

Hyperspectral Image (HSI) Set to RGB Image

Computational Photography

CSE 273

Lecture 3

Announcements

- Assignment 1 is due today, 11:59 PM
- Assignment 2 will be released today
 - Due Jan 24, 11:59 PM

Burst photography

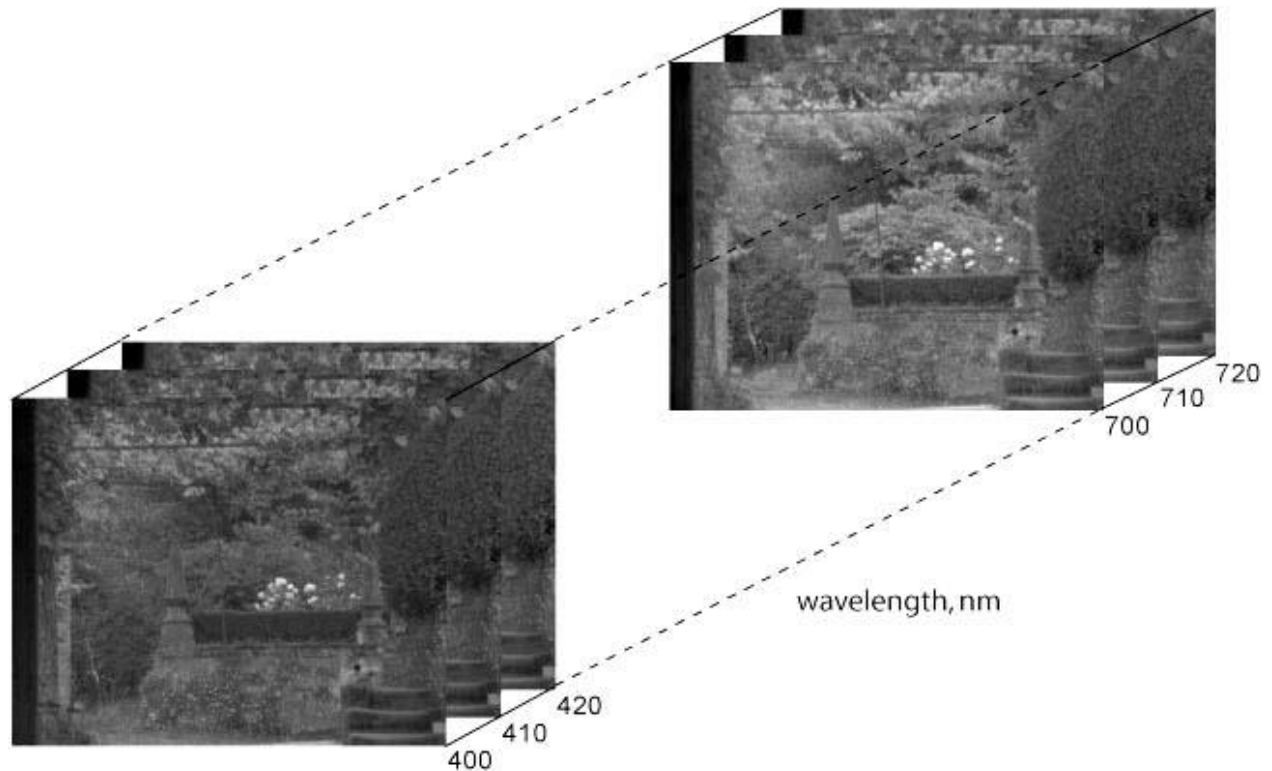
- Acquisition of several images by a single camera in quick succession

Burst photography

- Hyperspectral image (HSI) set



Color filter wheel



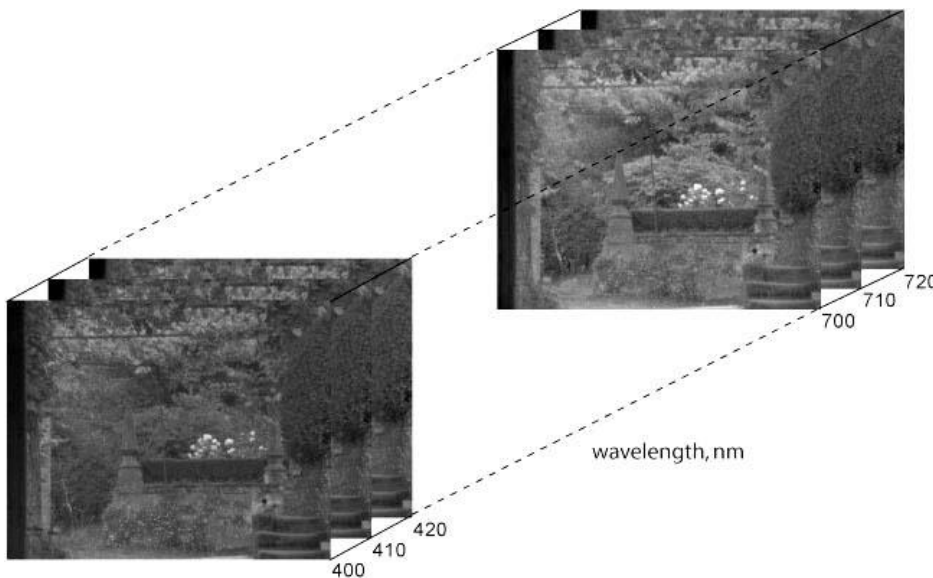
An image for each filter

Multispectral and hyperspectral images

- Multispectral (including RGB) images
 - In general, moderate spectral resolution (e.g., ~100 nm passband per channel)
 - 2 to 100 bands (channels)
 - In general, noncontiguous electromagnetic spectrum range
- Hyperspectral images
 - High spectral resolution (e.g., 10 nm passband per channel)
 - 100 to 1000 bands (channels)
 - Contiguous coverage of the spectrum range

Burst photography

- Hyperspectral image (HSI) set to RGB image

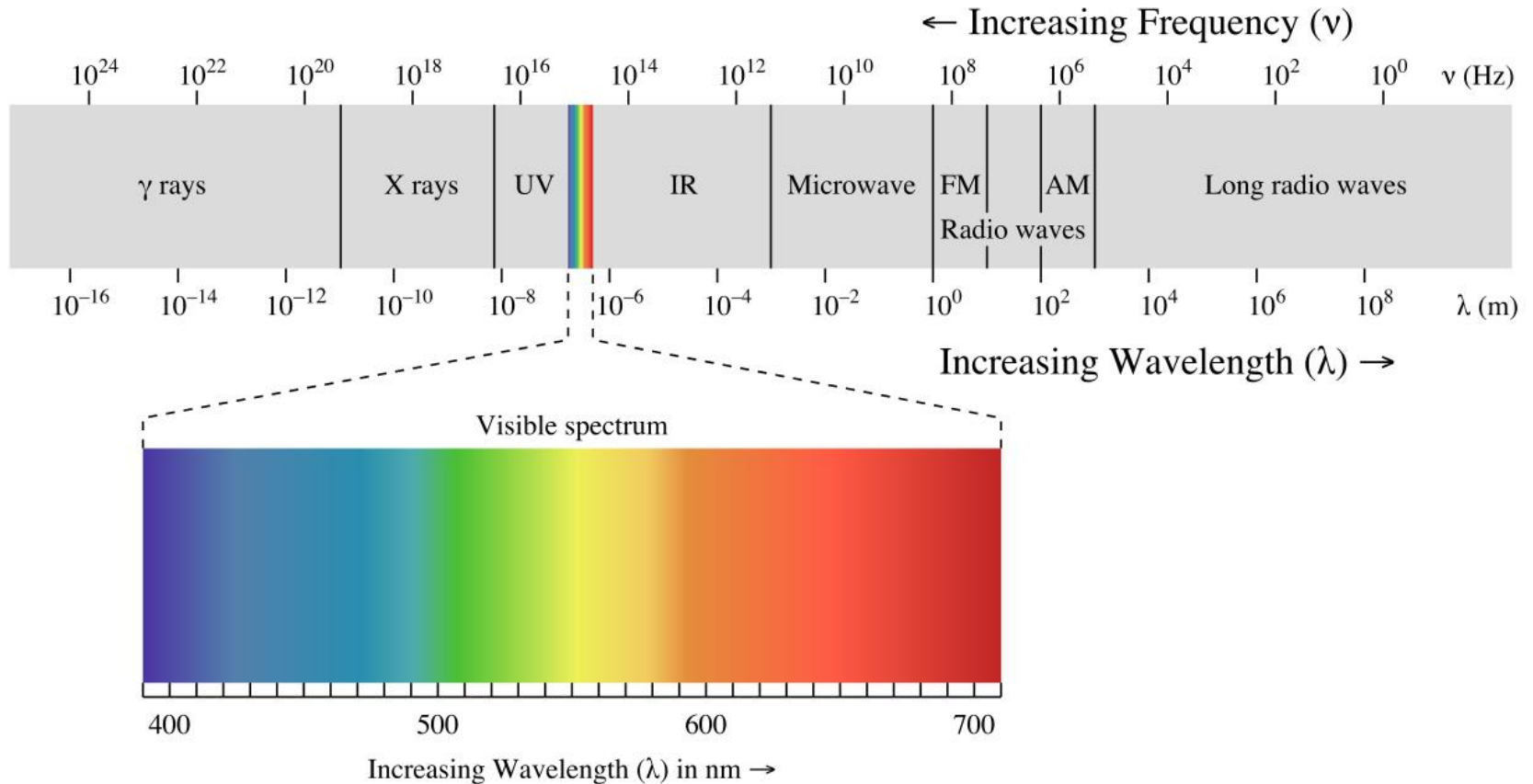


Hyperspectral image



RGB image

Electromagnetic spectrum

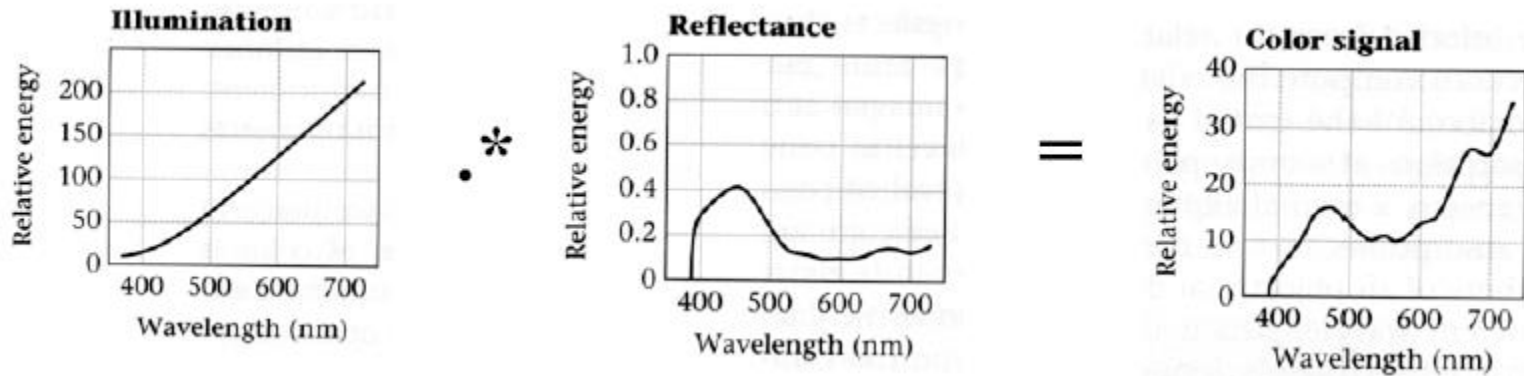


Hyperspectral image (HSI) set to RGB image

- Motivation
 - What does the scene look like (to a human)?
 - Registration of a hyperspectral image set and an RGB image

Measuring color

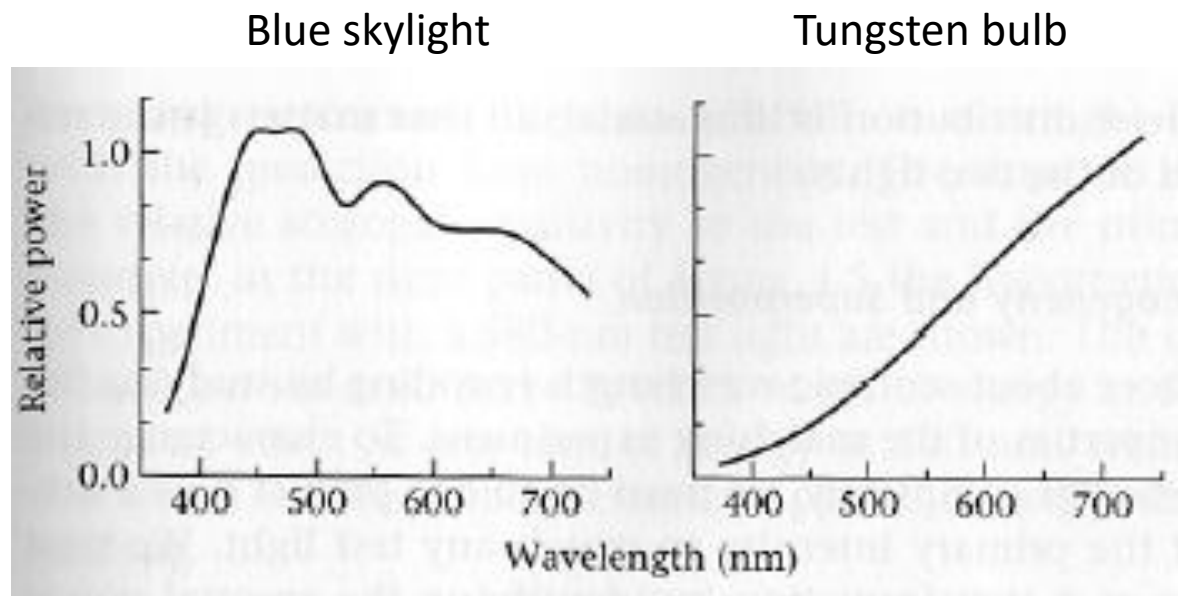
Measured color spectrum is a function of the spectrum of the illumination and reflectance



From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Illumination spectra

- Different illumination spectra yield different measured color spectra



From Foundations of Vision, Brian Wandell, 1995, via B. Freeman slides

Standard illuminants

Hue of each white point, calculated with luminance $Y = 0.54$

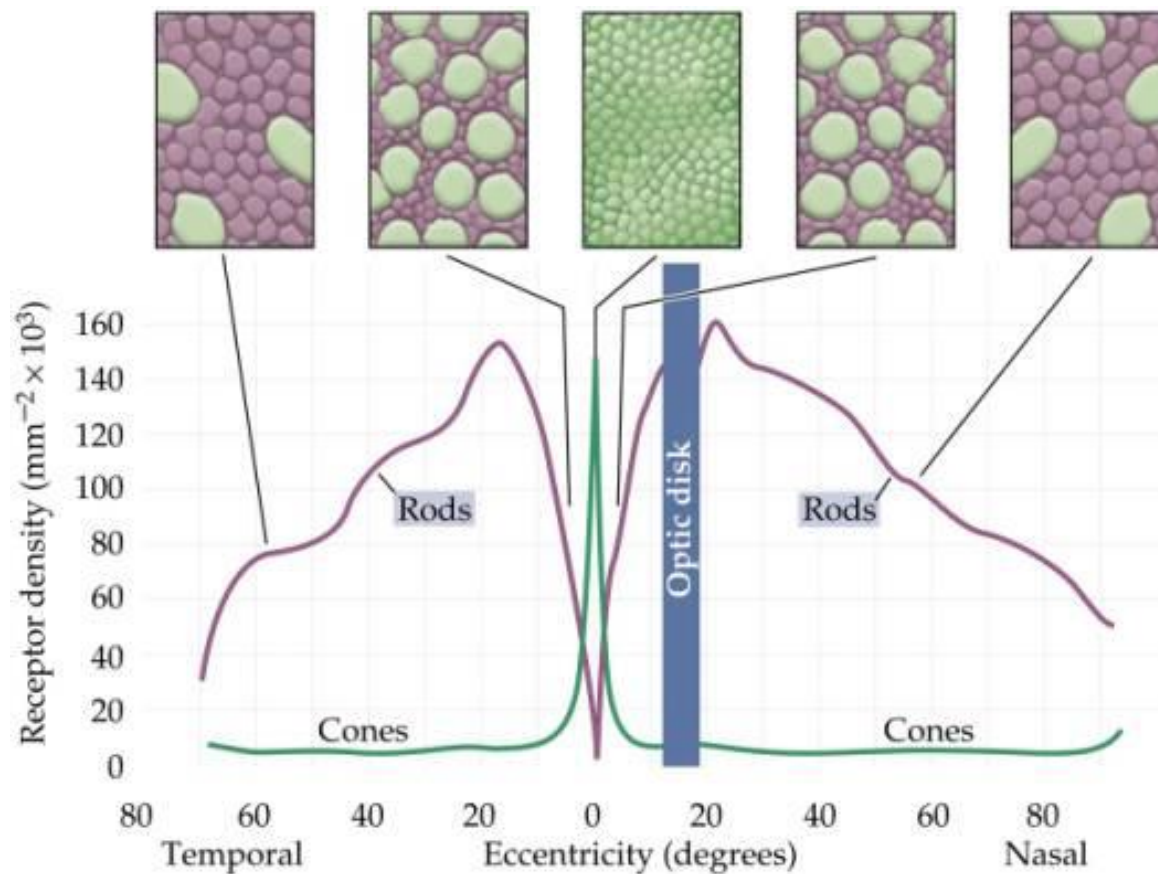
Name	CIE 1931 2°		CIE 1964 10°		CCT (K)	Hue	Note
	x_2	y_2	x_{10}	y_{10}			
A	0.44757	0.40745	0.45117	0.40594	2856		Incandescent / Tungsten
B	0.34842	0.35161	0.34980	0.35270	4874		{obsolete} Direct sunlight at noon
C	0.31006	0.31616	0.31039	0.31905	6774		{obsolete} Average / North sky Daylight
D50	0.34567	0.35850	0.34773	0.35952	5003		Horizon Light. ICC profile PCS
D55	0.33242	0.34743	0.33411	0.34877	5503		Mid-morning / Mid-afternoon Daylight
D65	0.31271	0.32902	0.31382	0.33100	6504		Noon Daylight: Television, sRGB color space
D75	0.29902	0.31485	0.29968	0.31740	7504		North sky Daylight
E	1/3	1/3	1/3	1/3	5454		Equal energy
F1	0.31310	0.33727	0.31811	0.33559	6430		Daylight Fluorescent
F2	0.37208	0.37529	0.37925	0.36733	4230		Cool White Fluorescent
F3	0.40910	0.39430	0.41761	0.38324	3450		White Fluorescent
F4	0.44018	0.40329	0.44920	0.39074	2940		Warm White Fluorescent
F5	0.31379	0.34531	0.31975	0.34246	6350		Daylight Fluorescent
F6	0.37790	0.38835	0.38660	0.37847	4150		Lite White Fluorescent
F7	0.31292	0.32933	0.31569	0.32960	6500		D65 simulator, Daylight simulator
F8	0.34588	0.35875	0.34902	0.35939	5000		D50 simulator, Sylvania F40 Design 50
F9	0.37417	0.37281	0.37829	0.37045	4150		Cool White Deluxe Fluorescent
F10	0.34609	0.35986	0.35090	0.35444	5000		Philips TL85, Ultralume 50
F11	0.38052	0.37713	0.38541	0.37123	4000		Philips TL84, Ultralume 40
F12	0.43695	0.40441	0.44256	0.39717	3000		Philips TL83, Ultralume 30

Why is this important?

- The color measured by a camera depends on
 - The camera response function
 - Spectrum of illuminant
 - Reflectance properties of objects in the scene
- The “color” of an object does not actually make a lot of sense, unless you talk about it under a reference light

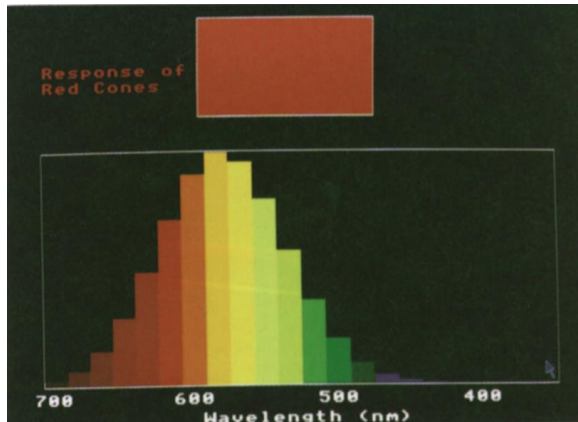
RGB color model

- Based on human perception of colors

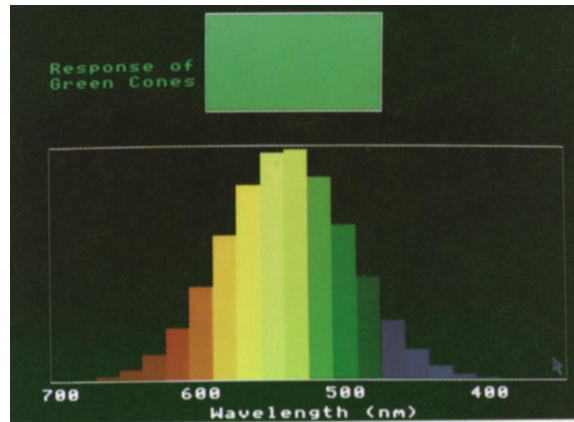


Color receptors

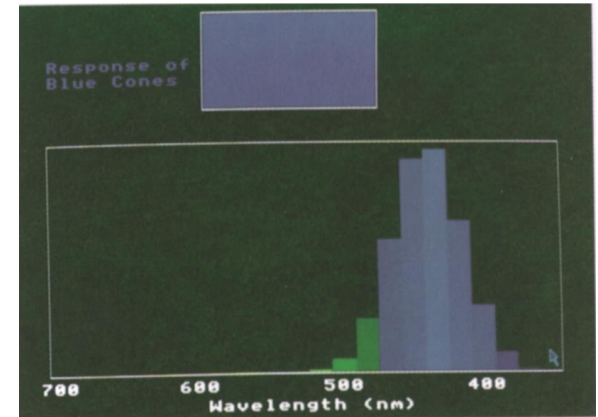
“Red” cone



“Green” cone



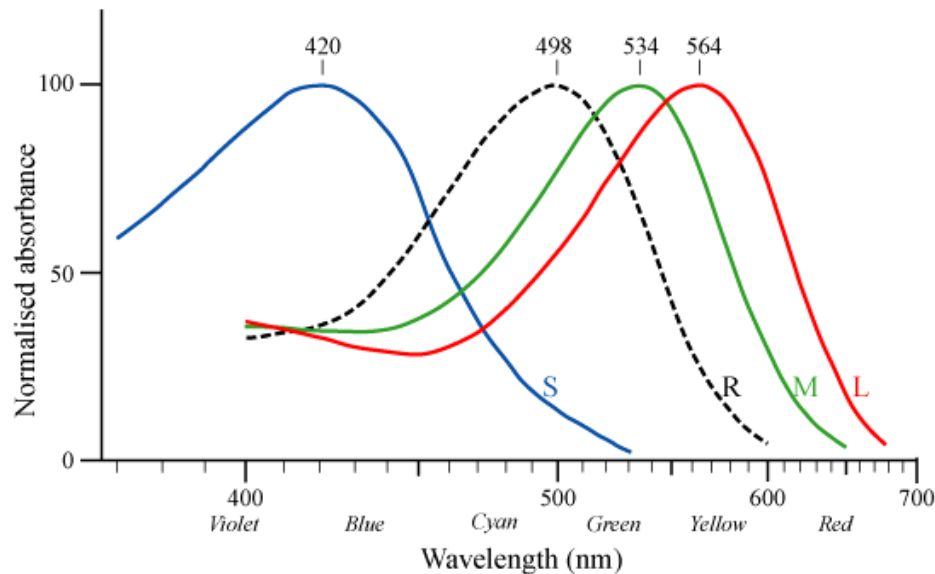
“Blue” cone



$$\text{Response of } k\text{th cone} = \int \rho_k(\lambda) E(\lambda) d\lambda$$

Cone responses

$$\text{Response of } k\text{th cone} = \int \rho_k(\lambda) E(\lambda) d\lambda$$



There are three types of cones

S: Short wave lengths (Blue)

M: Mid wave lengths (Green)

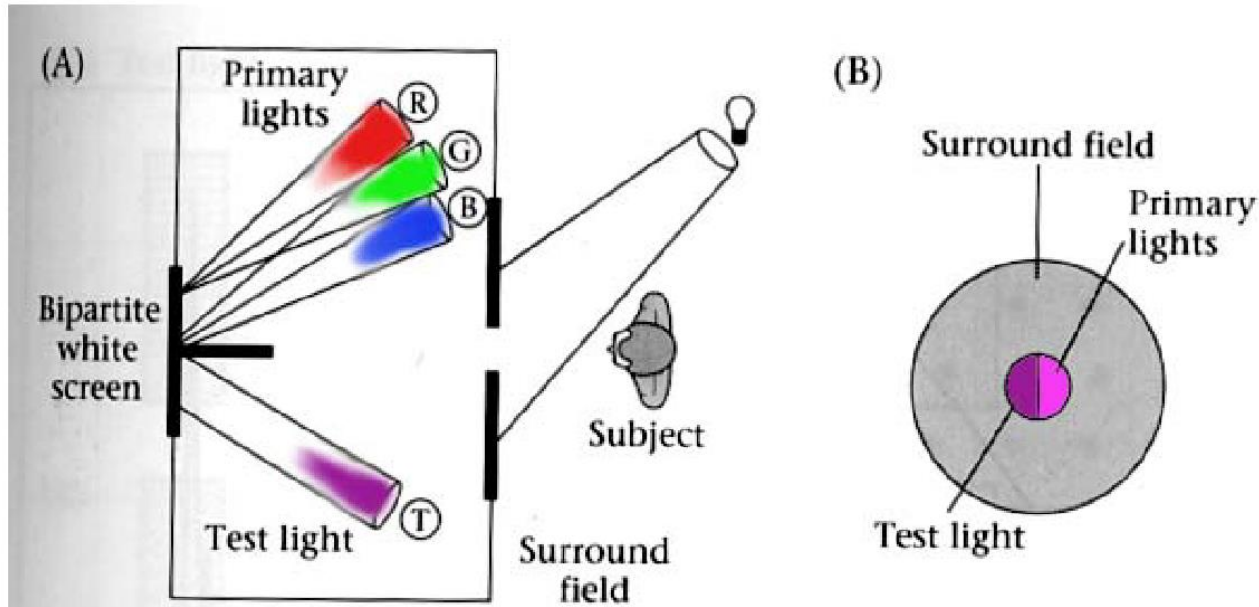
L: Long wave lengths (Red)



- Three attributes to a color
- Three numbers to describe a color

Color matching experiment

Not a
computer
screen



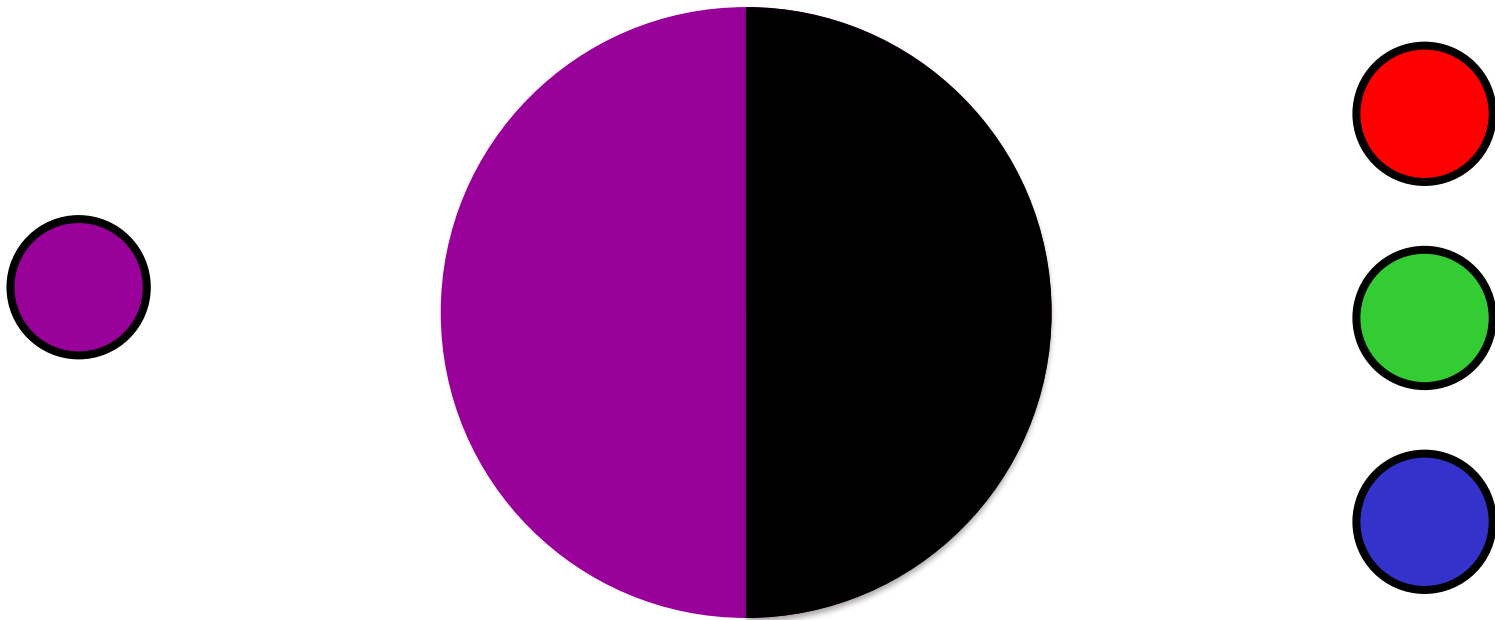
4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.

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

Slide from T. Darrel

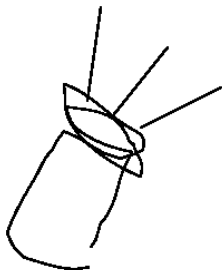
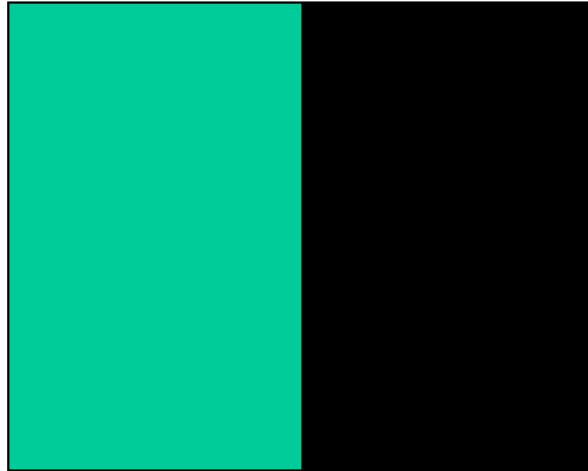
Color matching experiment

- Appearance of the stimuli to the observer



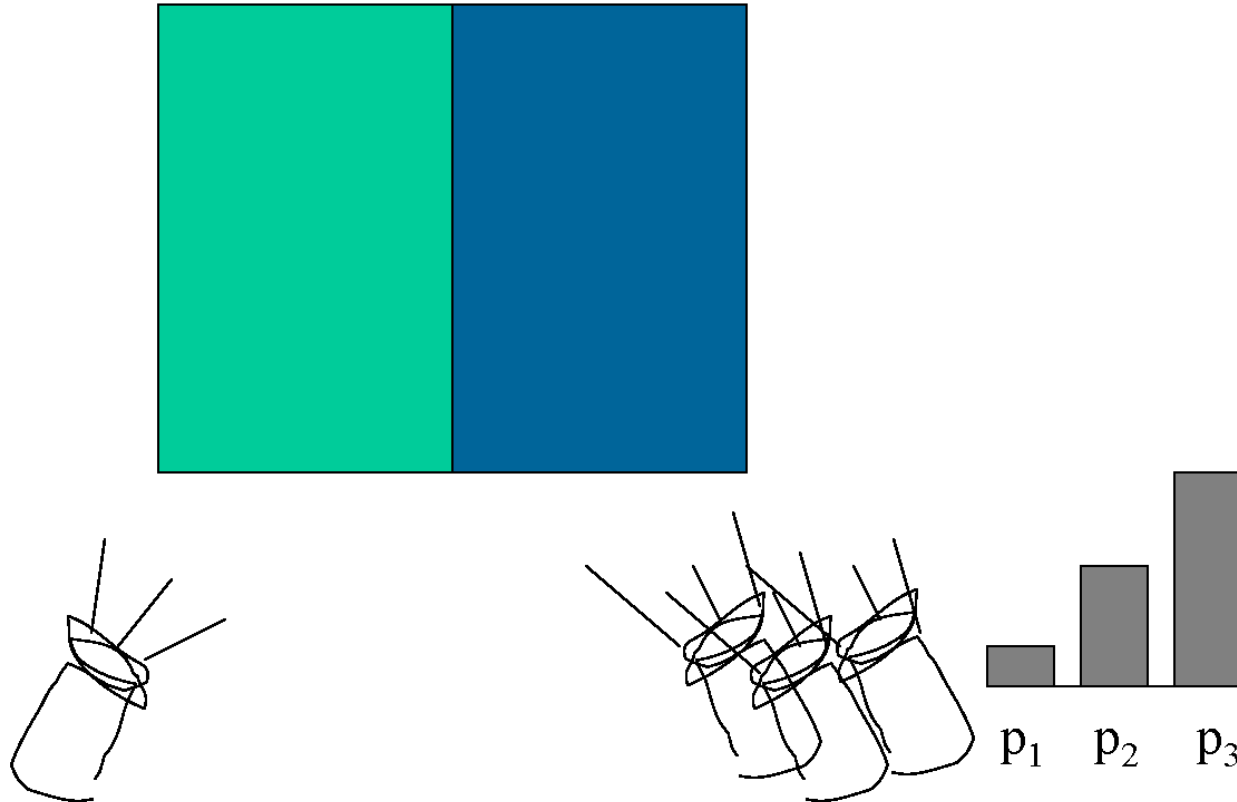
Not on a computer screen

Color matching experiment 1



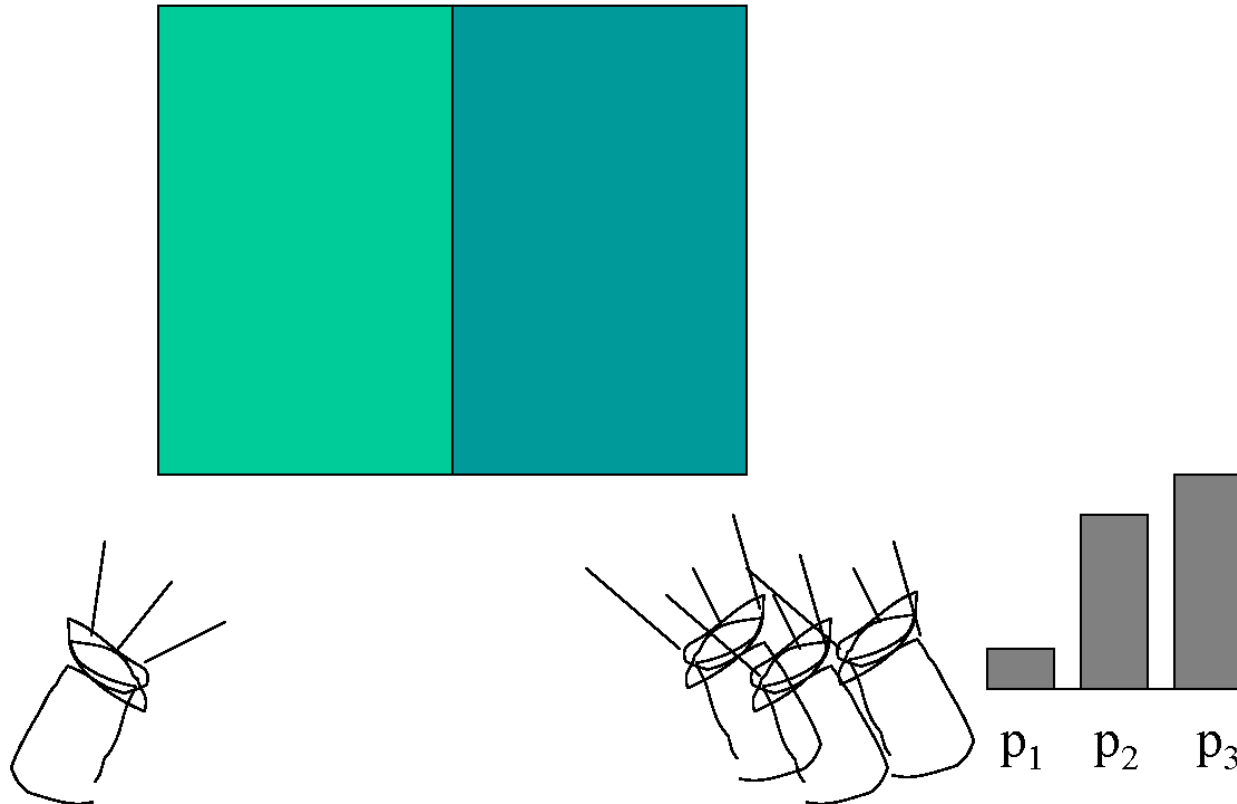
Slide from T. Darrel

Color matching experiment 1



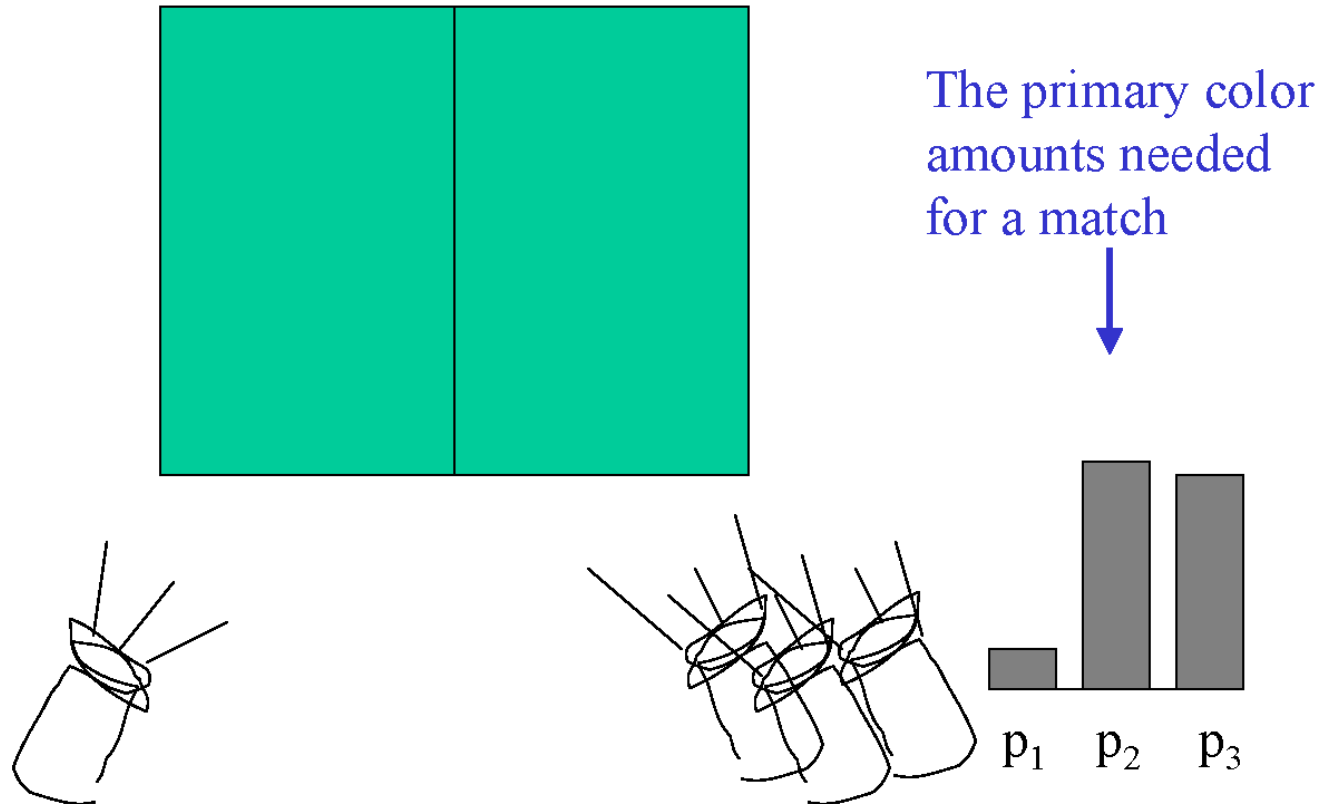
Slide from T. Darrel

Color matching experiment 1



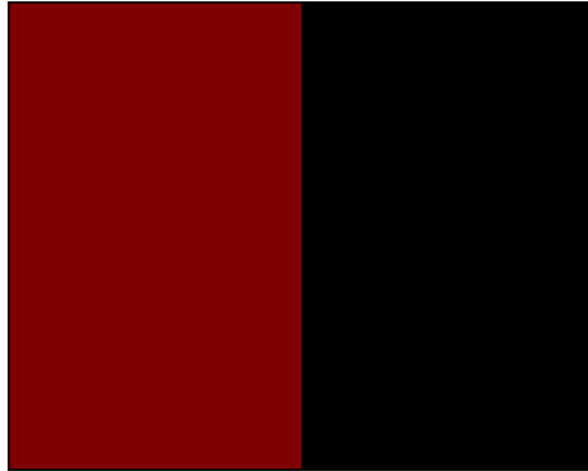
Slide from T. Darrel

Color matching experiment 1



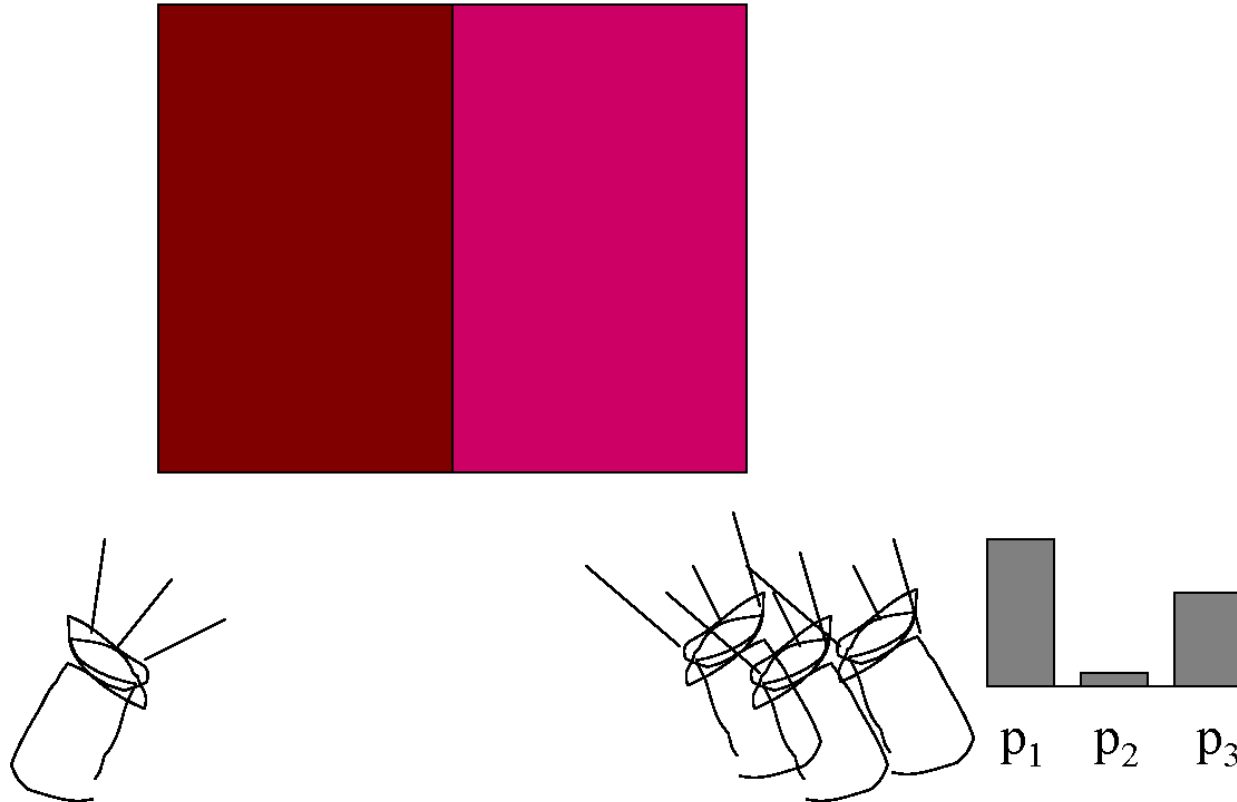
Slide from T. Darrel

Color matching experiment 2



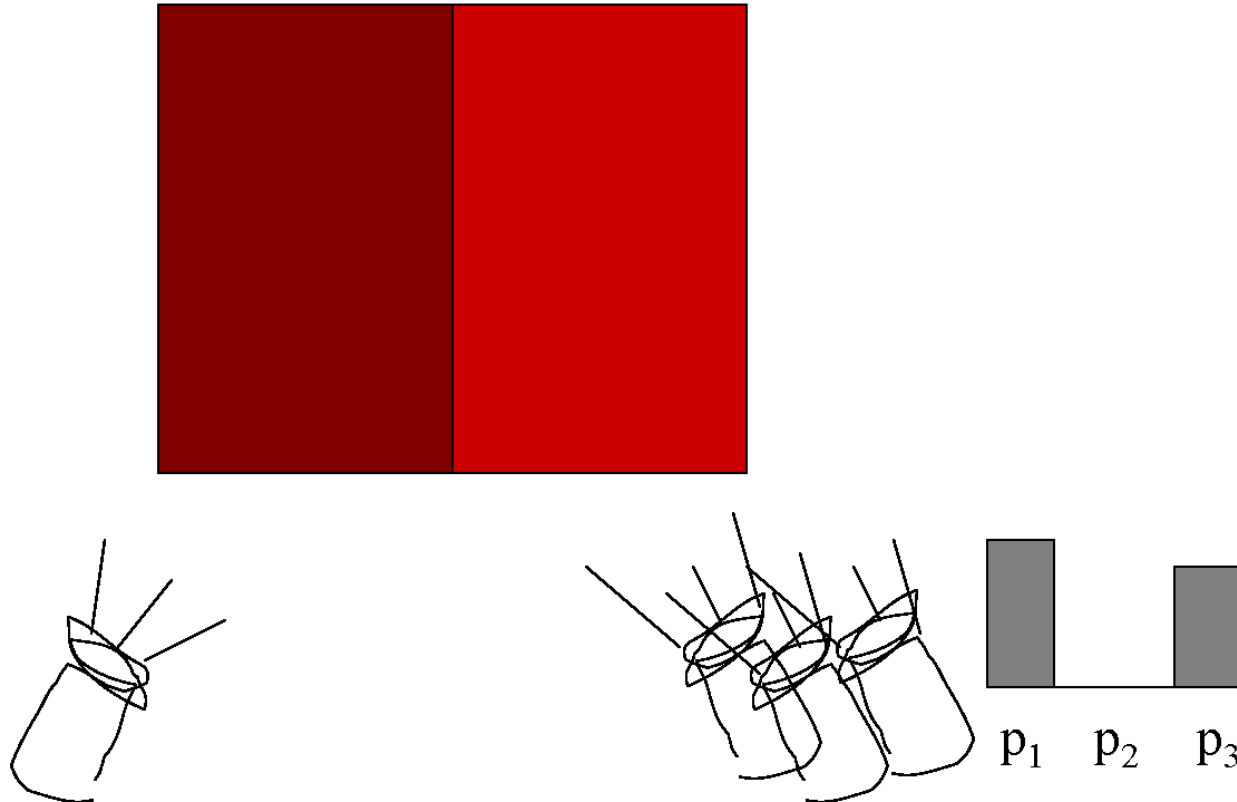
Slide from T. Darrel

Color matching experiment 2



Slide from T. Darrel

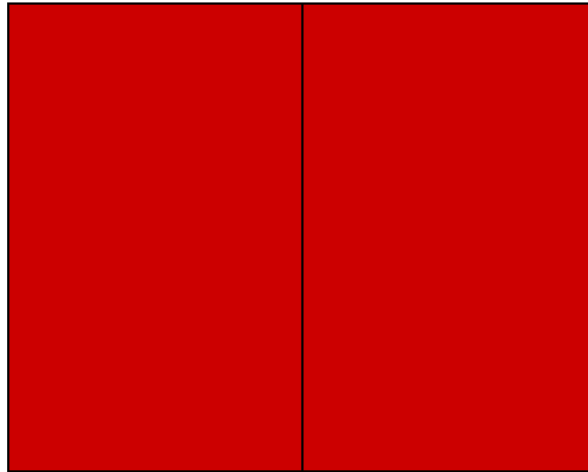
Color matching experiment 2



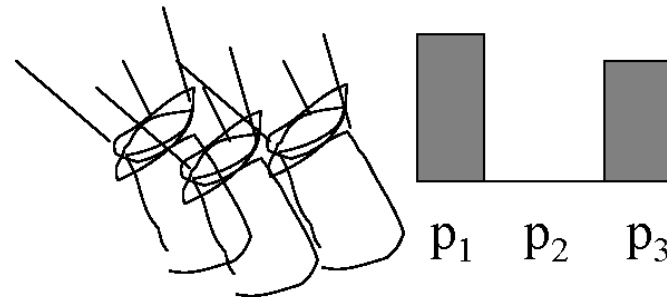
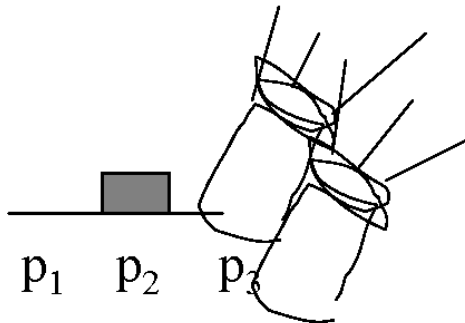
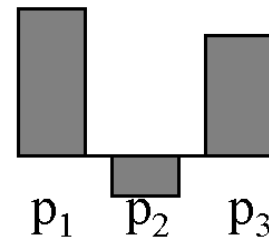
Slide from T. Darrel

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:



Slide from T. Darrel

Color matching experiment results

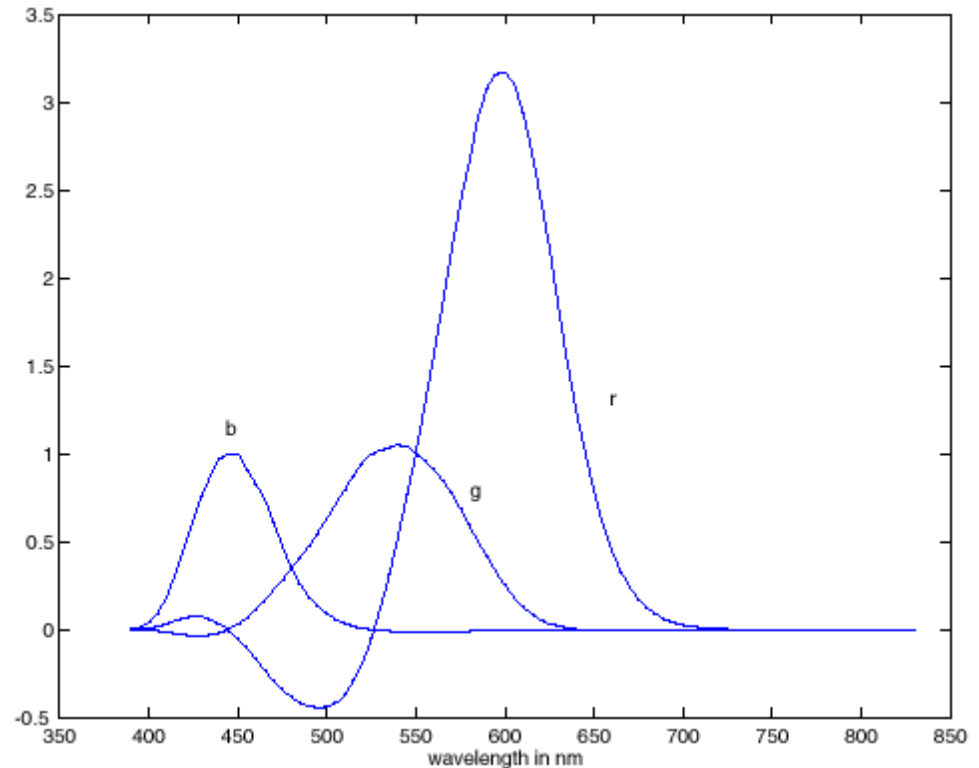
- Three primaries will work for most people if we allow subtractive matching
 - Exceptional people can match with two or only one primary
 - This could be caused by a variety of deficiencies
- Most people make the same matches
 - There are some anomalous trichromats, who use three primaries but make different combinations to match

Color matching functions

- Choose primaries, say $P_1(\lambda)$, $P_2(\lambda)$, $P_3(\lambda)$
- For monochromatic (single wavelength) energy function, what amounts of primaries will match it?
- That is, for each wavelength λ , determine how much of P_1 , P_2 , and P_3 is needed to match light of that wavelength alone
- These are color matching functions

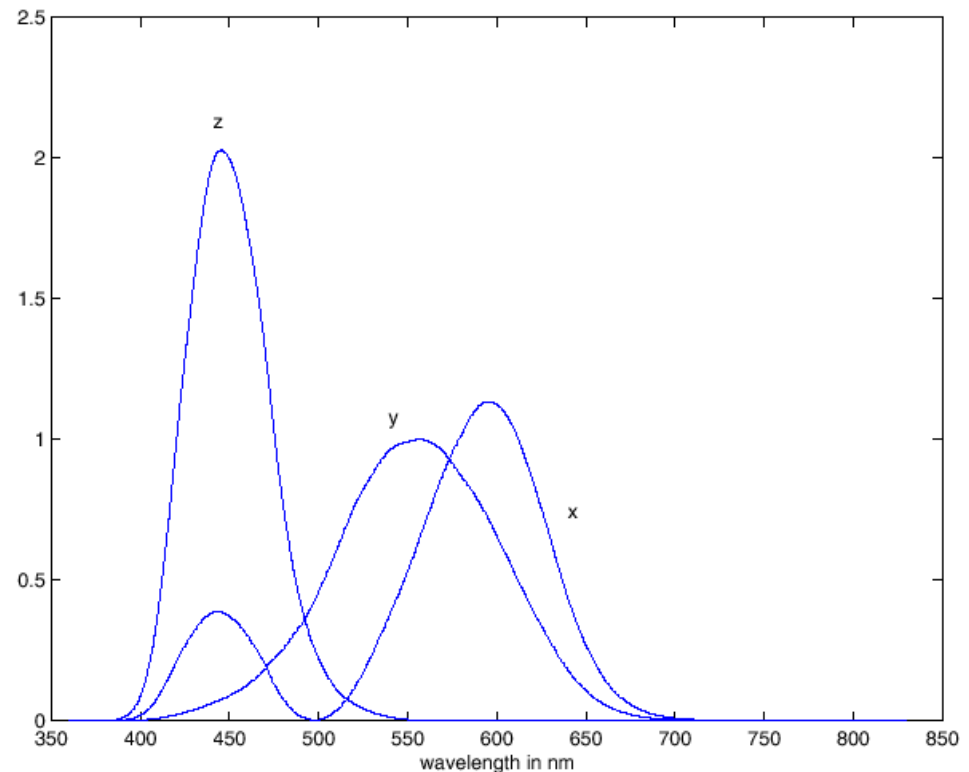
RGB

- Primaries are monochromatic, energies are 645.2 nm, 526.3 nm, and 444.4nm
- Color matching functions have negative parts
 - Some colors can be matched only subtractively



CIE XYZ

- Color matching functions are positive everywhere, but primaries are imaginary (i.e., not visible colors)



Human eye, RGB sensor, and hyperspectral sensor

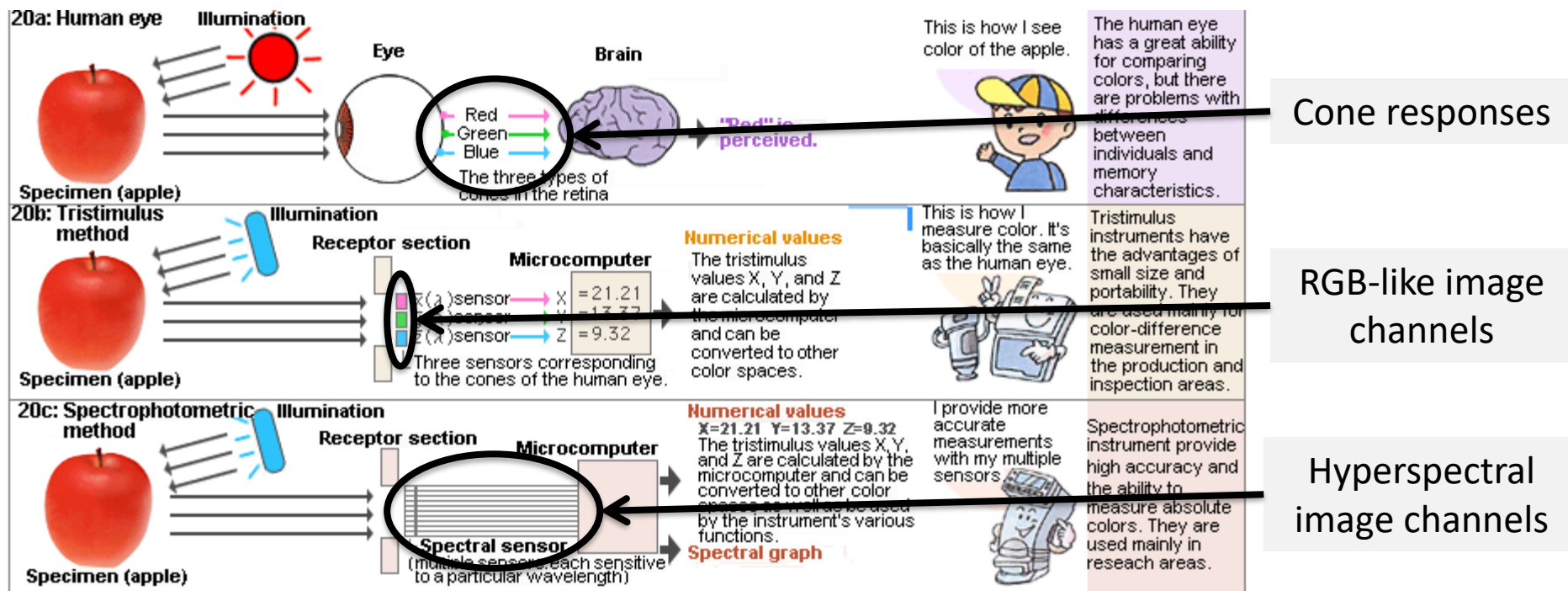
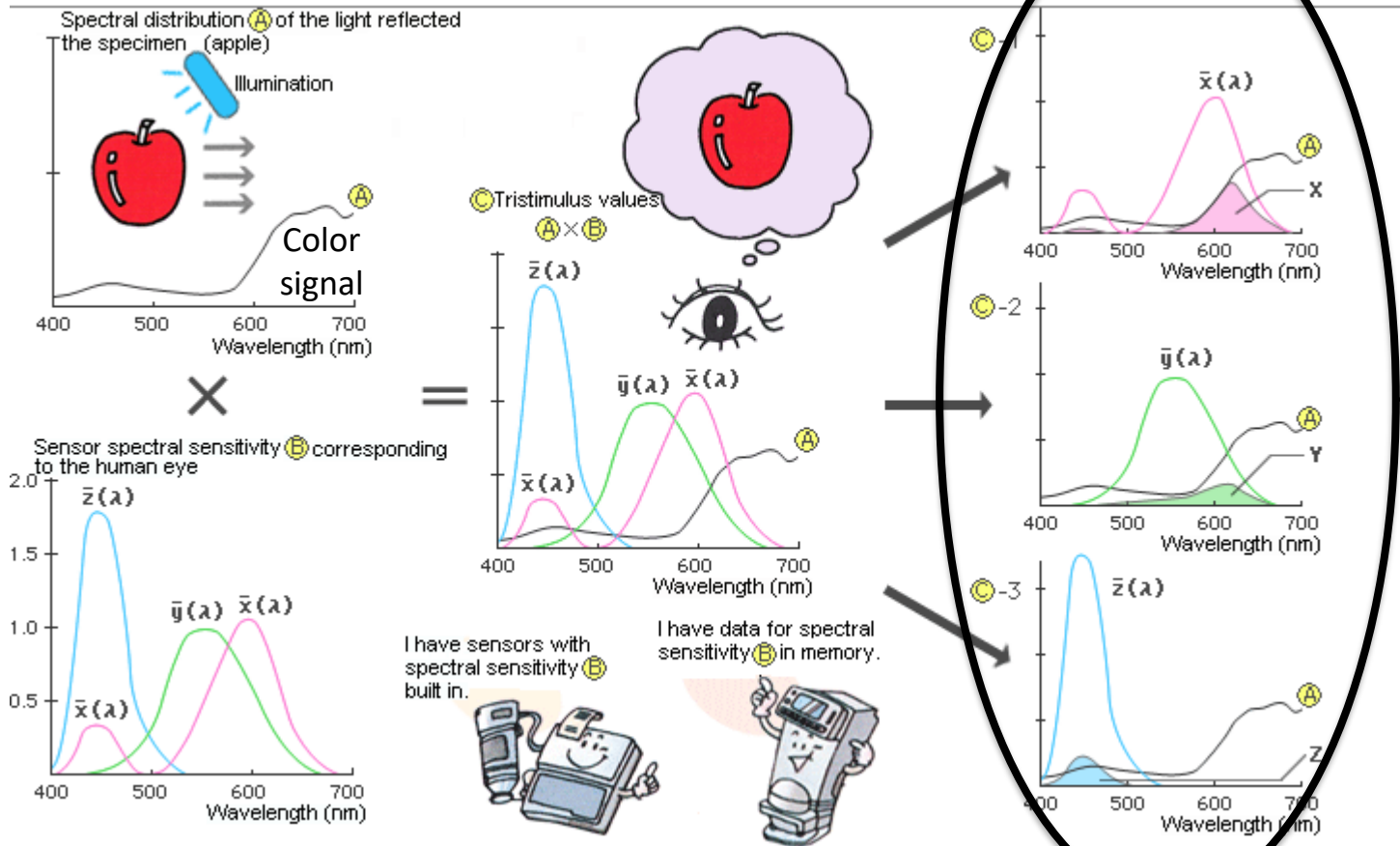


Image channels to XYZ



Hyperspectral to RGB

1. Hyperspectral to XYZ (for each pixel)

$$X = \sum_{\lambda} \text{spd}_{\text{illum}}(\lambda) \bar{x}(\lambda) I_{\text{HSI}}(\lambda)$$

$$Y = \sum_{\lambda} \text{spd}_{\text{illum}}(\lambda) \bar{y}(\lambda) I_{\text{HSI}}(\lambda)$$

$$Z = \sum_{\lambda} \text{spd}_{\text{illum}}(\lambda) \bar{z}(\lambda) I_{\text{HSI}}(\lambda)$$

where $\text{spd}_{\text{illum}}(\lambda)$ is the relative spectral power distribution (SPD) function of the illuminant, and $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ are the CIE color matching functions

- For example, use the values in <https://files.cie.co.at/204.xls> to create lookup tables (LUTs) for:
 - The relative spectral power distribution (SPD) function of CIE standard illuminant D65 at a given wavelength
 - The CIE 1931 standard colorimetric observer color matching functions at a given wavelength

Hyperspectral to RGB

In matrix form

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = s \begin{bmatrix} \text{spd}_{\text{illum}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{x}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{y}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{z}(\lambda_n) \end{bmatrix} \begin{bmatrix} I_{\text{HSI}}(\lambda_1) \\ \vdots \\ I_{\text{HSI}}(\lambda_n) \end{bmatrix}$$

The scale s of the $3 \times n$ matrix $\mathbf{M}_{\text{HSI},\text{XYZ}}$ that maps HSI to XYZ must be such that white maps to $Y = 1$ (i.e., the middle row sums to 1)

$$\begin{bmatrix} X \\ 1 \\ Z \end{bmatrix} = \frac{1}{\sum_{i=1}^n \text{spd}_{\text{illum}}(\lambda_i)\bar{y}(\lambda_i)} \begin{bmatrix} \text{spd}_{\text{illum}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{x}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{y}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{z}(\lambda_n) \end{bmatrix} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$
$$\begin{bmatrix} X \\ 1 \\ Z \end{bmatrix} = \mathbf{M}_{\text{HSI},\text{XYZ}} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix}$$

where

$$\mathbf{M}_{\text{HSI},\text{XYZ}} = \frac{1}{\sum_{i=1}^n \text{spd}_{\text{illum}}(\lambda_i)\bar{y}(\lambda_i)} \begin{bmatrix} \text{spd}_{\text{illum}}(\lambda_1)\bar{x}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{x}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{y}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{y}(\lambda_n) \\ \text{spd}_{\text{illum}}(\lambda_1)\bar{z}(\lambda_1) & \cdots & \text{spd}_{\text{illum}}(\lambda_n)\bar{z}(\lambda_n) \end{bmatrix}$$

Hyperspectral to RGB

2. Hyperspectral to RGB

See lecture 2

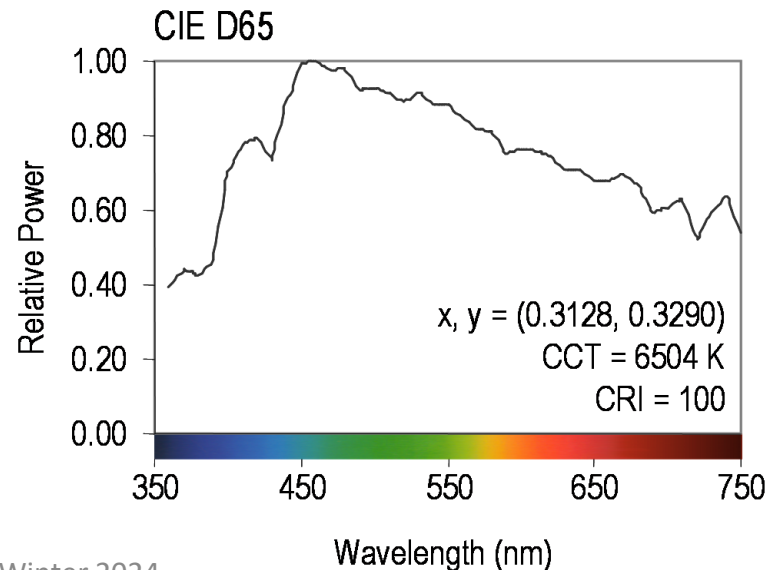
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}_{\text{XYZ,RGB}} \mathbf{M}_{\text{HSI,XYZ}} \begin{bmatrix} I_{\text{HSI}}(\lambda_1) \\ \vdots \\ I_{\text{HSI}}(\lambda_n) \end{bmatrix}$$
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}_{\text{HSI,RGB}} \begin{bmatrix} I_{\text{HSI}}(\lambda_1) \\ \vdots \\ I_{\text{HSI}}(\lambda_n) \end{bmatrix}$$

where

$$\mathbf{M}_{\text{HSI,RGB}} = \mathbf{M}_{\text{XYZ,RGB}} \mathbf{M}_{\text{HSI,XYZ}}$$

Example

- 31 bands
 - 410 nm to 710 nm, 10 nm increments
- CIE Standard Illuminant D65
 - The standard daylight illuminant



Example



410 nm



Example



420 nm



Example



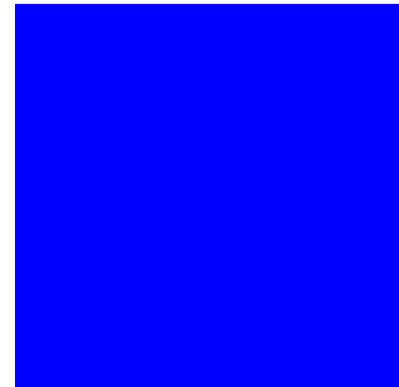
430 nm



Example



440 nm



Example



450 nm



Example



460 nm



Example



470 nm



Example



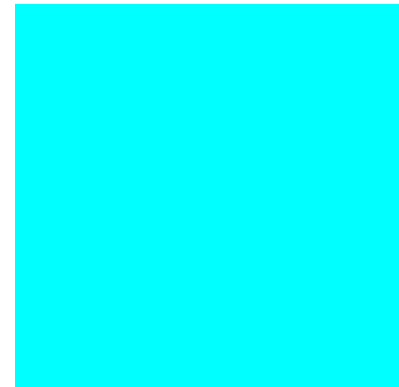
480 nm



Example



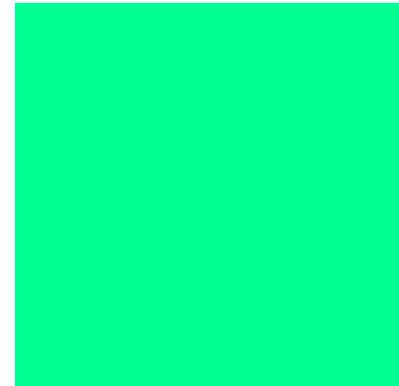
490 nm



Example



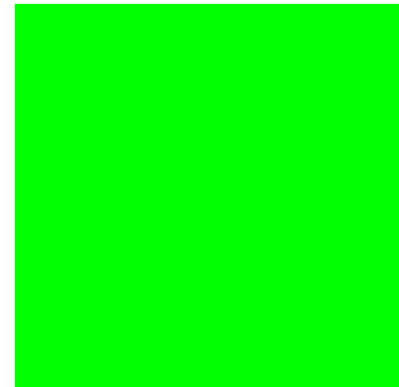
500 nm



Example



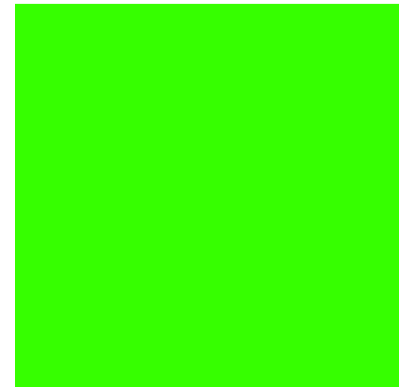
510 nm



Example



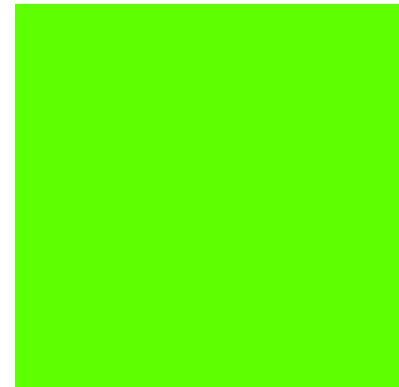
520 nm



Example



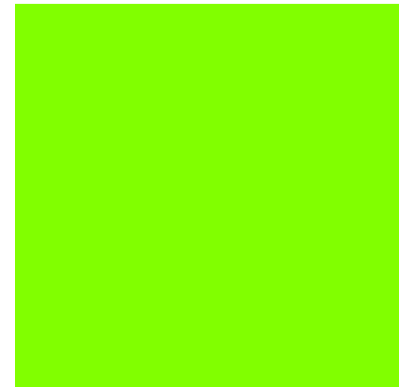
530 nm



Example



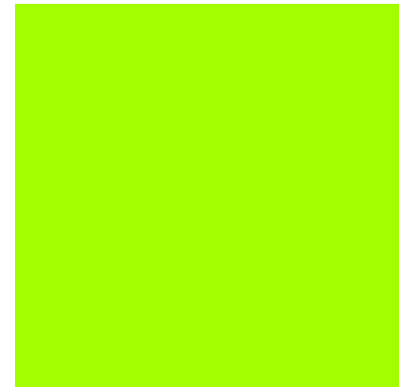
540 nm



Example



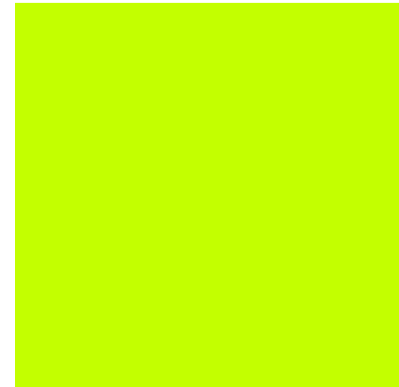
550 nm



Example



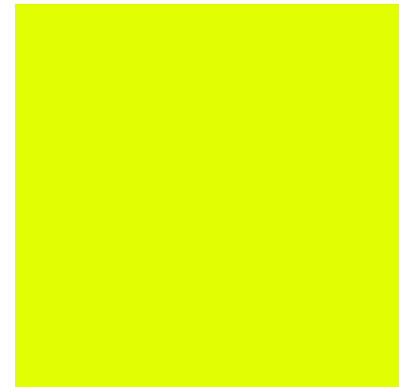
560 nm



Example



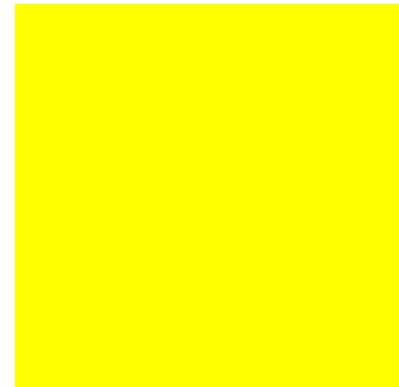
570 nm



Example



580 nm



Example



590 nm



Example



600 nm



Example



610 nm



Example



620 nm



Example



630 nm



Example



640 nm



Example



650 nm



Example



660 nm



Example



670 nm



Example



680 nm



Example



690 nm



Example



700 nm



Example



710 nm



Example

Result



RGB image

Hyperspectral to RGB

- Only dependent on the relative spectral power distribution (SPD) function of the illuminant and the CIE color matching functions (which are related to the human visual system)
- Linear transformation
 - Matrix-vector multiply
- Useful for visualization to a human and image registration

Next lecture

- Image processing