1. Camera & Color

Get Familiar with Cameras

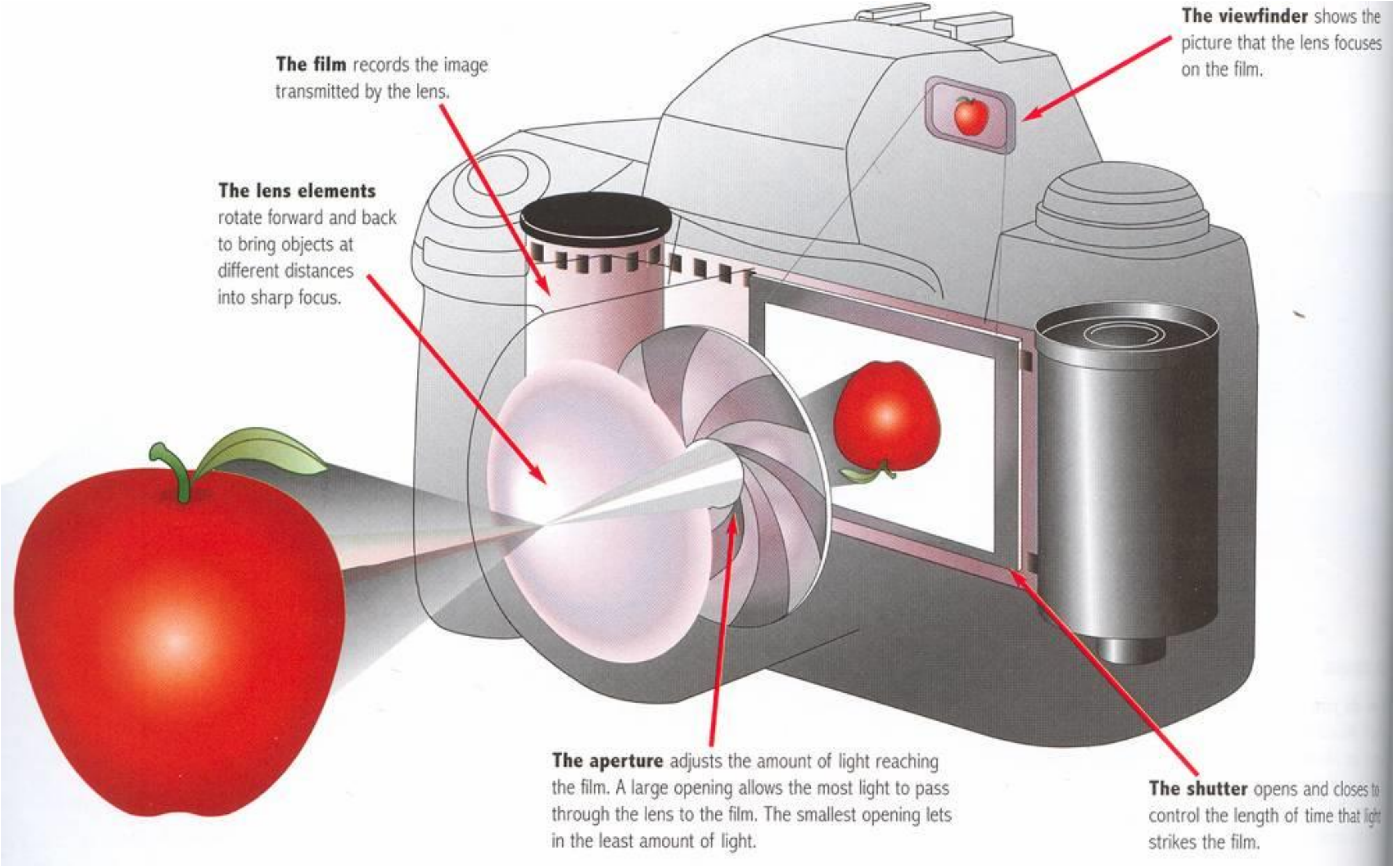
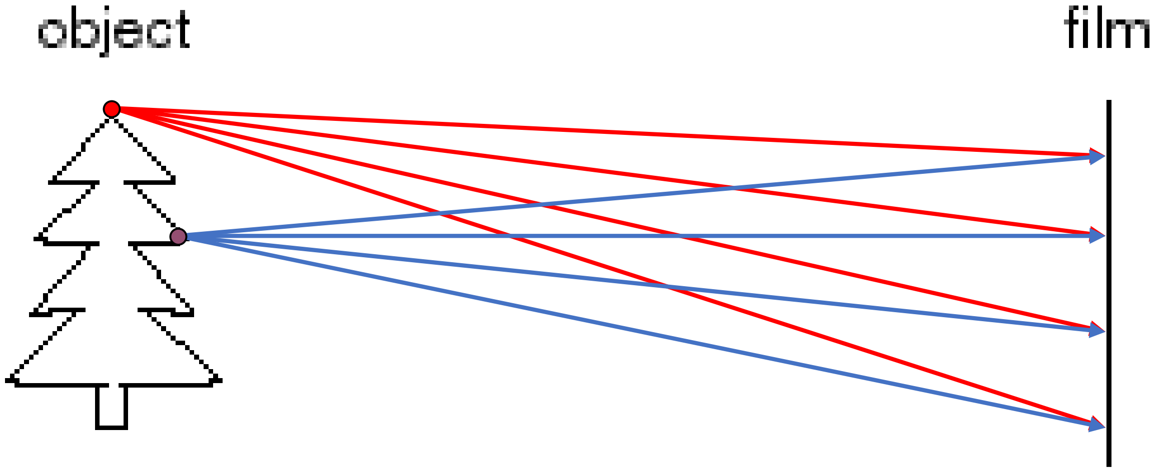
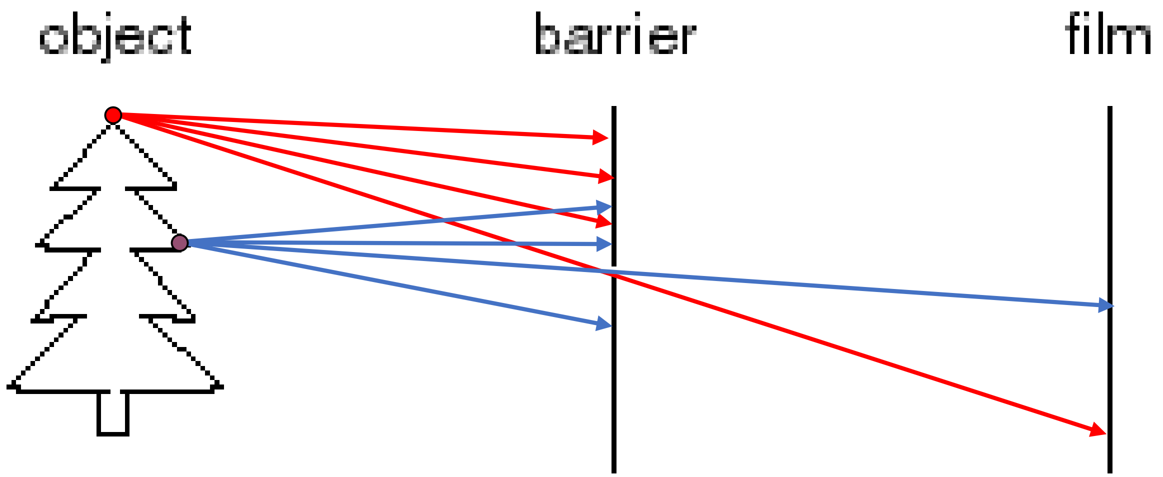


Image Formation



- Let's design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?

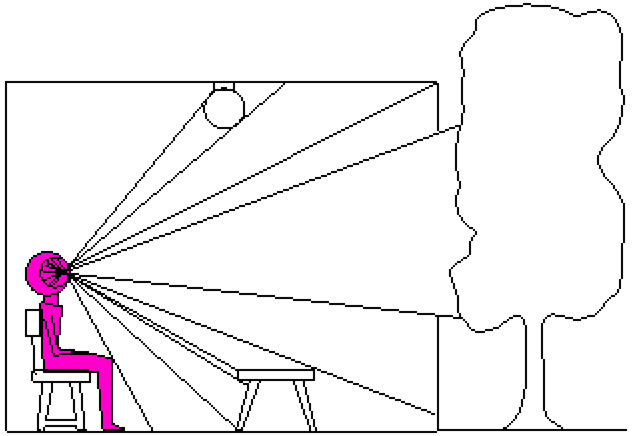
Pinhole Camera



- Add a barrier to select rays
  - The opening known as the **aperture**
  - How does this transform the image?

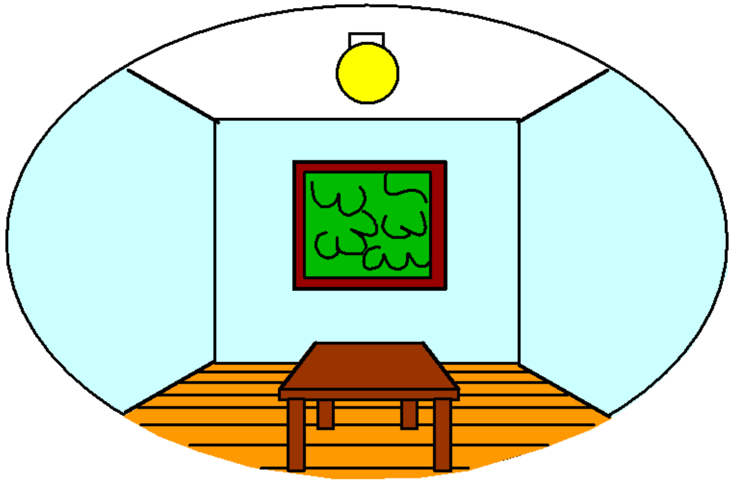
Dimensionality Reduction Machine (3D to 2D)

3D world



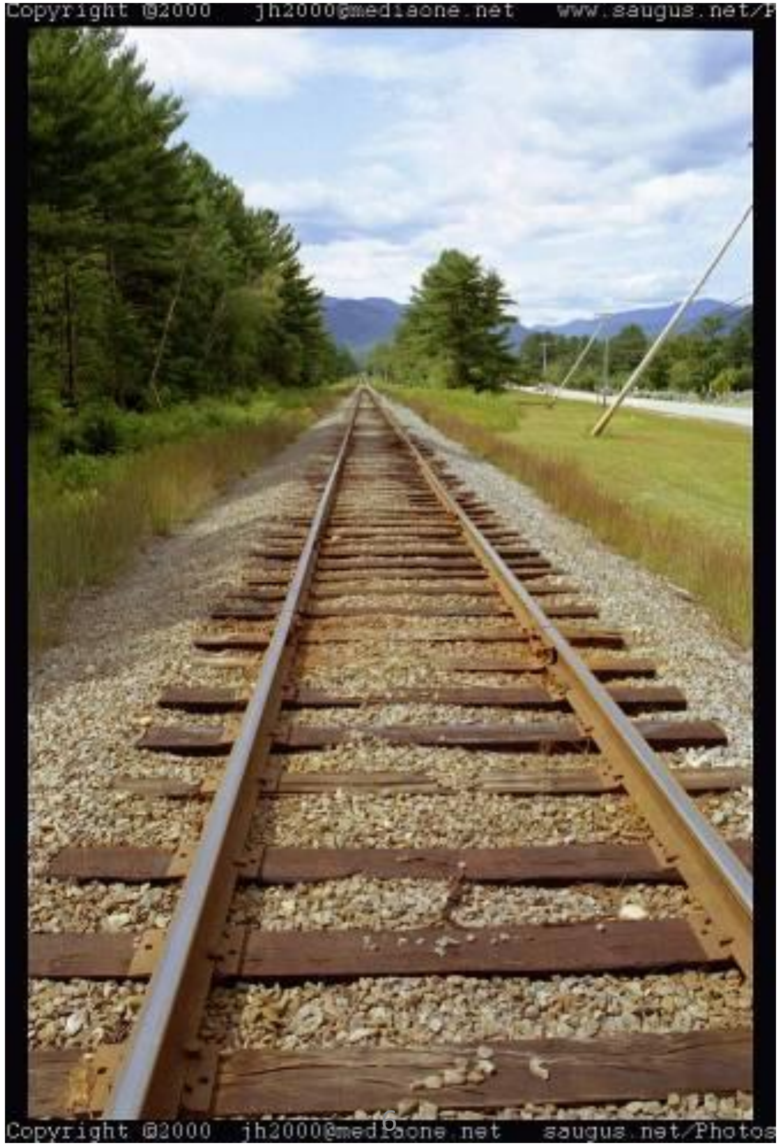
Point of observation

2D image

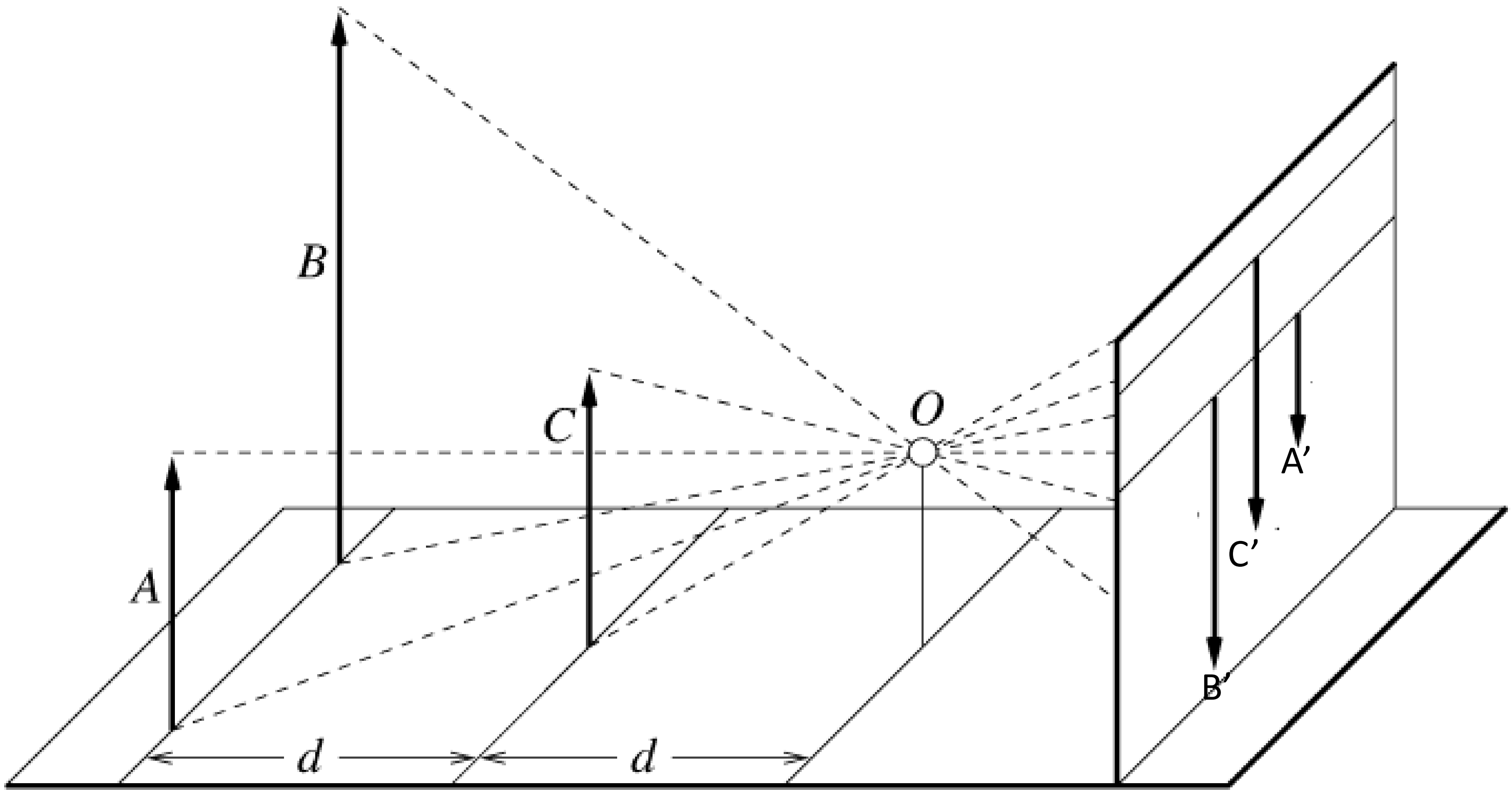


- We capture a 2D picture of the 3D world, what have we lost?
  - Distances (lengths)
  - Angles

Parallelism is lost

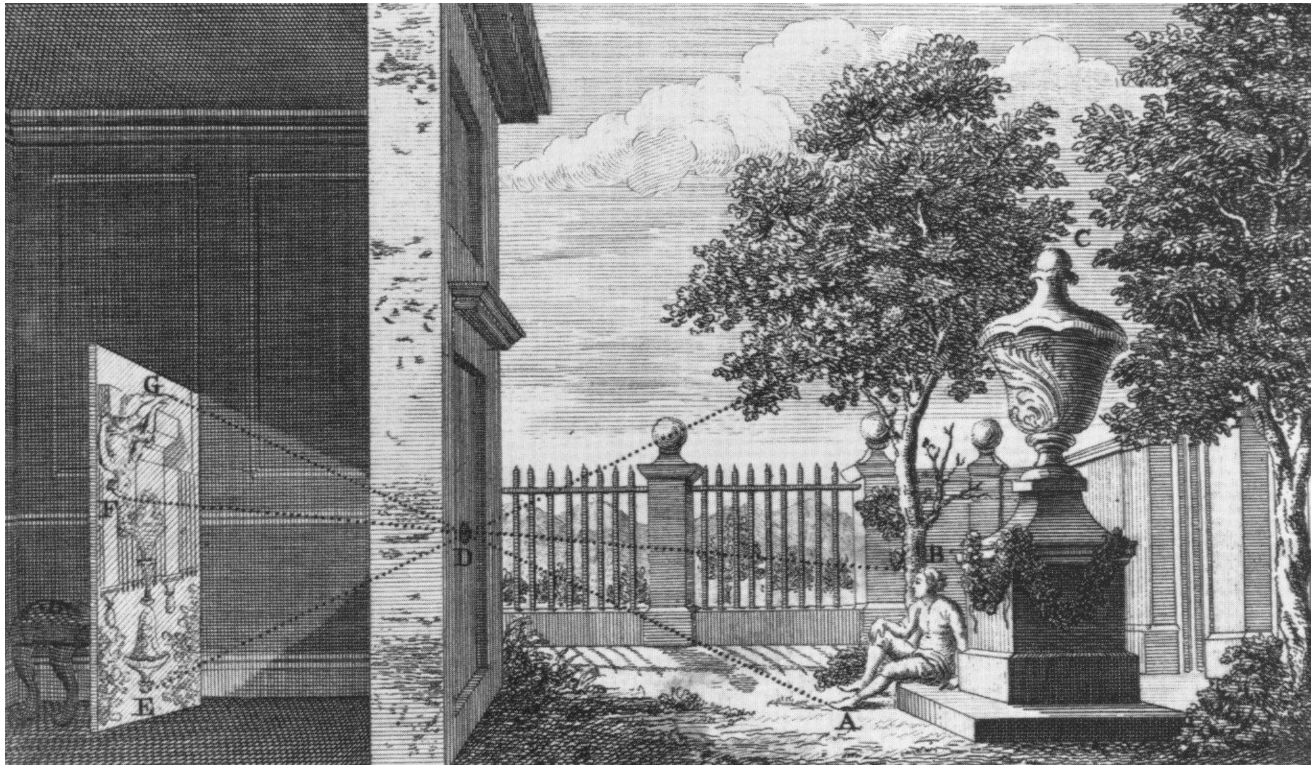


Lengths can’t be trusted...



Building a real camera

Pinhole Camera



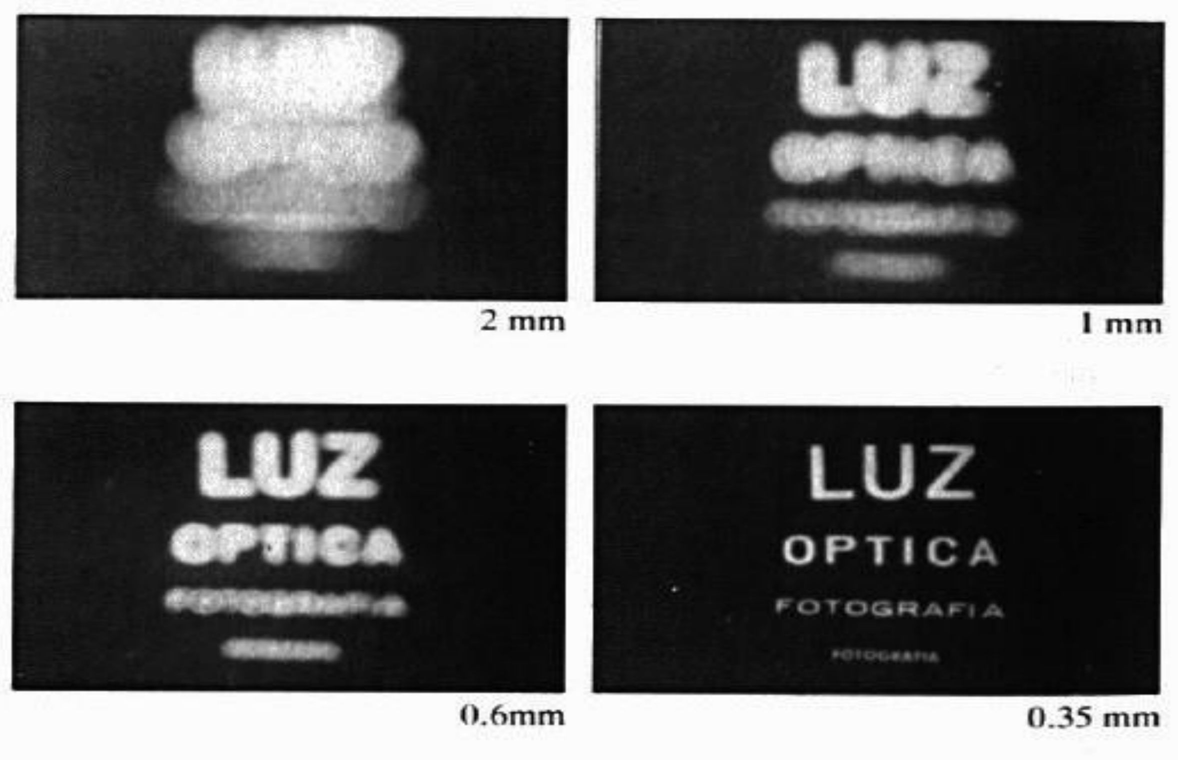
- First Idea: Mo-Ti, China (470-390 BC)
- First build: Al Hacen, Iraq/Egypt (965-1039 AD)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Home-made Pinhole Camera

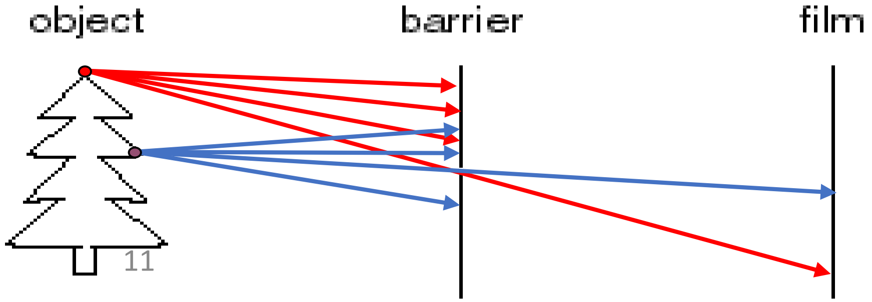
Why so blurry?

http://www.debevec.org/Pinhole/

Shrinking the Aperture



- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects



Shrinking the Aperture

8-hour exposure (Abelardo Morell)

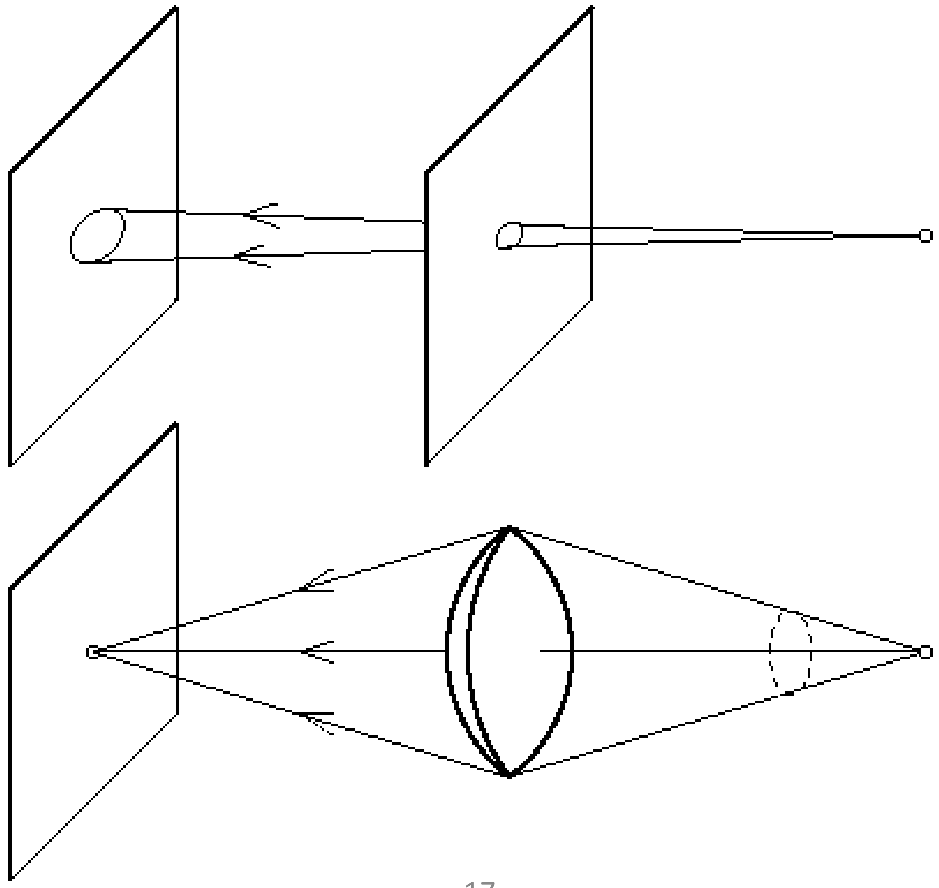
http://www.abelardomorell.net/books/books_m02.html

Questions?

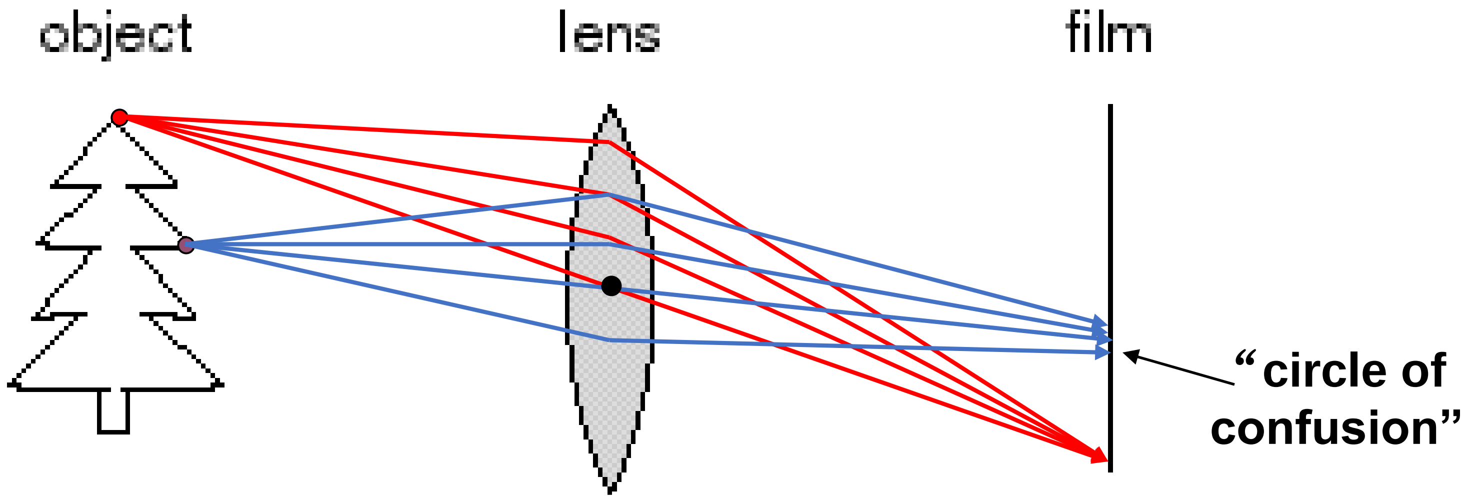
The reason for lenses

The reason for lenses

- Focus all lights shed on the lens to a single point
- Much more energy efficient than a pinhole

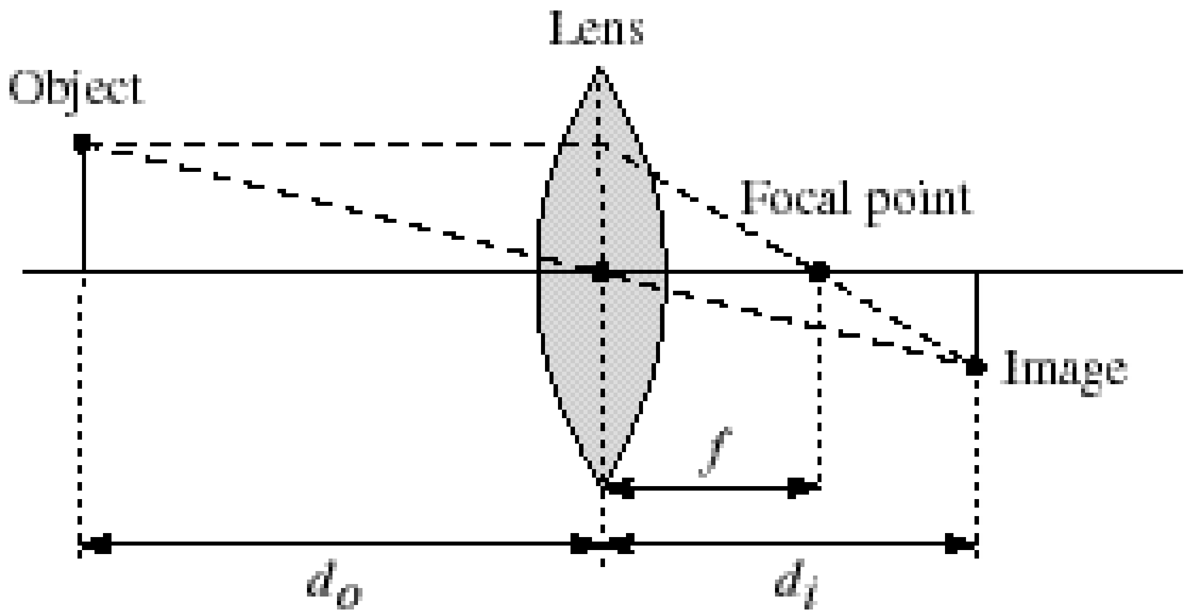


Problem with lenses



- There is a specific distance at which objects are "in focus"
  - other points project to a "circle of confusion" in the image
- Changing the shape of the lens changes this distance

Thin lenses



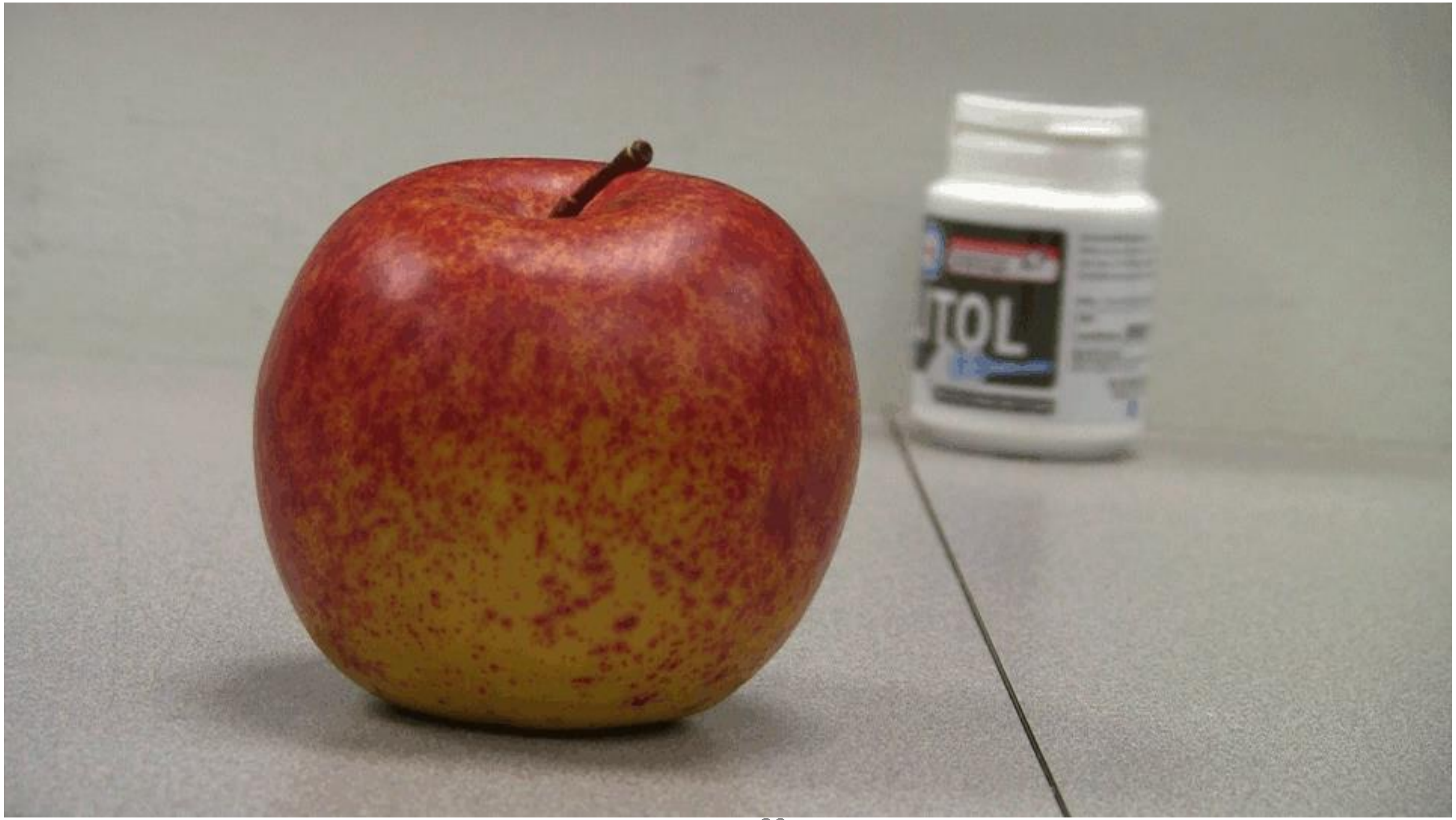
- Thin lens equation:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

  - Any object point satisfying this equation is in focus
  - Adjusting d_i to choose the object in focus

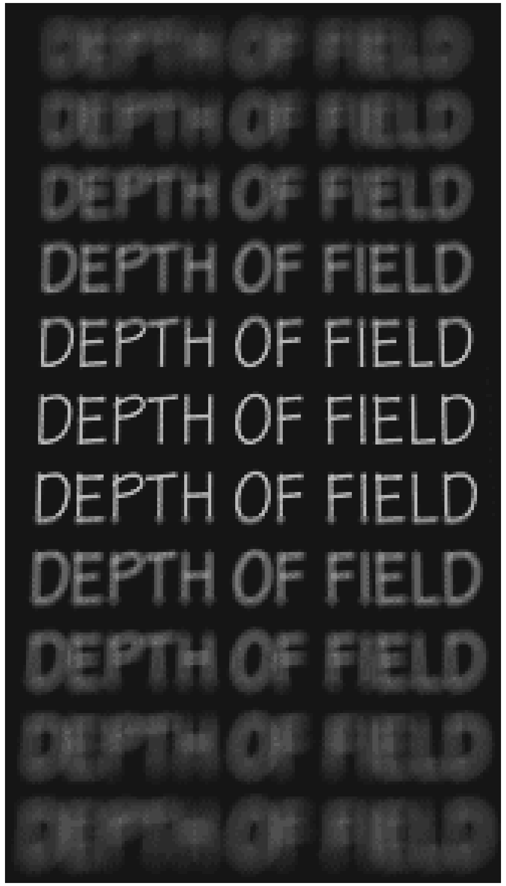
Varying Focus

- Changing the position of the sensor (image plane)

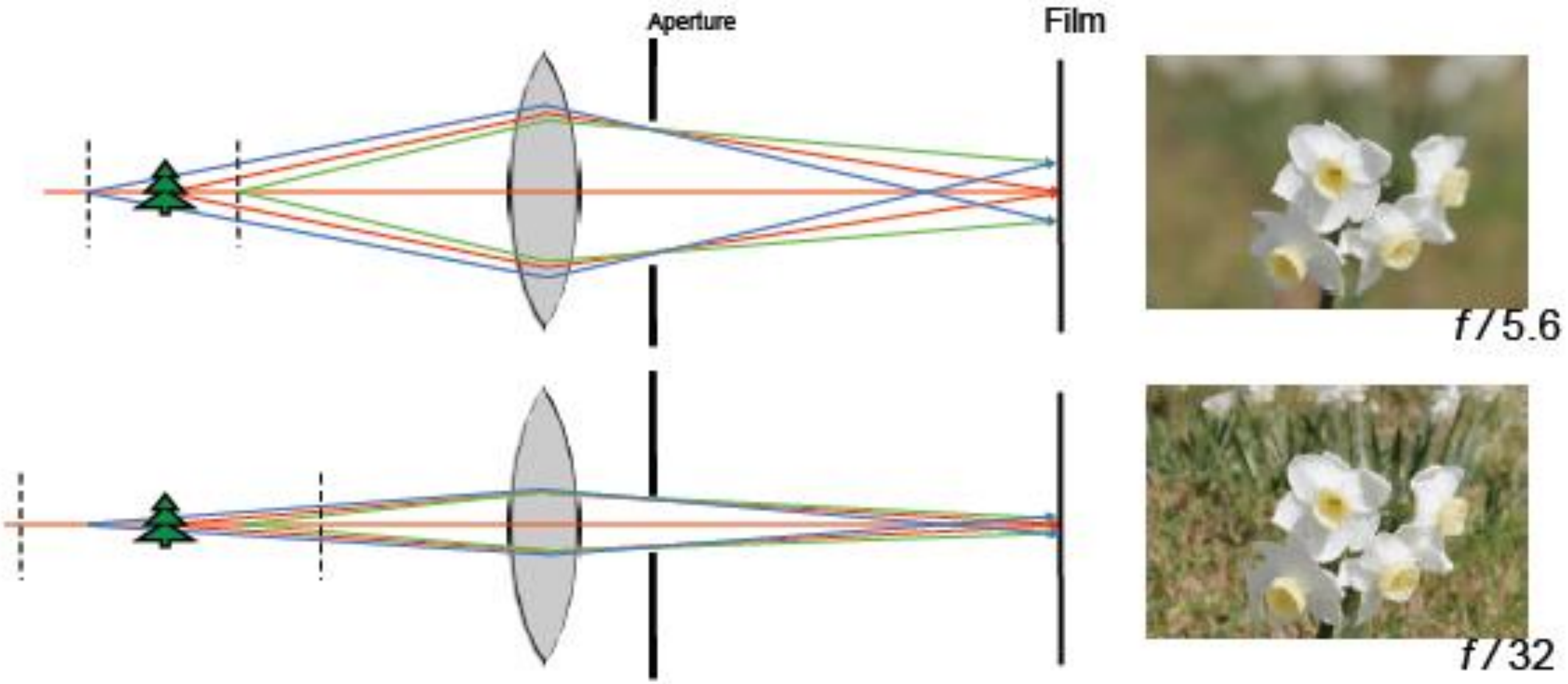


Depth of Field

- Only points at certain distance are in focus



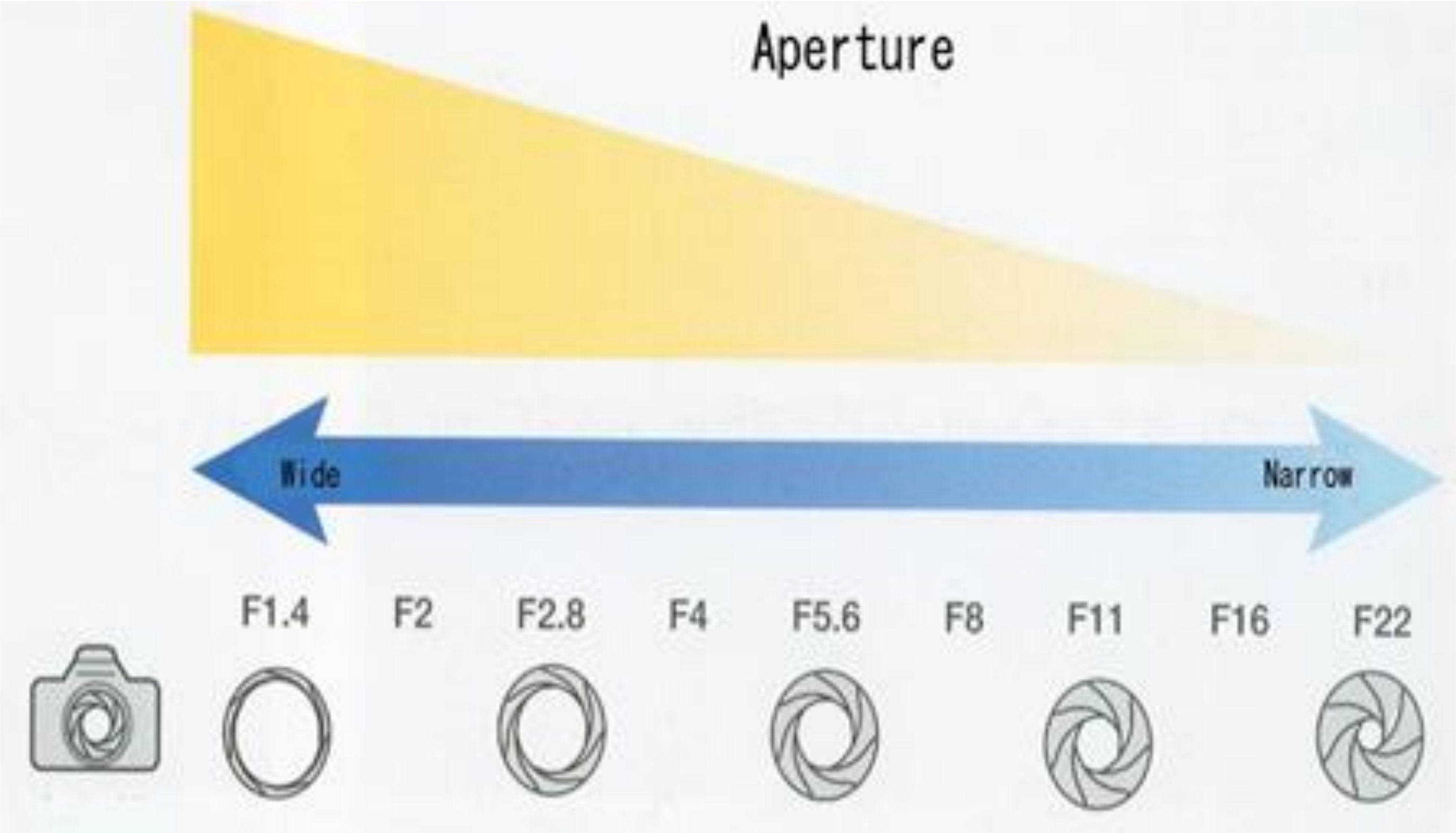
Aperture controls Depth of Field



- Changing the aperture size affects depth of field
  - A smaller aperture increases the range in which the object is approximately in focus
  - But small aperture reduces amount of light – need to increase exposure

F-number: focal length / aperture diameter

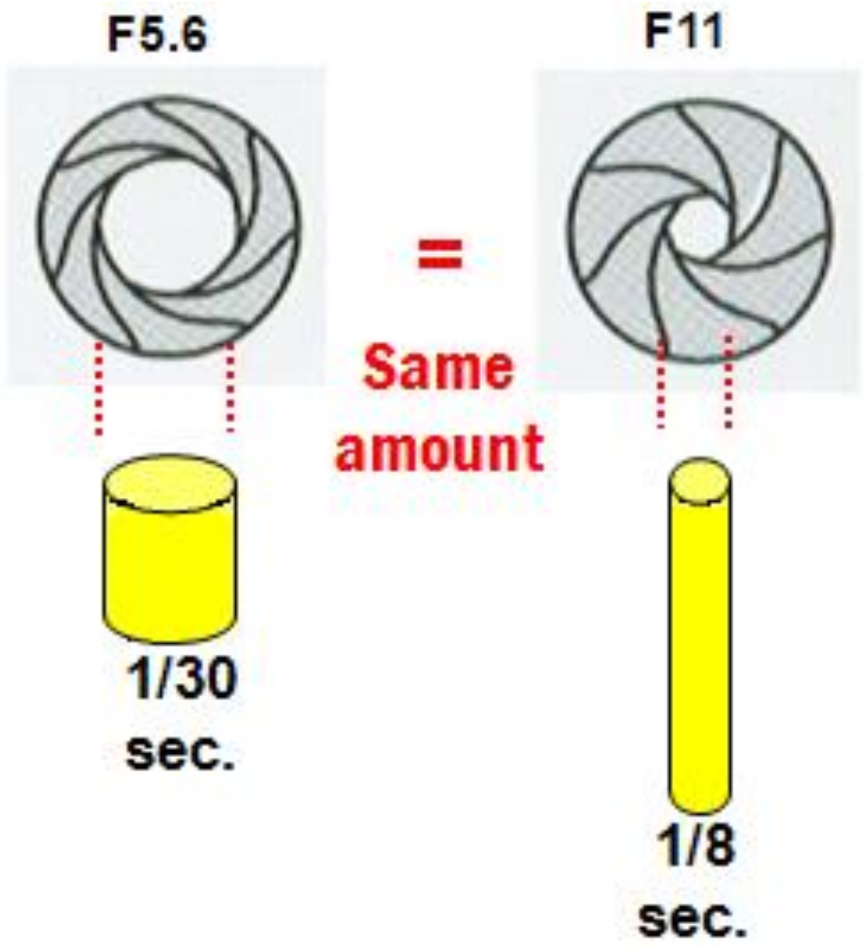
- Aperture size is controlled by the F-number



Varying the aperture

http://beginnersphotographyblog.com/842/how-changing-aperture-affects-depth-of-field/

Exposure: shutter speed vs. aperture

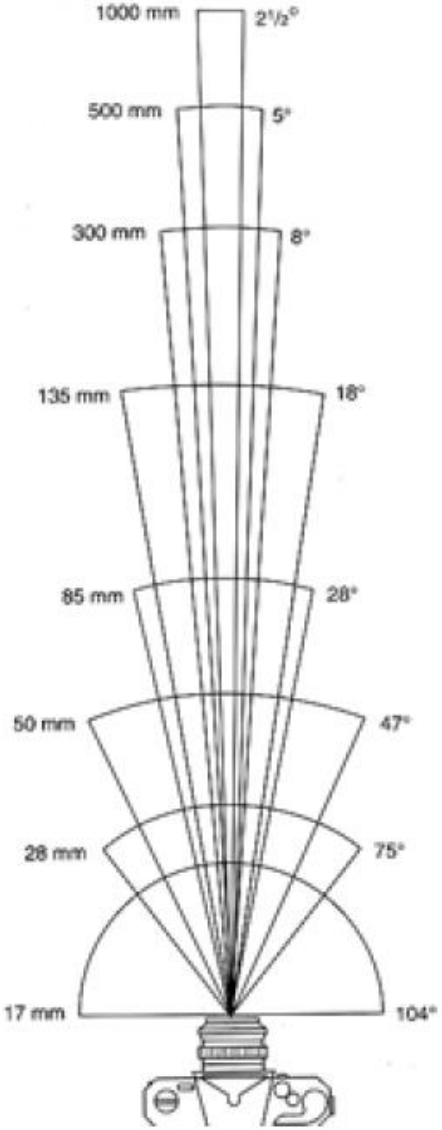


Shutter Speed

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

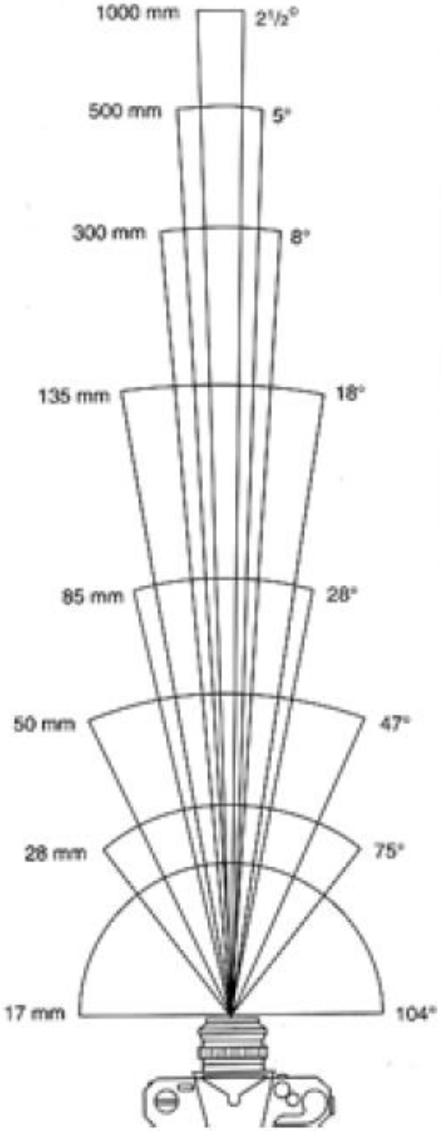
Questions?

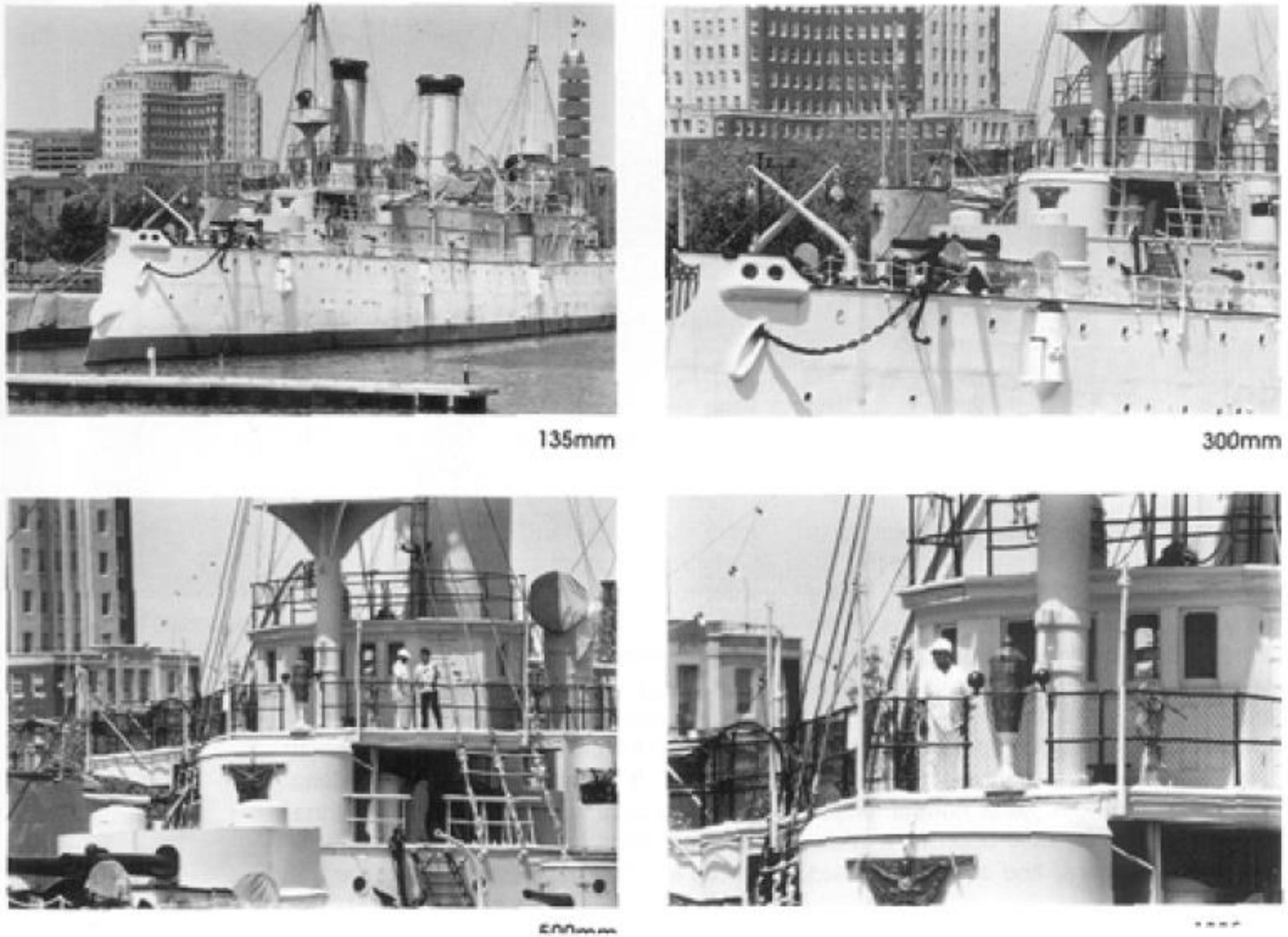
Field of View (Zoom)



From London and Upton

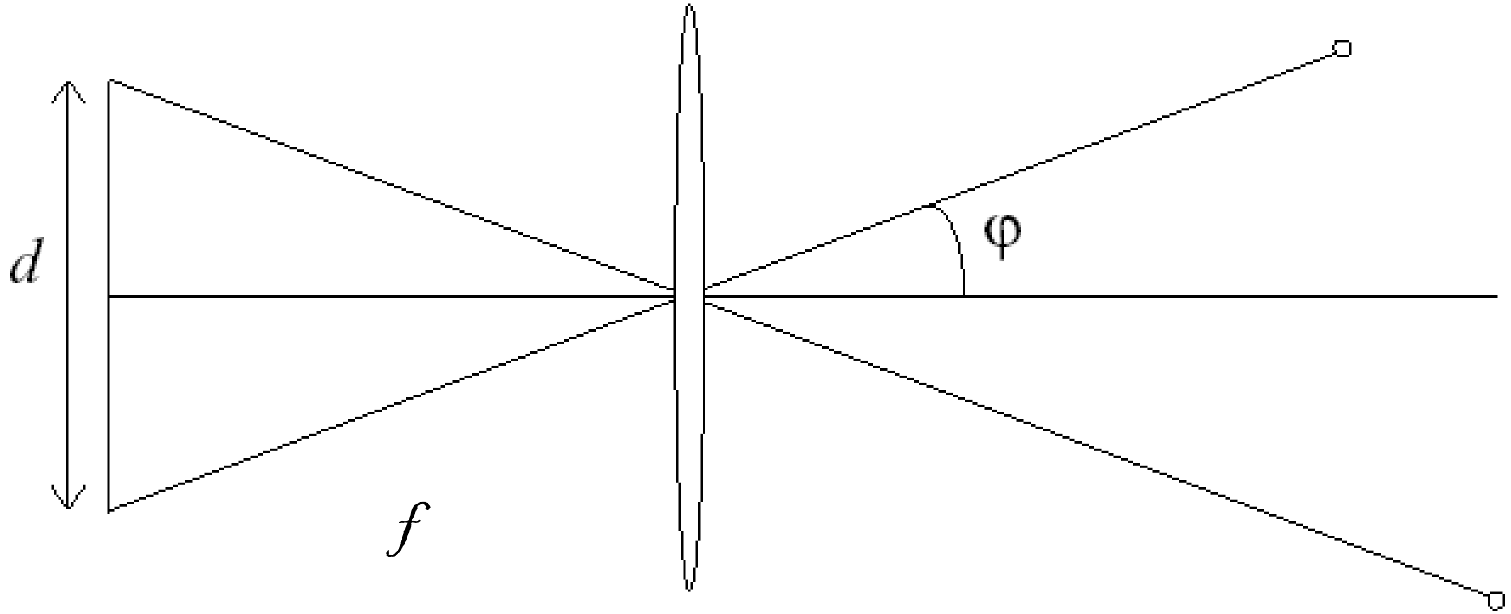
Field of View (Zoom)





From London and Upton

FOV depends on Focal Length



Size of field of view governed by size of the camera retina:

$$\varphi = \tan^{-1}\left(\frac{d}{2f}\right)$$

Smaller FOV = larger Focal Length, when the film is fixed

Expensive toys…

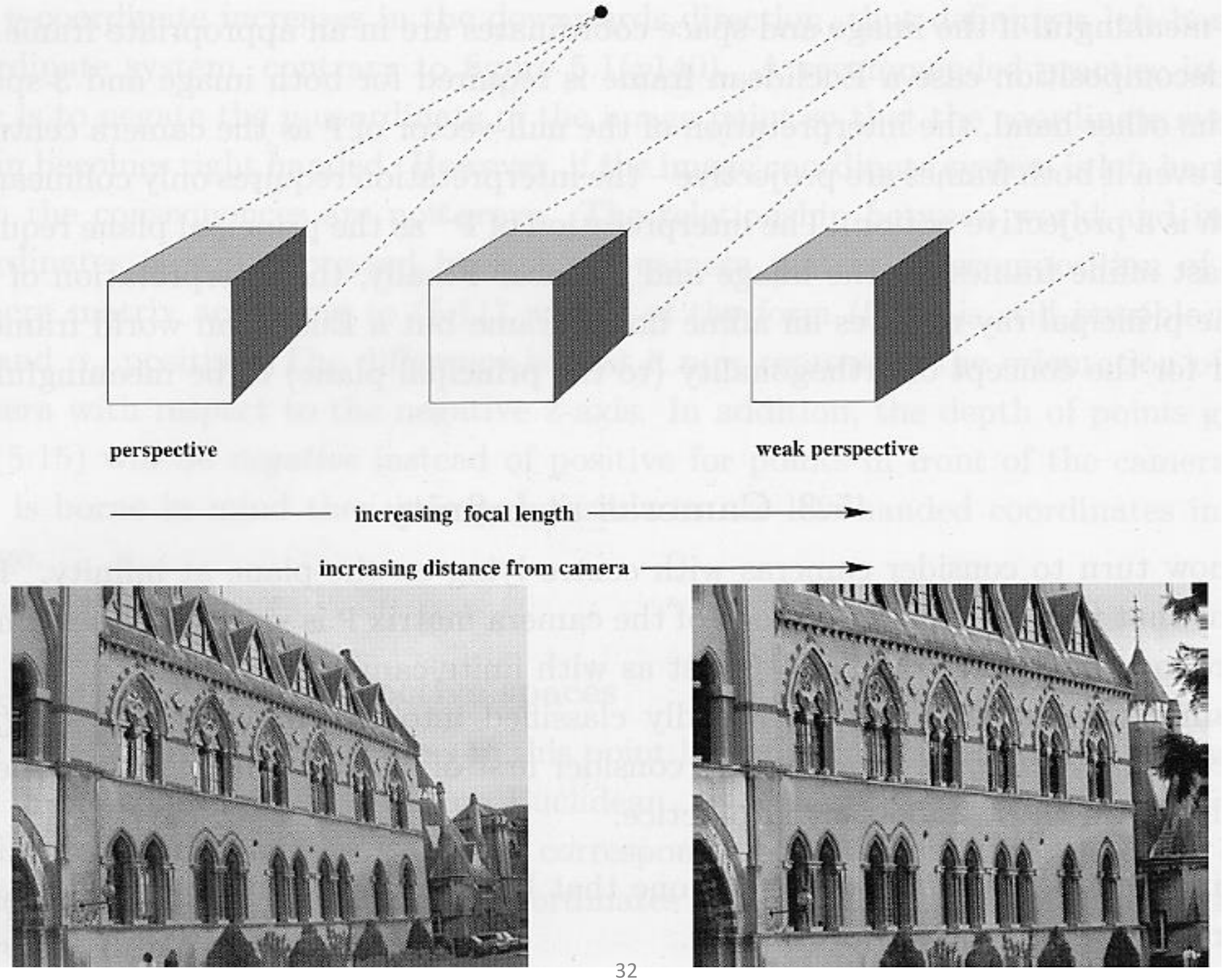
Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/

$14,600.00

http://dancarrphotography.com/blog/wp-content/uploads/2011/05/Canon_super_tele_comparison.jpg



From Zisserman & Hartley

Field of View / Focal Length

Large FOV
Camera close to car

Small FOV
Camera far from the car

Field of View / Focal Length

Large FOV
Camera close to face

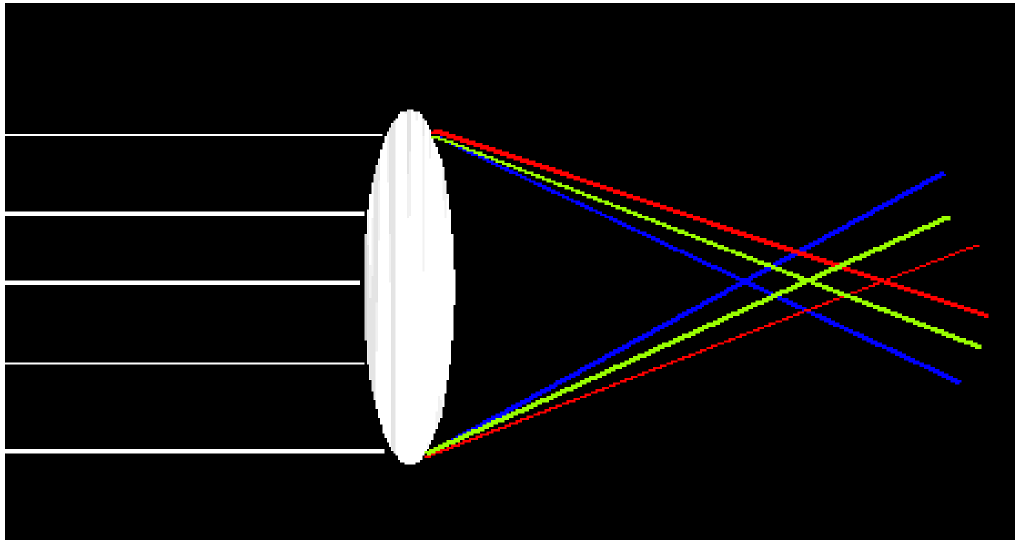
Standard

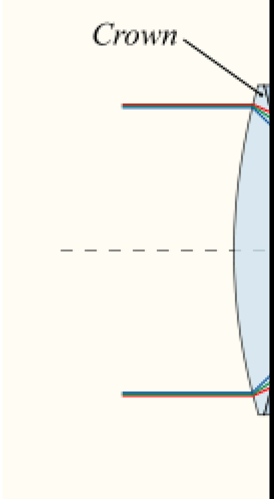
Small FOV
Camera far from the face

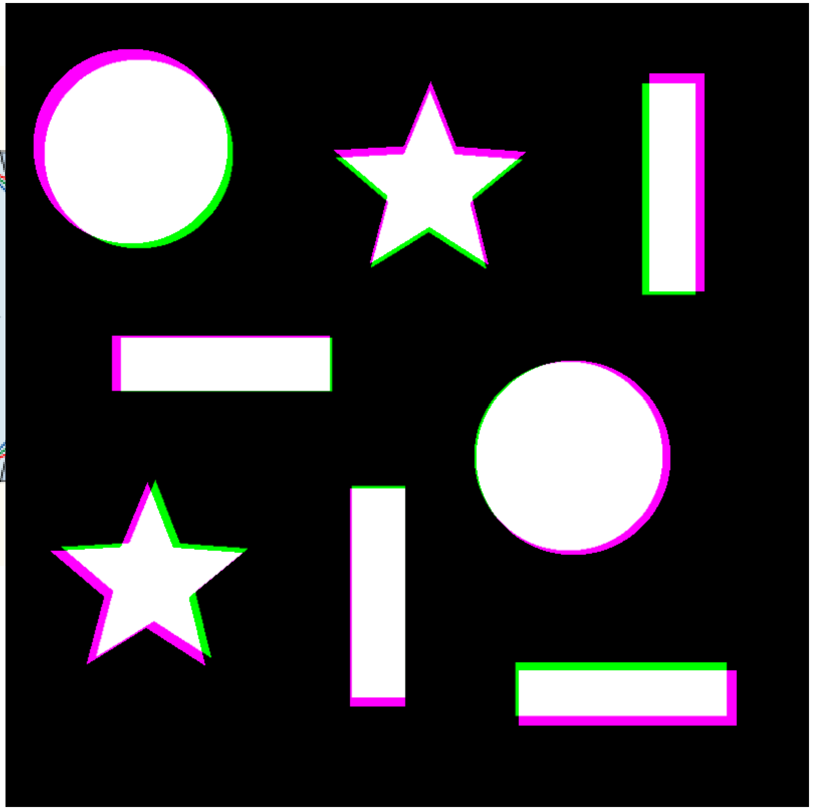
Questions?

Lens Flaws: Chromatic Aberration

- Dispersion: wavelength-dependent refractive index
  - (enables prism to spread white light beam into rainbow)
- Modifies ray-bending and lens focal length: f(λ)







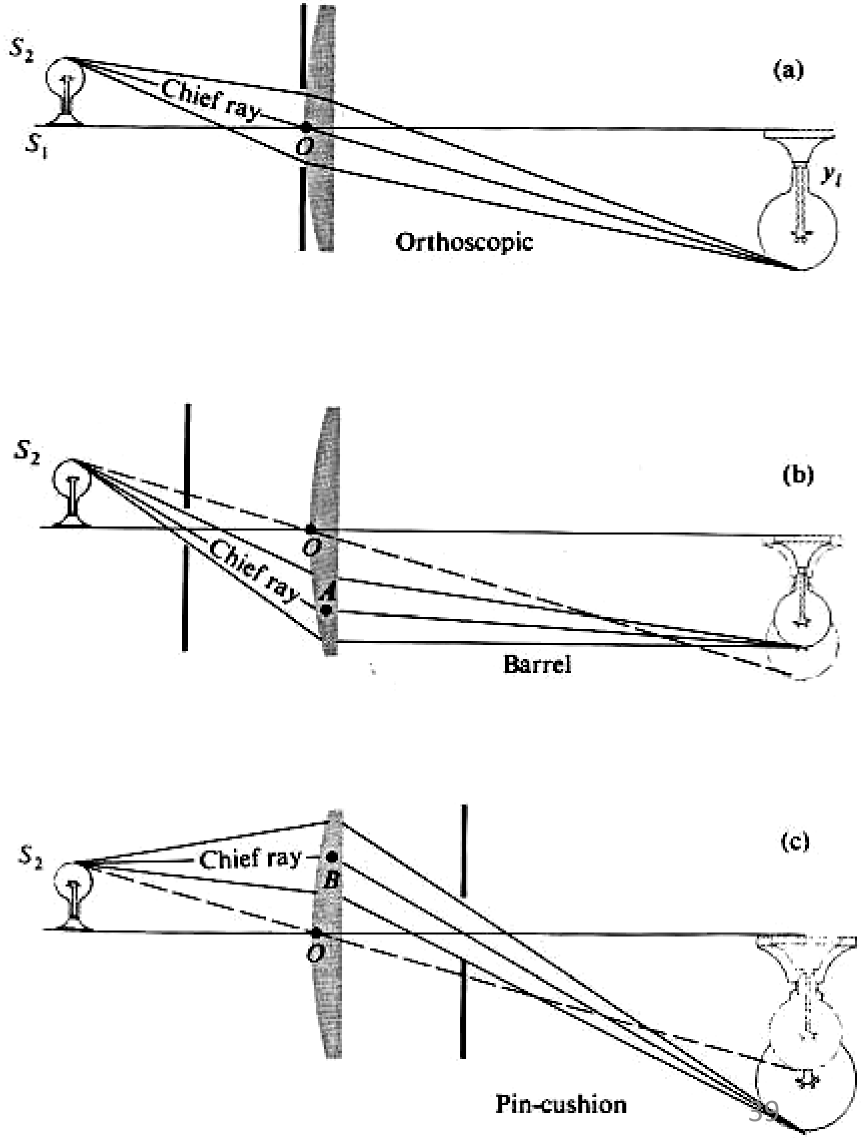
- Color fringes near edges of image
- Corrections: add 'doublet' lens of flint glass, etc.

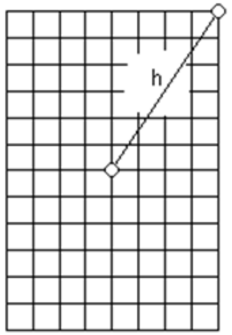
Chromatic Aberration

Near Lens Center

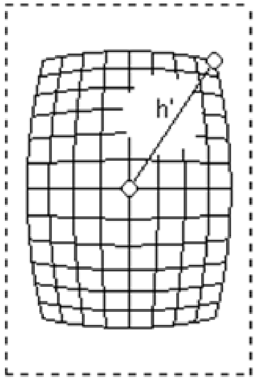
Near Lens Outer Edge

Radial Distortion

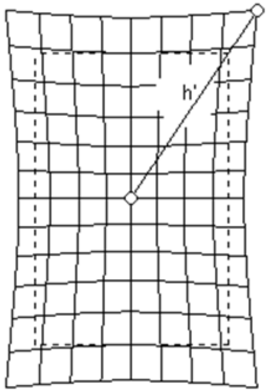




orthoscopic

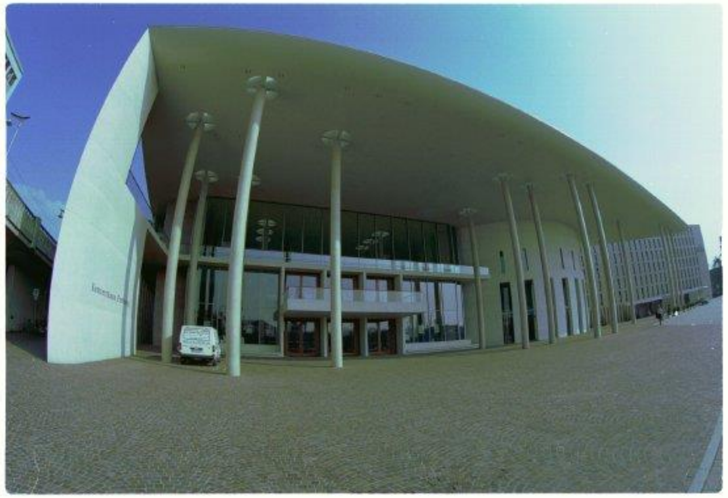


barrel



pincushion

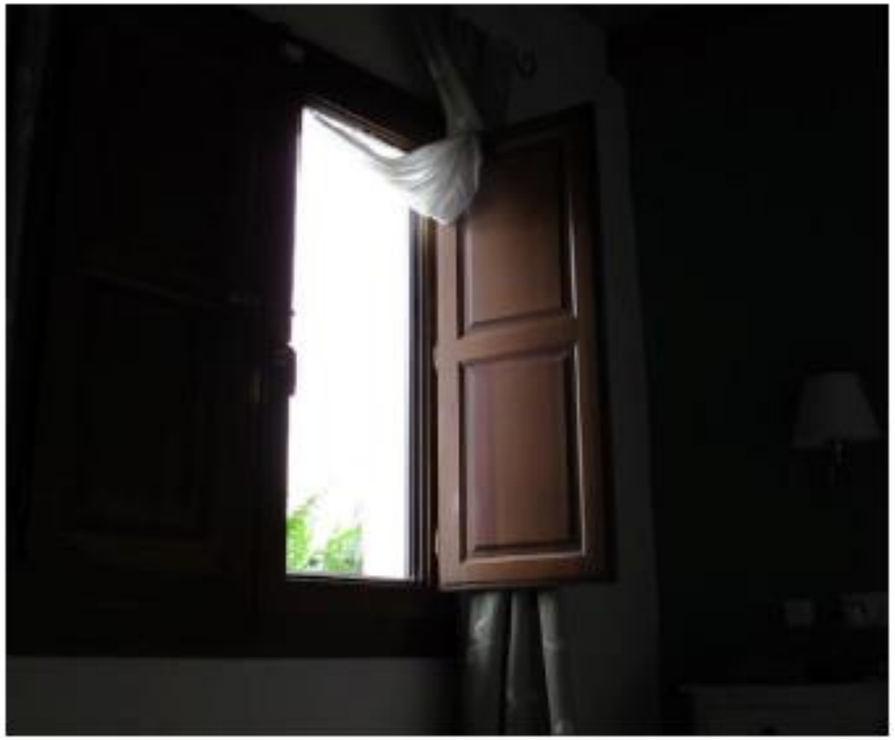
Correcting radial distortion



from Helmut Dersch

Questions?

Accidental Pinhole Camera

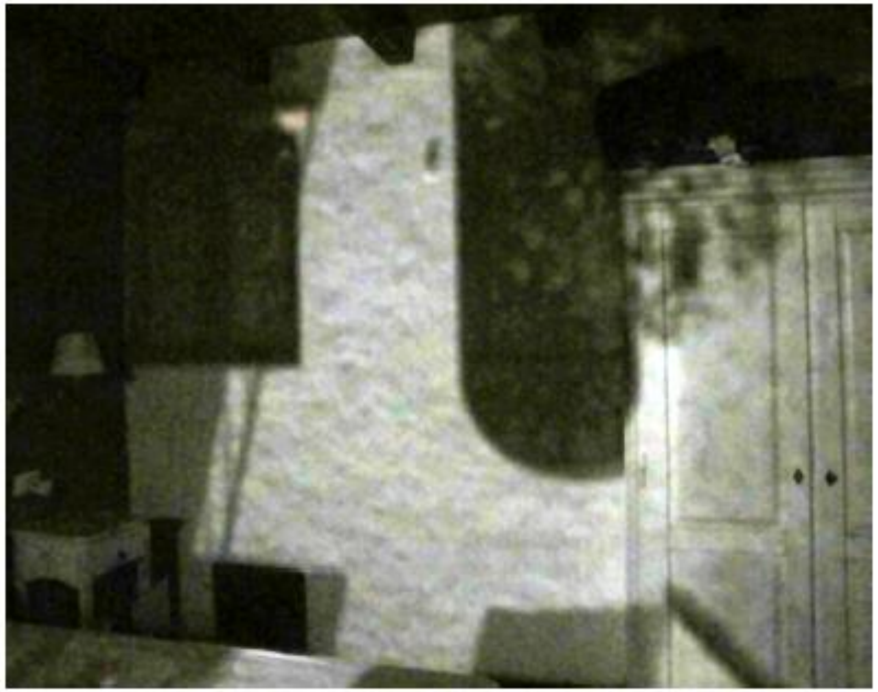


(a) an open window in a room

(b) a picture of the wall opposite the window

Accidental pinhole and pinspeck cameras: revealing the scene outside the picture; Antonio Torralba and William T. Freeman, CVPR 2012

Accidental Pinhole Camera



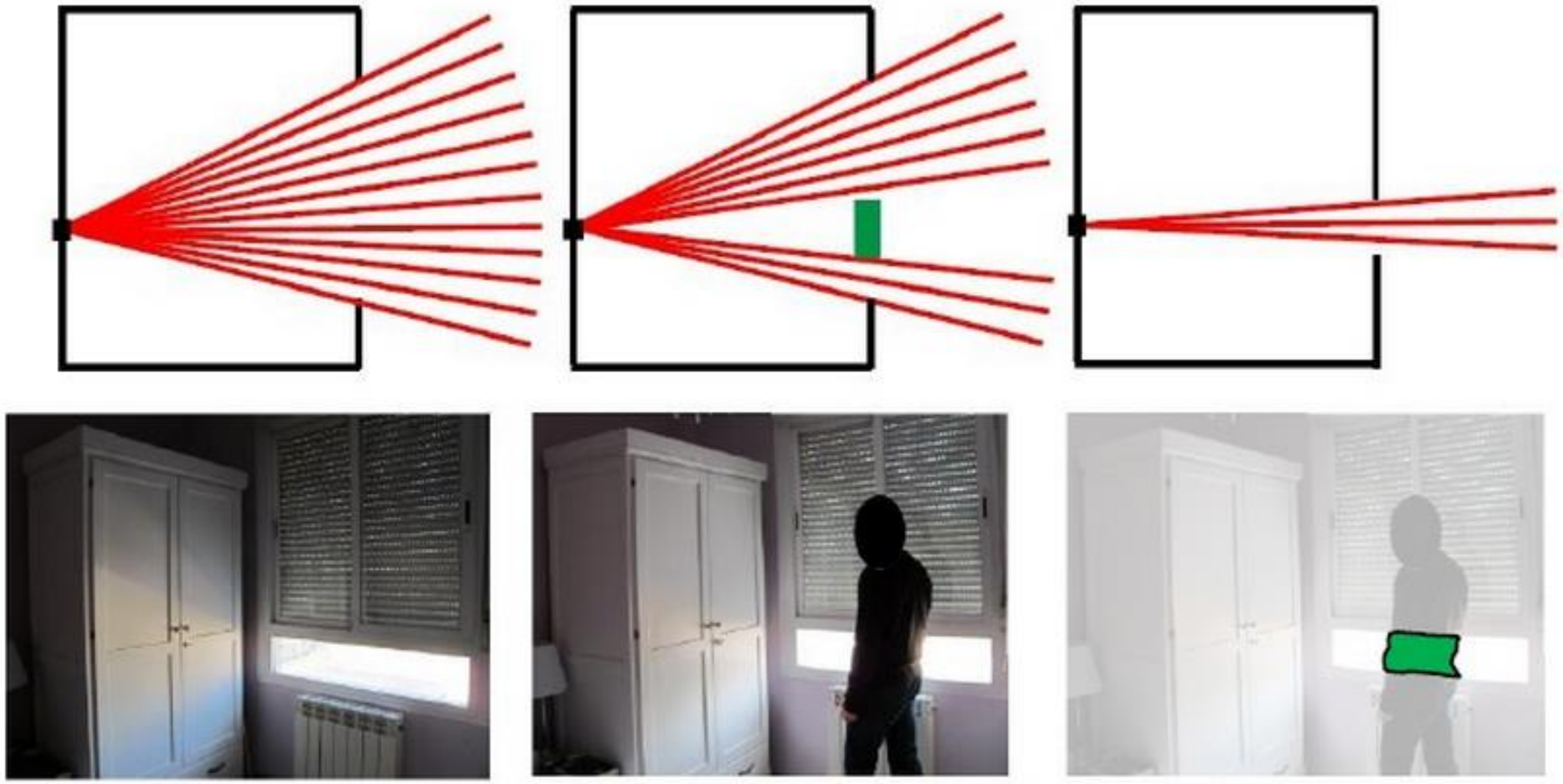
the same wall when the window is closed, leaving only a small hole

outside of the window

Accidental Pinhole Camera

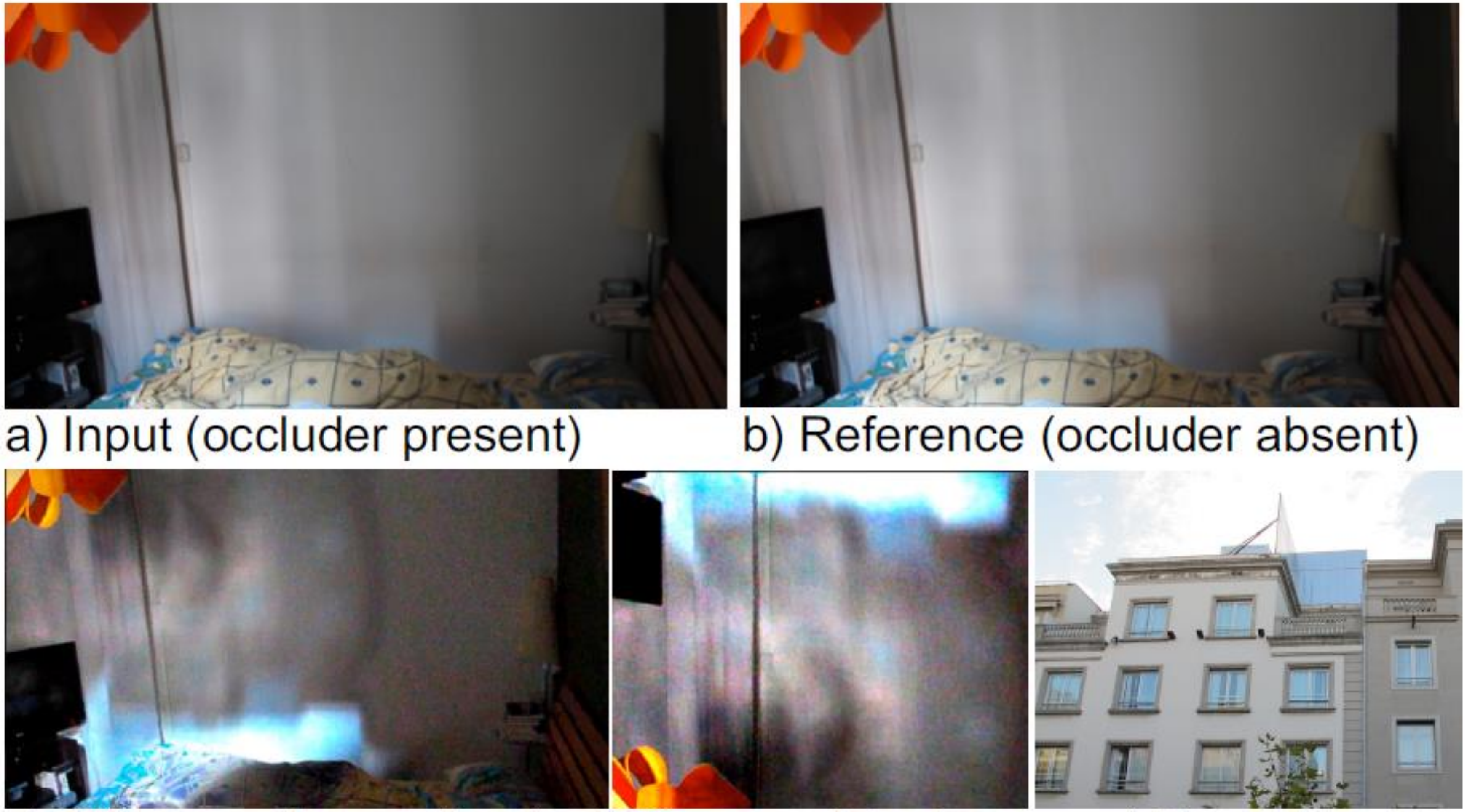
How can we obtain a clearer picture??
→ How to obtain an image with smaller pinhole??

Accidental Pinhole Camera



The difference image is the image captured by a camera with the occluder as a pinhole !

Accidental Pinhole Camera



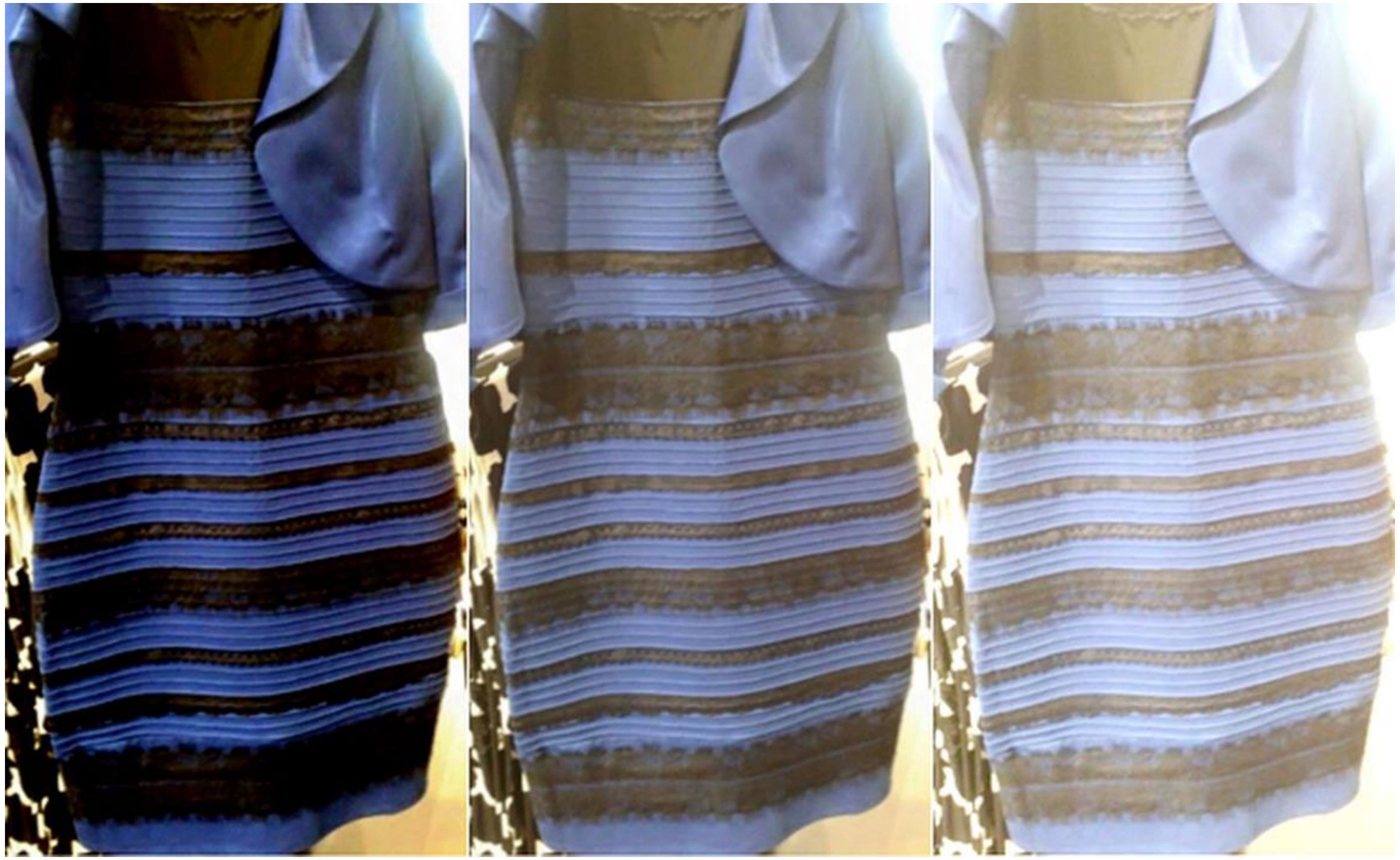
a) Input (occluder present) b) Reference (occluder absent)

c) Difference image (b-a) d) Crop upside down e) True view

Questions?

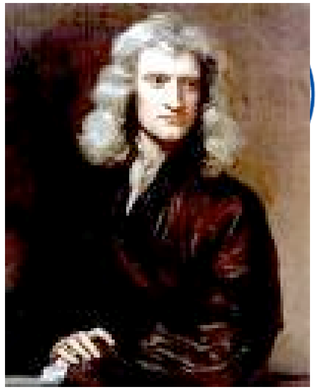
Why Study Color?

- Color sounds simple but can be complicated



Is this dress white-golden or black-blue?

Spectrum of Visible Light



Isaac Newton

- Visible spectrum: approx. 400 ~ 700 nm
- Visible colors: ROYGBIV with IR and UV at the two extremes

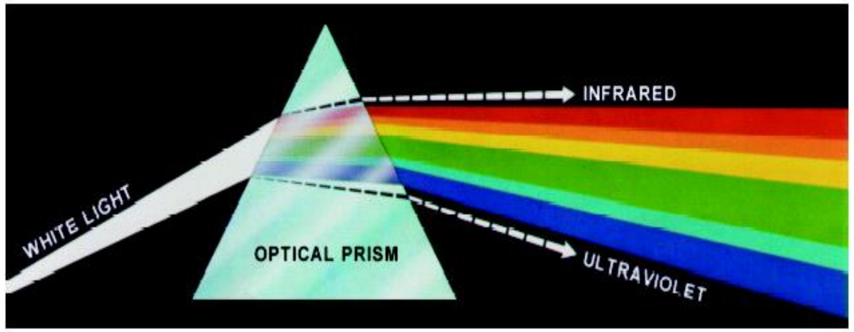


Fig: Color spectrum seen by passing white light through a prism (As of Gonzalez 2e Page 283)

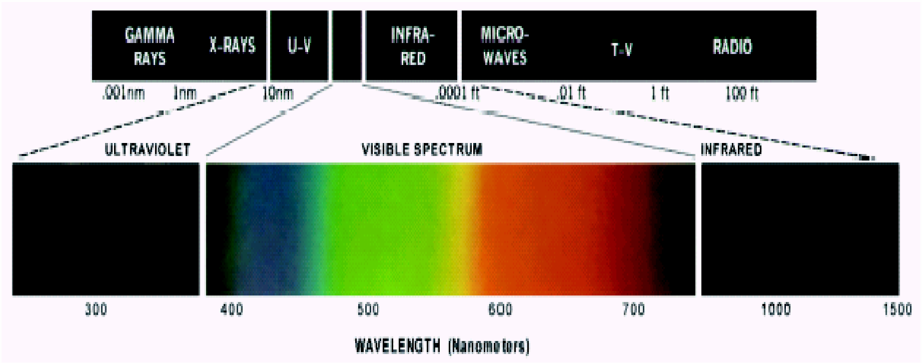
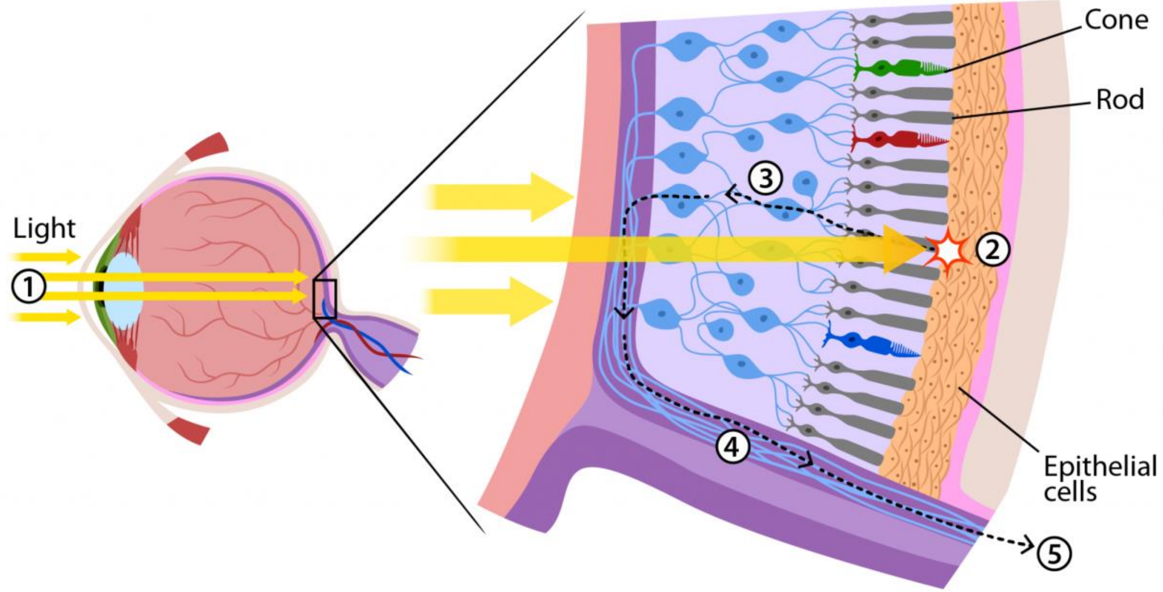


Fig: Wavelengths comprising the visible range of electromagnetic spectrum (As of Gonzalez 3e Page 284)

How do We Perceive Color?

- Cones are the cells in our eyes to sense color
  - Three types of cones more sensitive to “long”, “median”, and “short” wavelengths of light
- The sensation of a certain color is due to the mixed stimulus of these cones (the LMS color space)
  - So the perceived color is determined by the spectrum of the light
- Rods are responsible for low-light vision (color insensitive)



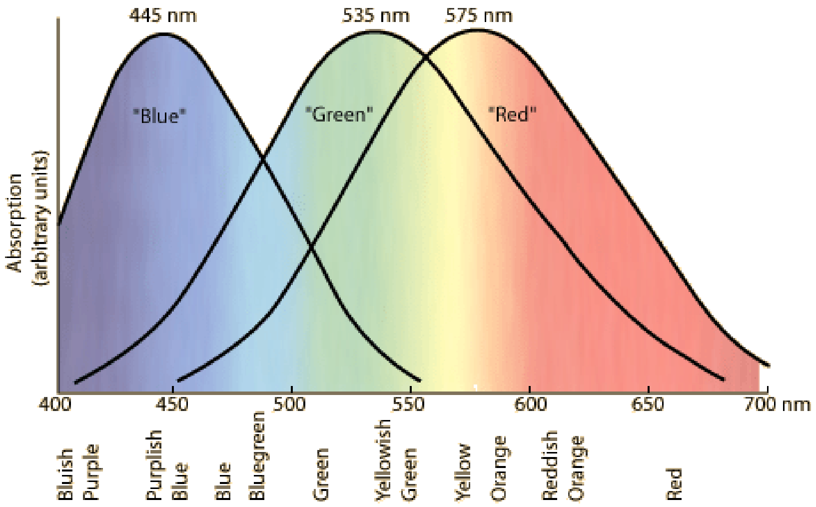
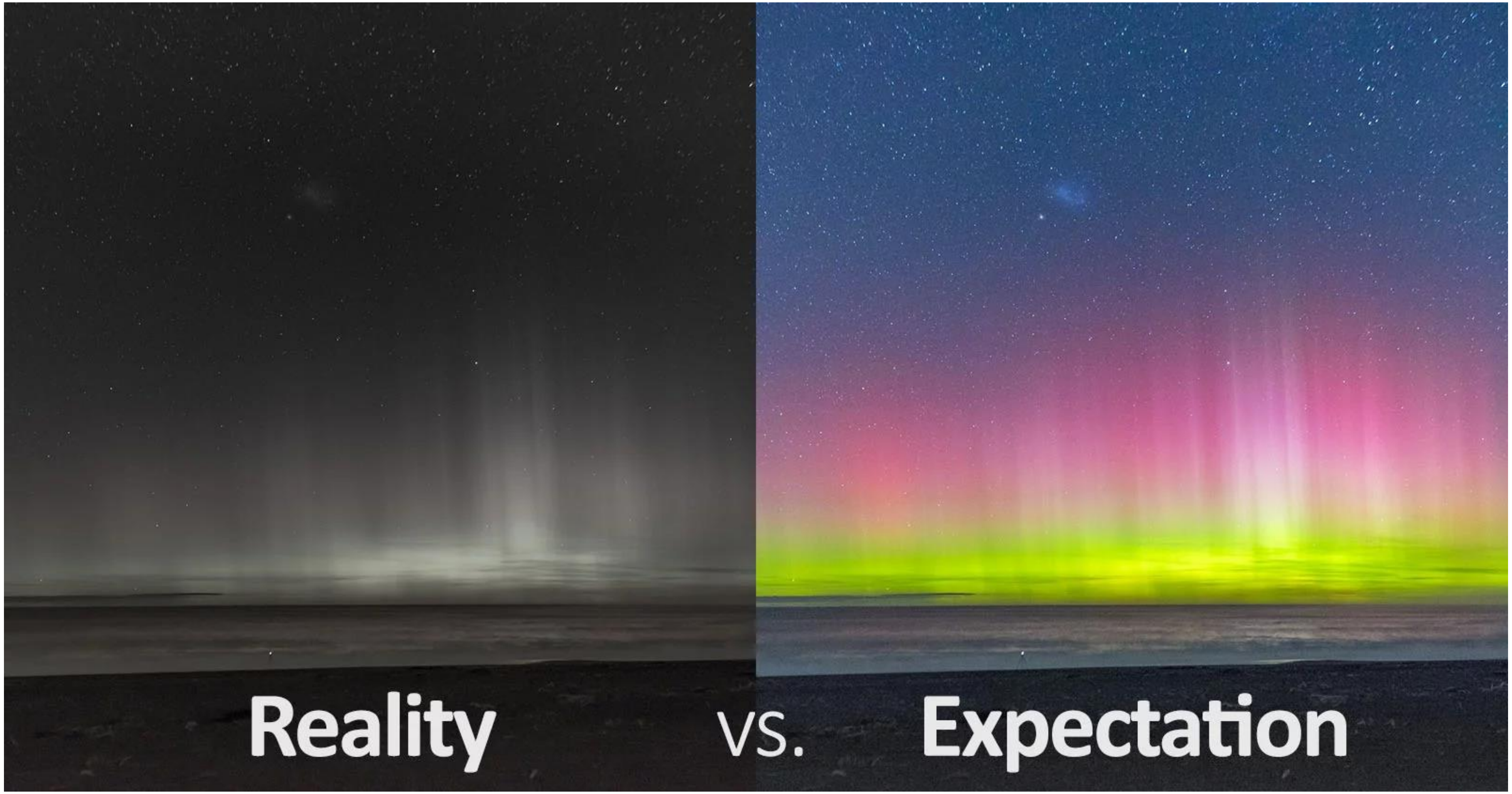


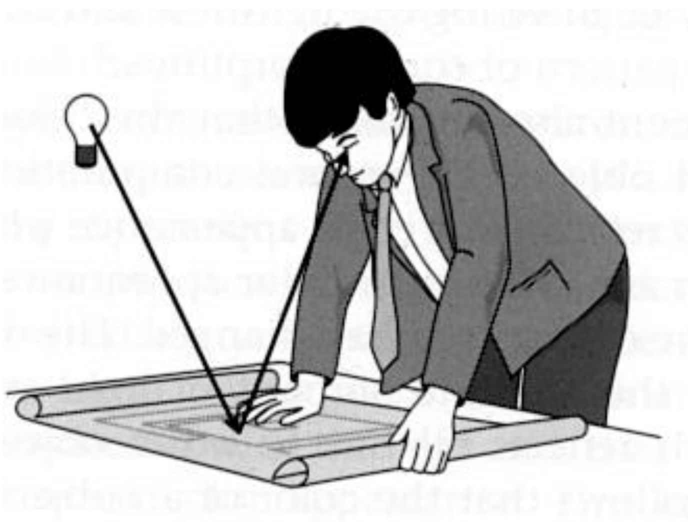
Fig: Absorption of light by red, green and blue cones in the human eye as a function of wavelength (As of Gonzalez 2e Page 285)

What does the aurora actually look like?

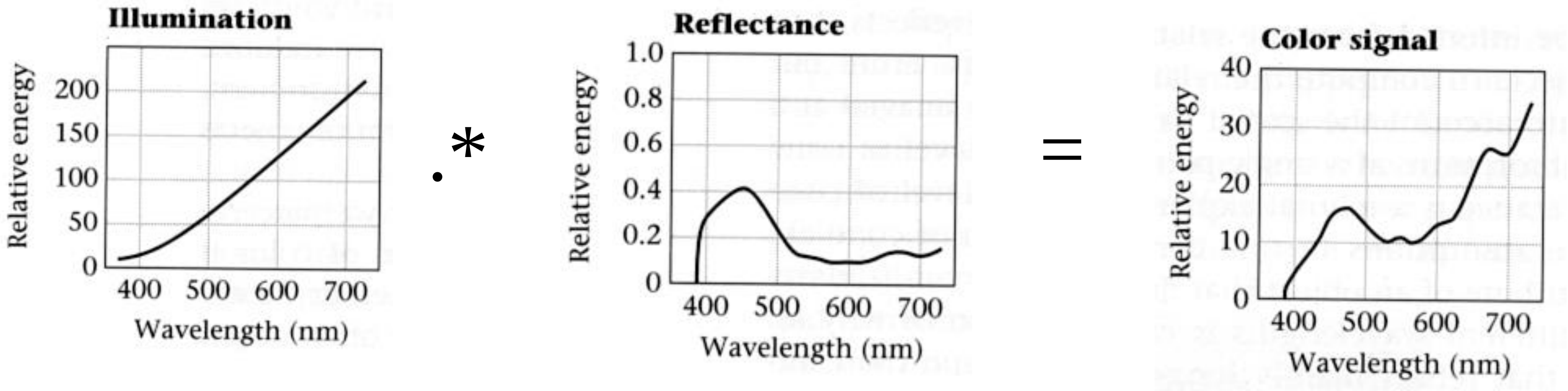


photoes by *Ekant Veer*

Spectrum of Reflected Light



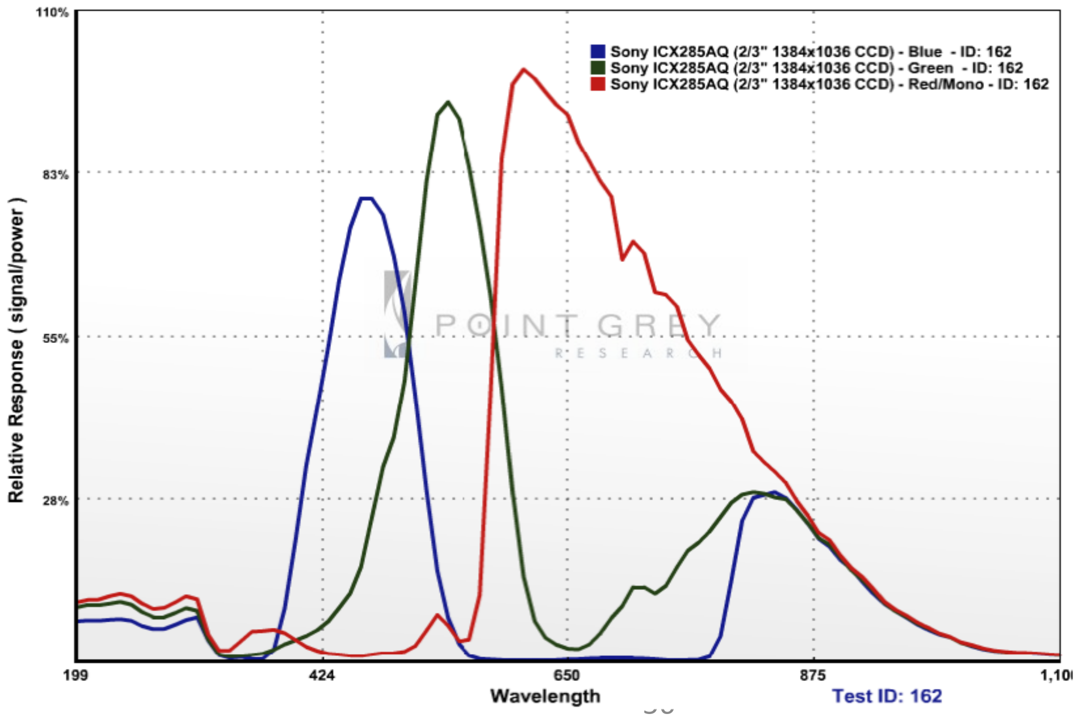
- Color is determined by the light spectrum
- This spectrum of reflected light depends on both the illumination and the object surface
  - spectral computation involves a wavelength-by-wavelength multiplication of relative energies



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

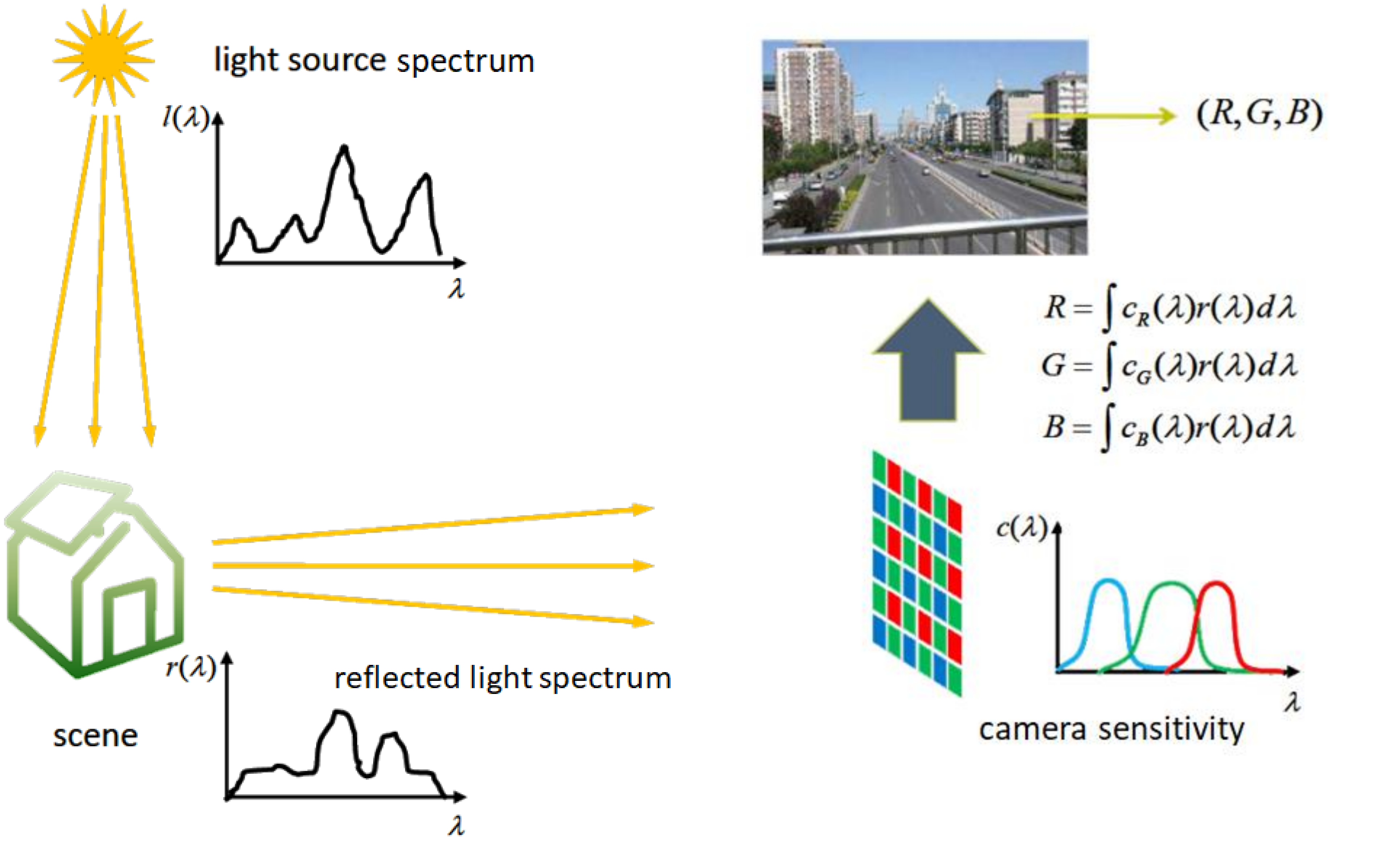
How do Cameras Capture Color?

- A color is represented as a [R,G,B] three vector
- At each pixel, there are three sensors (not precisely) to capture the stimulus of red, green, and blue lights
- Sample camera sensitivity curves



Grasshopper camera GRAS-14S5C from PointGray

How do Cameras Capture Color?



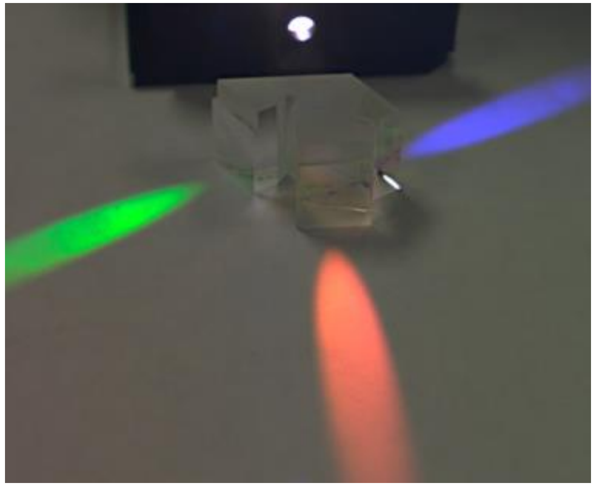
Capture Color Images

Sergei Prokudin-Gorskii
(1863-1944)

- Took three monochrome pictures in sequence, each through a different colored filter
- The original color scene can be reconstructed by projecting these three pictures using correctly colored light (and careful alignment)

Capture Color Images

- Color splitting prism and 3-CCD cameras
  - Split light by a prism
  - Capture each channel by a sensor



- The 'Bayer' pattern
  - A plastic film in front of the sensor
  - Each pixel see either red, green, or blue
  - Interpolate to recover unseen values (known as Demosaicing)
  - More green pixels than red and blue

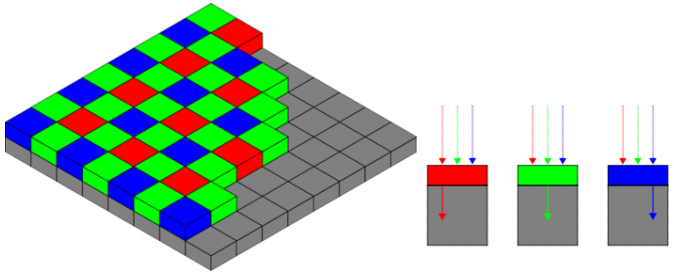


Fig: RGB Bayer filter (named after its inventor, Dr. Bryce E. Bayer from Kodak), picture from wiki

Questions?

Why Specify Color Numerically?

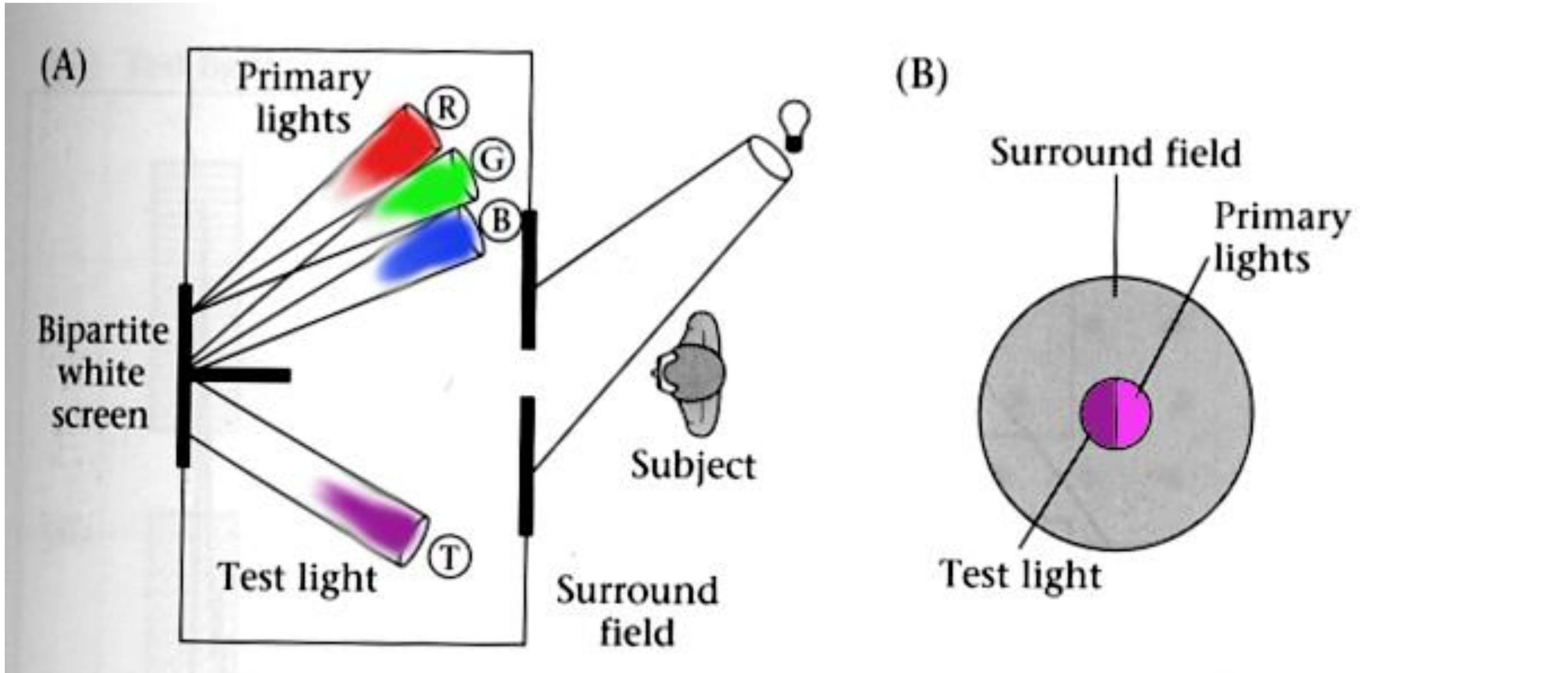
- Accurate color is commercially valuable
  - Many products are identified by color (“golden” arches of McDonald's);

- Few color names in natural languages
  - About 10 English words;
    other languages have fewer/more, but not many more
  - It’s common to disagree on appropriate color names

- How to specify color numerically?
  - Mix primary colors to represent other colors
  - How to decide the mixture coefficients??

Color Matching

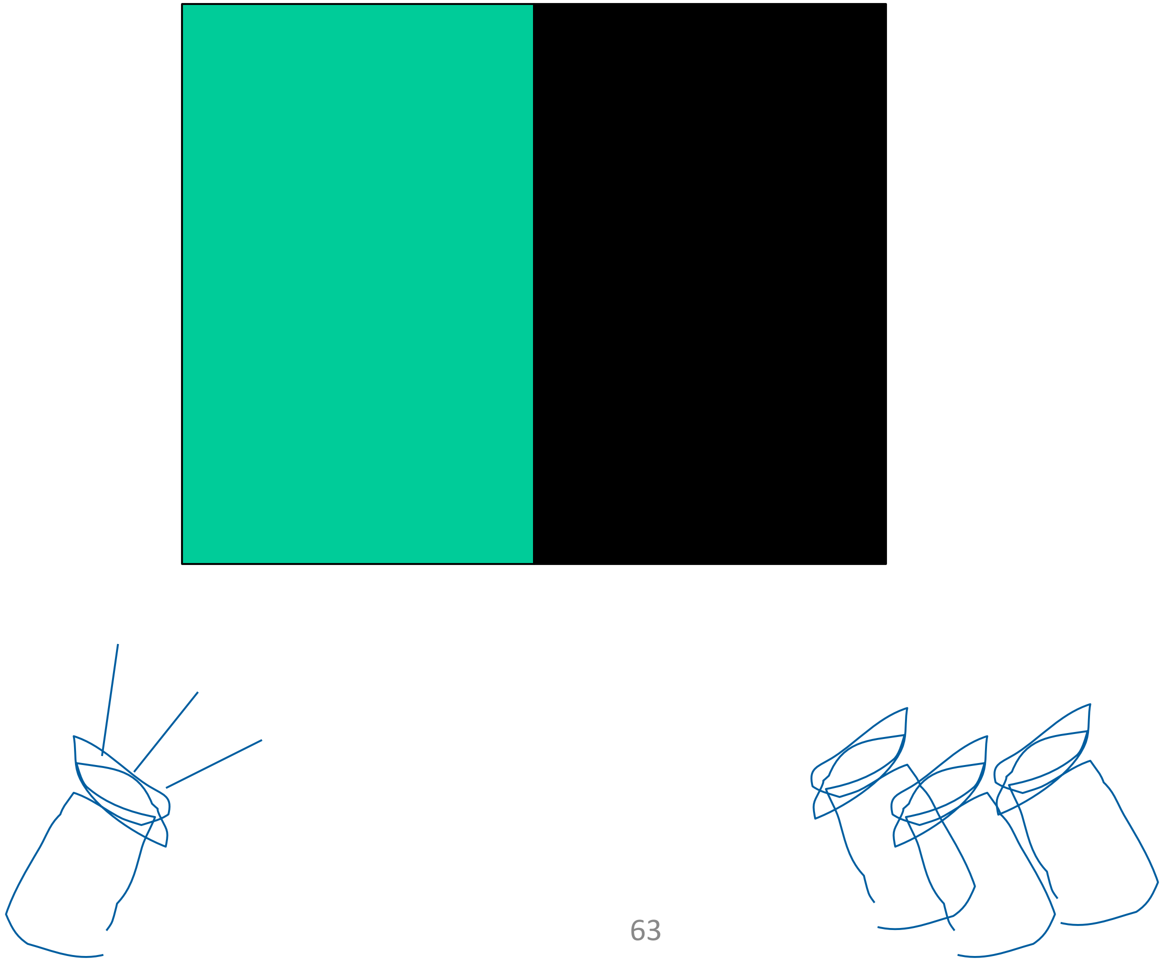
Color matching: use three primary colors to represent other colors



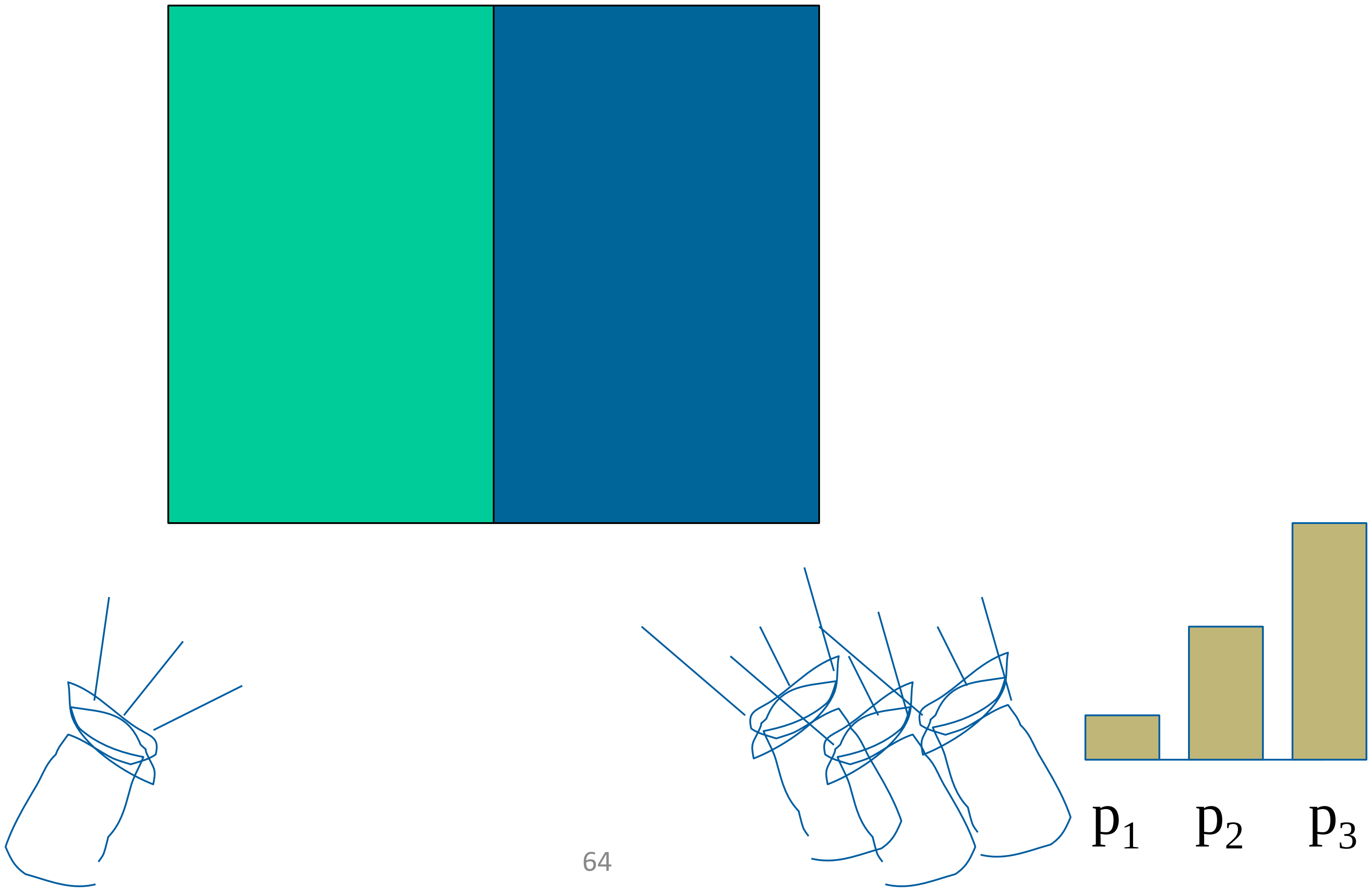
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

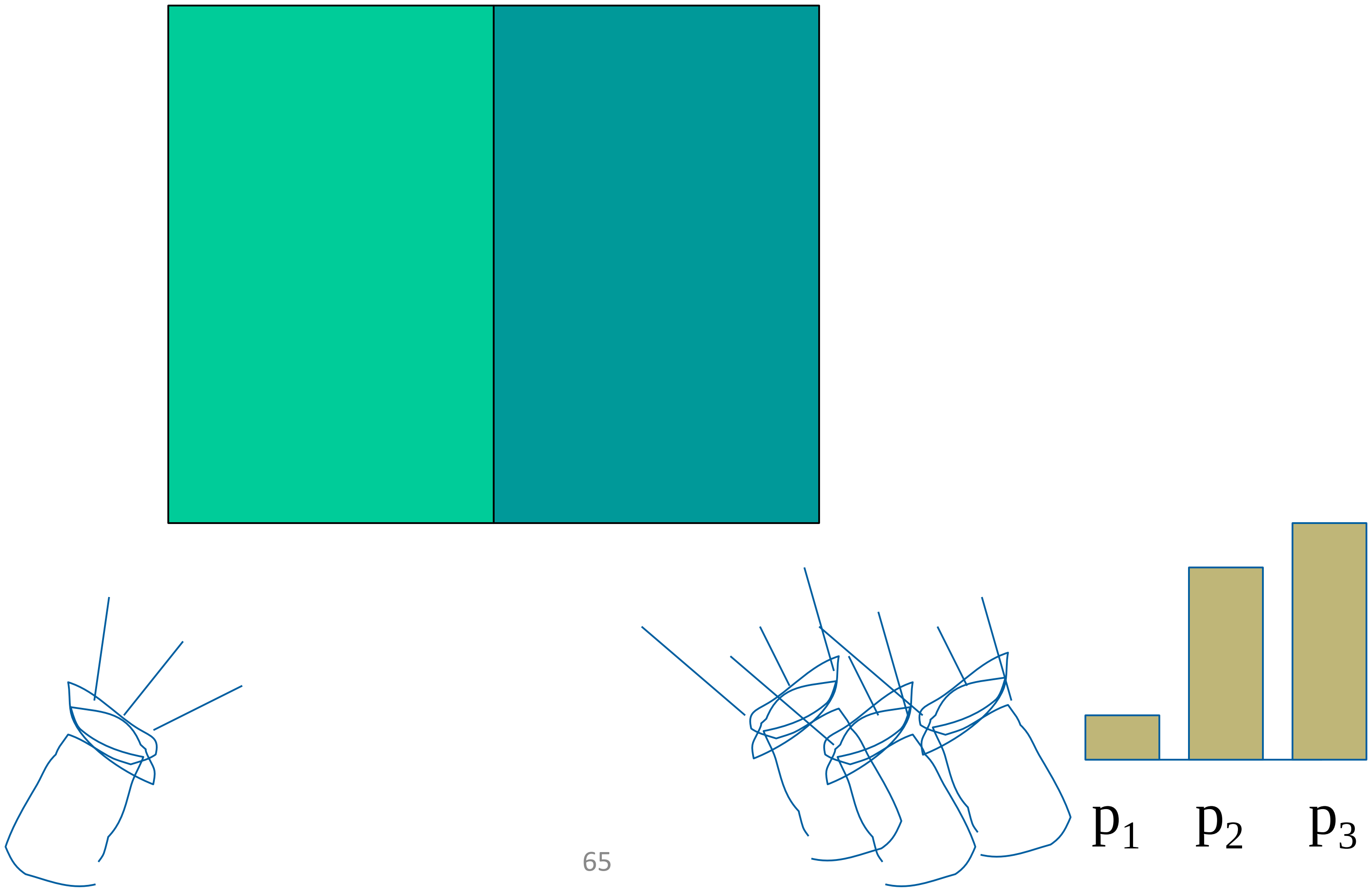
Color Matching Experiment 1



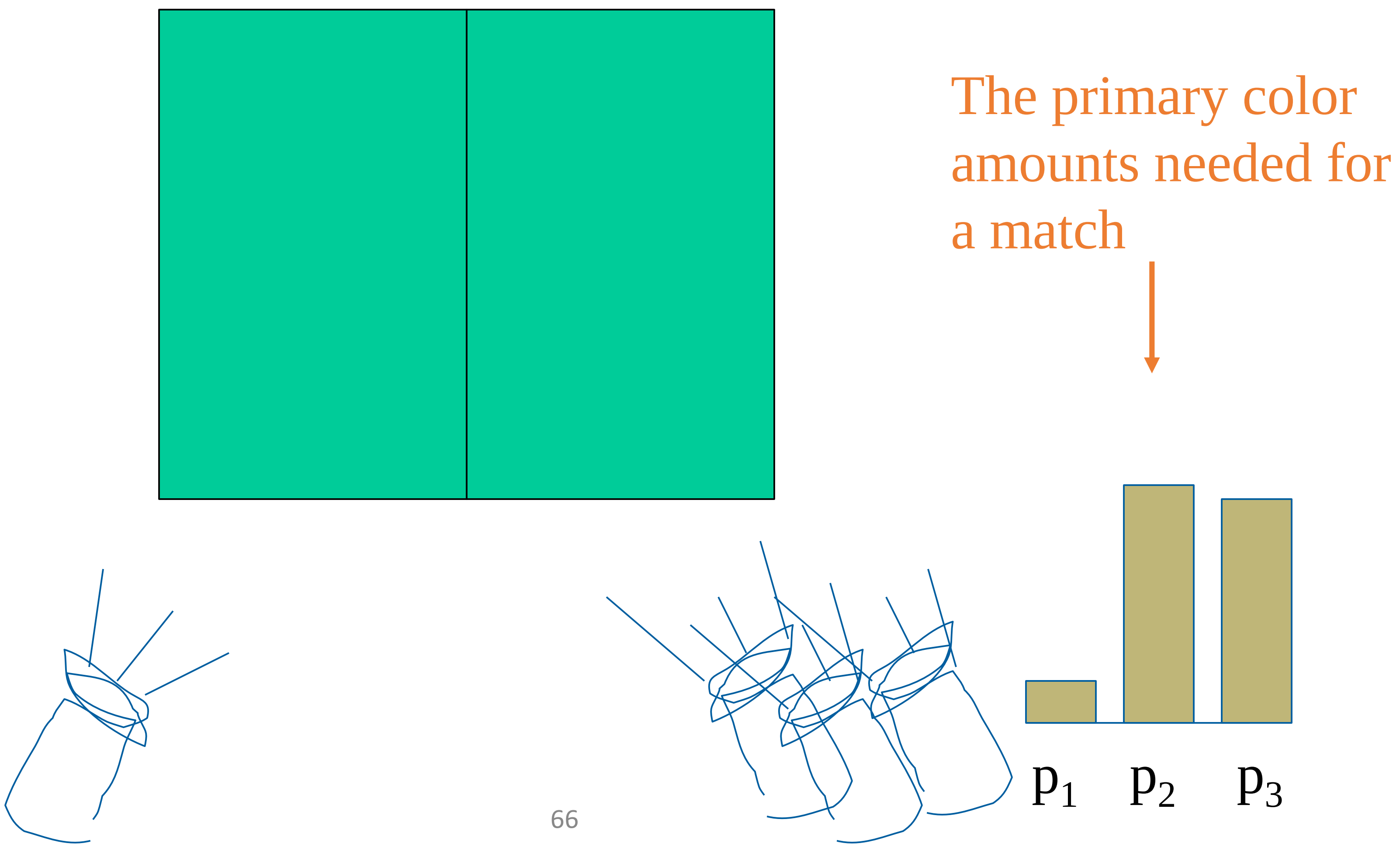
Color Matching Experiment 1



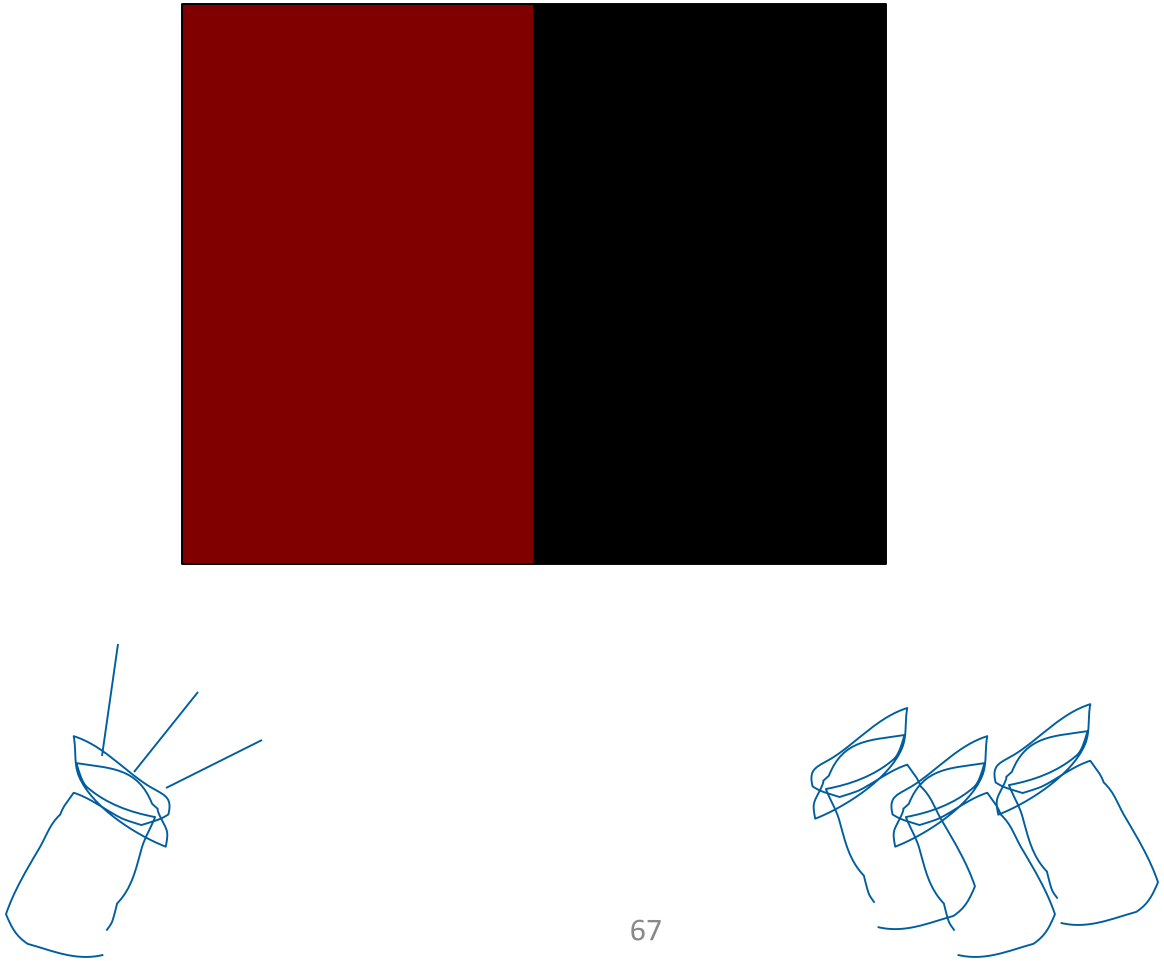
Color Matching Experiment 1



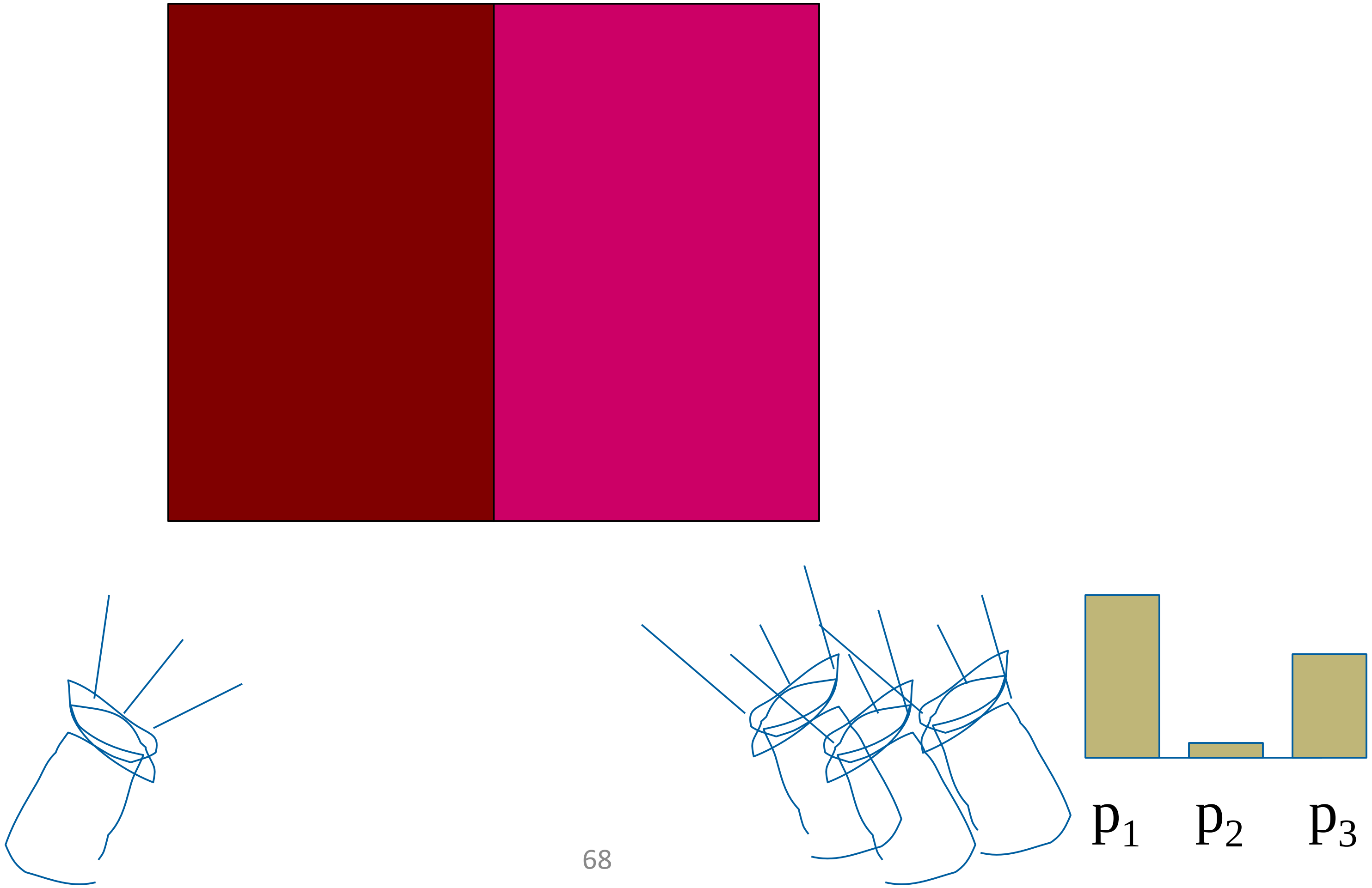
Color Matching Experiment 1



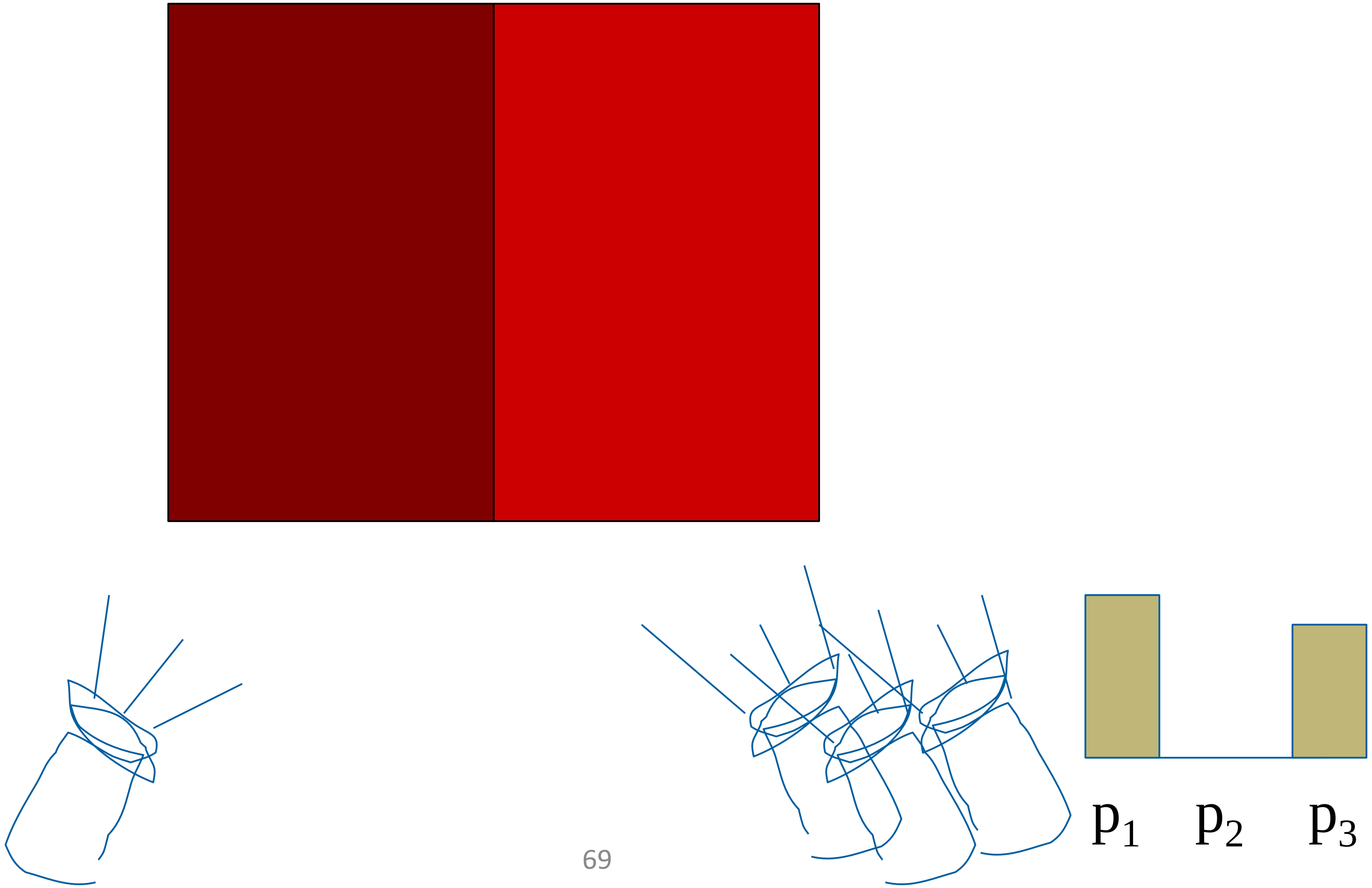
Color Matching Experiment 2



Color Matching Experiment 2

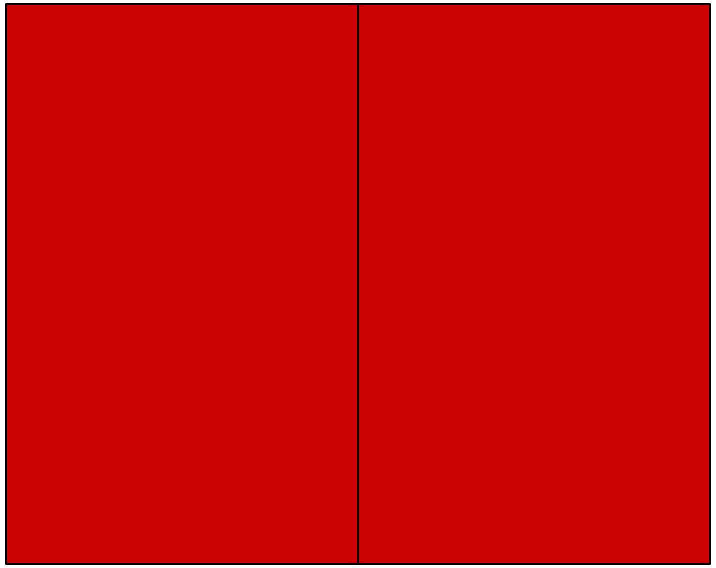


Color Matching Experiment 2

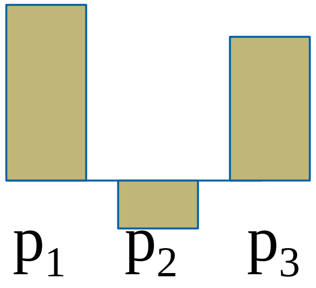


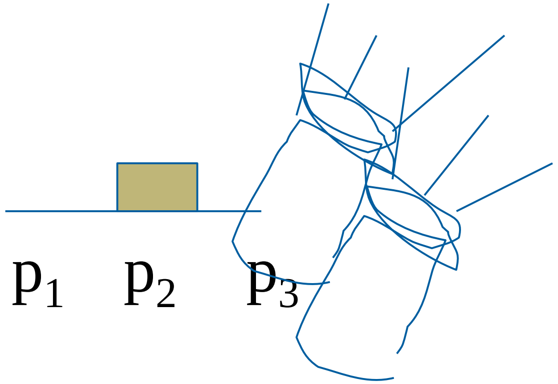
Color Matching Experiment 2

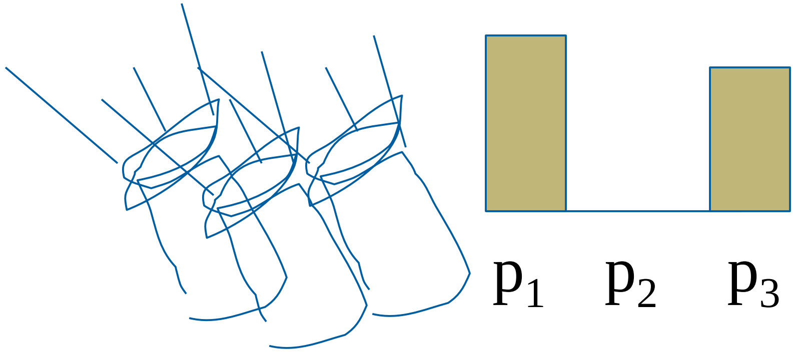
We say a "negative" amount of p_2 was needed to make the match, because we added it to the test color's side.



The primary color amounts needed for a match:

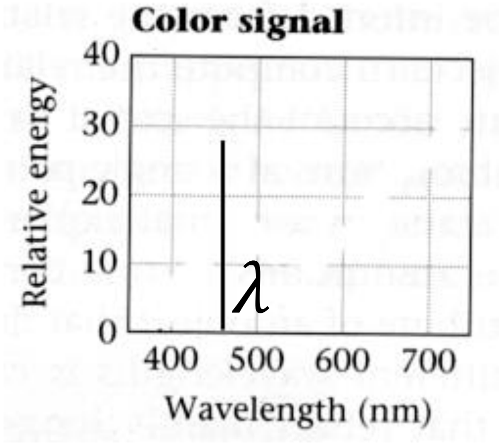


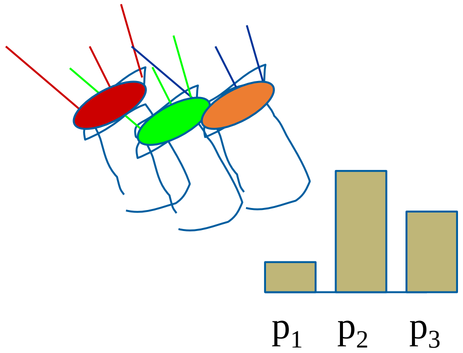


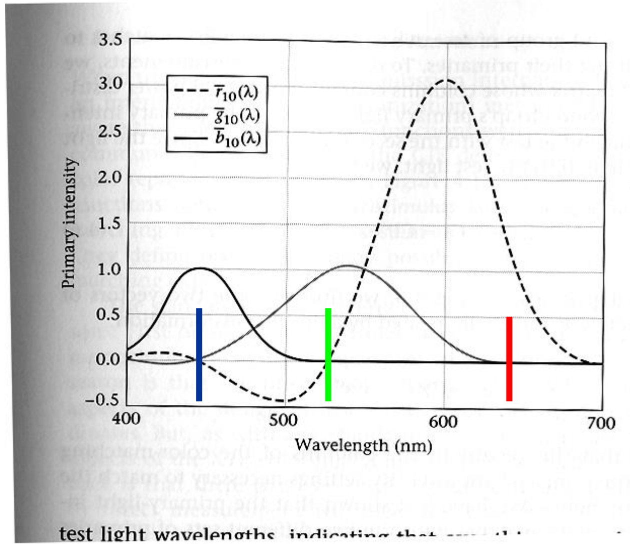


CIE XYZ Color Space

- Color matching for mono-chromatic lights
  - By Commission Internationale d'Eclairage (International Commission on Illumination) in 1931
- The results are the color matching functions $r(\lambda), g(\lambda), b(\lambda)$
- The three stimulus of any light spectrum can be computed from these color matching functions
  - Human color perception is linear (the Grassman's law)





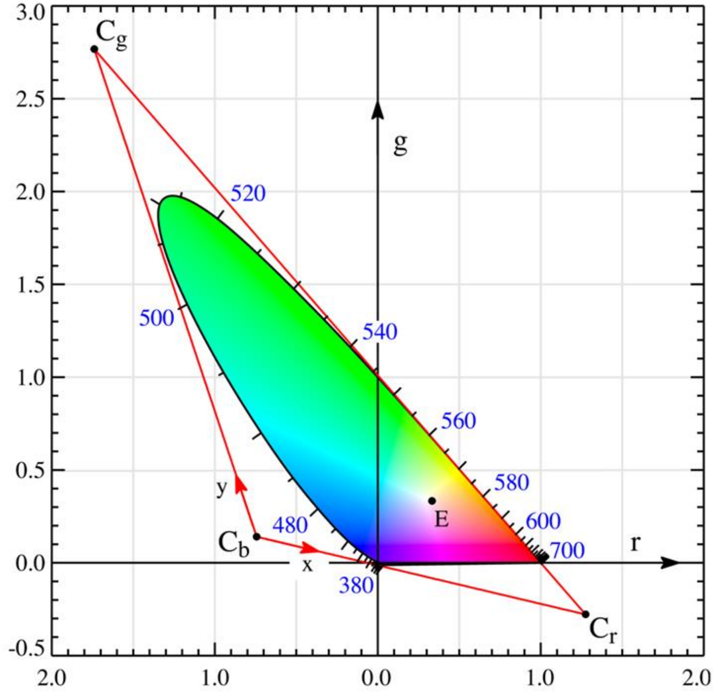


p_1 = 645.2 nm
p_2 = 525.3 nm
p_3 = 444.4 nm

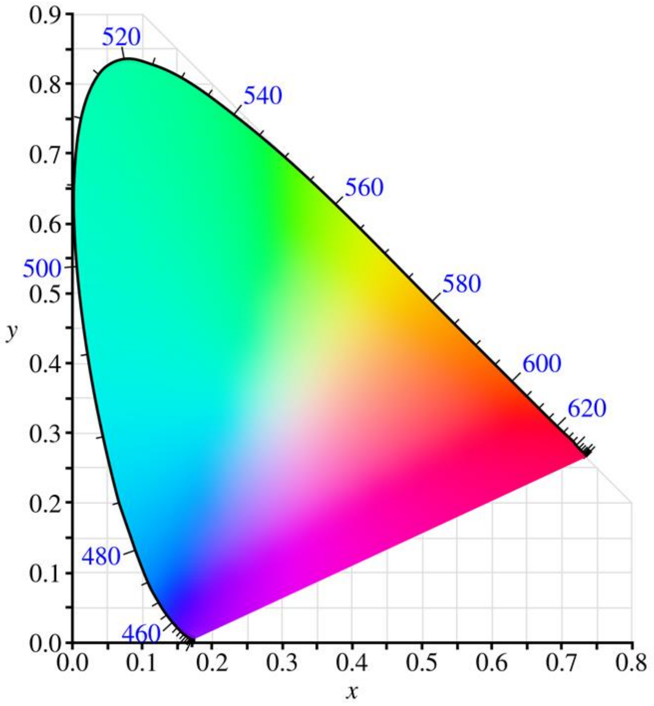
4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this figure are called $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, and $\bar{b}_{10}(\lambda)$.

CIE XYZ Color Space

- The original color matching functions have negative values
- An additional transform is chosen to make all coefficients positive
  - Making all combination coefficients positive
  - Making the y-axis closer to brightness



CIE *rg* chromaticity space



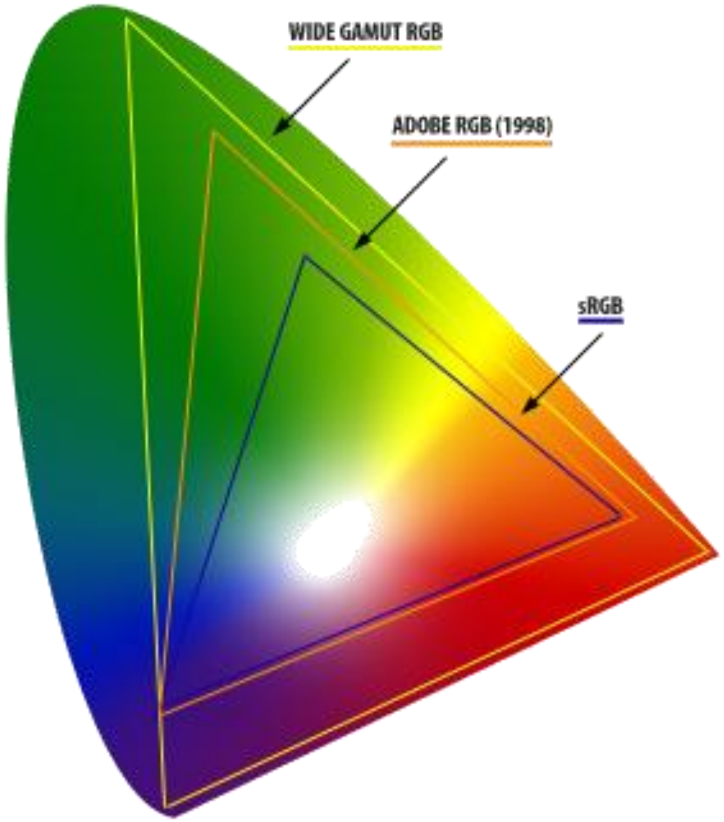
CIE 1931 *xy* chromaticity space

RGB and XYZ

- XYZ is rarely used for storage, often RGB is used
- There are tons of flavors of RGB (sRGB, Adobe RGB), all different matrices!
- But none of the RGB spaces can generate all visible colors
  - Some cameras have four primary colors
- Linear transform from XYZ to sRGB

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$



YUV Color Space

- The YUV color model defines a color space in terms of one luminance and two chrominance components
- It is used in the many video compression standards

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.14713 & -0.28886 & 0.436 \\ 0.615 & -0.51499 & -0.10001 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

It is supposed, in all the previous equations, that $R, G, B \in [0, 1]$.

As a consequence, the range of the transformed components is given by

$$Y \in [0,1], \quad U \in [-0.436, 0.436], \quad V \in [-0.615, 0.615]$$

Spatial Resolution and Color

original

R

G

B

Blurring the G Component

original

processed

R

G

B

Blurring the R Component

original

processed

R

G

B

Blurring the B Component

original

processed

R

G

B

YUV Color Components

original

Y

U

V

Blurring the Y Lab Component

original

processed

Y

U

V

Blurring the U Lab Component

original

processed

Y

U

V

Blurring the V Lab Component

original

processed

Y

U

V

Questions?