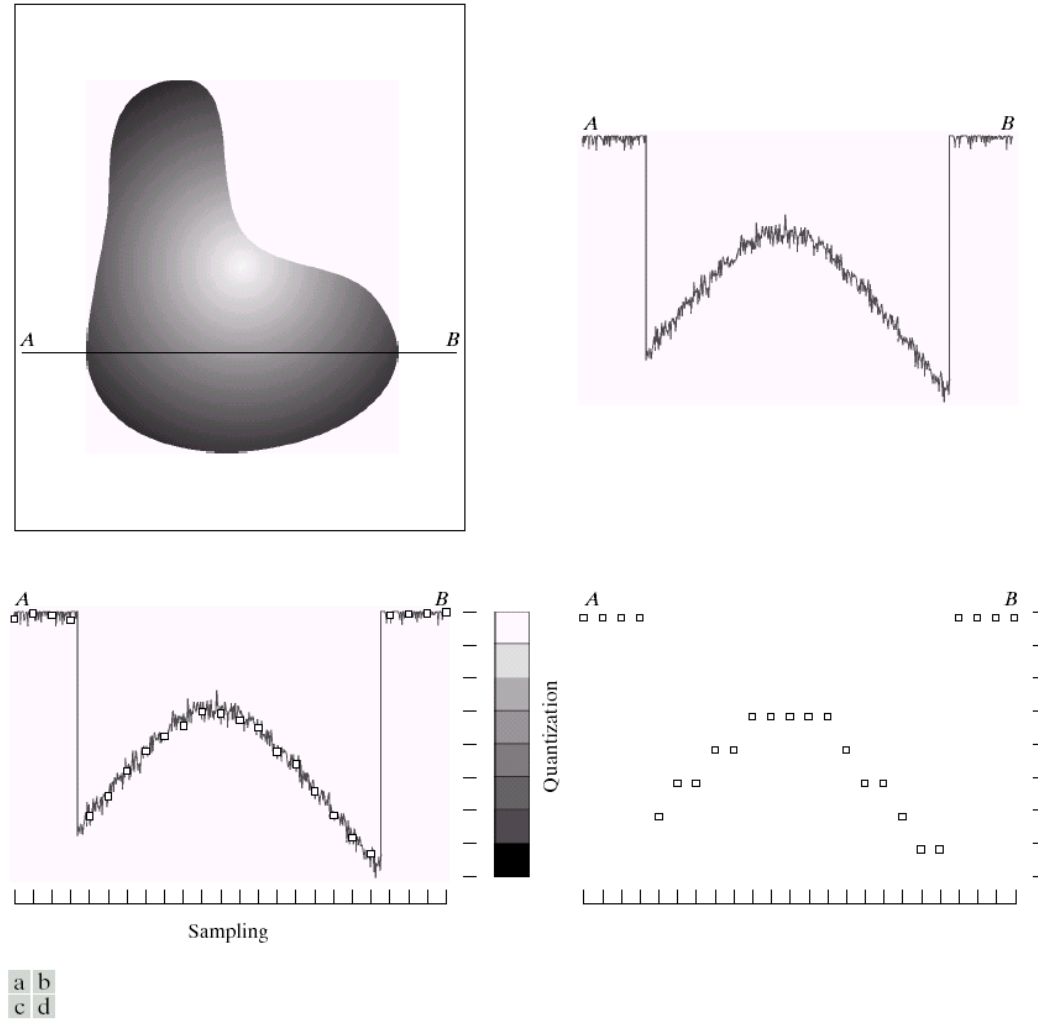
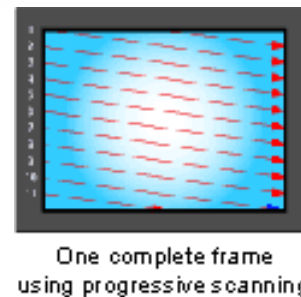
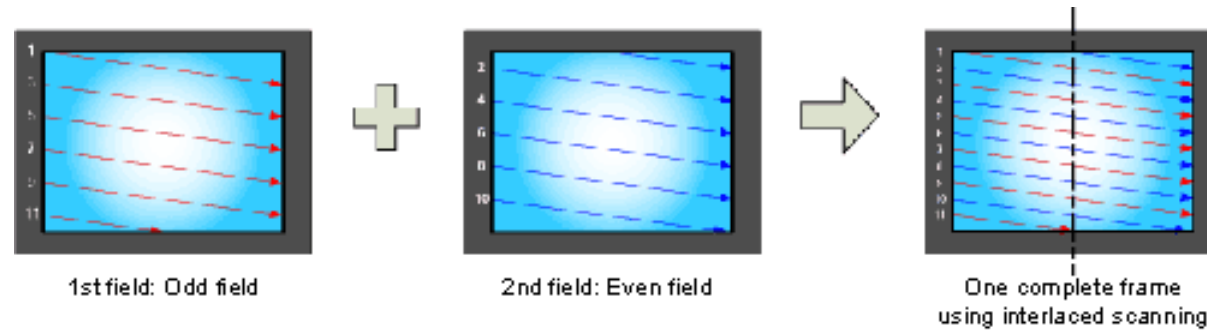


FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Interlace vs. progressive scan



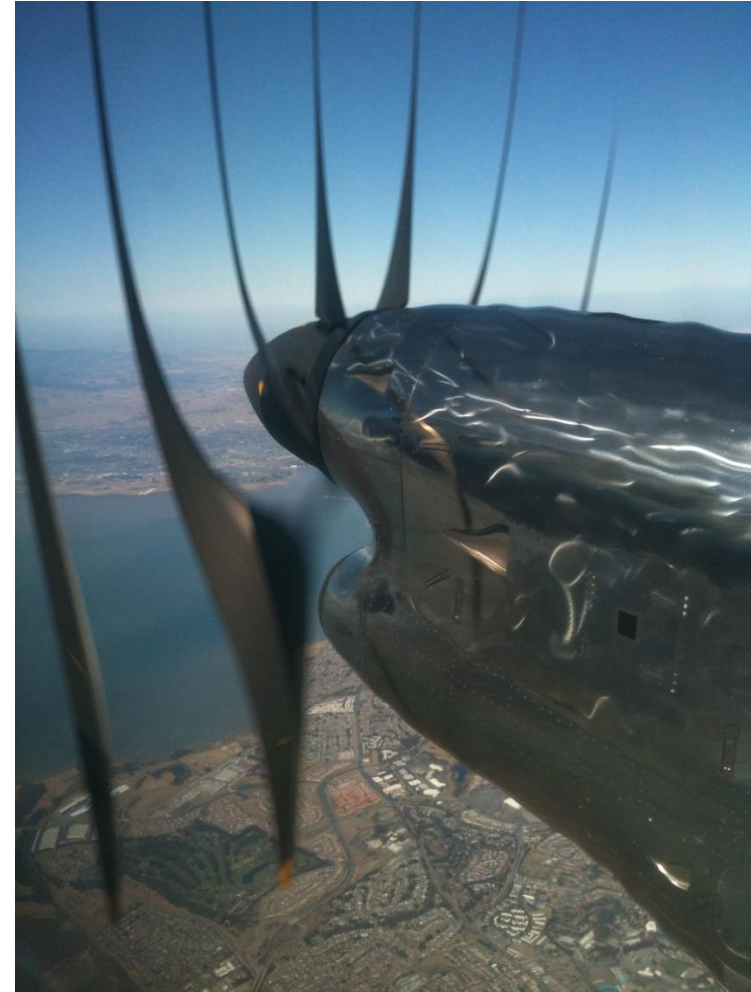
Progressive scan or Global shutter



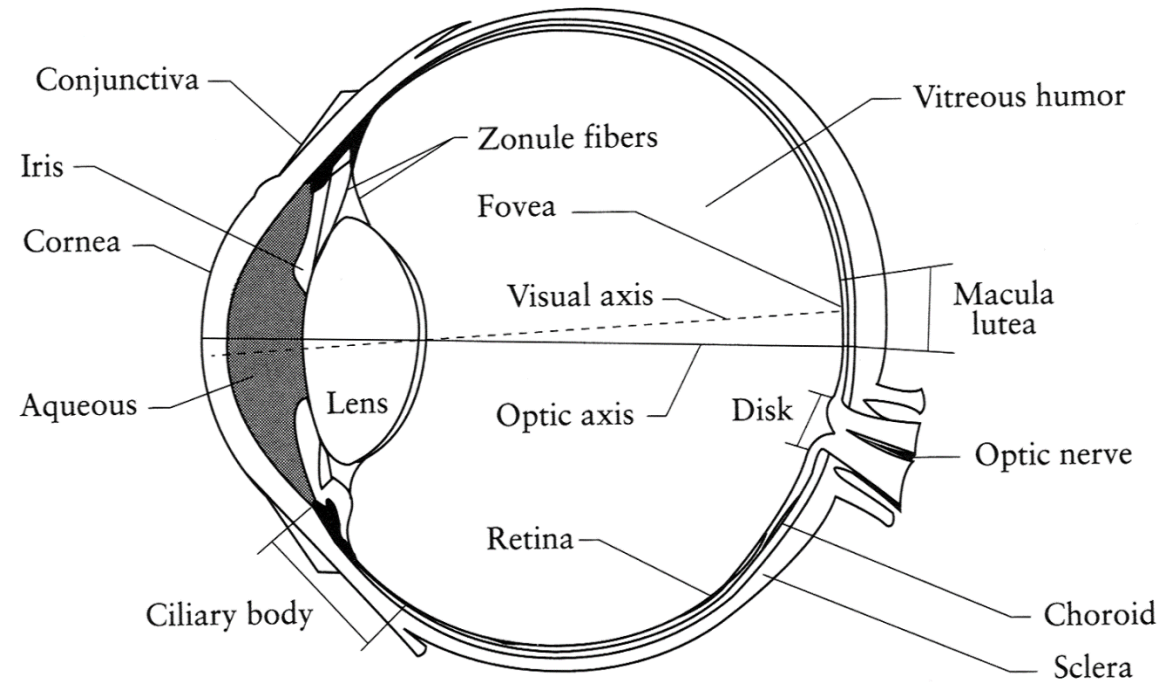
Interlaced



Rolling Shutter



The Eye

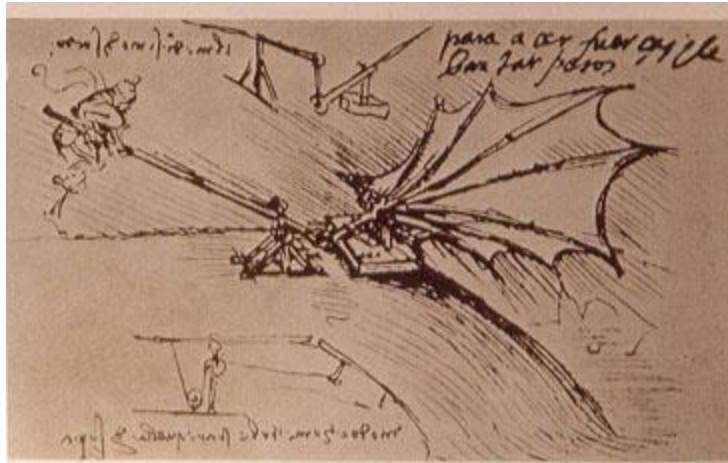


- The human eye is a camera!
 - **Iris** - colored annulus with radial muscles
 - **Pupil** - the hole (aperture) whose size is controlled by the iris
 - What's the "film"?
 - photoreceptor cells (rods and cones) in the **retina**

Aside: why do we care about human vision in this class?

- We don't, necessarily.

Ornithopters



Why do we care about human vision?

- We don't, necessarily.
- But cameras necessarily imitate the frequency response of the human eye, so we should know that much.
- Also, computer vision probably wouldn't get as much scrutiny if biological vision (especially human vision) hadn't proved that it was possible to make important judgements from 2d images.

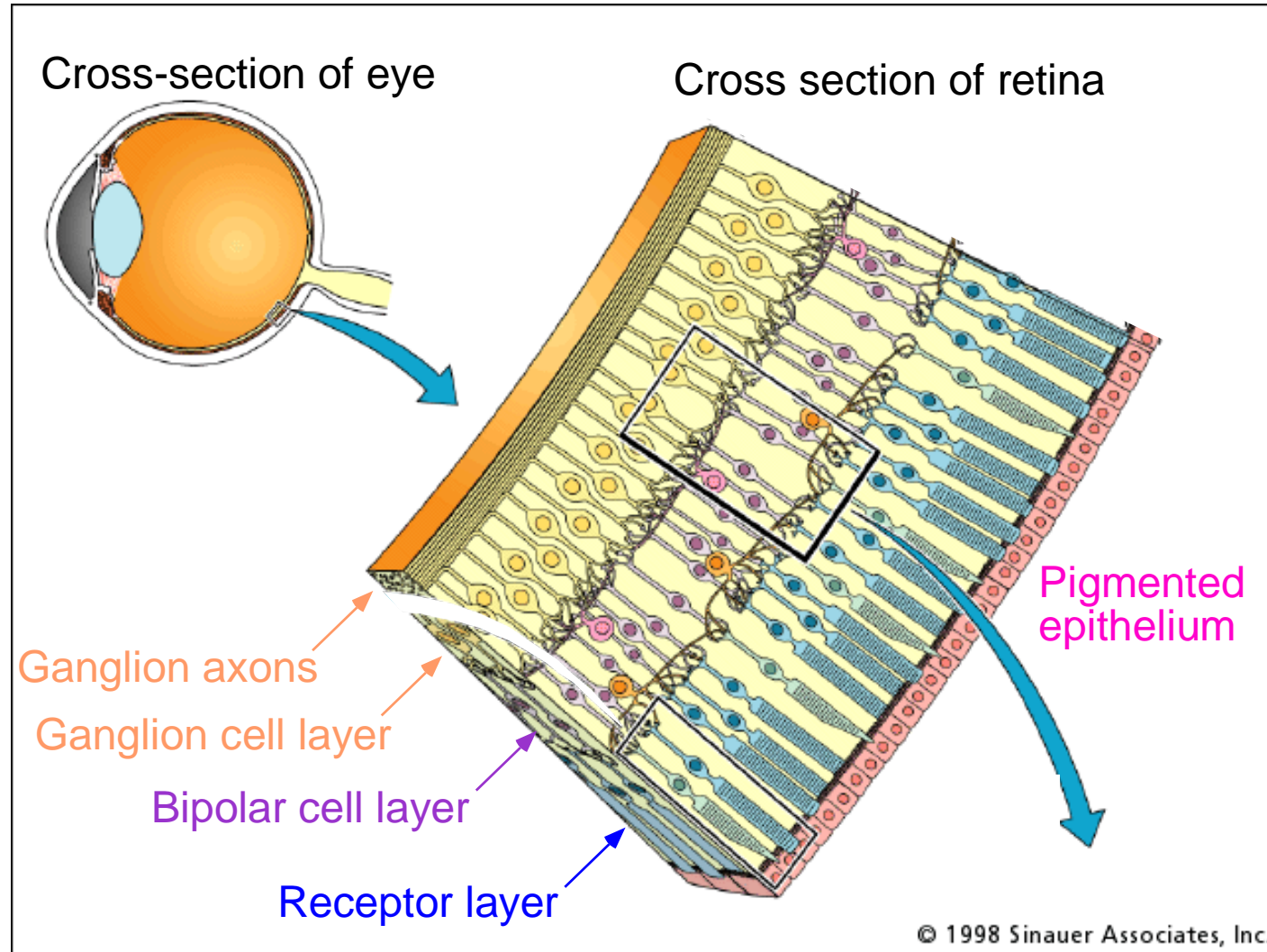
Does computer vision “understand” images?

"Can machines fly?" The answer is yes, because airplanes fly.

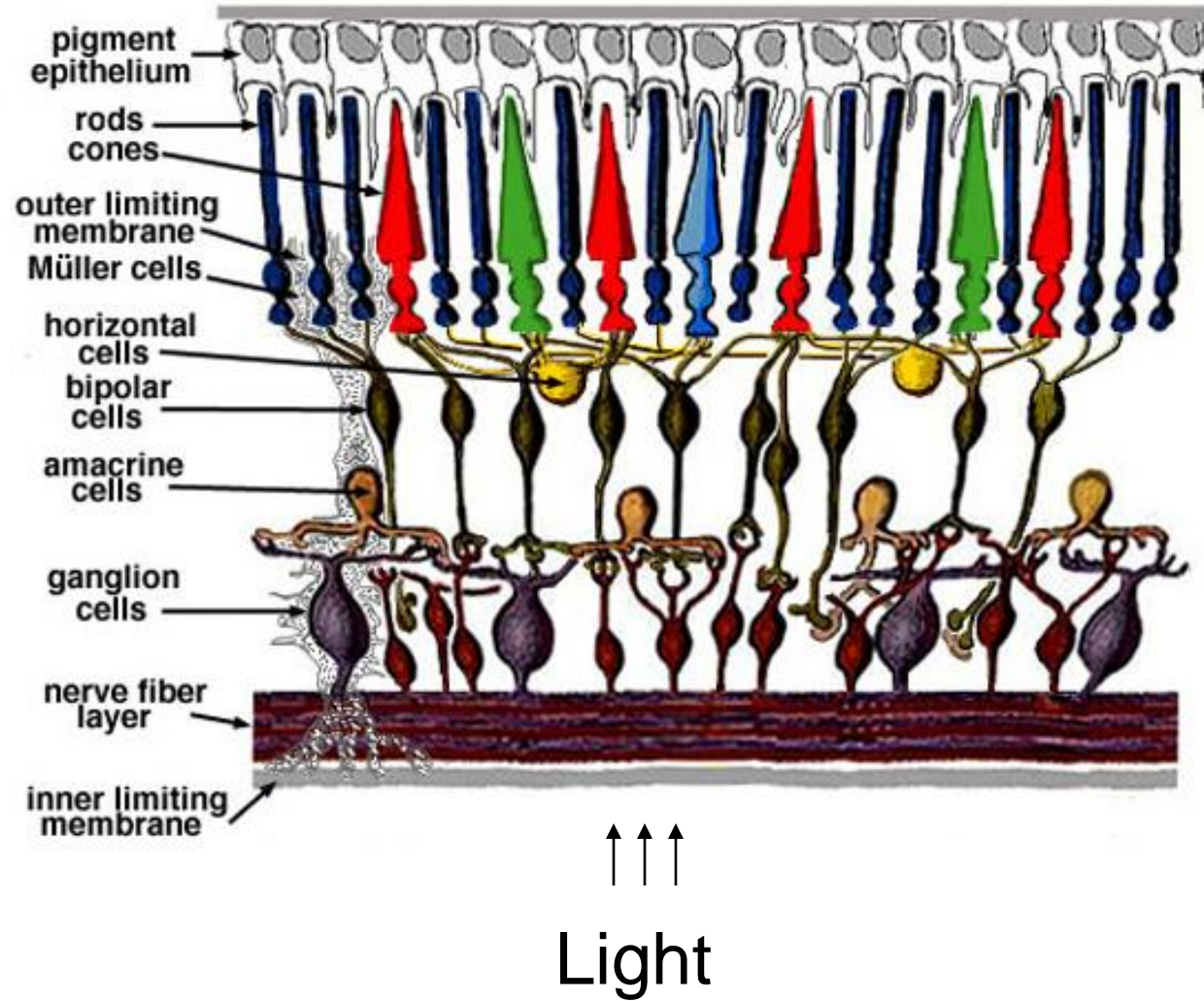
"Can machines swim?" The answer is no, because submarines don't swim.

"Can machines think?" Is this question like the first, or like the second?

The Retina



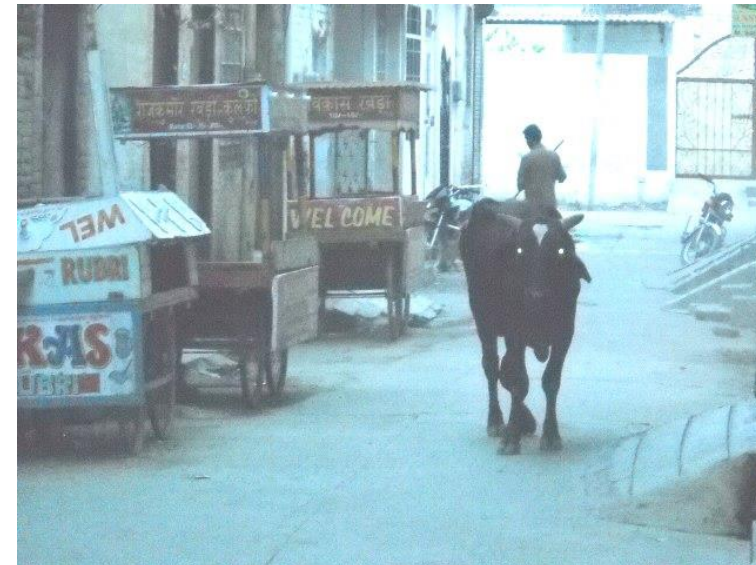
Retina up-close



What humans don't have: tapetum lucidum



Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.



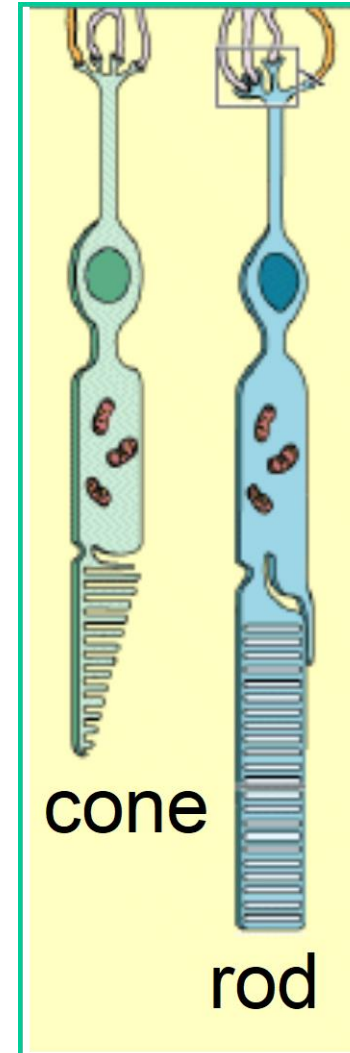
Two types of light-sensitive receptors

Cones

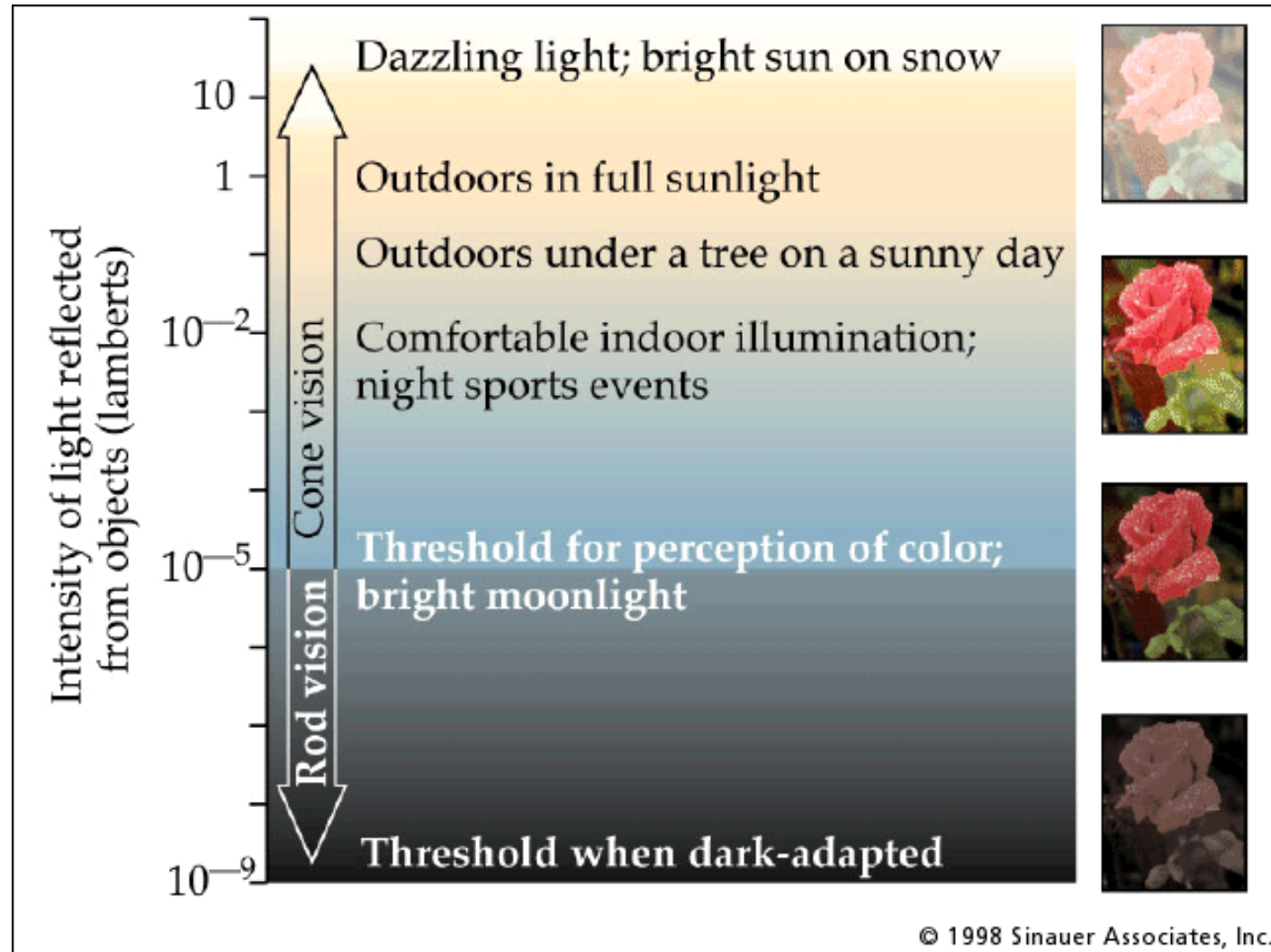
cone-shaped
less sensitive
operate in high light
color vision

Rods

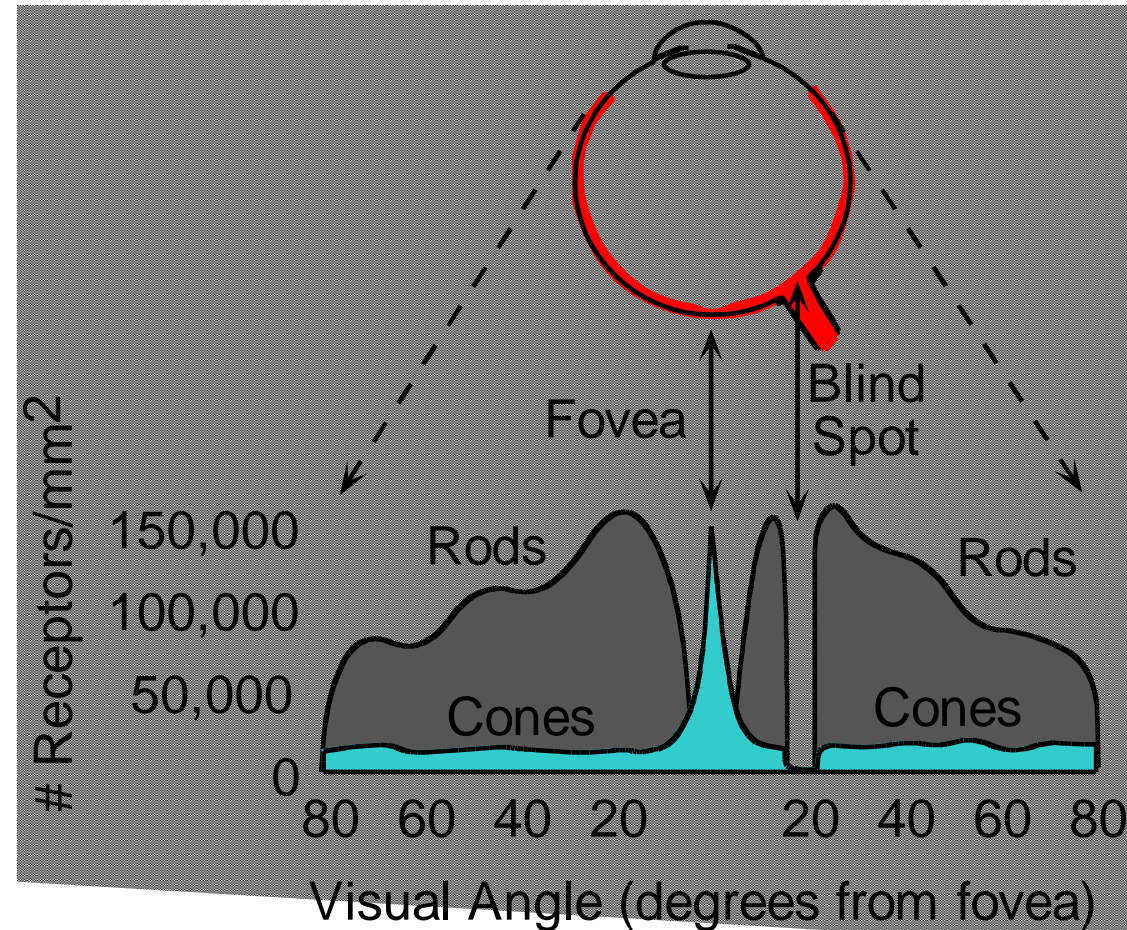
rod-shaped
highly sensitive
operate at night
gray-scale vision



Rod / Cone sensitivity



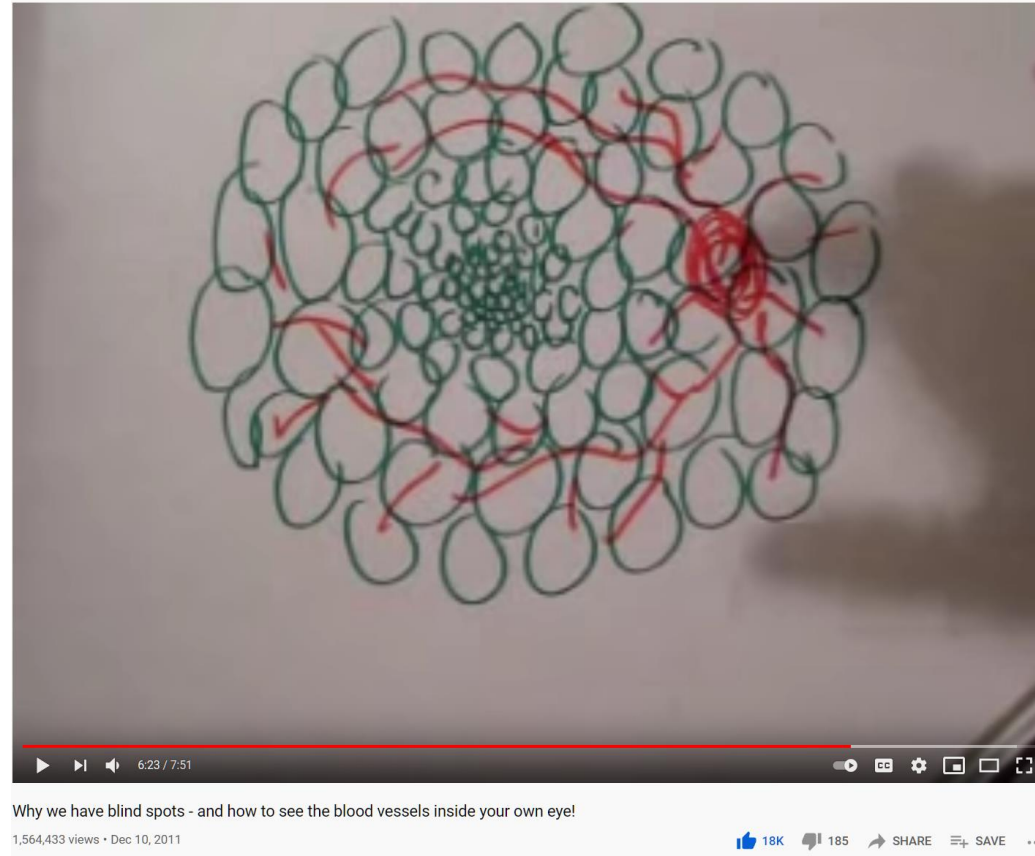
Distribution of Rods and Cones



Night Sky: why are there more stars off-center?

Averted vision: http://en.wikipedia.org/wiki/Averted_vision

Wait, the blood vessels are in front of the photoreceptors??



https://www.youtube.com/watch?v=L_W-IXqoxHA

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.

- Ocular microtremor (OMT)

- Involuntary. high frequency (up to 80Hz), small amplitude.

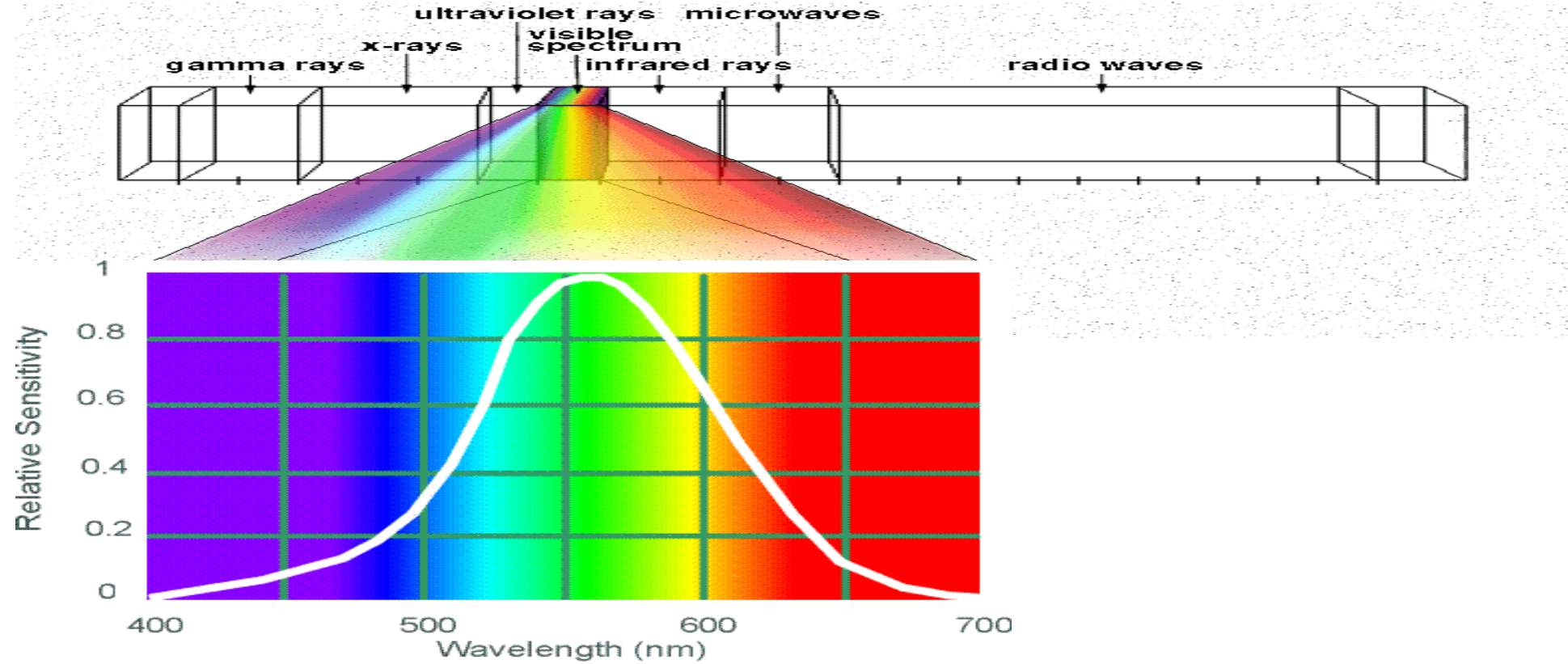
- Smooth pursuit – tracking an object

Intermission

Slow mo guys – Saccades and CRTs

- <https://youtu.be/Fmg9ZOHESgQ?t=21s>
- <https://youtu.be/3BJU2drirtCM>

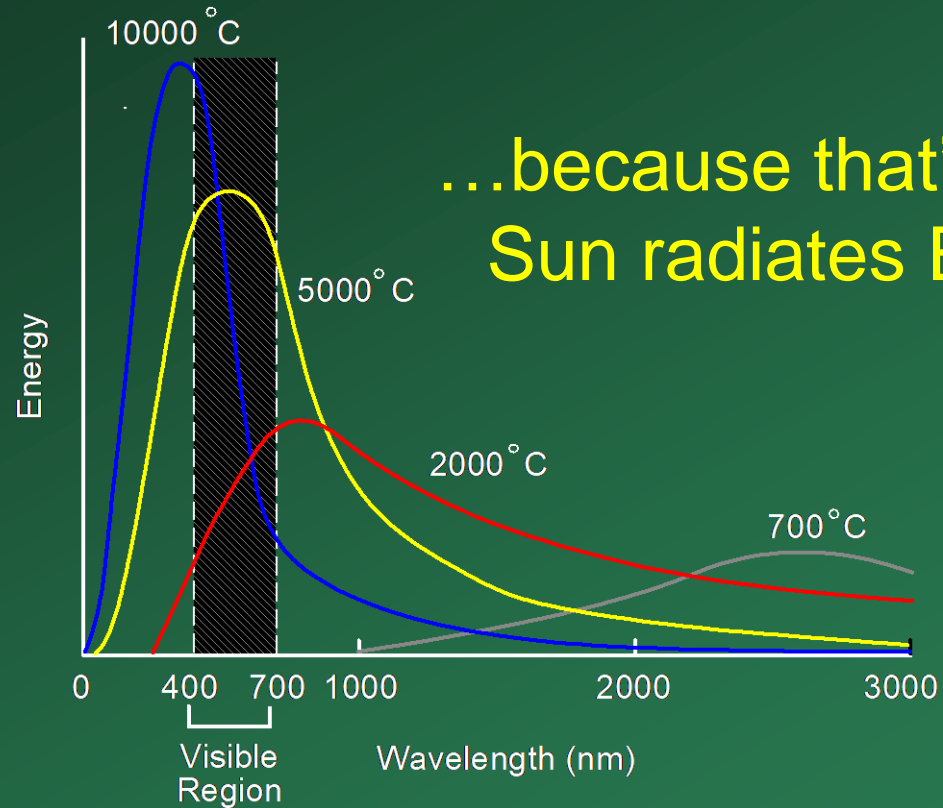
Electromagnetic Spectrum



Human Luminance Sensitivity Function

Visible Light

Why do we see light of these wavelengths?

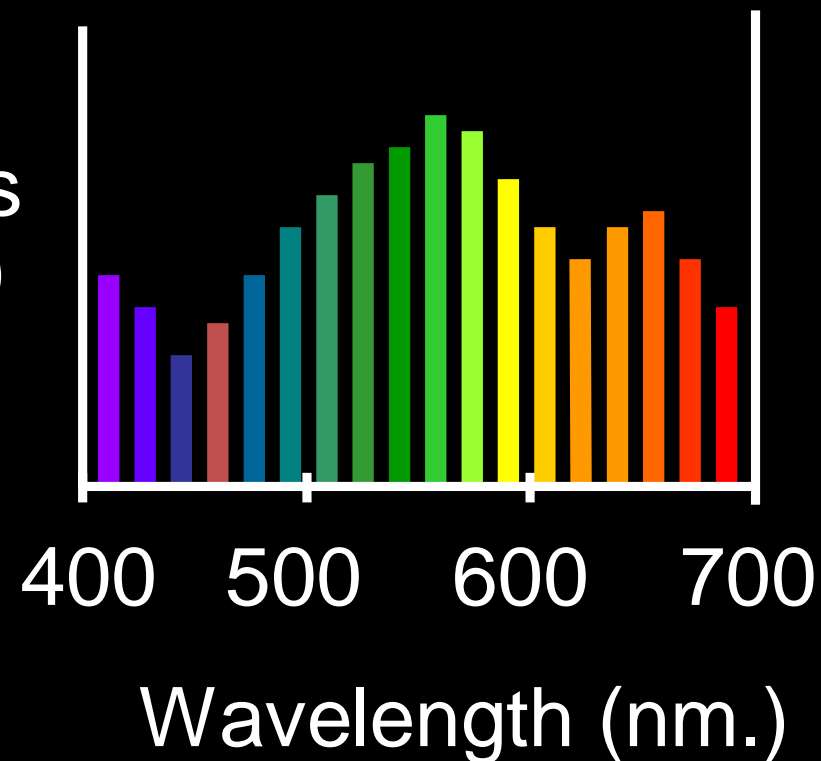


...because that's where the Sun radiates EM energy

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.

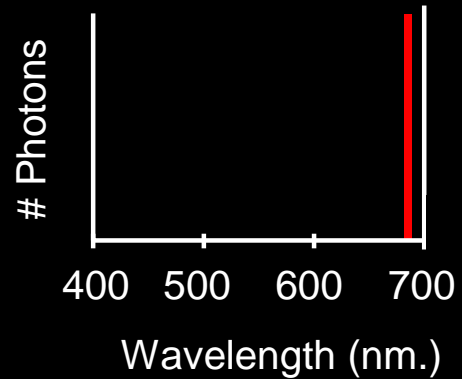
Photons
(per ms.)



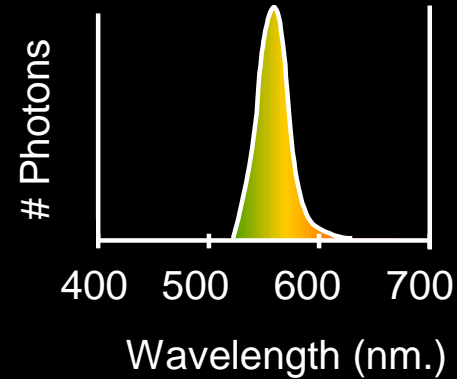
The Physics of Light

Some examples of the spectra of light sources

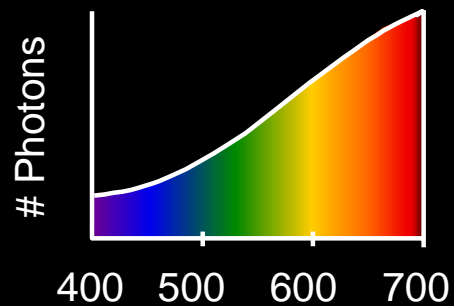
A. Ruby Laser



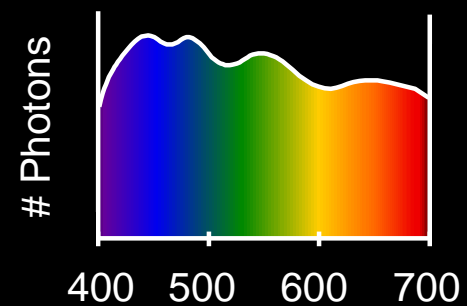
B. Gallium Phosphide Crystal



C. Tungsten Lightbulb

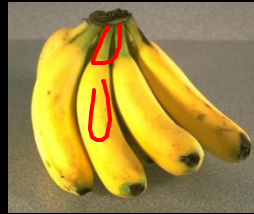


D. Normal Daylight

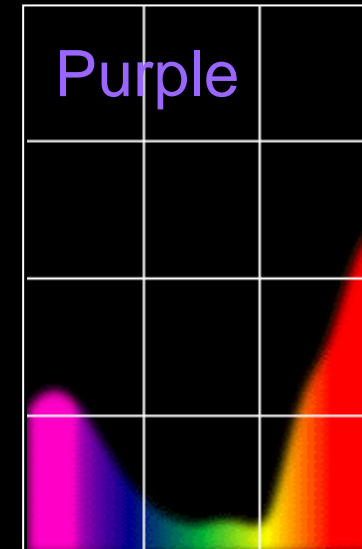
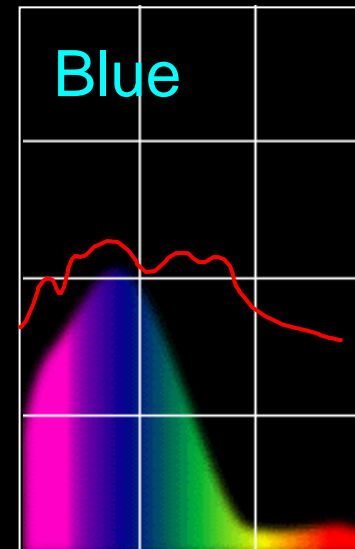
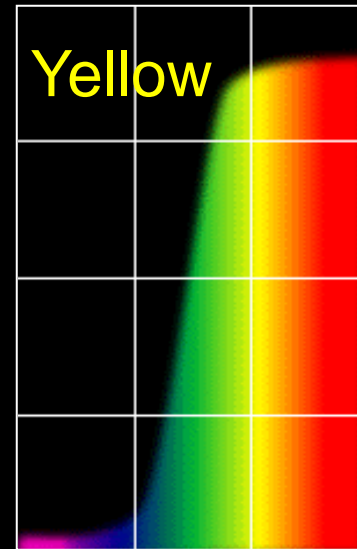
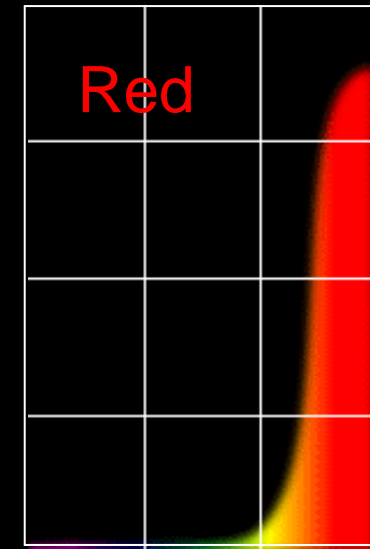


The Physics of Light

Some examples of the reflectance spectra of surfaces



% Photons Reflected



400 700

400 700

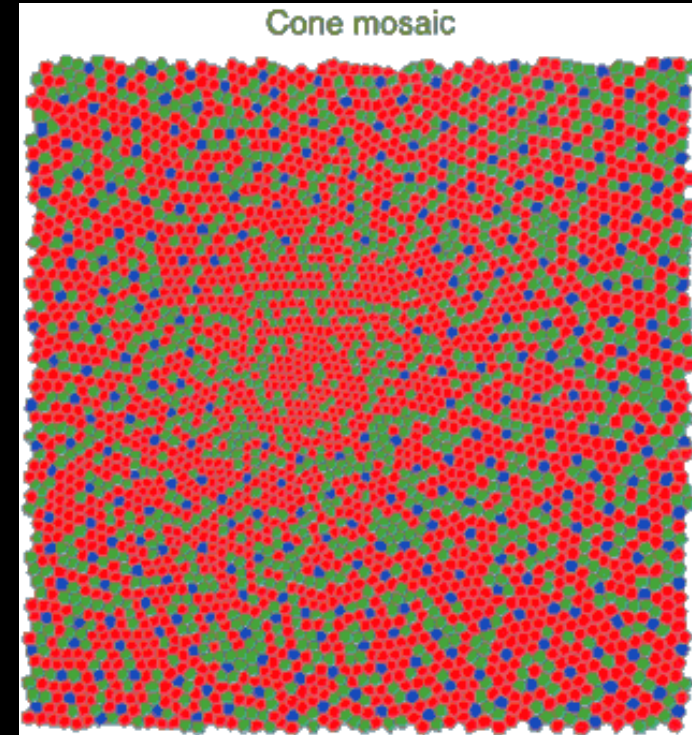
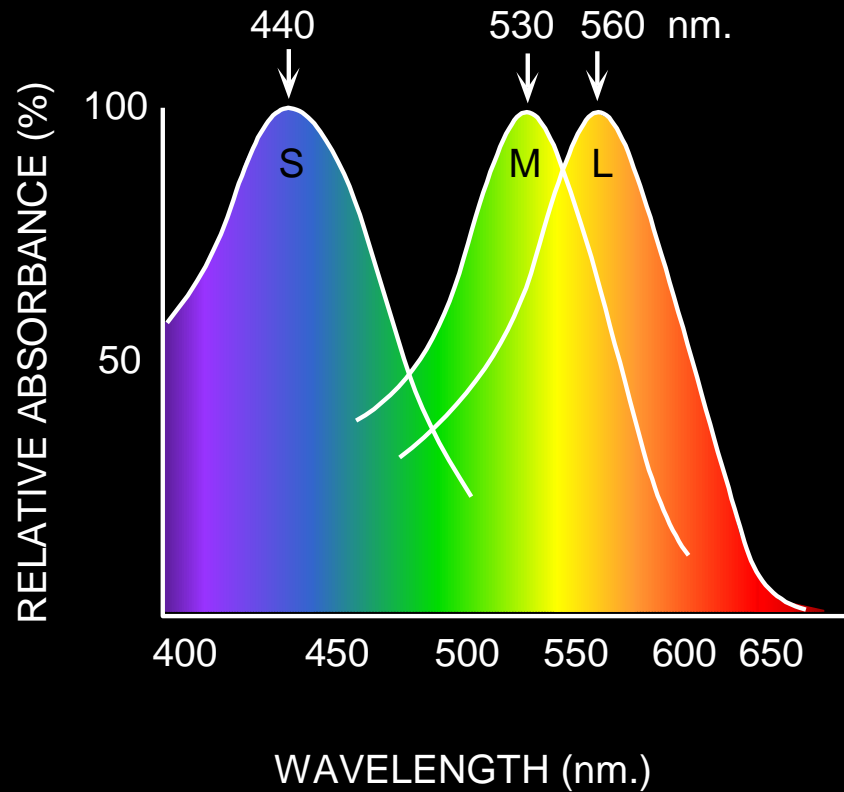
400 700

400 700

Wavelength (nm)

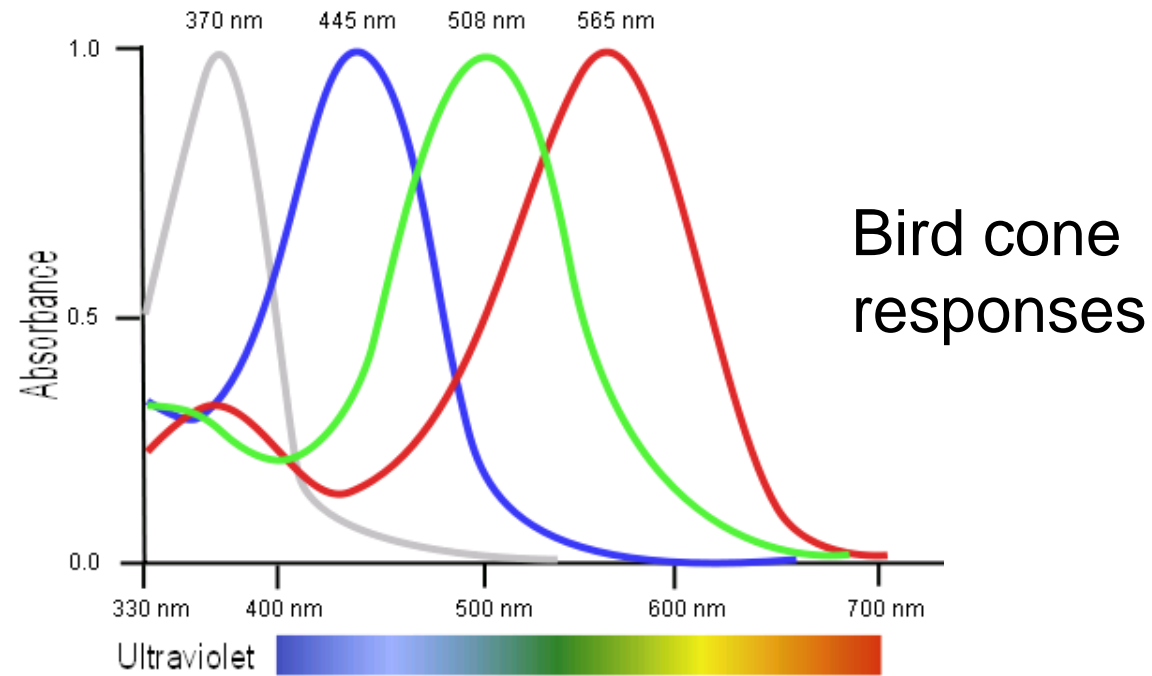
Physiology of Color Vision

Three kinds of cones:



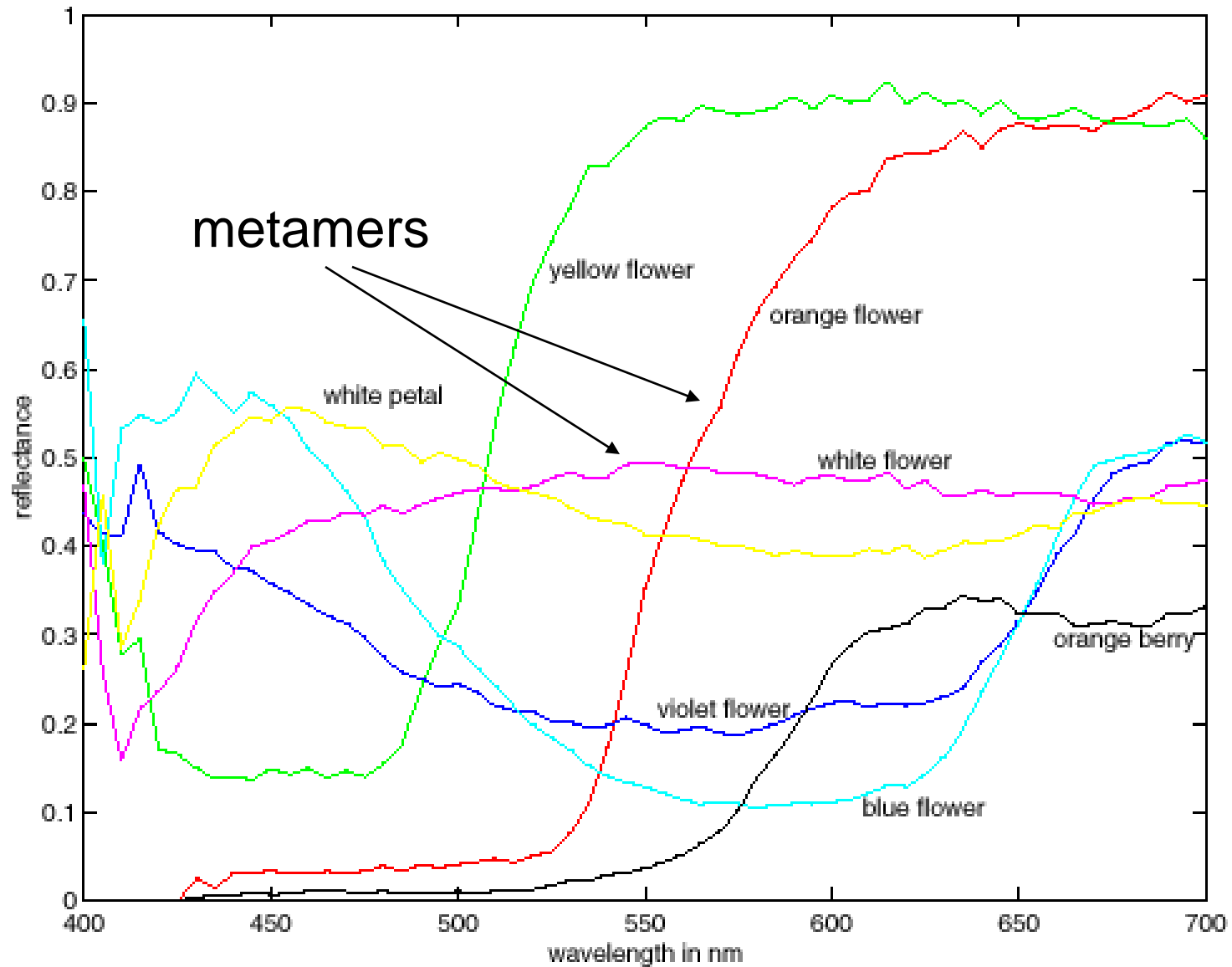
- Why are M and L cones so close?
- Why are there 3?

Tetrachromatism



- Most birds, and many other animals, have cones for ultraviolet light.
- Some humans, mostly female, seem to have slight tetrachromatism.

More Spectra



Color can be ambiguous



Color can be ambiguous



The dress



From Wikipedia, the free encyclopedia

For other uses, see [The Dress](#).

The dress is a photograph that became a [viral](#) internet sensation on 26 February 2015, when viewers disagreed over whether the dress pictured was coloured black and blue, or white and gold. The phenomenon revealed differences in human colour perception, which have been the subject of ongoing scientific investigations into [neuroscience](#) and [vision science](#), producing a number of papers published in peer-reviewed science journals.

The photo originated from a washed-out colour photograph of a [dress](#) posted on the [social networking service Facebook](#). Within the first week after the surfacing of the image, more than 10 million tweets mentioned the dress, using [hashtags](#) such as [#thedress](#), [#whiteandgold](#), and [#blackandblue](#). Although the colour of the dress was eventually confirmed as black and blue,^{[3][4]} the image prompted many discussions, with users discussing their different perceptions of the dress's colour. Members of the scientific community began to investigate the photo for fresh insights into human [colour vision](#).

The dress itself, which was identified as a product of the retailer Roman Originals, experienced a major surge in sales as a result of the incident. The retailer also produced a one-off version of the dress in white and gold as a charity campaign.

Contents [\[hide\]](#)

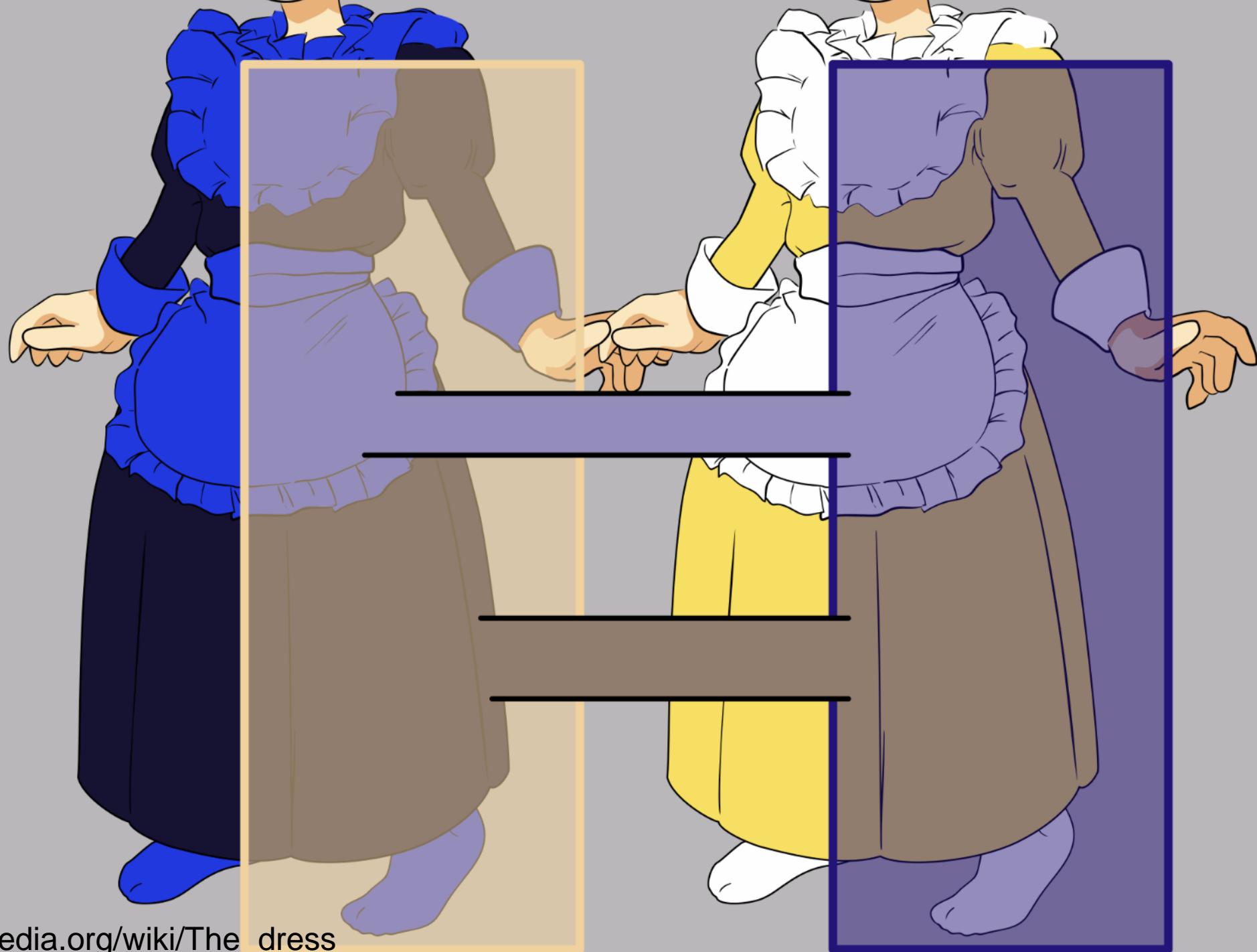
The dress



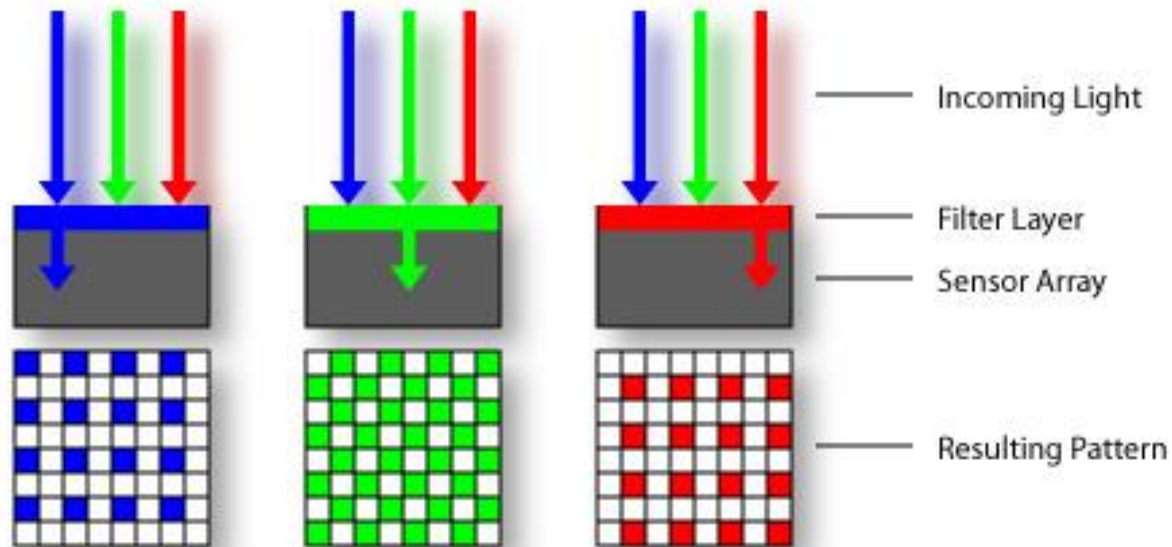
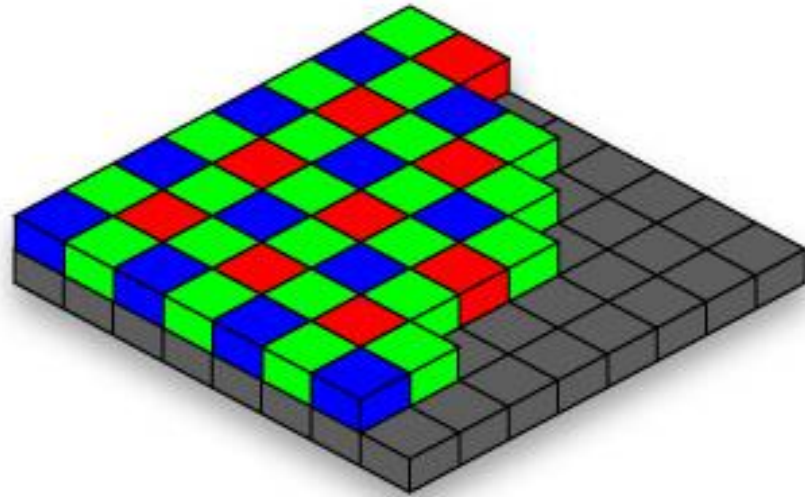
The original *The dress* picture

Designer

Roman Originals^[1]

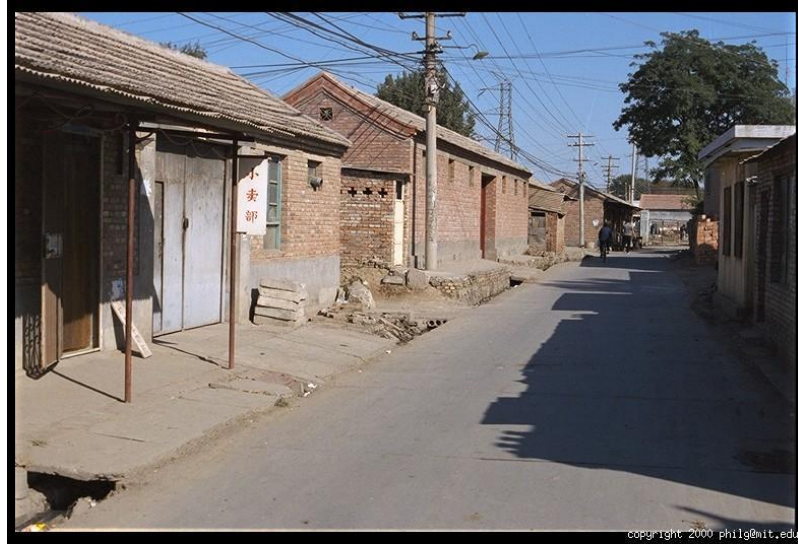


Practical Color Sensing: Bayer Grid



- Estimate RGB at 'G' cells from neighboring values

Color Image



Images in ~~Matlab~~ Python

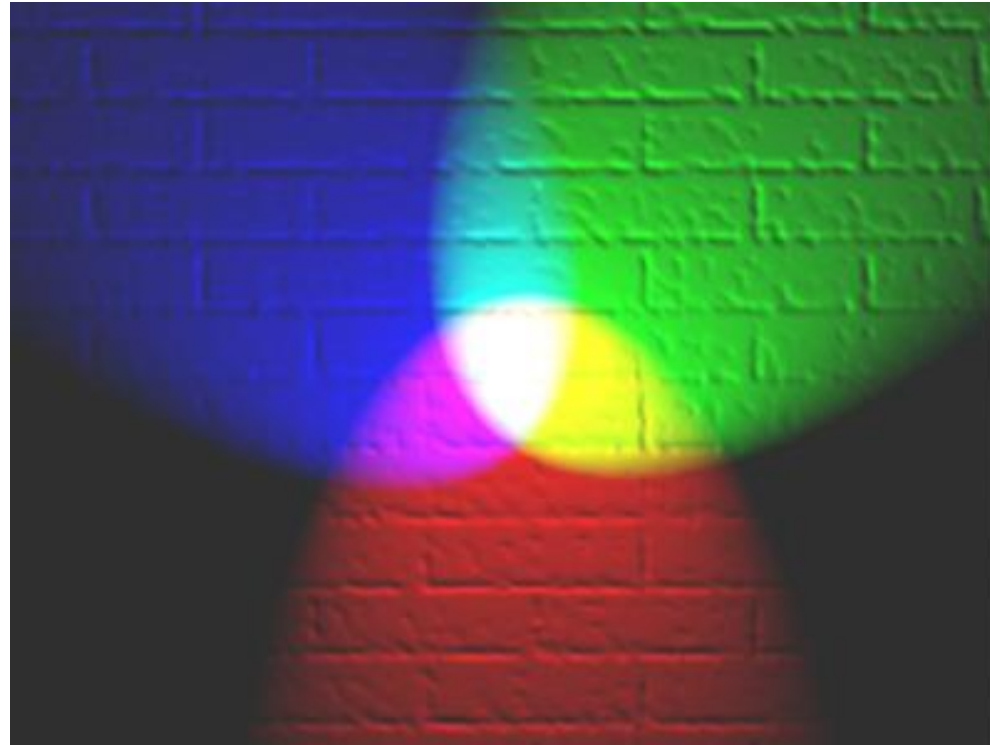
- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
 - $im(0,0,0)$ = top-left pixel value in R-channel
 - $im(y, x, b)$ = y pixels down, x pixels to right in the b^{th} channel
 - $im(N-1, M-1, 2)$ = bottom-right pixel in B-channel

The diagram illustrates an RGB image matrix. A large 10x10 grid of numerical values represents the image. A blue arrow labeled 'row' points downwards on the left side, and another blue arrow labeled 'column' points to the right above the grid. To the right of the grid, three smaller 2x2 grids are shown, labeled 'R', 'G', and 'B', representing the Red, Green, and Blue channels respectively. The 'R' channel is a 10x10 grid, the 'G' channel is a 10x2 grid, and the 'B' channel is a 10x2 grid. The values in the 'R' channel are the first 10 columns of the main grid. The values in the 'G' channel are the 11th and 12th columns of the main grid. The values in the 'B' channel are the 13th and 14th columns of the main grid. The main grid values are as follows:

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

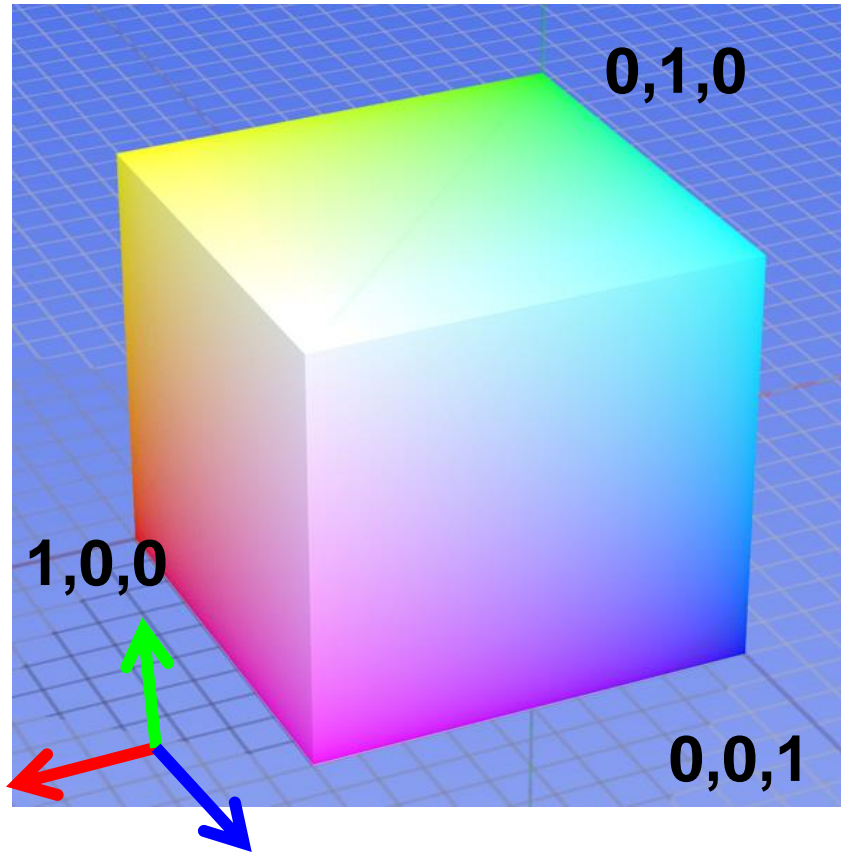
Color spaces

- How can we represent color?



Color spaces: RGB

Default color space



Some drawbacks

- Strongly correlated channels
- Non-perceptual



R
(G=0,B=0)



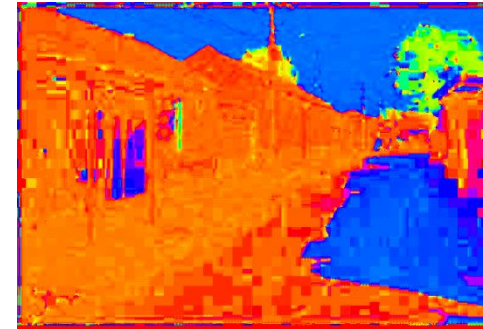
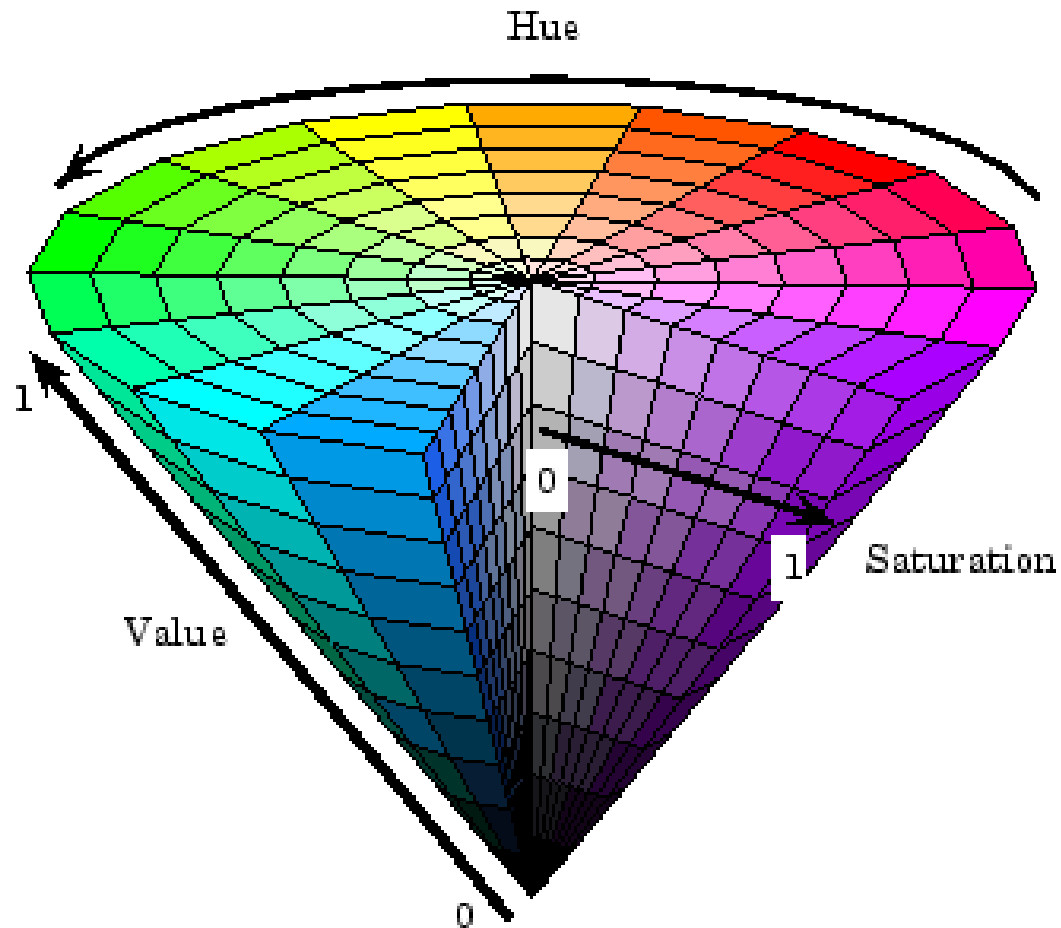
G
(R=0,B=0)



B
(R=0,G=0)

Color spaces: HSV

Intuitive color space



H
(S=1,V=1)



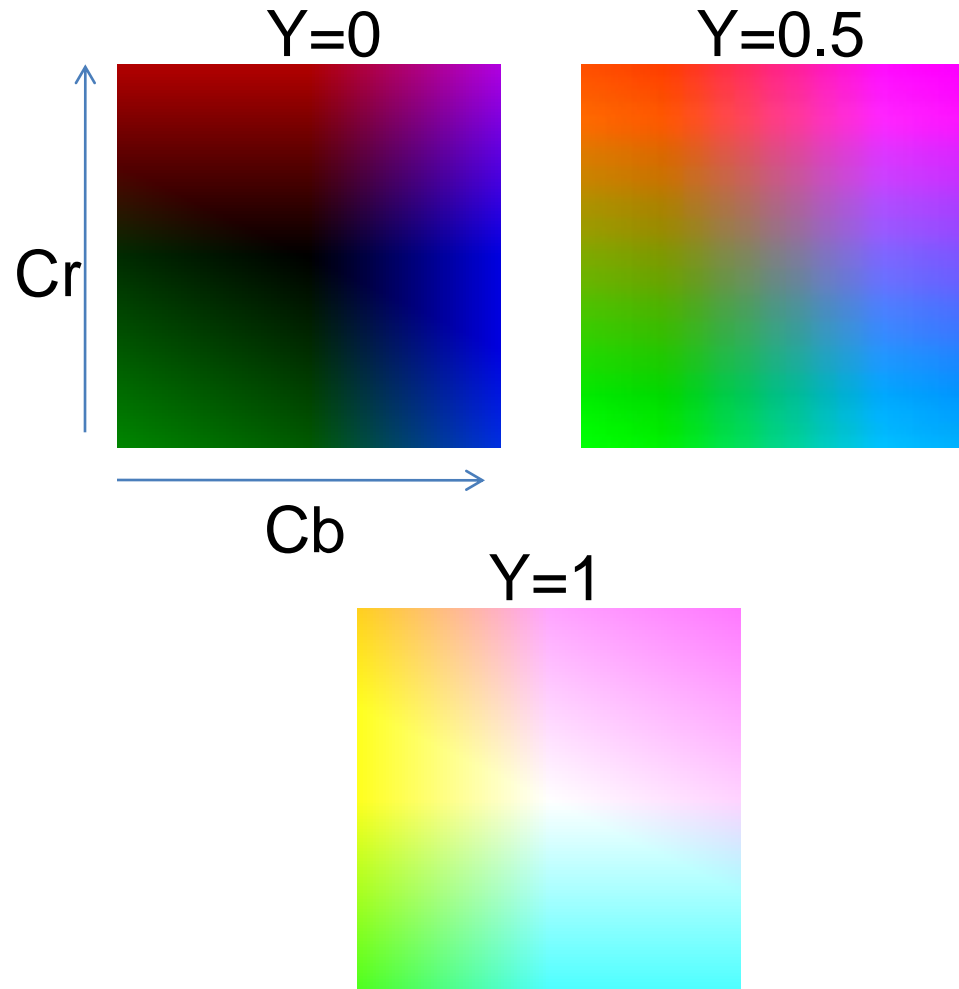
S
(H=1,V=1)



V
(H=1,S=0)

Color spaces: YCbCr

Fast to compute, good for compression, used by TV



Y
(Cb=0.5,Cr=0.5)



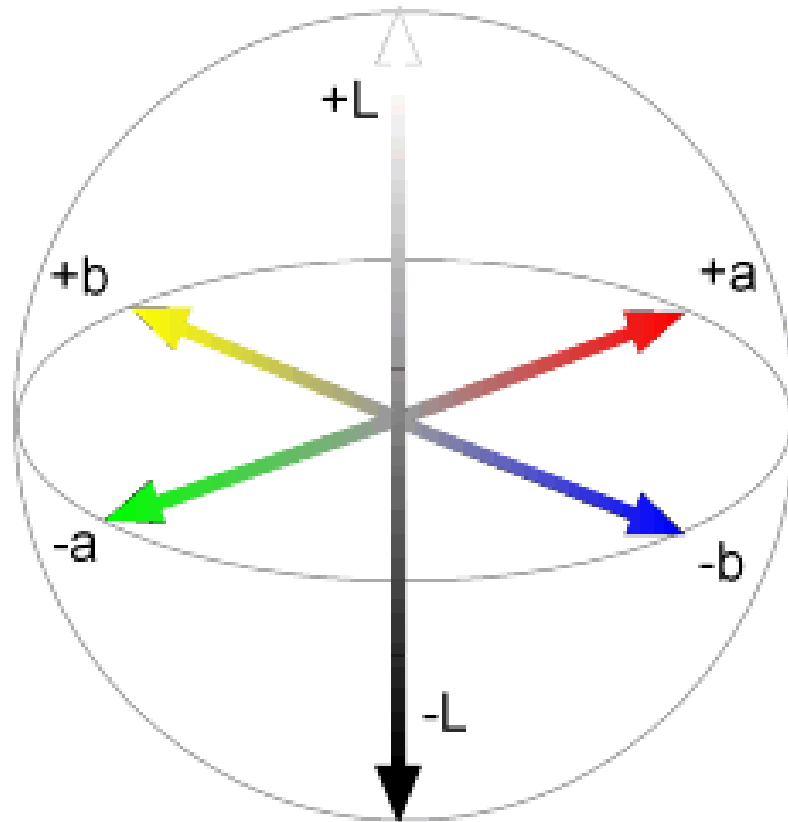
Cb
(Y=0.5,Cr=0.5)



Cr
(Y=0.5,Cb=0.5)

Color spaces: L*a*b*

“Perceptually uniform”* color space



L
(a=0,b=0)



a
(L=65,b=0)



b
(L=65,a=0)

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

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



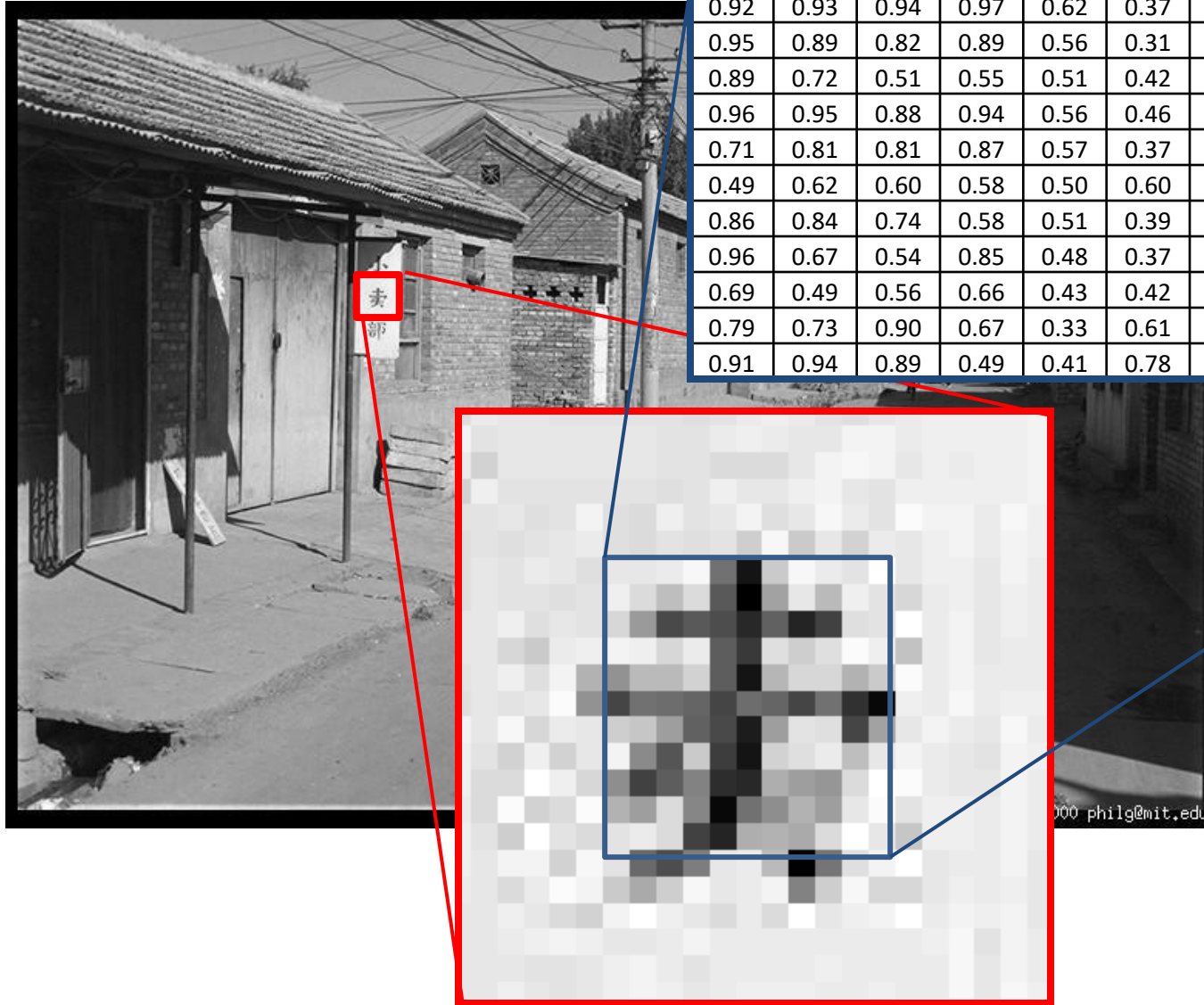
Only intensity shown – constant color

Most information in intensity



Original image

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