# Color

- Fredo Durand
- Many slides by Victor Ostromoukhov

# *Today: color*

Disclaimer:

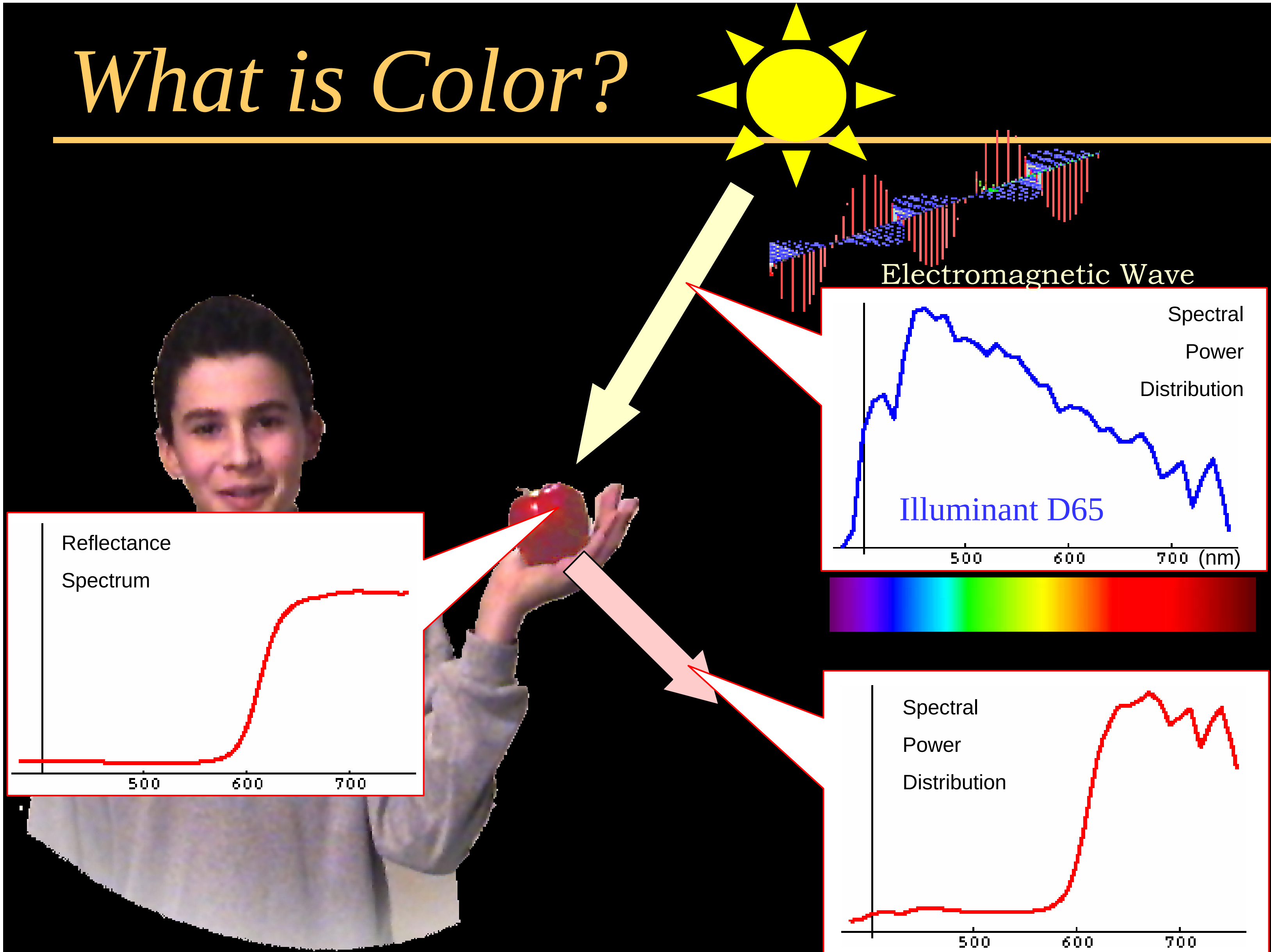
- Color is both quite simple and quite complex
- There are two options to teach color:
  - pretend it all makes sense and it's all simple
  - Expose the complexity and arbitrary choices
- Unfortunately I have chosen the latter
  - Too bad if you believe ignorance is bliss

# *Plan*

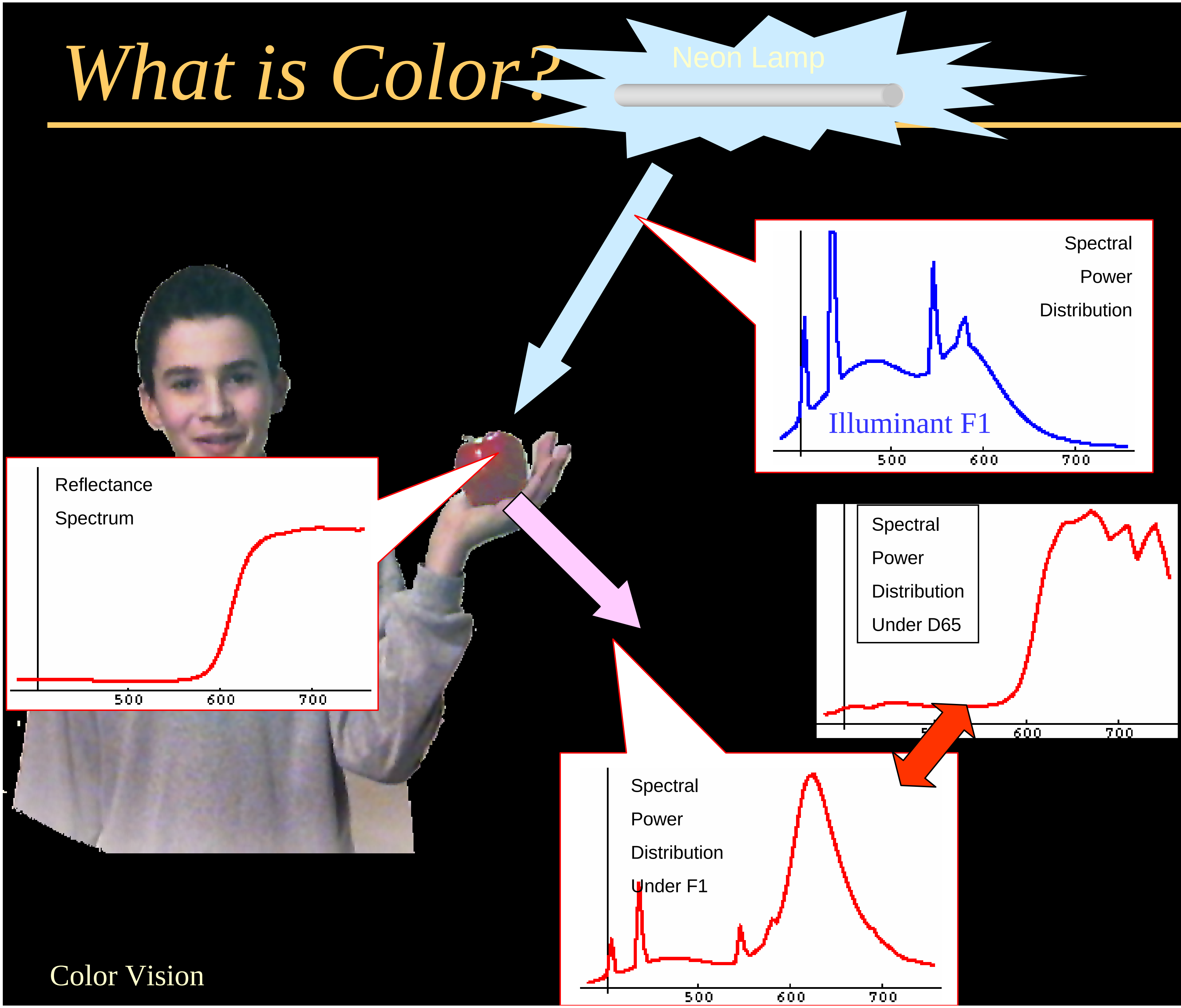
- What is color
- Cones and spectral response
- Color blindness and metamers
- Fundamental difficulty with colors
- Colorimetry and color spaces

- Next time:
  More perception
  Gamma

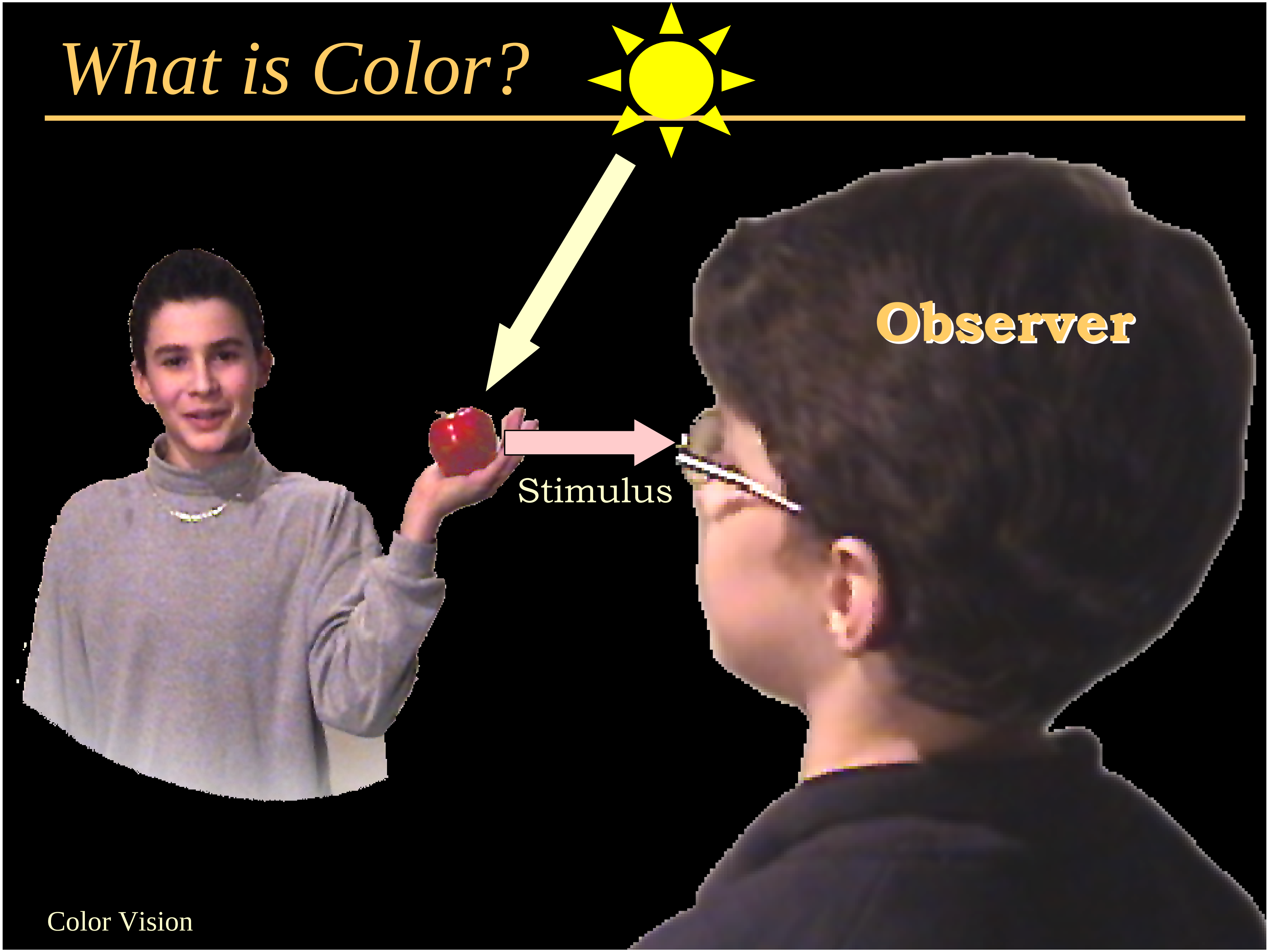
# *What is Color?*



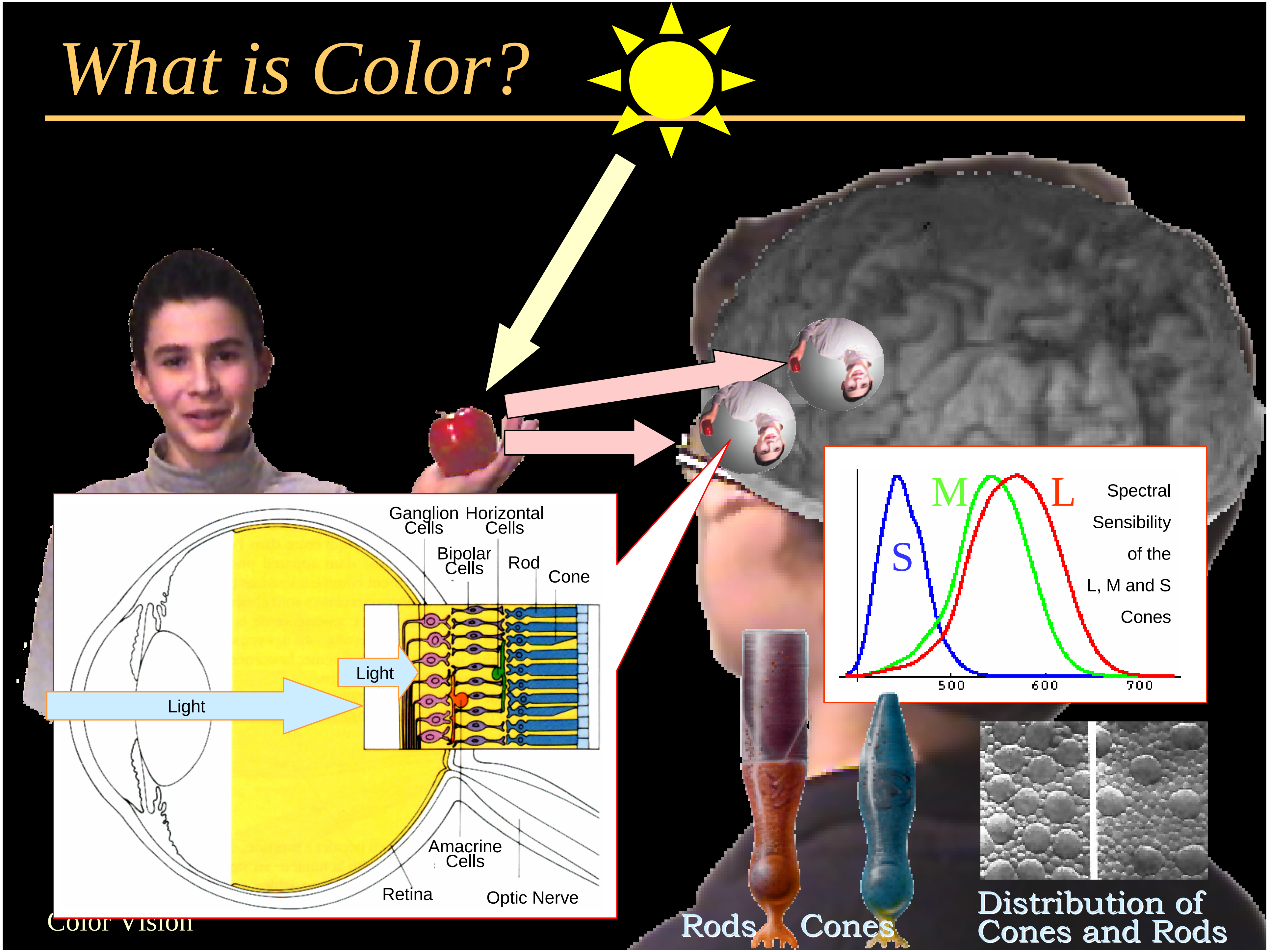
# What is Color?



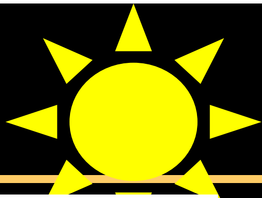
# *What is Color?*



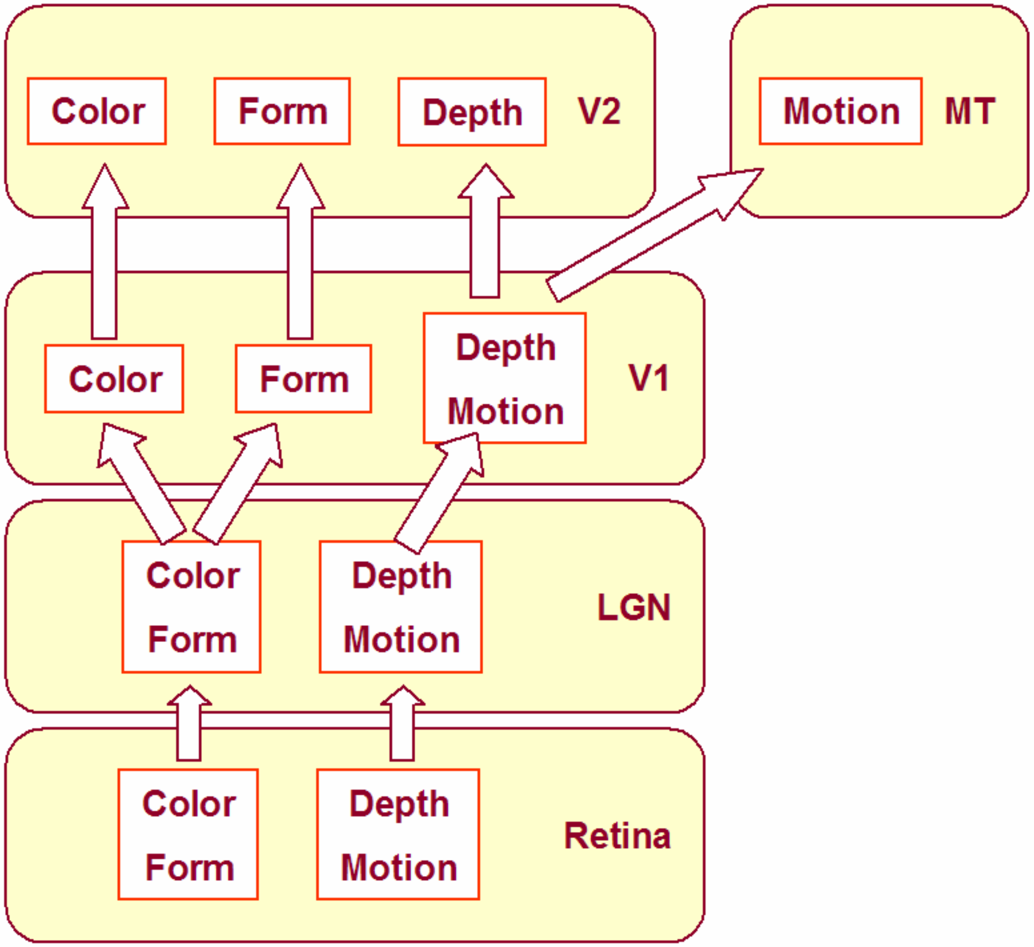
# What is Color?

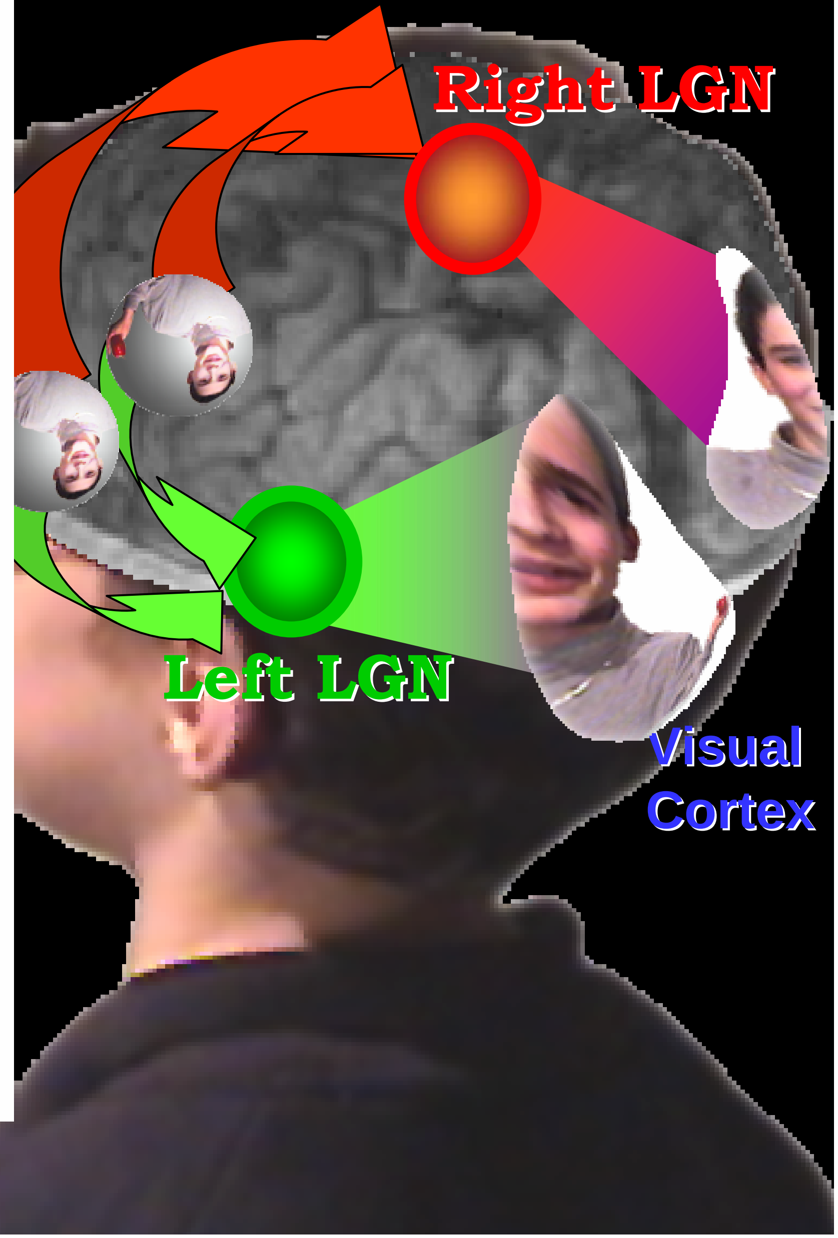


# *What is Color?*



## Visual Pathways [Palmer99]




LGN = Lateral Geniculate Nucleus

# *Questions?*

# *Plan*

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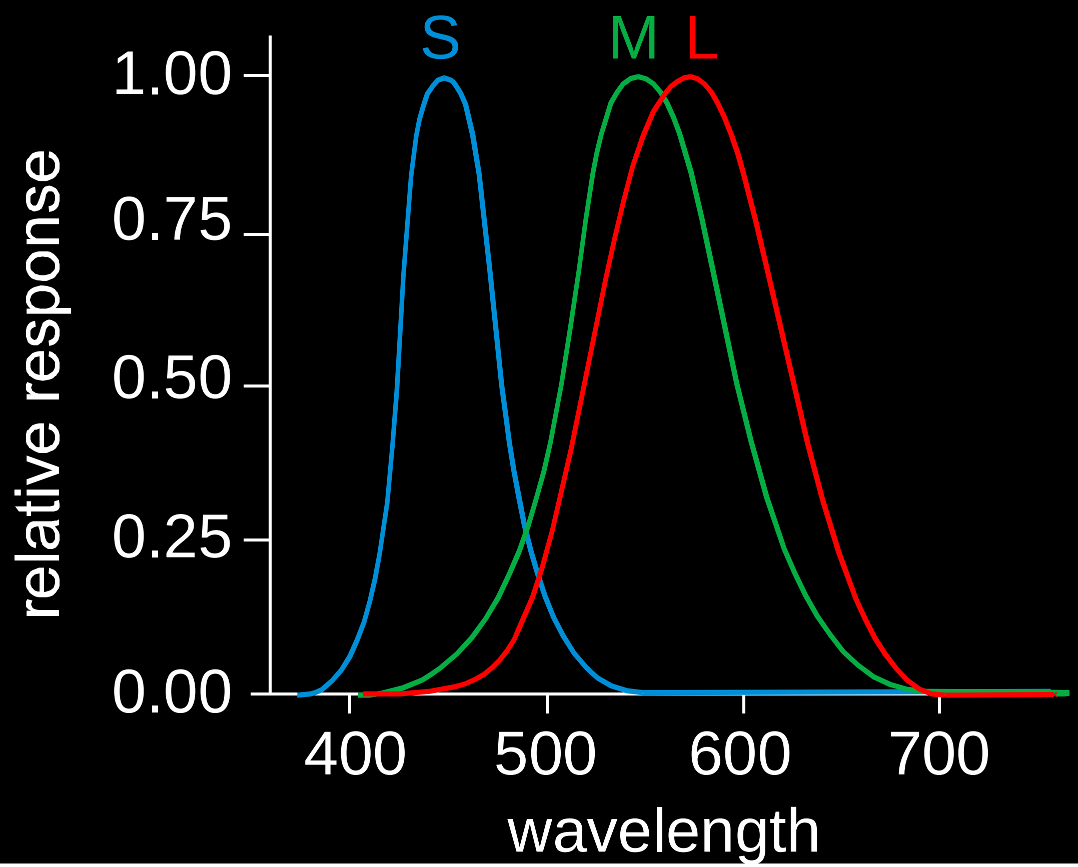
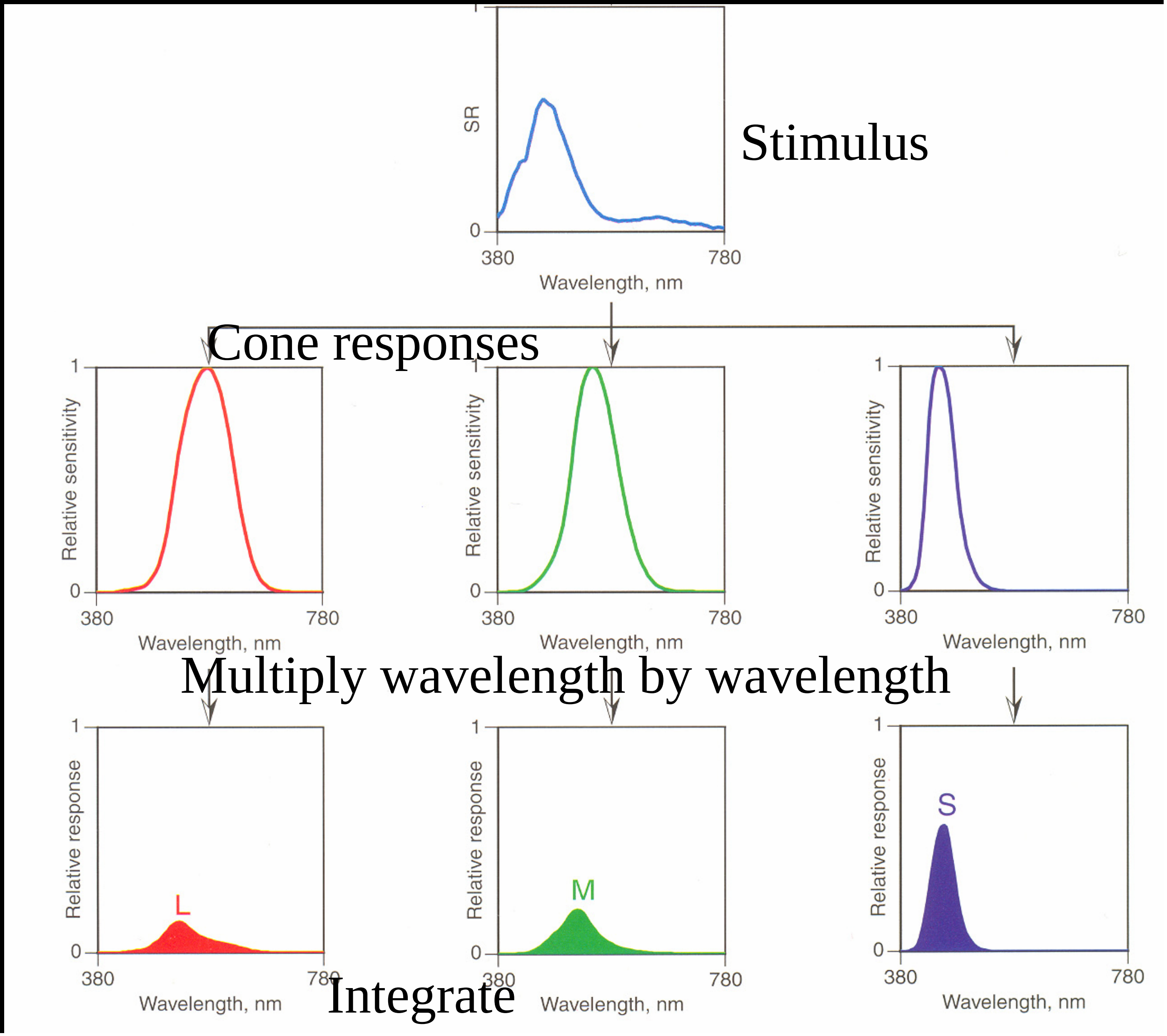
# *Cone spectral sensitivity*

- Short, Medium and Long wavelength
- Response = $\int_{\text{wavelength}} \text{stimulus}(\lambda) * \text{response}(\lambda)\, d\lambda$

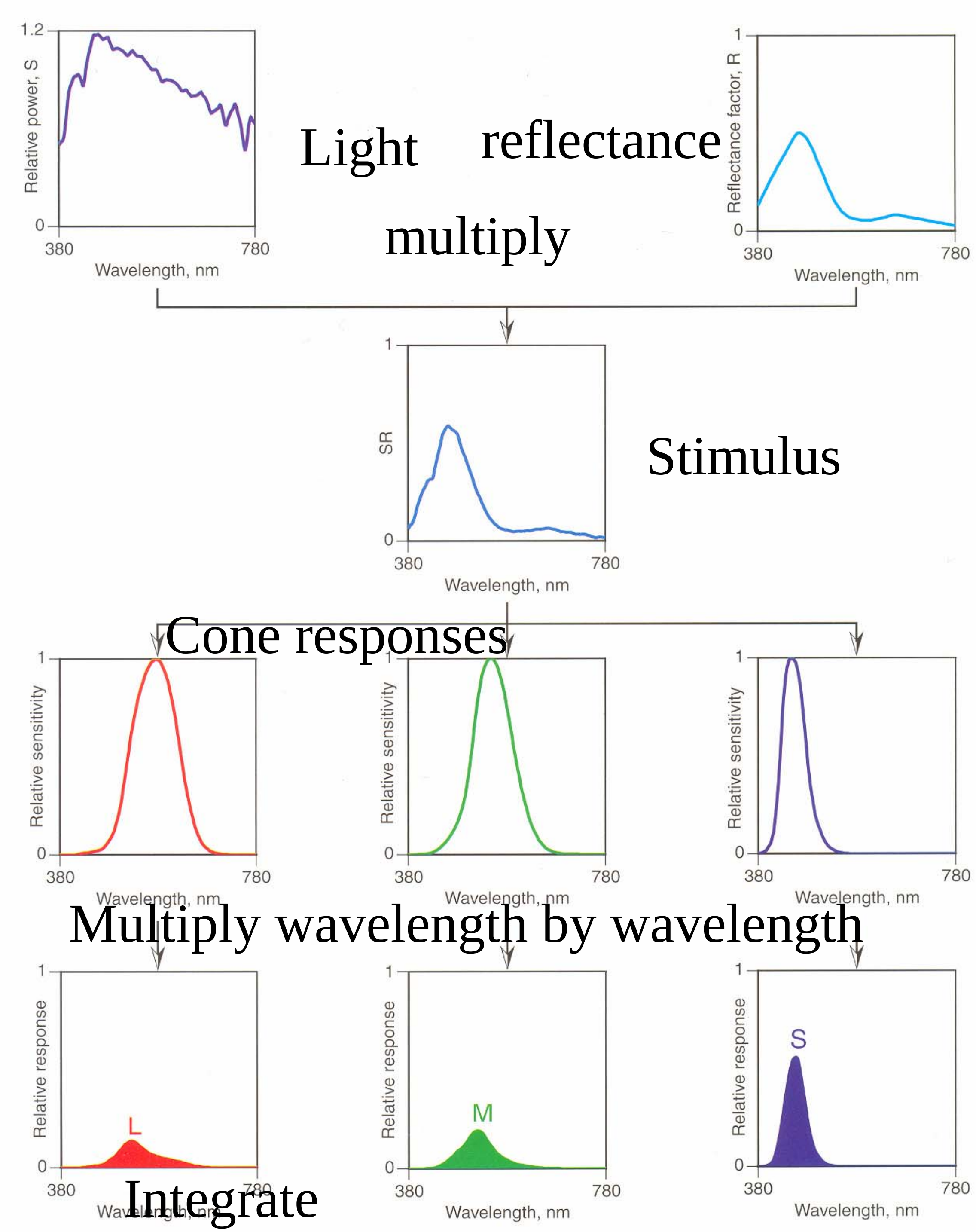


# *Cone response*



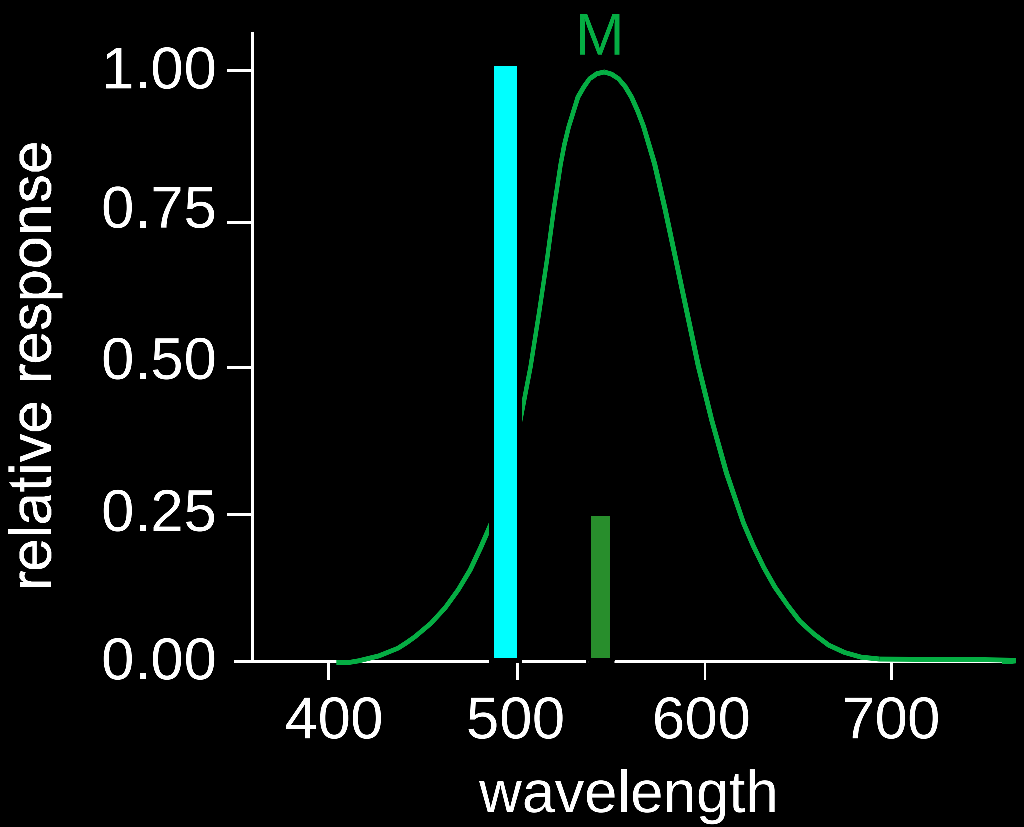
# *Big picture*

- It’s all linear!



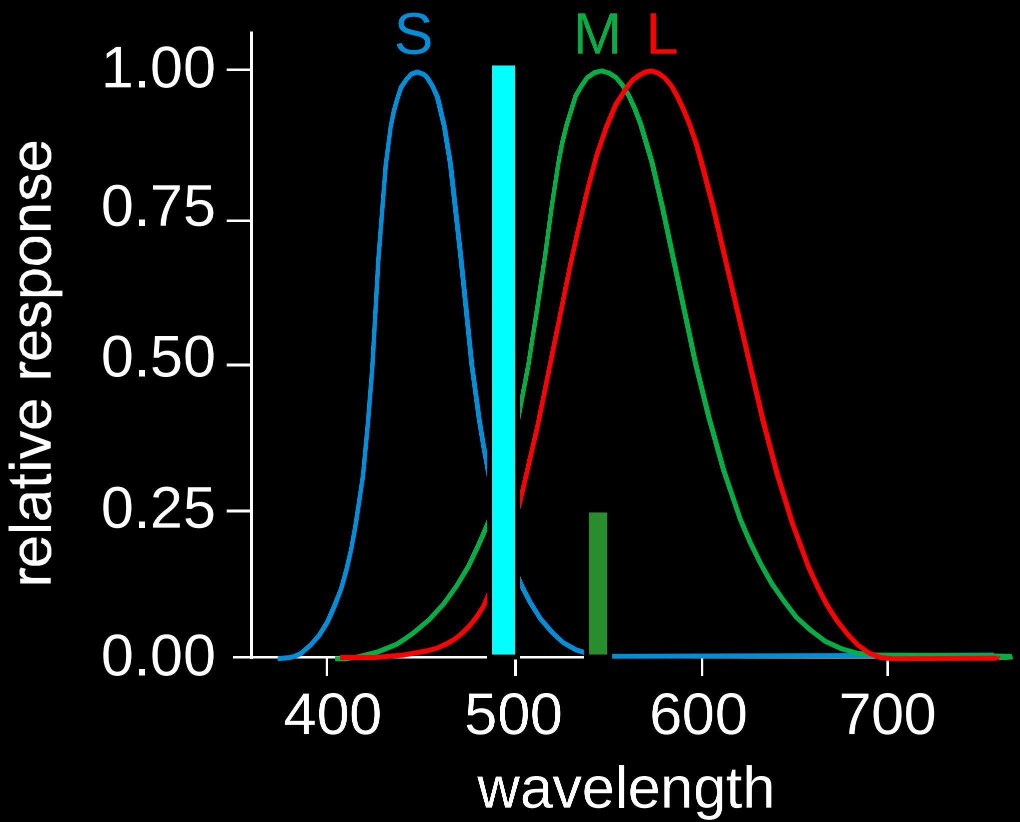
# *Cones do not "see" colors*

- Different wavelength, different intensity
- Same response



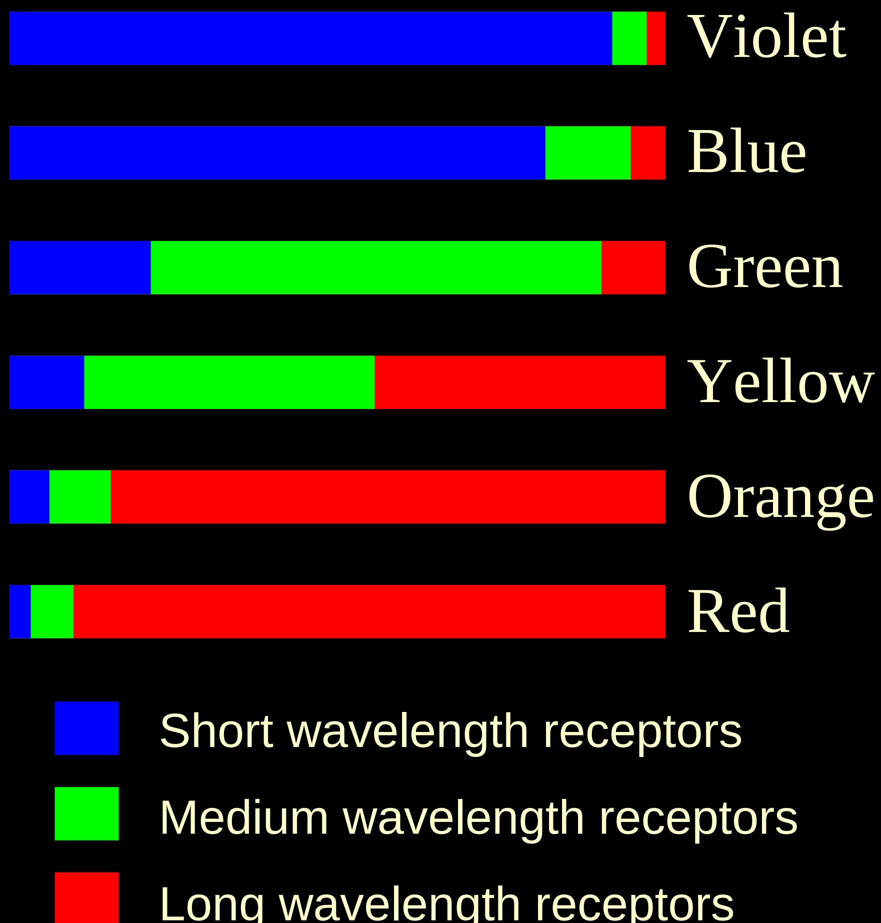
# *Response comparison*

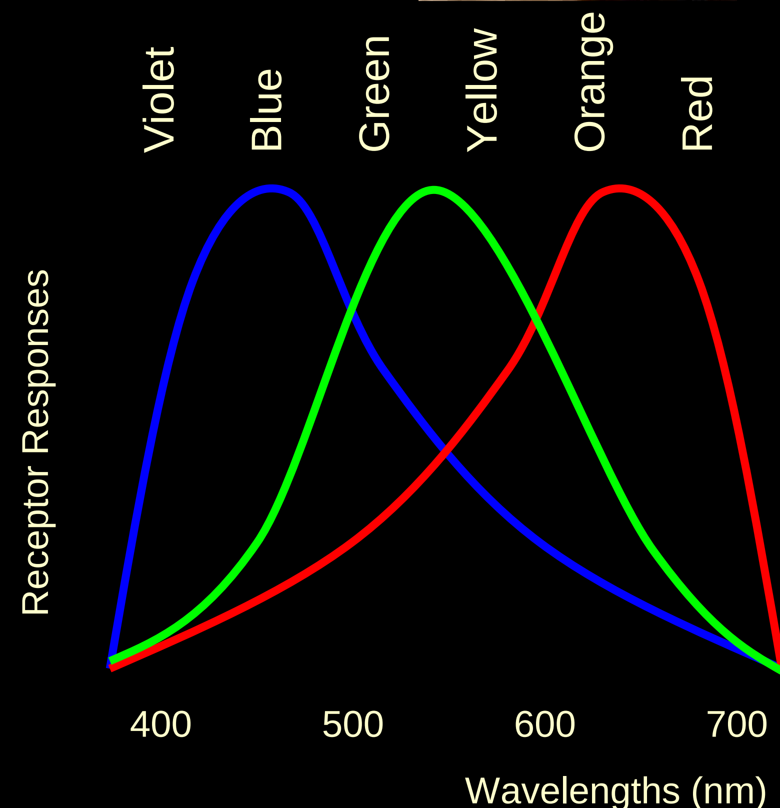
- Different wavelength, different intensity
- But different response for different cones



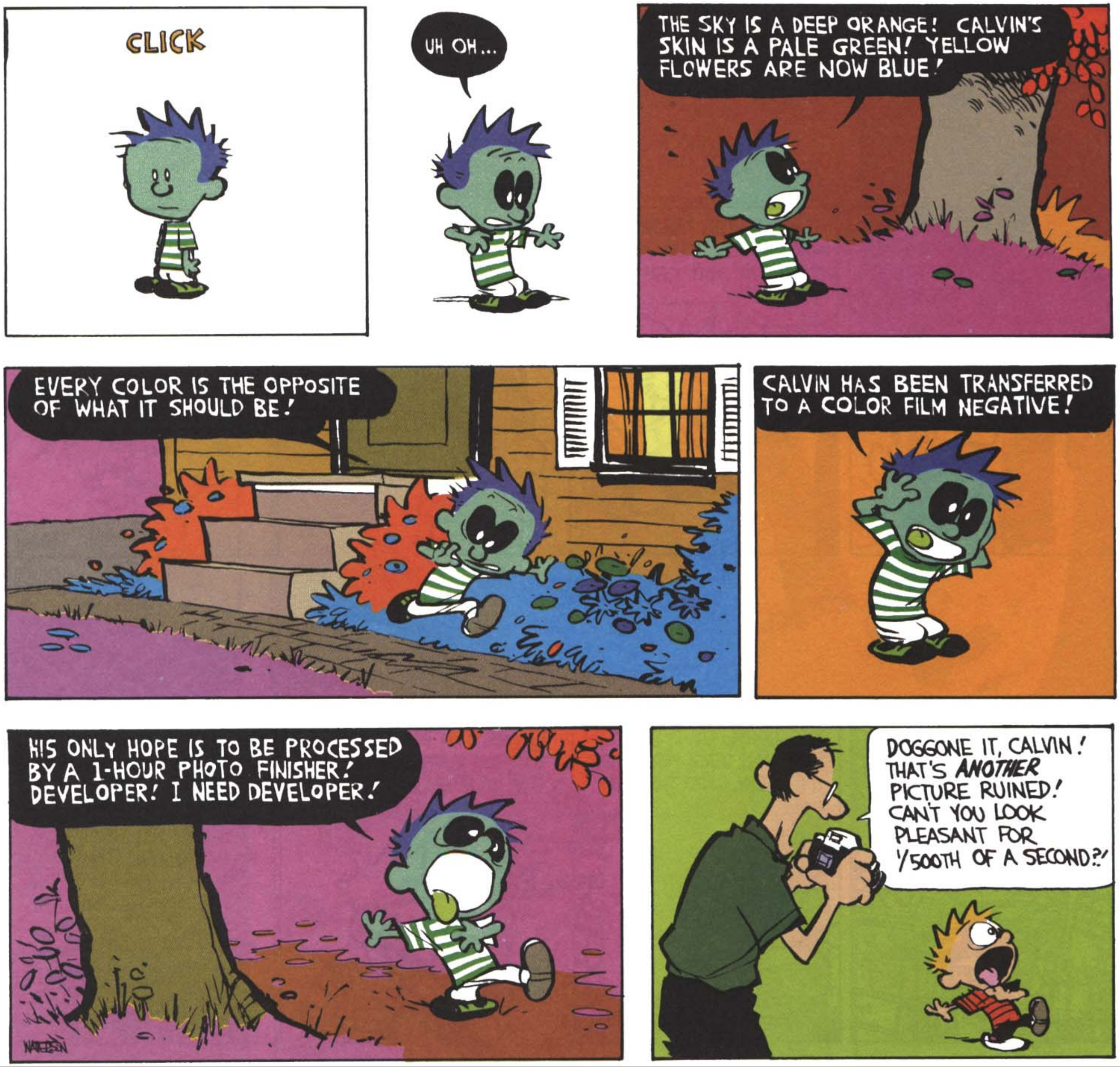
# *von Helmholtz 1859: Trichromatic theory*

- Colors as relative responses (ratios)



# Questions?



CLICK
UH OH...
THE SKY IS A DEEP ORANGE! CALVIN'S SKIN IS A PALE GREEN! YELLOW FLOWERS ARE NOW BLUE!
EVERY COLOR IS THE OPPOSITE OF WHAT IT SHOULD BE!
CALVIN HAS BEEN TRANSFERRED TO A COLOR FILM NEGATIVE!
HIS ONLY HOPE IS TO BE PROCESSED BY A 1-HOUR PHOTO FINISHER! DEVELOPER! I NEED DEVELOPER!
DOGGONE IT, CALVIN! THAT'S ANOTHER PICTURE RUINED! CAN'T YOU LOOK PLEASANT FOR 1/500TH OF A SECOND?!

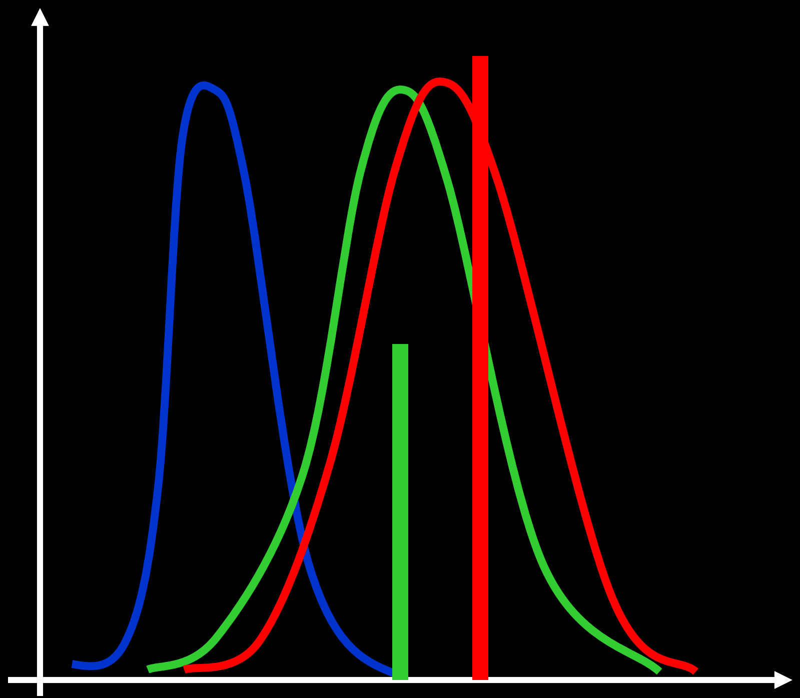
# *Plan*

- What is color
- Cones and spectral response
- Color blindness and metamers
- Fundamental difficulty with colors
- Colorimetry and color spaces

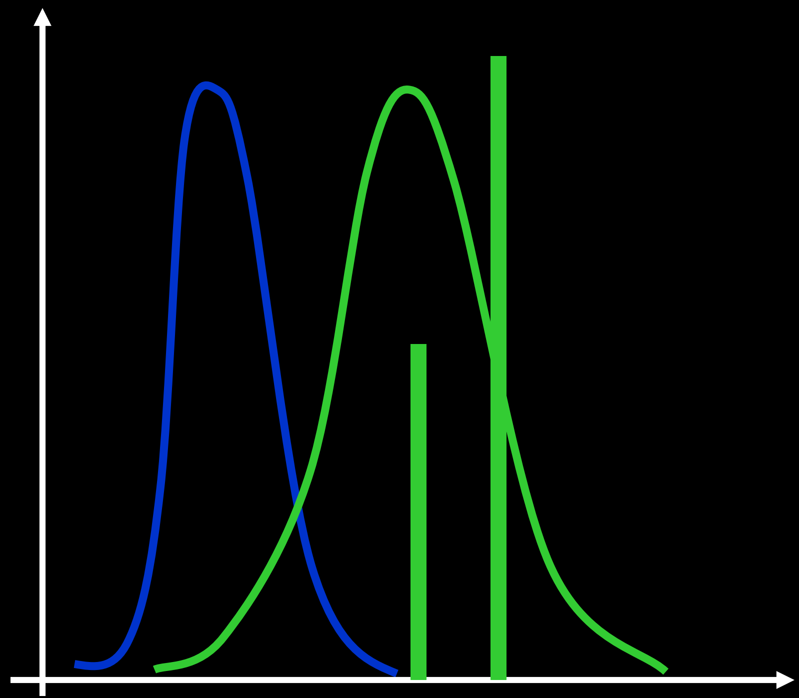
- Next time:
  More perception
  Gamma

# *Color blindness*

- Classical case: 1 type of cone is missing (e.g. red)
- Now Project onto lower-dim space (2D)
- Makes it impossible to distinguish some spectra



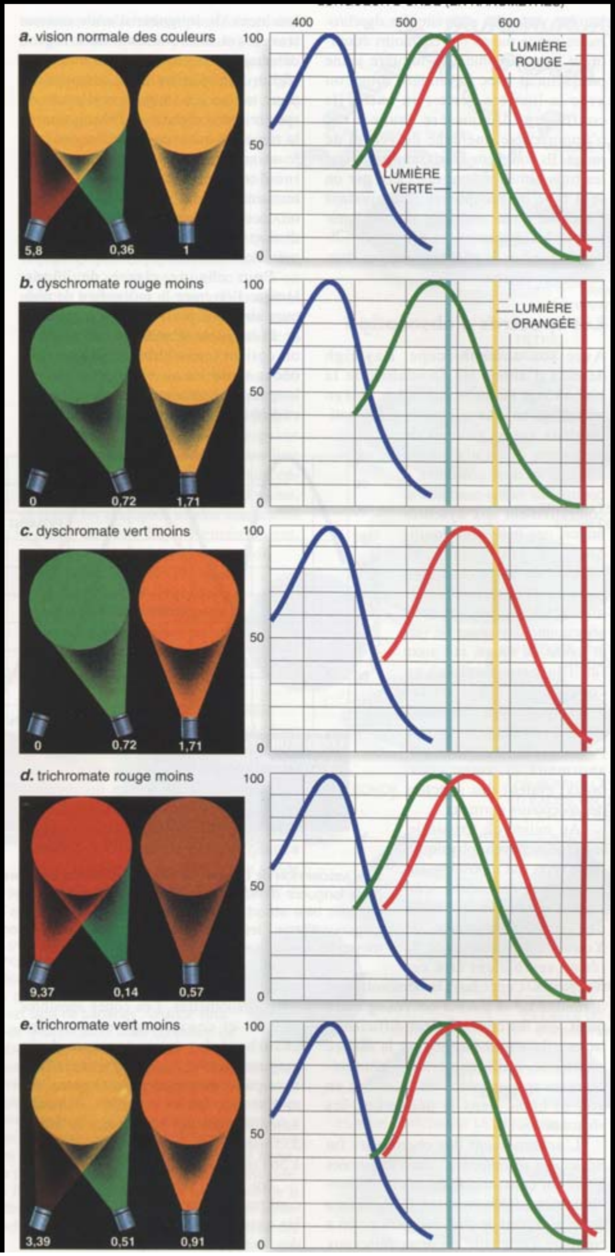
differentiated



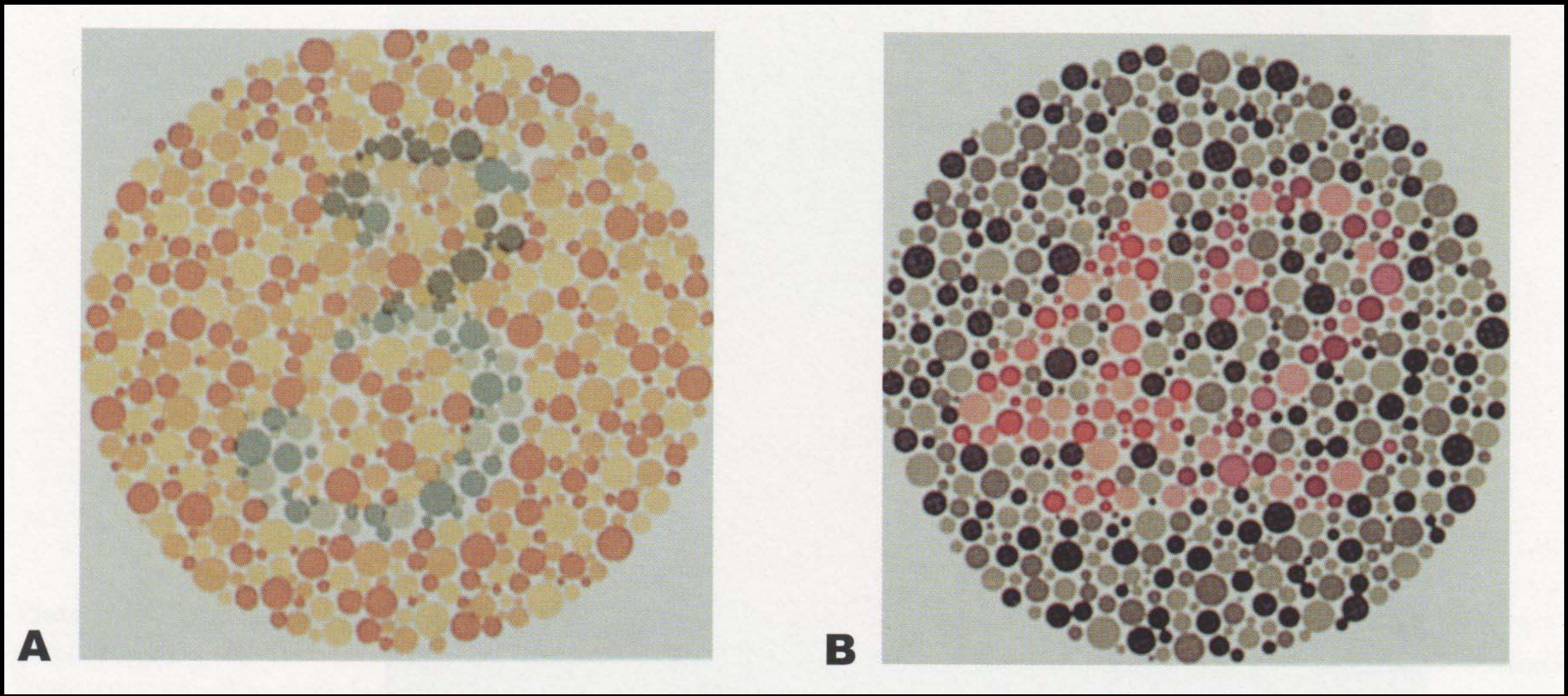
Same responses

# *Color blindness – more general*

- Dalton
- 8% male, 0.6% female
- Genetic
- Dichromate (2% male)
  - One type of cone missing
  - L (protanope), M (deuteranope), S (tritanope)
- Anomalous trichromat
  - Shifted sensitivity

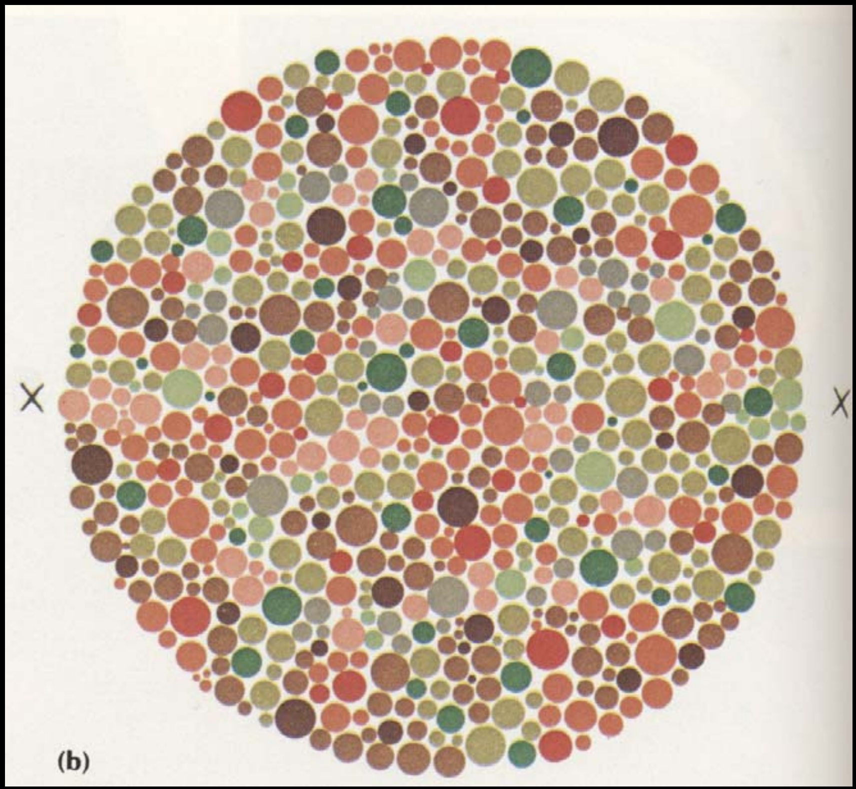


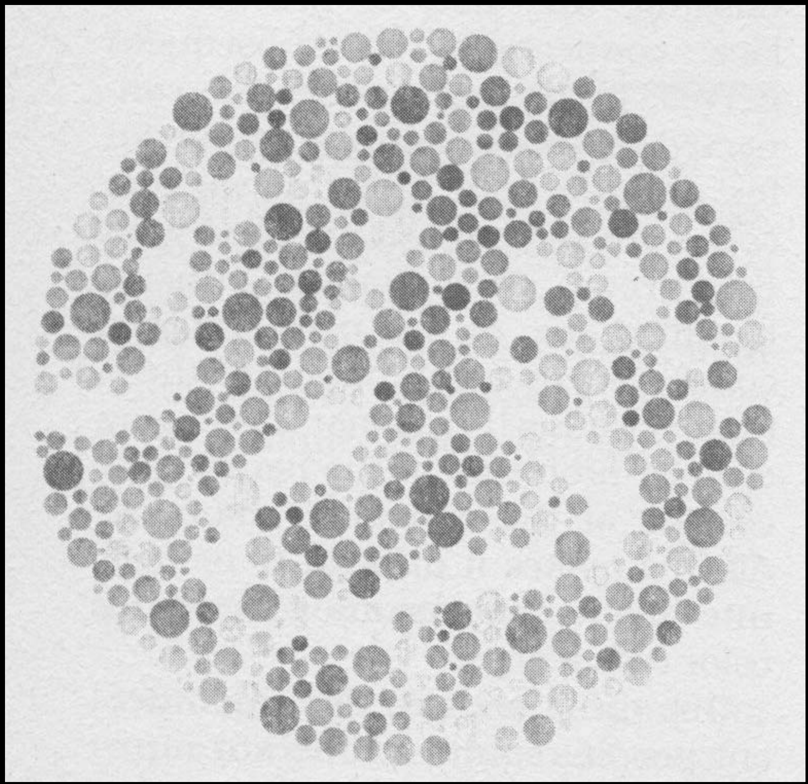
# *Color blindness test*



# *Color blindness test*

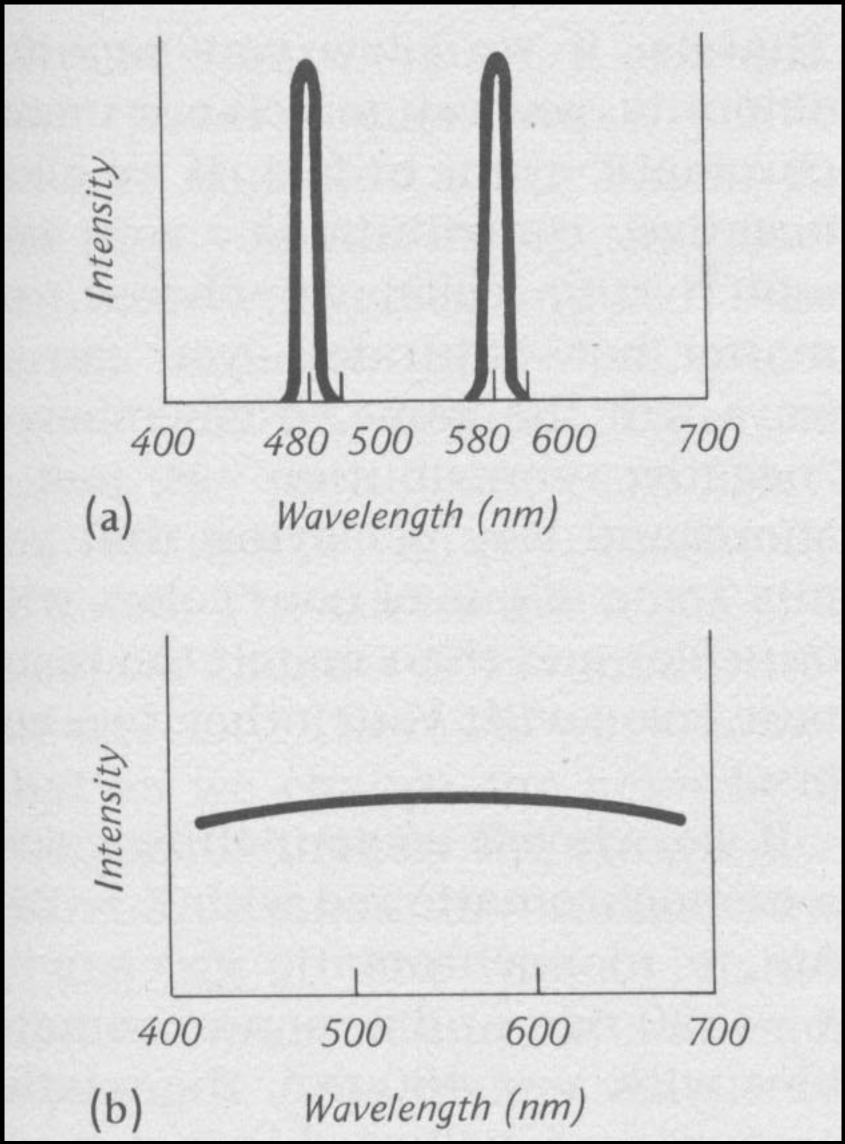
- Maze in subtle intensity contrast
- Visible only to color blinds
- Color contrast overrides intensity otherwise



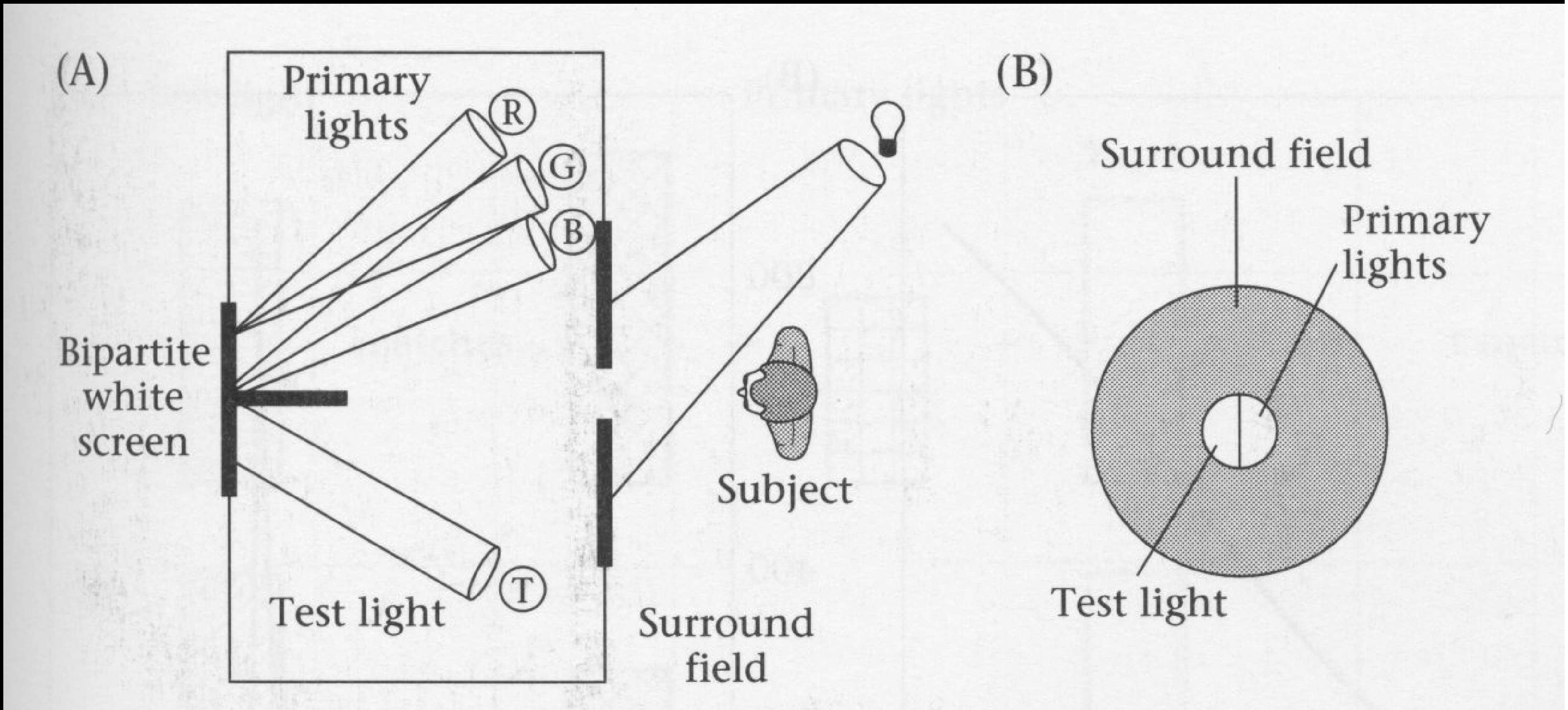
# *Metamers*

- We are all color blind!
- Different spectrum
- Same response
- Essentially, we have projected from an infinite-dimensional spectrum to a 3D space: we loose information



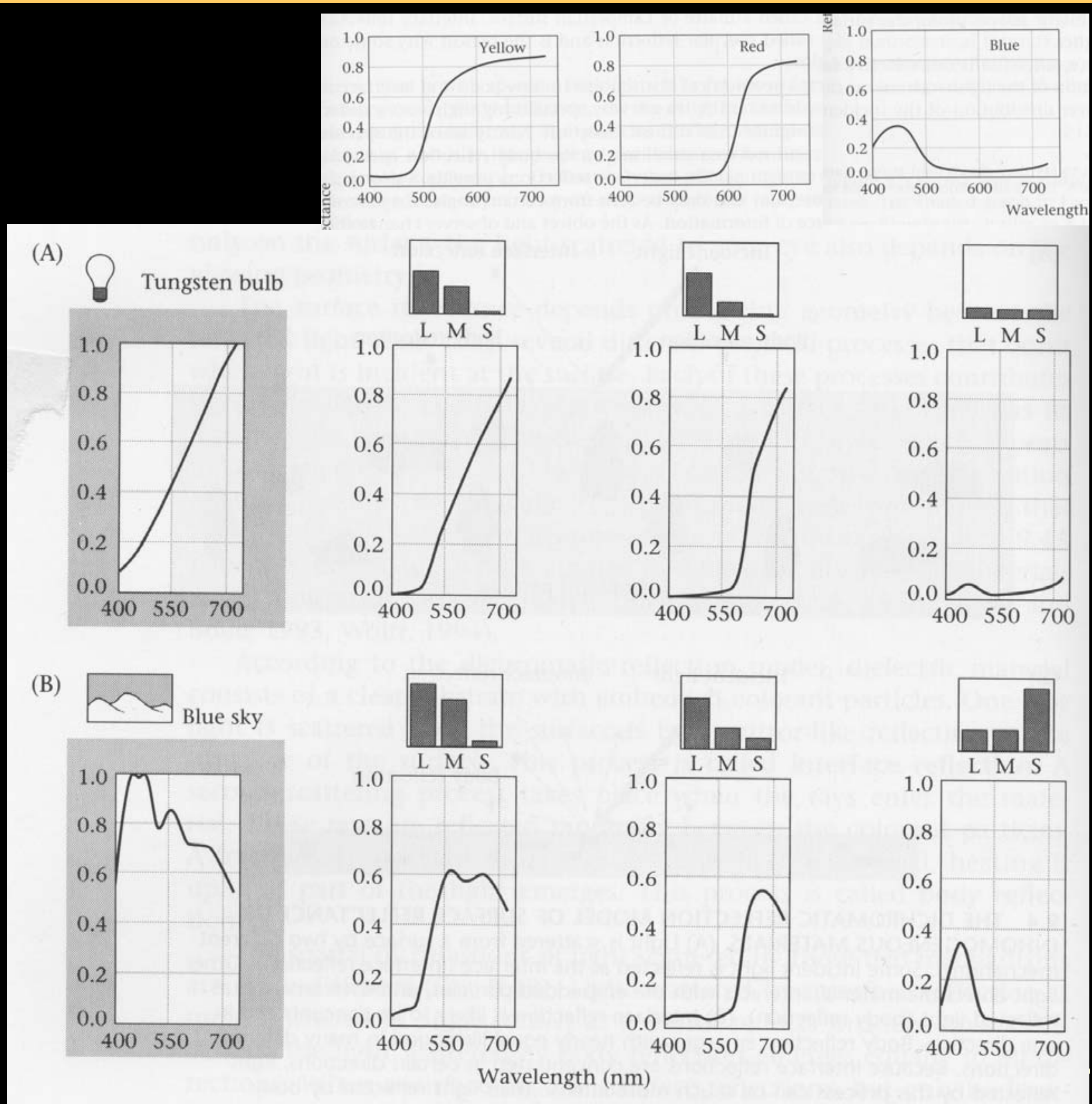
# *Metamers allows for color matching*

- Reproduce the color of any test lamp with the addition of 3 given primary lights
- Essentially exploit metamers

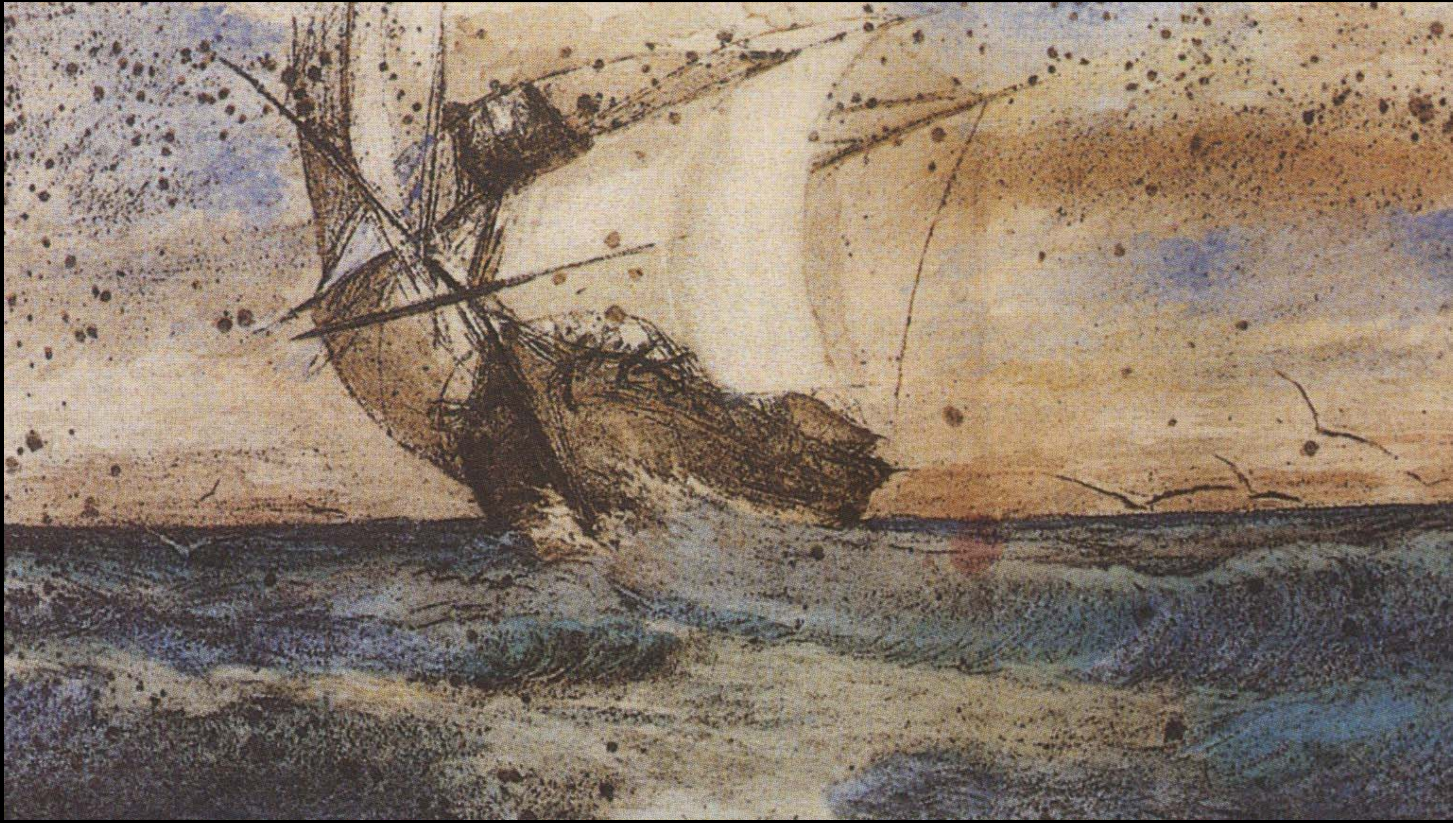


# *Metamerism & light source*

- Metamers under a given light source
- May not be metamers under a different lamp



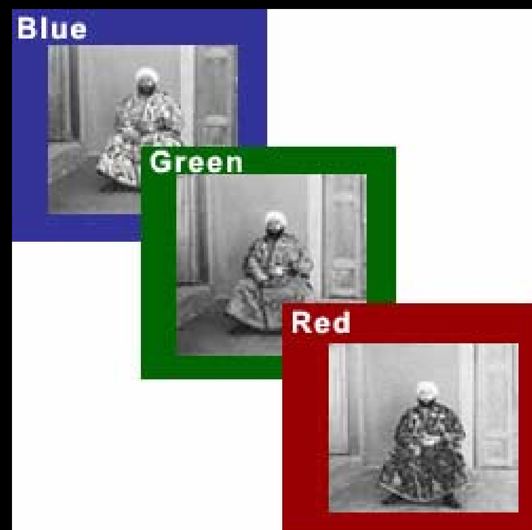
# *Questions?*



Meryon (a colorblind painter), *Le Vaisseau Fantôme*

# *Playtime: Prokudin-Gorskii*

- Russia circa 1900
- One camera, move the film with filters to get 3 exposures




http://www.loc.gov/exhibits/empire/

# *Playtime: Prokudin-Gorskii*

- Digital restoration

http://www.loc.gov/exhibits/empire/

# Playtime: Prokudin-Gorskii

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# *Warning*

Tricky thing with spectra & color:

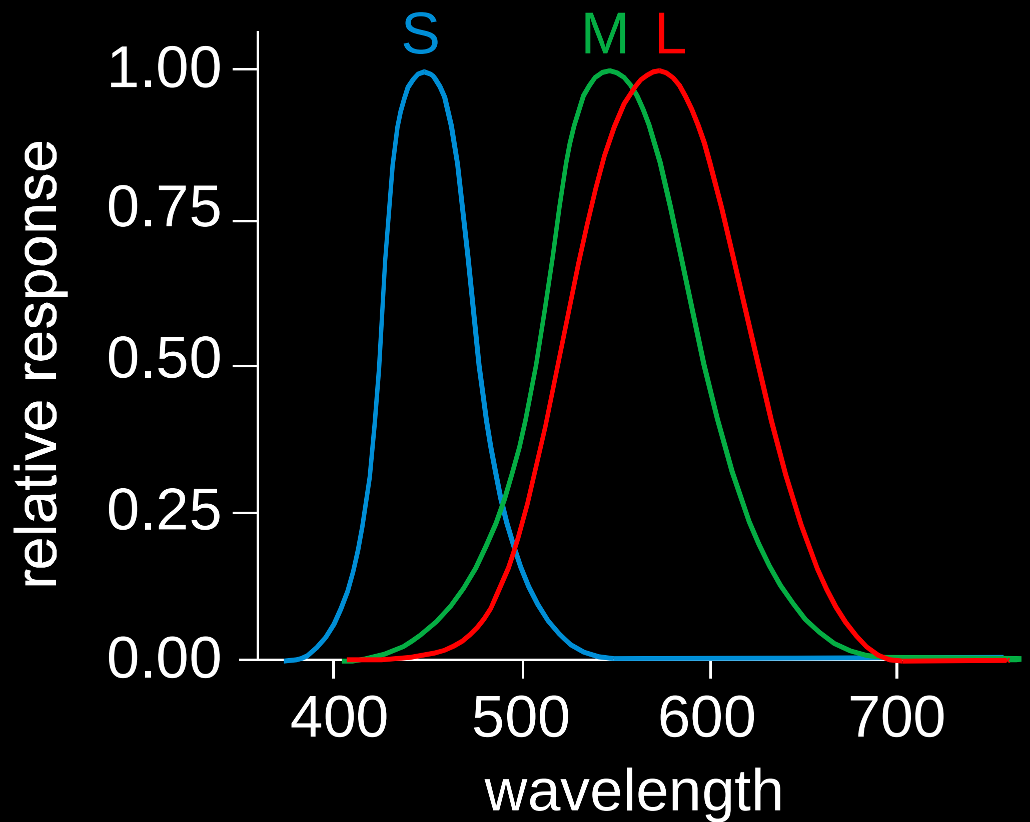
- Spectrum for the stimulus / synthesis
  - Light, monitor, reflectance
- Response curve for receptor /analysis
  - Cones, camera, scanner

They are usually not the same

There are good reasons for this

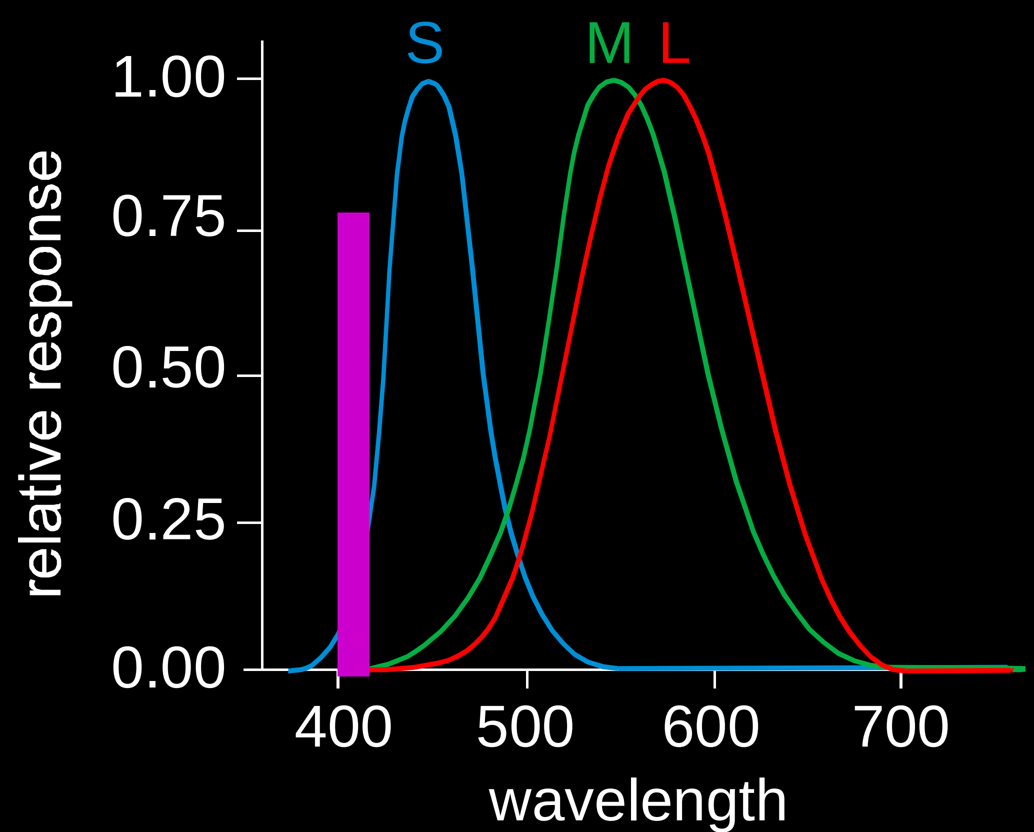
# *Synthesis*

- If we have monitor phosphors with the same spectrum as the cones, can we use them directly?



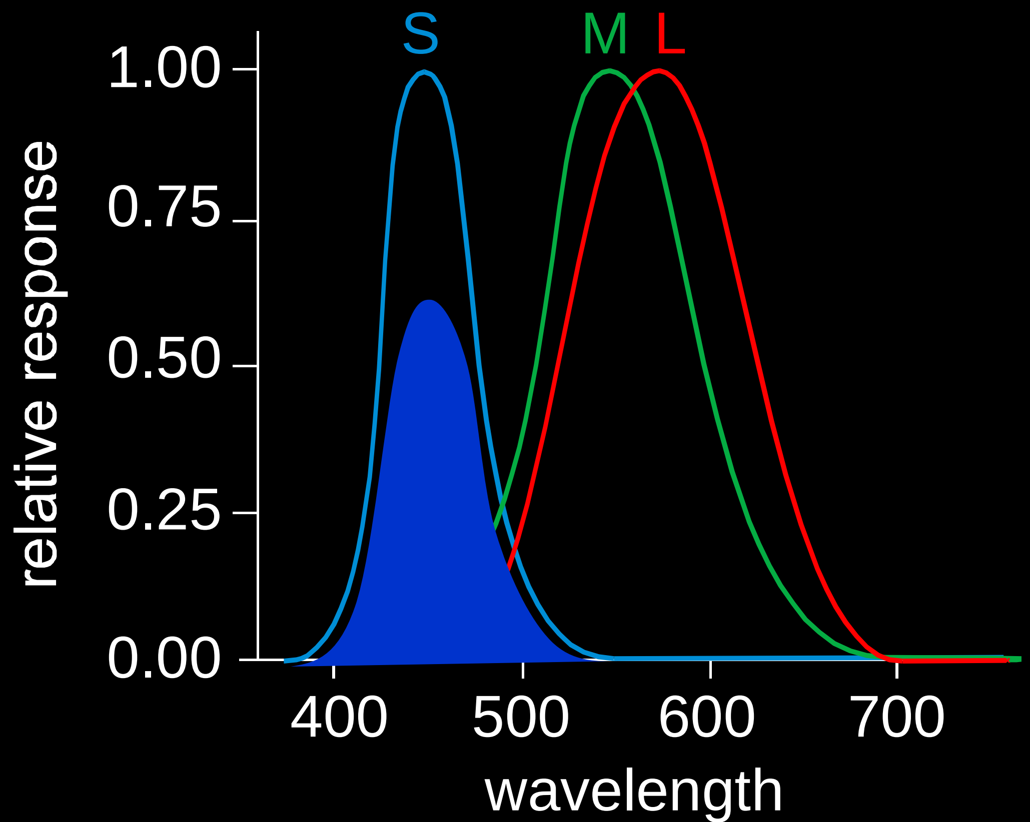
# *Synthesis*

- Take a given stimulus and the corresponding responses s, m, l (here 0.5, 0, 0)



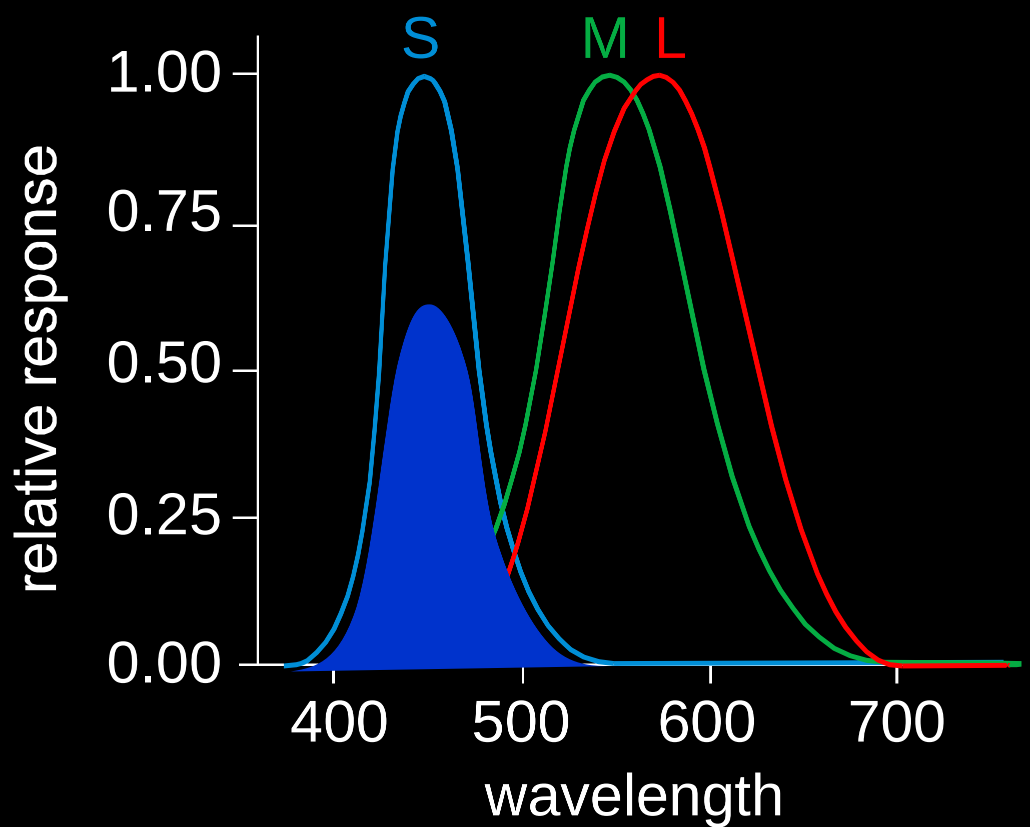
# *Synthesis*

- Use it to scale the cone spectra (here 0.5 * S)
- You don't get the same cone response! (here 0.5, 0.1, 0.1)



# *What's going on?*

- The three cone responses are not orthogonal
- i.e. they overlap and "pollute" each other



# *Questions?*

# *Plan*

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# *Standard color spaces*

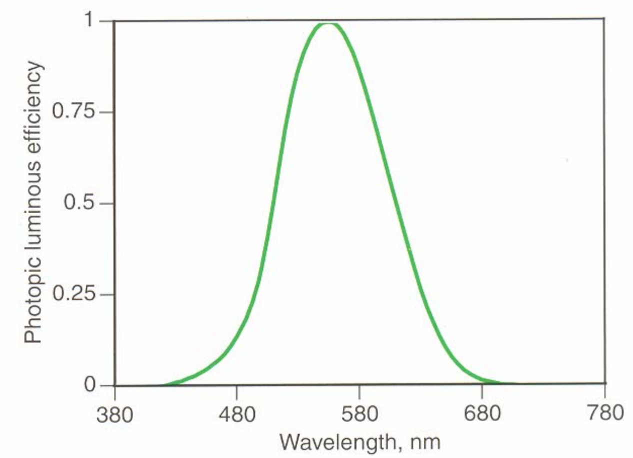
- Colorimetry: science of color measurement
- Quantitative measurements of colors are crucial in many industries
  - Television, computers, print, paint, luminaires
- So far, we have used some vague notion of RGB
- Unfortunately, RGB is not precisely defined, and depending on your monitor, you might get something different
- We need a principled color space

# *Standard color spaces*

- We need a principled color space
- Many possible definition
  - Including cone response (LMS)
  - Unfortunately not really used
- The good news is that color vision is linear and 3-dimensional, so any color space based on color matching can be obtained using 3x3 matrix
- But there are non-linear color spaces (e.g. Hue Saturation Value, Lab)

# CIE

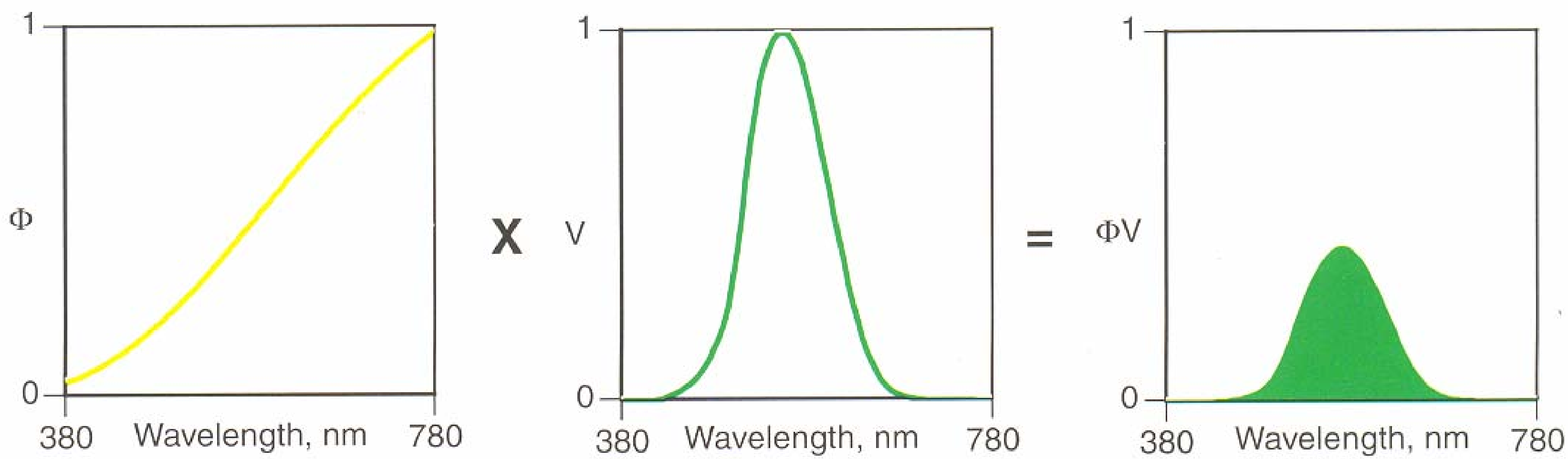
- Commission Internationale de l'Eclairage (International Lighting Commission)
- Circa 1920
- First in charge of measuring brightness for different light chromaticities (monochromatic wavelength)




The 1924 CIE standard photometric observer. Observers are less *efficient* in converting power to brightness at each end of the visible spectrum in comparison to 555 nm.

# *CIE*

- First in charge of measuring brightness for different light chromaticities
- Predict brightness of arbitrary spectrum (linearity)




Photometric quantities are calculated by multiplying the stimulus, $\Phi_\lambda$, and the standard photopic observer, $V_\lambda$, wavelength by wavelength, to give the curve $(\Phi V)_\lambda$. The area under this curve, suitably normalized, is the photometric quantity. Photometric quantities include luminance, illuminance, luminous reflectance, luminous transmittance, and luminance factor. Whenever "lum" is used, such as lumen, illuminance, or luminance, the standard photopic observer has been incorporated. The most common, luminance, illuminance, and luminance factor, are defined further in this chapter. Photometric calculations are similar to tristimulus calculations, described in detail on pages 56–59.

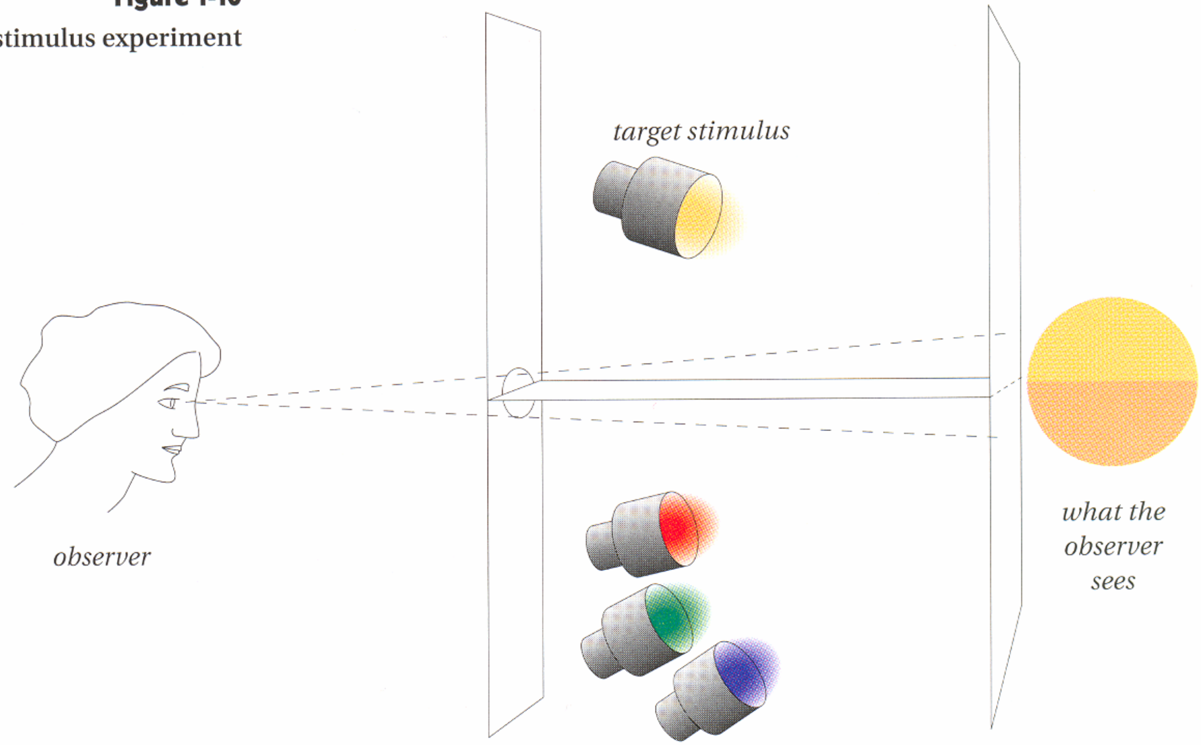
# *Questions?*

# CIE color matching: same for color

- Primaries (synthesis) at 435.8, 546.1 and 700
  - Chosen for robust reproduction, good separation in red-green
- Measure matching curves as function of wavelength (analysis)

**Figure 1-10**

Tristimulus experiment

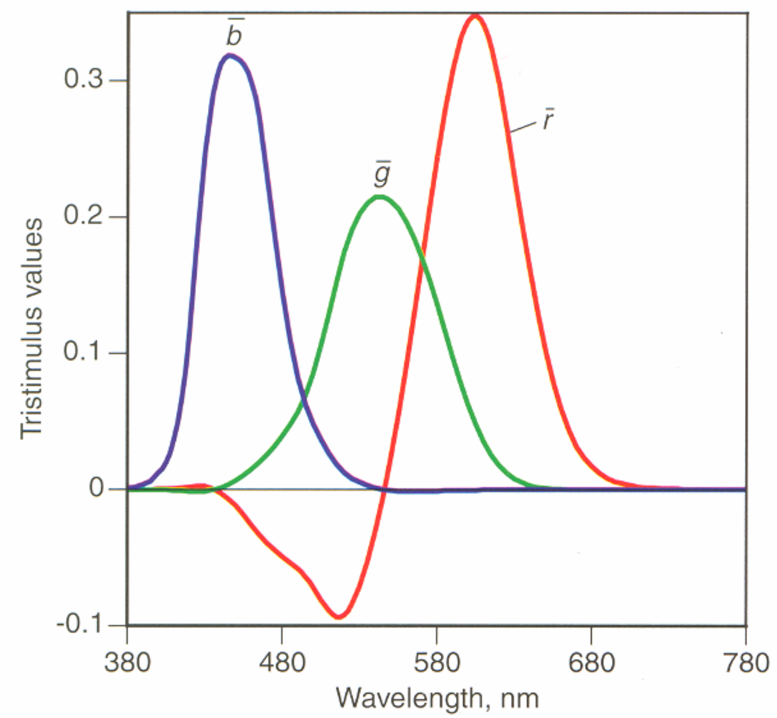



*The observer adjusts the intensities of the red, green, and blue lamps until they*

# CIE color matching

- Primaries (synthesis) at 435.8, 546.1 and 700
  - For robust reproduction, good separation in red-green
- Measure matching curves as function of wavelength (analysis)

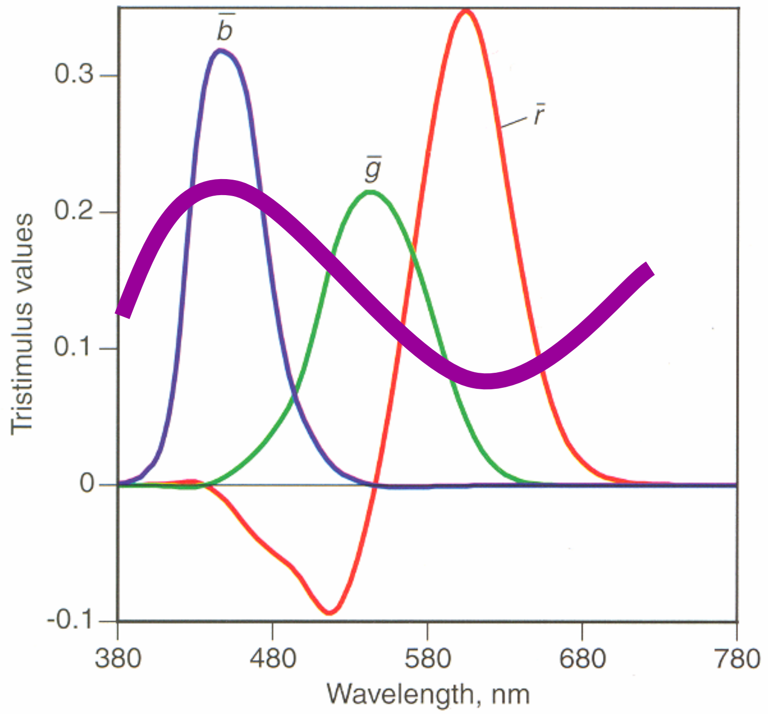
- Note that the primaries (monochromatic 435.8, 546.1 and 700nm) are not the same as the matching curve!!!)




These curves are the color-matching functions for the 1931 standard observer, The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

# CIE color matching: what does it mean?

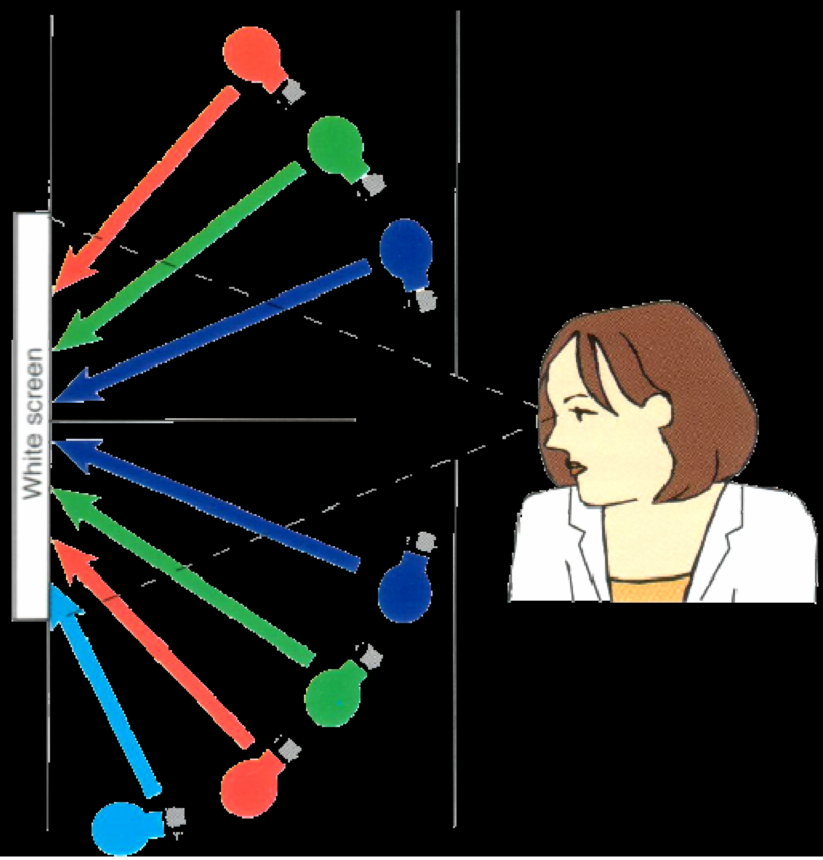
- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)
- However, note that one of the responses could be negative




These curves are the color-matching functions for the 1931 standard observer, The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

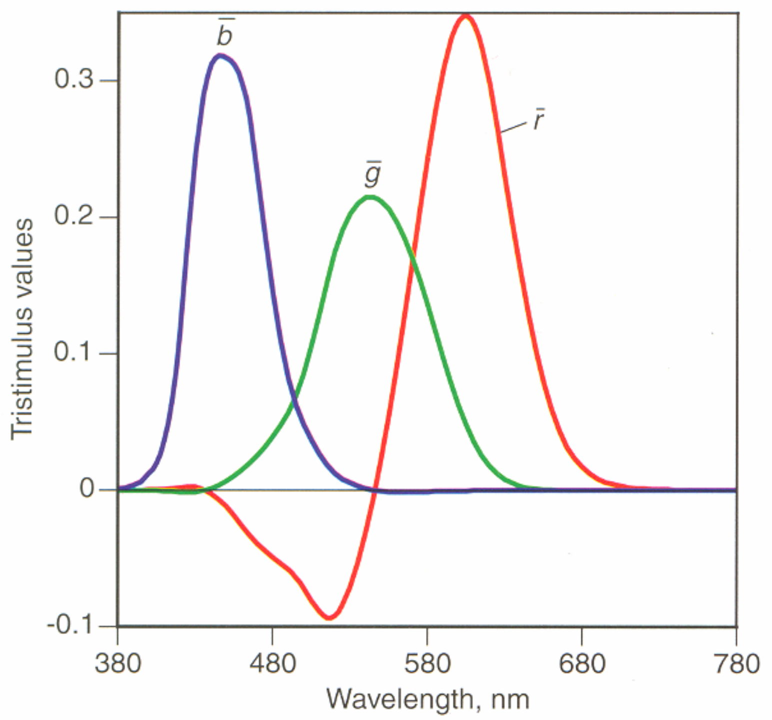
# *Color Matching Problem*

- Some colors cannot be produced using only positively weighted primaries
- Solution: add light on the other side!



# *CIE color matching*

- Problem with these curves:
  - Negative values (was a big deal to implement in a measurement hardware)
  - No direct notion of brightness
- Hence the definition of a new standard

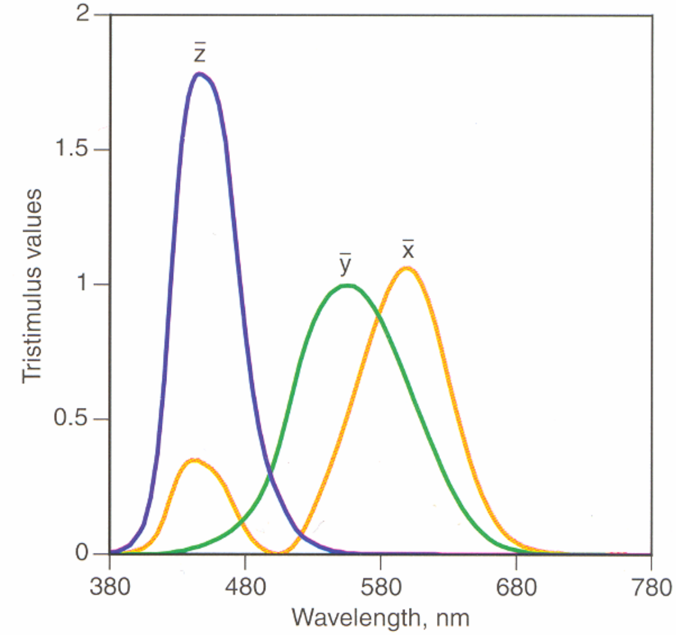



These curves are the color-matching functions for the 1931 standard observer, The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

# *Questions?*

# CIE XYZ

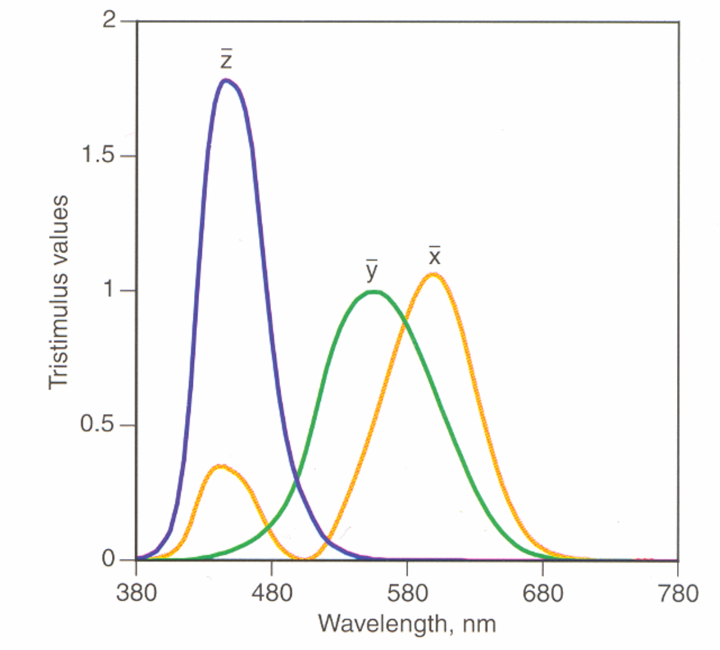
- The most widely recognized color space
- Linear transform of the previous space
- Y corresponds to brightness (1924 CIE standard photometric observer)
- No negative value of matching curve
- But no physically-realizable primary (negative values in primary rather than in matching curve)



The 1931 standard observer, as it is usually shown.

# *CIE XYZ*

- The most widely recognized color space
- A number of the motivations are historical
- Now we're stuck with it ;-)
- But remember, it is always good to agree on a standard



The 1931 standard observer, as it is usually shown.

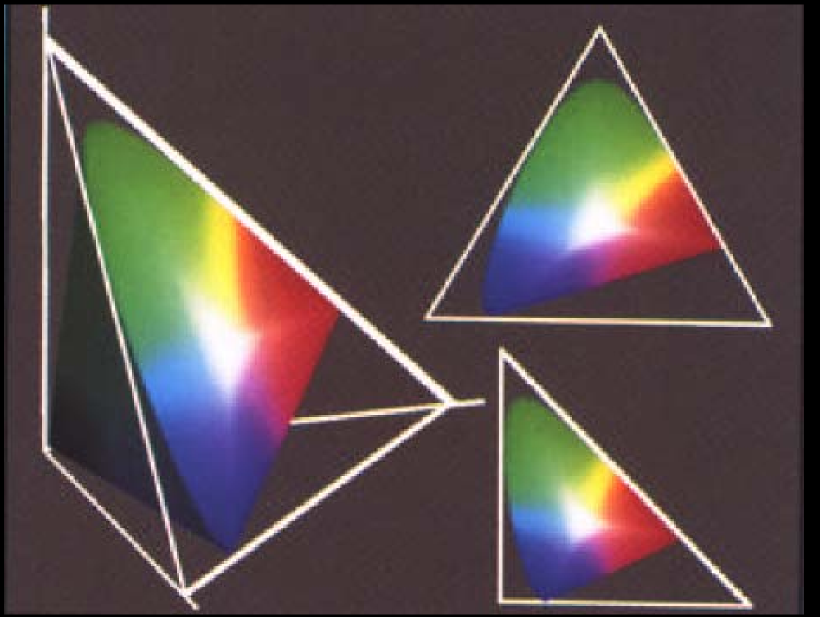
- Although, well, there are two versions of CIE XYZ (1931 and 1964)
- We'll ignore this!

# *CIE color space*

- Can think of $X$, $Y$, $Z$ as coordinates
- Linear transform from typical RGB or LMS
- Always positive (because physical spectrum is positive and matching curves are positives)

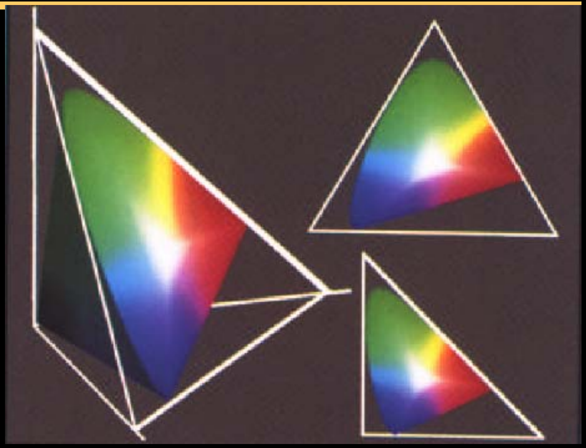
$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

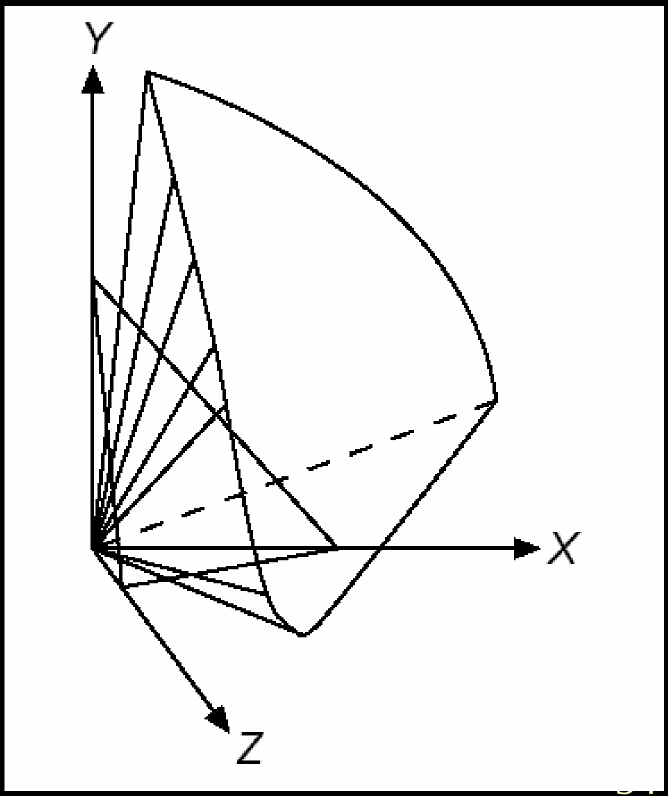
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$



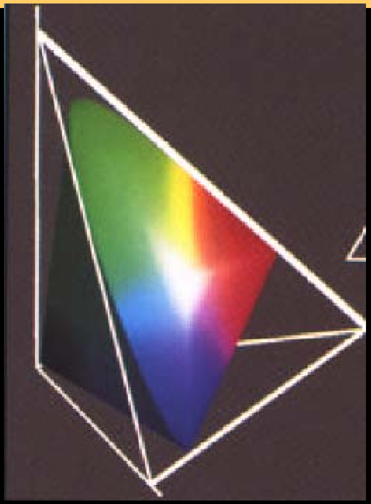
# *CIE color space*

- Odd-shaped cone contains visible colors
  - Note that many points in $XYZ$ do not correspond to visible colors!
  - Essentially, this is because our cone responses overlap and because spectrum have to be positive
  - We will get back to this





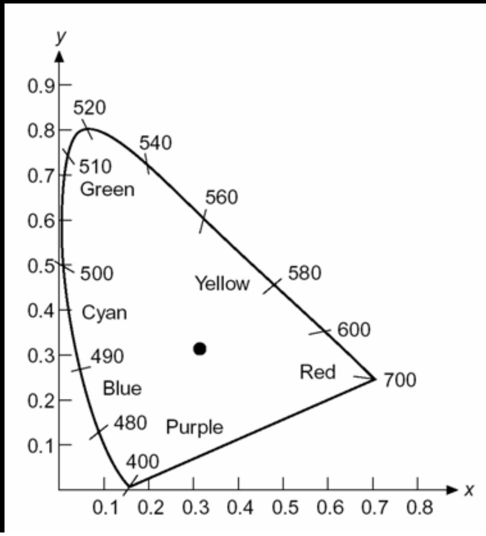
# *Chromaticity diagrams*



- 3D space are tough to visualize
- Usually project to 2D for clarity
- Chromaticity diagram:
  - normalize against $X + Y + Z$:

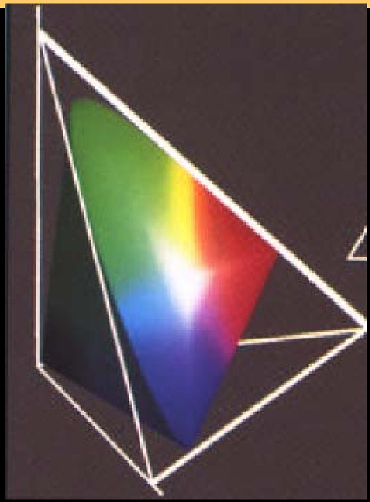
$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z}; \quad z = \frac{Z}{X+Y+Z}$$

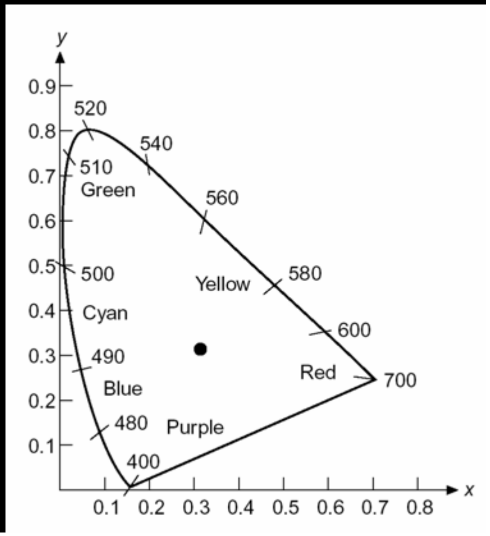
  - Perspective projection to plane X+Y+Z=1



# *Chromaticity diagrams*

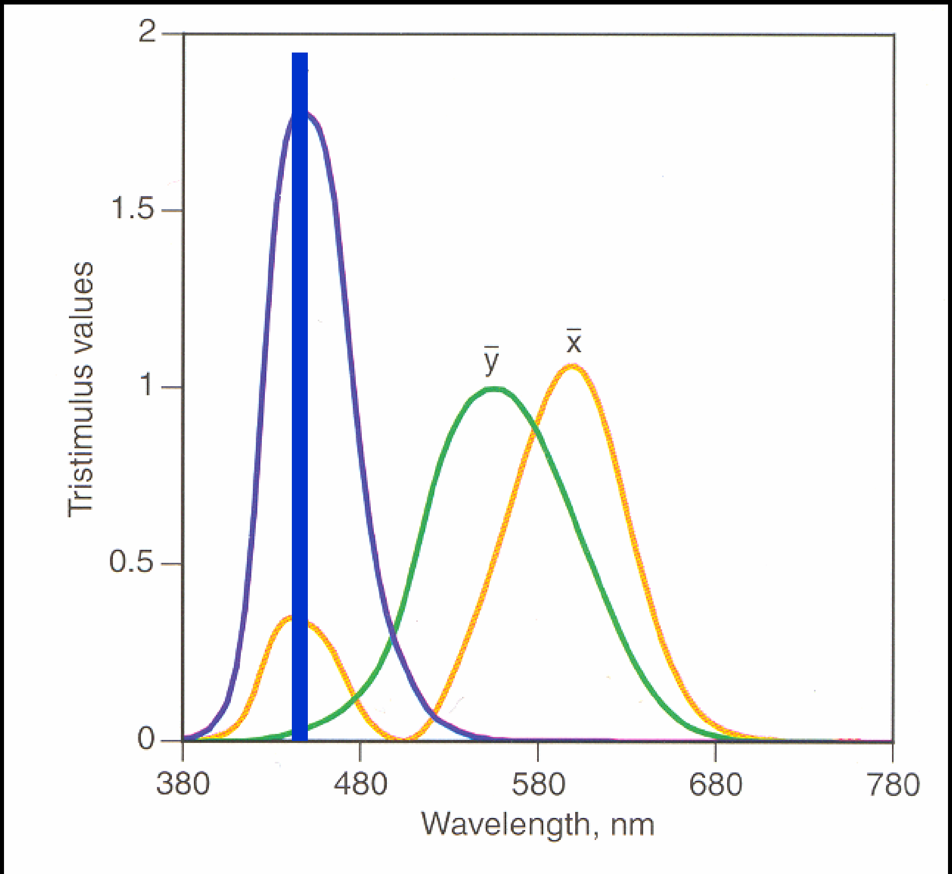
- Chromaticity diagram:
  - normalize against $X+Y+Z$:
- To get full color, usually specify x, y and Y
  - because Y is brightness
  - $X = xY/y$; $Z = (1.0-x-y)\,Y/y$
- Why not normalize against Y?
  - Not clear!



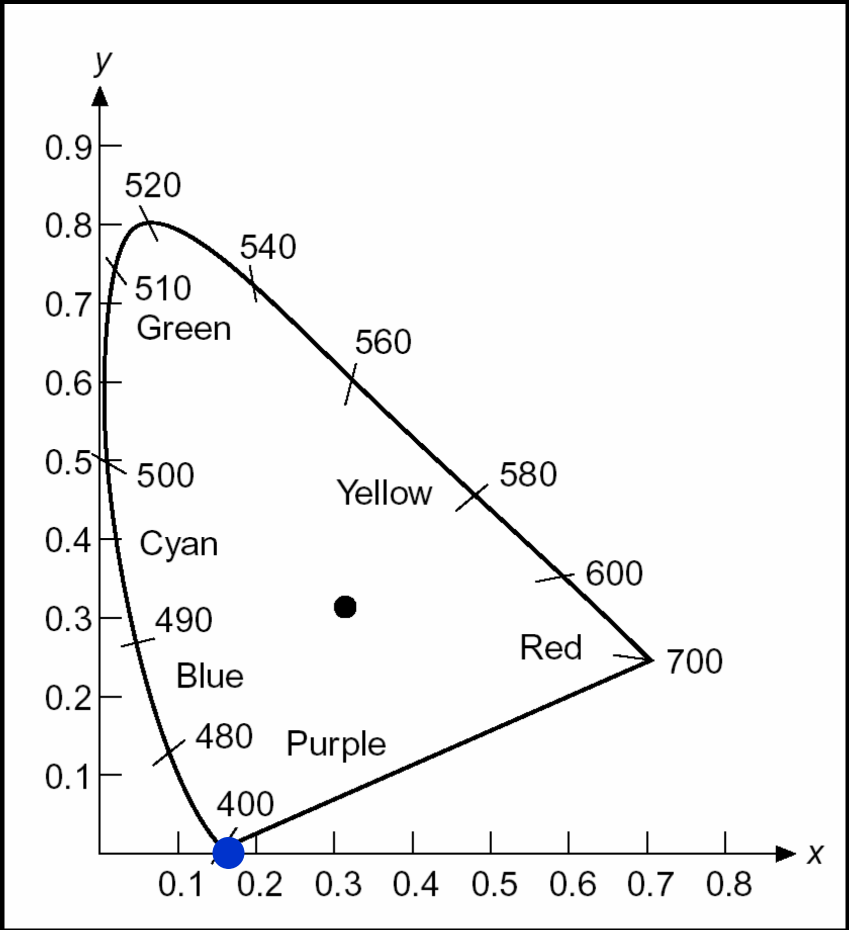


# *Pure wavelength in chromaticity diagram*

- Blue: big value of Z, therefore x and y small

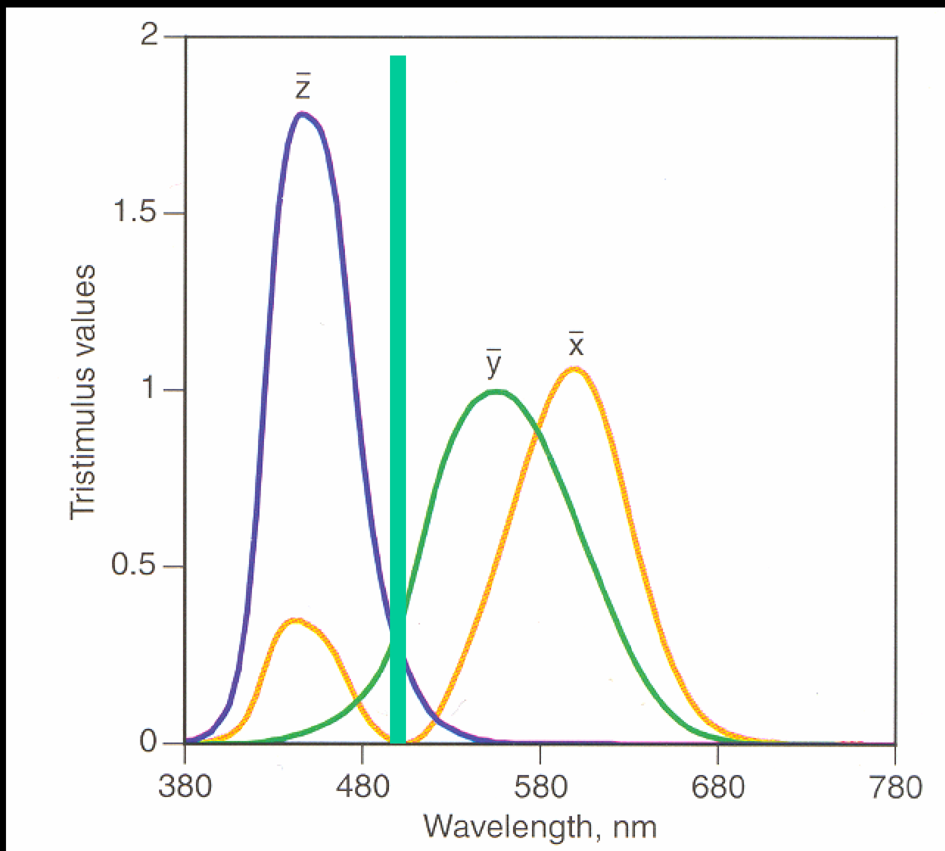


The 1931 standard observer, as it is usually shown.

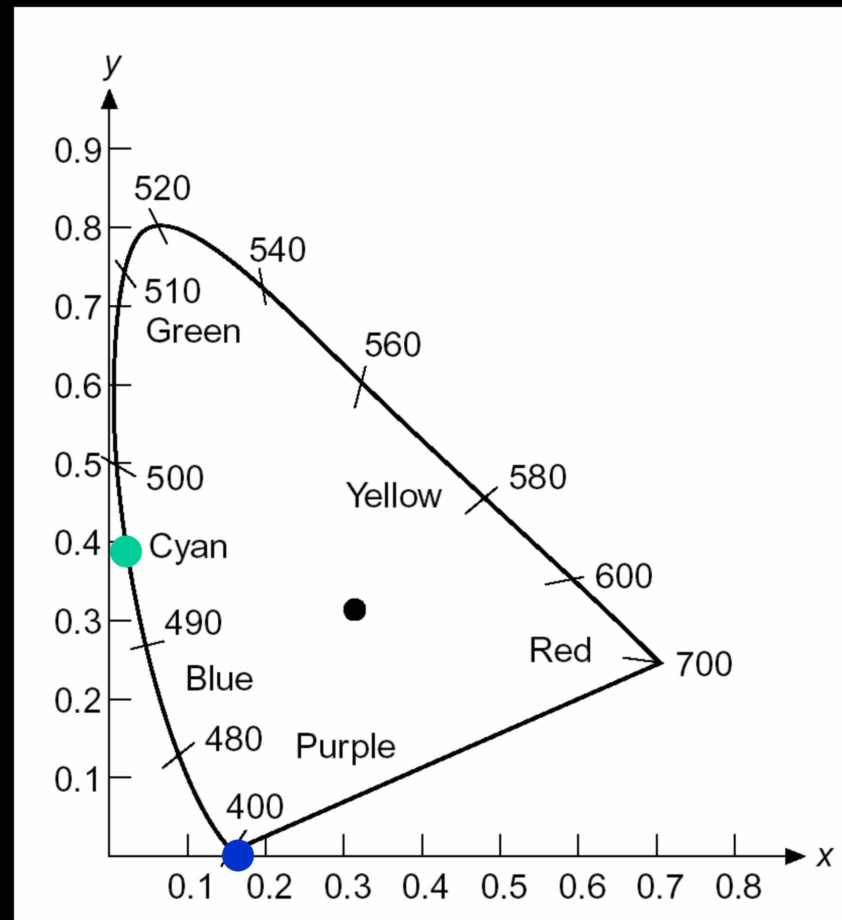


# *Pure wavelength in chromaticity diagram*

- Then y increases

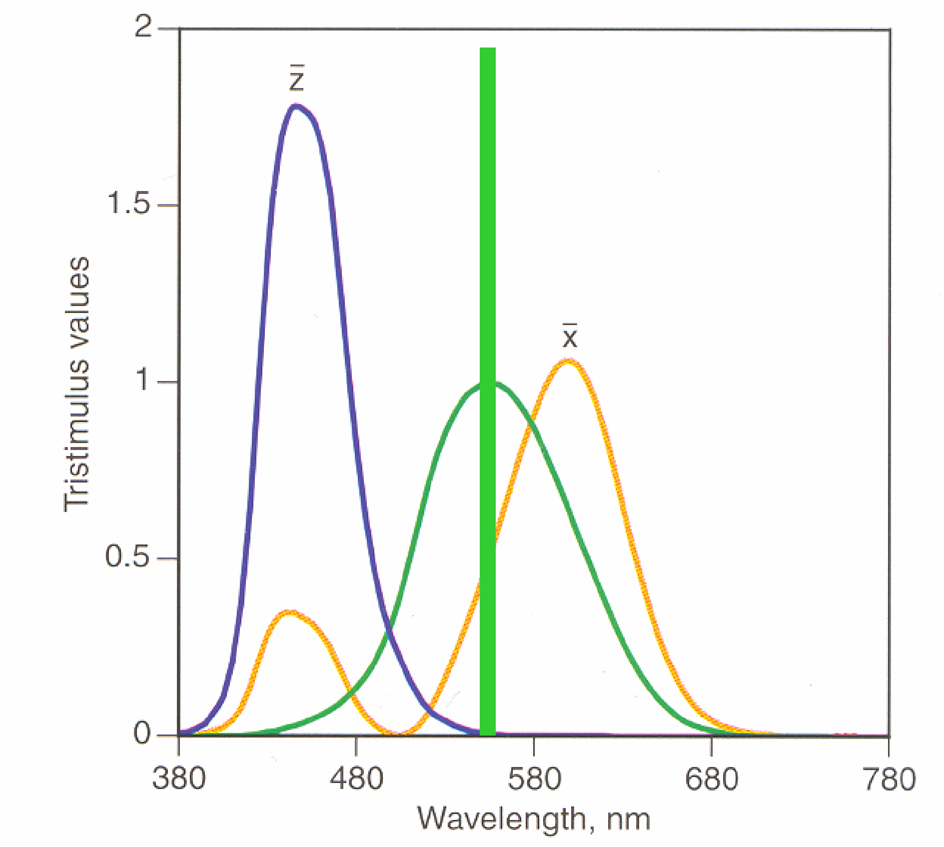



The 1931 standard observer, as it is usually shown.

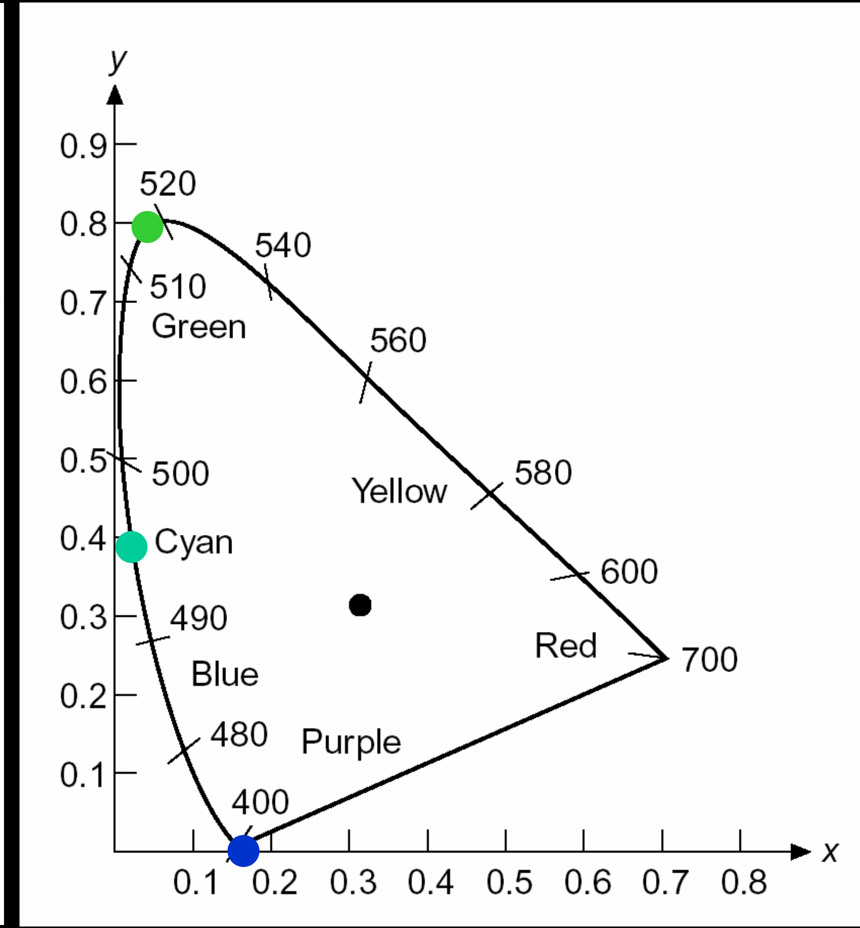


# *Pure wavelength in chromaticity diagram*

- Green: y is big

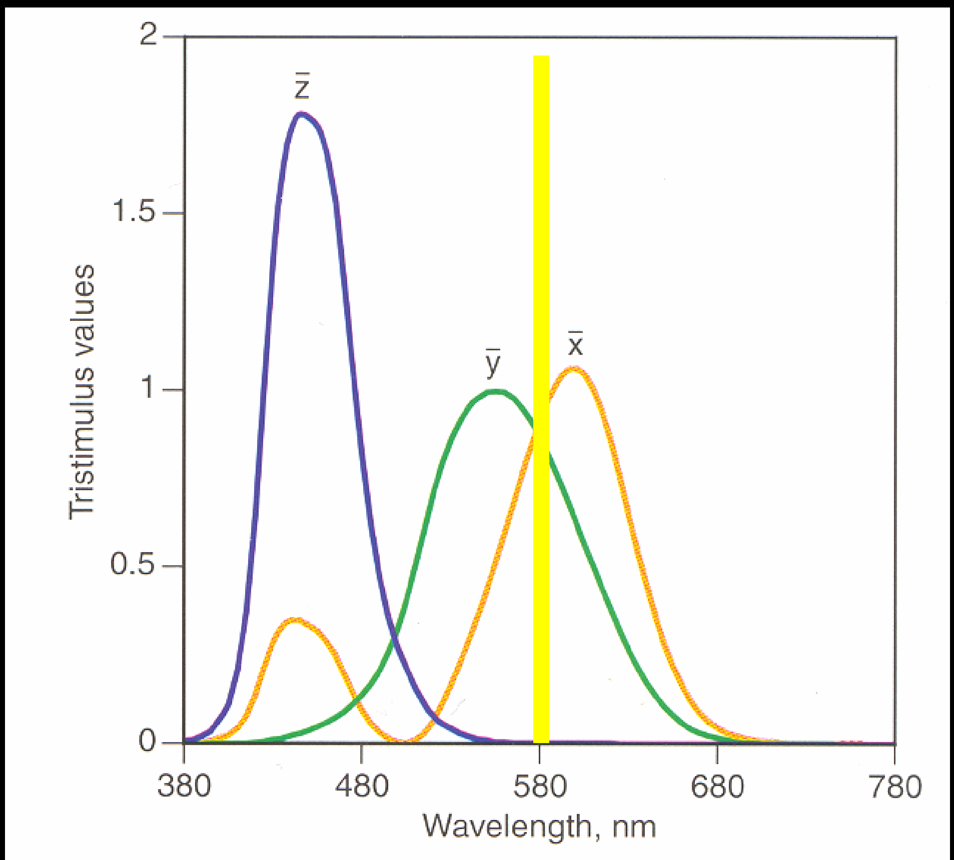


The 1931 standard observer, as it is usually shown.

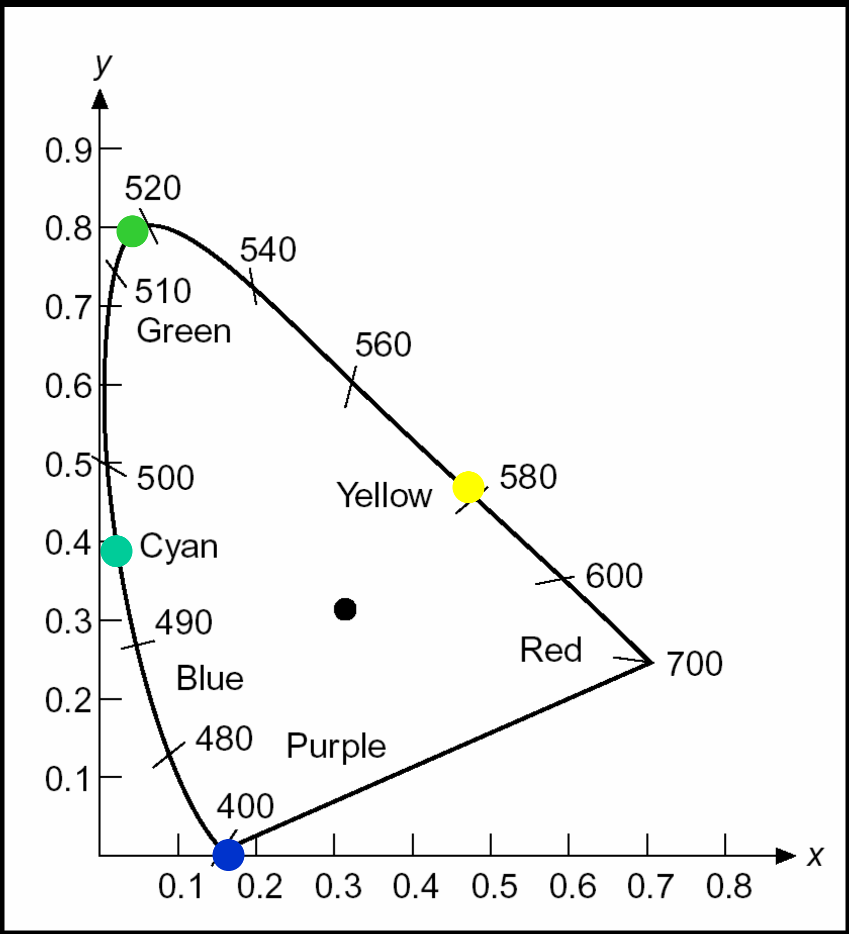


# *Pure wavelength in chromaticity diagram*

- Yellow: x & y are equal

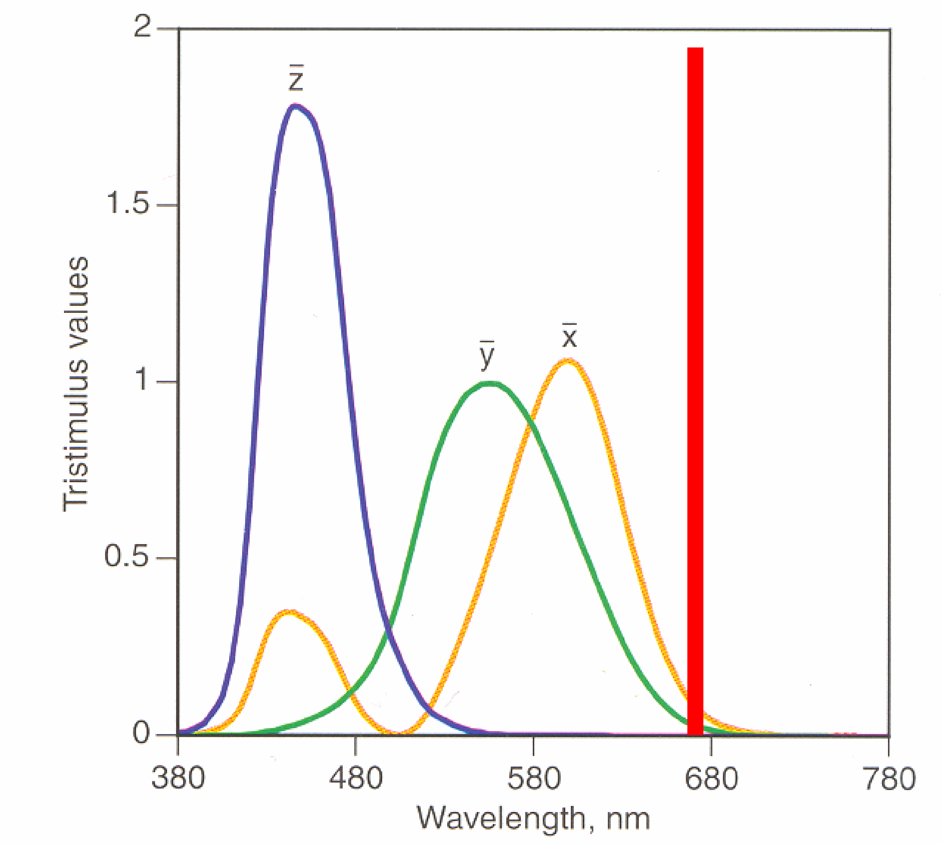



The 1931 standard observer, as it is usually shown.

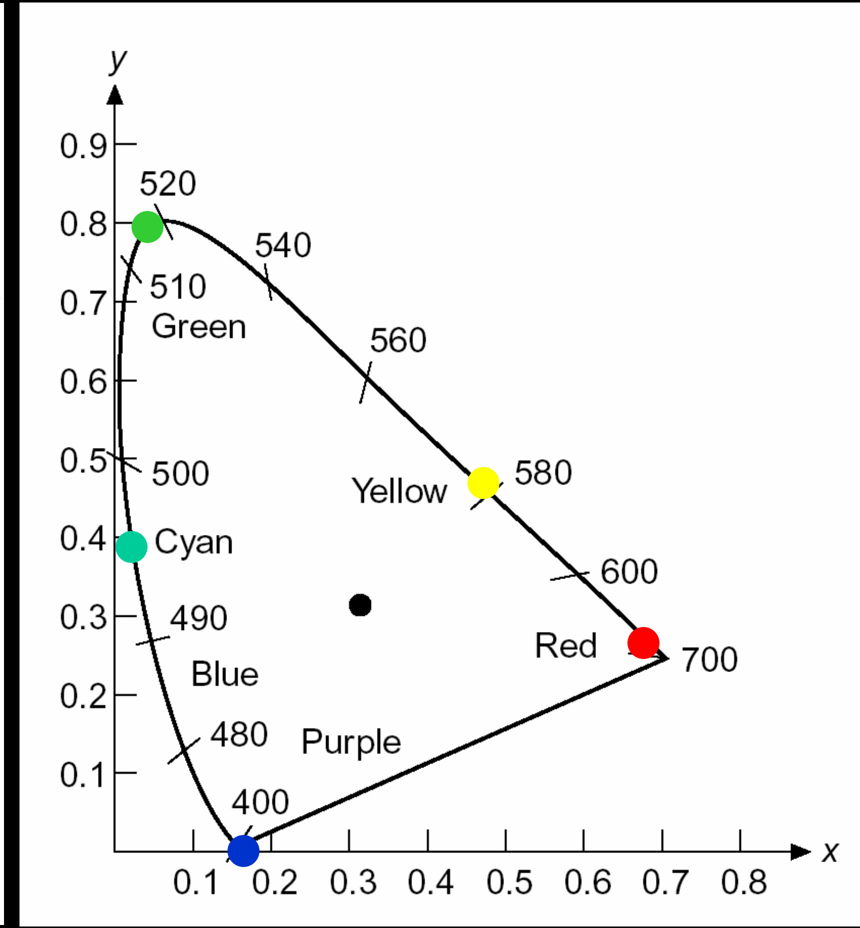


# *Pure wavelength in chromaticity diagram*

- Red: big x, but y is not null

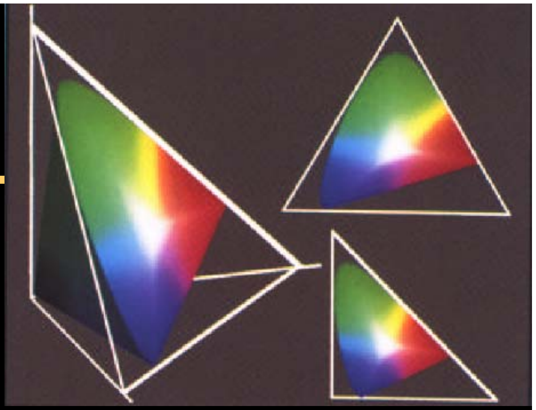


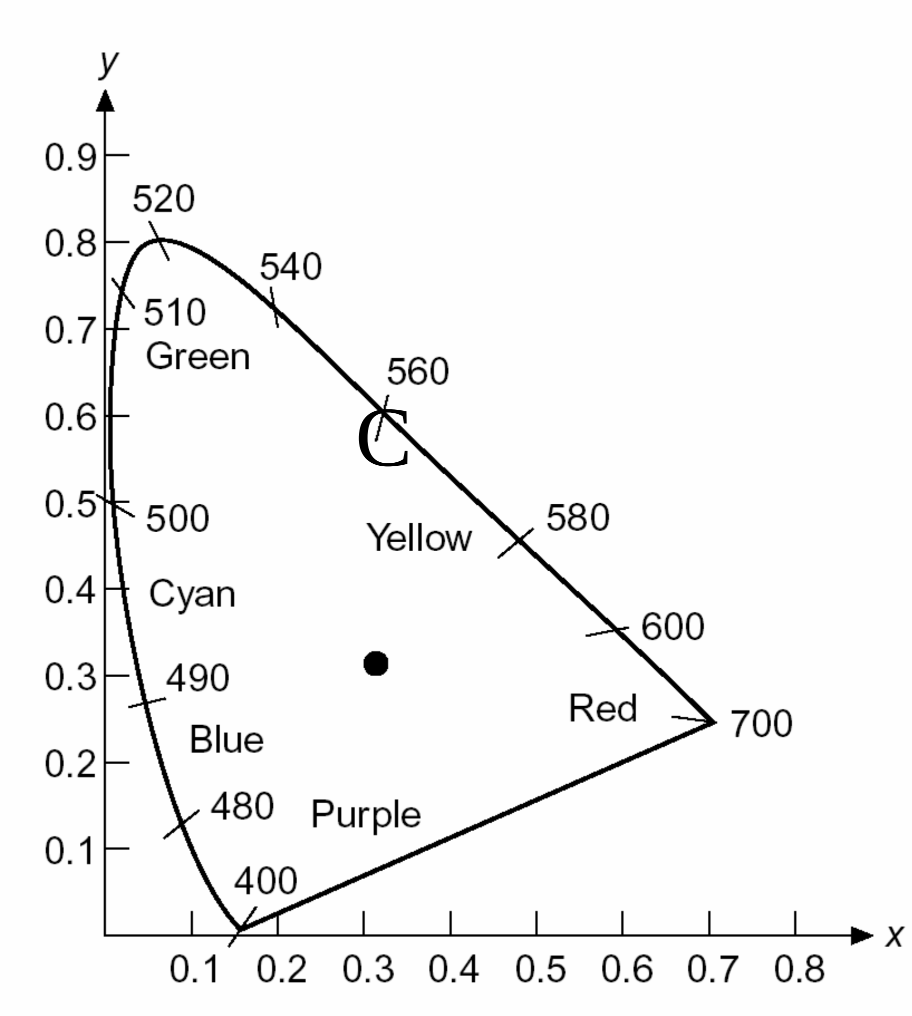

The 1931 standard observer, as it is usually shown.



# CIE chromaticity diagram

- Spectrally pure colors lie along boundary
- Weird shape comes from shape of matching curves and restriction to positive stimuli
- Note that some hues do not correspond to a pure spectrum (purple-violet)
- Standard white light (approximates sunlight) at **C**





# *XYZ vs. RGB*

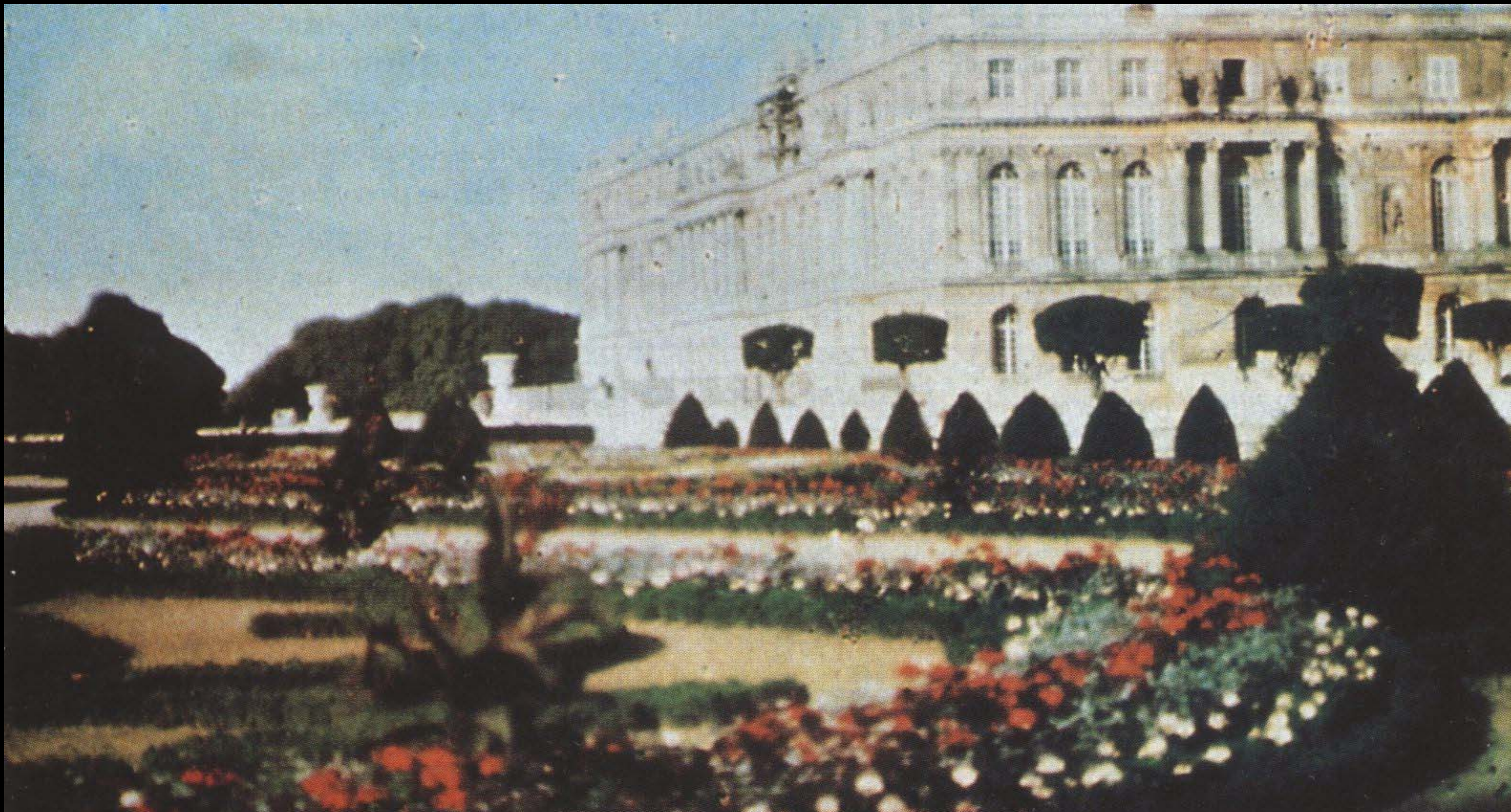
- Linear transform

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

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

- XYZ is more standardized
- XYZ can reproduce all colors with positive values
- XYZ is not realizable physically !!
  - What happens if you go “off” the diagram
  - In fact, the orthogonal (synthesis) basis of XYZ requires negative values.

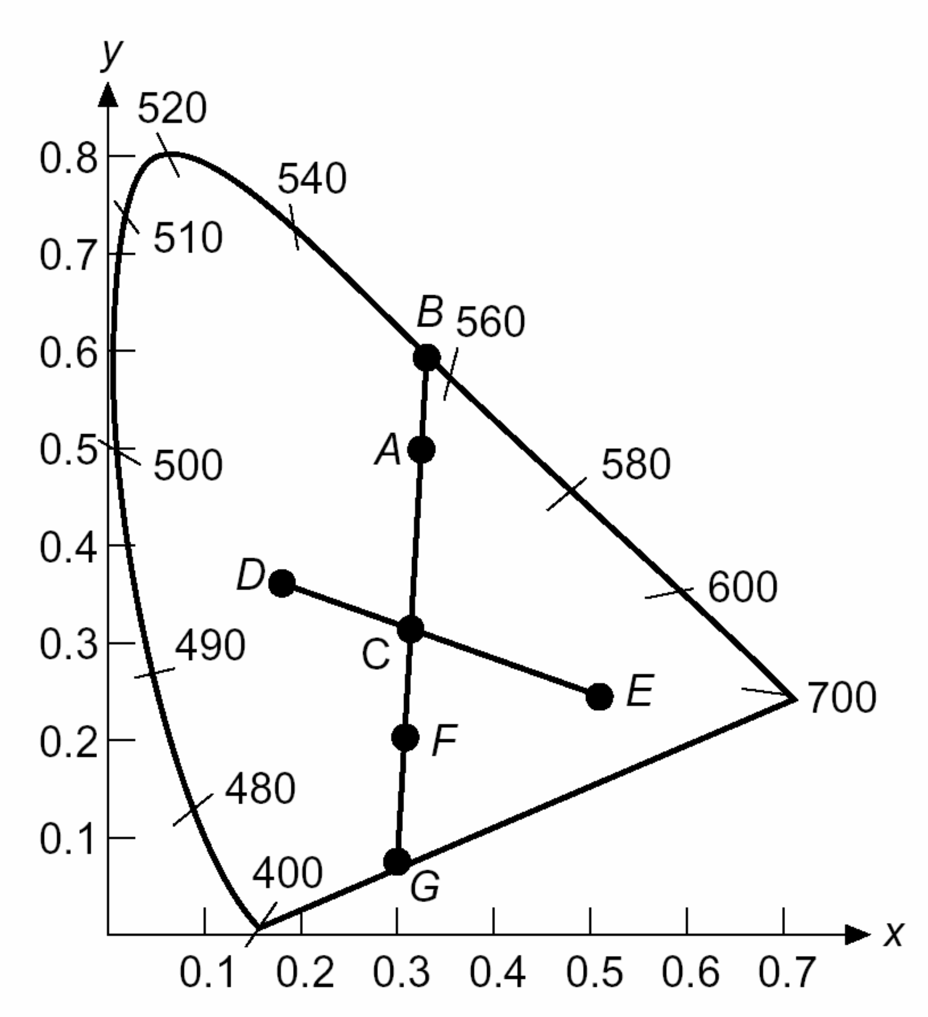
# *Questions?*



Lippman spectral color reproduction

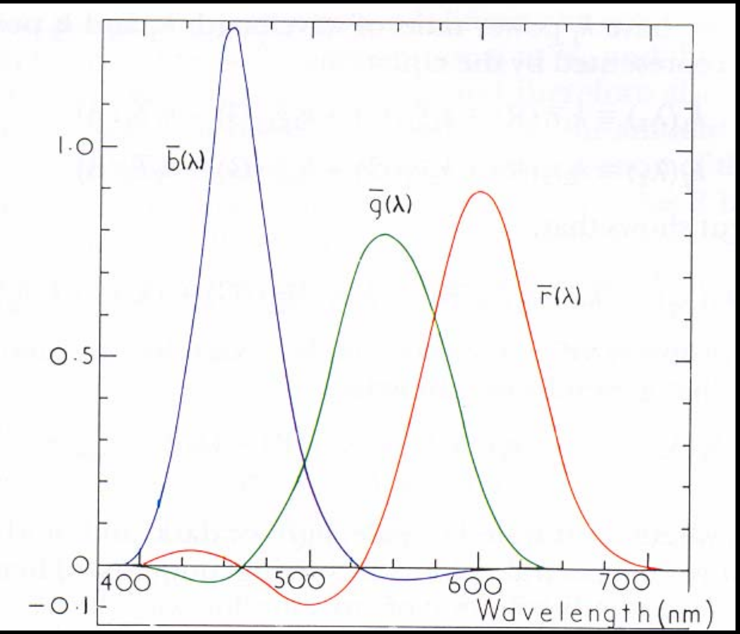
# *CIE color space*

- Match color at some point **A**
- **A** is mix of white **C**, spectral **B**!
- What is dominant wavelength of **A**?
- What is excitation purity (%) of **A**?
  - – Move along AC/BC



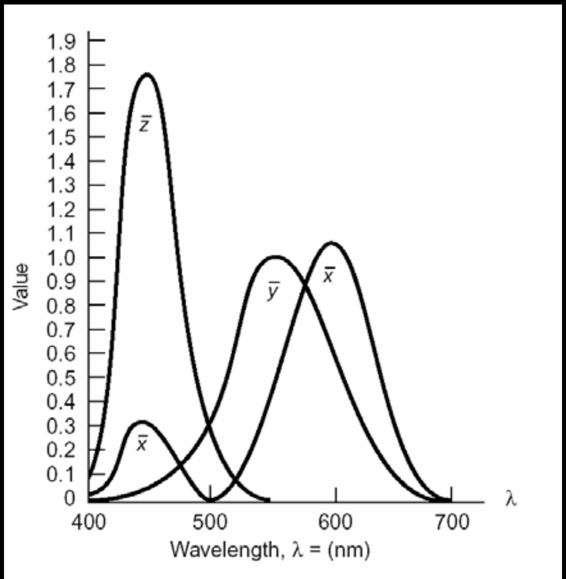
# *Color Matching Problem*

- Some colors cannot be produced using only positively weighted primaries
- E.g. primaries: pure wavelength
  - 650, 530, 460
- Some colors need negative amounts of primaries
- Analysis spectrum has negative lobes



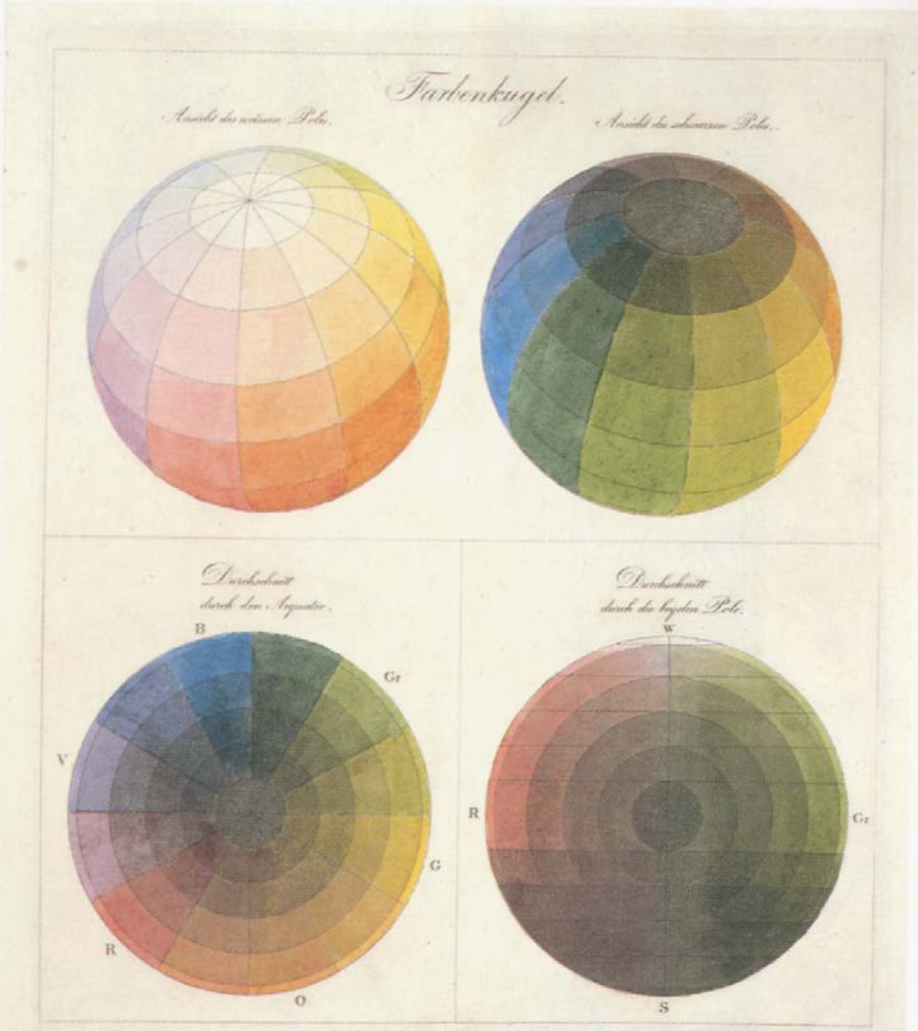
# *Color Matching Problem*

- Some colors cannot be produced using only positively weighted primaries
- Some tradeoff must be found between negative lobes in analysis vs. synthesis
- In 1931, the CIE (Commission Internationale de L'Eclairage) defined three new primaries
- Called $X$, $Y$, $Z$,
  - with **positive** color matching functions

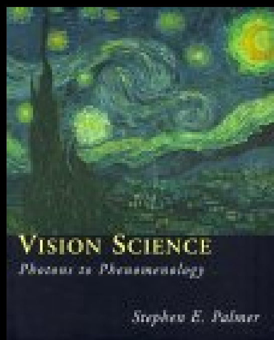


# *Questions?*

VIII. Philipp Otto Runge, *Colour Sphere*, 1809, Hamburg Kunsthalle.

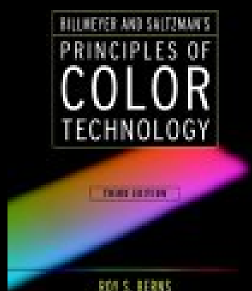


# *Selected Bibliography*



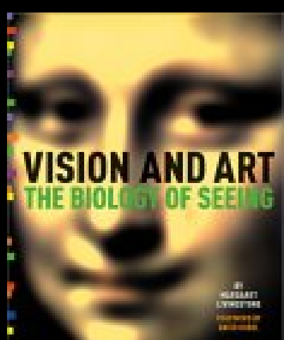


**Vision Science**
by Stephen E. Palmer
MIT Press; ISBN: 0262161834
760 pages (May 7, 1999)



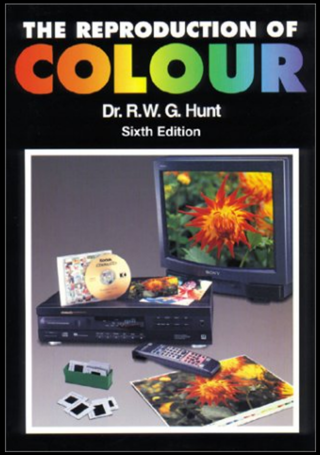
**Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition**
by Roy S. Berns, Fred W. Billmeyer, Max Saltzman
Wiley-Interscience; ISBN: 047119459X
304 pages 3 edition (March 31, 2000)

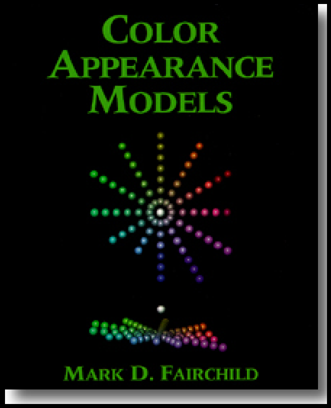


**Vision and Art : The Biology of Seeing**
by Margaret Livingstone, David H. Hubel
Harry N Abrams; ISBN: 0810904063
208 pages (May 2002)

# *Selected Bibliography*

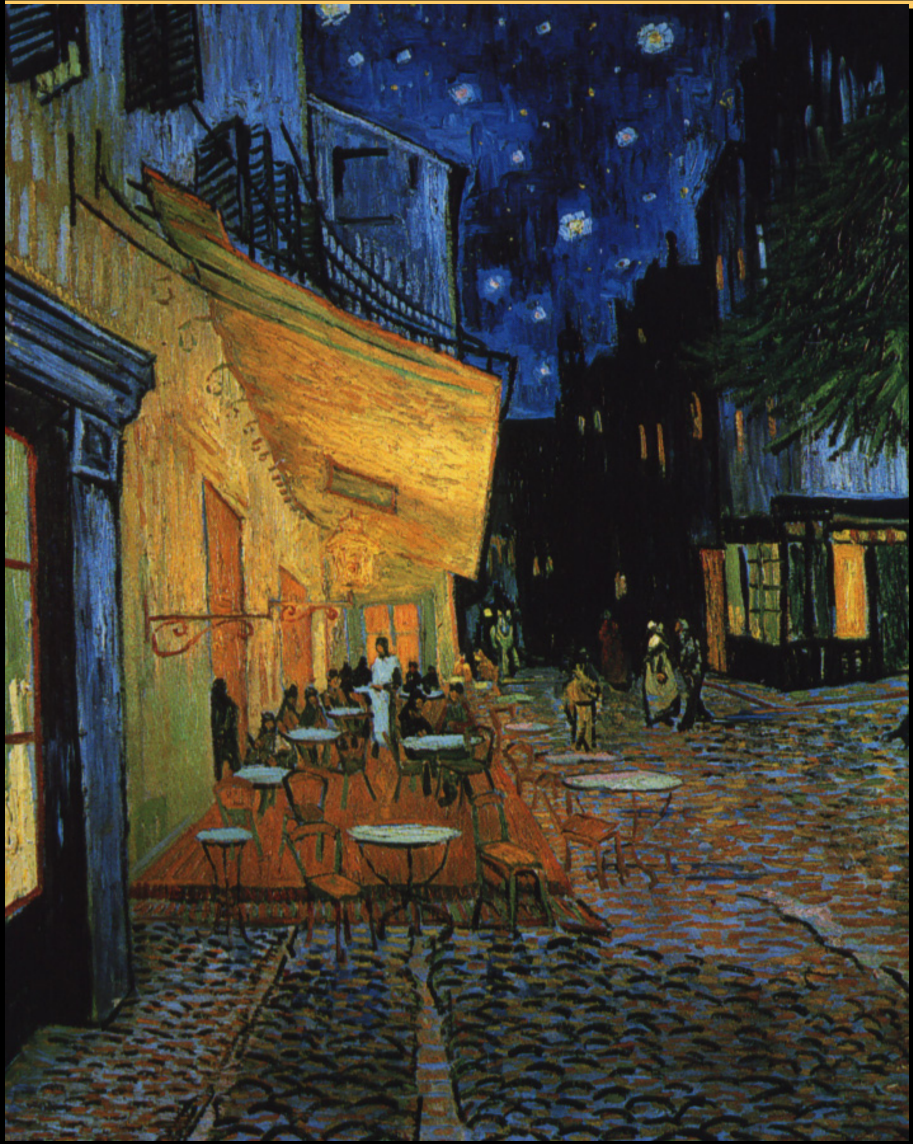

**The Reproduction of Color**
by R. W. G. Hunt
Fountain Press, 1995




**Color Appearance Models**
by Mark Fairchild
Addison Wesley, 1998

# Introduction to color vision

# Questions?

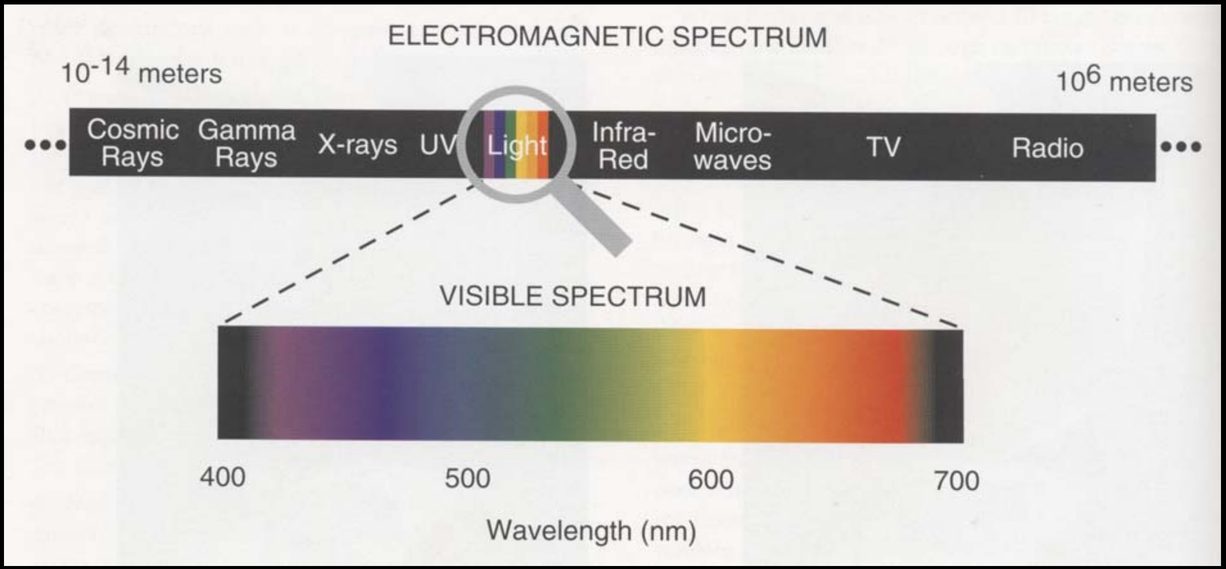


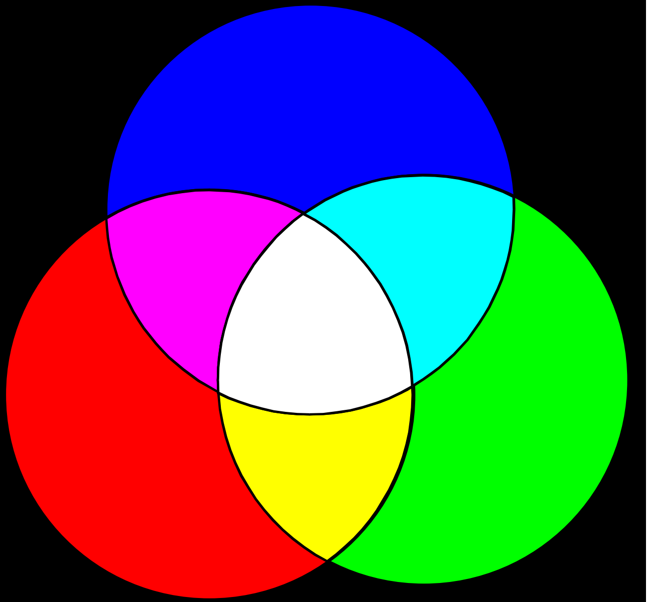
Van Gogh

Jawlensky

# *You believe you know it all*

- Color is about spectrum and wavelength
- We can get everything from red, green and blue



- Well, life is more confusing than that!

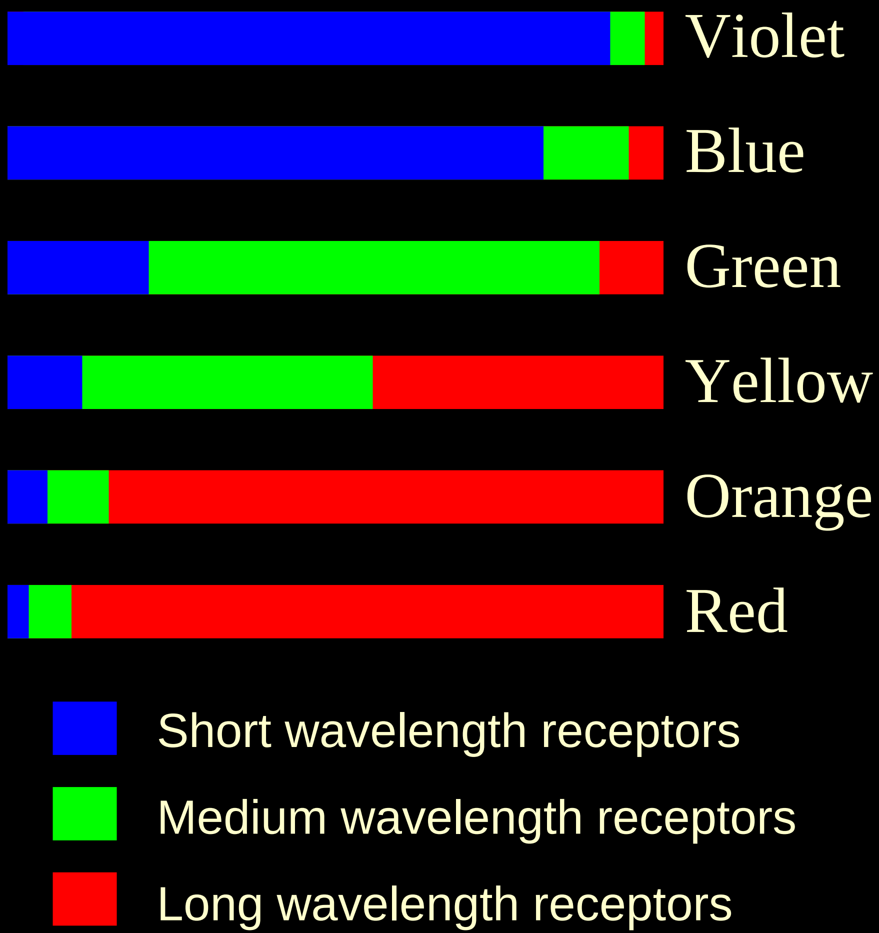
# *Puzzles about color*

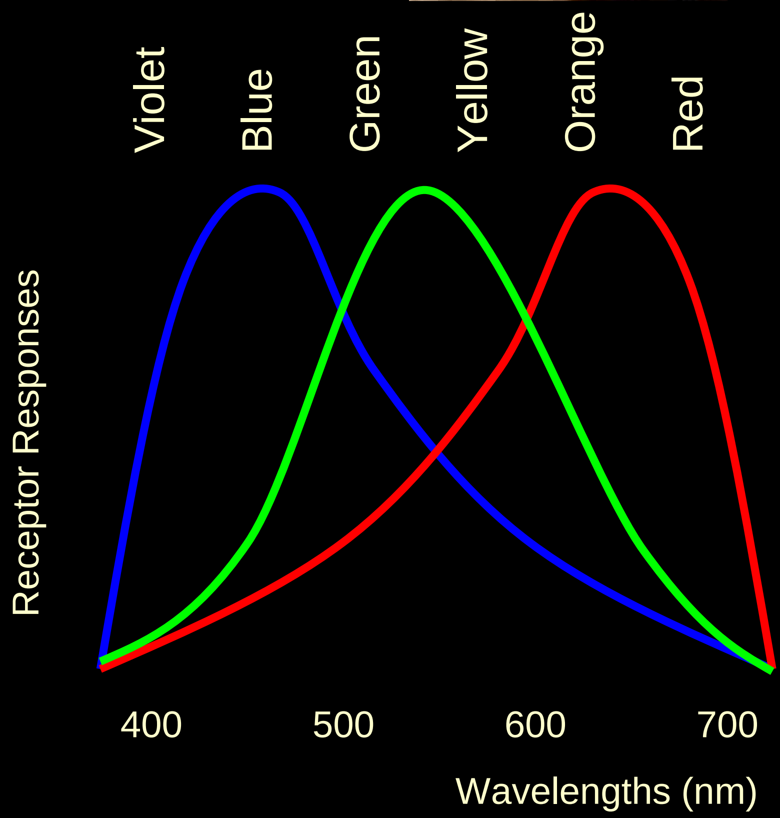
- How comes a continuous spectrum ends up as a 3D color space
- Why is violet “close” to red
- Primaries: 3 or 4? Which ones
  - Red, blue, yellow, green
  - Cyan and magenta are not “spontaneous” primaries
- Color mixing
- What is the color of Henry IV’s white horse?

# *Linearity of color*

# *Remember von Helmholtz*

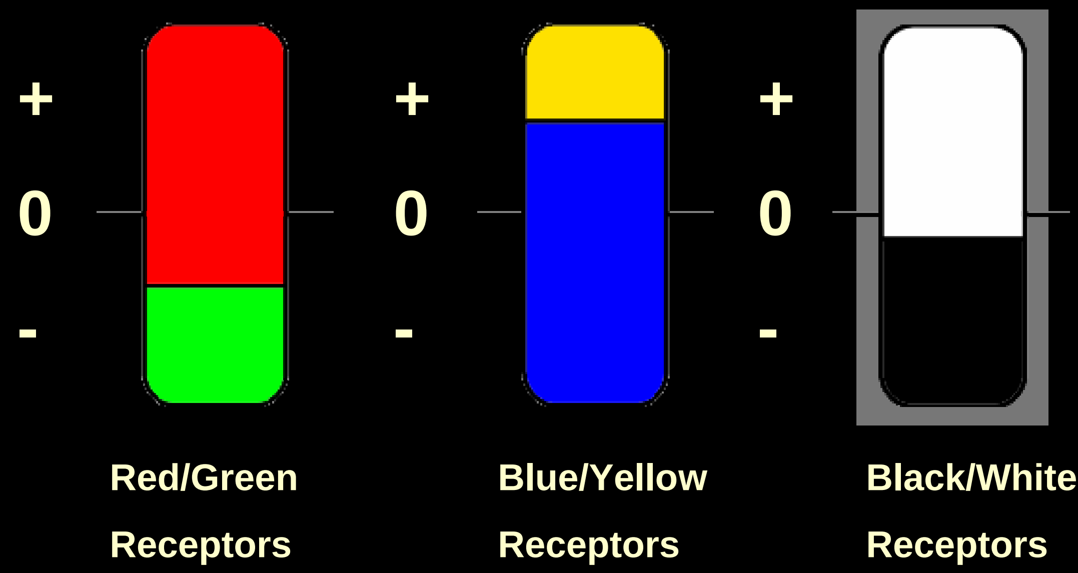
- Colors as relative responses (ratios)



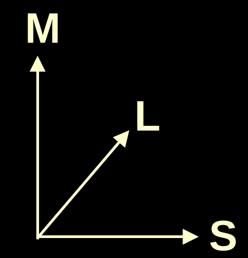
# *Hering 1874: Opponent Colors*

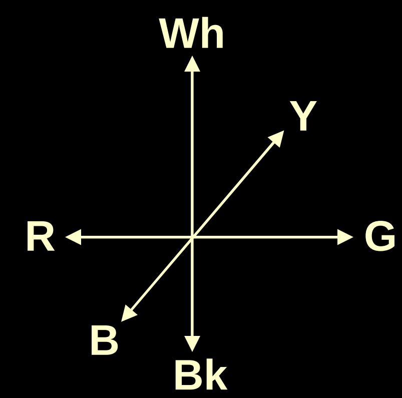
- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena

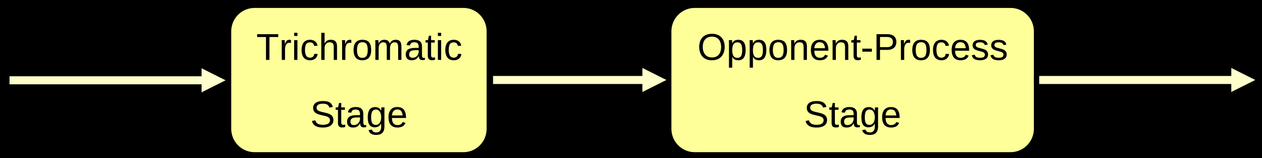



# *Dual Process Theory*

- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green

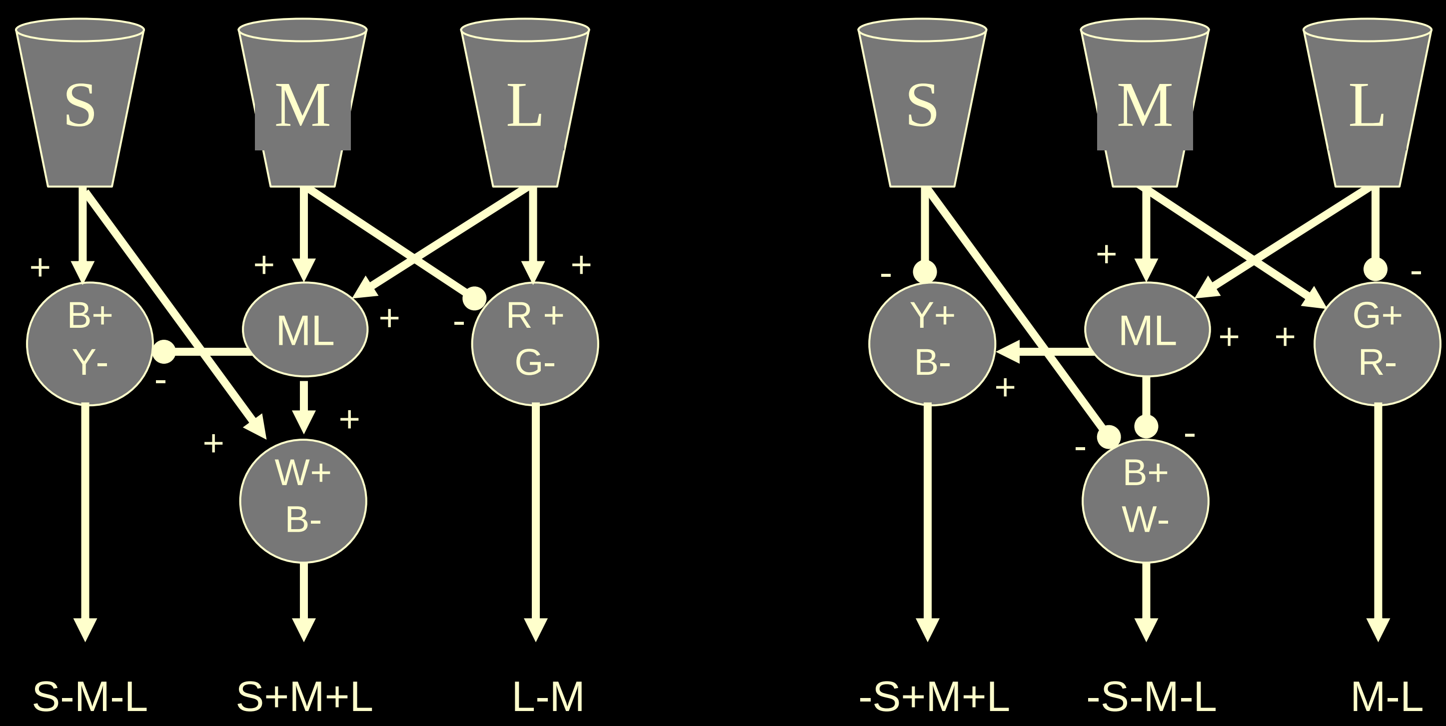


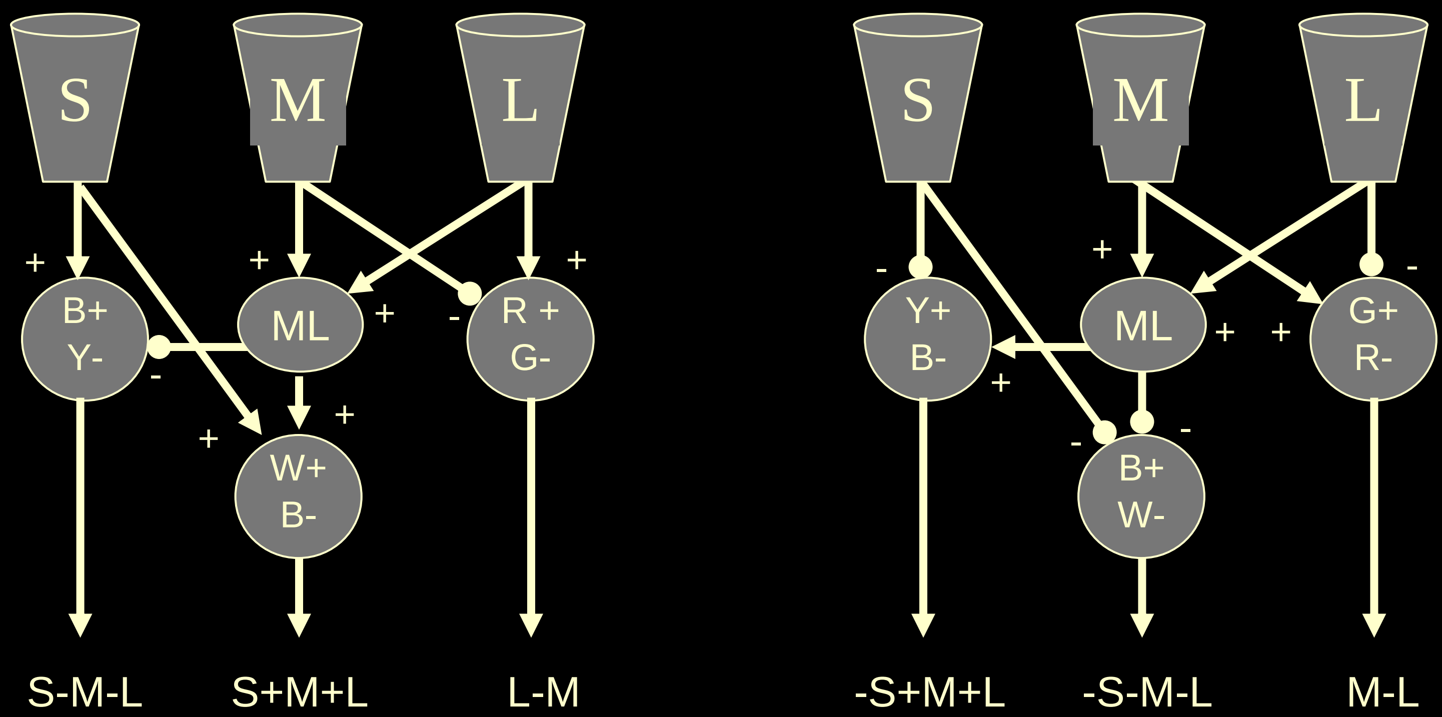
# Color opponents wiring

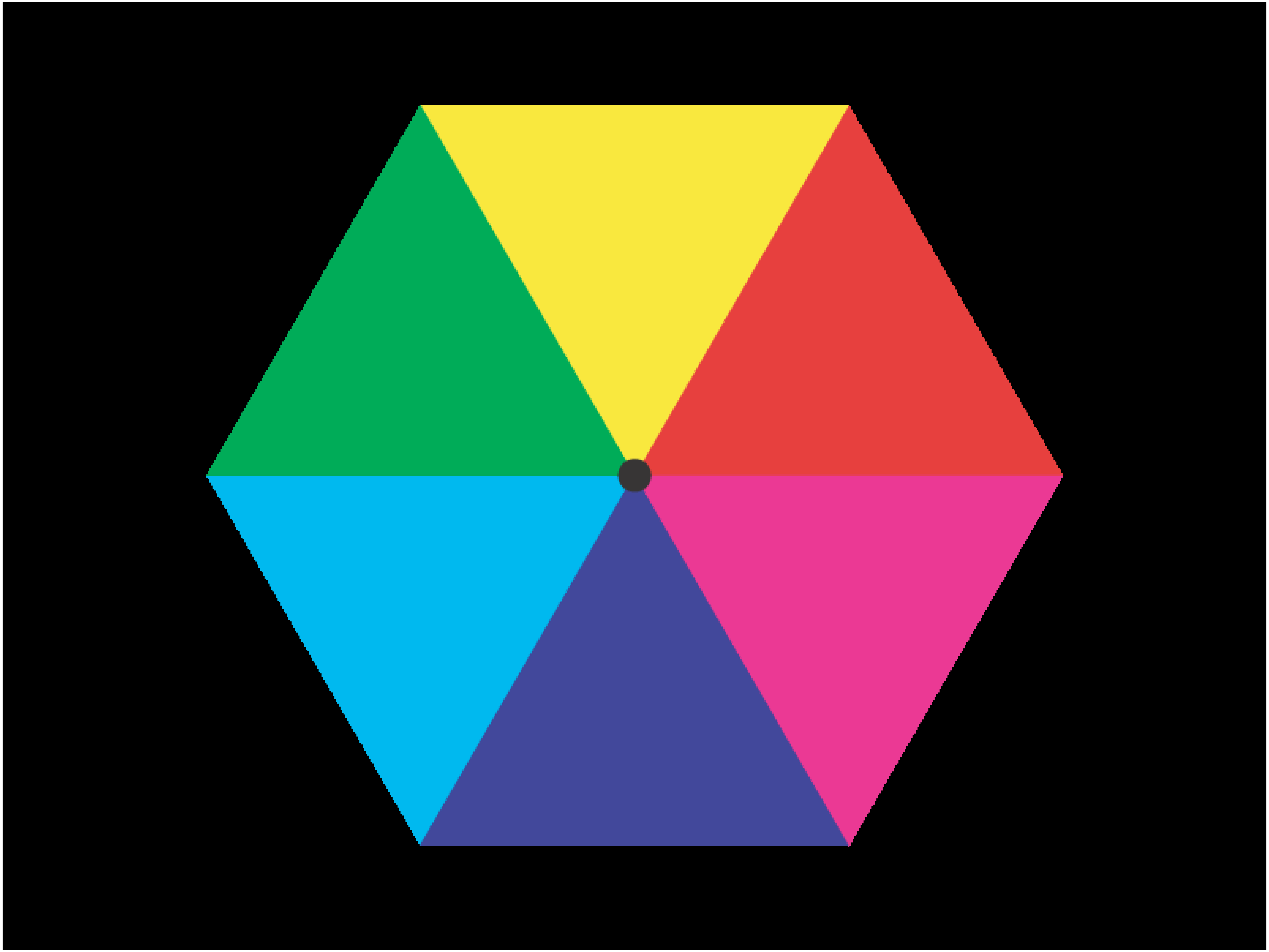
- Sums for brightness
- Differences for color opponents



# *Color opponents wiring*

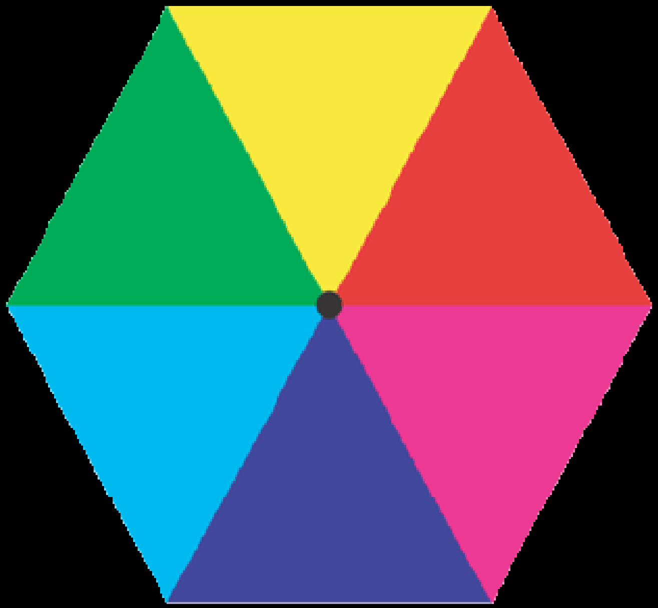
- At the end, it's just a 3x3 matrix compared to LMS



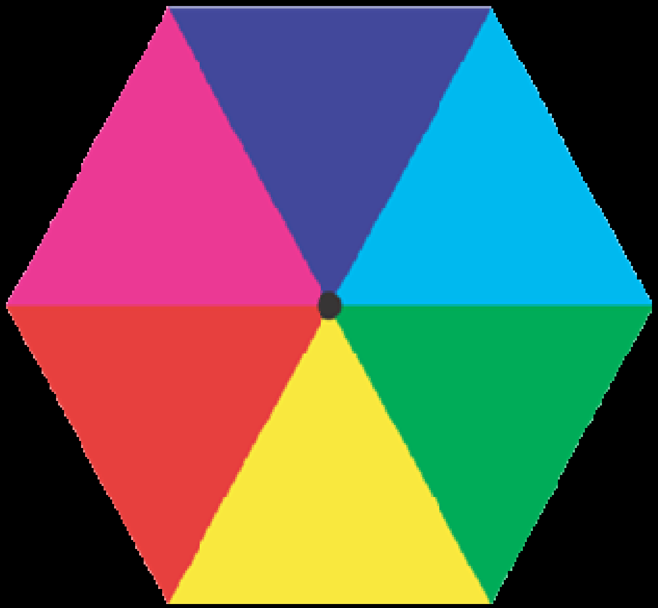


# *Opponent Colors*

Image



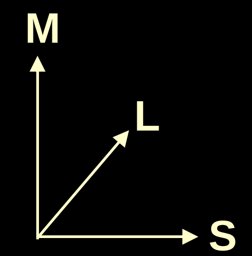
Afterimage

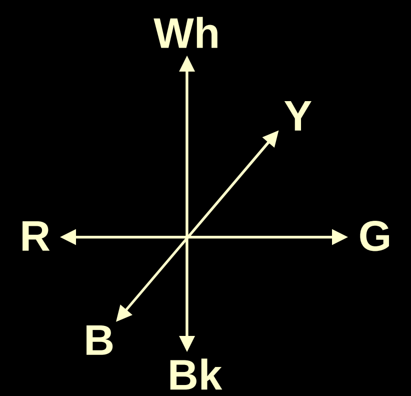


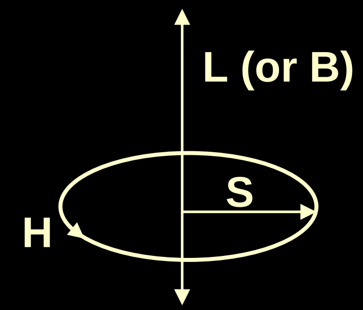
# *Plan*

- Color Vision
  - Cone response, trichromats
  - Opponent theory
  - Higher-level
- Color spaces
- Producing color
- Color effects

# *Color reparameterization*

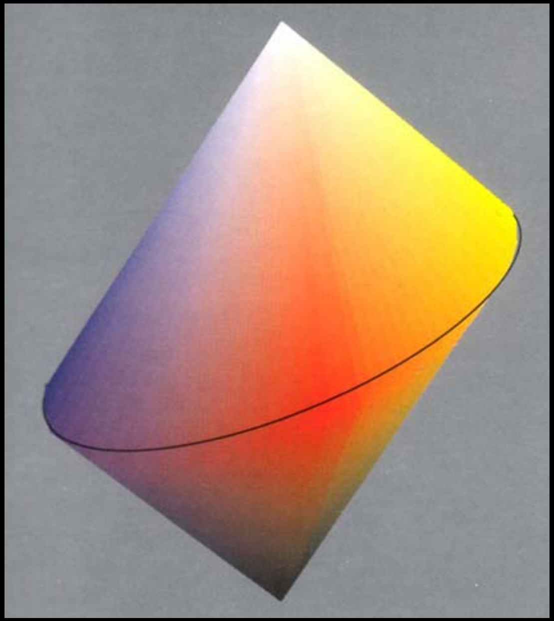


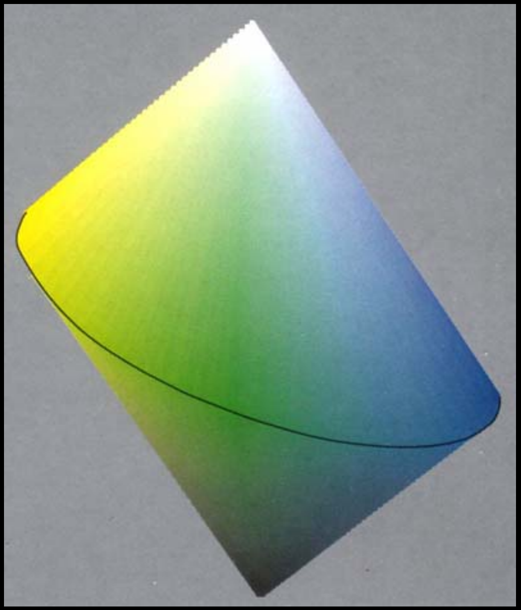



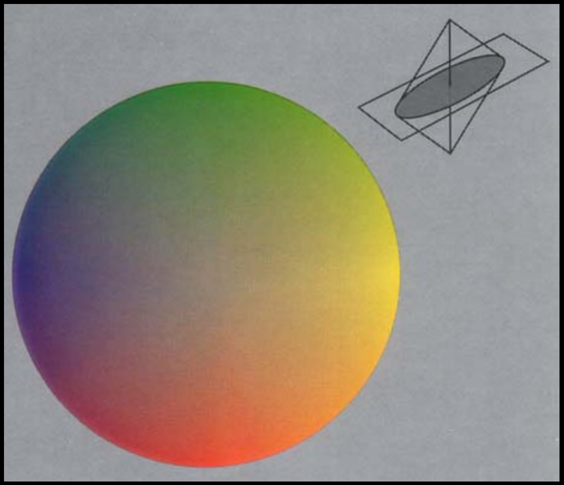



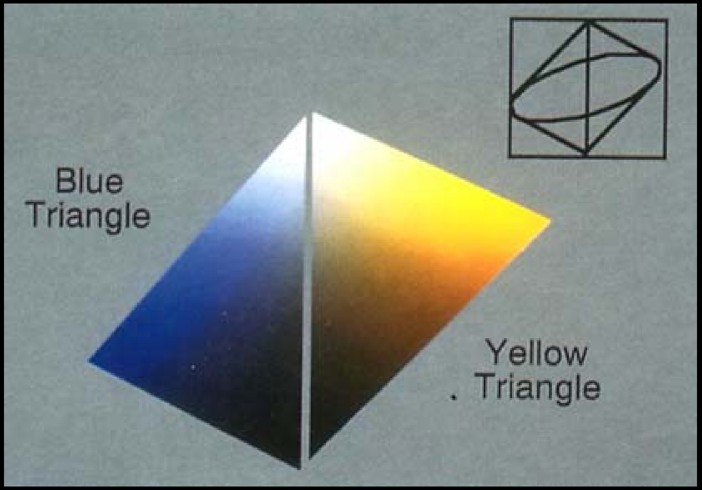

- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green
- A later stage may reparameterize:
  - Brightness or Luminance or Value
  - Hue
  - Saturation

# *Hue Saturation Value*









# *Hue Saturation Value*

- One interpretation in spectrum space
- Not the only one because of metamerism

- Dominant wavelength (hue)
- Intensity
- Purity (saturation)