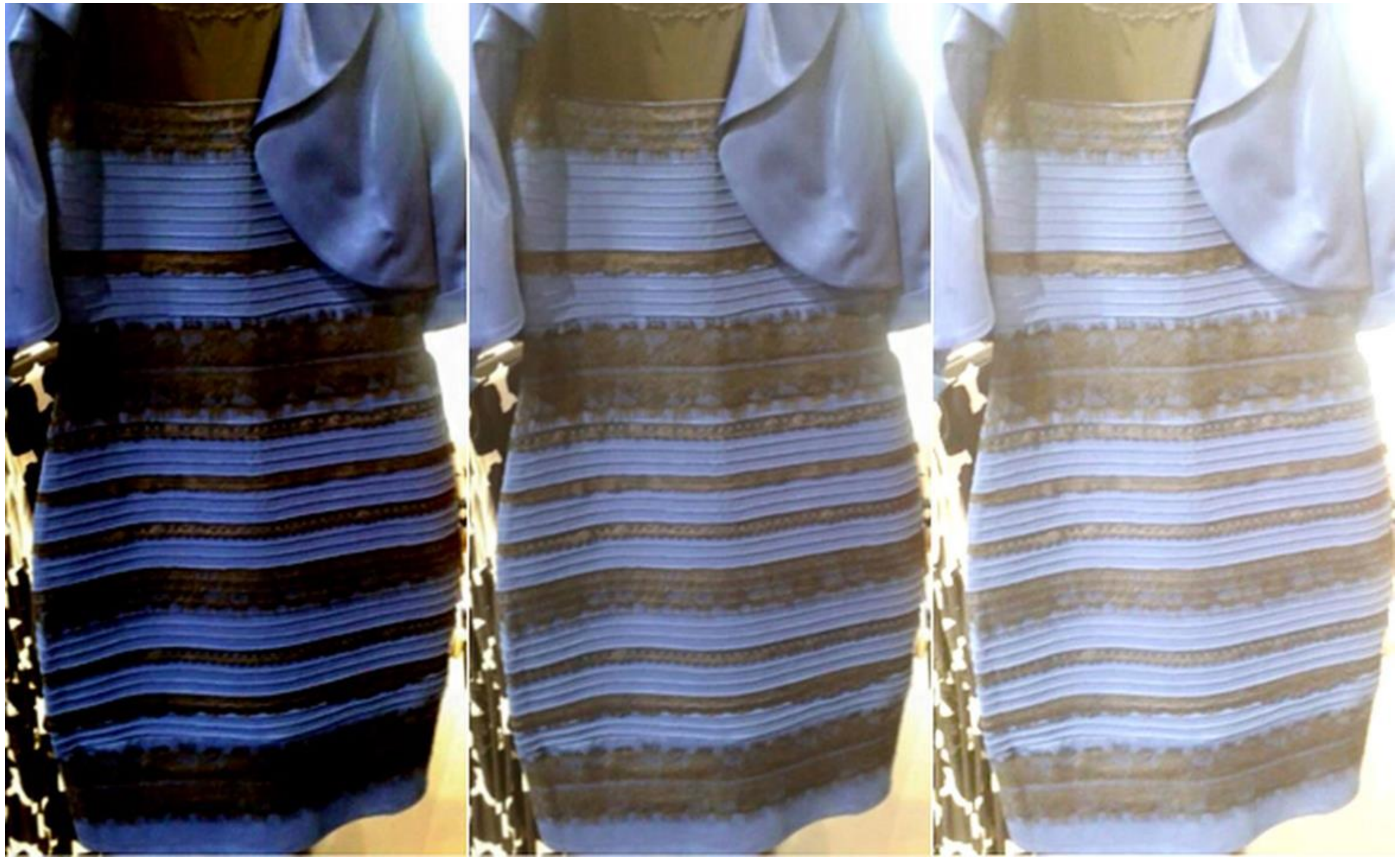
2. Color

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

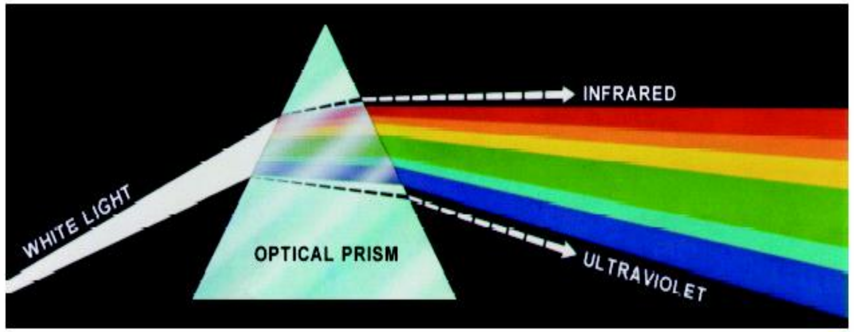


Fig: Color spectrum seen by passing white light through a prism (As of Gonzalez 2e Page 283)

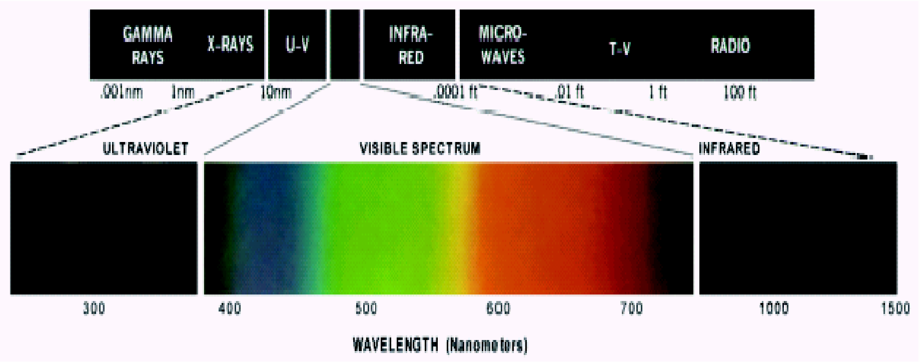
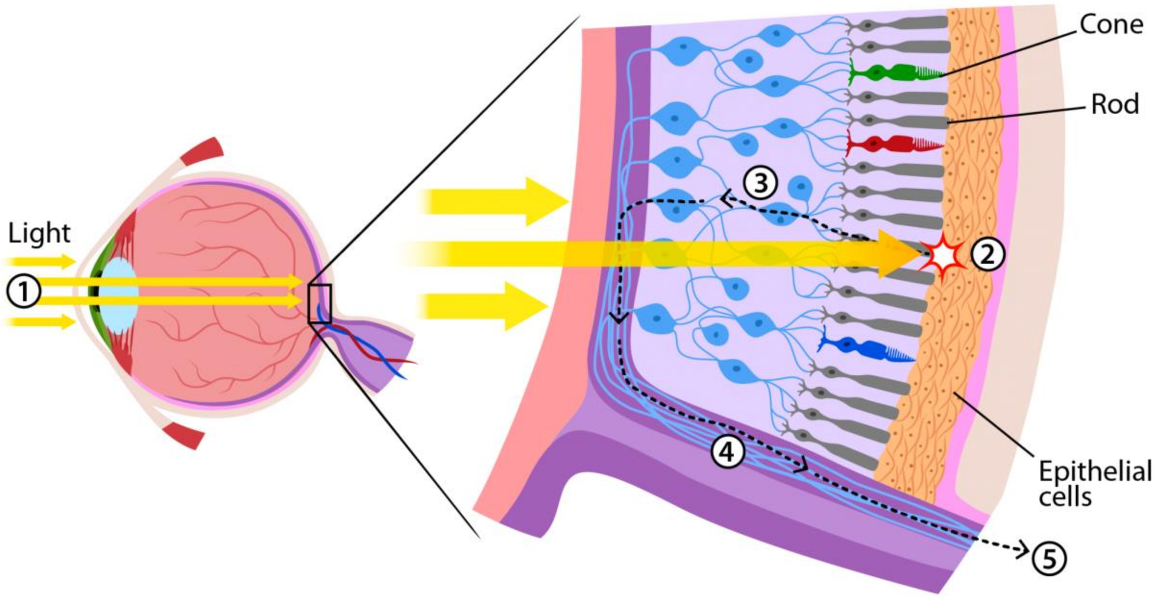


Fig: Wavelengths comprising the visible range of electromagnetic spectrum (As of Gonzalez 3e Page 284)

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)



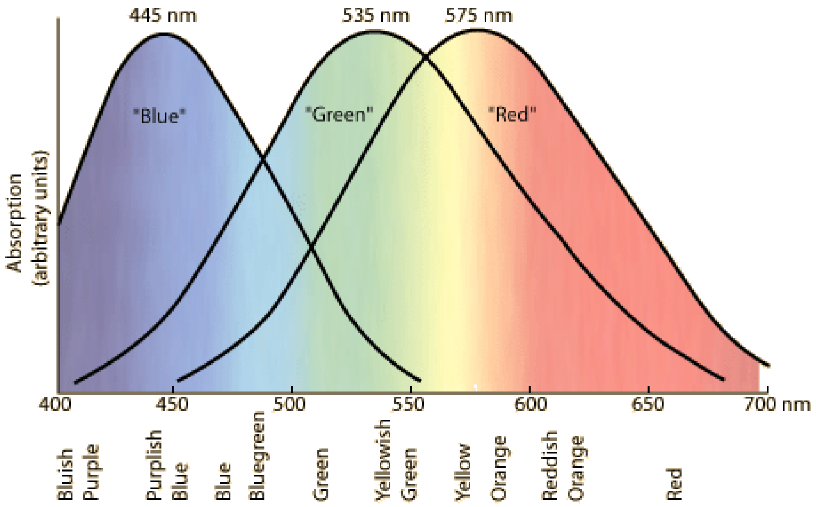
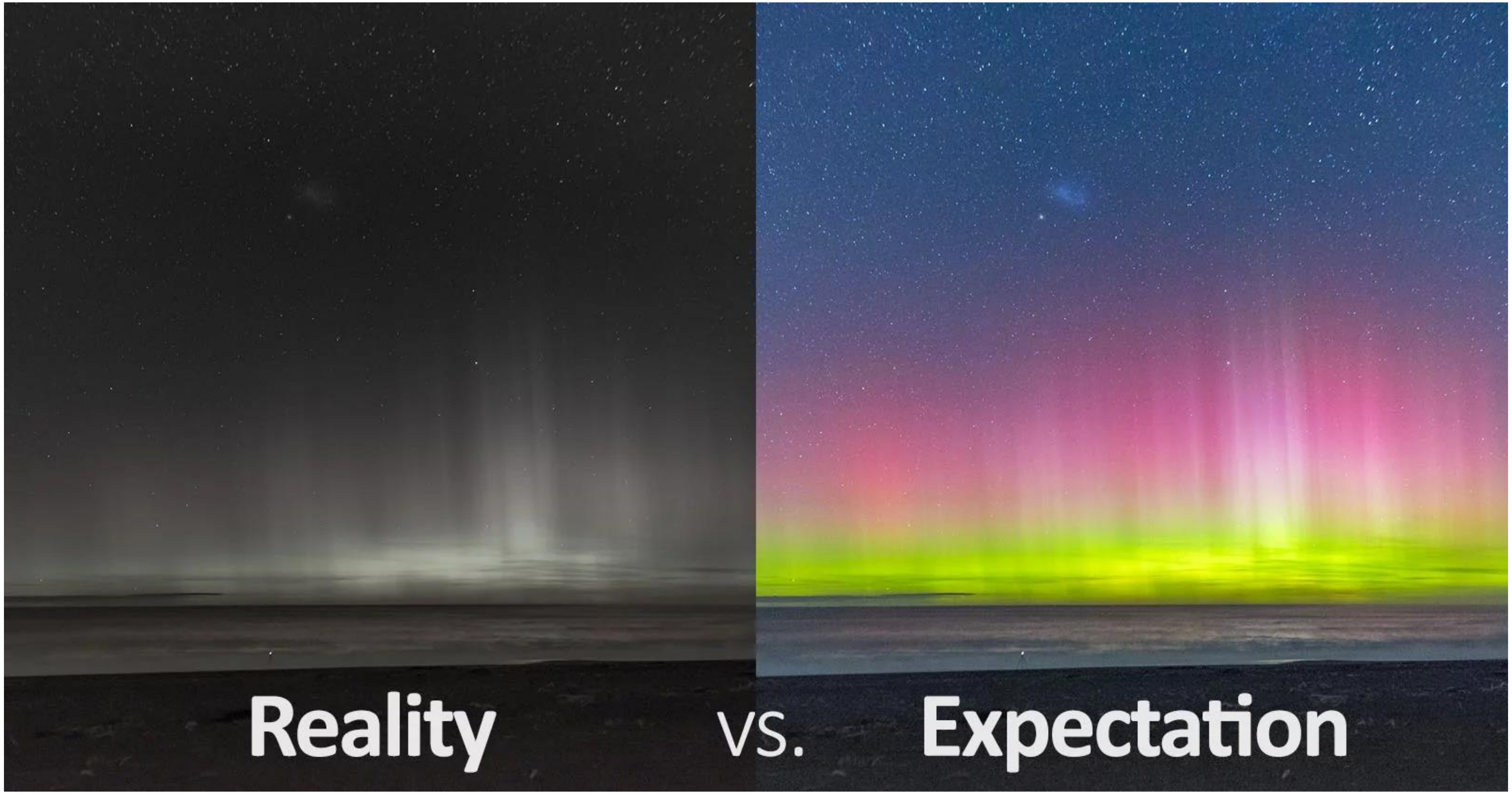


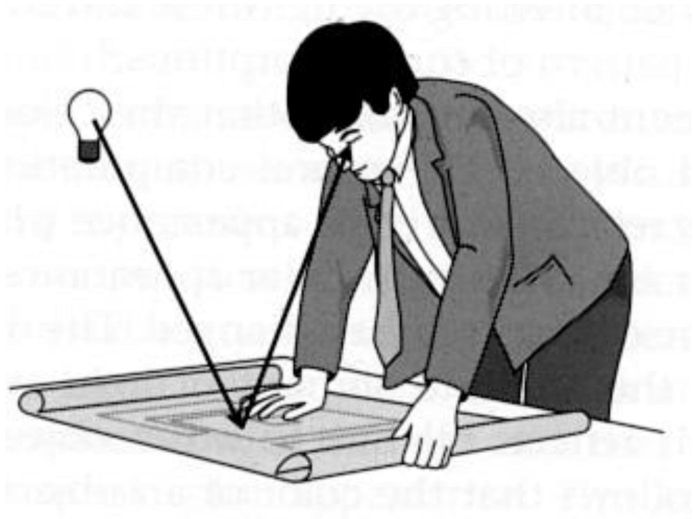
Fig: Absorption of light by red, green and blue cones in the human eye as a function of wavelength (As of Gonzalez 2e Page 285)

What does the aurora actually look like?

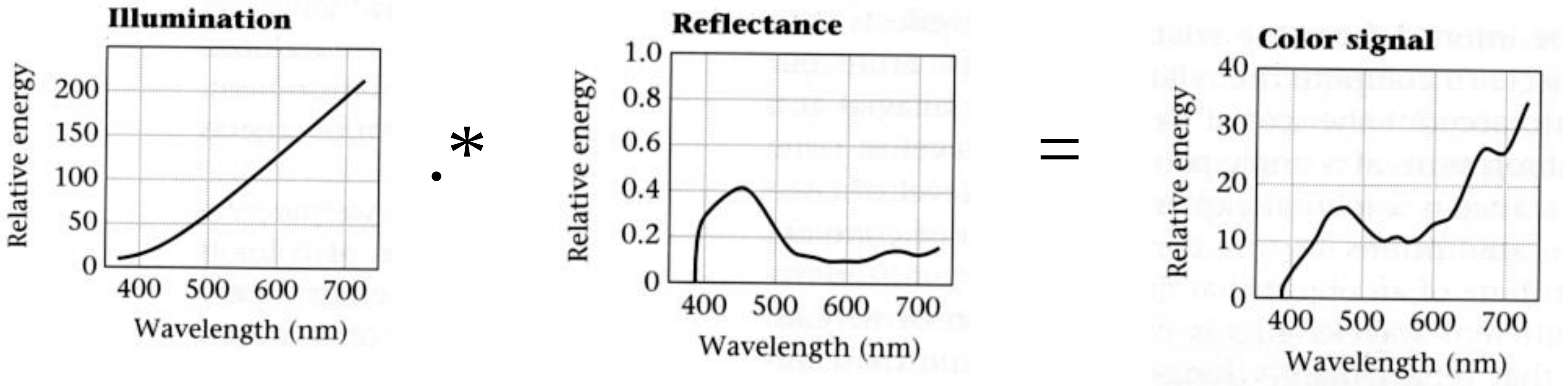


photoes by *Ekant Veer*

Spectrum of Reflected Light

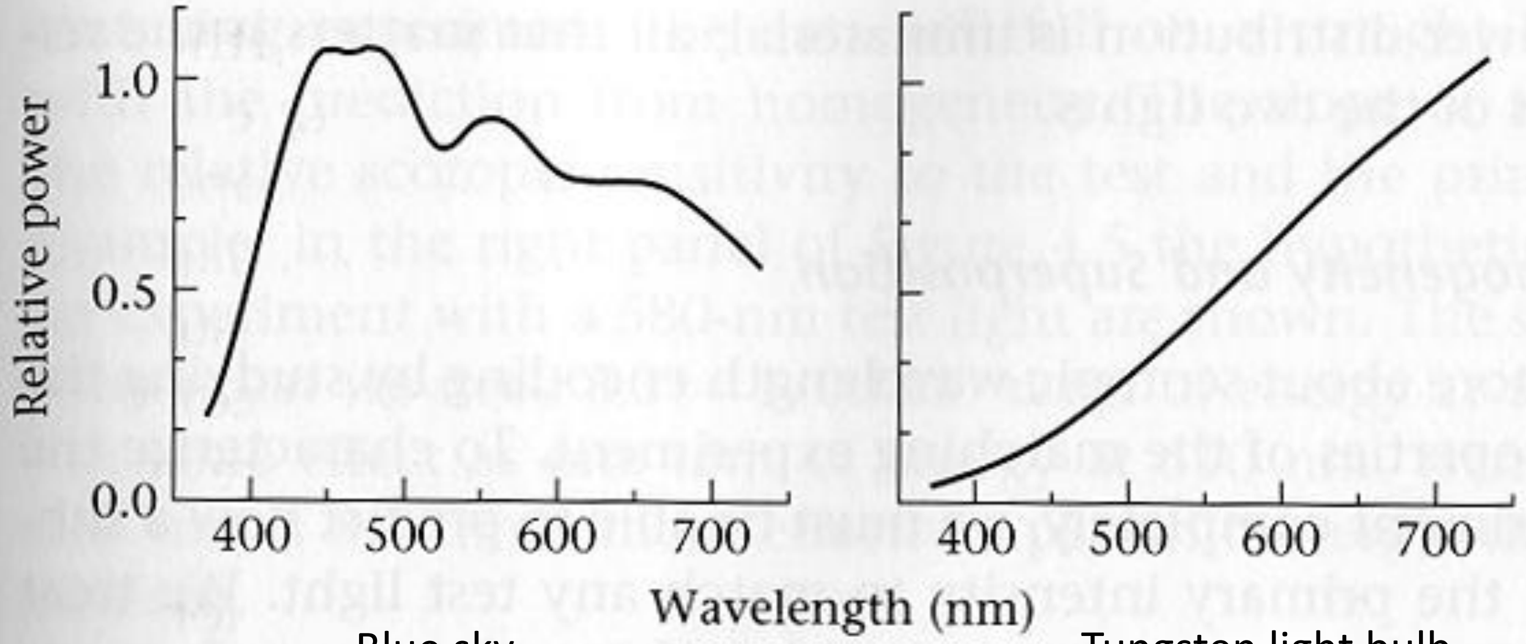


- Color is determined by the light spectrum
- This spectrum of reflected light depends on both the illumination and the object surface
  - spectral computation involves a wavelength-by-wavelength multiplication of relative energies



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

The Spectra of Light Sources



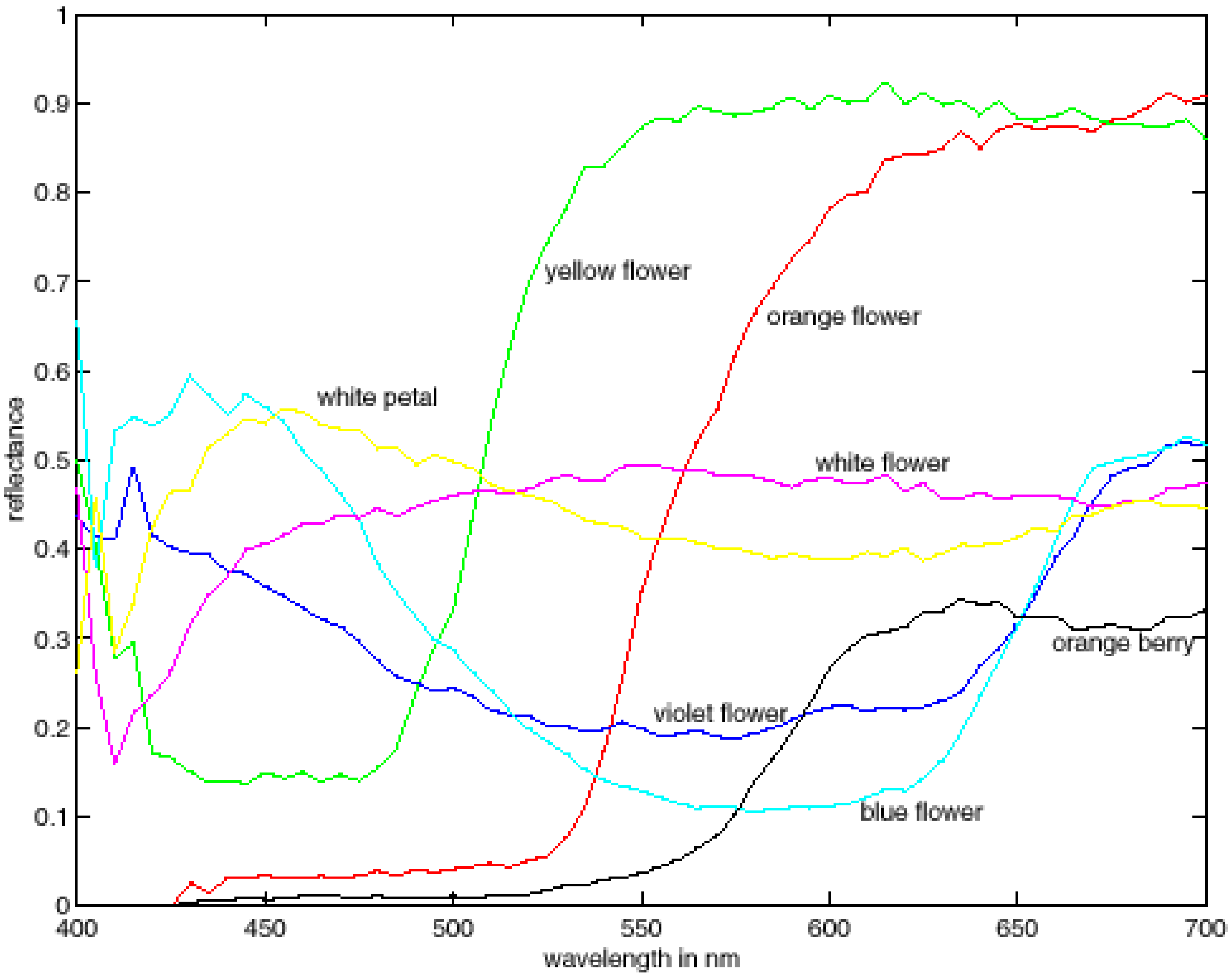
Blue sky

Tungsten light bulb

4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.

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

The Spectral Albedo of Surfaces

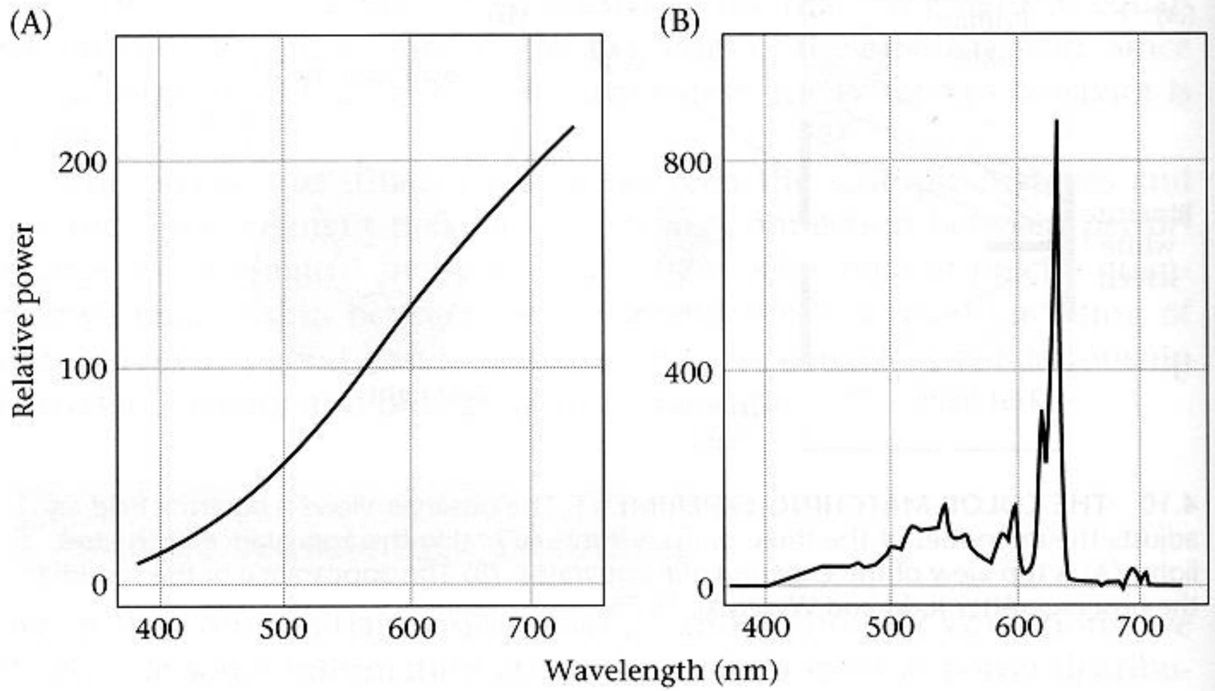


Computer Vision – A Modern Approach, Forsyth and Ponce, 2002

- Spectral albedo for several different leaves, with color names attached.
- Notice that different colors typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites).

Metameric Lights

- Sometimes, two different light spectrum can cause the same color sensation

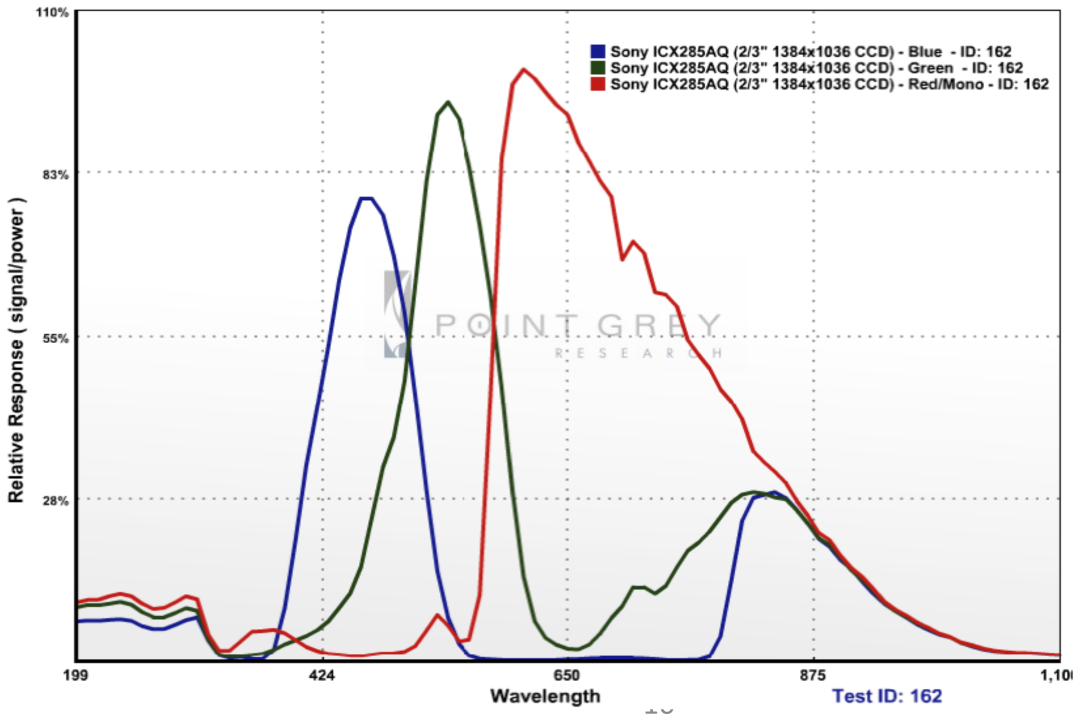


4.11 **METAMERIC LIGHTS.** Two lights with these spectral power distributions appear identical to most observers and are called metamers. (A) An approximation to the spectral power distribution of a tungsten bulb. (B) The spectral power distribution of light emitted from a conventional television monitor whose three phosphor intensities were set to match the light in panel A in appearance.

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

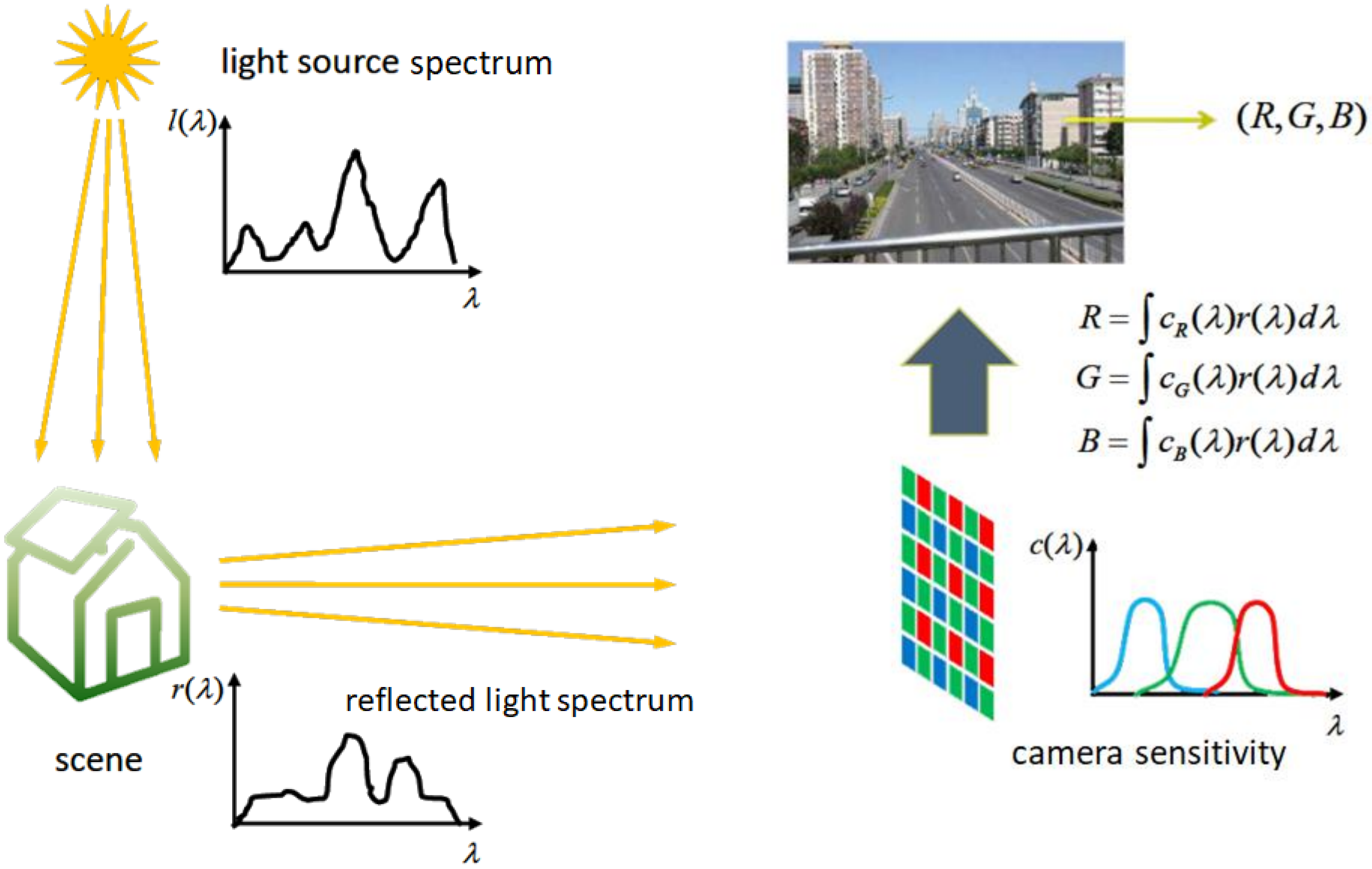
How do Cameras Capture Color?

- 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?



Questions?

Why Specify Color Numerically?

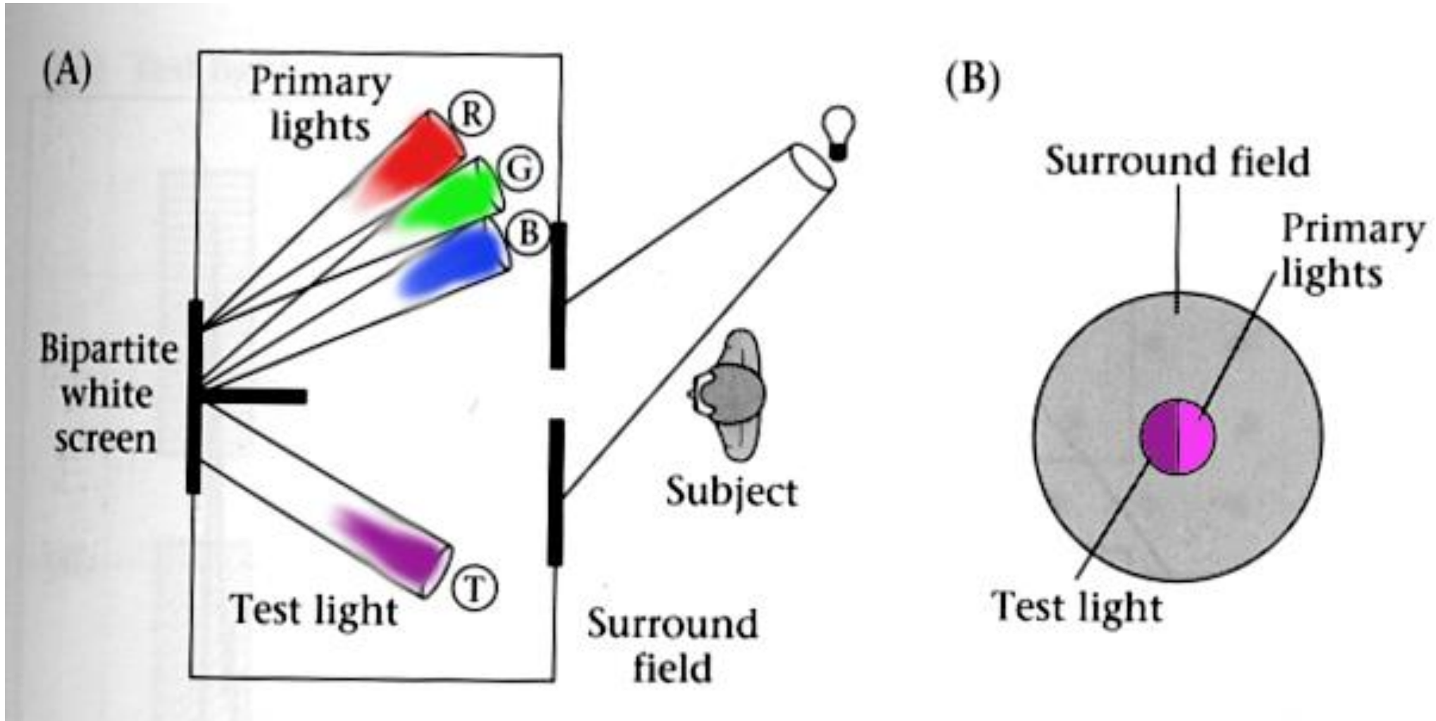
- Accurate color is commercially valuable
  - Many products are identified by color (“golden” arches of McDonald's);

- 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

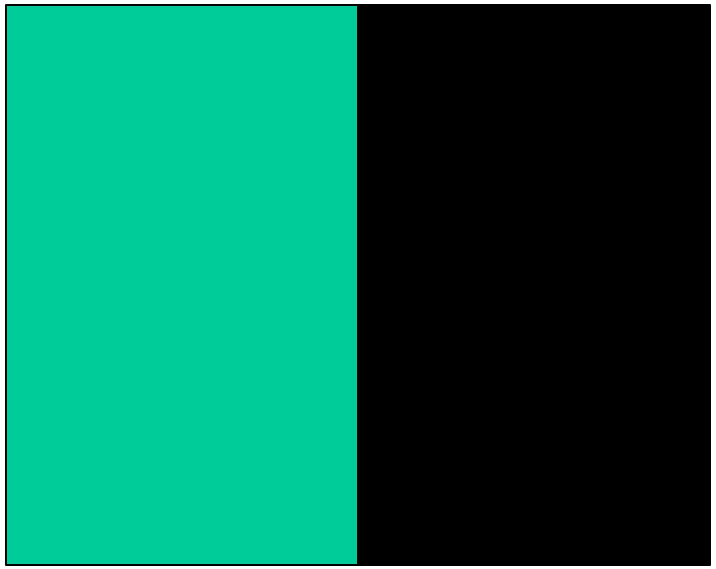
Color matching: use three primary colors to represent other colors

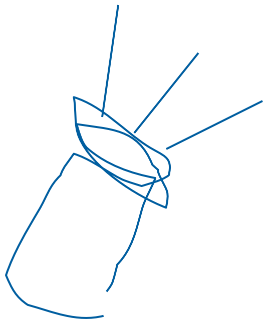


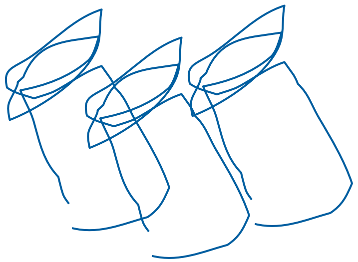
4.10 **THE COLOR-MATCHING EXPERIMENT.** The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

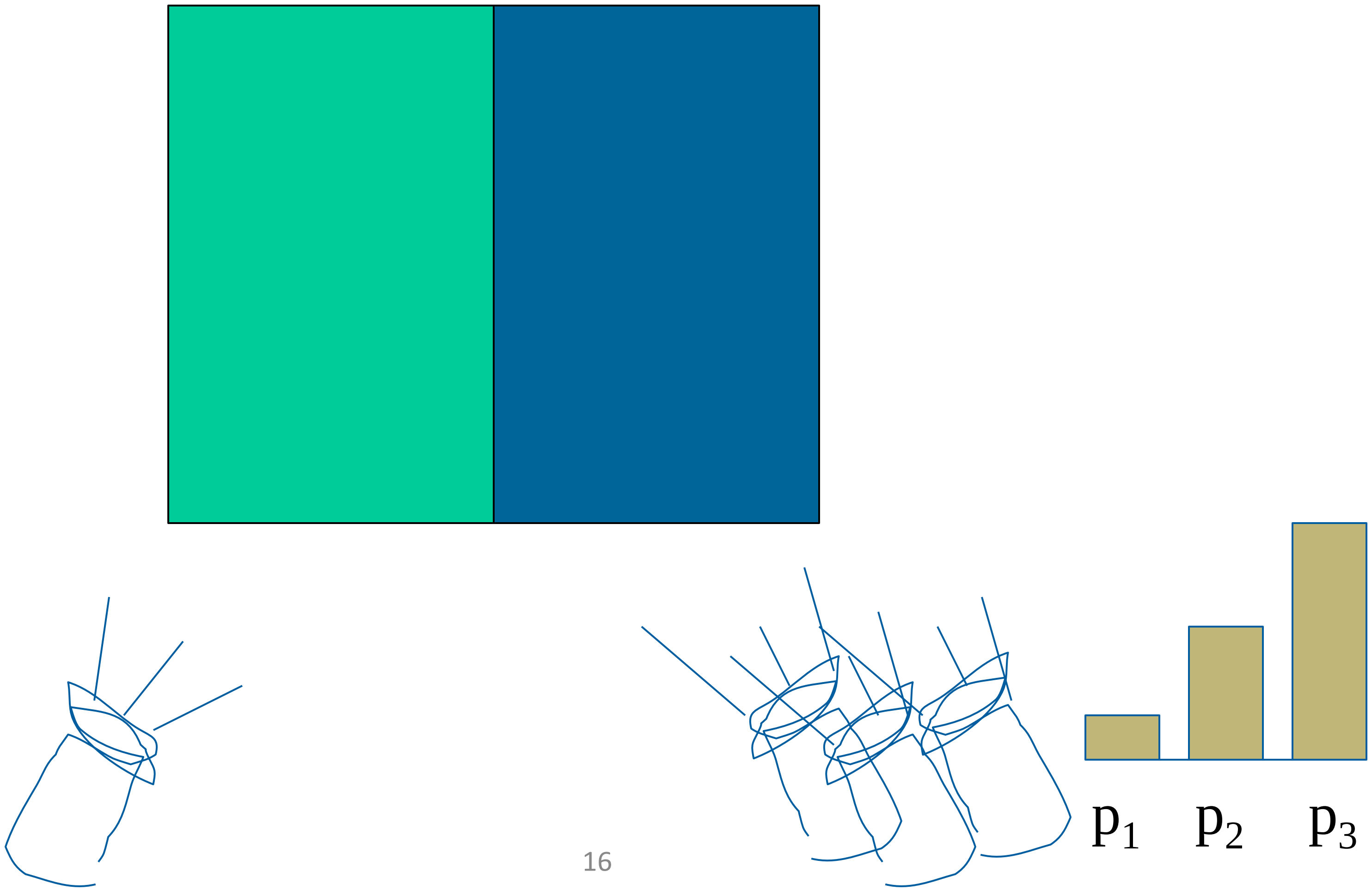
Color Matching Experiment 1



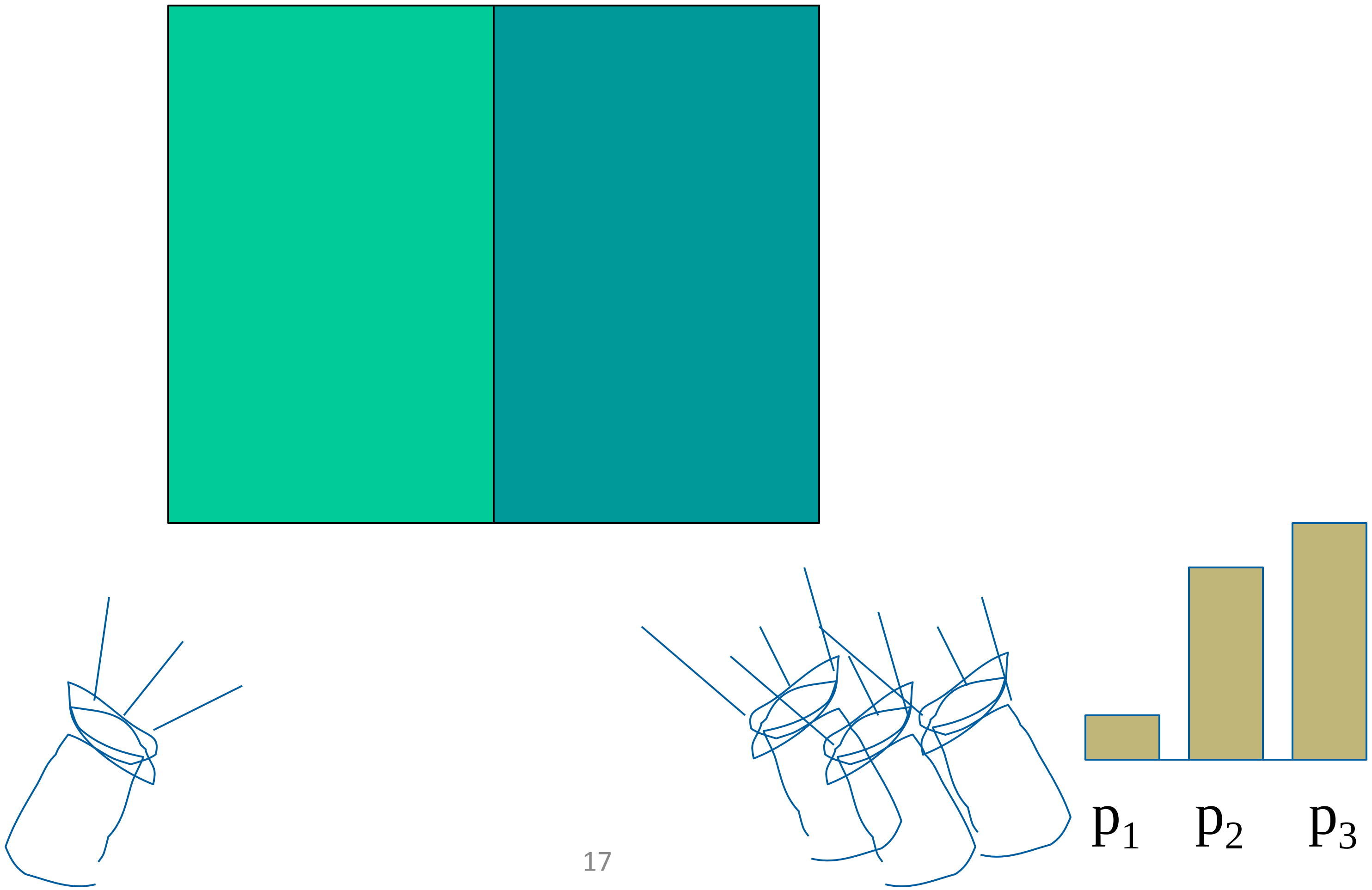




Color Matching Experiment 1

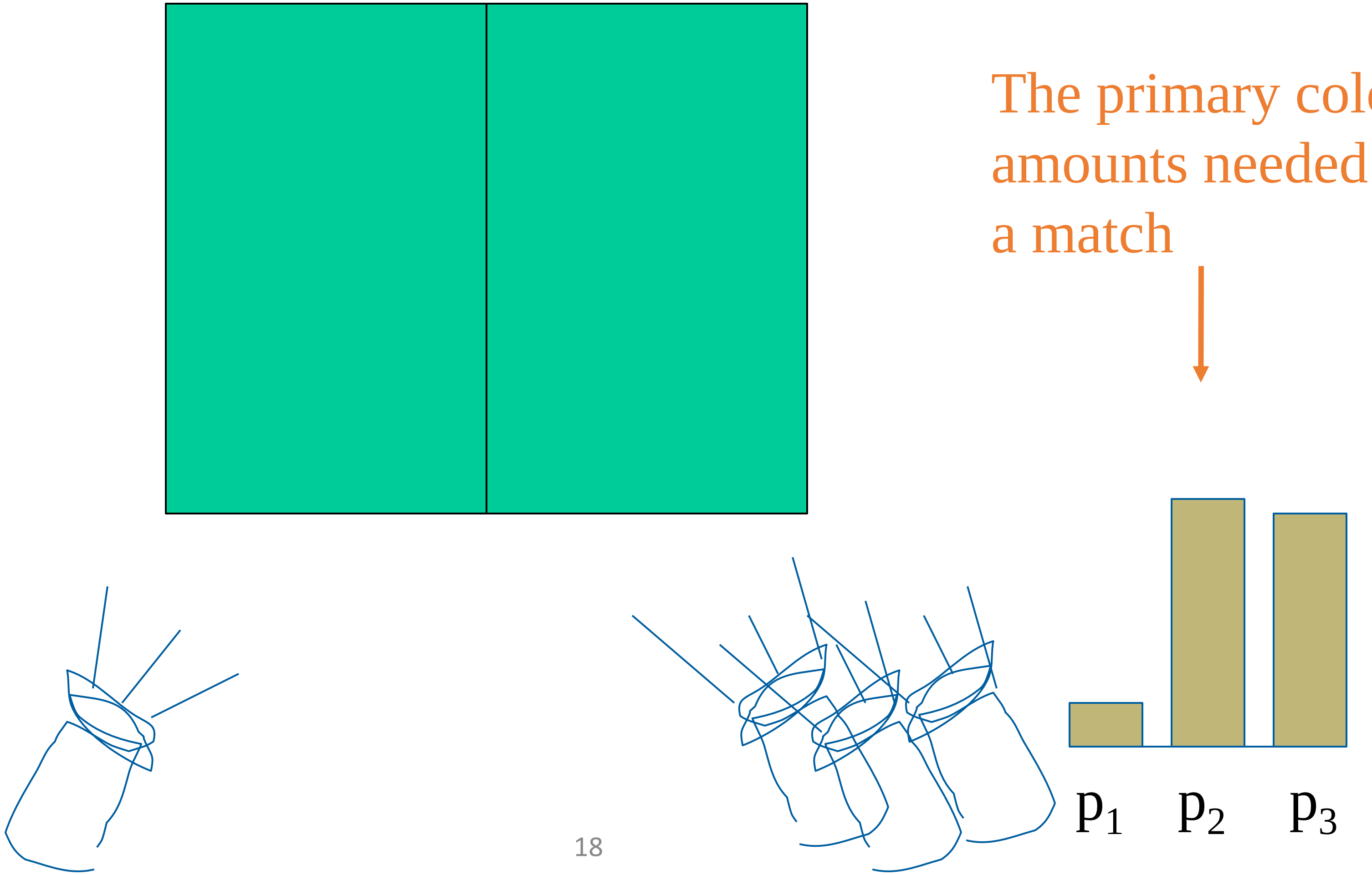


Color Matching Experiment 1

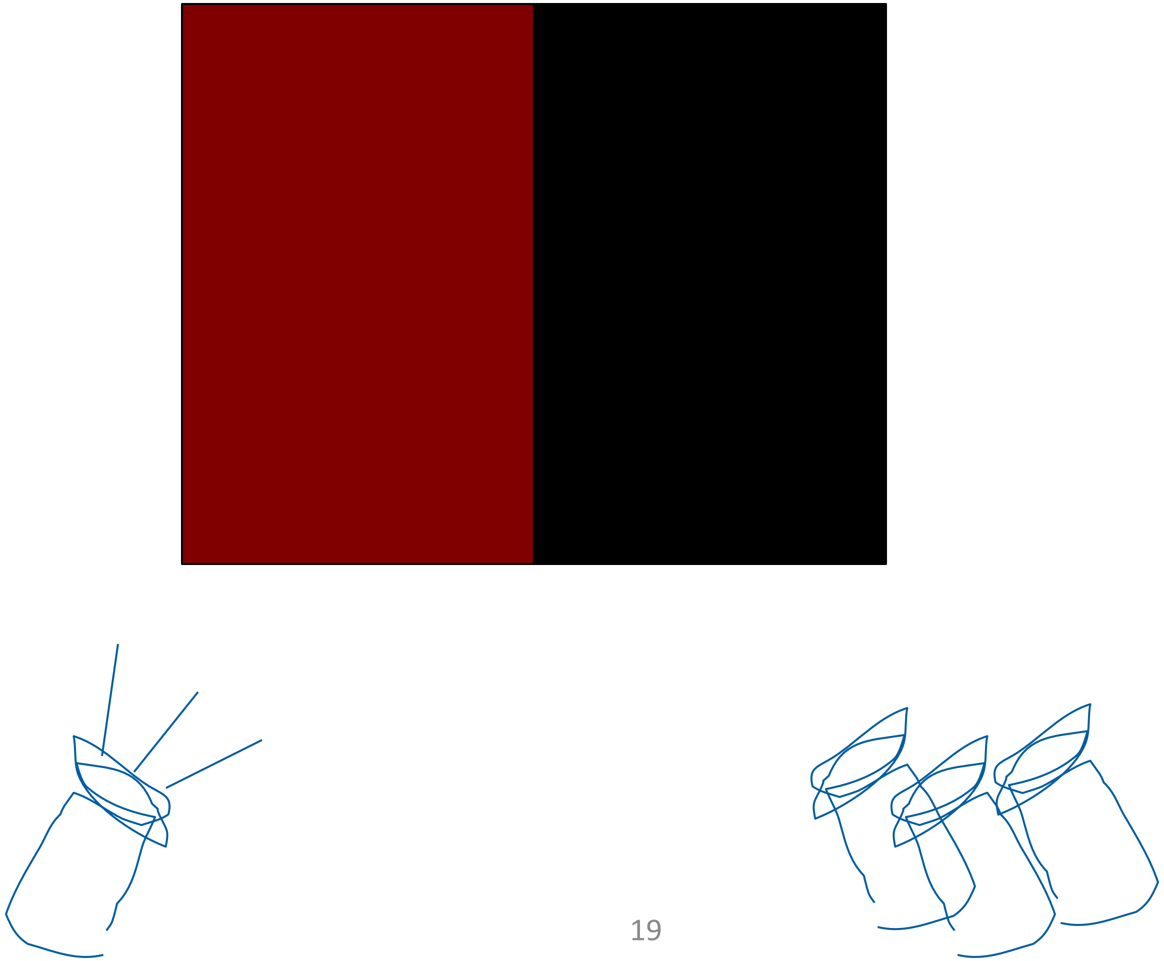


Color Matching Experiment 1

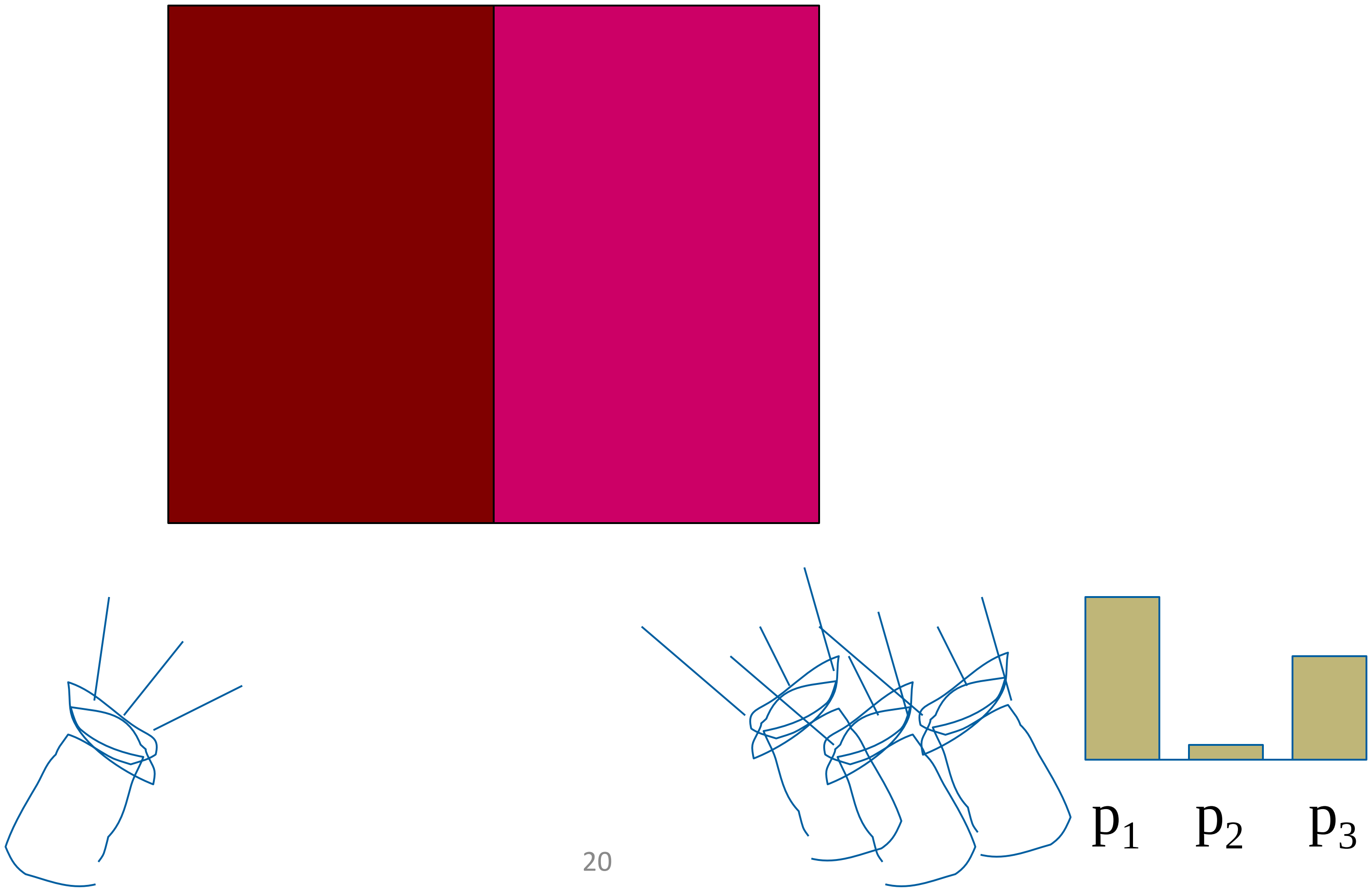
The primary color amounts needed for a match



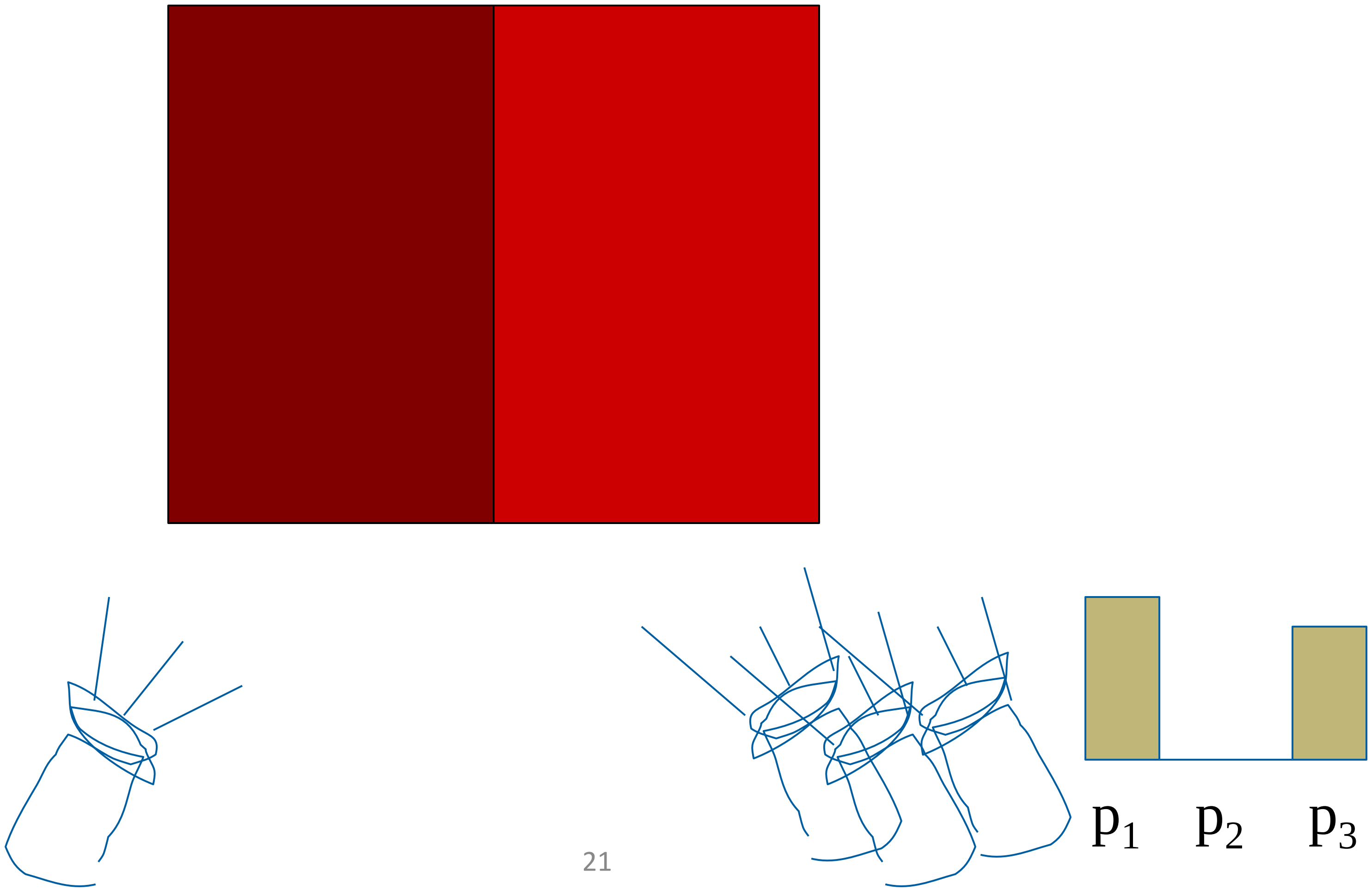
Color Matching Experiment 2



Color Matching Experiment 2

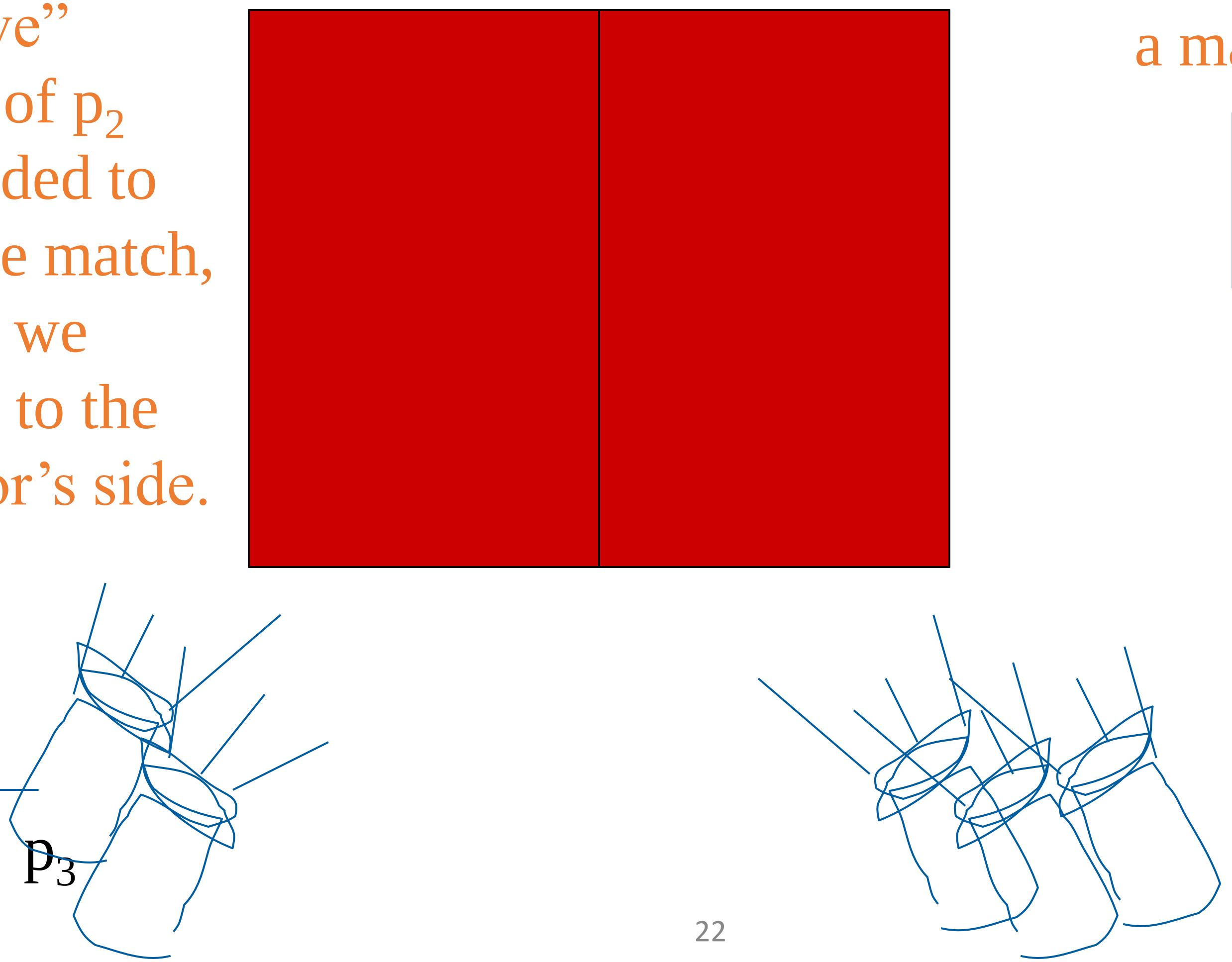


Color Matching Experiment 2

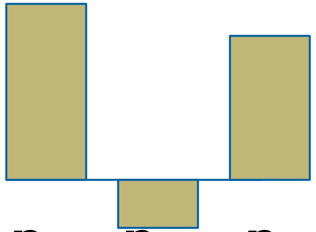


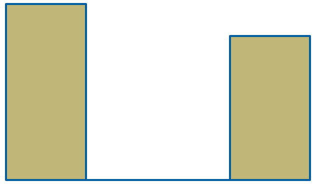
Color Matching Experiment 2

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



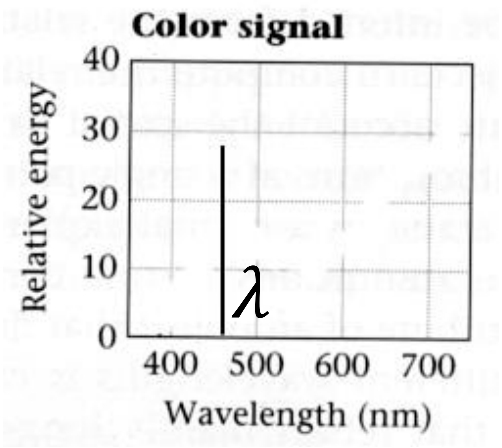
The primary color amounts needed for a match:

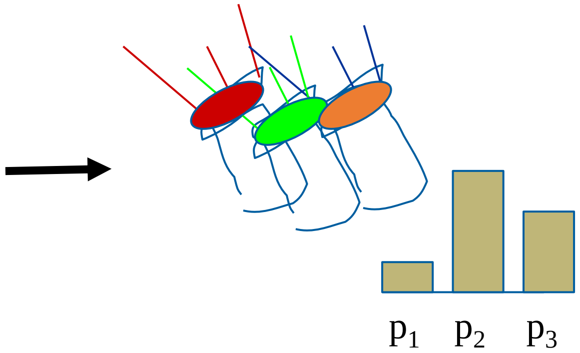


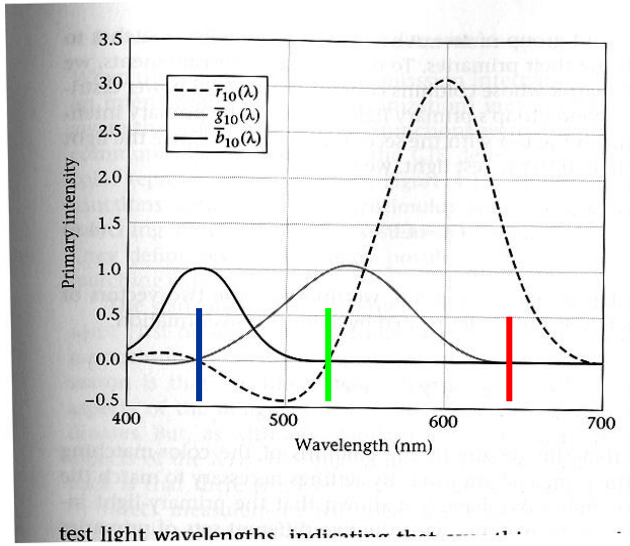


CIE XYZ Color Space

- 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)





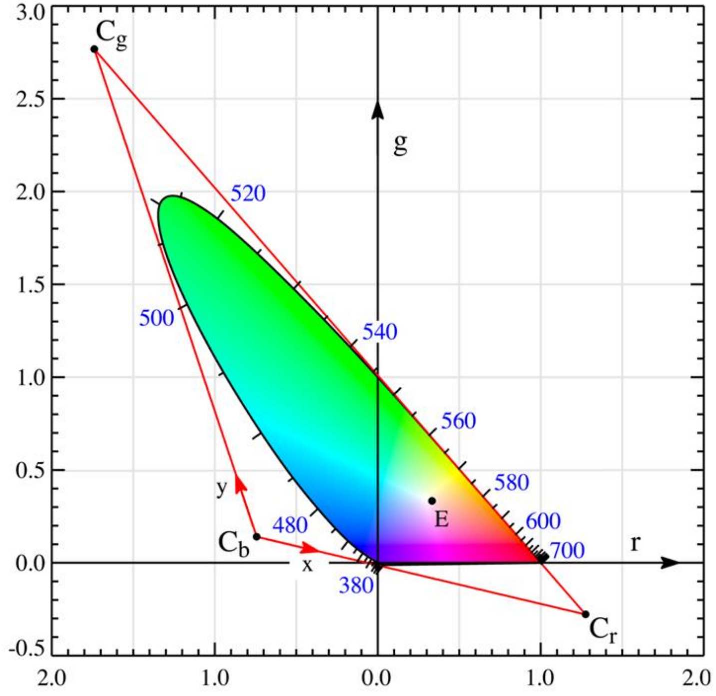


p_1 = 645.2 nm
p_2 = 525.3 nm
p_3 = 444.4 nm

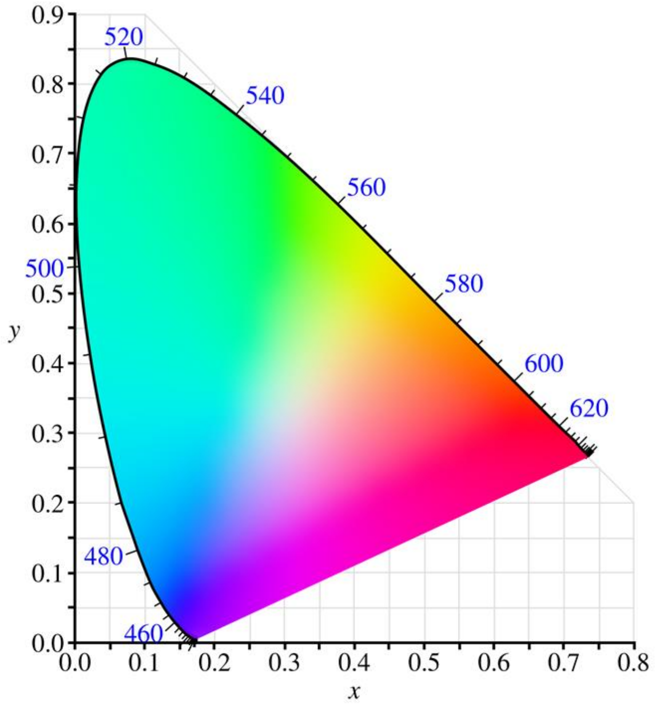
4.13 THE COLOR-MATCHING FUNCTIONS ARE THE ROWS OF THE COLOR-MATCHING SYSTEM MATRIX. The functions measured by Stiles and Burch (1959) using a 10-degree bipartite field and primary lights at the wavelengths 645.2 nm, 525.3 nm, and 444.4 nm with unit radiant power are shown. The three functions in this 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



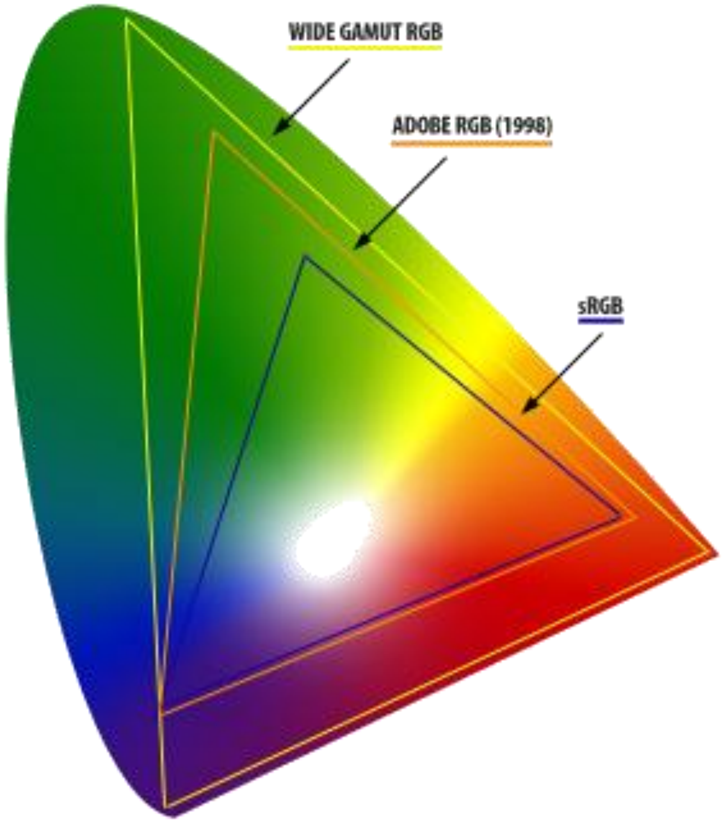
CIE 1931 *xy* chromaticity space

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

R

G

processed

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?

Capture Color Images

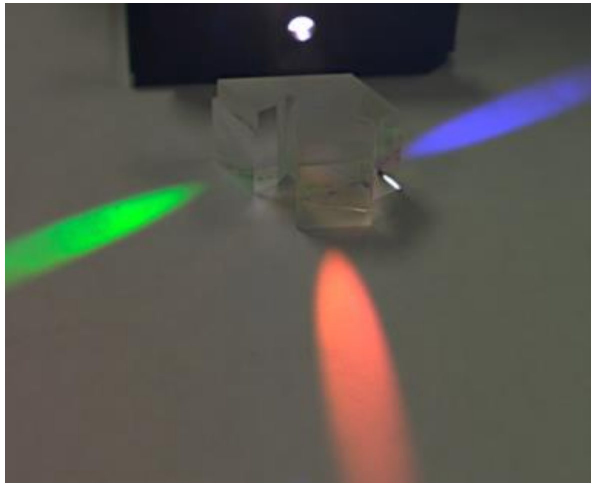
- Took three monochrome pictures in sequence, each through a different colored filter
- The original color scene can be reconstructed by projecting these three pictures using correctly colored light (and careful alignment)

Sergei Prokudin-Gorskii
(1863-1944)




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

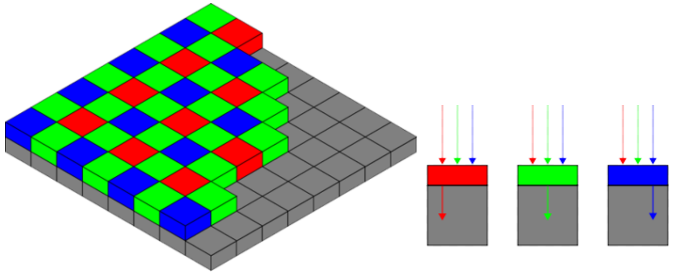


Fig: RGB Bayer filter (named after its inventor, Dr. Bryce E. Bayer from Kodak), picture from wiki

Switchable Primary Colors

Switchable Primaries Using Shiftable Layers of Color Filter Arrays

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Aditi Majumder†
University of California, Irvine

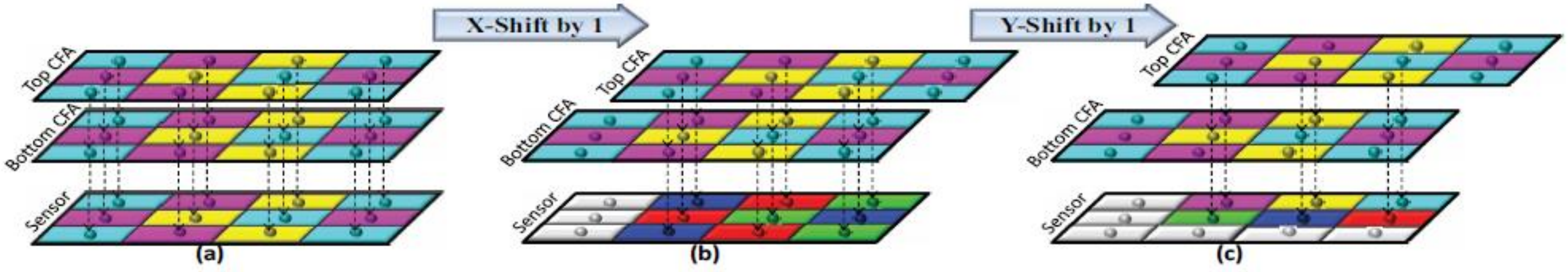
Kazuhiro Hiwada‡
Toshiba Corporation

Atsuto Maki§
Toshiba Research Europe
Cambridge Laboratory

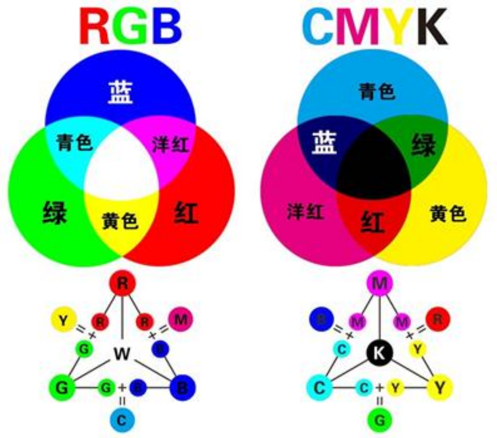
Ramesh Raskar¶
Camera Culture Group
MIT Media Lab

Siggraph 2011

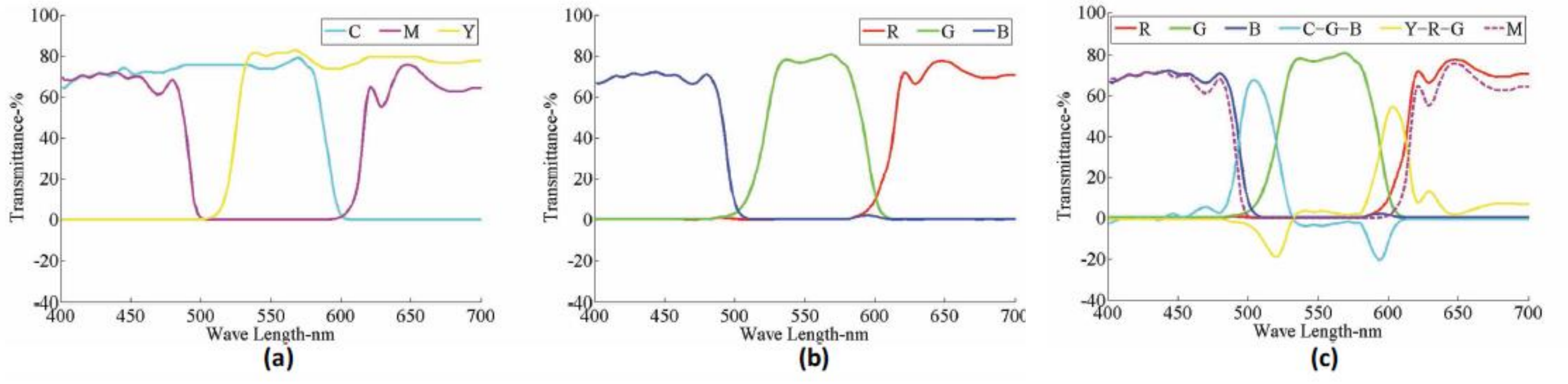
Switchable Primary Colors

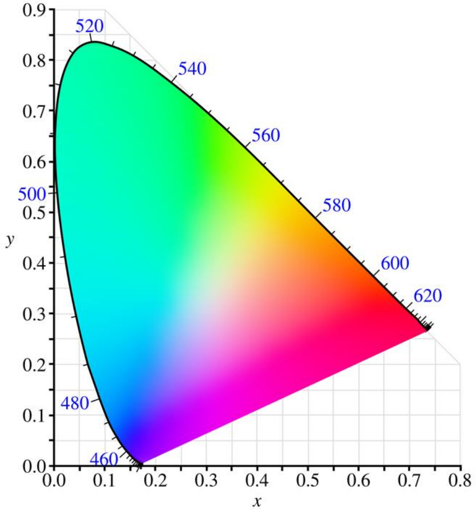


- Two layers of CMY filters inside the camera
- Shift the relative positions to generate different primary colors:
    a) CMY primary colors
    b) RGB primary colors
    c) RGBCMY primary colors



Advantages over Conventional Cameras





- CMY primaries allow more light to pass, hence better SNR (useful at low light scenes)
- RGB primaries produce better color than CMY at brighter scenes
- RGBCMY capture the best color fidelity

Results

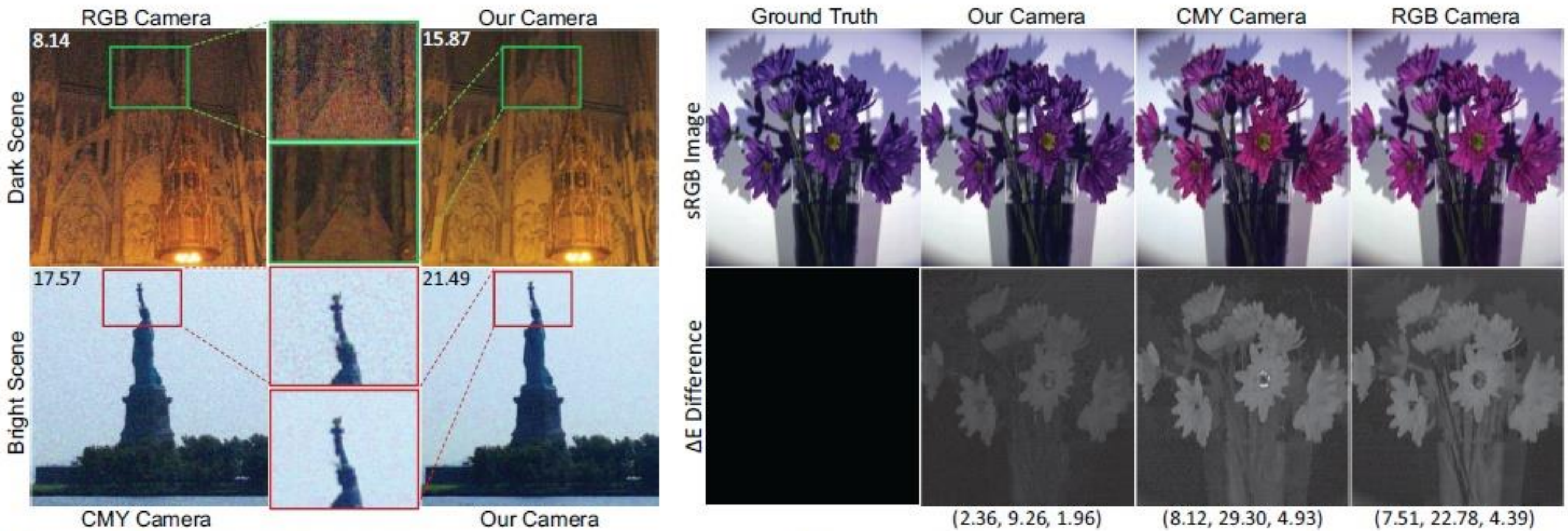


Figure 1: *Left: The CMY mode of our camera provides a superior SNR over a RGB camera when capturing a dark scene (top) and the RGB mode provides superior SNR over CMY camera when capturing a lighted scene. To demonstrate this, each image is marked with its quantitative SNR on the top left. Right: The RGBCY mode of our camera provides better color fidelity than a RGB or CMY camera for colorful scene (top). The ΔE deviation in CIELAB space of each of these images from a ground truth (captured using SOC-730 hyperspectral camera) is encoded as grayscale images with error statistics (mean, maximum and standard deviation) provided at the bottom of each image. Note the close match between the image captured with our camera and the ground truth.*

Polarimetric Dense Monocular SLAM

Luwei Yang[1,*] Feitong Tan[1,*] Ao Li[1] Zhaopeng Cui[1,2] Yasutaka Furukawa[1] Ping Tan[1]

[1] Simon Fraser University [2] ETH Zurich

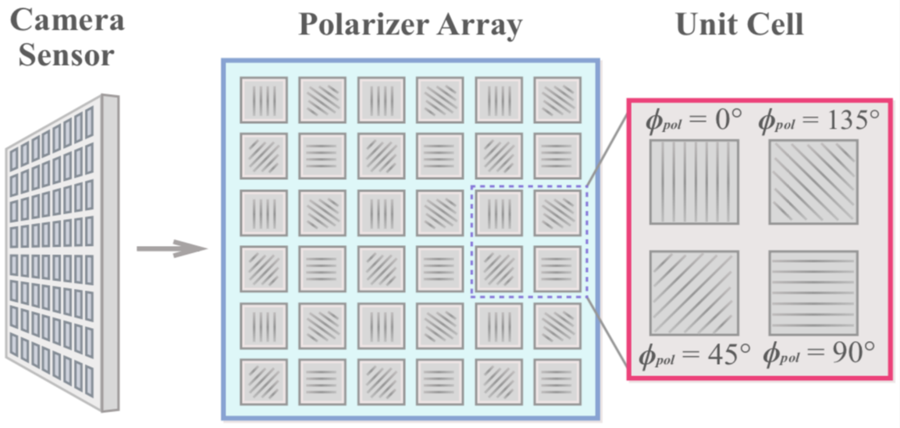
CVPR 2018

Polarization Camera

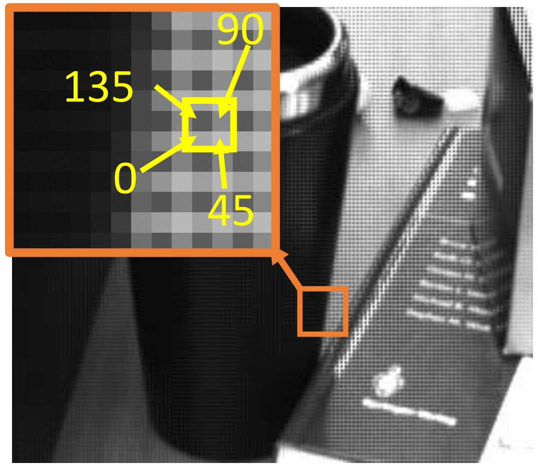
- Polarization can be used for defog, reduce inter-reflection, or even 3D reconstruction for navigation
  - Typically, requires multiple images with different polarization angles
- Captures multiple polarized images in a single shot (by interpolation)

DSLR + filters

Polarization cameras

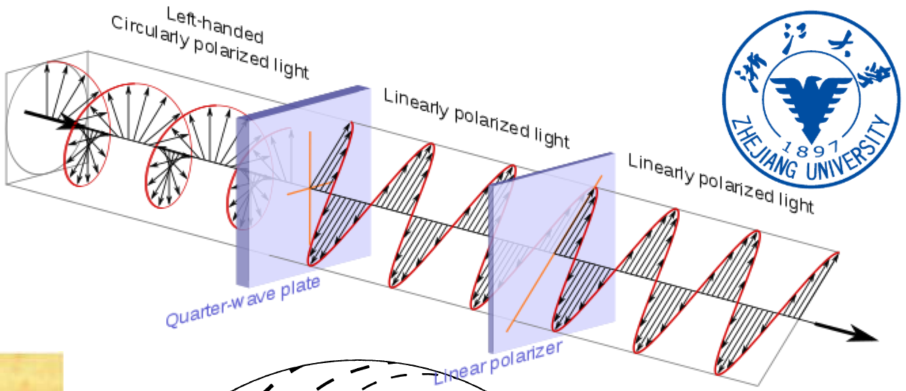


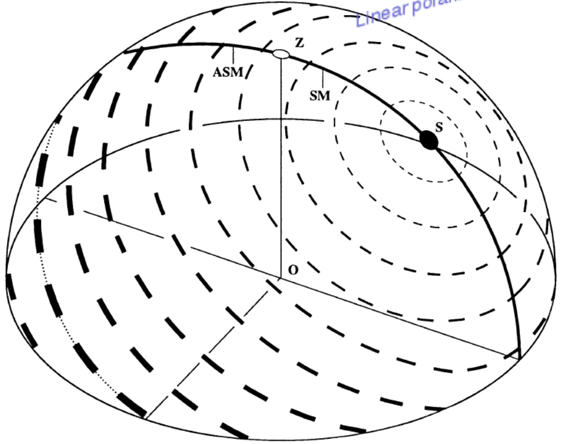
CMOS Sensor



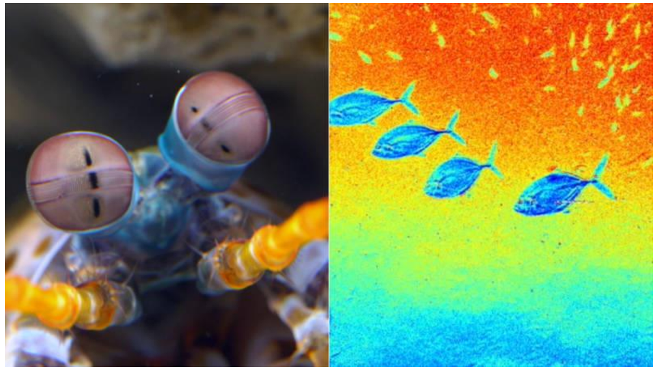
Raw data

Light Polarization



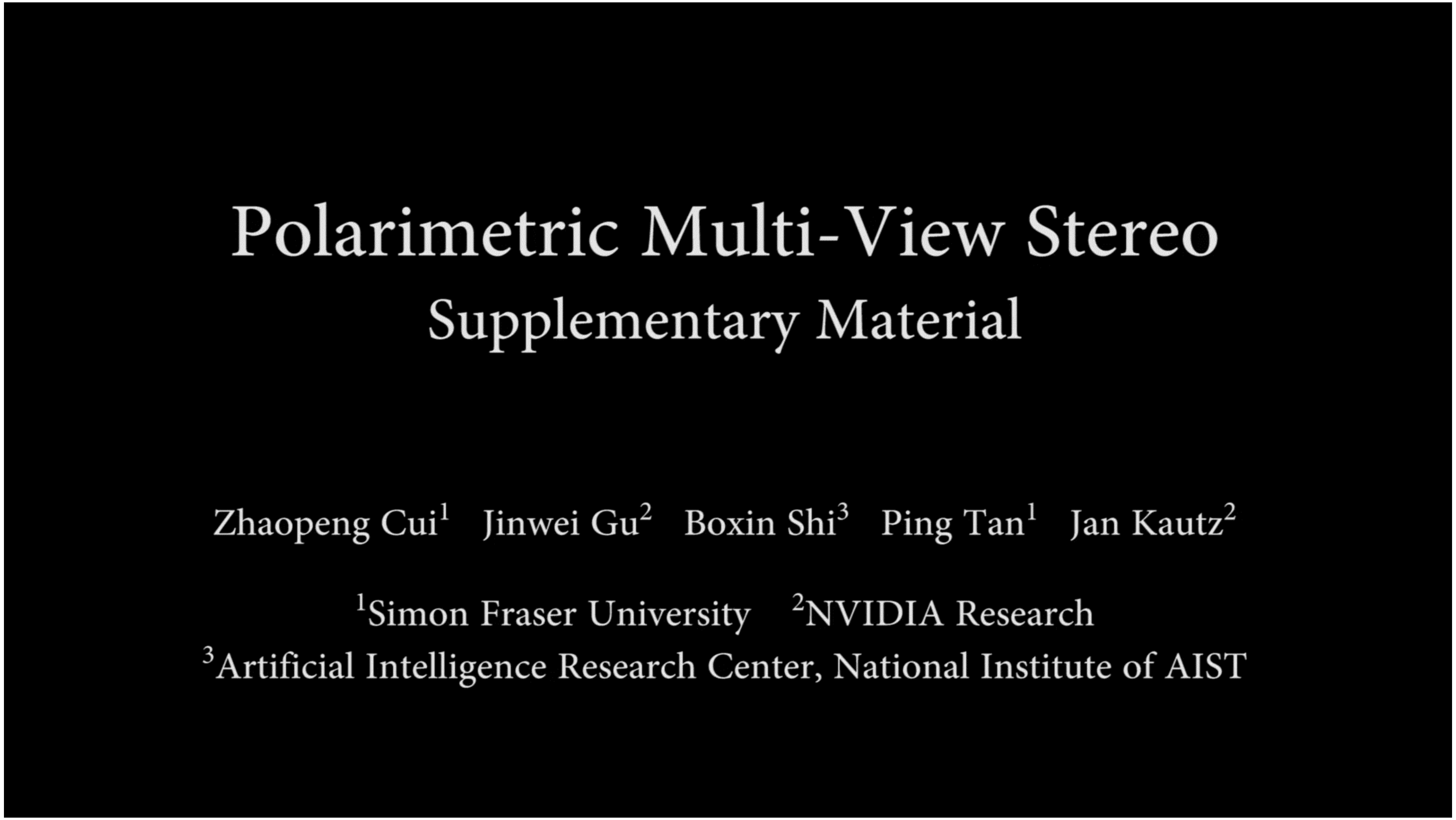


imaging through scattering media or reflection



navigation and perception of nature’s creatures

Polarimetric 3D Reconstruction

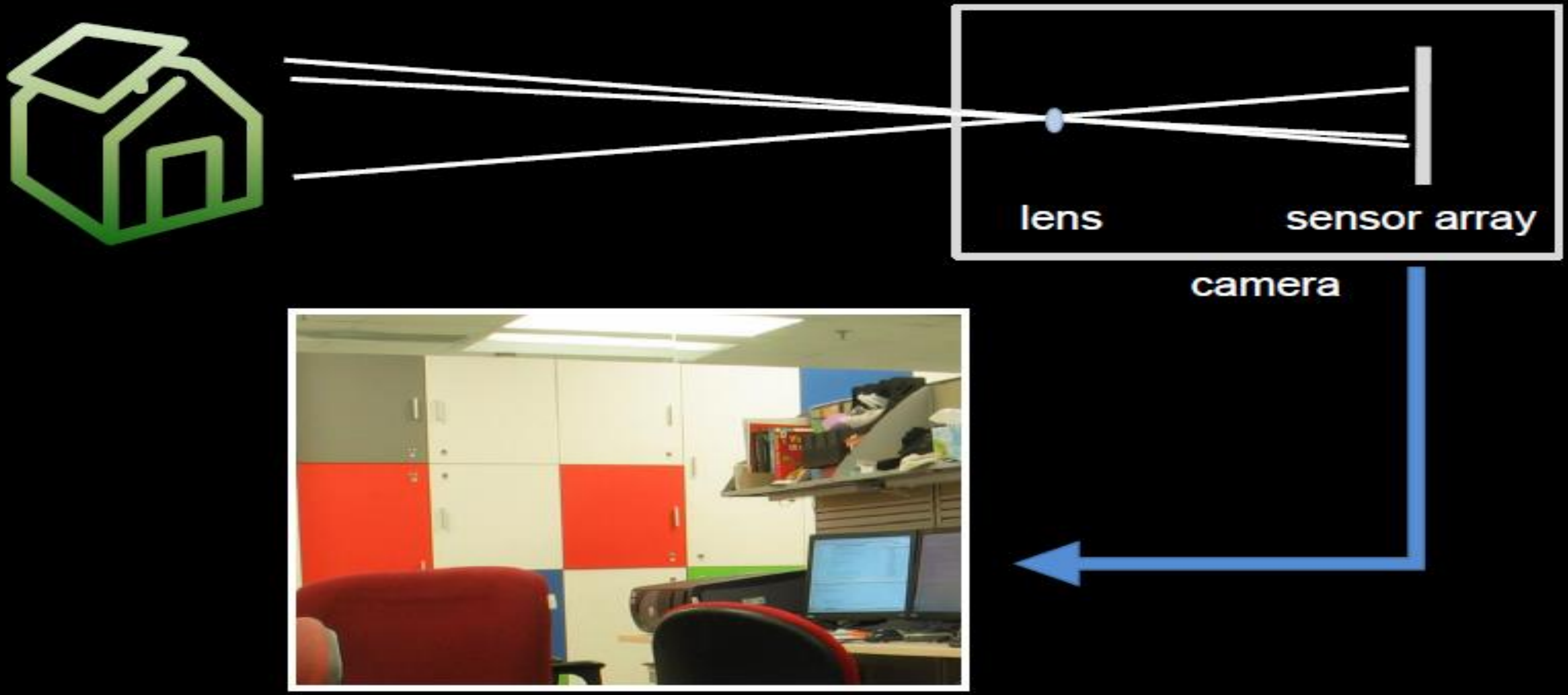


A Prism-based System for Multispectral Video Acquisition

Hao Du[*†] Xin Tong[‡] Xun Cao[§] Stephen Lin[‡]
[*]Fudan University [†]University of Washington [‡]Microsoft Research Asia [§]Tsinghua University

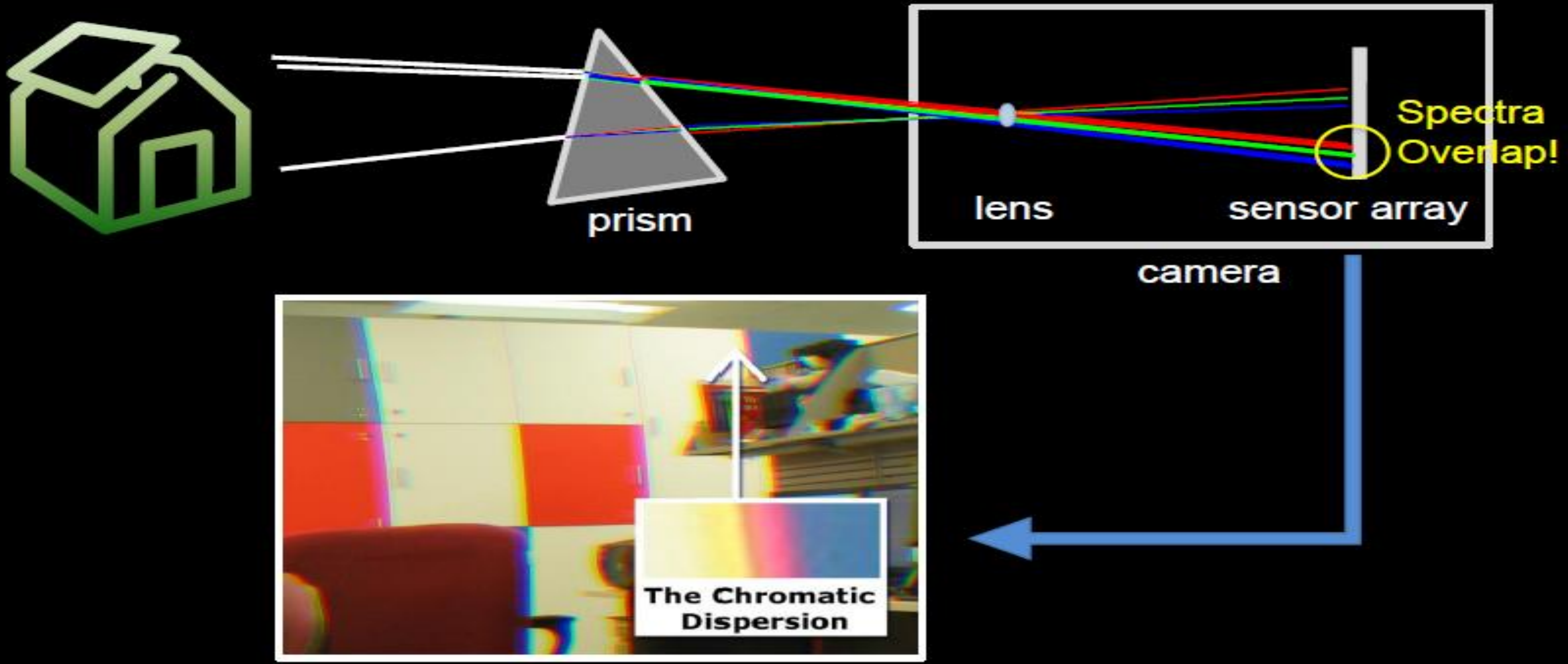
ICCV 2009

A Typical Camera



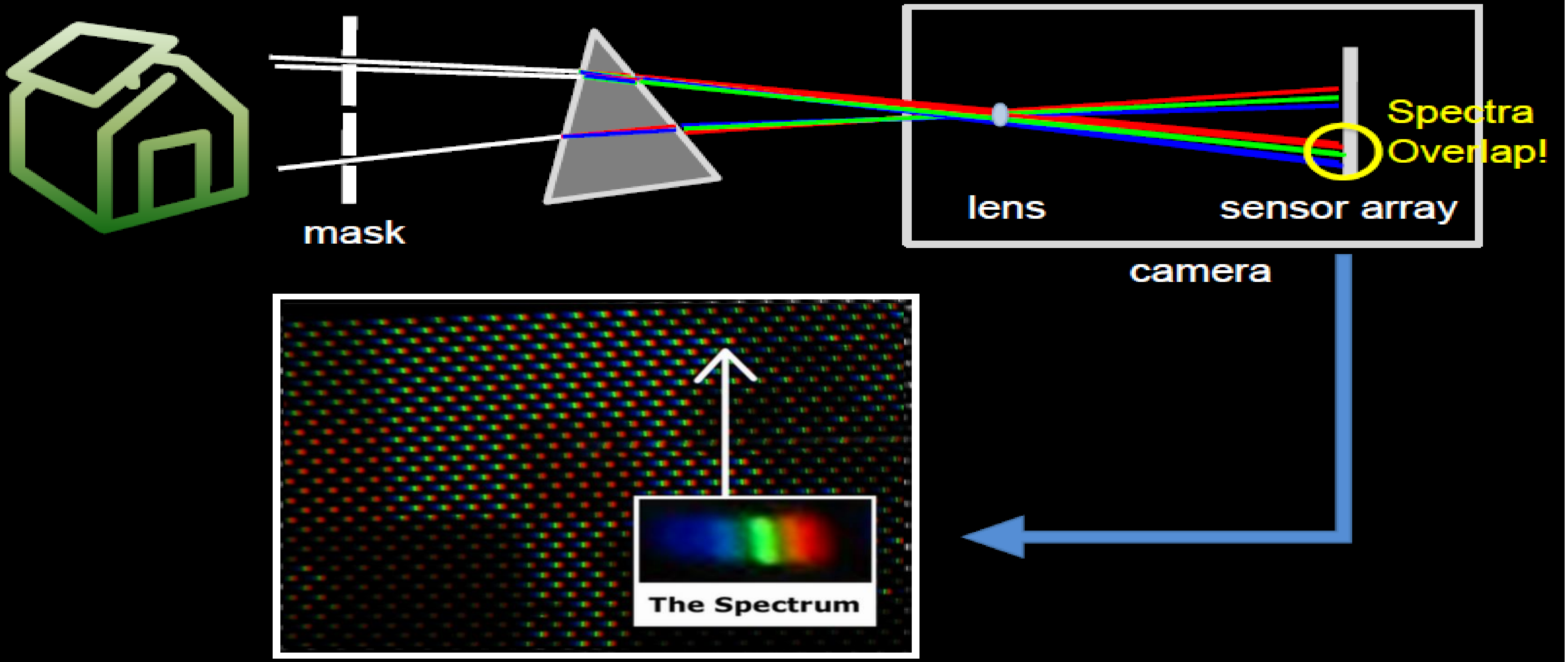
slides from Stephen Lin, ICCV 2009

Camera & Prism



slides from Stephen Lin, ICCV 2009

Camera & Mask & Prism

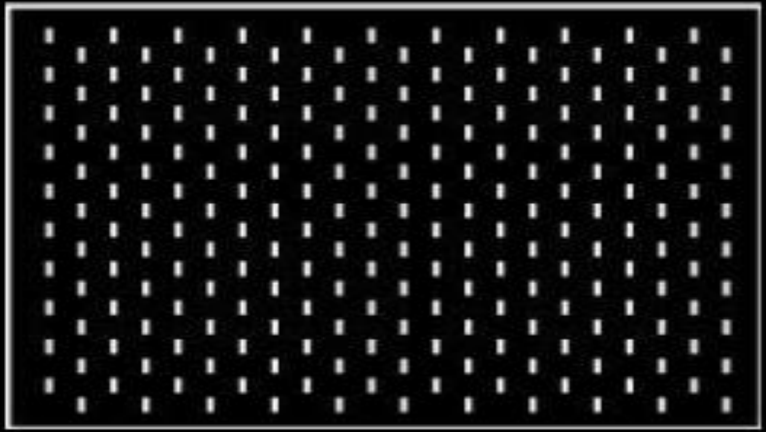


slides from Stephen Lin, ICCV 2009

Prototype System

capturing system

Pointgrey grayscale camera
2248x2048 @15fps

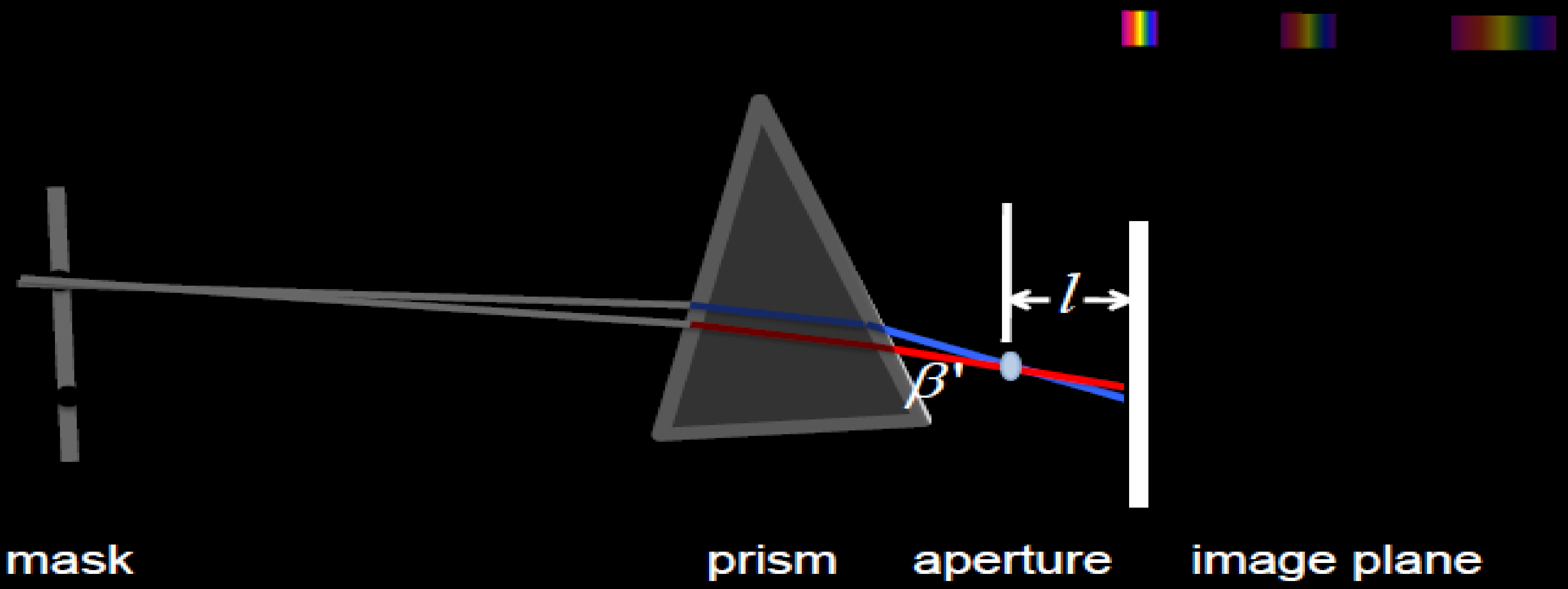


mask

slides from Stephen Lin, ICCV 2009

Spectrum Width

- Tradeoff Spatial/Spectral Resolution



$$w(S_1) = l \cdot \left(\tan(a + \beta'(\lambda_e)) - \tan(a + \beta'(\lambda_s))\right)$$

slides from Stephen Lin, ICCV 2009

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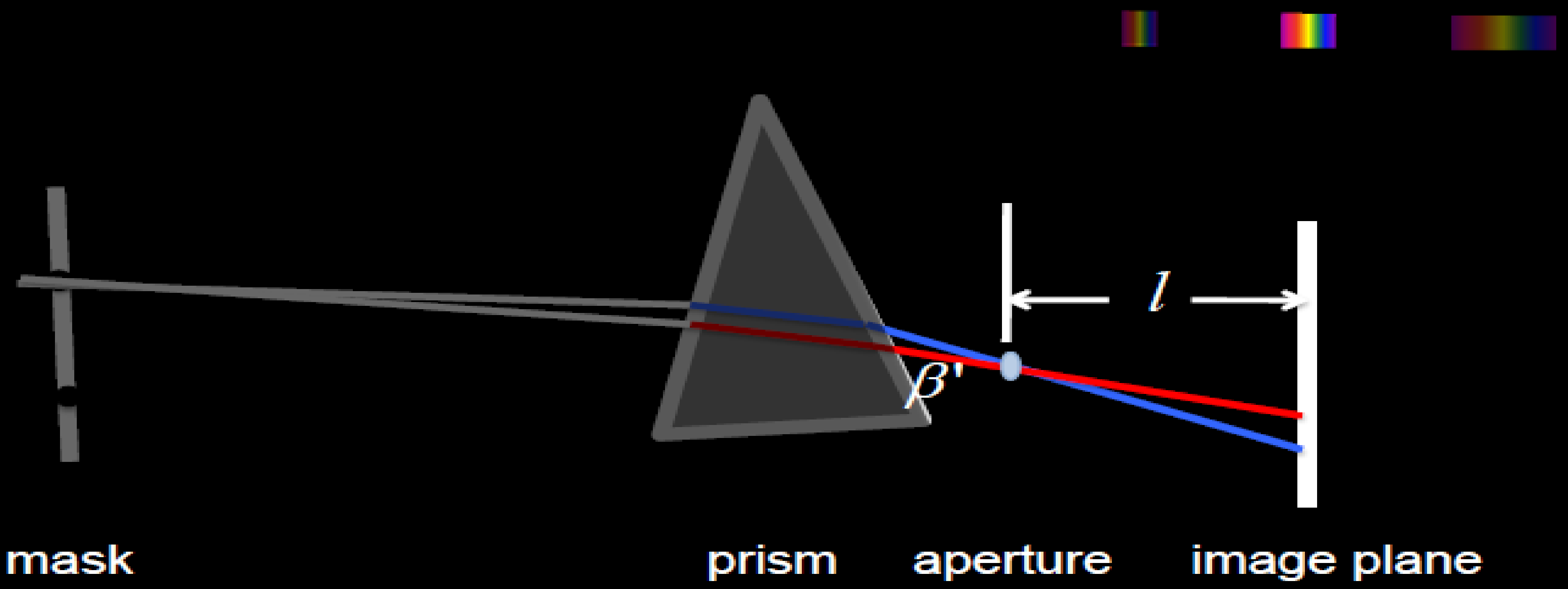

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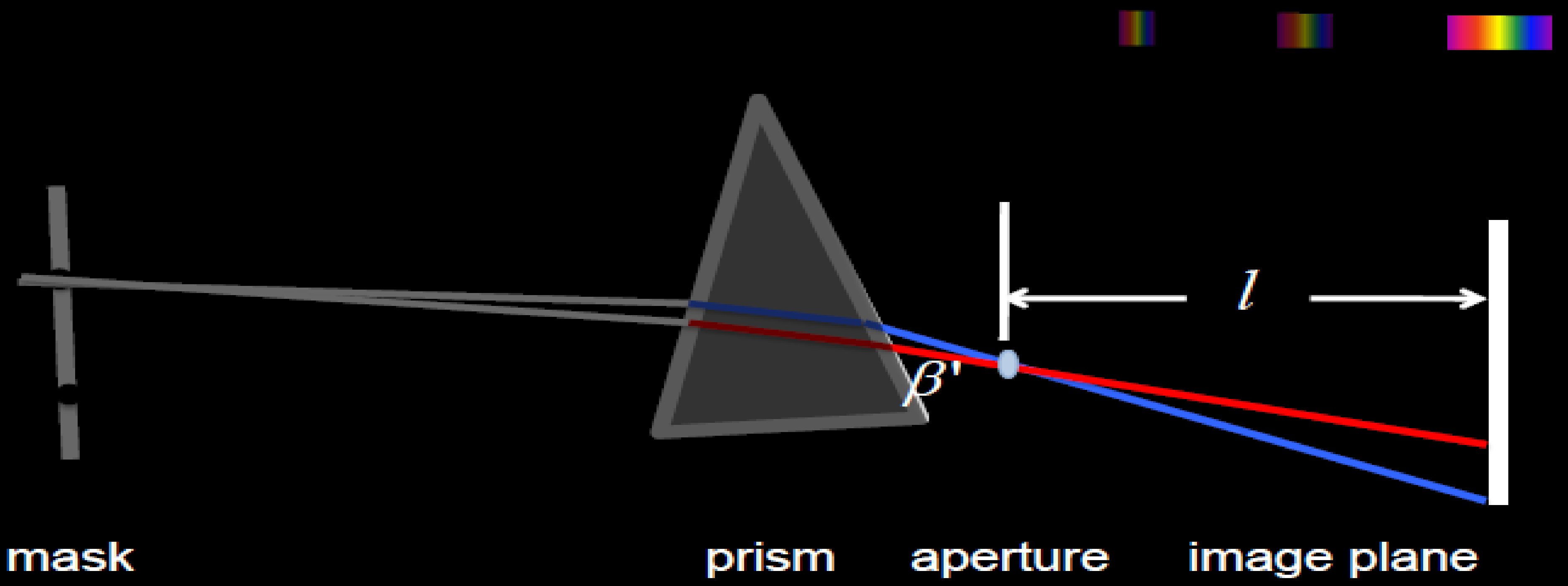

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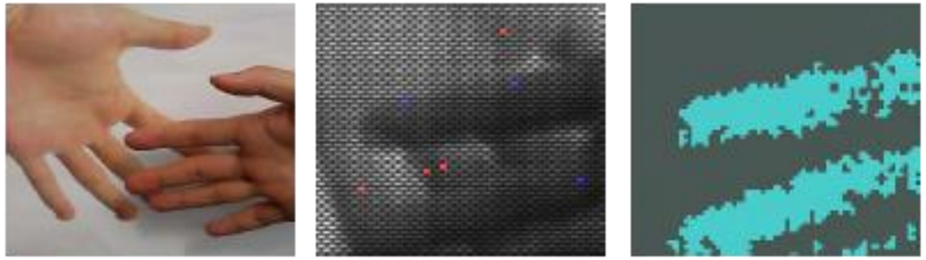
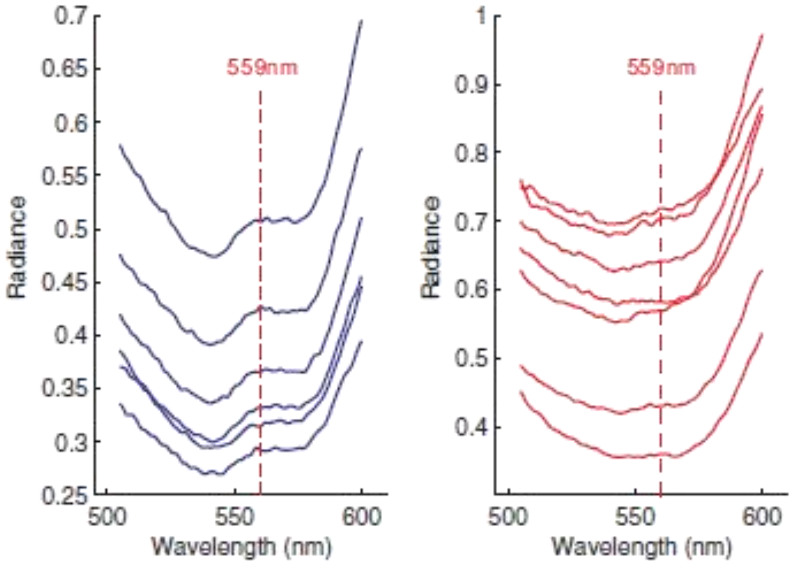
slides from Stephen Lin, ICCV 2009

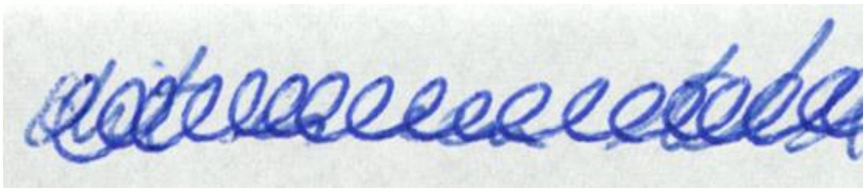
Why Multispectral Imaging?

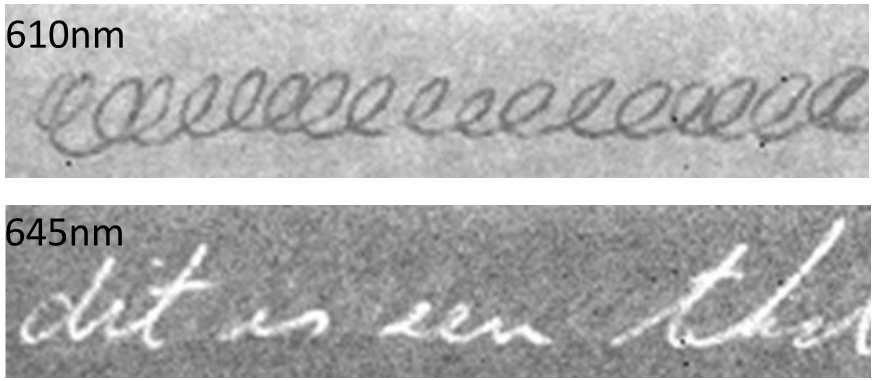
- Additional information to solve difficult vision problems
- Examples 1: distinct real and printed skin





- Example 2: see throw inks





Questions?