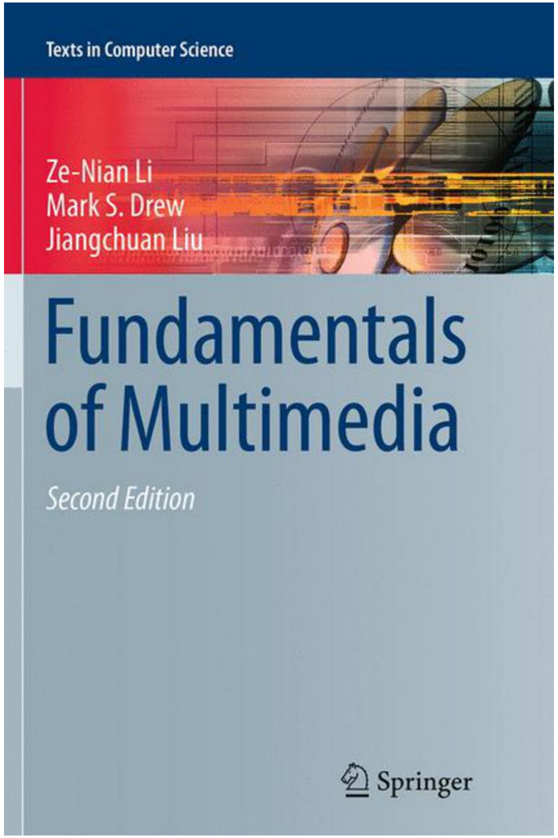
Background Photo:
Opera Garnier Ceiling

MULTIMEDIA

Dr Siba HAIDAR • INFO430 • 2019-2020

Textbook: Fundamentals of Multimedia • Li, Drew & Liu

Course Outline



1. Introduction to multimedia
2. Digital representation of graphics and images
3. Colors in images and video
4. Fundamentals video
5. Lossless compression algorithms
6. Lossy compression algorithms (JPEG)
7. Video Coding (MPEG)
8. Introduction to Image Processing

Background Photo:
The Starry Night

COLOR IN IMAGE AND VIDEO

Chapter Outline

- Color in Image and Video
- chapter 4 in textbook

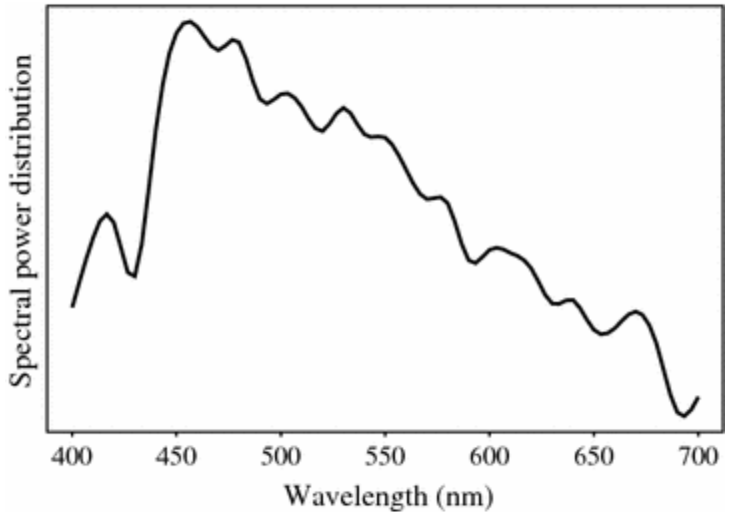
1. Color Science
2. Color Models in Images
3. Color Models in Video

Background Photo:
The Milk Maid

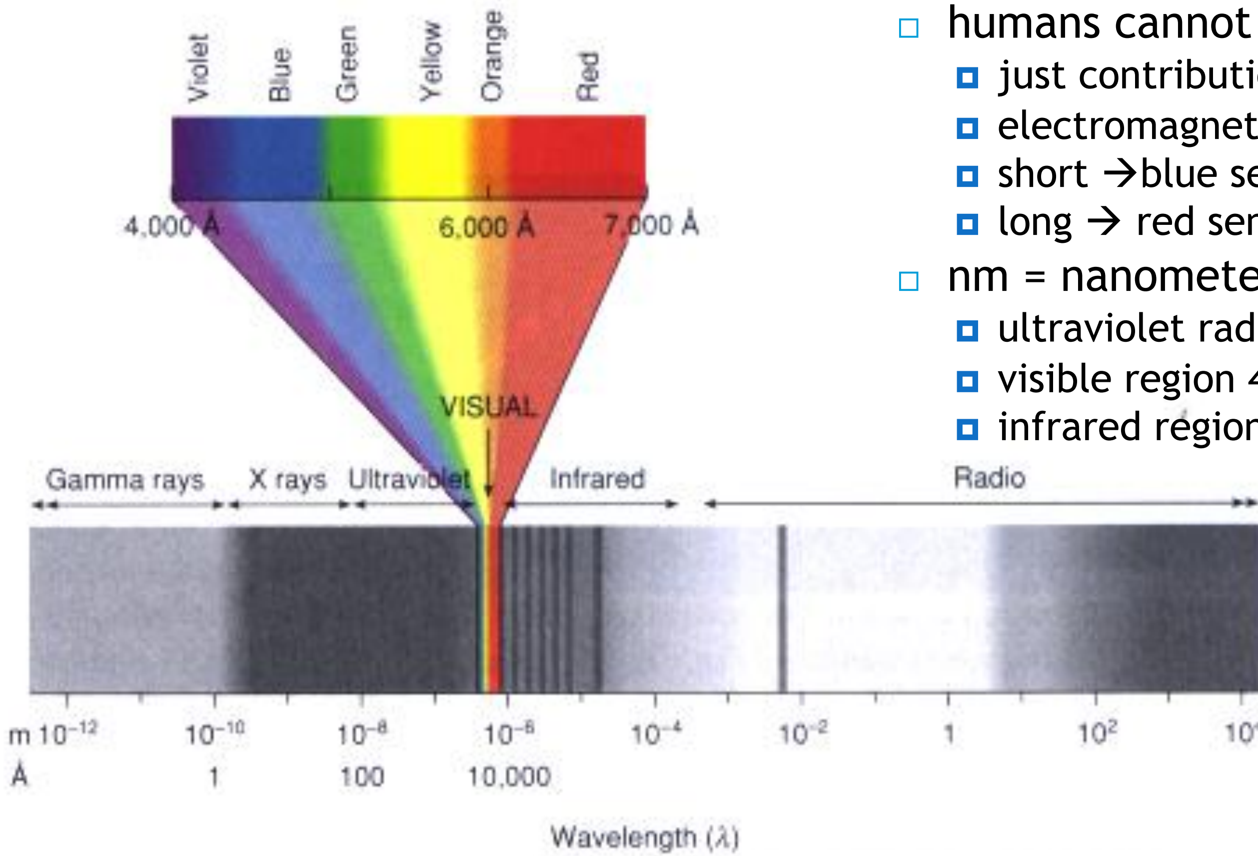
Color Science

Light and Spectra

- light is an electromagnetic wave
  - its color is characterized by the wavelength content of the light
- ex:
  - laser light → single wavelength
  - ruby laser produces bright scarlet-red beam 694.3 nm
- spectral power distribution of daylight



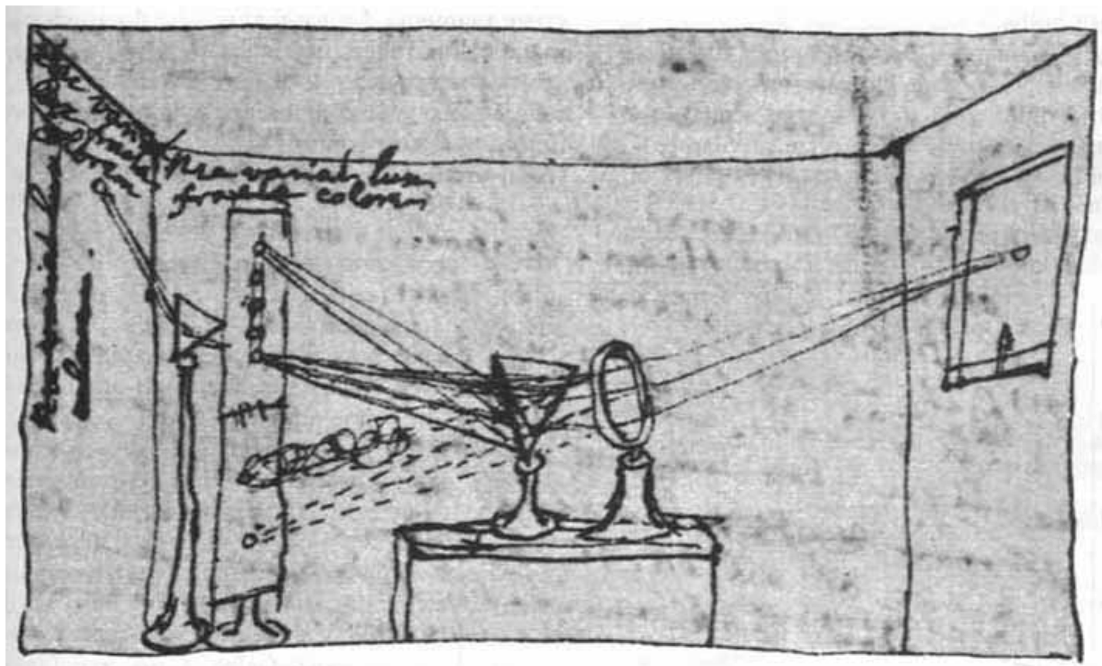
Visible Wavelengths



- humans cannot detect all light
  - just contributions in "visible wavelengths”
  - electromagnetic wave
  - short →blue sensation
  - long → red sensation
- nm = nanometer = 10^{-9} meters
  - ultraviolet radiation lasers 180 - 400 nm
  - visible region 400 - 700 nm
  - infrared region 700 nm - 1 mm

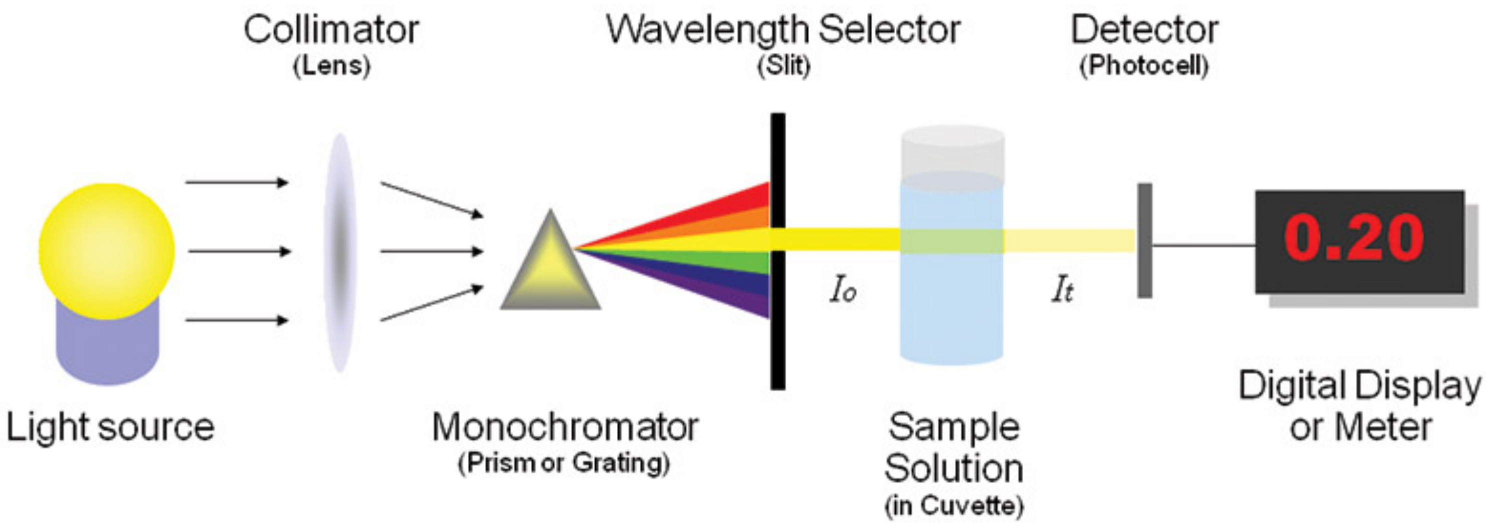
Sir Isaac Newton's experiments

- most light sources produce contributions over many wavelengths
- phenomenon → dispersion



Spectrophotometer

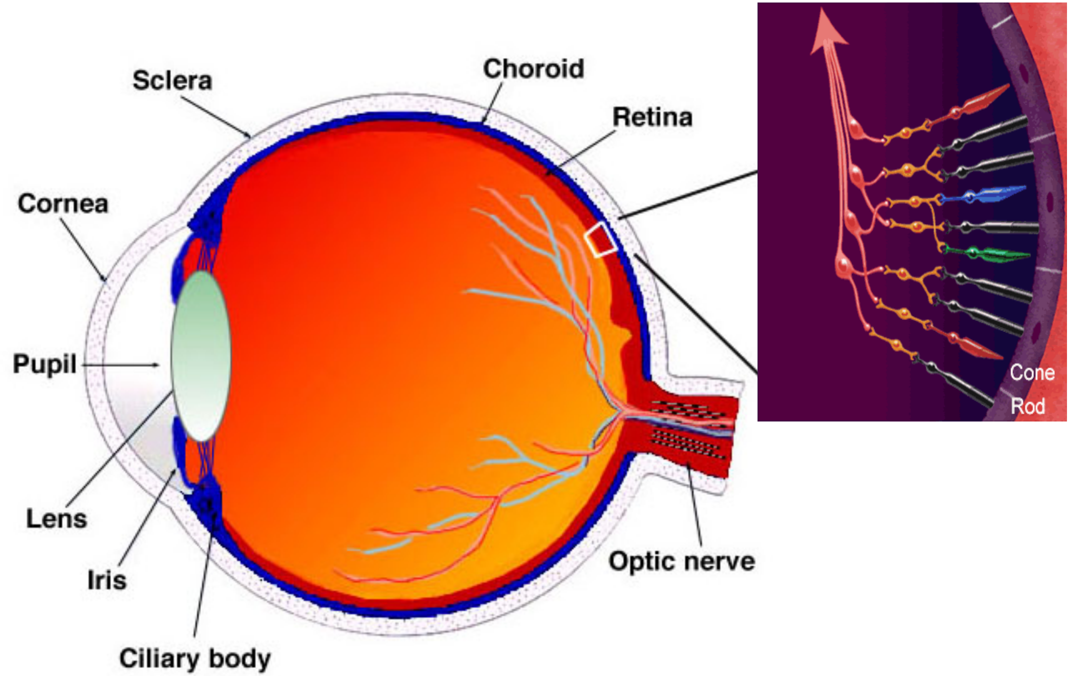
- device used to measure visible light
  - by reflecting light from a diffraction grating (a ruled surface)
  - that spreads out the different wavelengths



Human Vision

- eye works like a camera
  - lens focusing an image onto the retina
  - upside-down & left-right reversed
- retina = array of
  - rods + 3 kinds of cones
- rods
  - come into play when light levels are low
  - produce a image in shades of gray
  - “all cats are gray at night!”
- cones
  - 3 kinds
  - each produce a signal
  - differing pigments
  - most sensitive to R|G|B light
- it seems like brain
  - makes use of differences R-G, G-B, B-R
  - and combination
  - → high-light-level achromatic channel

- drawing of a section through the human eye with a schematic enlargement of the retina



Spectral Sensitivity of the Eye

- eye is most sensitive to light in middle of visible spectrum
- sensitivity of receptors = function of wavelength
  - blue receptor sensitivity
    - is not to scale in figure
    - because much smaller
    - due to its late addition in evolution
  - statistically blue is favorite color of humans ← latecomer thus surprising!
- luminous-efficiency function
  - dashed line
  - overall sensitivity
  - V (λ) = sum of response curves RGB

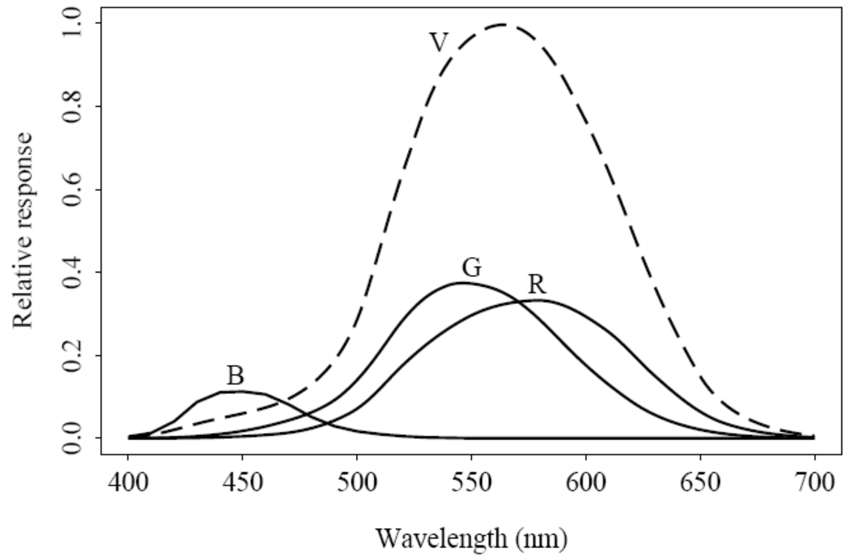
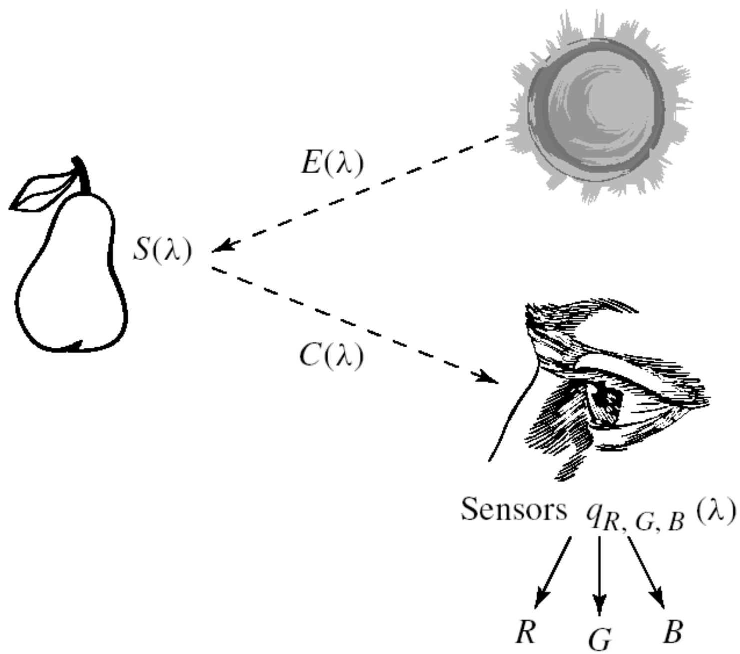


Image Formation

- we actually image light that is reflected from a surface
  - surfaces reflect different amounts of light at different wavelengths
  - dark surfaces reflect less energy than light surfaces
- light from illuminant with SPD E(λ)
  - 1) impinges on a surface
    - surface spectral reflectance function S(λ)
  - 2) reflected
  - 3) filtered by eye's cone
    - functions $q_R(\lambda), q_G(\lambda), q_B(\lambda)$
- C(λ) = color signal
  - C(λ) = E(λ) x S(λ)



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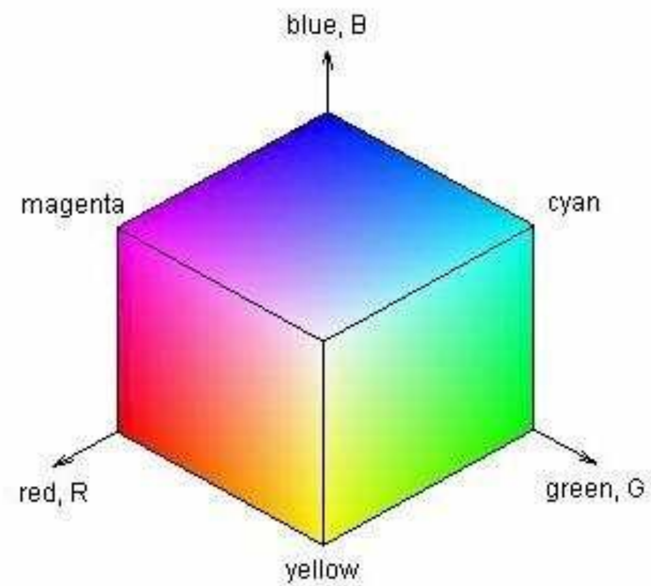
Camera Systems

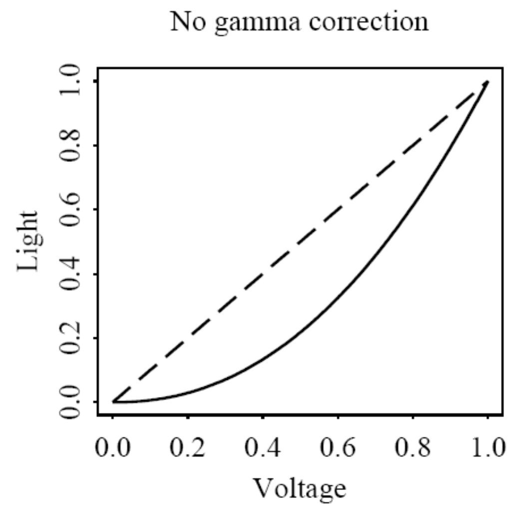
- similar fashion
- 3 signals produced at each pixel location
  - analog signals → digital
  - truncated to integers
  - stored
- if precision 8-bit for R | G | B
  - max = 255
  - min = 0
- light entering eye of computer user
  - emitted by screen\
  - screen = self-luminous source
  - we need to know light E(λ) entering eye

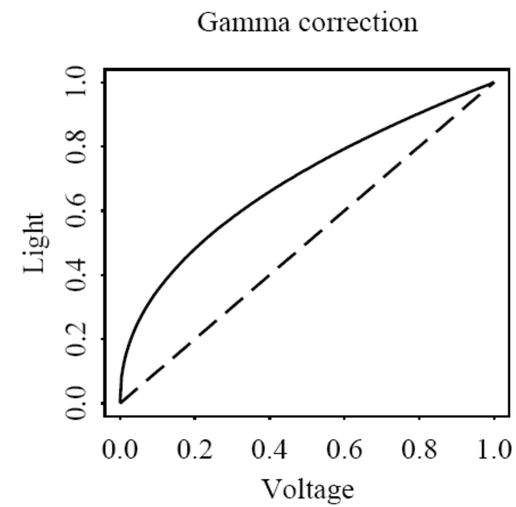
- RGB color cube

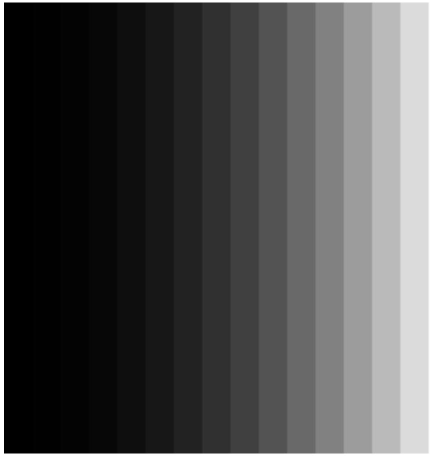


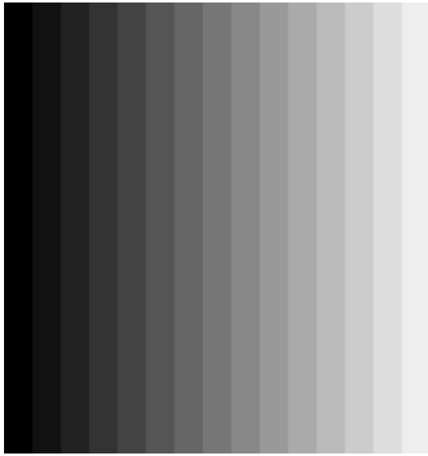
Gamma Correction

- in old CRT screens
  - light emitted
  - proportional to voltage
  - raised to a power
  - $\gamma \approx 2.2$
- correct
  - raise to power $1/\gamma$
- notice effect of correction for small values









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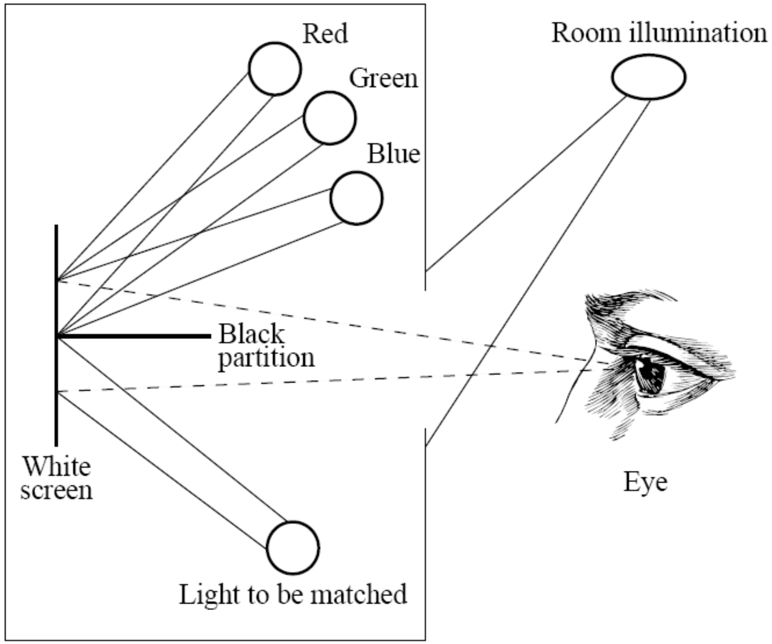
Color-Matching Functions

- technique evolved in psychology
- matching a combination of basic RGB lights to a given shade
- set of color primaries
- match a given color
  - subject asked to separately adjust brightness of 3 primaries
  - using a set of controls
- device → colorimeter

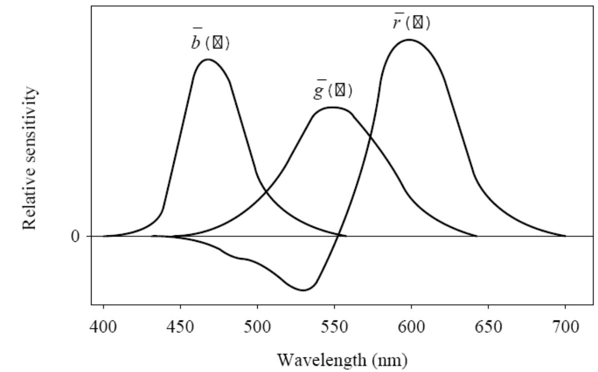


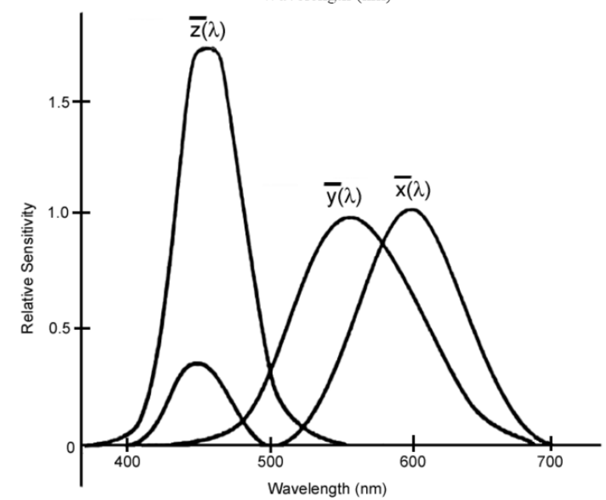
CIE Chromaticity Diagram

- Commission Internationale de l'Éclairage
- International Commission on Illumination

- CIE RGB color-matching functions
  - amounts of R & G & B selected to match each single-wavelength light
  - → color-matching curves $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$
- problem
  - $\bar{r}(\lambda)$ color-matching curve has a <0 lobe
  - → a set of fictitious primaries
  - color-matching functions >=0 values

- CIE standard XYZ color-matching functions
  - $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$
  - 3×3 matrix away from $\bar{r}, \bar{g}, \bar{b}$ curves
  - matrix chosen such that
  - middle = exactly = luminous-efficiency curve V(λ)





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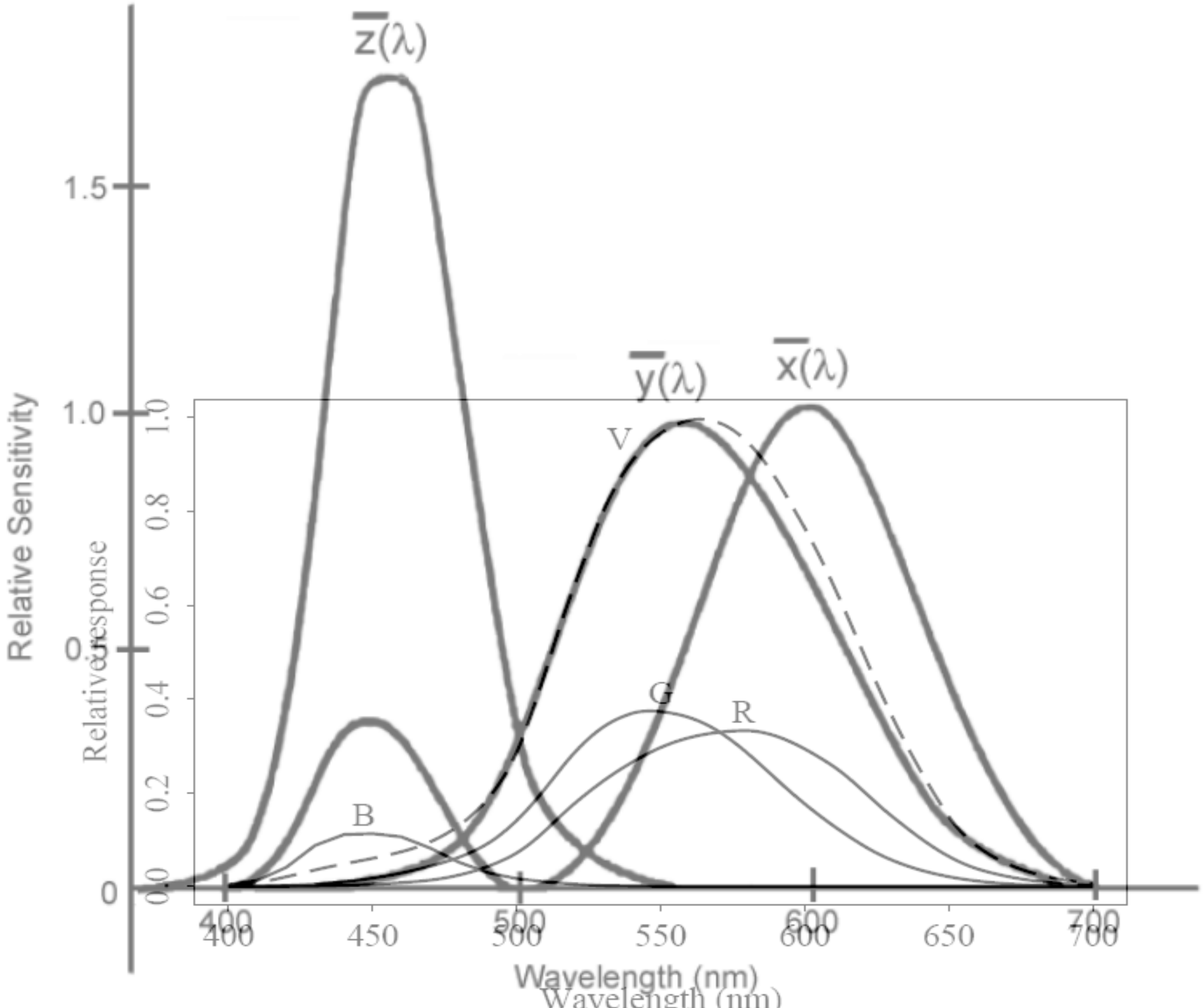
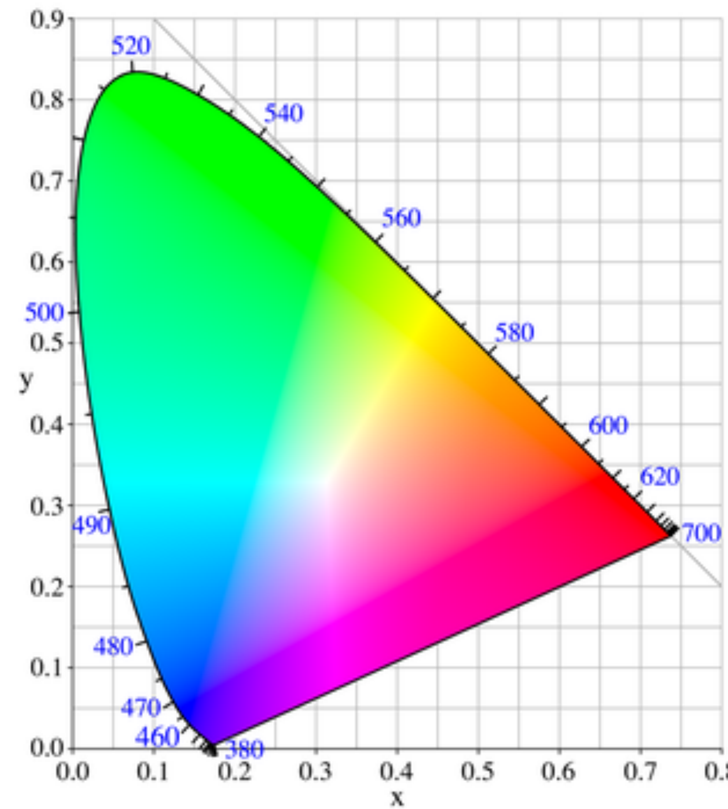


$\bar{z}(\lambda)$
$\bar{y}(\lambda)$
$\bar{x}(\lambda)$
Relative Sensitivity
1.5
1.0
0.5
0
Relative response
1.0
0.8
0.6
0.4
0.2
0.0
V
G
R
B
400
450
500
550
600
650
700
Wavelength (nm)
Wavelength (nm)

CIE Chromaticity Diagram

- go to 2D by factoring out magnitude of vectors (X, Y, Z)
- we could divide by $\sqrt{X^2 + Y^2 + Z^2}$
- but instead divided by the sum X+Y+Z:
  - x = X/(X +Y +Z)
  - y = Y/(X +Y +Z)
  - z = Z/(X +Y +Z)
- z is redundant since $x + y + z = 1$
  - → (x,y)
- locus of points for monochromatic light
  - projection of each
  - tristimulus vector (X, Y, Z)
  - onto plane connecting
  - points (1,0,0), (0,1,0) & (0,0,1)



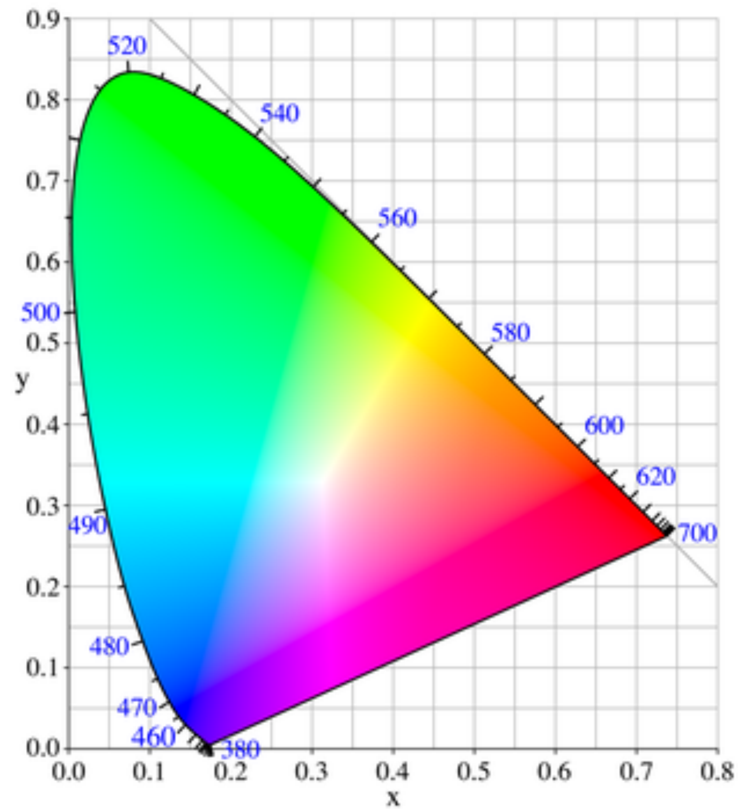
CIE Chromaticity Diagram

- chromaticities on
  - spectrum locus = "horseshoe"
  - represent "pure" colors
  - most "saturated”

- colors close to white point →++ unsaturated

- for a mixture of two lights
  - resulting chromaticity lies on
  - straight line joining chromaticities of 2 lights

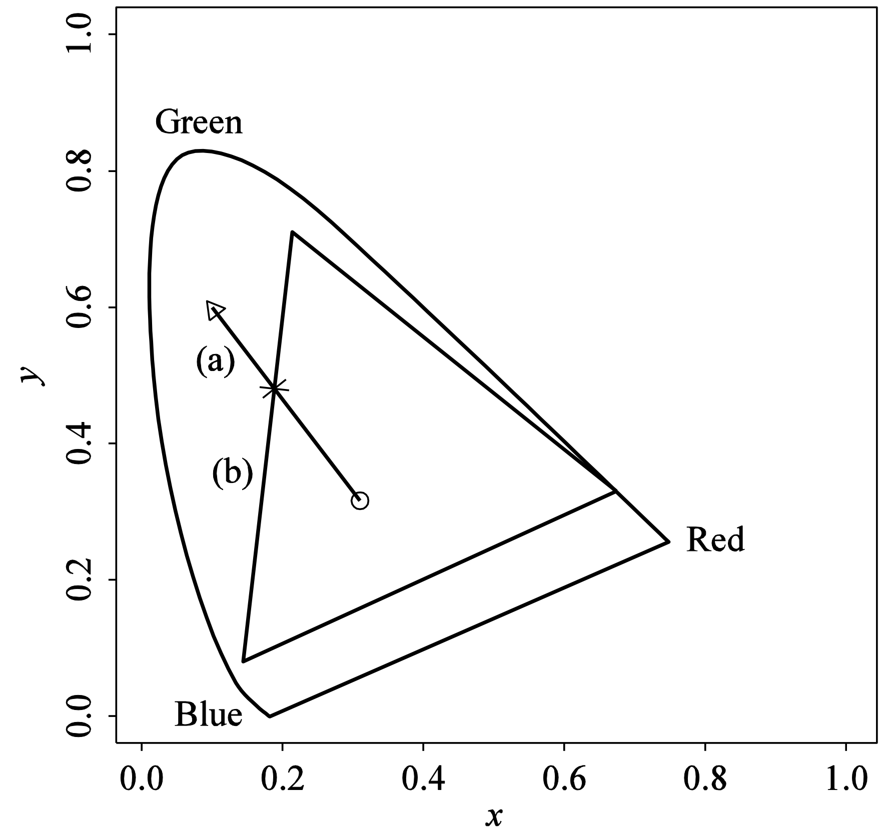
- "dominant wavelength"
  - position on spectrum locus of
  - intersection of line joining white point to given color
  - and extended through it



Out-of-Gamut colors

- transform matrix
  - device specific NTSC | SMPTE | EBU …
  - $\begin{bmatrix} x_r & x_g & x_b \\ y_r & y_g & y_b \\ z_r & z_g & z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$

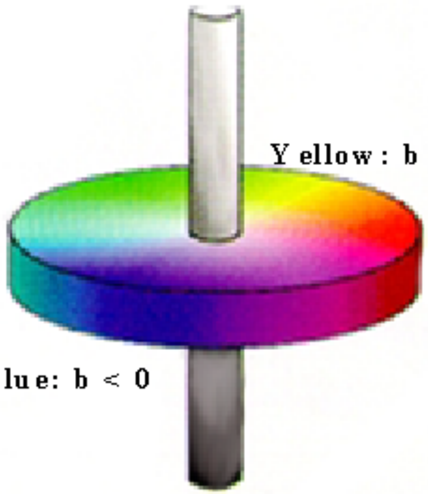
- have RGB? → can get (x,y)
- have (x,y)? → can get RGB
- what if any of RGB numbers is <0?
  - color visible to humans
  - out-of-gamut for our display
    - triangle
- solution #1:
  - use closest in-gamut color available
  - intersection of
  - (a) line from color to white point, with
  - (b) boundary of device color gamut
- solution #2:
  - select closest complementary color
- see also transform with gamma correction



L*a*b* (CIELAB) color Model

- Weber's Law:
  - equally-perceived differences are proportional to magnitude
- rule of thumb
  - equally-perceived changes must be relative
  - ratio of change same for dark or bright lights
- mathematically
  - intensity I equally perceived if $\frac{\Delta I}{I}$ constant
- take sound as example
  - if it's quiet → can hear small change in sound
  - if there is a lot of noise
    - change has to be of same proportion
    - in order to experience same difference
- human vision
  - CIELAB space
  - quantify differences perceived in color & brightness

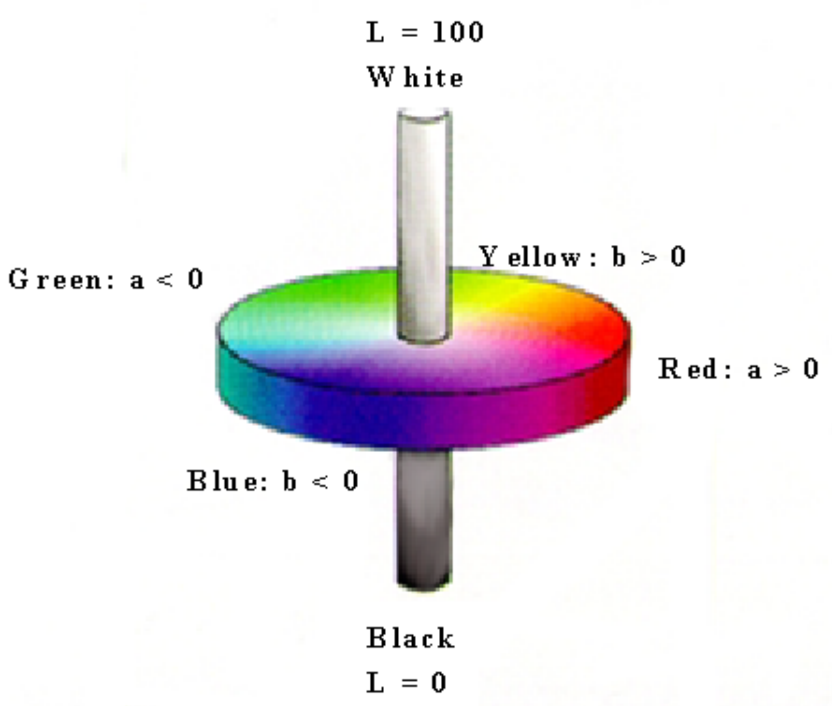
- cutaway into 3D solid of coordinate space associated with color difference metric



L*a*b* (CIELAB) color Model

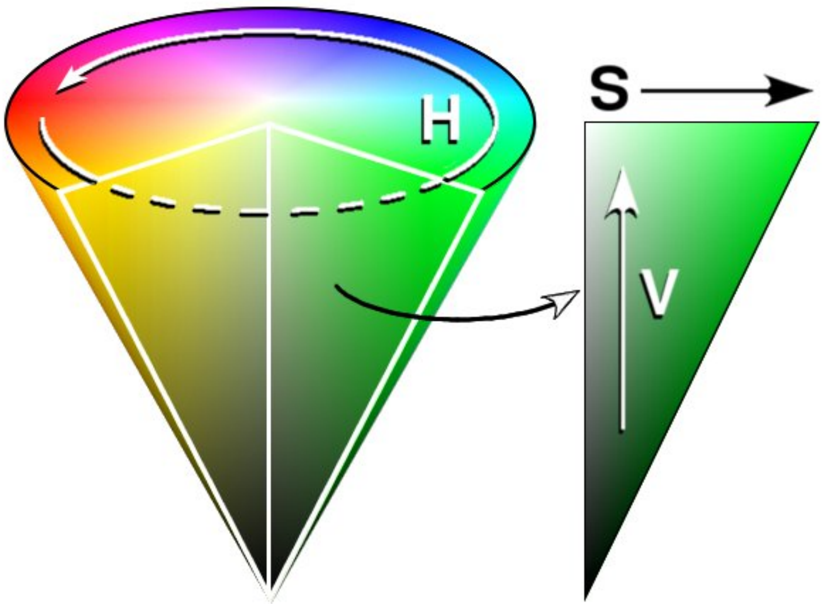
- CIELAB:
  - $\Delta E = \sqrt{(L*)^2 + (a*)^2 + (b*)^2}$
  - $L* = 116(Y/Y_n)^{1/3} - 16$
  - $a* = 500\left[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\right]$
  - $b* = 200\left[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\right]$
  - $X_n Y_n Z_n$ → XYZ values of the white point
- auxiliary definitions
  - $chroma = c* = \sqrt{(a*)^2 + (b*)^2}$
  - $hue\ angle = h = \arctan(b*/a*)$

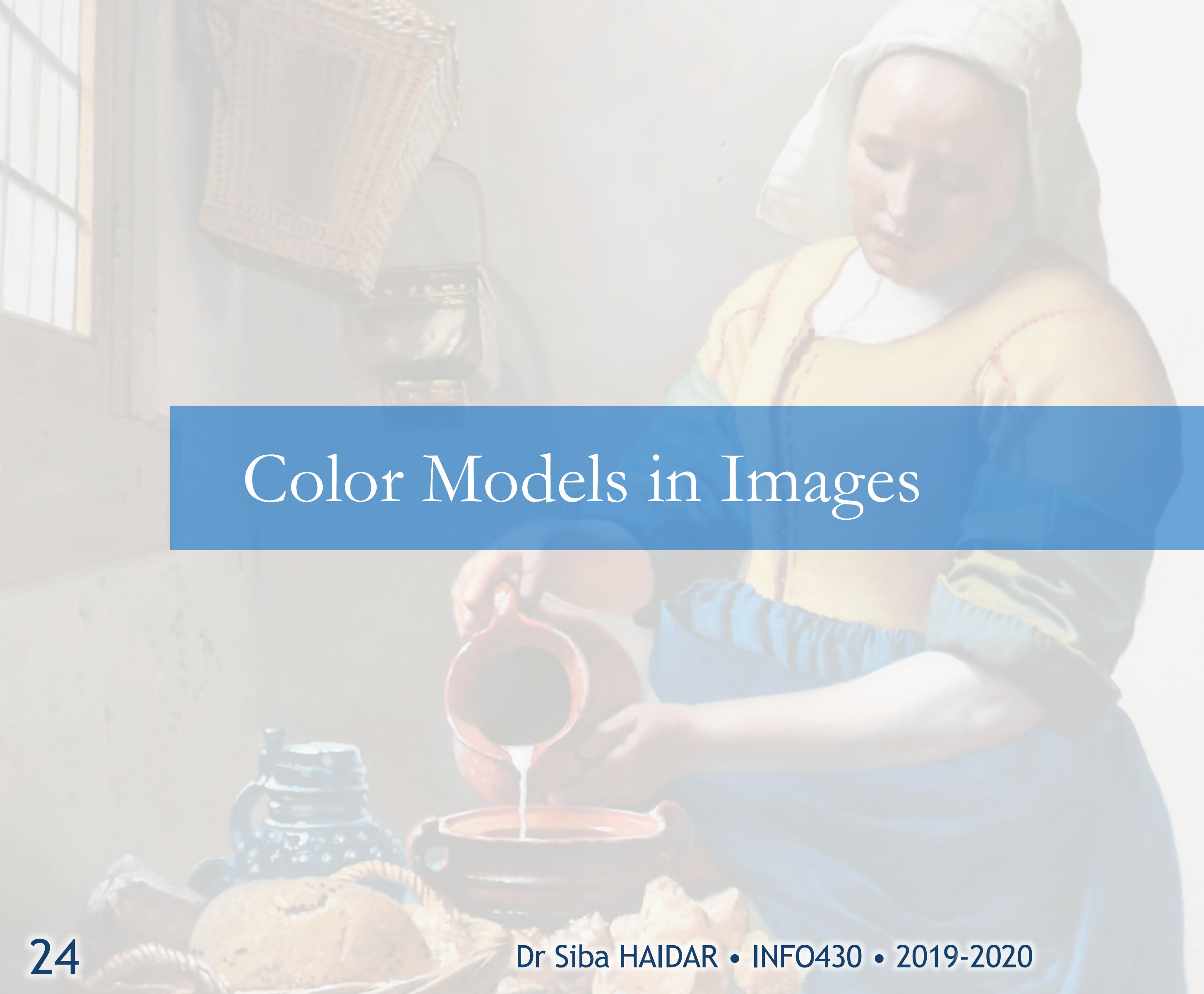
- cutaway into 3D solid of coordinate space associated with color difference metric



More Color Coordinate Schemes

- beware:
  - gamma correction or not is usually ignored
- schemes include:
  - CMY — Cyan Magenta Yellow
  - HSL — Hue Saturation Lightness
  - HSV — Hue Saturation Value
  - HSI — Hue Saturation Intensity
  - HCI — C = Chroma
  - HVC — V = Value
  - HSD — D = Darkness





Background Photo:
The Milk Maid

Color Models in Images

RGB Color Model for Displays

- store color information directly in RGB
- form device-dependent
- use 8 bits per color channel
  - in fact 12 bits to avoid an aliasing effect in dark image areas
  - contour bands result from gamma correction
    - in fewer available integer levels
- computer graphics
  - store integers proportional to intensity in frame buffer
  - then gamma correction LUT between frame buffer and display
  - if gamma correction applied to floats
    - before quantizing to integers
    - before storage in the frame buffer
    - then use only 8 bits per channel

Multisensor Cameras

- more accurate color can be achieved by using cameras
  - with more than 3 sensors
  - = more than 3 color filters
- one way of doing this
  - use a rotating filter
  - places a different color filter in the light path over a quick series of shots
- Museum of Modern Art in New York City
  - six-channel camera
  - capture images of important artworks
- also
  - removing the near-infrared filter typically placed in a camera
  - to extend the camera’s sensitivity into the infrared

Camera-Dependent Color: HSV

- HSV
  - H → hue
  - S → saturation of a color
    - Chroma divided by its luminance
    - the more desaturated the color is the closer it is to gray
  - V → value
    - correlate of brightness as perceived by humans
- commonly used in image processing and editing software

- RGB → HSV
  - R,G,B in [0..255]

$$M = \max\{R, G, B\}$$
$$m = \min\{R, G, B\}$$
$$V = M$$
$$S = \begin{cases} 0 & \text{if } V = 0 \\ \big(V - m\big)/V & \text{if } V > 0 \end{cases}$$
$$H = \begin{cases} 0 & \text{if } S = 0 \\ 60(G - B)/(M - m) & \text{if } (M = R \text{ and } G \geq B) \\ 60(G - B)/(M - m) + 360 & \text{if } (M = R \text{ and } G < B) \\ 60(B - R)/(M - m) + 120 & \text{if } M = G \\ 60(R - G)/(M - m) + 240 & \text{if } M = B \end{cases}$$

Camera-Dependent Color: sRGB

- proposed by Hewlett-Packard & Microsoft
- later standardized by the IEC
  - International Electrotechnical Commission
- balance between human color perception and device-dependent color
- tied to color space of a particular reference display device
- adopted as a reference color space on the web
- unless otherwise stated
  - color space for encoded/transmitted values

- presupposes certain standard viewing conditions
- specifies a transform
  - standard gamma-corrected $\gamma \approx 2.2$
- transform sRGB → CIEXYZ tristimulus

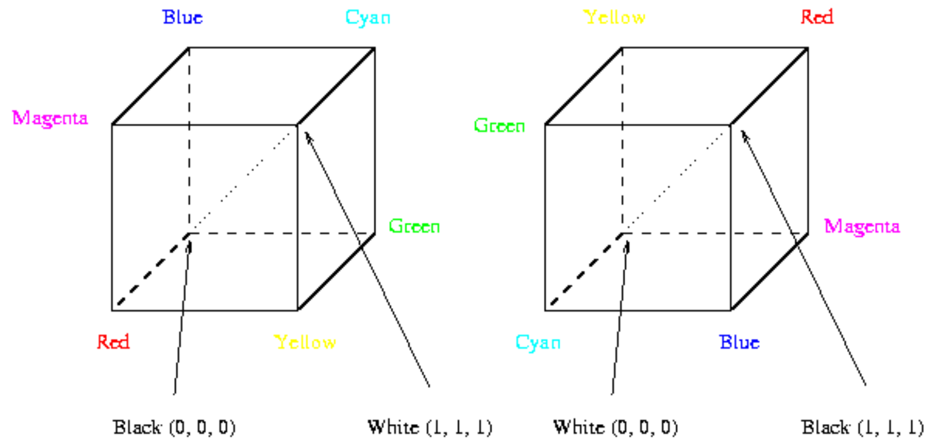
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.4124 & 0.3576 & 0.1805 \\ 0.2126 & 0.7152 & 0.0722 \\ 0.0193 & 0.1192 & 0.9505 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

- when white is (R,G,B)=(1,1,1)
- XYZ triple → standard light D65 divided by 100
- (X,Y,Z) = (0.9505, 1.0000, 1.0890)

Subtractive Color: CMY Color Model

- so far → additive color
  - 2 light beams impinge on a target
    - their colors add
  - 2 phosphors on CRT screen ON
    - their colors add
- but for ink deposited on paper
  - opposite situation holds
  - example: yellow ink
    - subtracts blue from white illumination
    - reflects red and green
    - → it appears yellow
- transform

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

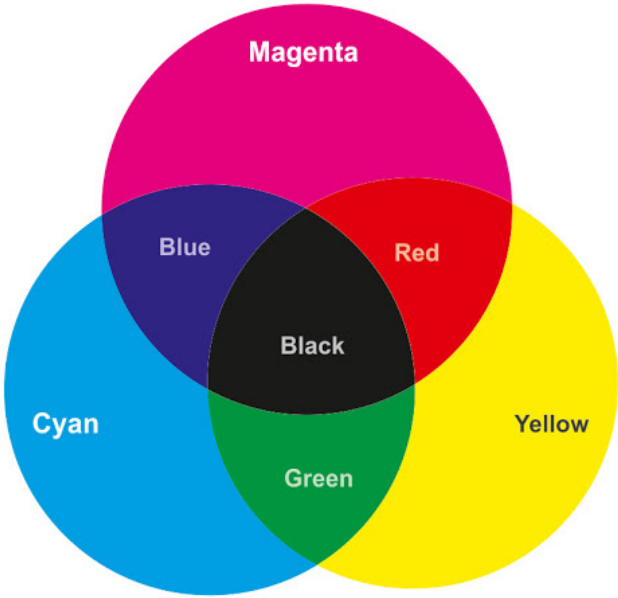


The RGB Cube

The CMY Cube

Undercolor Removal: CMYK System

- sharper and cheaper printer colors
  - calculate that part of the CMY mix that would be black
  - remove it from the color proportions
  - and add it back as real black
- new specification of inks
  - $K \equiv min\{C, M, Y\}$ $\begin{bmatrix} C \\ M \\ Y \end{bmatrix} \Rightarrow \begin{bmatrix} C-K \\ M-K \\ Y-K \end{bmatrix}$
- what is printer gamut?



CMYK - Cyan, Magenta, Yellow, Black
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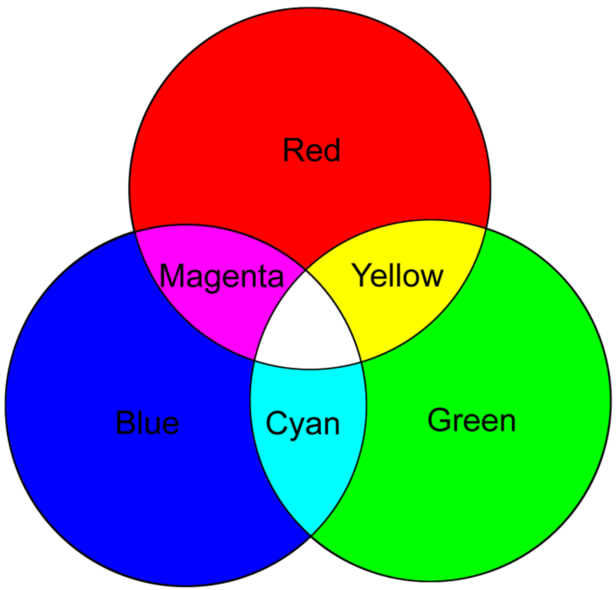
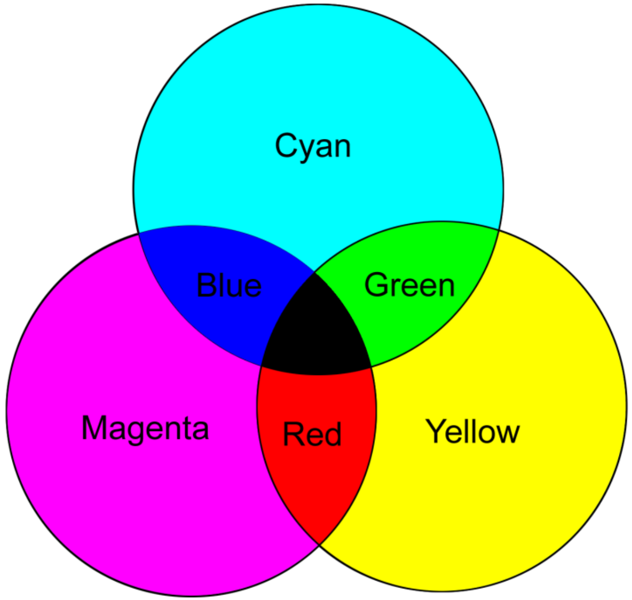
Color Combinations in Additive and Subtractive Colors

RGB: additive color	CMY: subtractive color



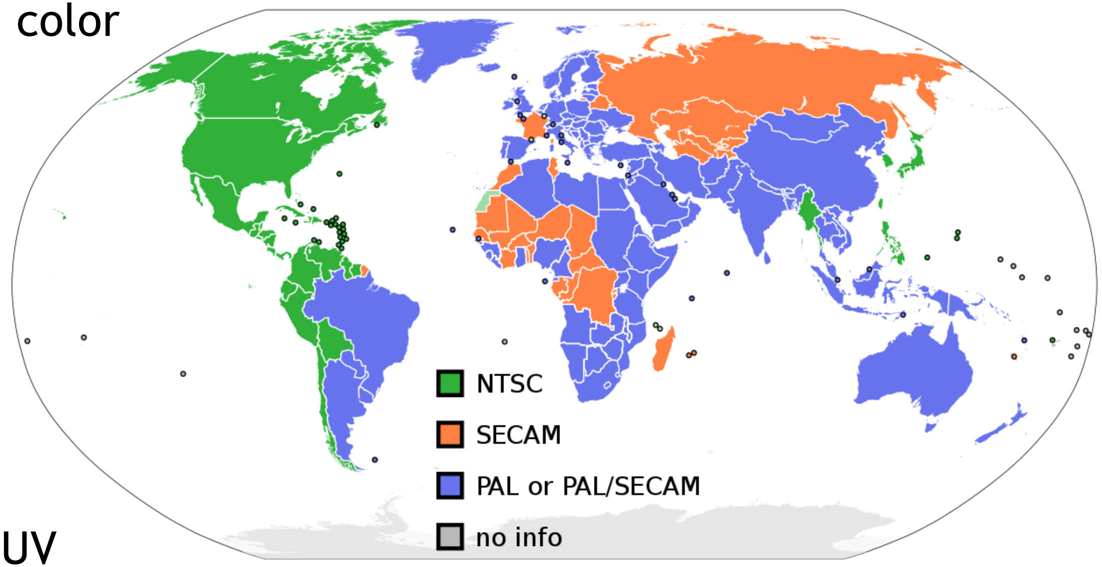


Background Photo:
The Milk Maid

Color Models in Video

Video Color Transforms

- methods derive from older analog methods of coding color for TV
  - luminance separated from color information
  - matrix transform method
- 2 major analog models
  - NTSC → YIQ
    - North America and Japan
  - PAL or SECAM → YUV
    - Europe
- digital video
  - YCbCr closely related to YUV



YUV Color Model

- initially in PAL analog video
- now in CCIR 601 standard for digital video
- YUV codes
  - a luminance signal
    - Y′ gamma-corrected → "luma"
    - similar to CIE luminance value Y
  - colorfulness scale → chrominance
    - difference between color & reference white at same luminance
    - → use color differences U, V:
    - U = B′ − Y′
    - V = R′ − Y′

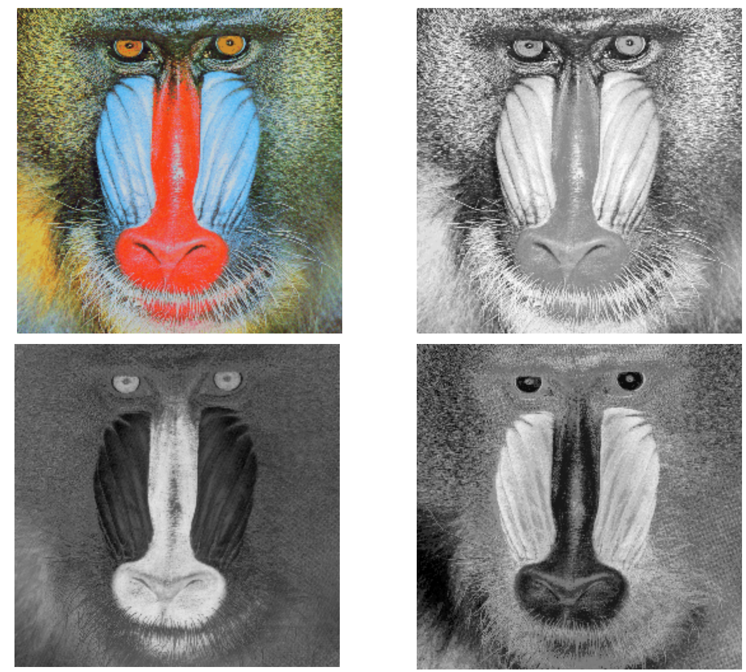
$$\begin{bmatrix} Y' \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.299 & -0.587 & 0.886 \\ 0.701 & -0.587 & -0.114 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

  - where R'G'B' nonlinear gamma-corrected
- for gray
  - R′ = G′ = B′
  - luminance Y′ → that gray
    - since 0.299+0.587+0.114 = 1.0.
  - chrominance (U, V) is zero
- composite video → convenient
  - $Y' \pm \sqrt{U^2 + V^2} \in [^{-1}/_3, ^{+4}/_3]$
  - U and V are rescaled:
    - U = 0.492111 (B′ − Y′)
    - V = 0.877283 (R′ − Y′)
- chrominance = composite signal
  - C = U·cos(ωt) + V ·sin(ωt)

YUV Color Model

- both U and V go negative
  - Zero is not minimum value for U, V.
  - images displayed are shifted and rescaled
    - use imagesc in MATLAB and not imshow
- in the RGB cube
  - U ~
    - from blue (U > 0)
    - to yellow (U < 0)
  - V ~
    - from red (V > 0)
    - to cyan (V < 0)

- Y′UV decomposition of color image
  - top left image (a) is original color image
  - (b) is Y ′; (c,d) are (U, V)

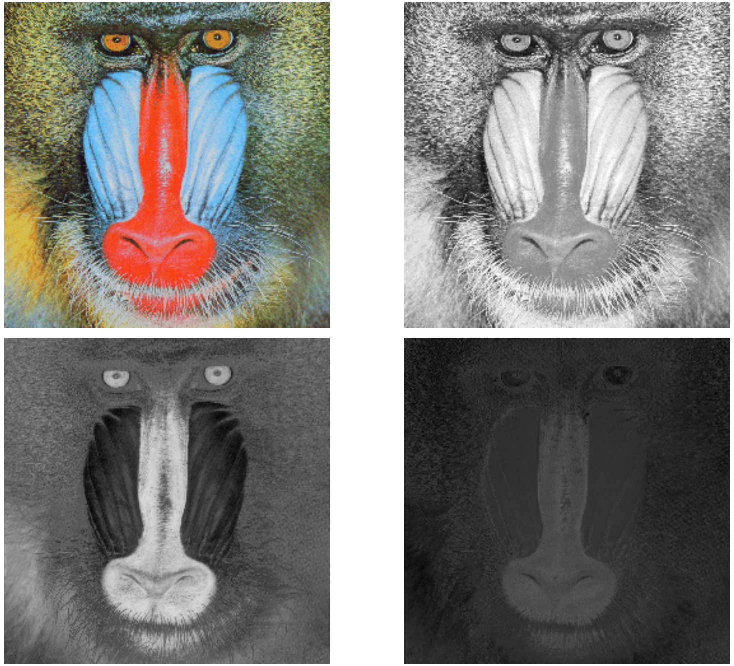


YIQ Color Model

- YIQ is used in NTSC color TV broadcasting
  - gray pixels → zero (I, Q) chrominance signal
  - I & Q are rotated version of U & V
  - Y' in YIQ is the same as in YUV;
  - U & V rotated by 33°:
    - I=0.492111(R′−Y′) cos33° − 0.877283(B′−Y′)sin33°
    - Q=0.492111(R′−Y′) sin33°+0.877283(B′−Y′)cos33°
- matrix transform:

$$\begin{bmatrix} Y' \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.595879 & -0.274133 & -0.321746 \\ 0.211205 & -0.523083 & 0.311878 \end{bmatrix} = \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix}$$

- Y′IQ decomposition of color image
  - top left image (a) is original color image
  - (b) is Y ′; (c,d) are (I,Q)



YCbCr Color Model

- Rec. 601 standard for digital video
- used in JPEG image compression and MPEG video compression
- YUV is changed by scaling such that
  - Cb is U, but with coefficient 0.5 x B′
  - Cb and Cr shifted → values 0 ..1
- equations
  - Cb = ((B′ – Y′)/1.772)+0.5
  - Cr = ((R′ – Y′)/1.402)+0.5
- however Rec 601 → 8-bit coding
  - Y′ max 219 & min +16
  - Cb & Cr
    - range ±112 & offset +128
    - → max 240 & min 16
- if R′G′B′ in [0.. + 1] → Y′CbCr in [0..255] via the transform:

$$\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ -0.168736 & -0.331264 & 0.5 \\ 0.5 & -0.418688 & -0.081312 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 0 \\ 0.5 \\ 0.5 \end{bmatrix}$$

$$\begin{bmatrix} Y' \\ C_b \\ C_r \end{bmatrix} = \begin{bmatrix} 65.481 & 128.553 & 24.966 \\ -37.797 & -74.203 & 112 \\ 112 & -93.786 & -18.214 \end{bmatrix} \begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}$$