Color fidelity and Color spaces

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What is a color?

- physical description: wavelengths
- psychological perception: stimulus
- computer description:
  - different sets of basis and coordinates
  - dithering/halftoning
- color correction:
  - ensure that *percepted* colors are correct

Map of the lecture

- Physical and biological description of colors:
  - wavelength, CIE color space…
- Computer description of colors:
  - color spaces: RGB, CMYK, HSV,…
  - color fidelity
  - gamma correction
  - halftoning and dithering

Physical and Biological

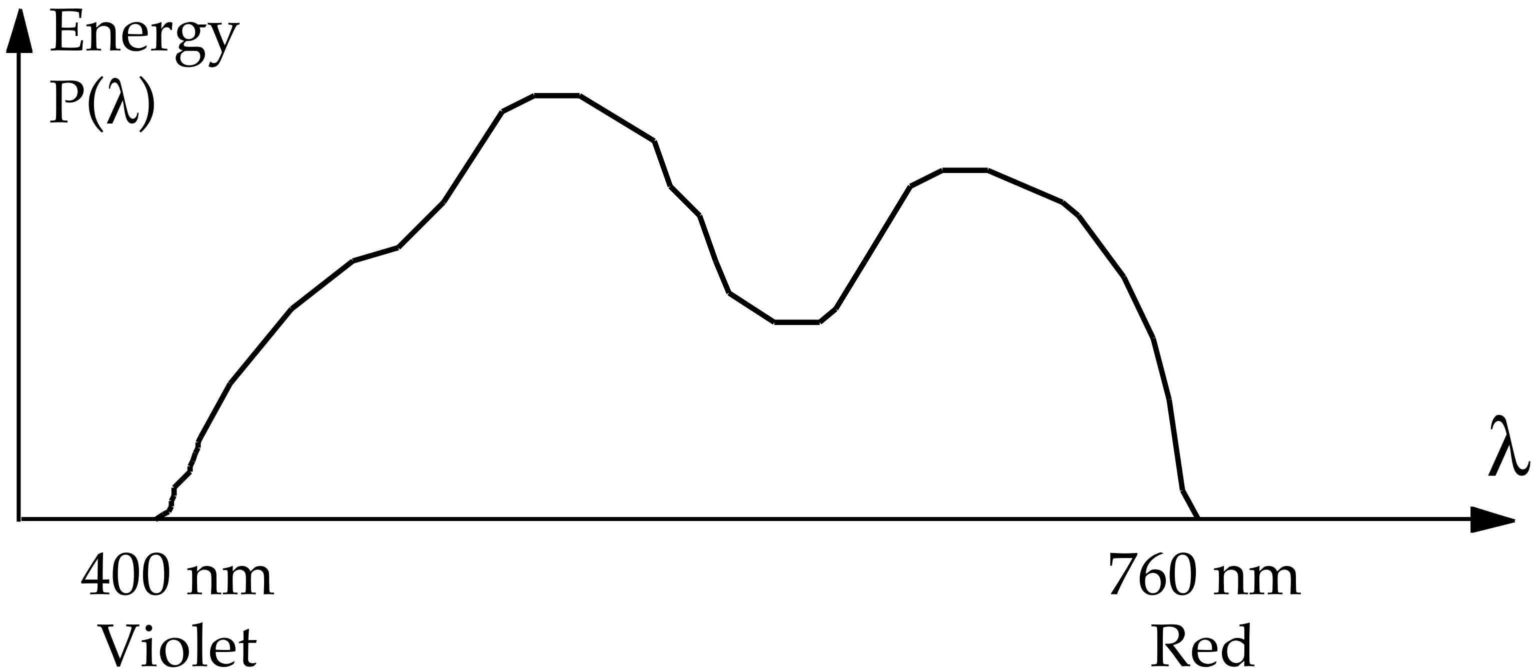
- wavelengths / spectrum
- hues, tints, shades, saturation, brightness
- cones on the retina, perception
- display independant description:
  - Commission Internationale de l'Éclairage

Computer description

- Display based color-spaces:
  - RGB, CMYK, YIQ, YCbCr…
- Perception based color-spaces: HSV
- Color correction:
  - gamma correction
- Conversion between these color descriptions

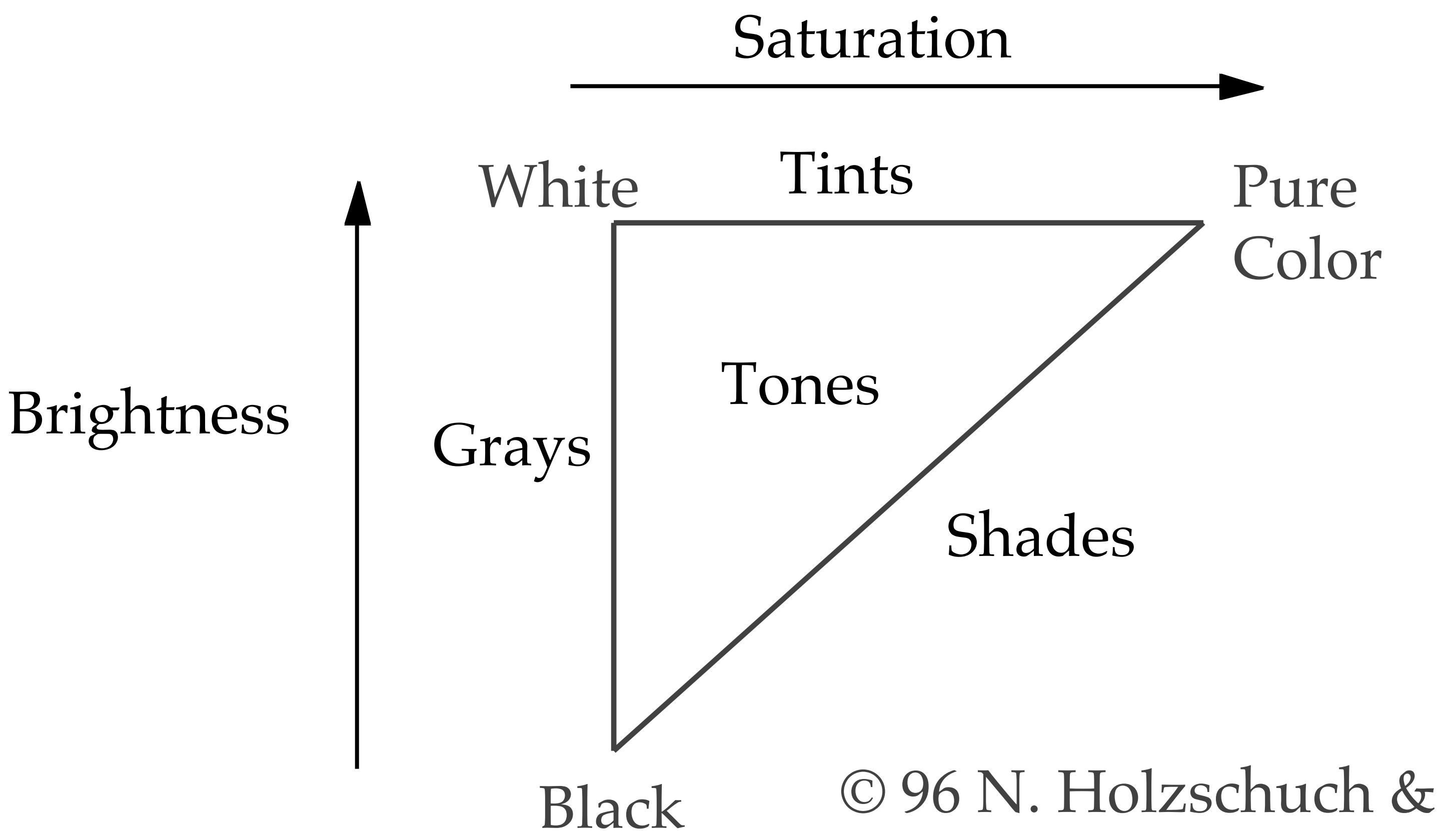
Spectral Distribution

- One color = one spectral distribution



“Pure” colors, shades and hues

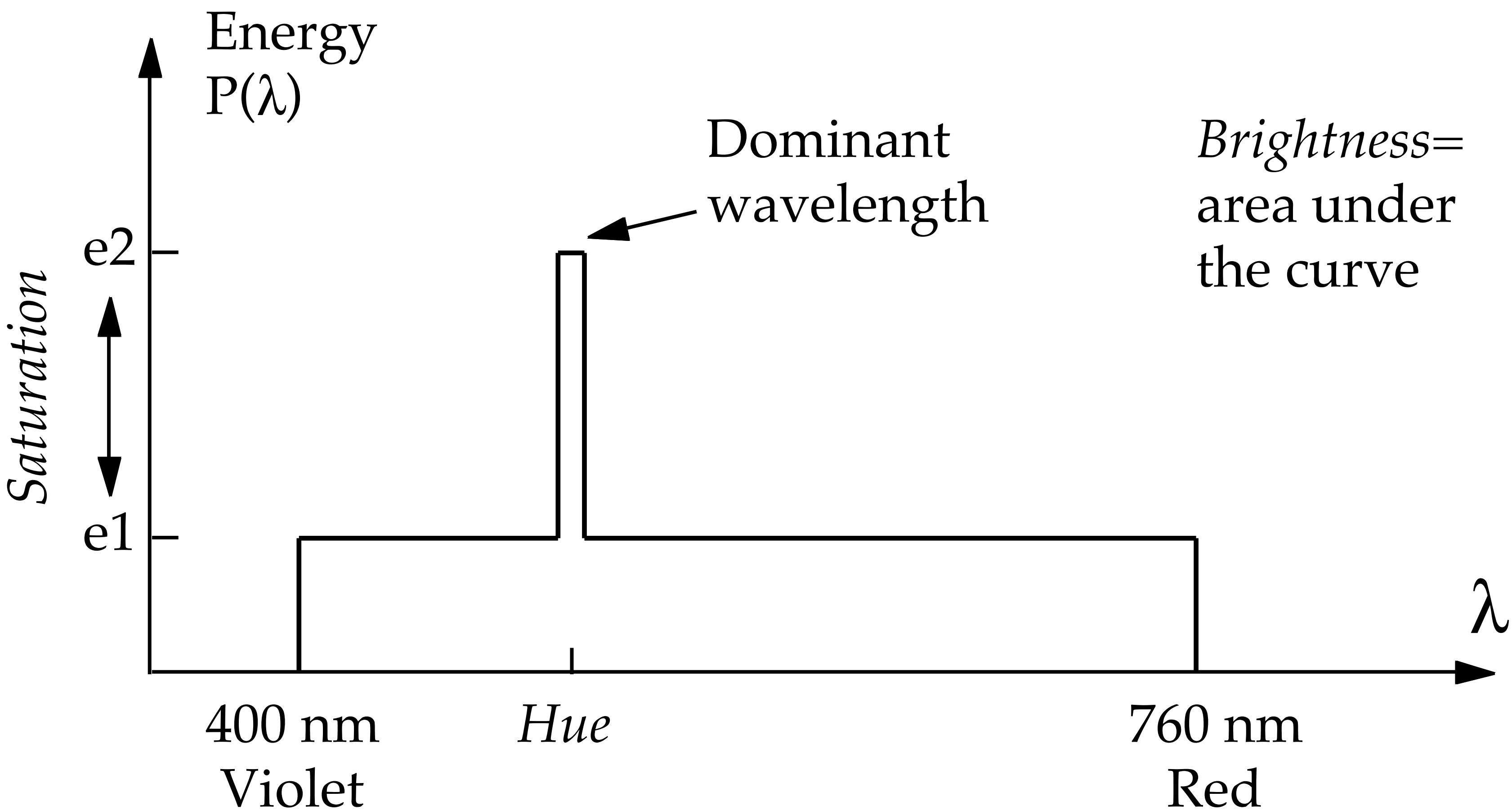
- Initially: artist perception



Colors, shades and hues (2)

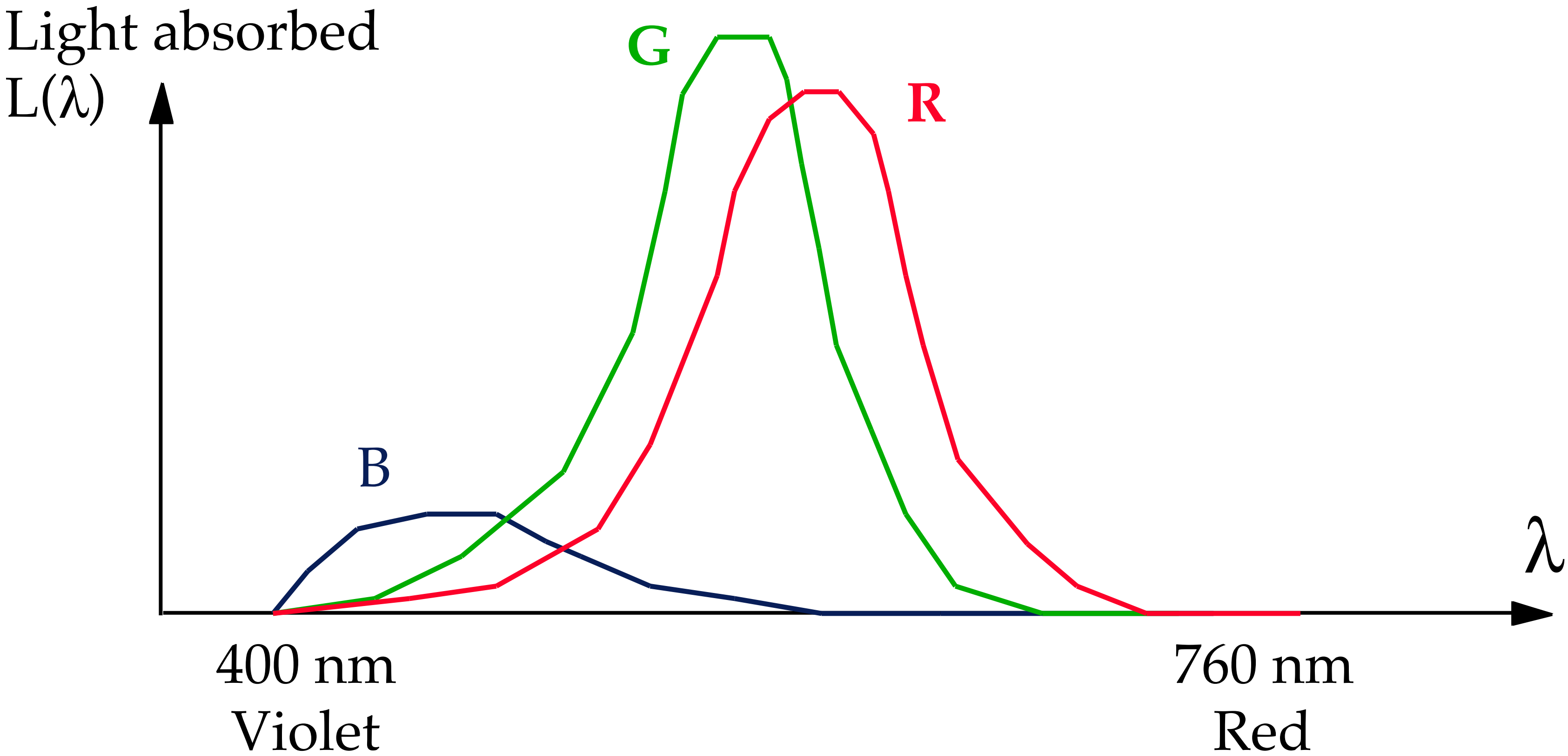
- Physical definition:
  - Hue= dominant wavelength
  - Saturation= excitation purity
  - Luminance, brightness: amount of light
  - Pure color: one single wavelength

Hue, Saturation and Brightness

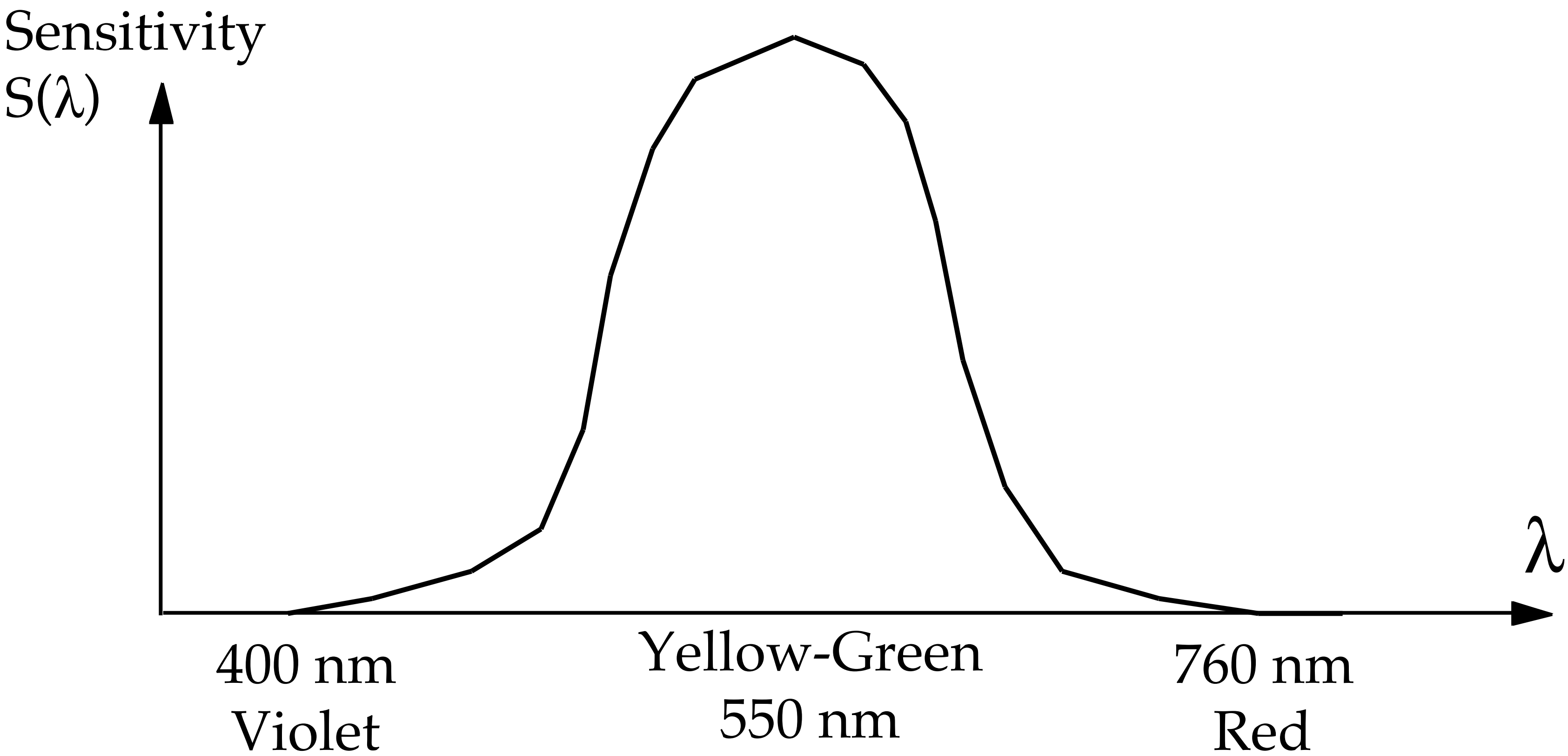


Retina Response

- Three types of cones on the retina:



Retina Luminous Efficiency

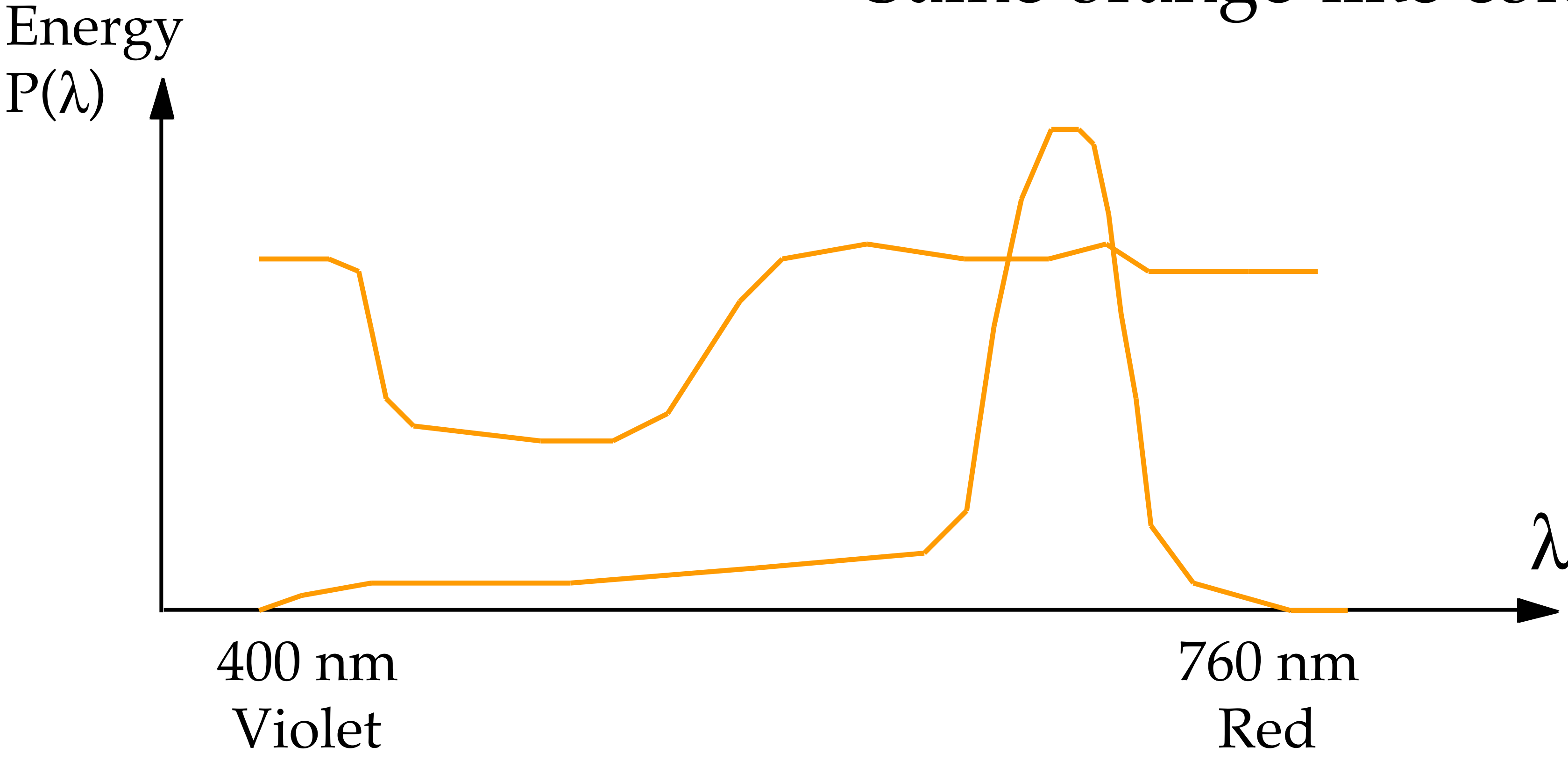


Color Definition

- Define a color by its spectral distribution:
  - memory requirements…
  - non unicity (see next slide)
- Need for simpler bases:
  - describing all colors
  - with a unique set of coordinates

Non Unicity

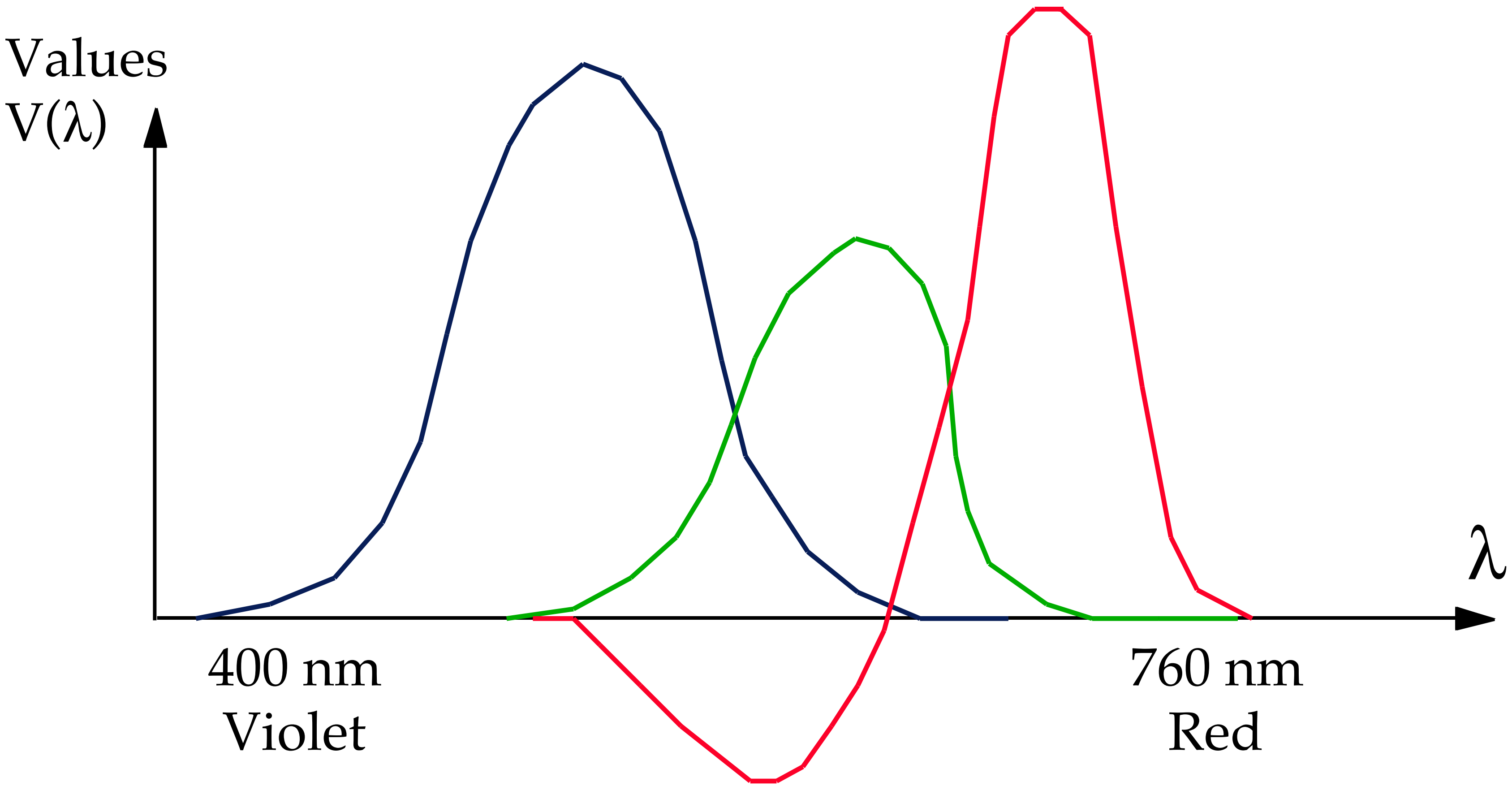
Same orange-like color



Using Primary Colors

- Use the three primary colors:
  - Red, Green and Blue
- Describe all colors as a linear combination of red, green and blue
  - three coordinates by color
- Simple model, but…

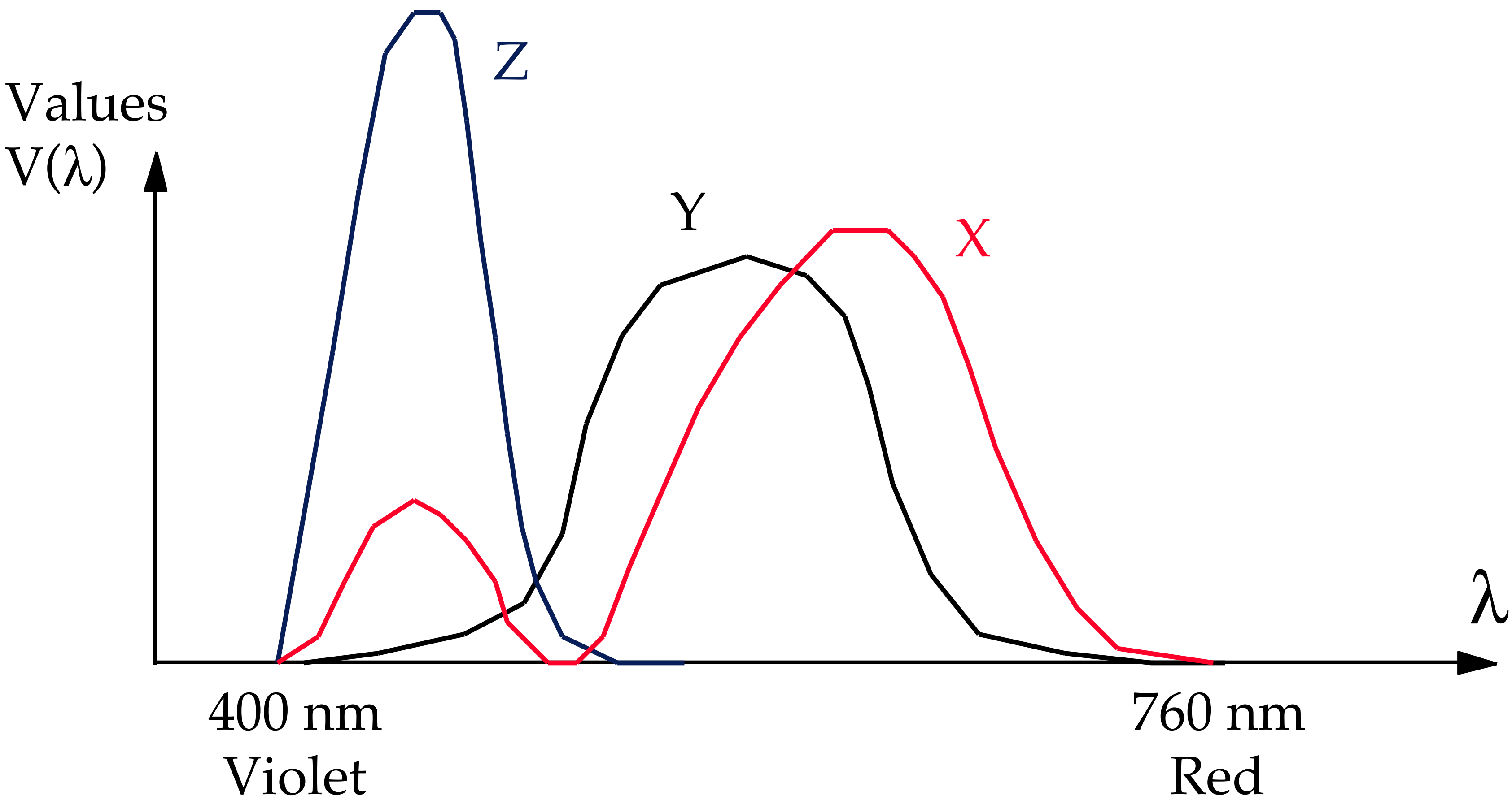
Using Primary Colors (2)



Commission Internationale de l'Éclairage

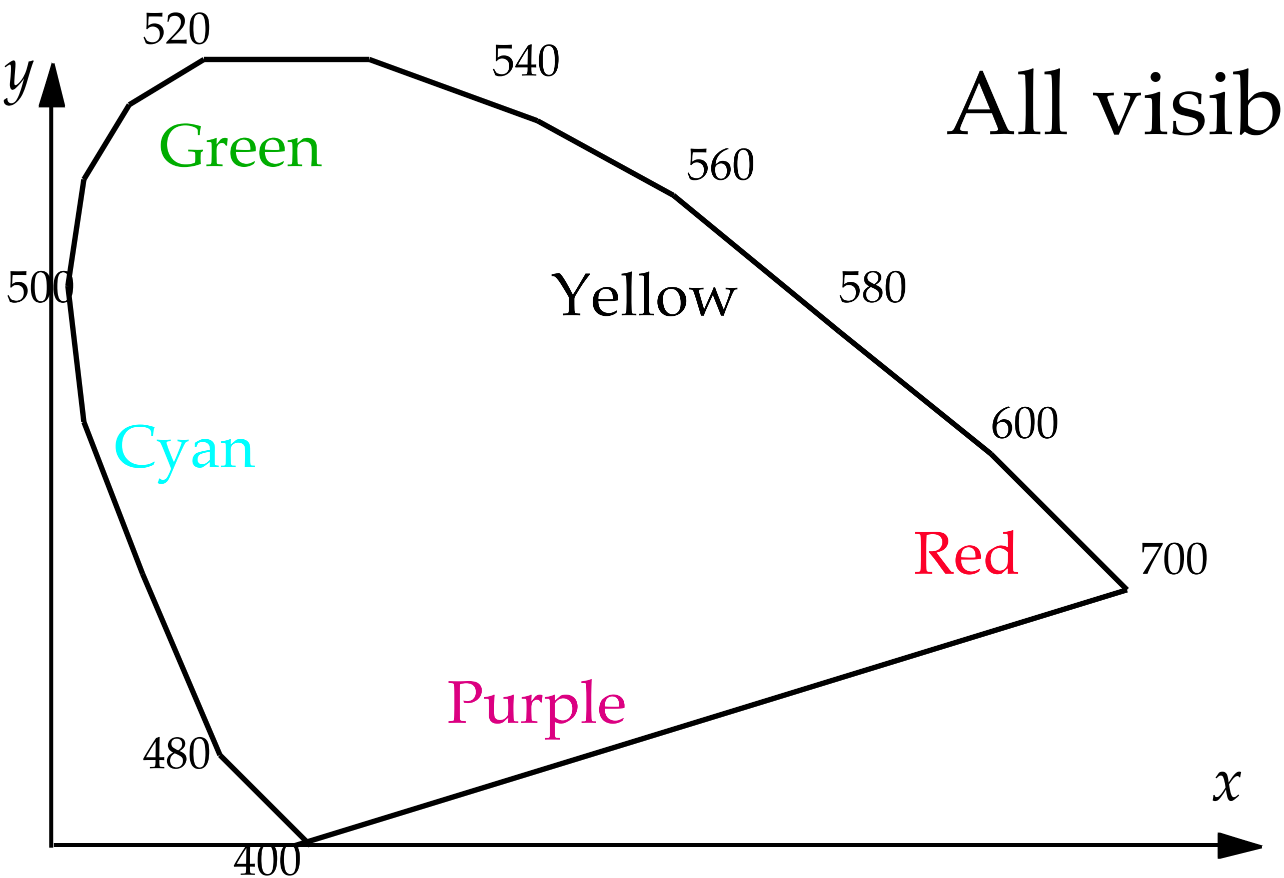
- CIÉ: 1931
- Three standard primary functions:
  - X, Y, Z
  - defines all visible colors
  - with only *positive* coefficients
- Y = retina luminance perception
- x and y = chromaticity

CIÉ Base Functions

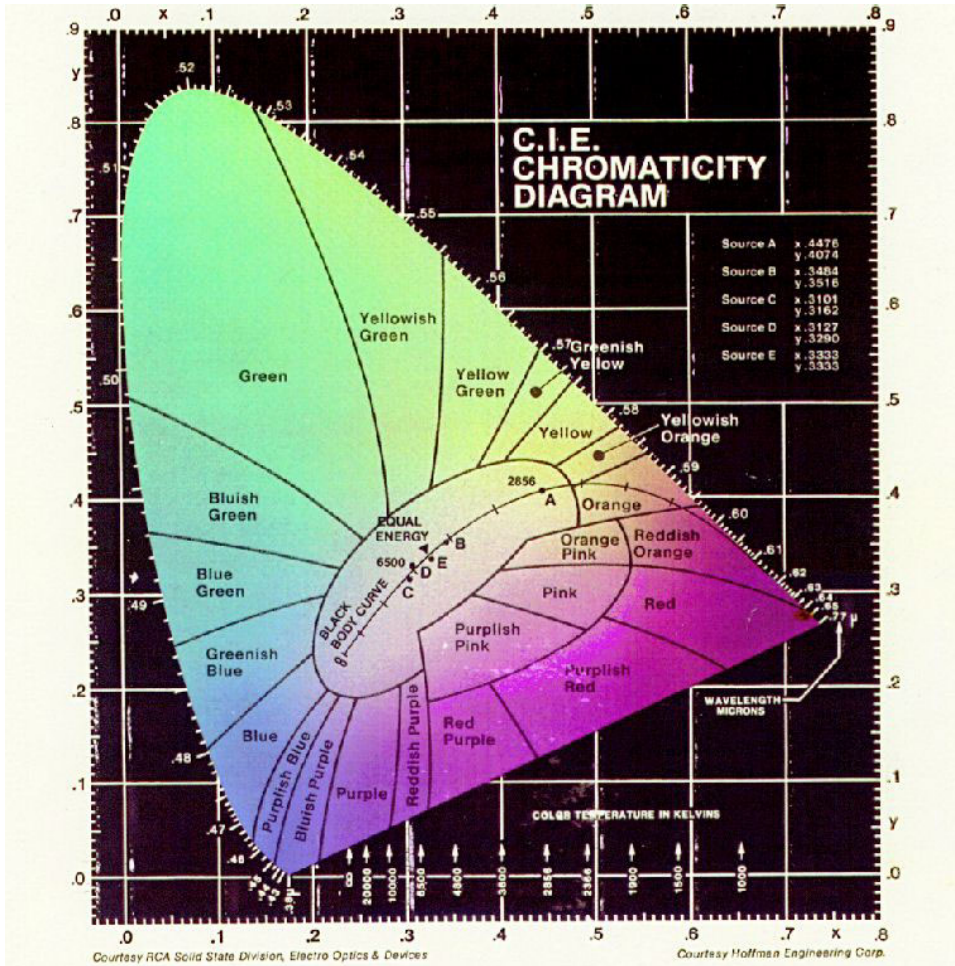


CIÉ Chromaticity Diagram

All visible colors

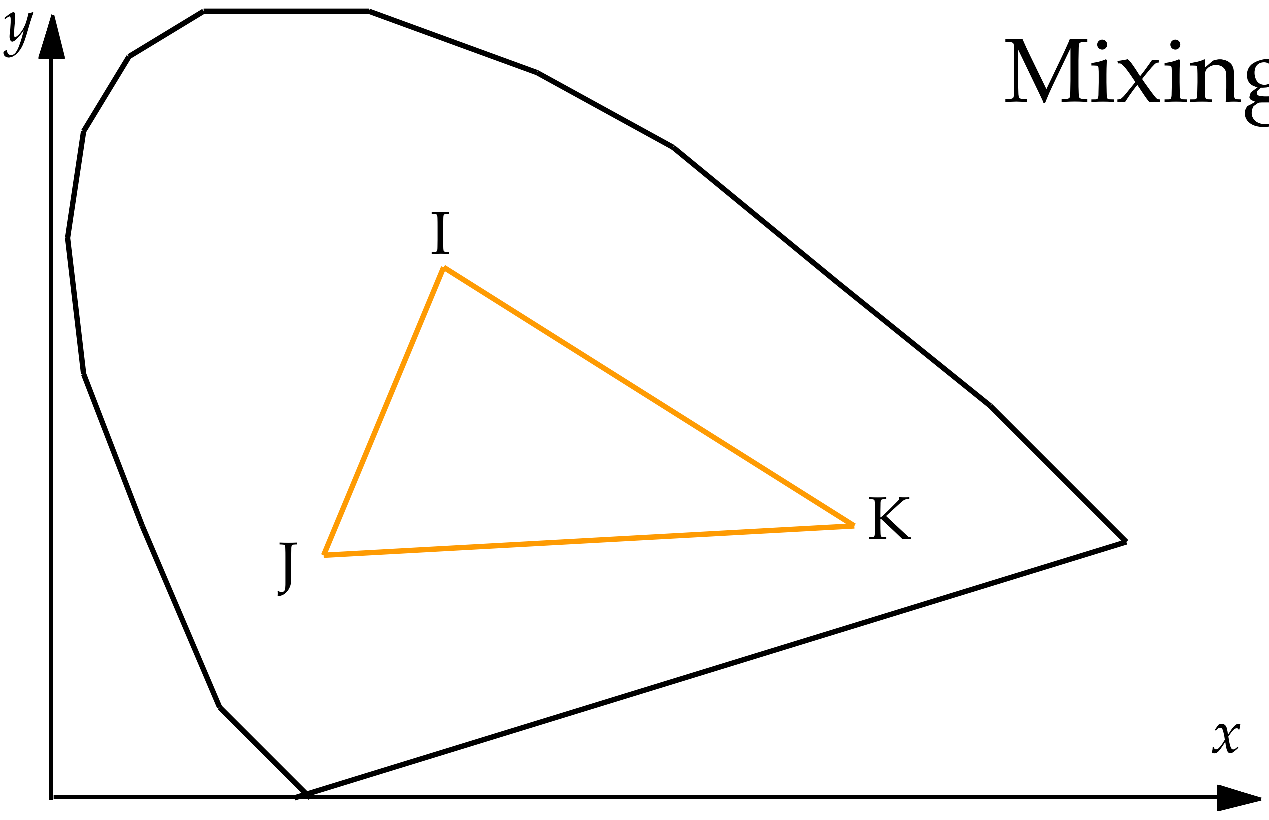


CIÉ Chromaticity Diagram (2)

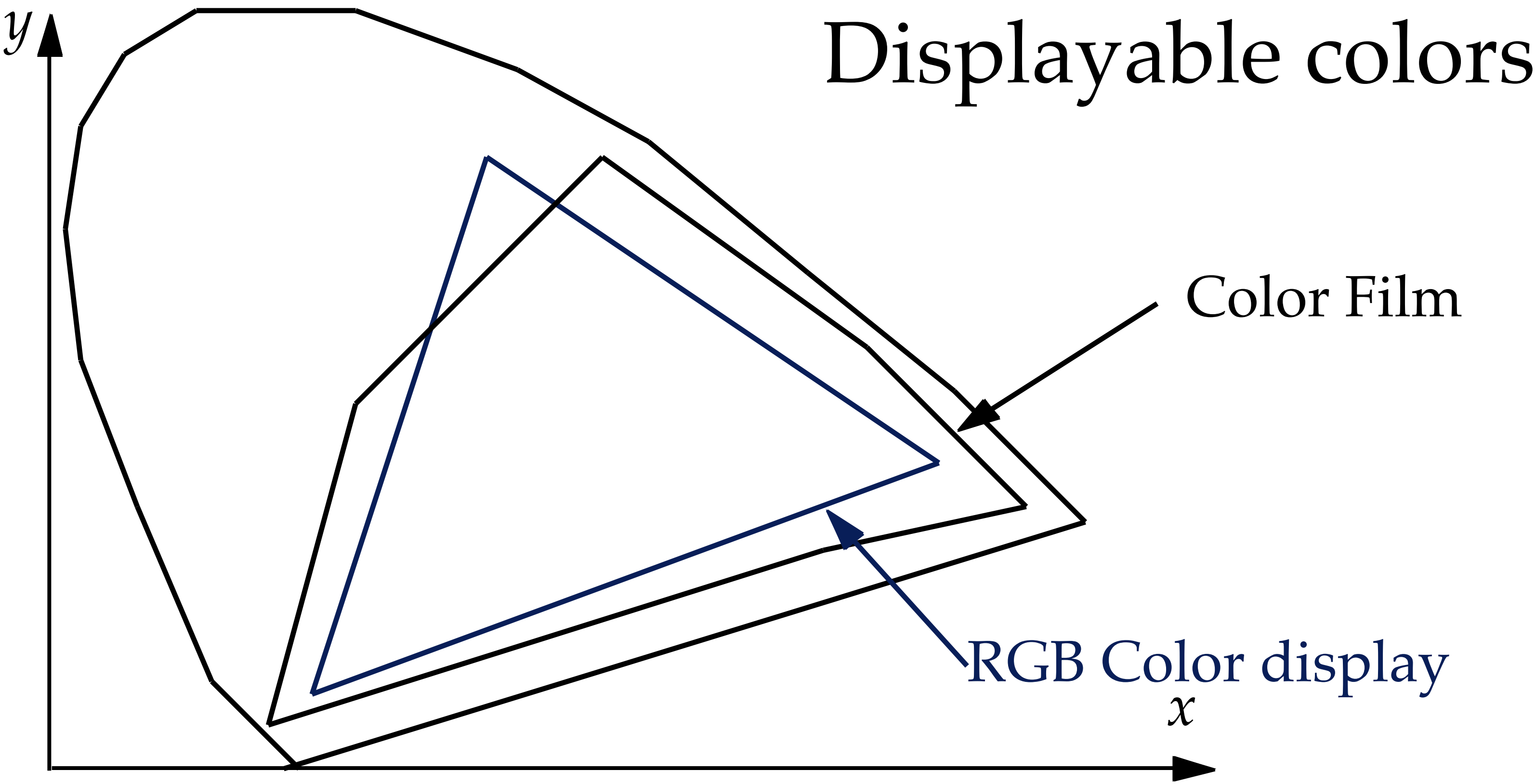


CIÉ Chromaticity Diagram (3)

Mixing colors



CIÉ Chromaticity Diagram (4)



Beyond CIÉ 1931…

- Distance in chromaticity diagram:
  - – not linked to perceptual distance
- CIÉ 1976: perceptually uniform
- LUV:
  - – L for lightness
  - – U and V for chromaticity
- L*a*b: perceptually uniform *and* orthogonal

Colors in computer graphics

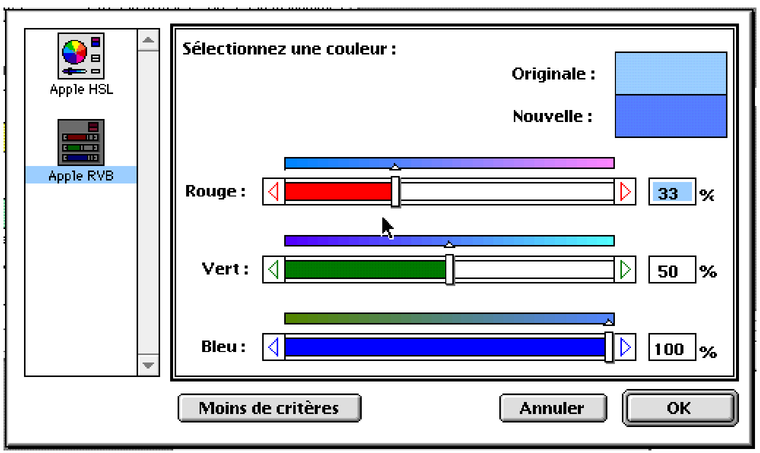
- How to specify a color?
  - set of coordinates in a color space
- Several "Color spaces"
- Color fidelity?
  - why is my orange blue?
- Relation to the task/perception
  - blue for hot water

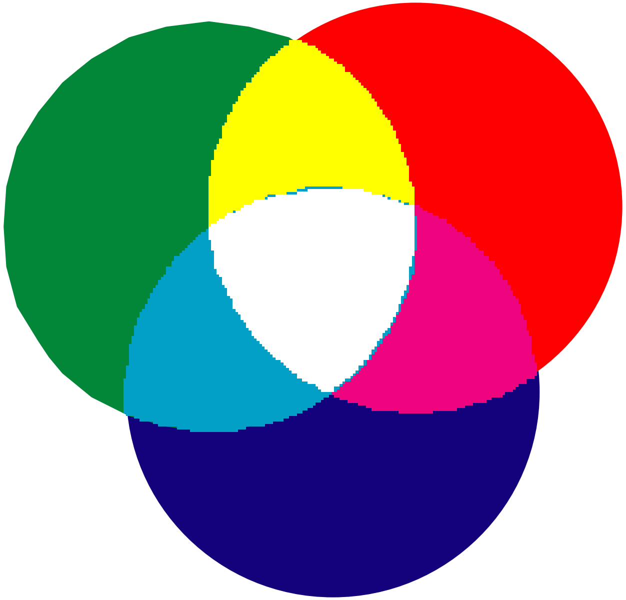
Color spaces

- Device based color spaces:
  - color spaces based on the internal of the device: RGB, CMYK, YCbCr
- Perception based color spaces:
  - color spaces made for interaction: HSV
- Conversion between them?
- Conversion to device independant?

Red-Green-Blue

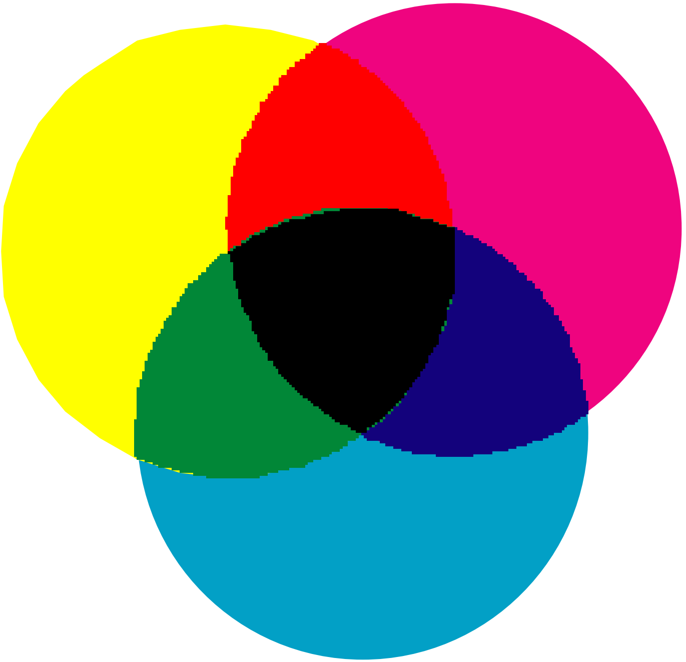
- Most commonly known color space
  - used (internally) in every monitor
  - additive





Cyan-Magenta-Yellow

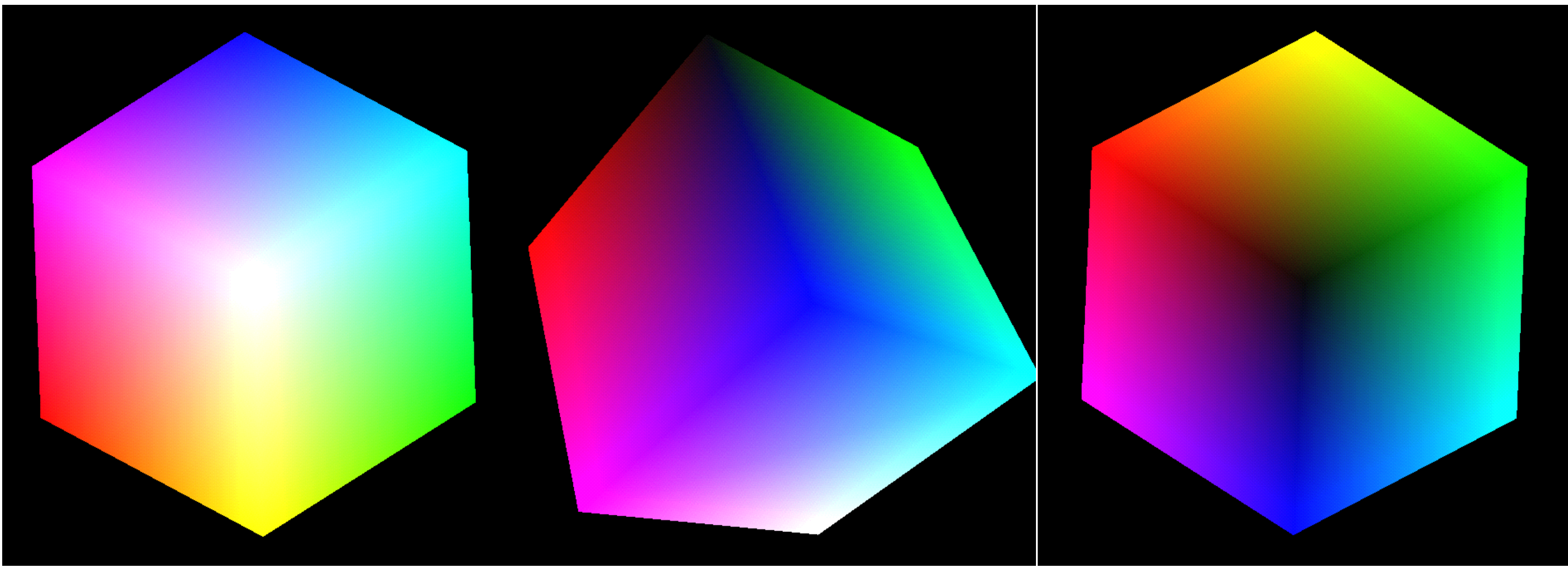
- Used internally in color printers
- Substractive
- Complementary to RGB:
  - C=1-R
  - M=1-G
  - Y=1-B
- Also CMYK (blacK)
  - mostly for printer use



CMYK

- K is for blacK
- Save on color inks, by using black ink preferably
- $K = \min(C,M,Y)$
- $C = C-K$
- $M = M-K$
- $Y = Y-K$

The RGB/CMY cube



The RGB / CMY cube

"Class Y" Color space

- YIQ, YUV, YcbCr…
- Used in television sets and videos
  - Y is luminance
  - I and Q is chromaticity
- BW television sets display only Y
- Color TV sets convert to RGB
- YUV=PAL, YIQ=NTSC

YCbCr Color Spaces

- Y must be equal to luminance:

  $Y = \mathit{LumaRed} * R + \mathit{LumaGreen} * G + \mathit{LumaBlue} * B$

- Cb is blue chromaticity:

  $Cb = (B-Y)/(2-2 * \mathit{LumaBlue})$

- Cr is red chromaticity:

  $Cr = (R-Y)/(2-2 * \mathit{LumaRed})$

- *LumaRed, LumaGreen, LumaBlue* values given by measurements

Class Y values

- Values depend on standard:
  - CCIR 601: Lr=0.299, Lg=0.587, Lb=0.114
  - CCIR 709: Lr=0.2125, Lg=0?7154, Lb=0.0721
- YIQ color space:

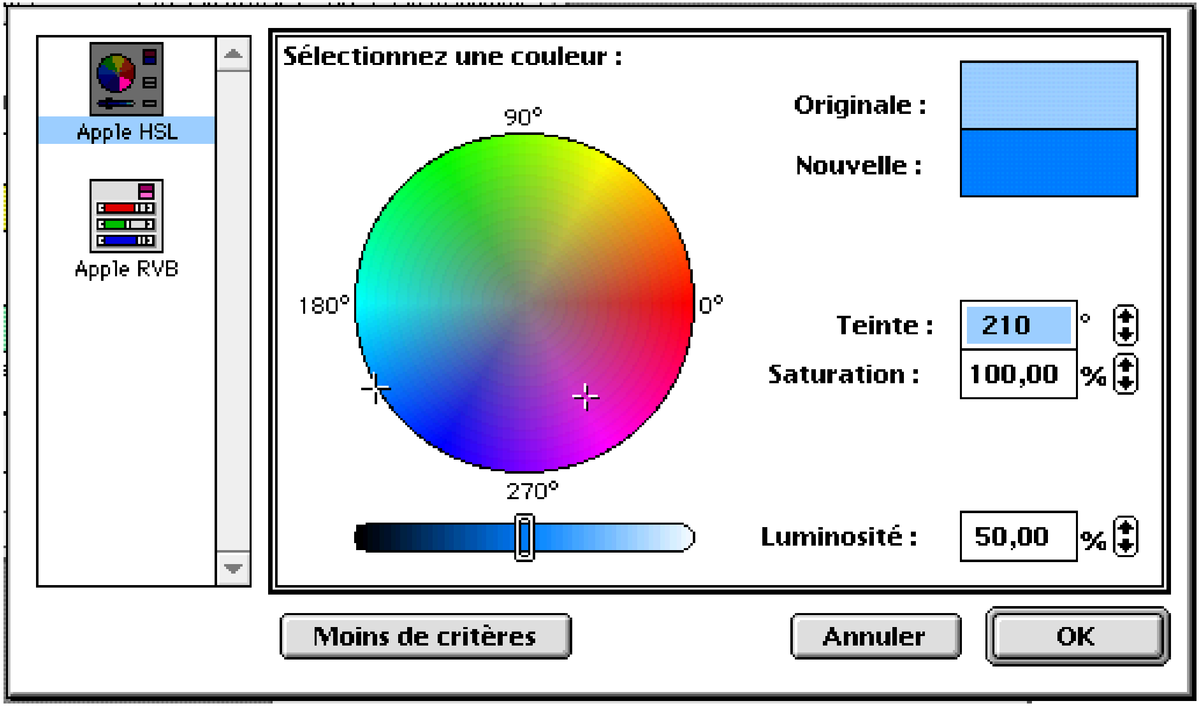
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Interests of “Class Y”

- Sometimes you have to use it
  - video input/output
- Makes sense in image compression:
  - better compression ratio if changing class Y before compression
  - High bandwidth for Y
  - Small bandwidth for chromaticity
  - Lab is fine for that too

Hue-Saturation-Value

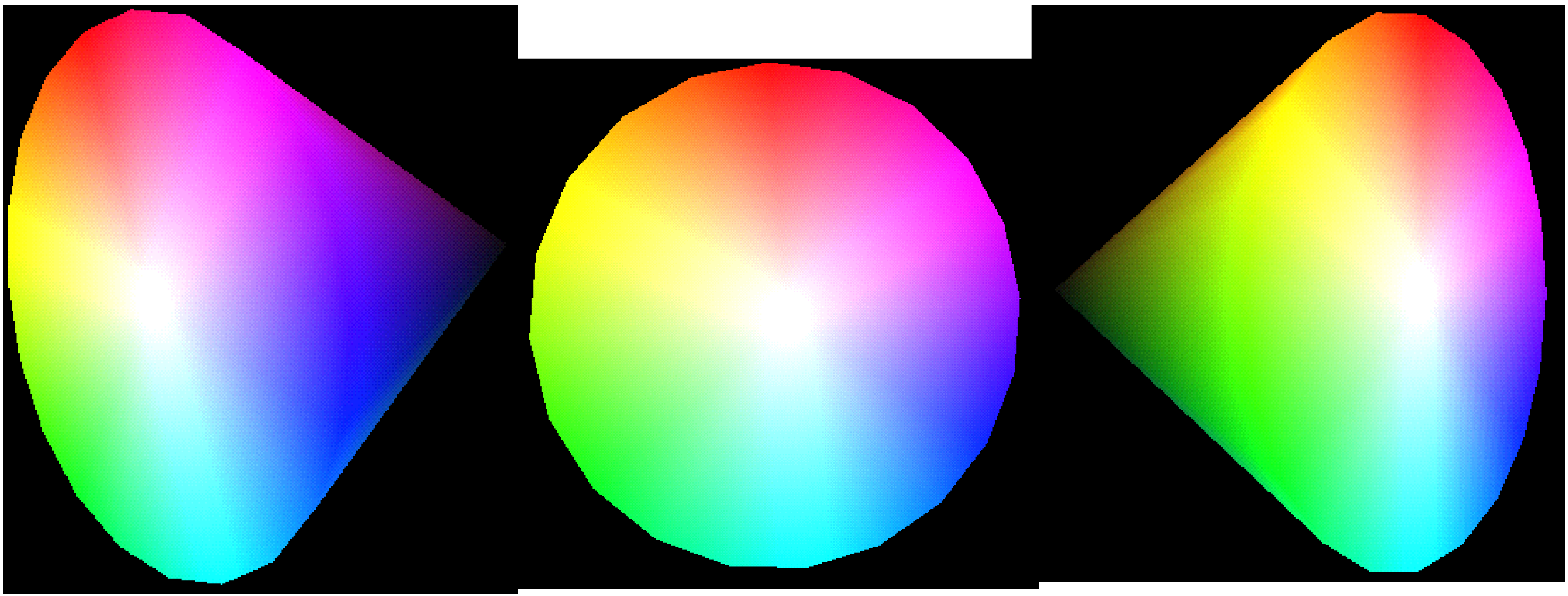
- Nice for user interface:



Hue-Saturation-Value

- V=max(r,g,b)
- S=(max-min)/max
- H=…
- Excellent for interpolations
- Color effects for visualization:
  - change saturation, at constant hue
  - change hue, at constant saturation (maps)

The HSV cone



The HSV cone

Color Fidelity

- Problem: ensure that colors look the same when changing device
- Sample the RGB phosphors
- Convert to XYZ:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} Xr & Xg & Xb \\ Yr & Yg & Yb \\ Zr & Zg & Zb \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color Fidelity (2)

- Device description available from manufacturers
- Extract *Xr*, *Xg*, *Xb*,…
- For other devices: multi-dimensional lookup-tables
- Convert to and from device independant

Intensity Perception

- Human perception is logarithmic
- Cause for Mach-Banding
- perceptual “just noticeable differences”

$$I(j) \propto r^j$$

Gamma Correction

- Human perception is logarithmic:

$$I(j) \alpha\, r^{j}$$

- CRT intensity related to voltage:

$$I \alpha V^{\gamma}$$

- Need correction for both: $V=(kr^{j})^{1/\gamma}$

Gamma Correction

- Hardware in Graphics Workstations:
  - Silicon Graphics, HP, some monitors
  - graphics accelerators
- Extremely useful if well used
- Can lead to strange effects if forgotten
  - tranfer of a picture between monitors with different gamma values = oups!

Displaying colors

- Color ability of the display
  - measured in bits:
    - 1 bit=2 levels, 8 bits=256 levels
  - bits per color primitive:
    - 24 bits=256 levels for each of R,G,B
- Depends on the medium:

TV Screen: 30 dpi, 8bits color

Computer Screen: 70-100 dpi, 24 bits color

Laser Printer: 300-2400 dpi, 3 bits color (8 colors)

Photo: 800 dpi, 36 bits color

Gaining color resolution

- Sometimes, this color resolution is not enough
- How to display more colors?
- Basic idea: sacrifice some of the spatial resolution
  - halftoning and dithering

Gaining color resolution

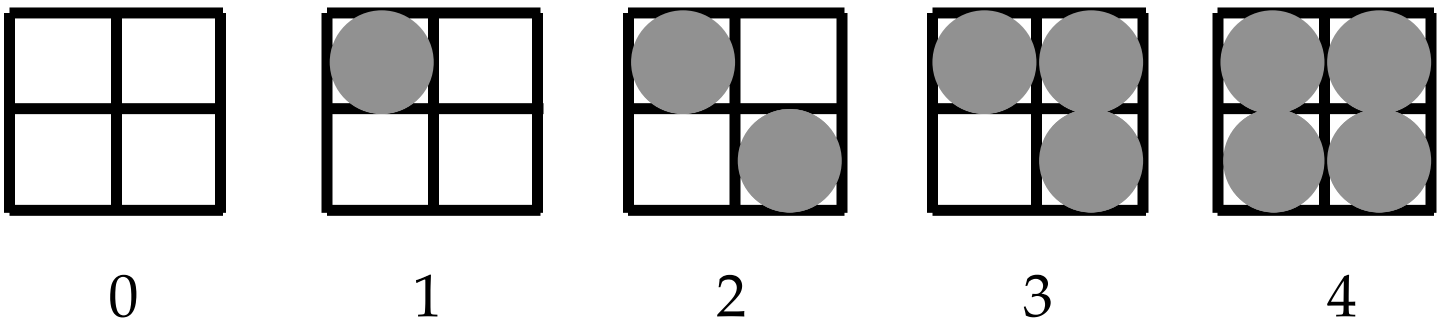
- For top-quality printers:
  - discs of size varying inversely with *I*
  - pattern angle (called *screen angle*)
  - halftone resolution (different from spatial resolution)
    - 60-80 dpi for newspapers, 120-200 for books
- Called “Halftoning”

Simulating halftoning

- If you don't have halftoning
  - wrong printer, or computer screen
- Use dither patterns
  - groups of n*n pixels = n*n+1 intensity levels

Simulating Halftoning (2)

- Example for 2x2:



- Matrix notation: $$\begin{bmatrix} 0 & 2 \\ 3 & 1 \end{bmatrix}$$

Matrix notation

- For level *i*, display pixels with $v<i$
- Requirement on matrix depend on device:
  - dispersed dots for CRT
  - clustered dots for printers

$$\begin{bmatrix} 0 & 8 & 2 & 10 \\ 12 & 4 & 14 & 6 \\ 3 & 11 & 1 & 9 \\ 15 & 7 & 13 & 5 \end{bmatrix}$$

$$\begin{bmatrix} 6 & 8 & 4 \\ 1 & 0 & 3 \\ 5 & 2 & 7 \end{bmatrix}$$

Halftoning: the next step

- One image pixel= 4 or 9 printer pixels
- What if I want one image pixel=one printer pixel?
- Use modulo:
  - i=x modulo n
  - j=y modulo n
  - Lit the pixel if point (i,j) in dithering matrix is smaller than I(x,y)

Halftoning, the next step (2)

- There is an error at each pixel
- Dithering pattern is sometimes visible
- Floyd-Steinberg: spread the error to neighbouring pixels

Conclusion

- Several ways to represent colors
- Each one fitted for a special task
- Easy conversion between them
- Conversion is often required:
  - for color fidelity:
    - convert to CIE, and back to device-space
  - for showing the image