Color


CALVIN AND HOBBES
BY WATTERSON
WOW, HONEY, YOU'RE MISSING A BEAUTIFUL SUNSET OUT HERE!
I'LL COUNT TO 10, AND THEN... POW!
DAD, HOW COME OLD PHOTOGRAPHS ARE ALWAYS BLACK AND WHITE? DIDN'T THEY HAVE COLOR FILM BACK THEN?
SURE THEY DID. IN FACT, THOSE OLD PHOTOGRAPHS ARE IN COLOR. IT'S JUST THE WORLD WAS BLACK AND WHITE THEN.
REALLY?
YEP. THE WORLD DIDN'T TURN COLOR UNTIL SOMETIME IN THE 1930s, AND IT WAS PRETTY GRAINY COLOR FOR A WHILE, TOO.
THAT'S REALLY WEIRD.
WELL, TRUTH IS STRANGER THAN FICTION.
BUT THEN WHY ARE OLD PAINTINGS IN COLOR?! IF THE WORLD WAS BLACK AND WHITE, WOULDN'T ARTISTS HAVE PAINTED IT THAT WAY?
NOT NECESSARILY. A LOT OF GREAT ARTISTS WERE INSANE.
BUT... BUT HOW COULD THEY HAVE PAINTED IN COLOR ANYWAY? WOULDN'T THEIR PAINTS HAVE BEEN SHADES OF GRAY BACK THEN?
OF COURSE, BUT THEY TURNED COLORS LIKE EVERYTHING ELSE DID IN THE '30s.
SO WHY DIDN'T OLD BLACK AND WHITE PHOTOS TURN COLOR TOO?
BECAUSE THEY WERE COLOR PICTURES OF BLACK AND WHITE, REMEMBER?
THE WORLD IS A COMPLICATED PLACE, HOBBES.
WHENEVER IT SEEMS THAT WAY, I TAKE A NAP IN A TREE AND WAIT FOR DINNER.

Send me an email

fredo@mit.edu

Frédo Durand

MIT- EECS

Some ideas

- Use CHDK to provide new features to Canon compact cameras
- Use flickr API to do something creative
- Explore different types of gradient reconstructions
- Improve time lapse
- Handle small parallax in panoramas
- Exploit flash/no-flash pairs
- Editing with images+depth (e.g. from stereo)
- Smart color to greyscale
- Face-aware image processing
- Sharpening out-of-focus images using other pictures from the sequences
- Application of morphing/warping
- Motion without movements and automatic illusions

Color

Frédo Durand
MIT- EECS

Many slides courtesy of Victor Ostromoukhov, Leonard McMillan, Bill Freeman

Does color puzzle you?

Puzzles and mysteries

- Aren’t colors spectra? Why do we need only 3 numbers to represent them
- Are black, and white, colors?
- Are primary colors red green and blue? Or red green yellow and blue? where do cyan and magenta come from?
- Why is there a color circle? what’s between red and blue? aren’t they at opposite ends of the spectrum?
- Should the camera RGB filters be the same as the projector’s RGB filters? Should they be the same as the human eye’s spectral response?

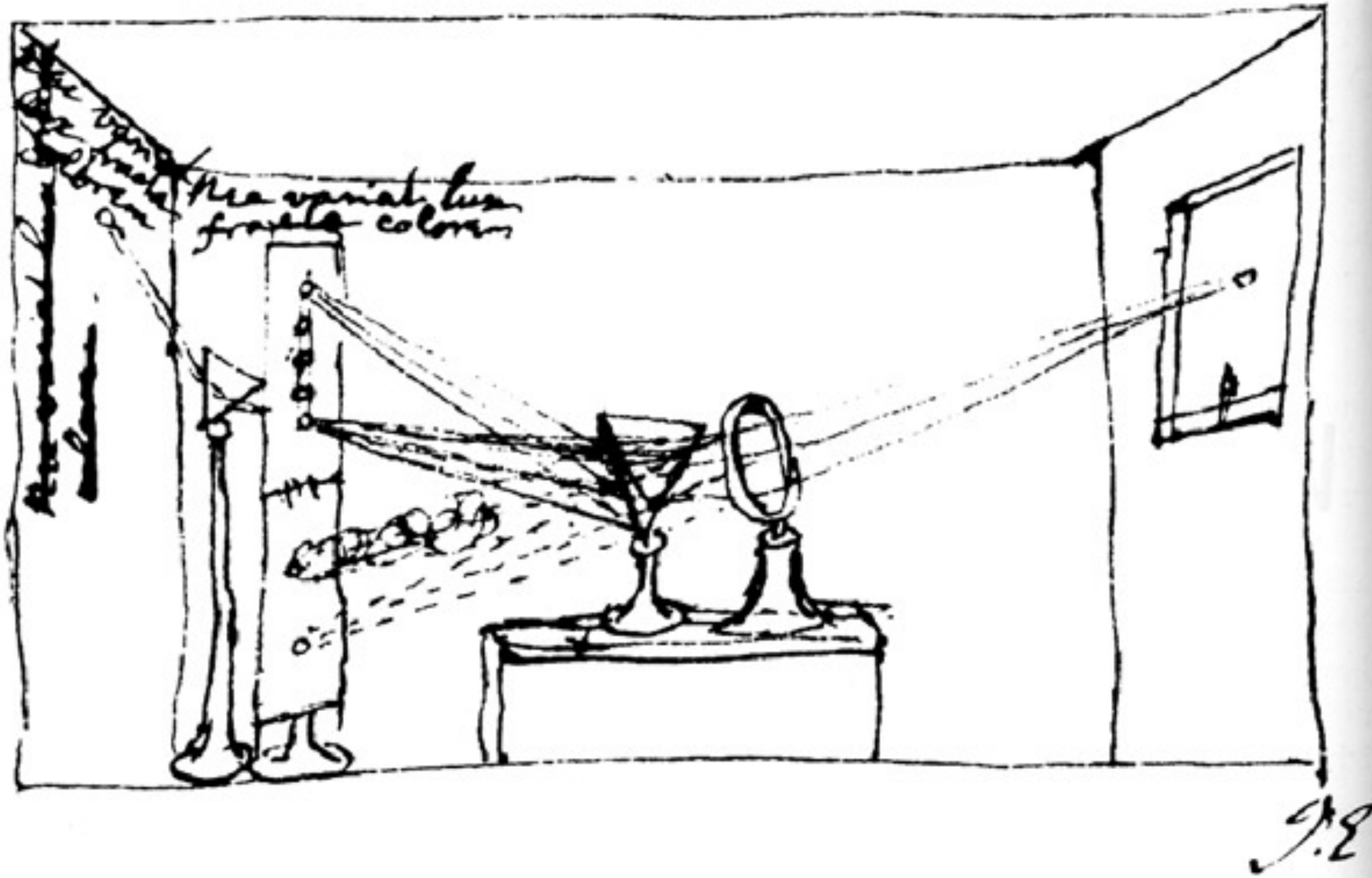
Answer

- It's all linear algebra

Plan

- Spectra
- Cones and spectral response
- Color blindness and metamers
- Color matching
- Color spaces

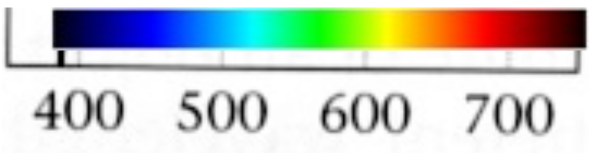
Color



4.1 NEWTON'S SUMMARY DRAWING of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

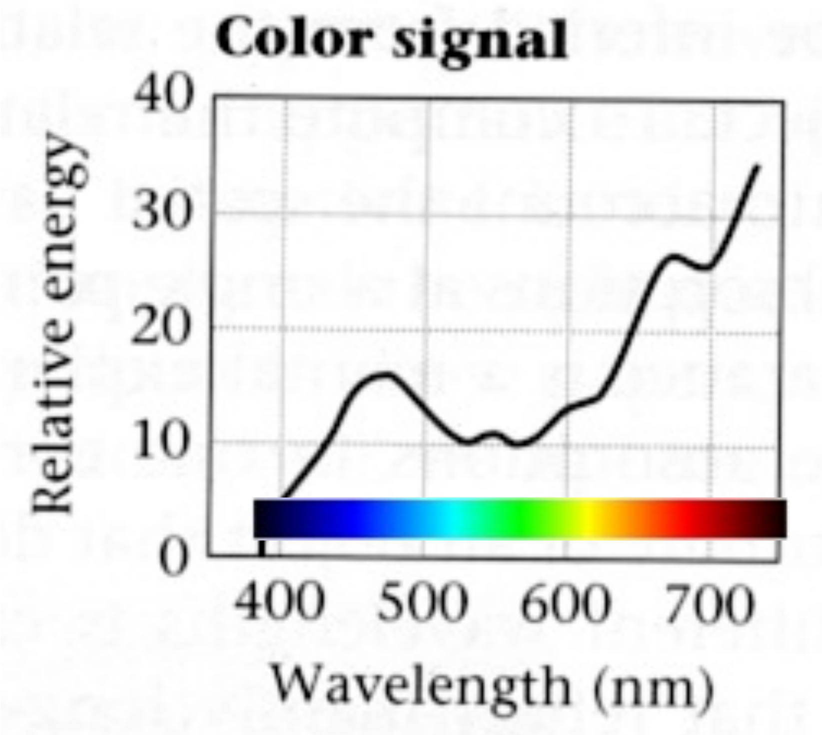
From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Spectrum



Light is a wave
Visible: between 450 and 700nm

Spectrum



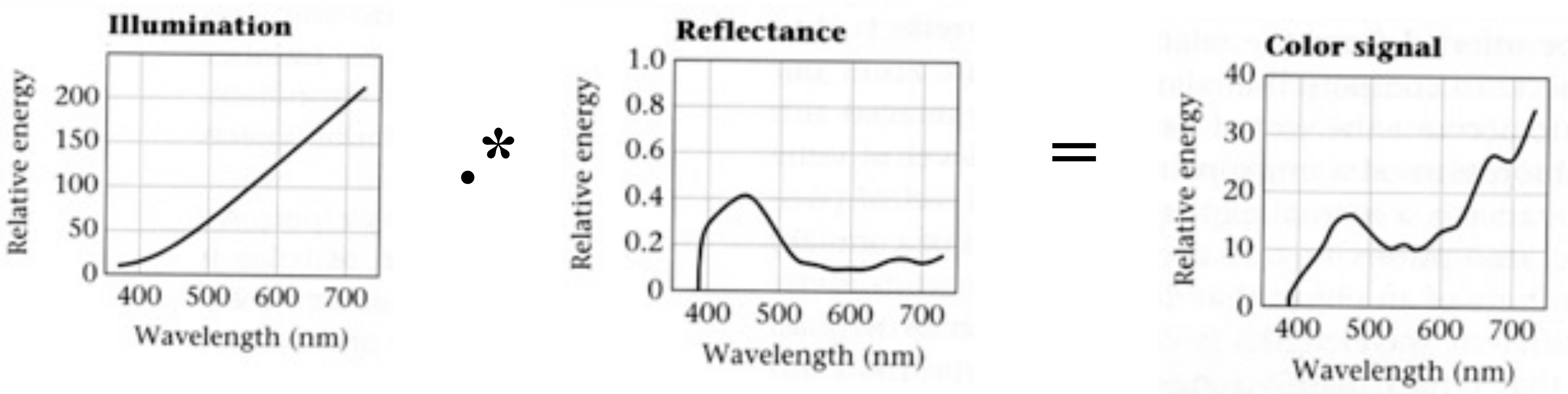
Light is characterized by its spectrum:
amount of energy at each wavelength
This is a full distribution:
one value per wavelength (infinite number of values)

Light-matter interaction

Where spectra come from:
- light source spectrum
- object reflectance (aka spectral albedo)

get multiplied wavelength by wavelength

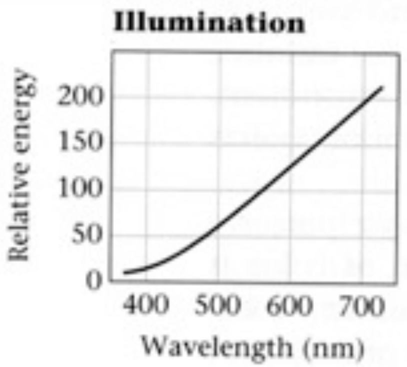
There are different physical processes that explain this multiplication
e.g. absorption, interferences



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

Alternative: transmittance

Also get multiplied



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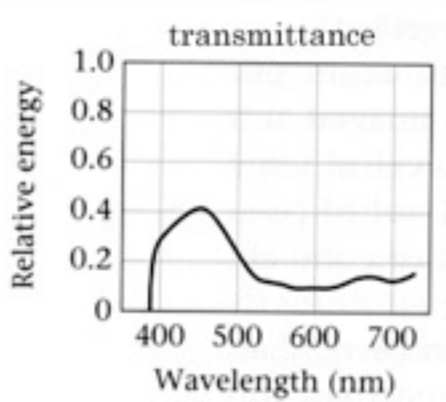

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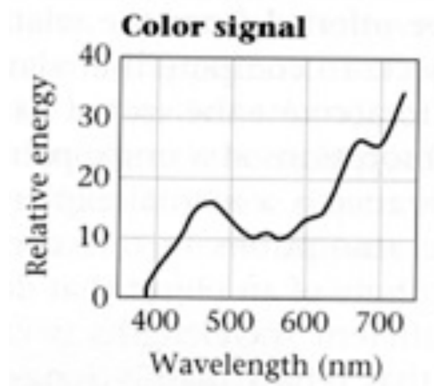
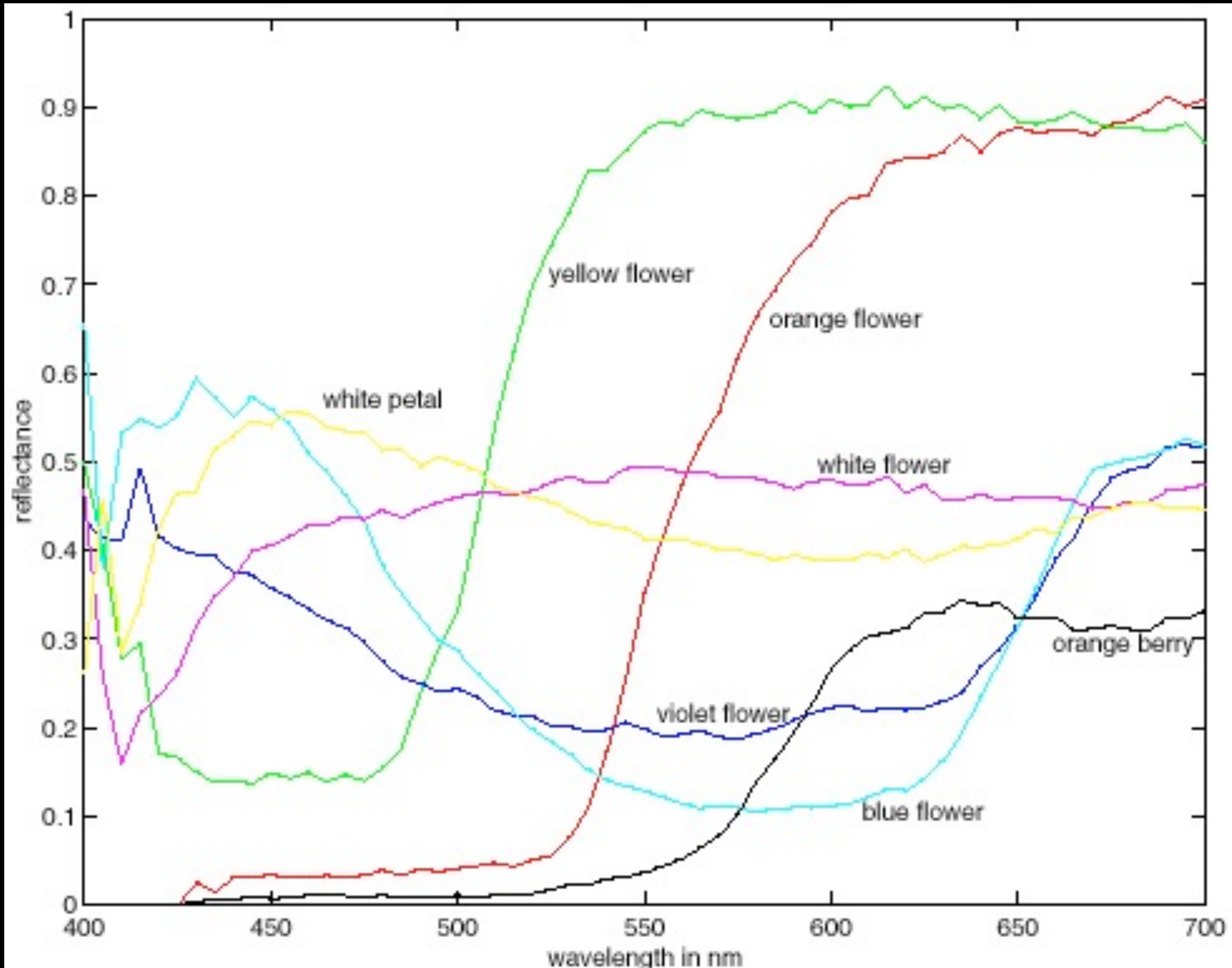


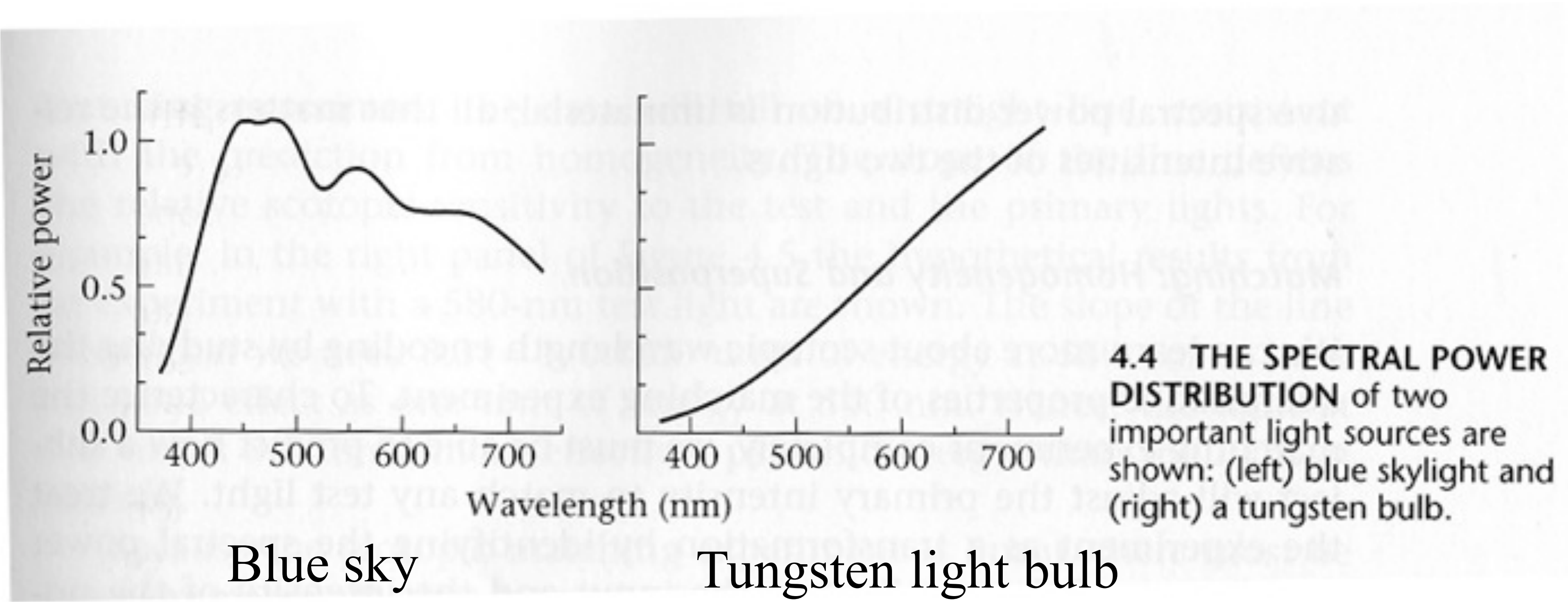
Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Examples of reflectance spectra



Spectral albedoes for several different leaves, with color names attached. Notice that different colours typically have different spectral albedo, but that different spectral albedoes may result in the same perceived color (compare the two whites). Spectral albedoes are typically quite smooth functions. Measurements by E.Koivisto.

Examples of illumination spectra



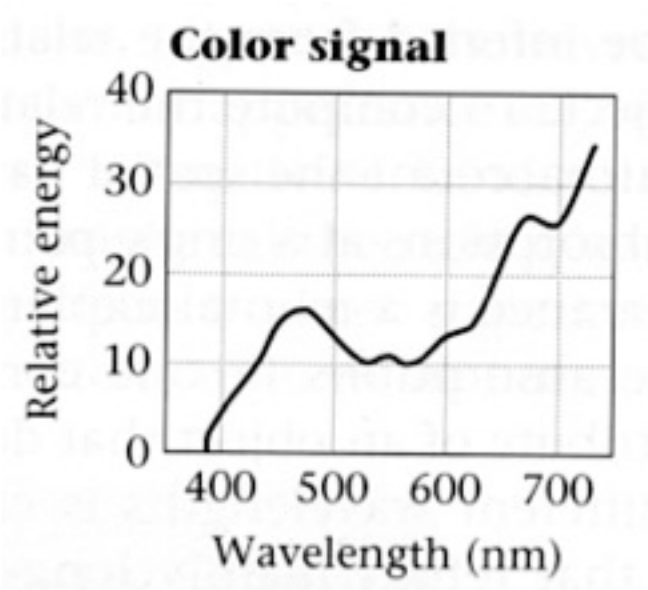
Blue sky Tungsten light bulb

- Important consequence:
  the spectrum leaving an object depends on the illumination

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

Questions?

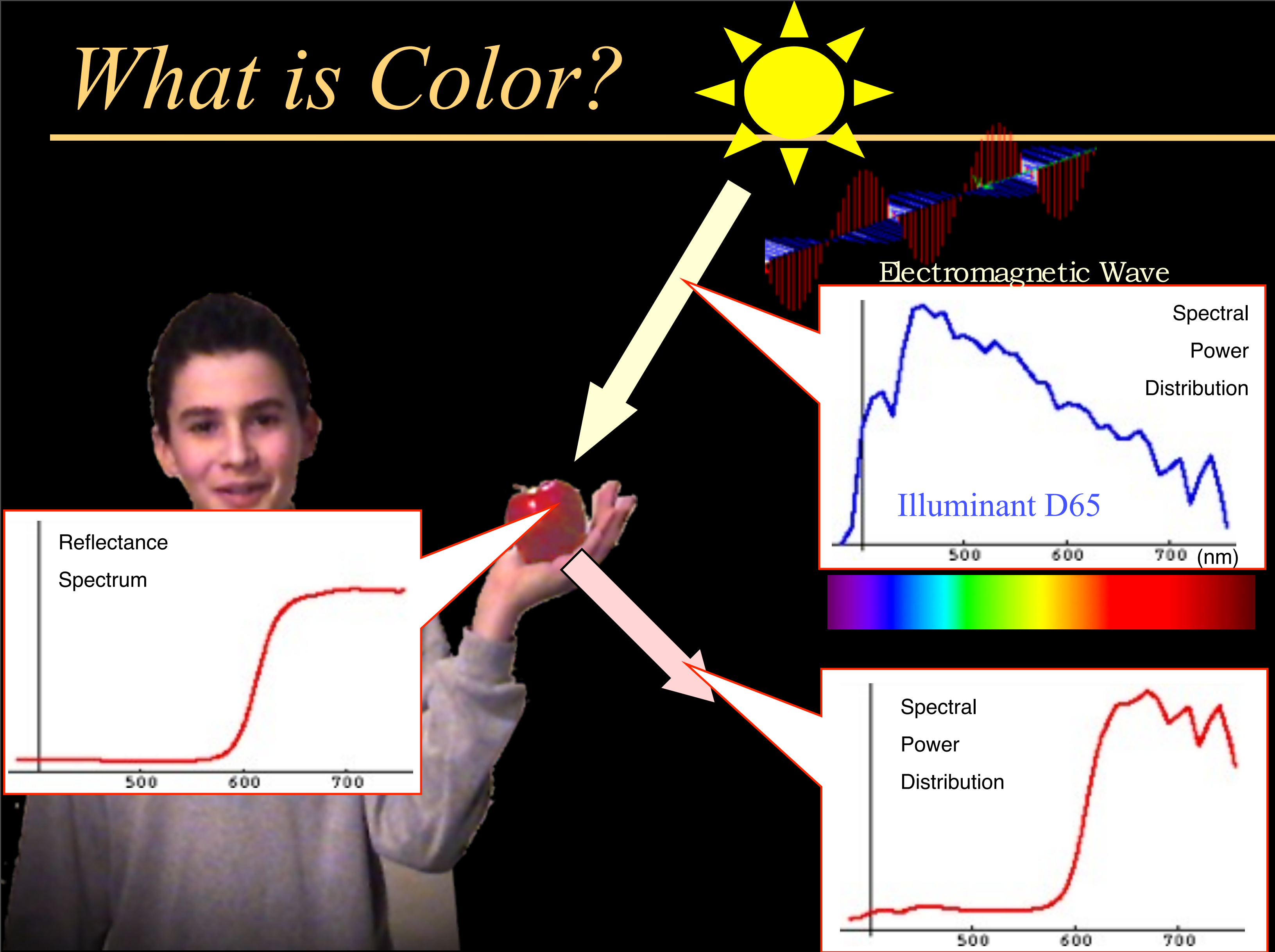
- So far, physical side of colors: **spectra**
  - an infinite number of values (one per wavelength)



Plan

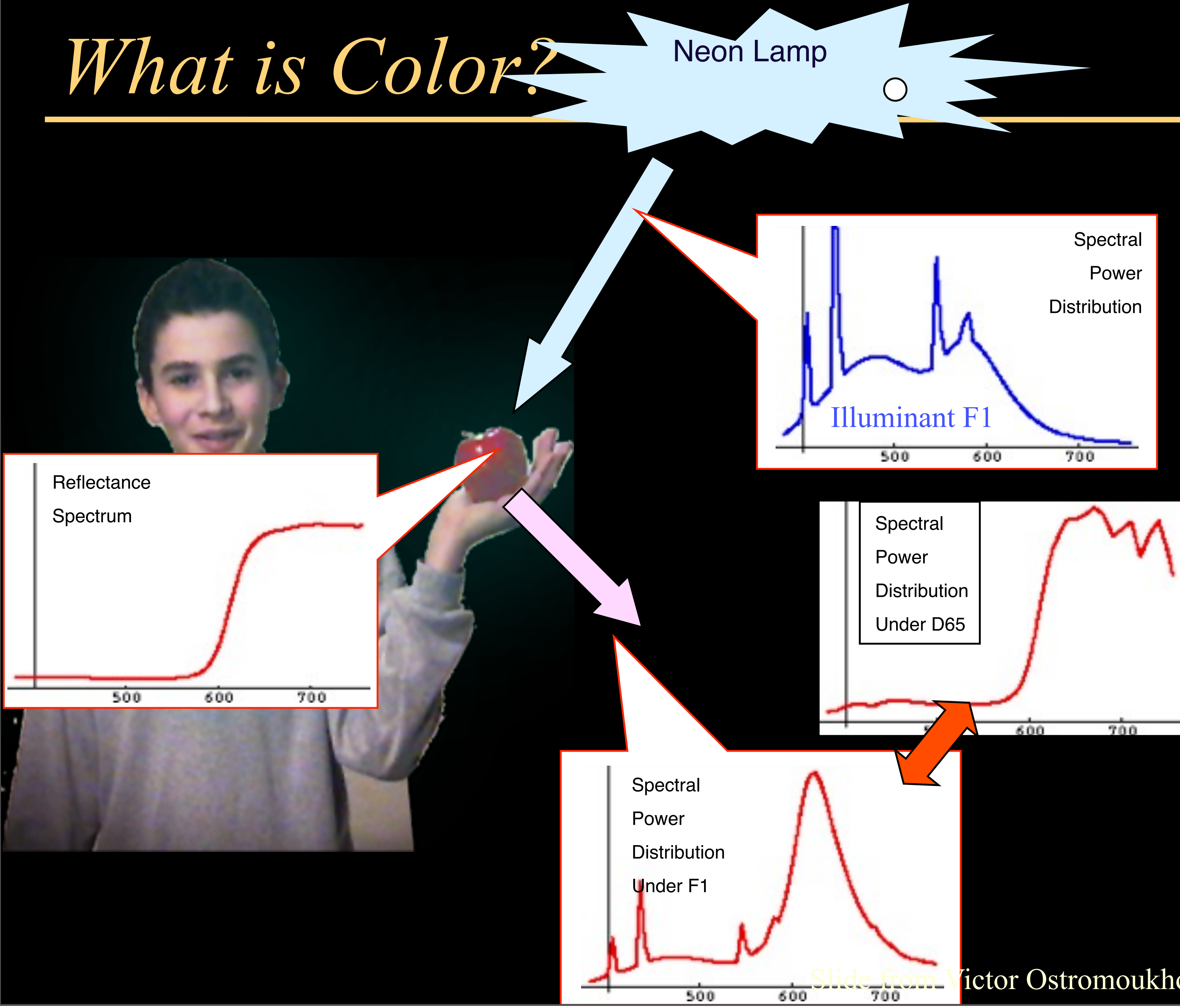
- Spectra
- **Cones and spectral response**
- Color blindness and metamers
- Color matching
- Color spaces

What is Color?



Slide from Victor Ostromoukhov

What is Color?



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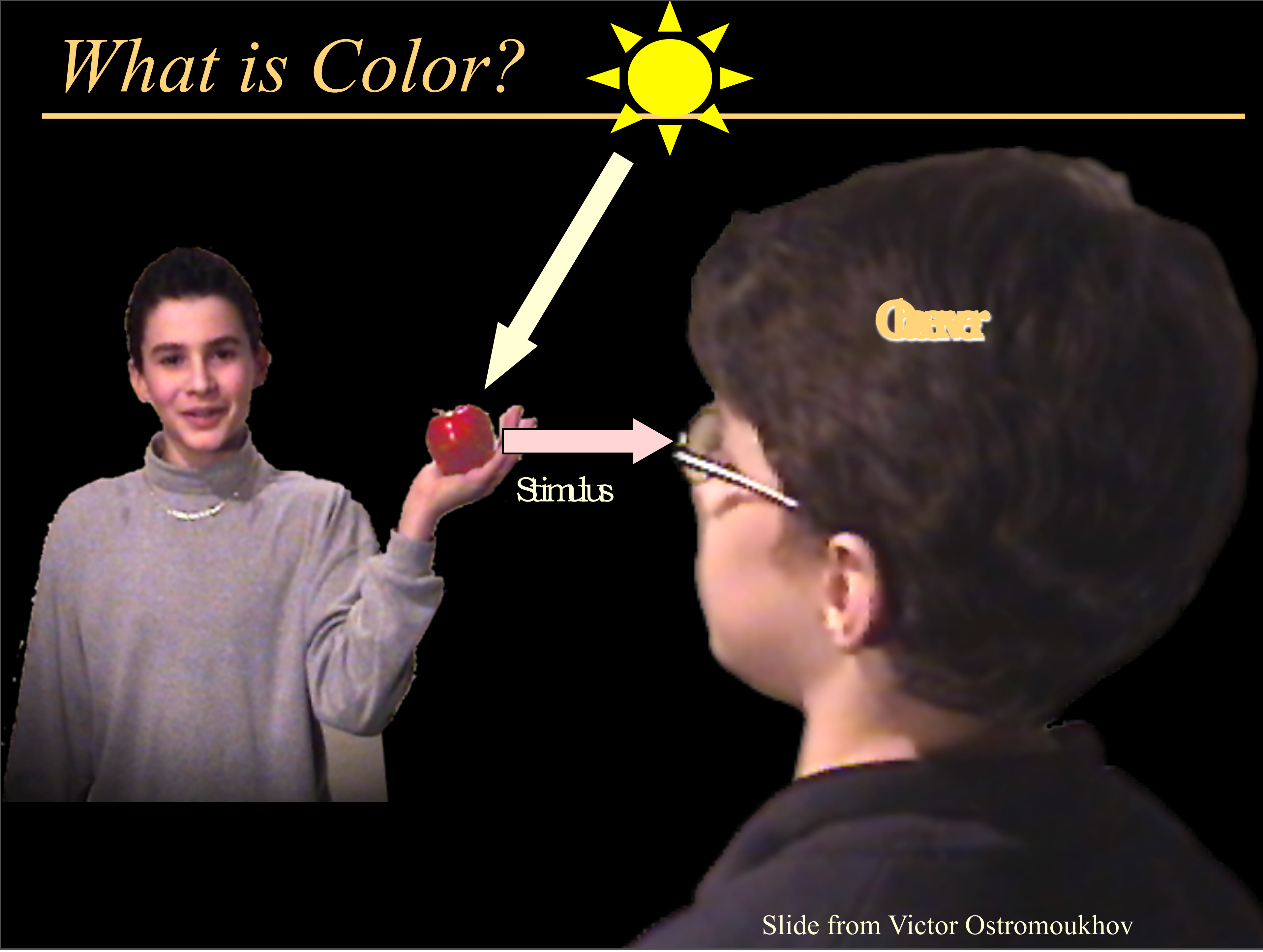

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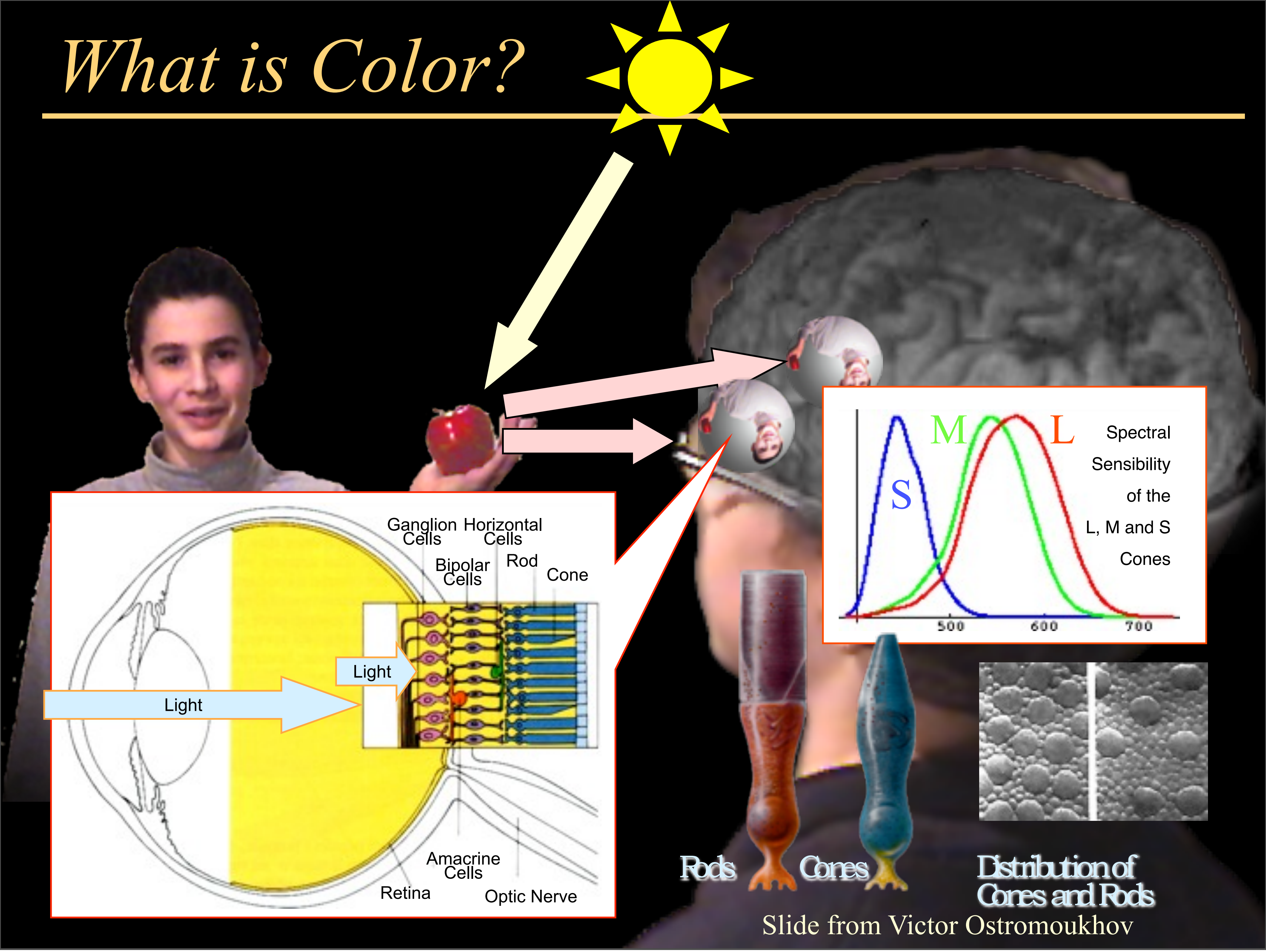

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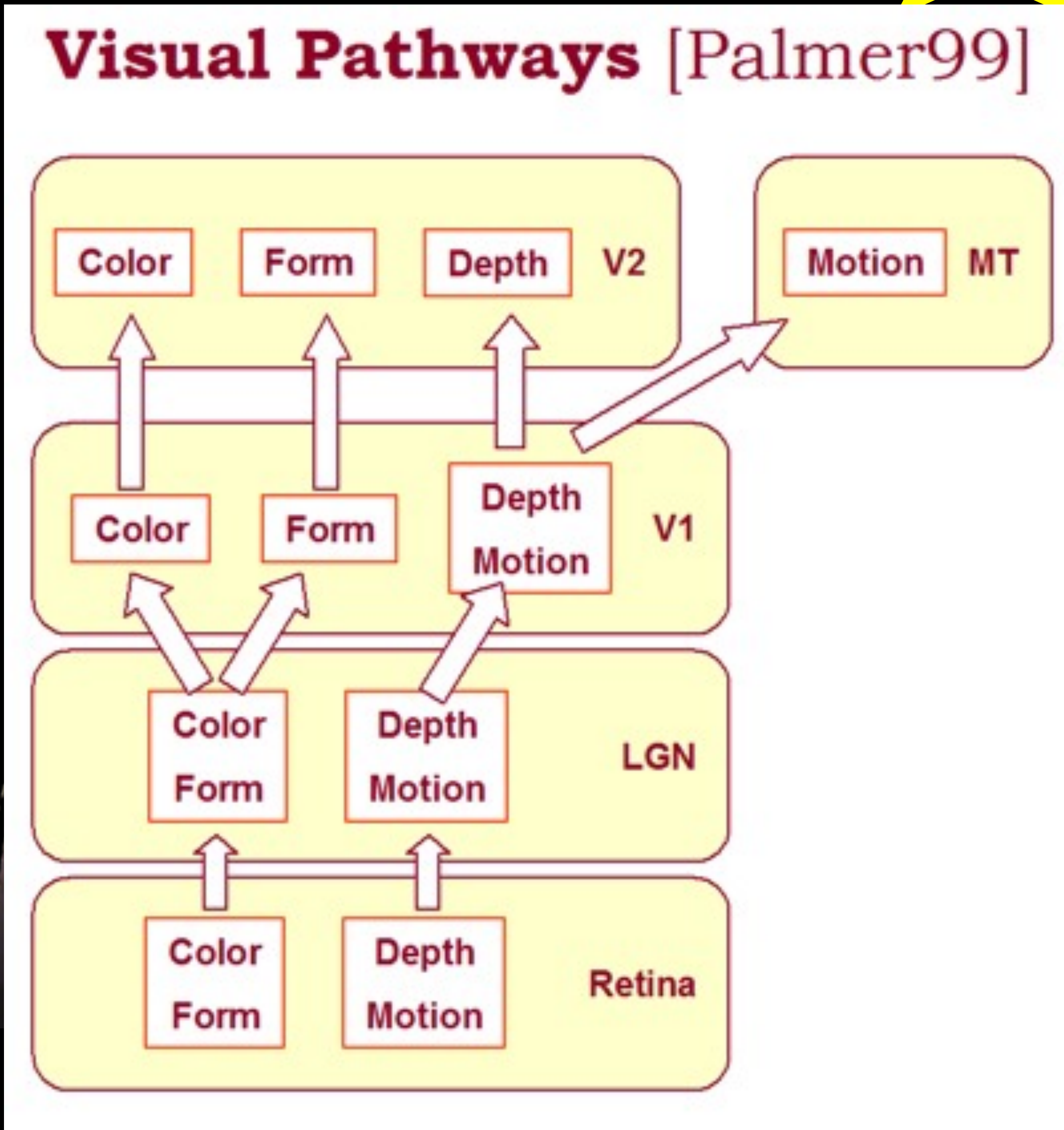
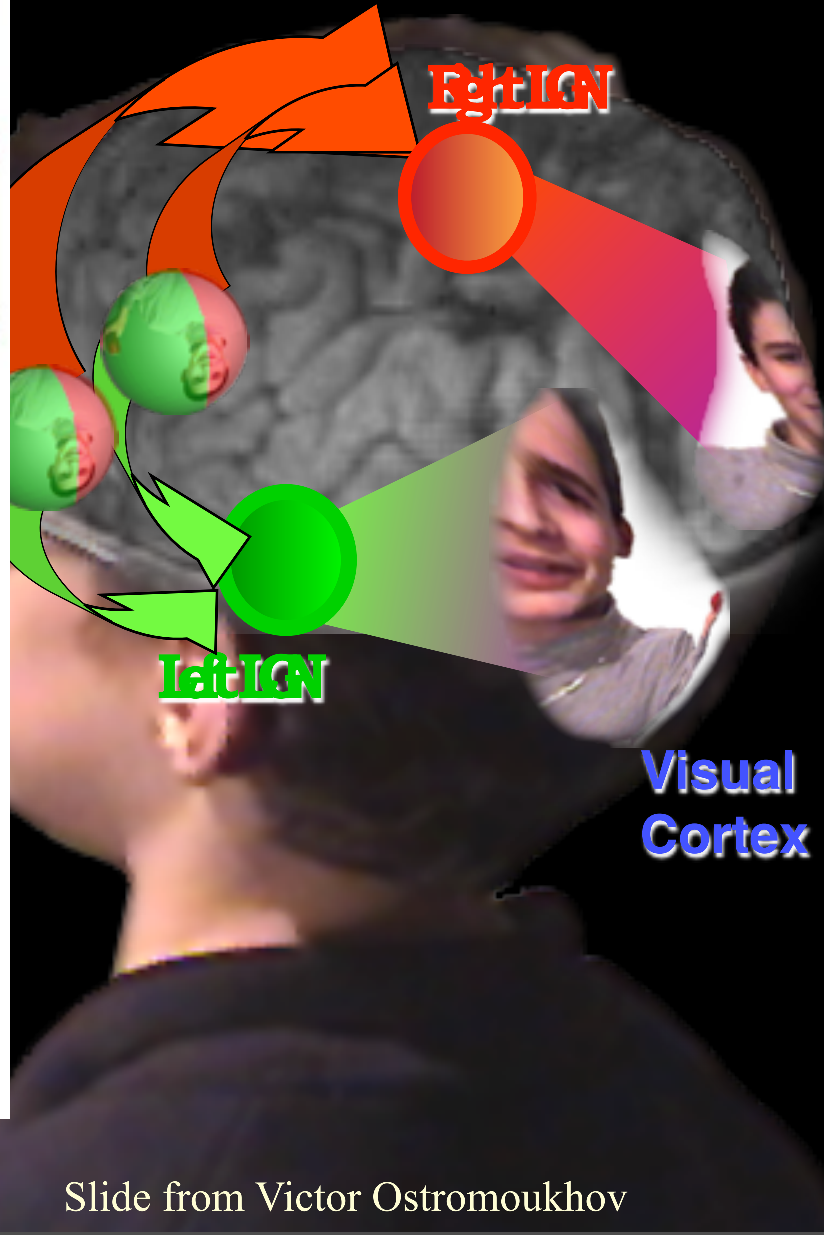
What is Color?



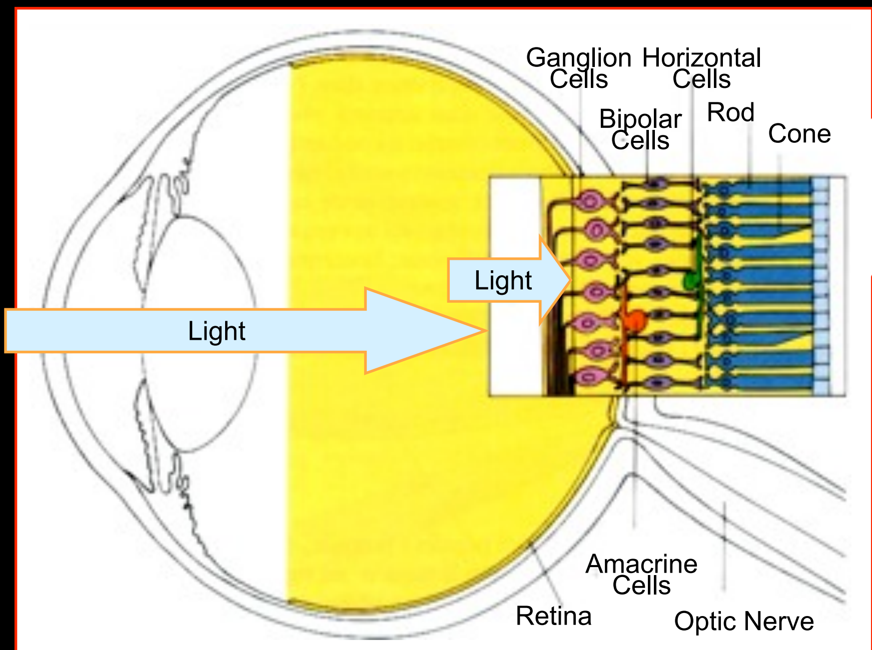


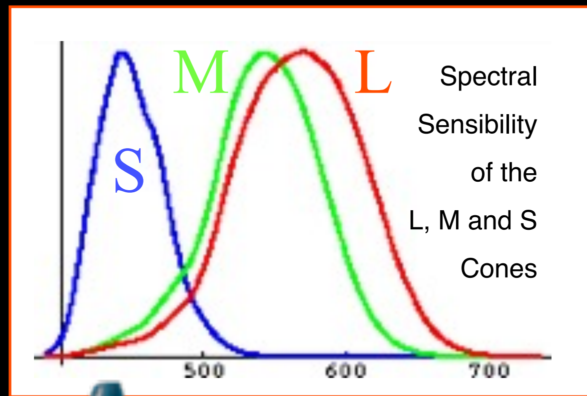
LGN = Lateral Geniculate Nucleus

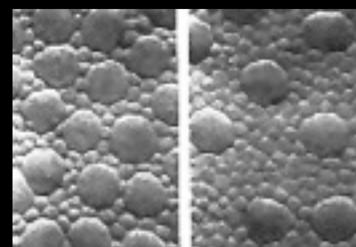
Slide from Victor Ostromoukhov

Cones

- We focus on low-level aspects of color
  - Cones and early processing in the retina
- We won’t talk about rods (night vision)







Distribution of Cones and Rods

Summary (and time for questions)

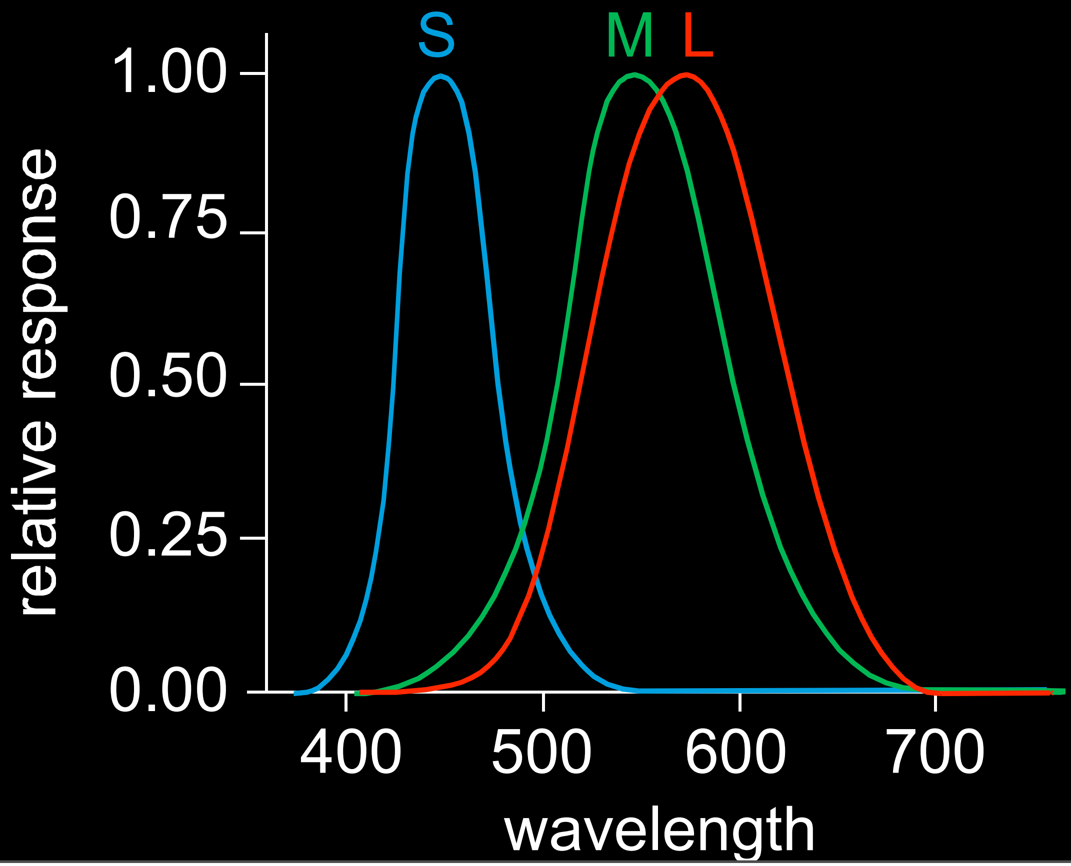
- Spectrum: infinite number of values
  - can be multiplied
  - can be added
- Light spectrum multiplied by reflectance spectrum
  - spectrum depends on illuminant
- Human visual system is complicated

Plan

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

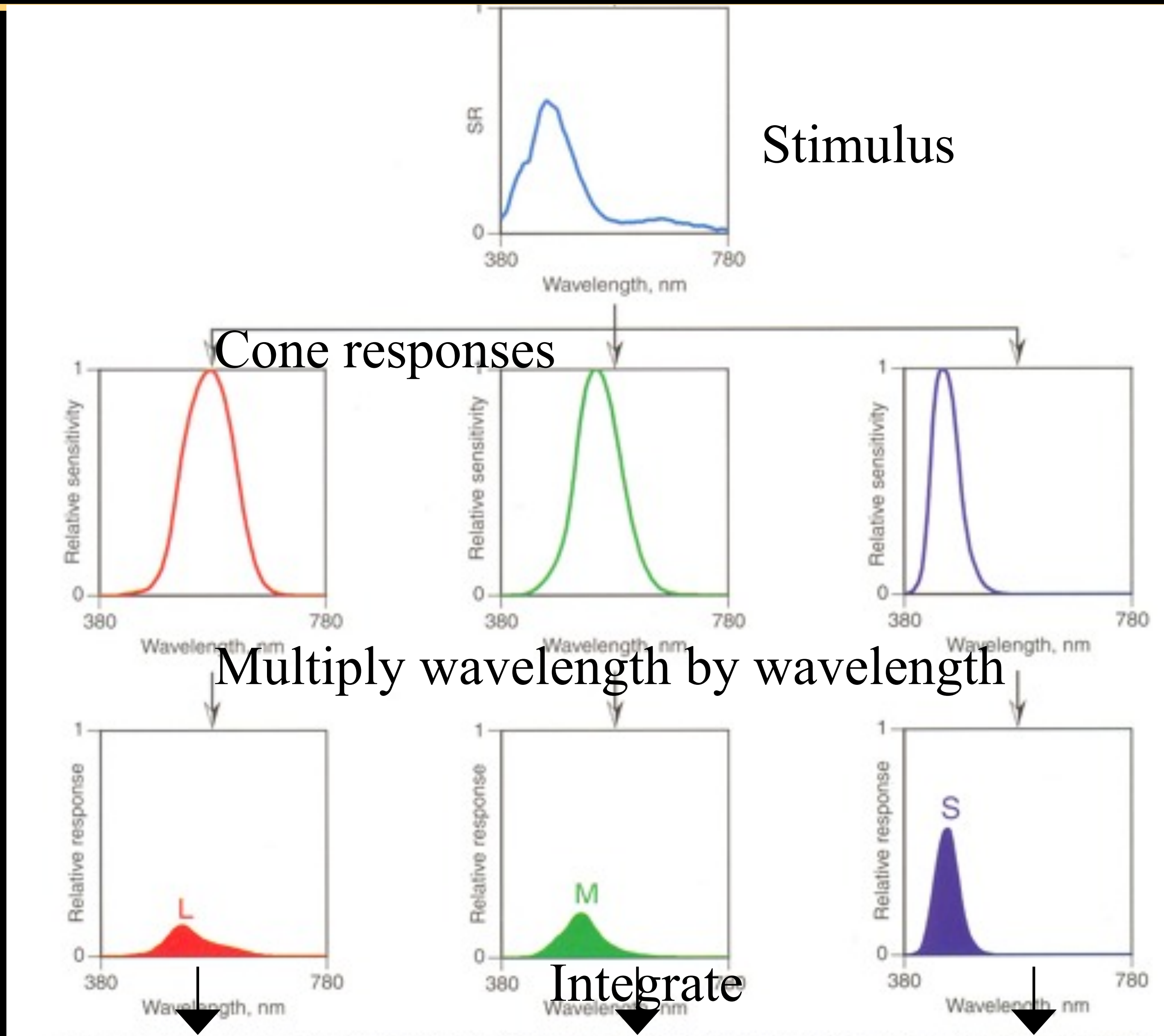
Cone spectral sensitivity

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



Cone response

Start from infinite number of values (one per wavelength)

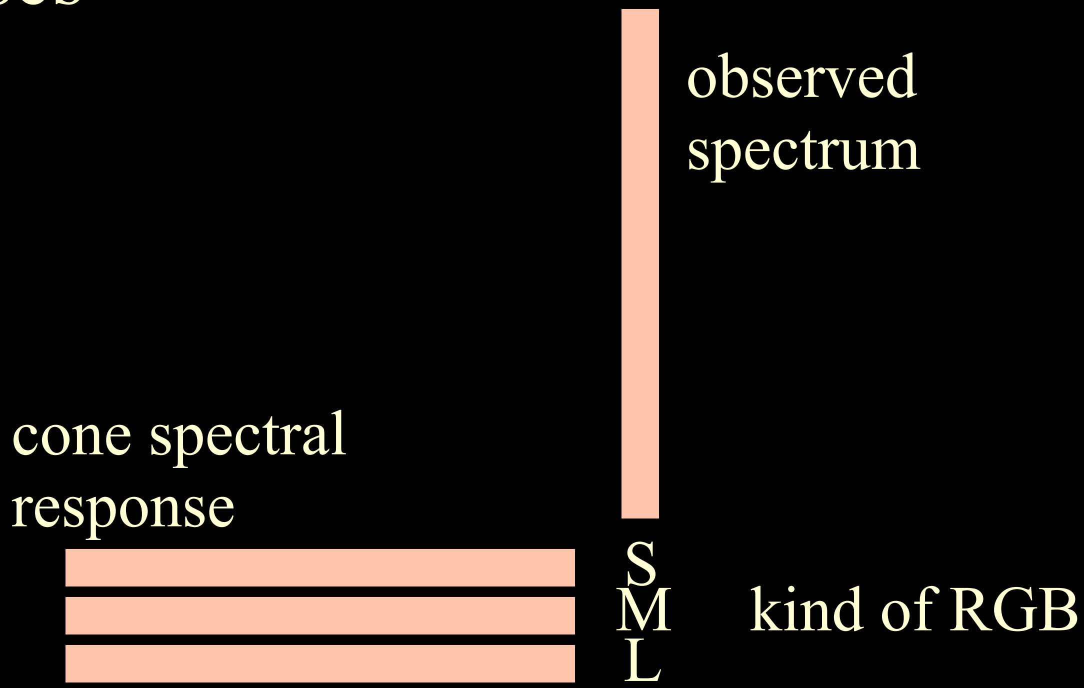


1 number 1 number 1 number

End up with 3 values (one per cone type)

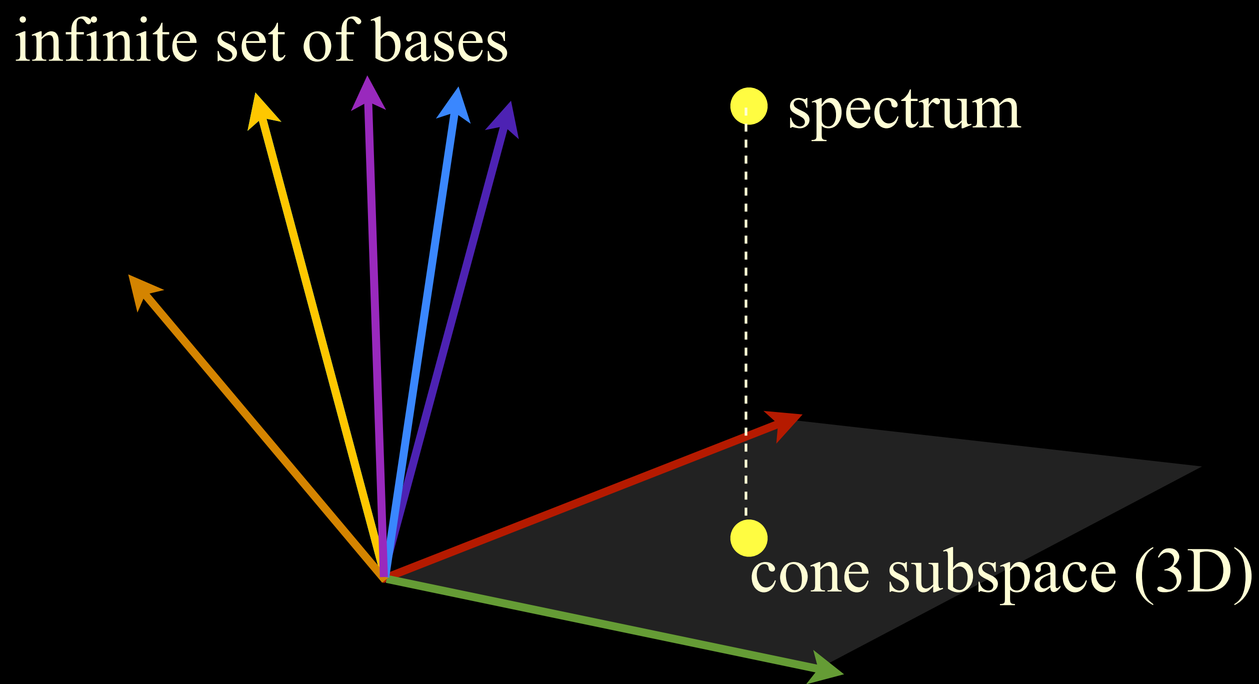
For matrix lovers

- Spectrum: big long vector size N where N=∞
- Cone response: 3xN matrix of individual responses



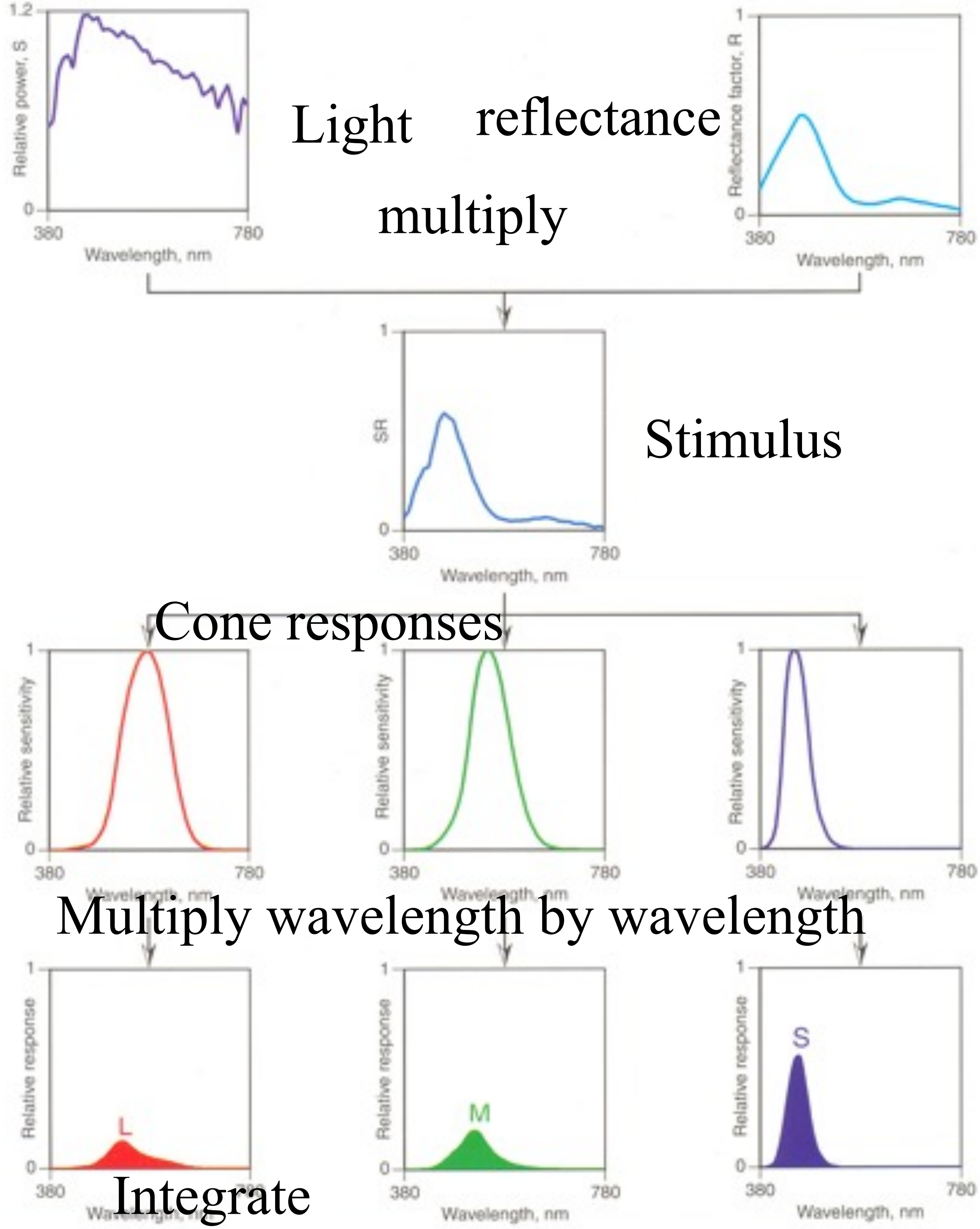
For geometry lovers

- Spectrum: point in infinite dimensional space
- Human vision: 3D linear subspace
- Projection



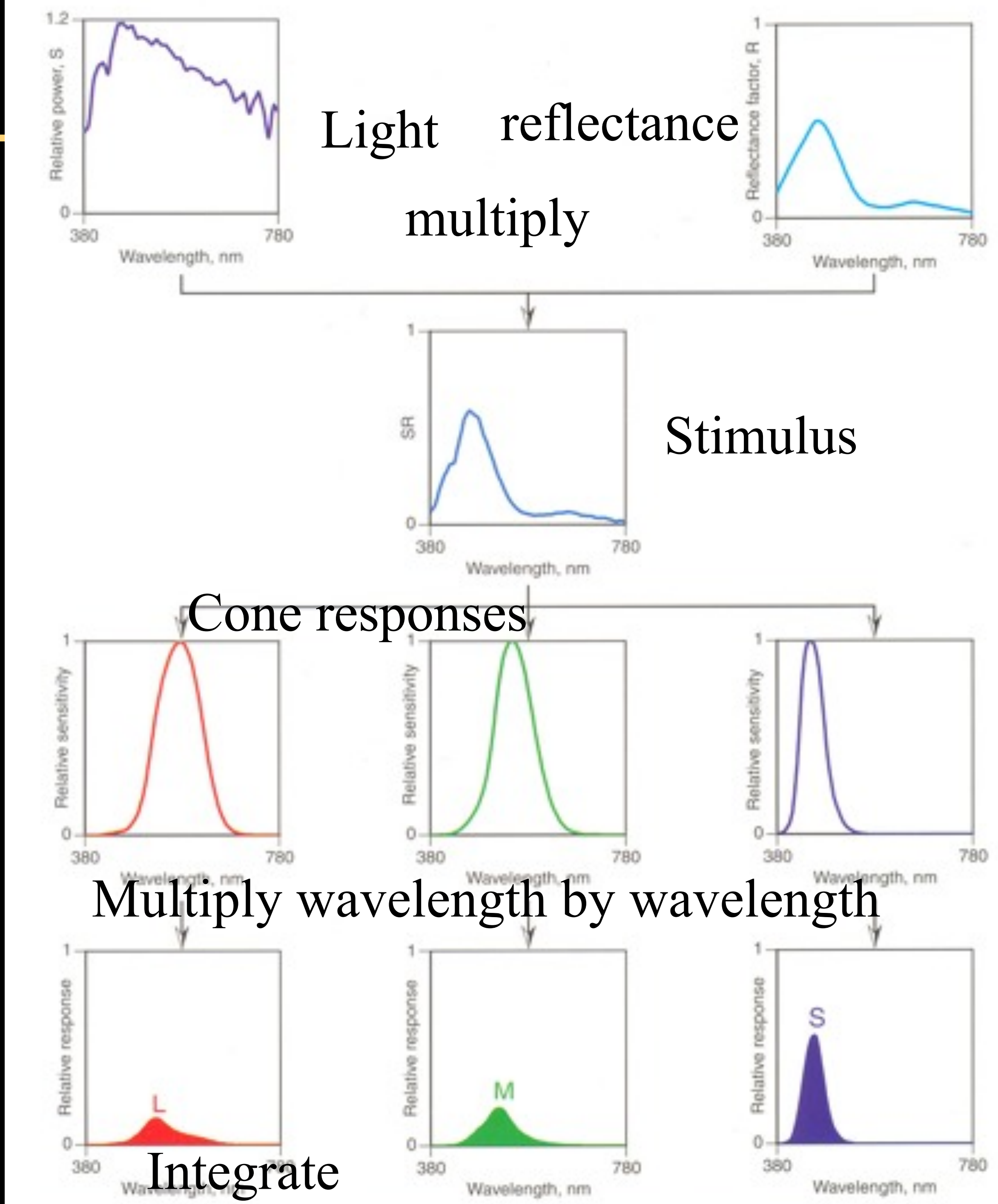
Big picture

- It's all linear!

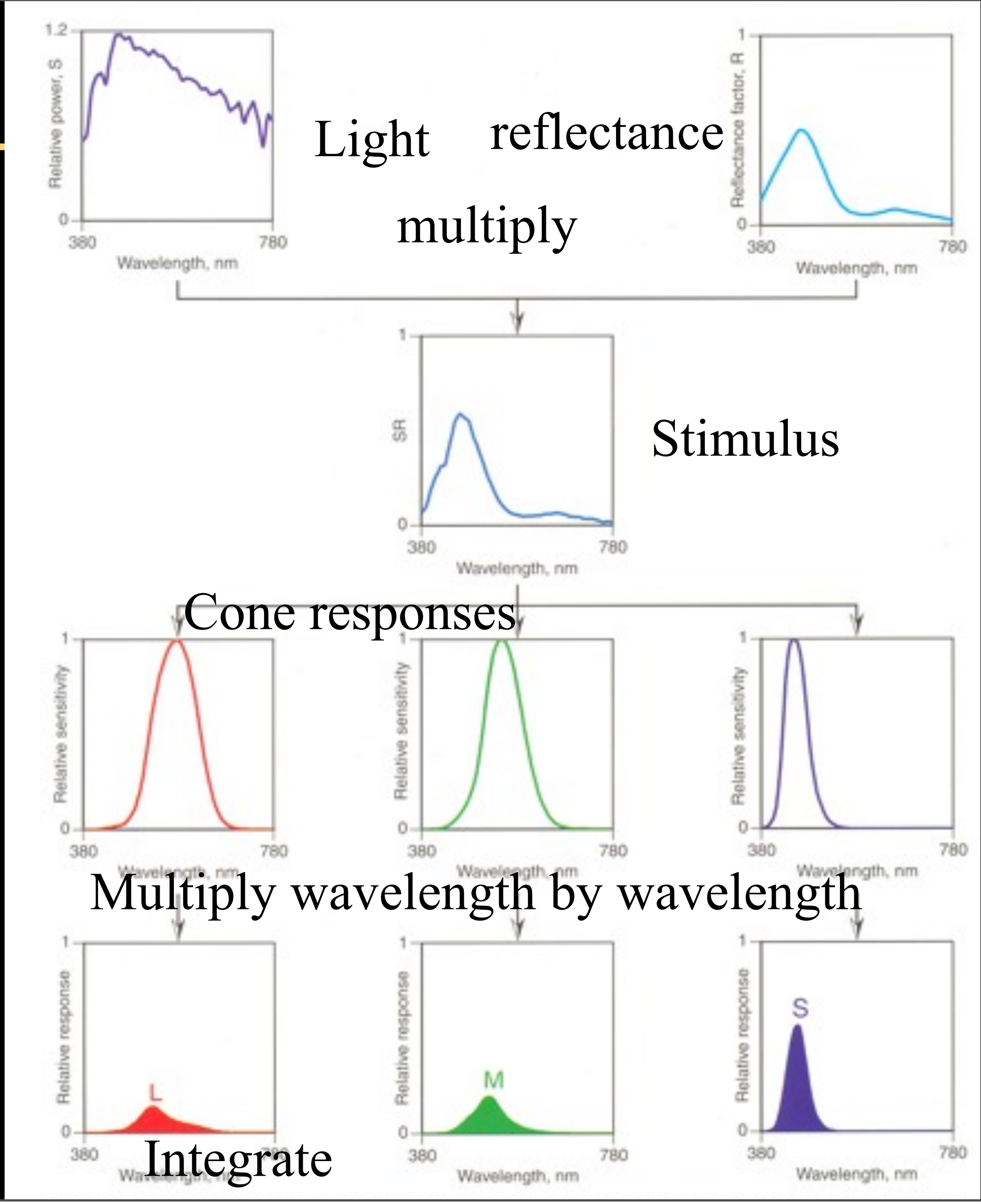


Big picture

- It's all linear!
  - multiply
  - add
- But
  - non-orthogonal bases
  - infinite dimension
  - light must be positive
- Depends on light source



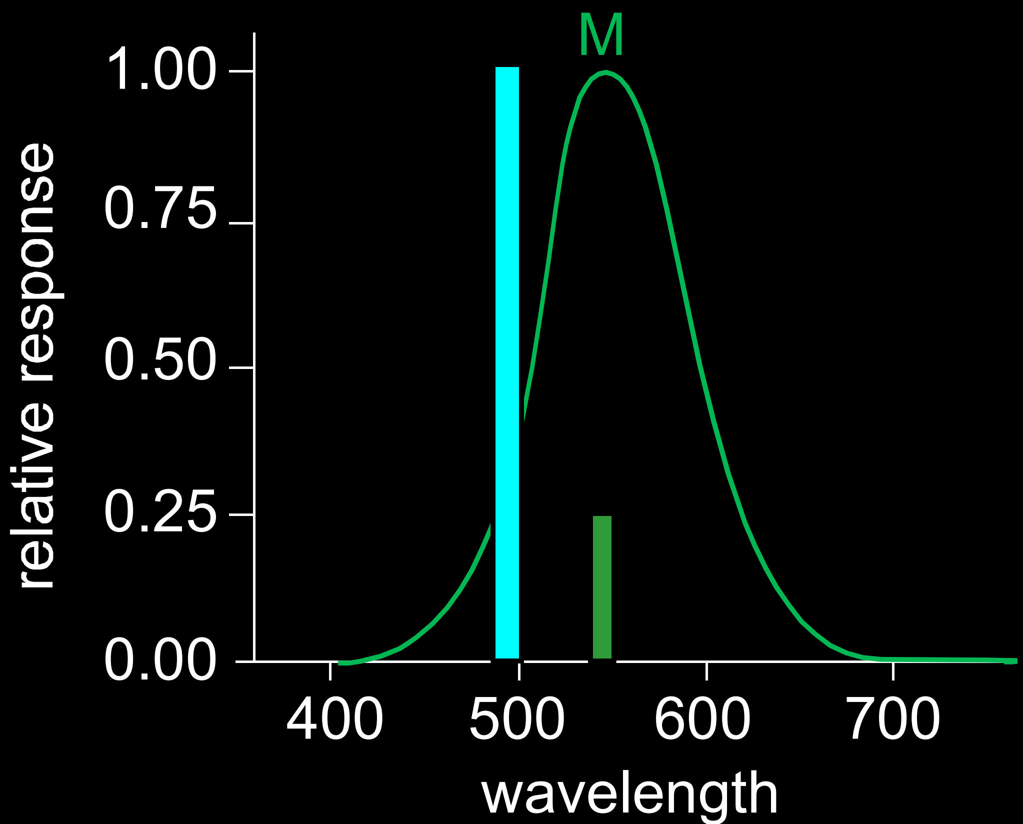
Questions?



Light
reflectance
multiply
Relative power, S
Reflectance factor, R
Wavelength, nm
SR
Stimulus
Cone responses
Relative sensitivity
Multiply wavelength by wavelength
Relative response
L
M
S
Integrate

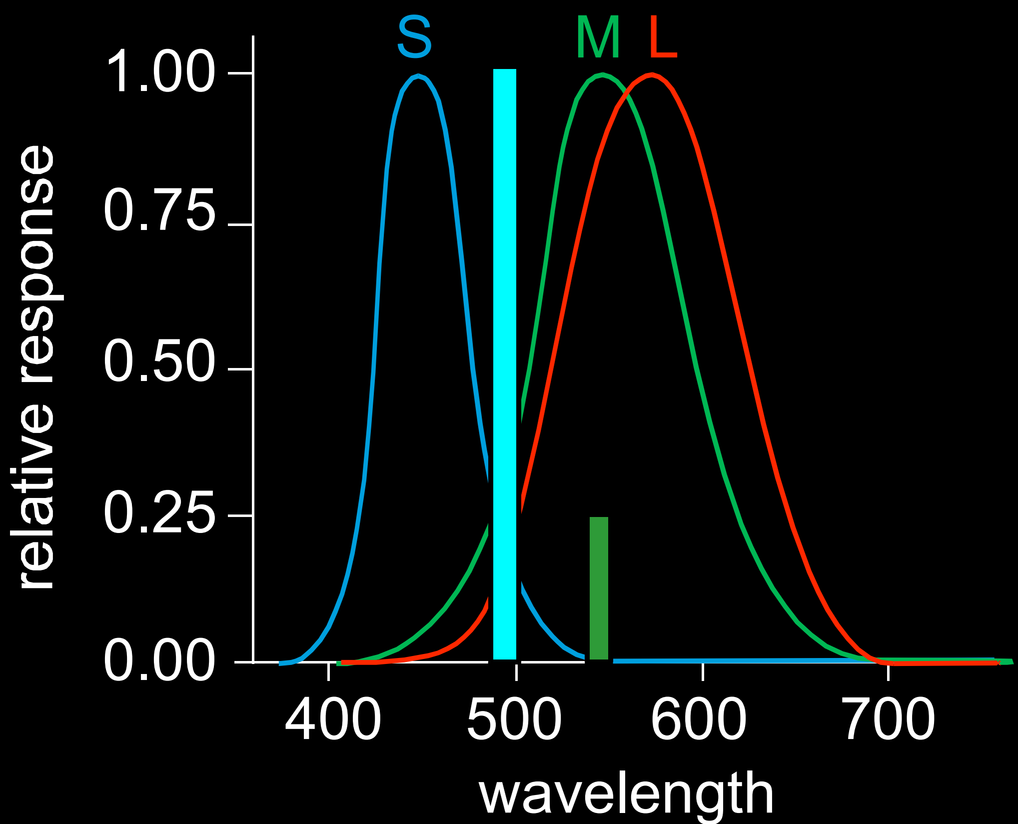
A cone does not “see” colors

- Different wavelength, different intensity
- Same response



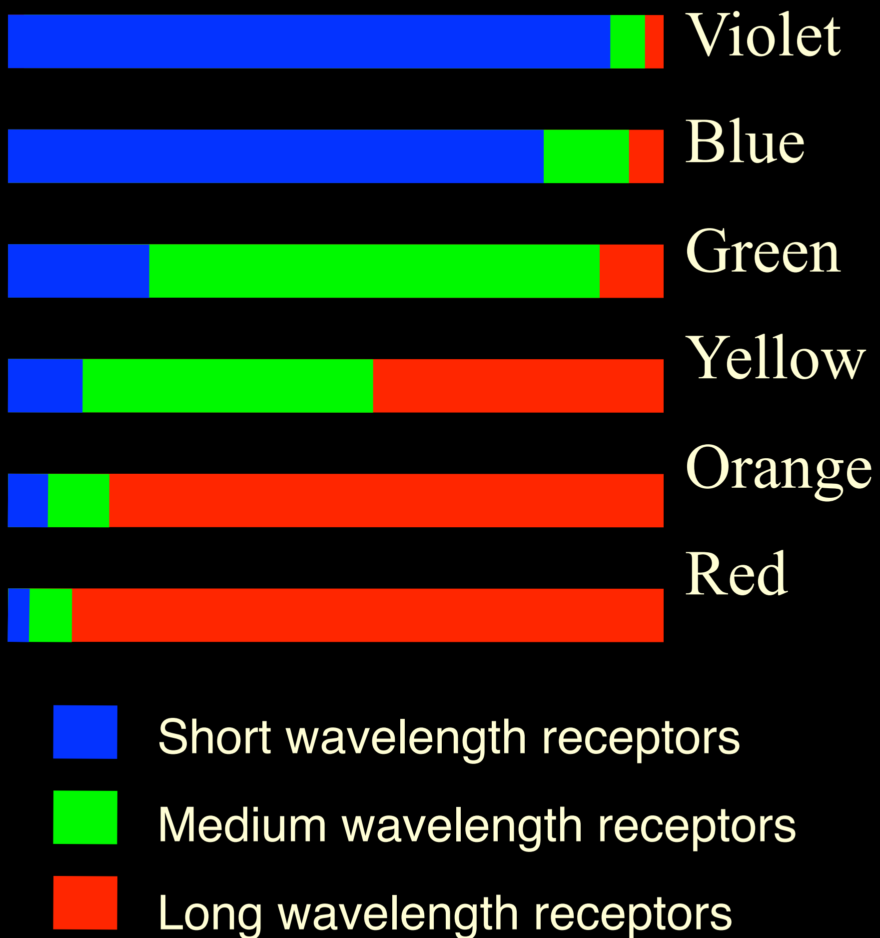
Response comparison

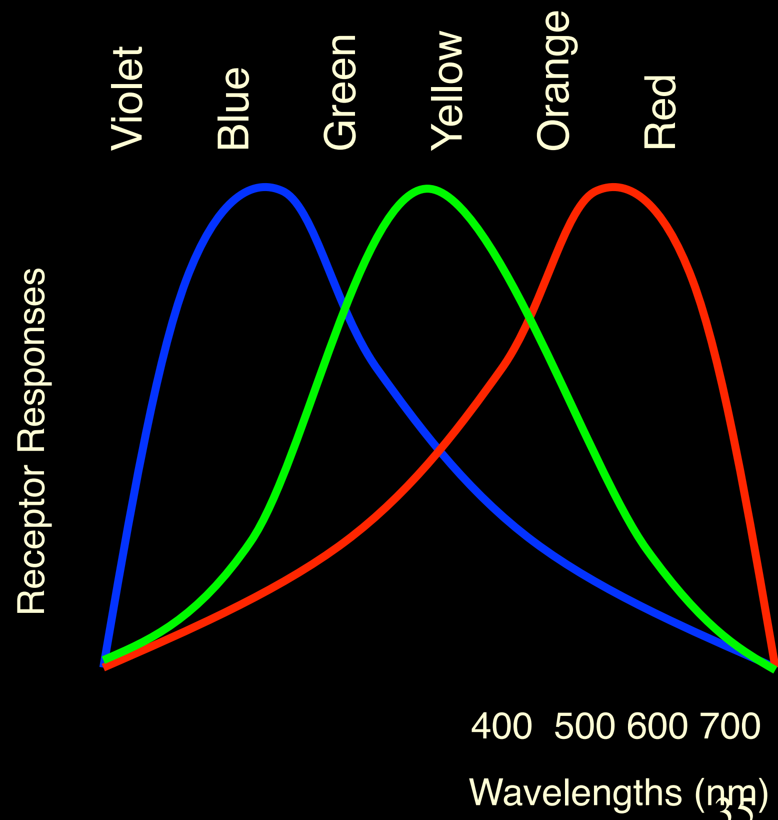
- Different wavelength, different intensity
- But different response for different cones



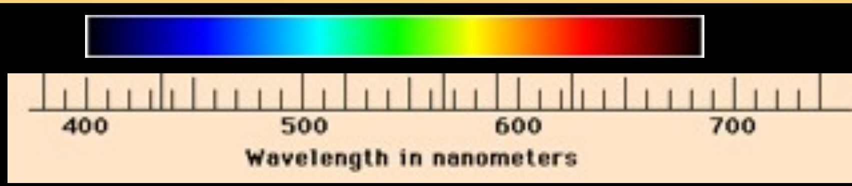
von Helmholtz 1859: Trichromatic theory

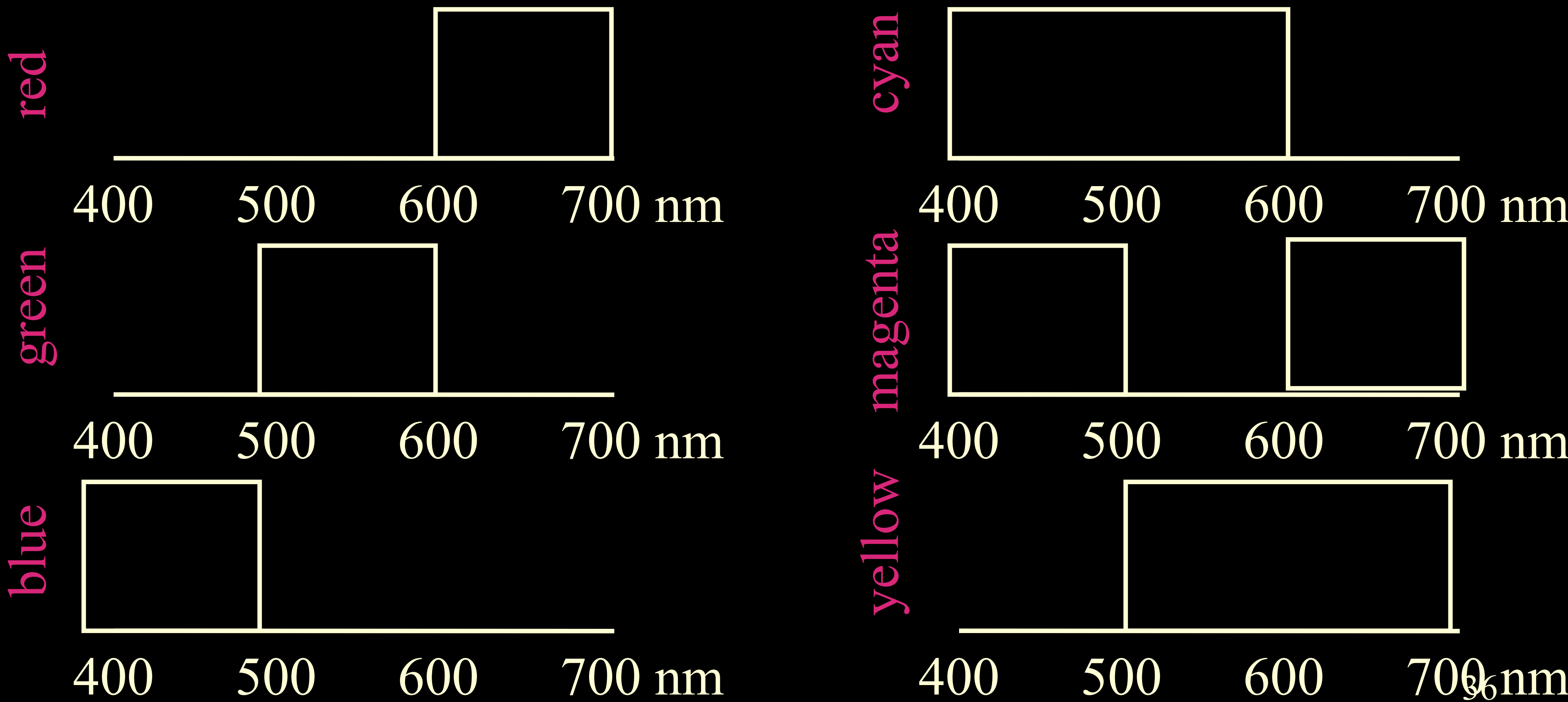
- Colors as relative responses (ratios)





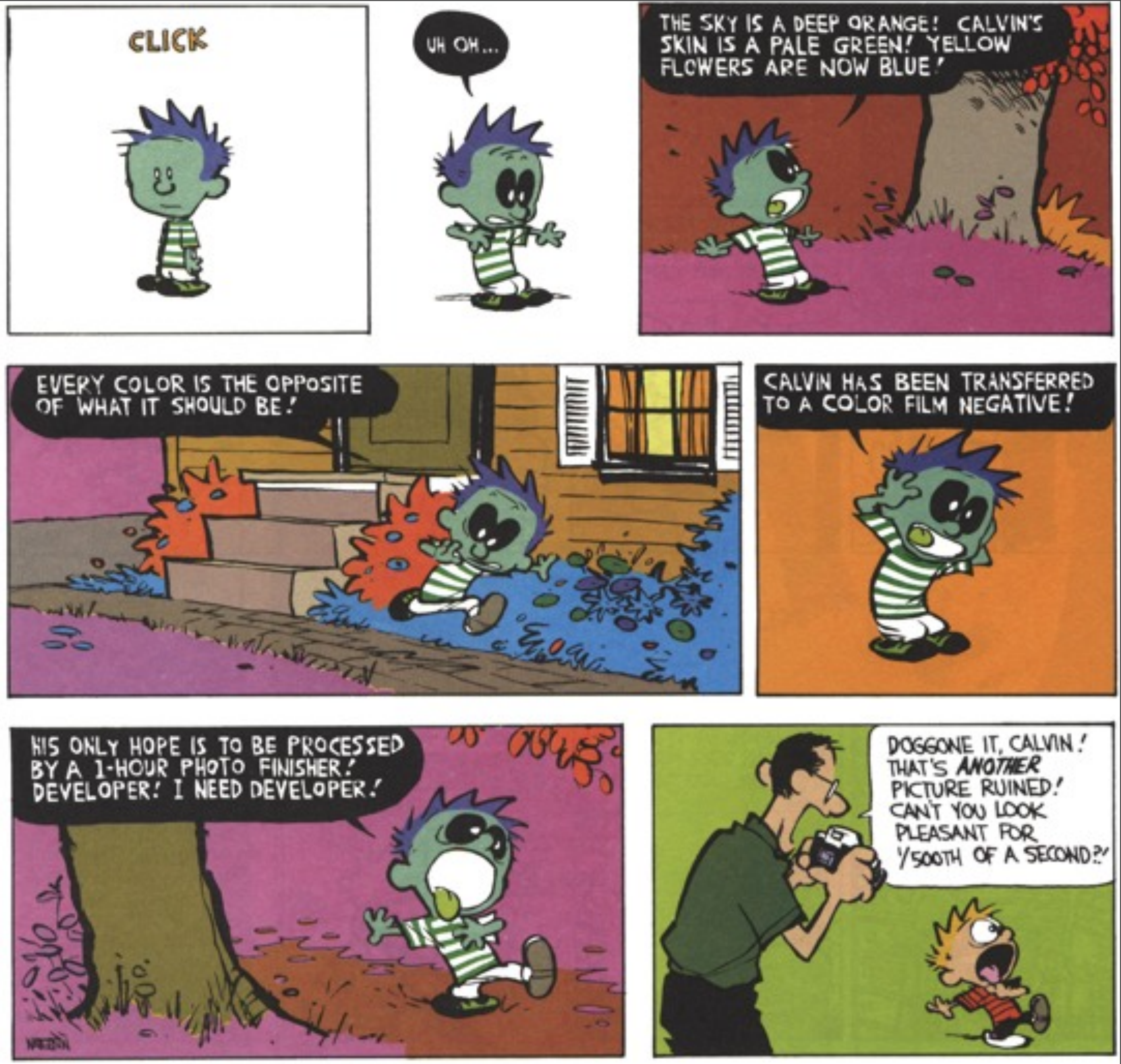
Color names for cartoon spectra





Slide from Bill Freeman

Questions?



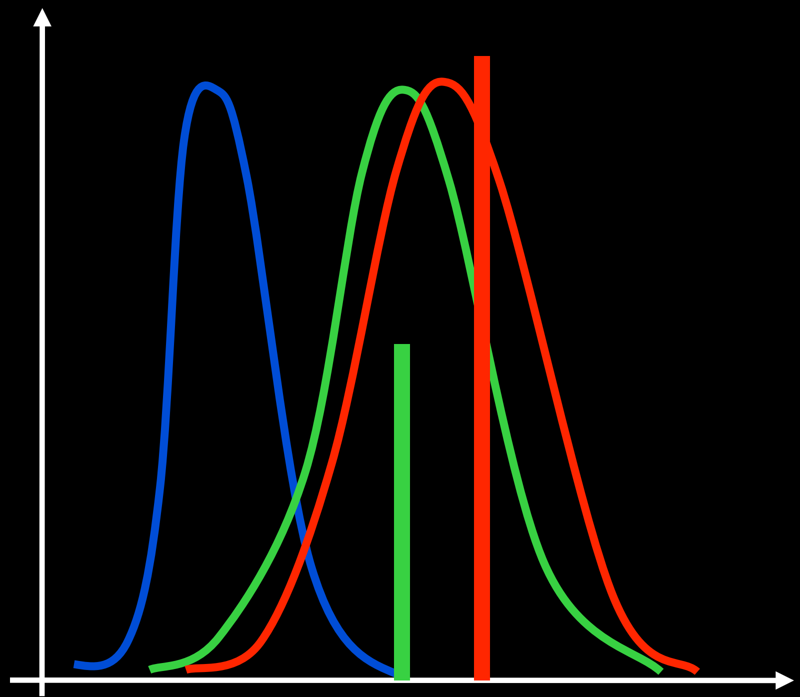
CLICK
UH OH...
THE SKY IS A DEEP ORANGE! CALVIN'S SKIN IS A PALE GREEN! YELLOW FLOWERS ARE NOW BLUE!
EVERY COLOR IS THE OPPOSITE OF WHAT IT SHOULD BE!
CALVIN HAS BEEN TRANSFERRED TO A COLOR FILM NEGATIVE!
HIS ONLY HOPE IS TO BE PROCESSED BY A 1-HOUR PHOTO FINISHER! DEVELOPER! I NEED DEVELOPER!
DOGGONE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

Plan

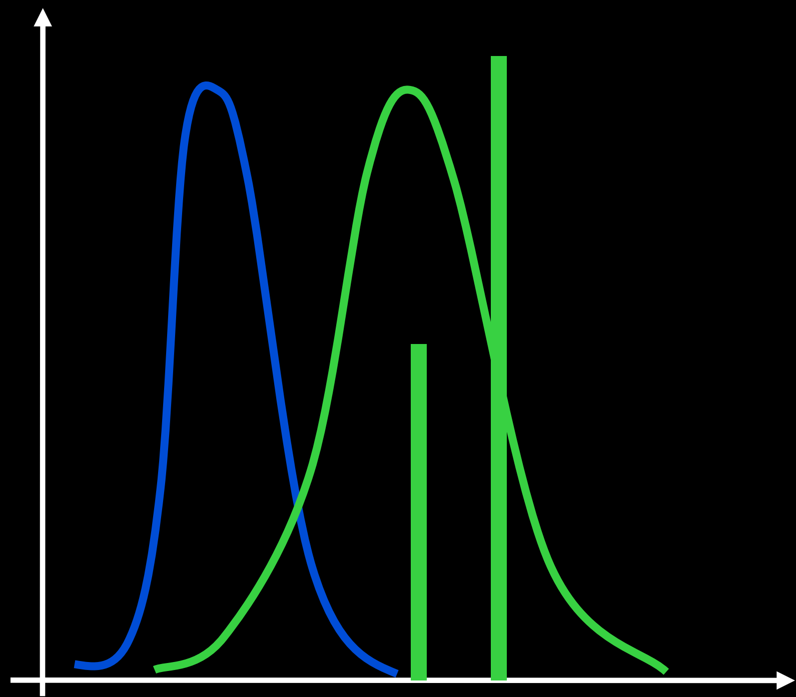
- Spectra
- Cones and spectral response
- **Color blindness and metamers**
- Color matching
- Color spaces

Color blindness

- Classical case: 1 type of cone is missing (e.g. red)
- Makes it impossible to distinguish some spectra



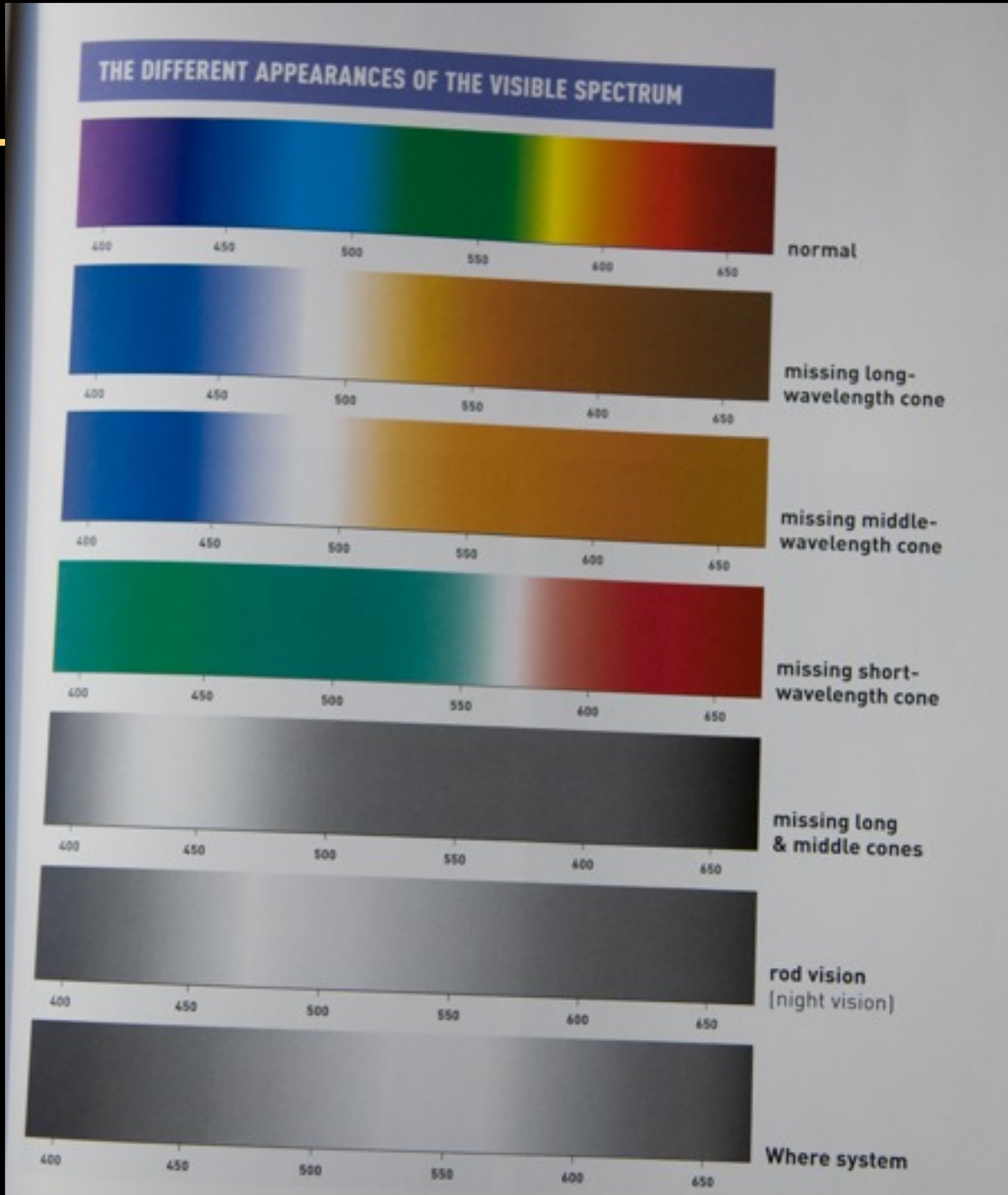
differentiated



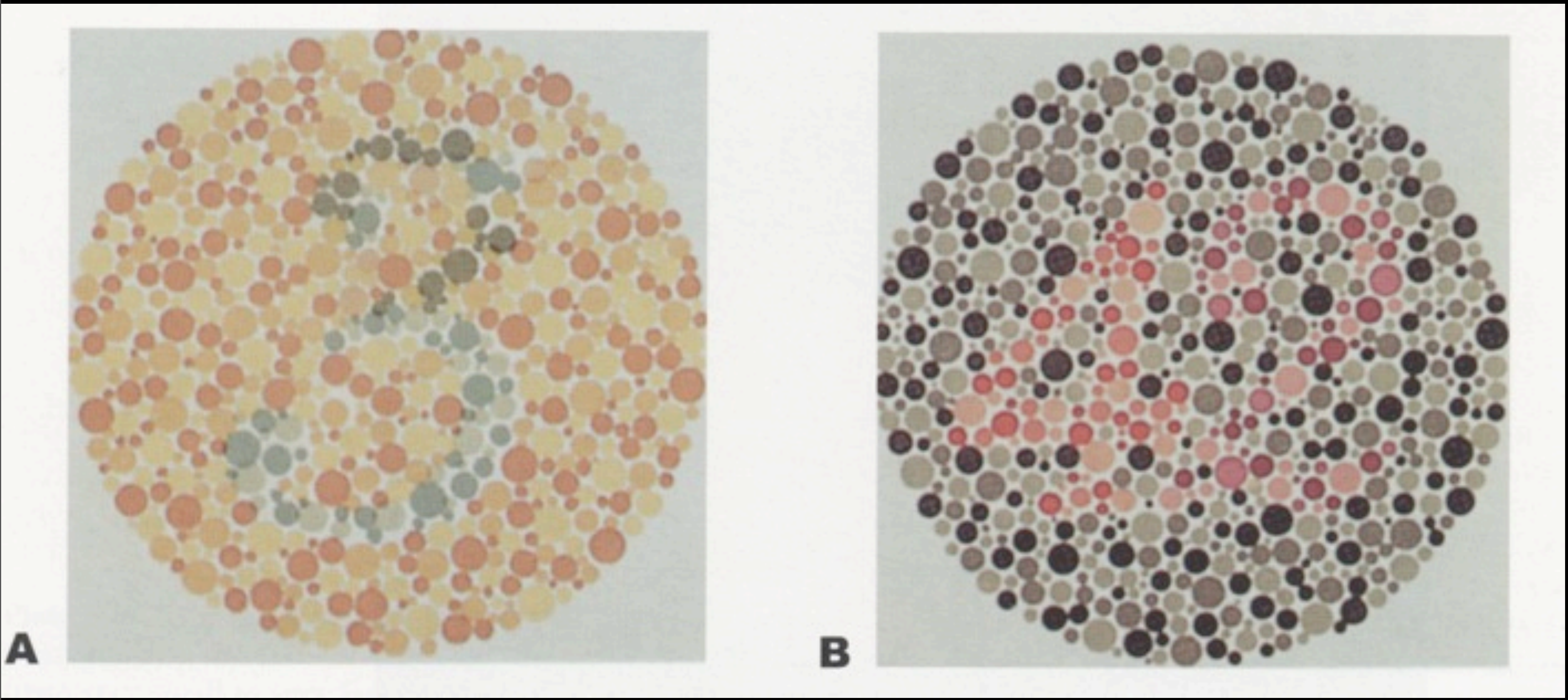
Same responses

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

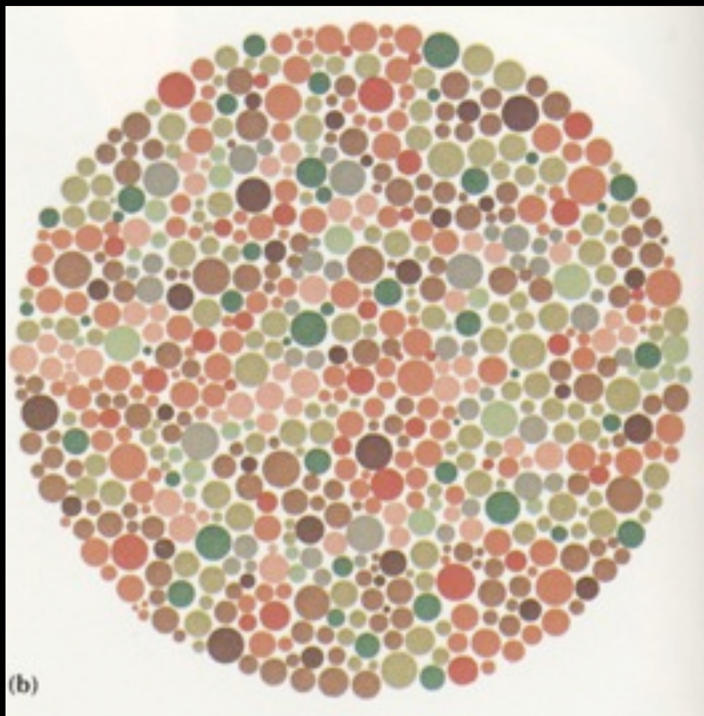

THE DIFFERENT APPEARANCES OF THE VISIBLE SPECTRUM
400
450
500
550
600
650
normal
missing long-wavelength cone
missing middle-wavelength cone
missing short-wavelength cone
missing long & middle cones
rod vision
(night vision)
Where system

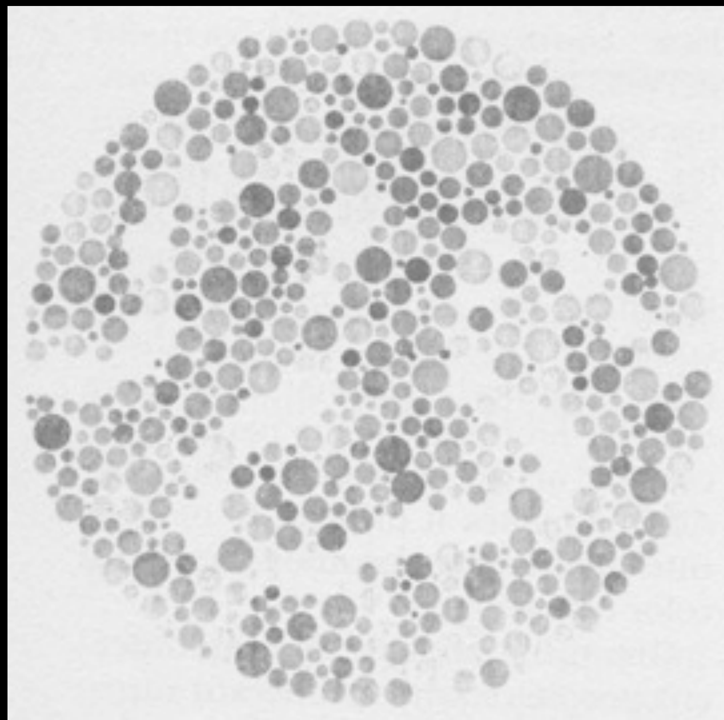
Color blindness test



Color blindness test

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



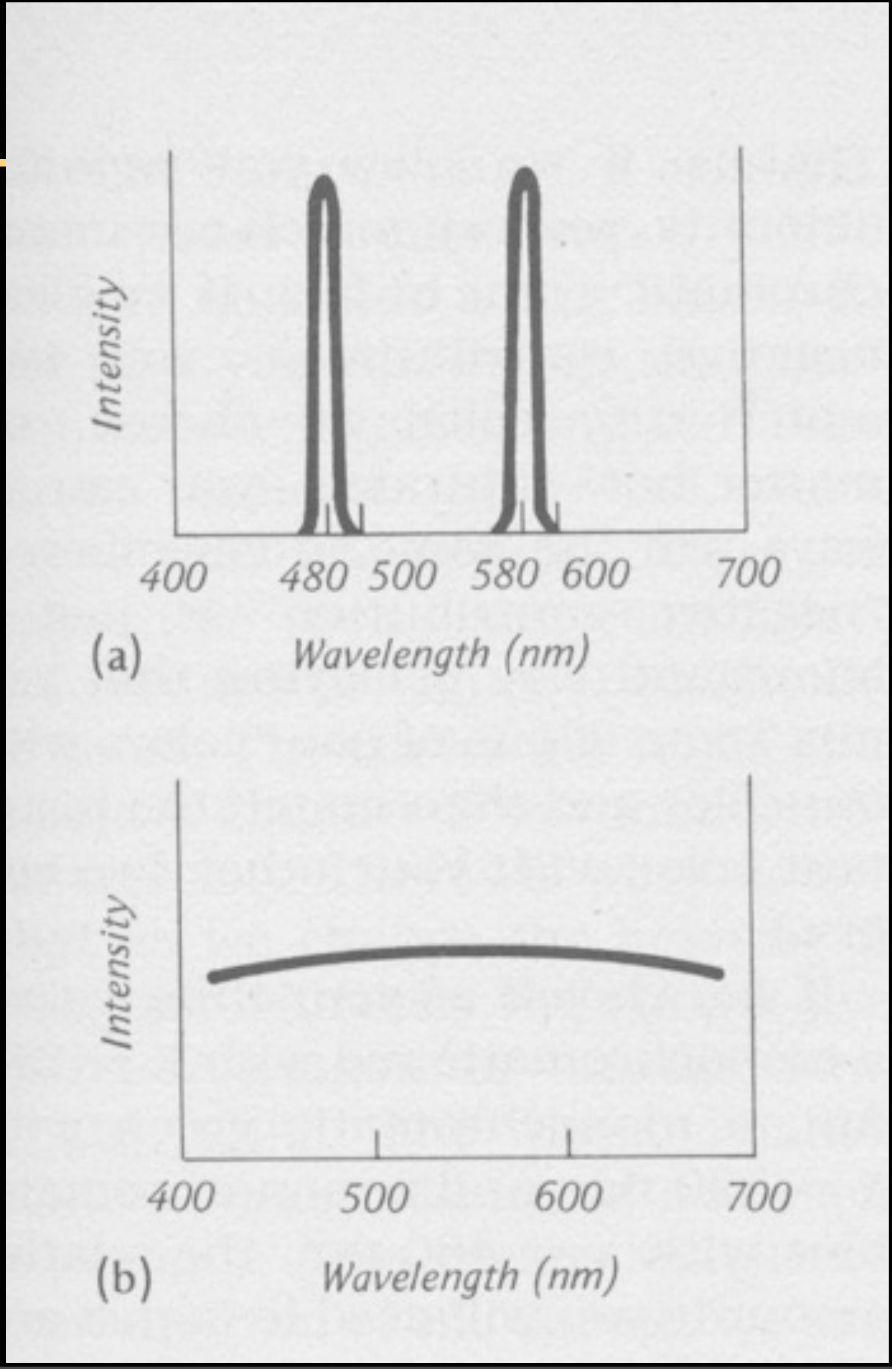


Questions?

- Links:
  - Vischeck shows you what an image looks like to someone who is colorblind.
  - http://www.vischeck.com/vischeck/
  - Daltonize, changes the red/green variation to brightness and
  - blue/yellow variations.
  - http://www.vischeck.com/daltonize/
  - http://www.vischeck.com/daltonize/runDaltonize.php

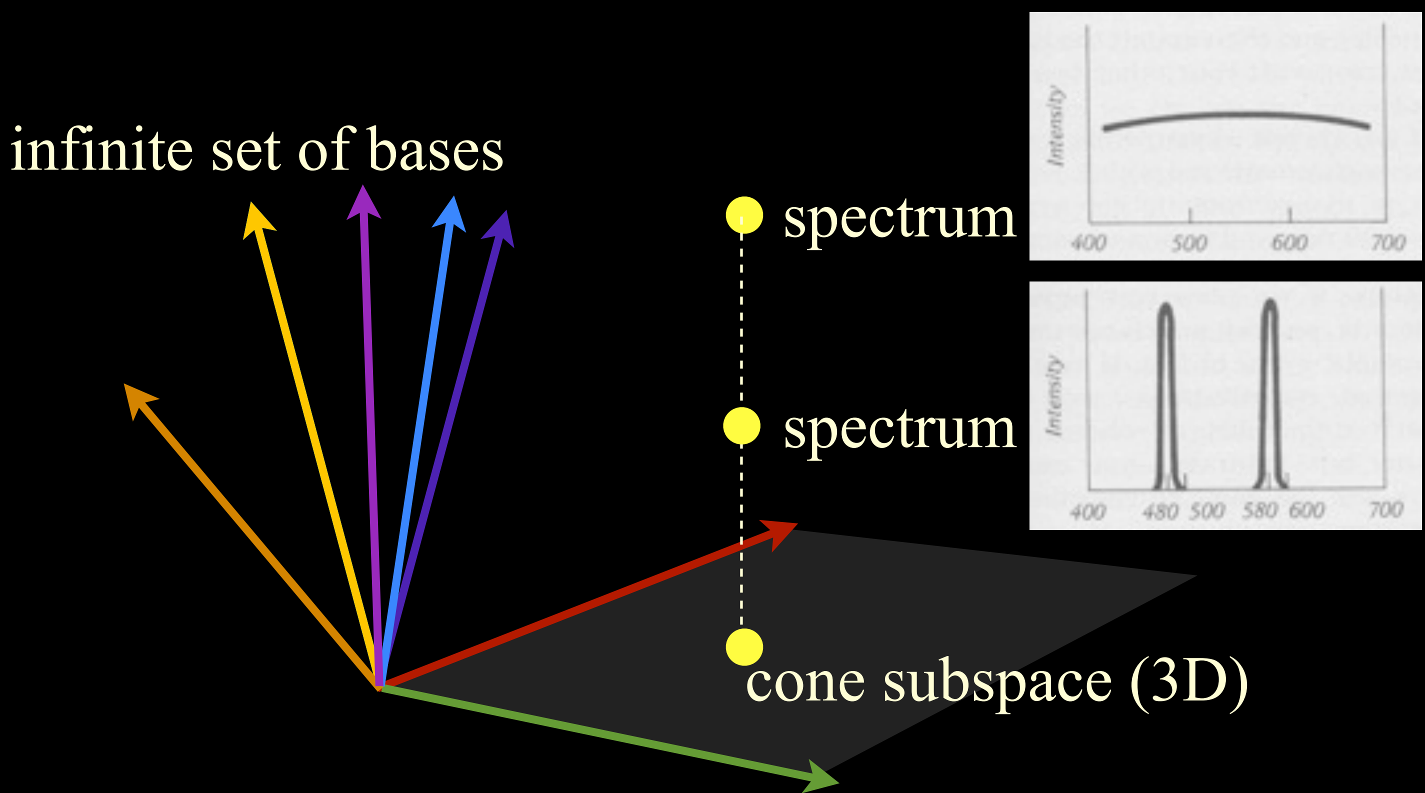
Metamers

- We are all color blind!
- These two different spectra elicit the same cone responses
- Called metamers

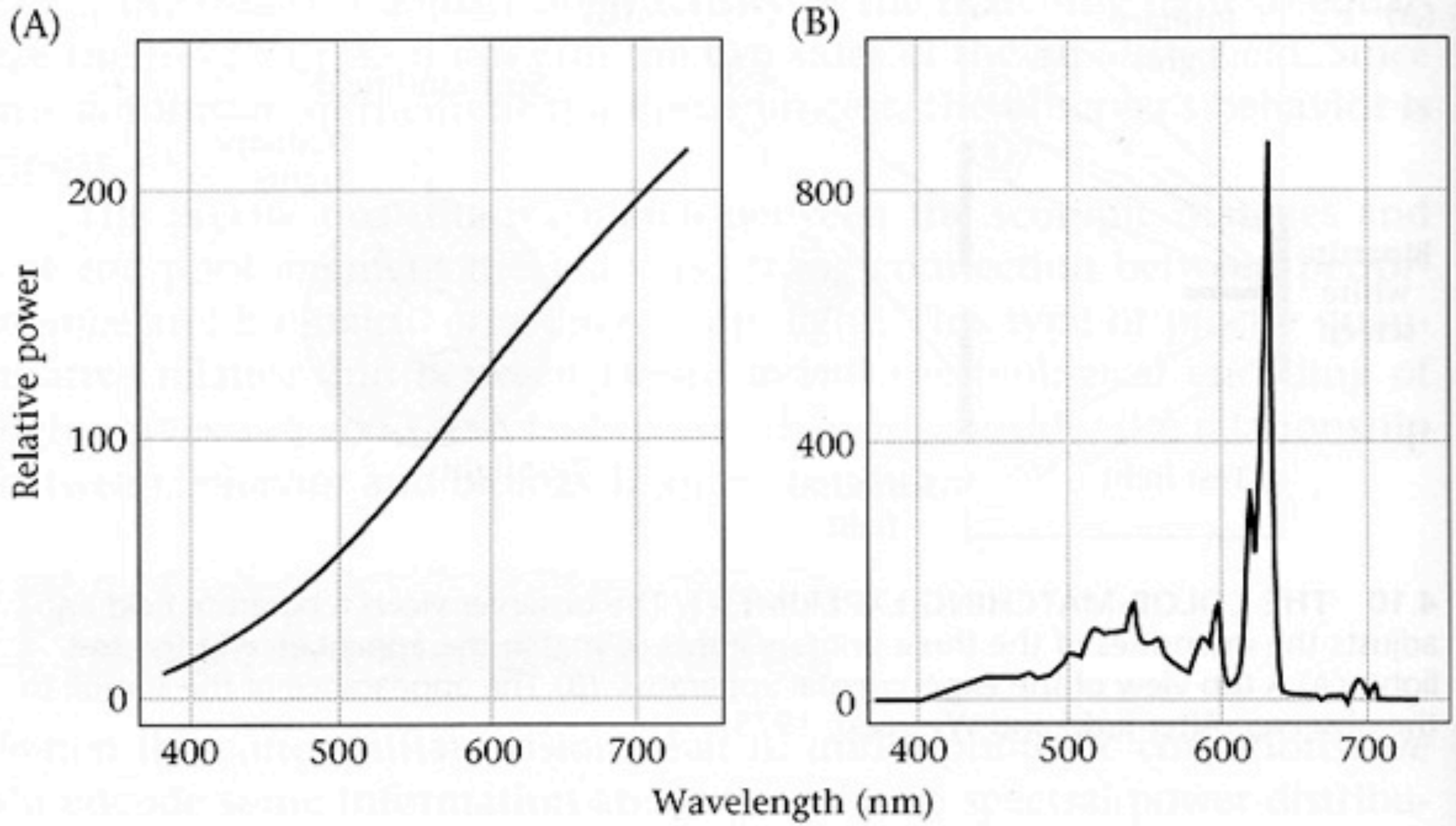


Metamers

- Essentially, we have projected from an infinite-dimensional spectrum to a 3D space: we loose information



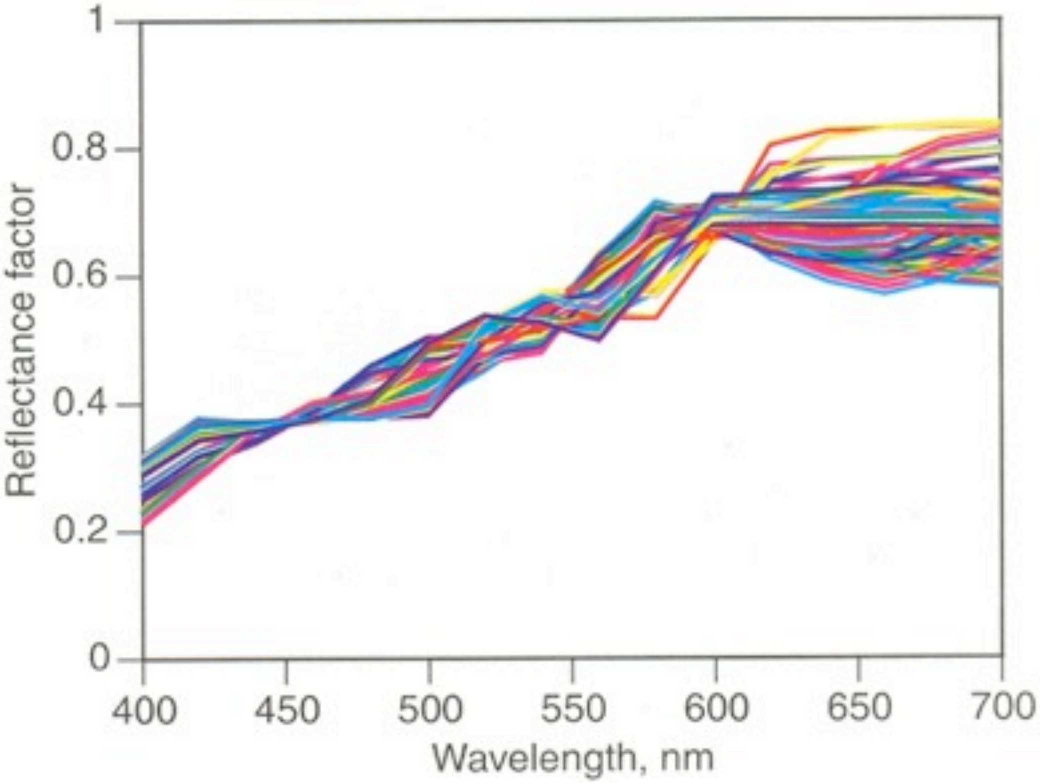
Metameric lights



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

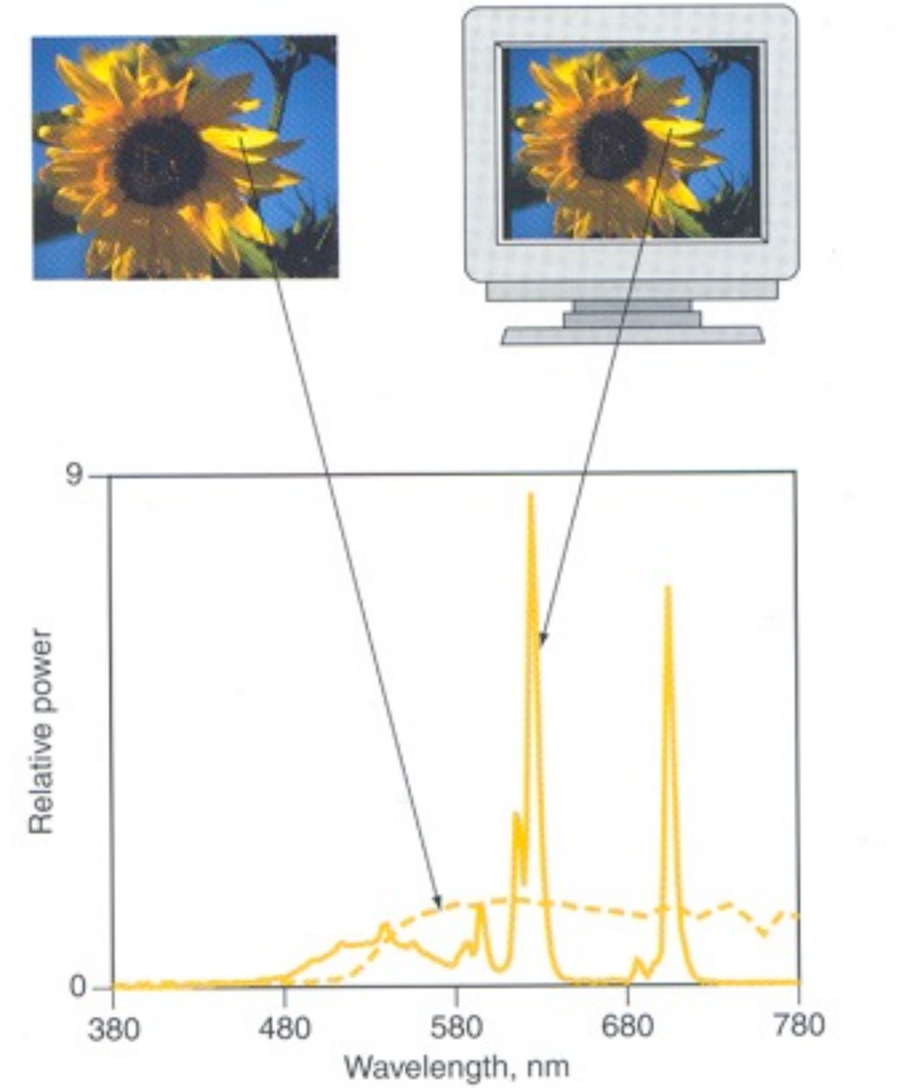
There is an infinity of metamers



Ensemble of spectral reflectance curves corresponding to three chromatic-pigment recipes all matching a tan material when viewed by an average observer under daylight illumination. [Based on Berns (1988b).]

Good news: color reproduction

- 3 primaries are (to a first order) enough to reproduce all colors



The dashed line represents daylight reflecting from sunflower petals, while the solid line represents the light emitted by a color CRT display adjusted to match the color of the sunflower.

Recap

- Spectrum: infinite number of values
- projected according to cone spectral response
  => 3 values
- metamers: spectra that induce the same response (physically different but look the same)

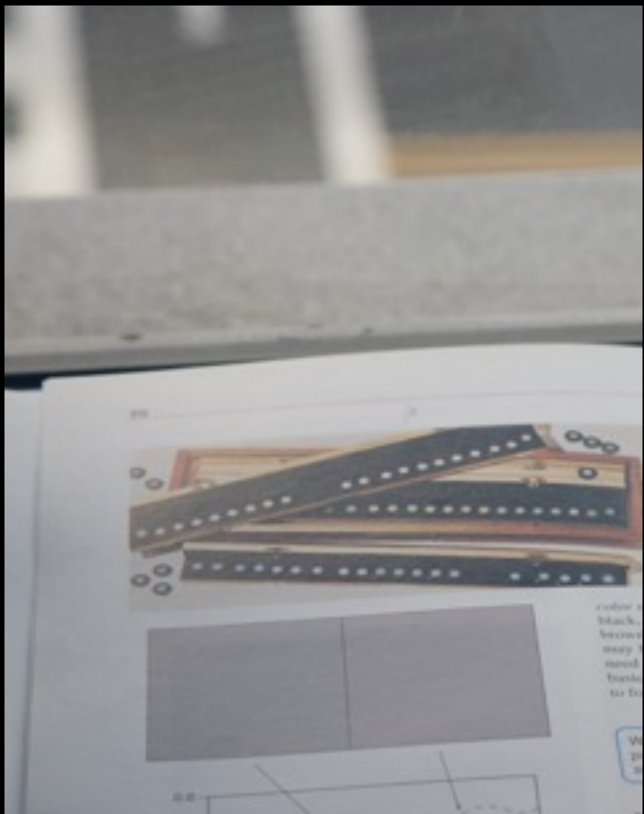
- Questions?

Metamerism & light source

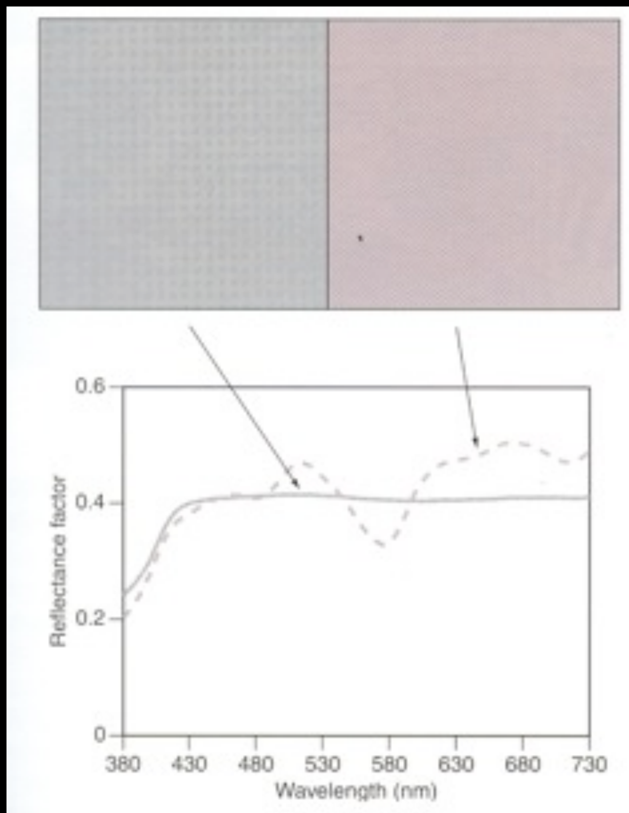
- Metamers under a given light source
- May not be metamers under a different lamp

Illuminant metamerism example

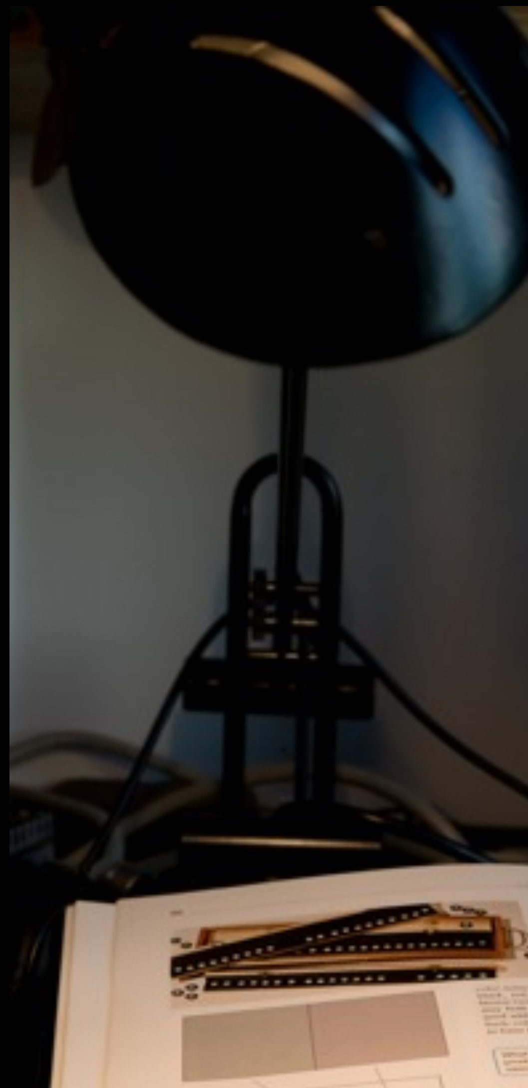
- Two grey patches in Billmeyer & Saltzman's book look the same under daylight but different under neon or halogen (& my camera agrees ;-)



Daylight



Scan (neon)



Hallogen

Bad consequences: printing

- http://www.inkjetart.com/2000p/metamerism.html
- 

  under 5000 degree Kelvin lighting

  under cold cathode lamp

Bad consequence II: cloth matching

- Clothes appear to match in store (e.g. under neon)
- Don’t match outdoor

Recap

- Spectrum is an infinity of numbers
- Projected to 3D cone-response space
  - for each cone, multiply per wavelength and integrate
  - a.k.a. dot product
- Metamerism: infinite-D points projected to the same 3D point
  (different spectrum, same perceived color)
  - affected by illuminant
  - enables color reproduction with only 3 primaries

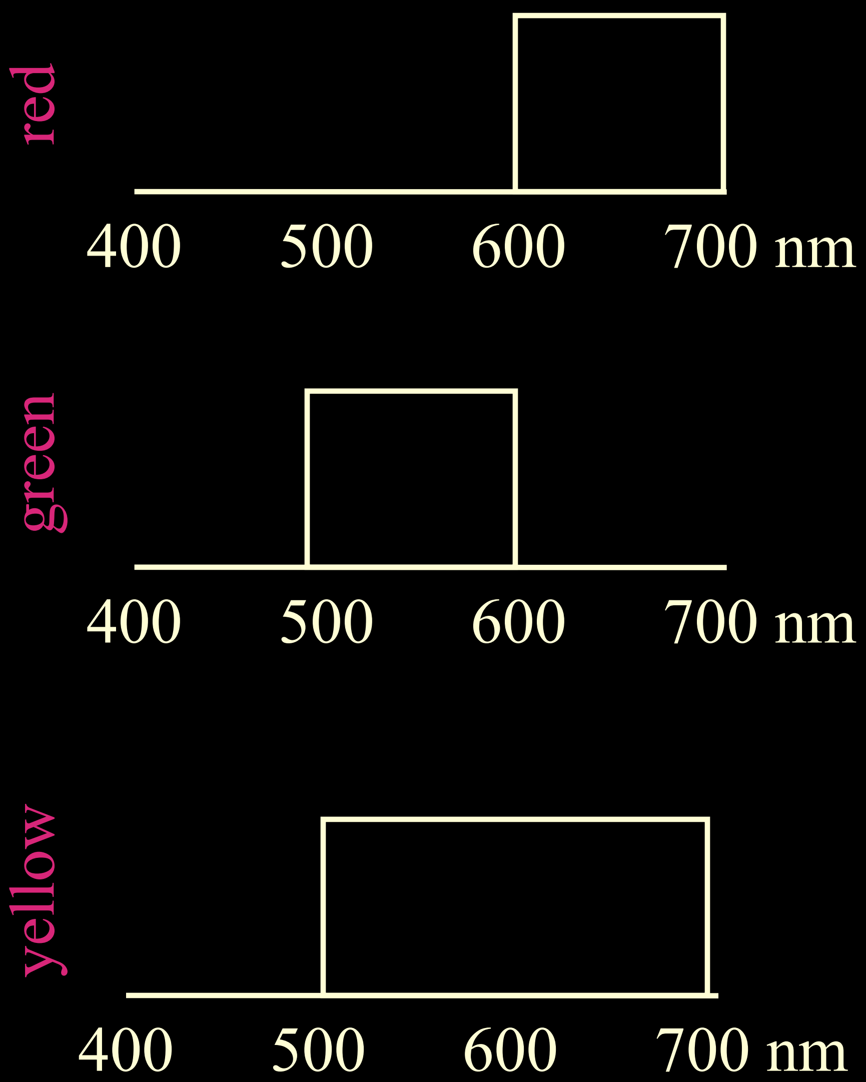
Questions?

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

Analysis & Synthesis

- Now let's switch to technology
- We want to measure & reproduce color as seen by humans
- No need for full spectrum
- Only need to match up to metamerism

Additive color mixing



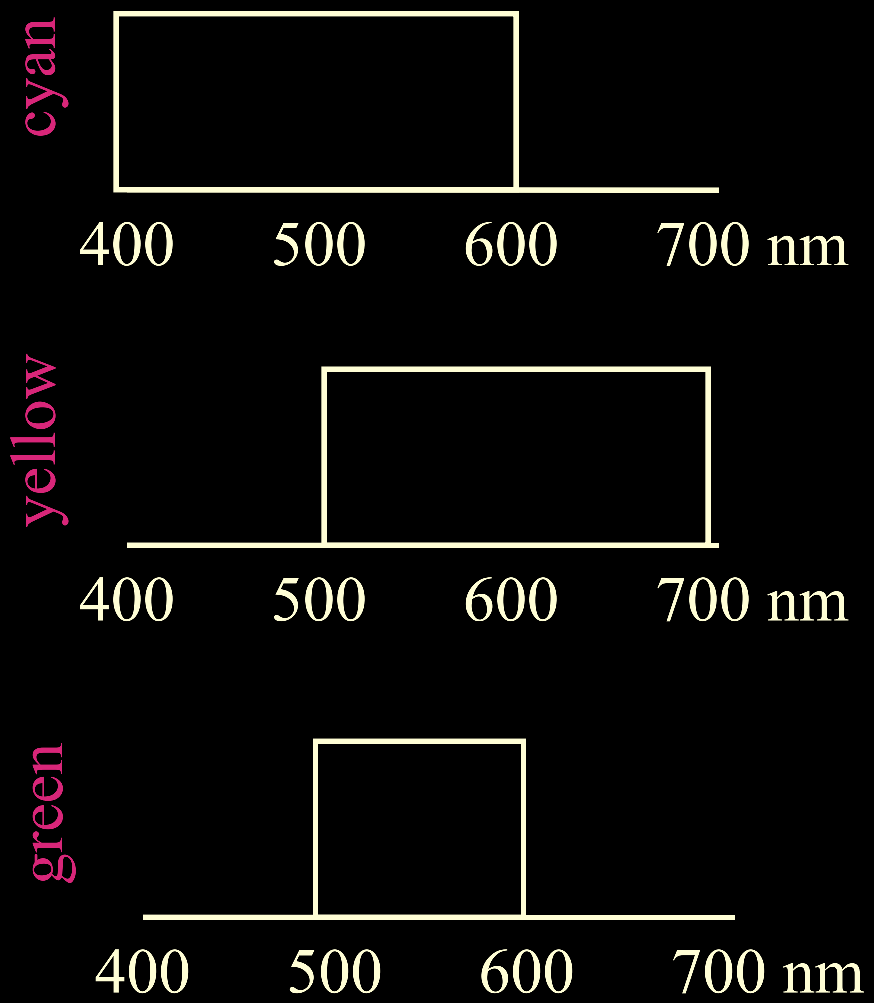
When colors combine by *adding* the color spectra. Example color displays that follow this mixing rule: CRT phosphors, multiple projectors aimed at a screen, Polachrome slide film.

Red and green make…

Yellow!

Slide from Bill Freeman

Subtractive color mixing



When colors combine by *multiplying* the color spectra. Examples that follow this mixing rule: most photographic films, paint, cascaded optical filters, crayons.

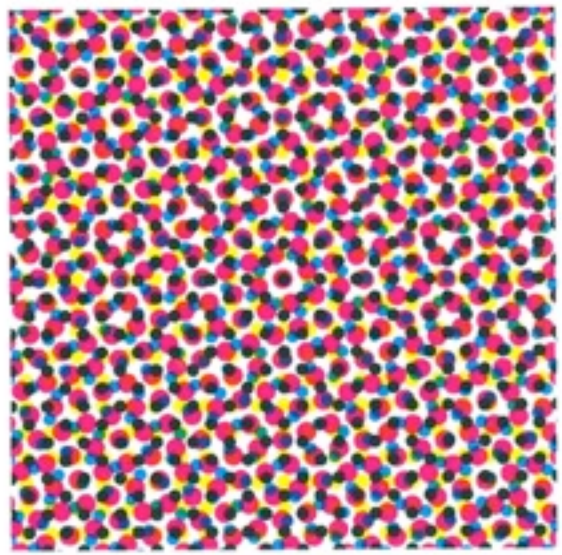
Cyan and yellow (in crayons, called "blue" and yellow) make…

Green!

Slide from Bill Freeman

Often a mix

- Additive+substractive phenomena
- e.g. projector has color filters (subtractive) to create primaries that are added
- color printing:



Color printing is often a combination of additive and subtractive mixing. When primaries are printed on top of each other, a subtractive color results. When viewed without magnification, the light from each colored area is added.

Analysis & Synthesis

- We want to measure & reproduce color as seen by humans
- Focus on additive color synthesis
- We'll use 3 primaries (e.g. red green and blue) to match all colors

- What should those primaries be?
- How do we tell the amount of each primary needed to reproduce a given target color?

Warning

Tricky thing with spectra & color:

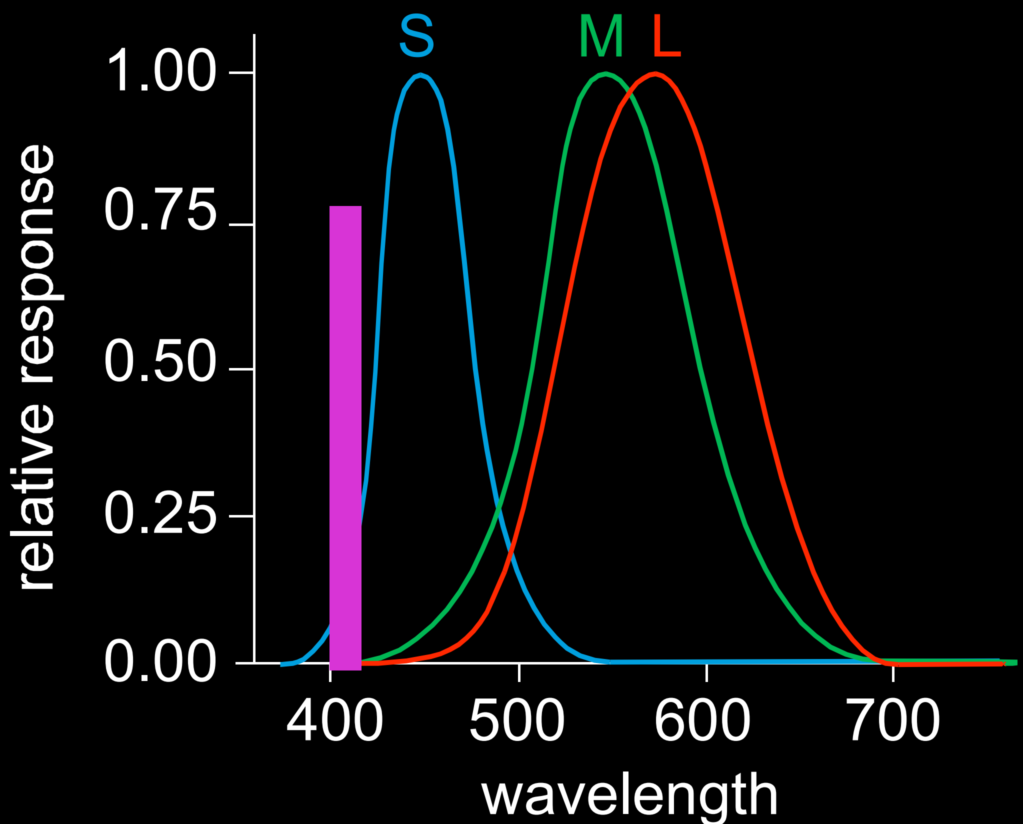
- Spectrum for the stimulus / synthesis
  - Light, monitor, reflectance
- Response curve for receptor /analysis
  - Cones, camera, scanner

They are usually not the same

There are good reasons for this

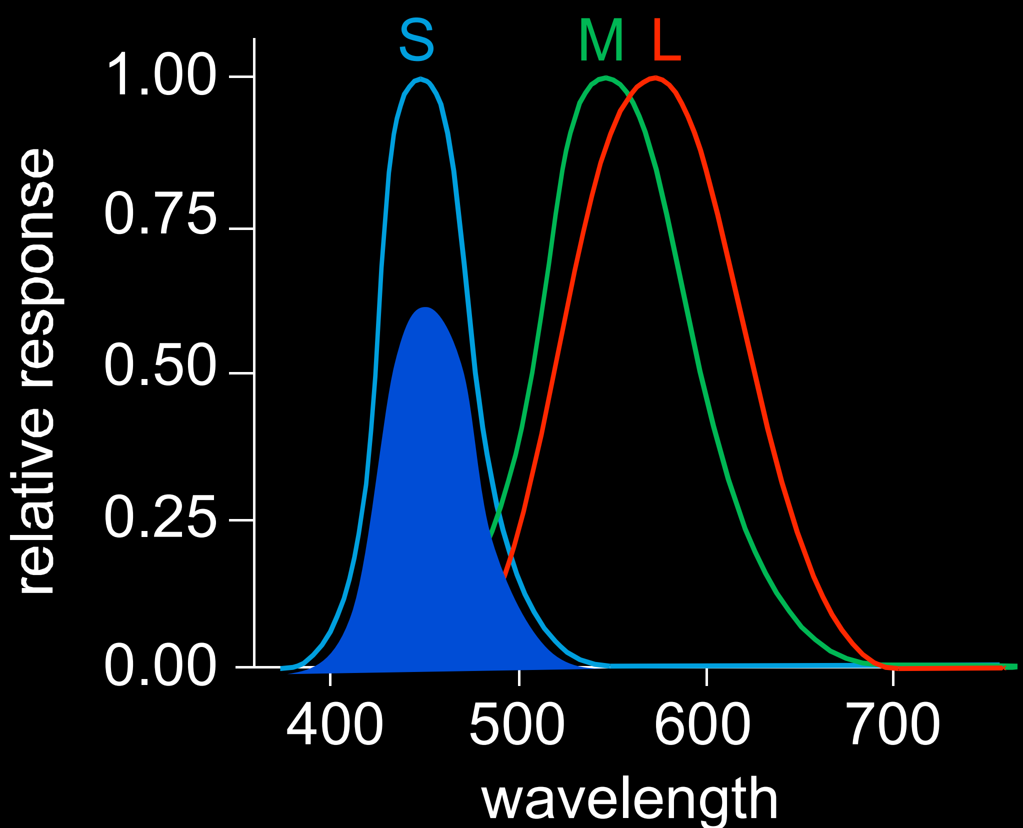
Additive Synthesis

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



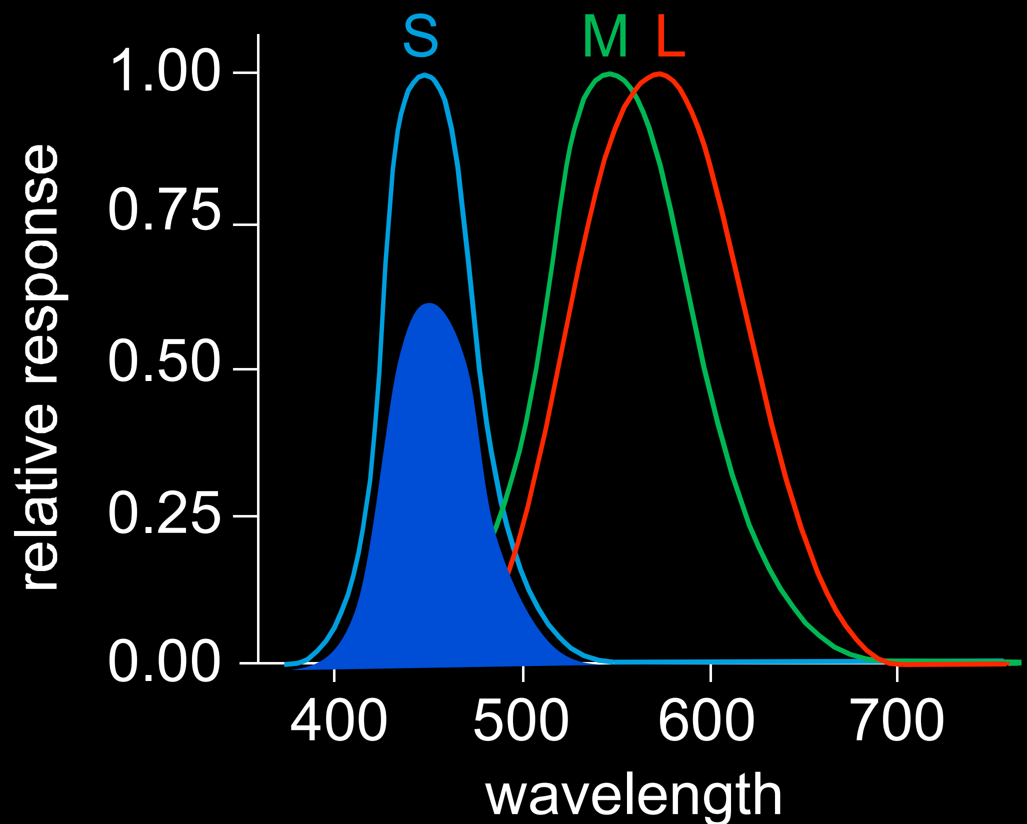
Synthesis

- 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)



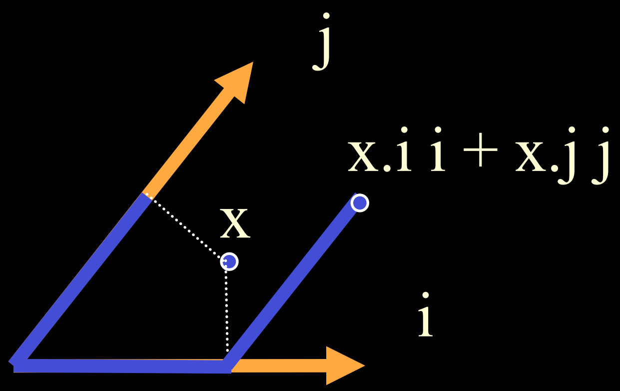
What's going on?

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



Same as non-orthogonal bases

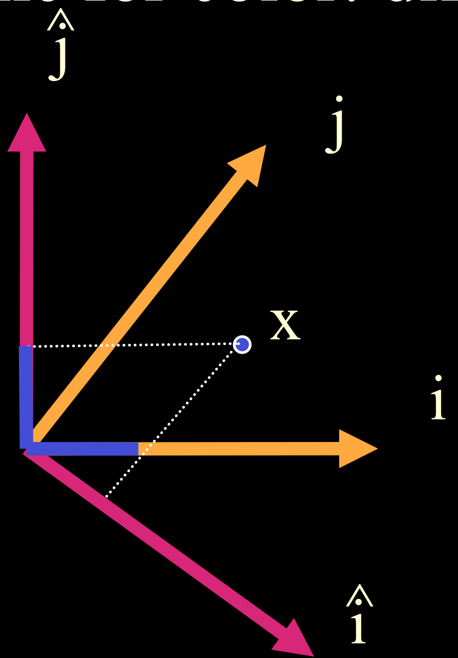
- Non orthogonal bases are harder to handle
- Can't use dot product on same vector to infer coordinates
  - Same problem as with cones, the i & j components pollute each other



x != x.i i + x.j j

Same as non-orthogonal bases

- Non orthogonal bases are harder to handle
- Can't use dot product on same vector to infer coordinates
- Need a so-called dual basis
  - Same for color: different basis for analysis/ synthesis



$$x = x.\hat{i}\; i + x.\hat{j}\; j$$

Note that $\hat{i}$ has negative coordinates

Fundamental problems

- Spectra are infinite-dimensional
- Only positive values are allowed
- Cones are non-orthogonal/overlap

Summary

- Physical color
  - Spectrum
  - multiplication of light & reflectance spectrum
- Perceptual color
  - Cone spectral response: 3 numbers
  - Metamers: different spectrum, same responses
    - Color matching, enables color reproduction with 3 primaries
- Fundamental difficulty
  - Spectra are infinite-dimensional (full function)
  - Projected to only 3 types of cones
  - Cone responses overlap / they are non-orthogonal
    - Means different primaries for analysis and synthesis
  - Negative numbers are not physical

Questions?

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

Color standards are important in industry

Address http://www.ams.usda.gov/fv/ppbweb/PPBfilecodes/105a15.htm

AMS USDA

Fruit and Vegetable Programs

AMS USDA SEARCH

Processed Products Standards and Quality Certification

Visual Aids and Inspection Aids Approved For Use in Ascertaining Grades of Processed Fruits and Vegetables (Photo)

- Frozen Red Tart Cherries
- Orange Juice (Processed)
- Canned Tomatoes
- Frozen French Fried Potatoes
- Tomato Products
- Maple Syrup
- Honey
- Frozen Lima Beans
- Canned Mushrooms
- Peanut Butter
- Canned Pimientos
- Frozen Peas
- Canned Clingstone Peaches
- Headspace Gauge
- Canned Applesauce
- Canned Freestone Peaches
- Canned Ripe Olives

Return to: Processed Products Bran

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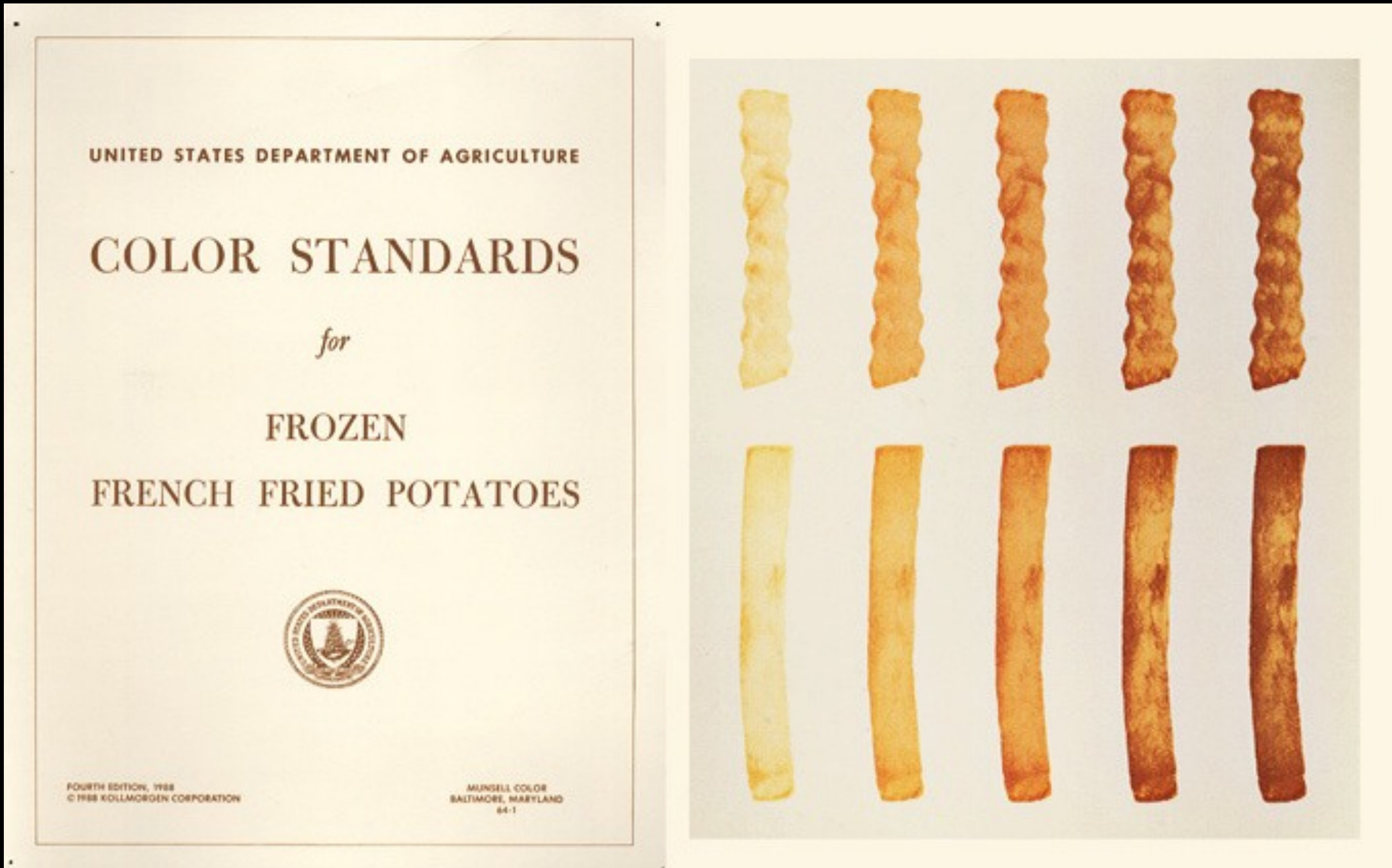
Slide from Bill Freeman



Slide from Bill Freeman

Standard color spaces

- We need a principled color space
- Many possible definition
  - Including cone response (LMS)
  - Unfortunately not really used,
    (because not known at the time)

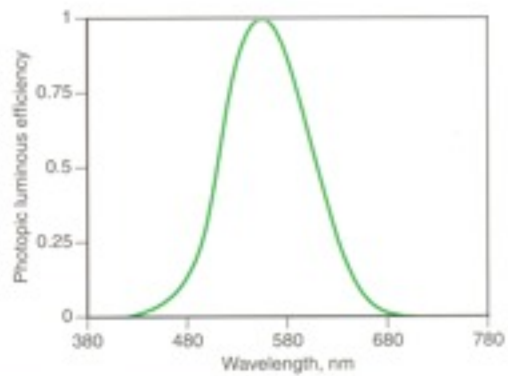
- The good news is that color vision is linear and 3-dimensional, so any new color space based on color matching can be obtained using 3x3 matrix
  - But there are also non-linear color spaces
    (e.g. Hue Saturation Value, Lab)

Difficulty with color science

- The good:
  - Lots of well-principled linear algebra
- The bad
  - non-orthogonal, non-negative
- The ugly
  - Historical reasons have multiplied the number of arbitrary choices

CIE

- Commission Internationale de l'Eclairage (International Lighting Commission)
- Circa 1920
- First in charge of measuring brightness for different light chromaticities (monochromatic wavelength)
- Then color
  - CIE XYZ space: most standard color space ever



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.

Why not measure cone sensitivity?

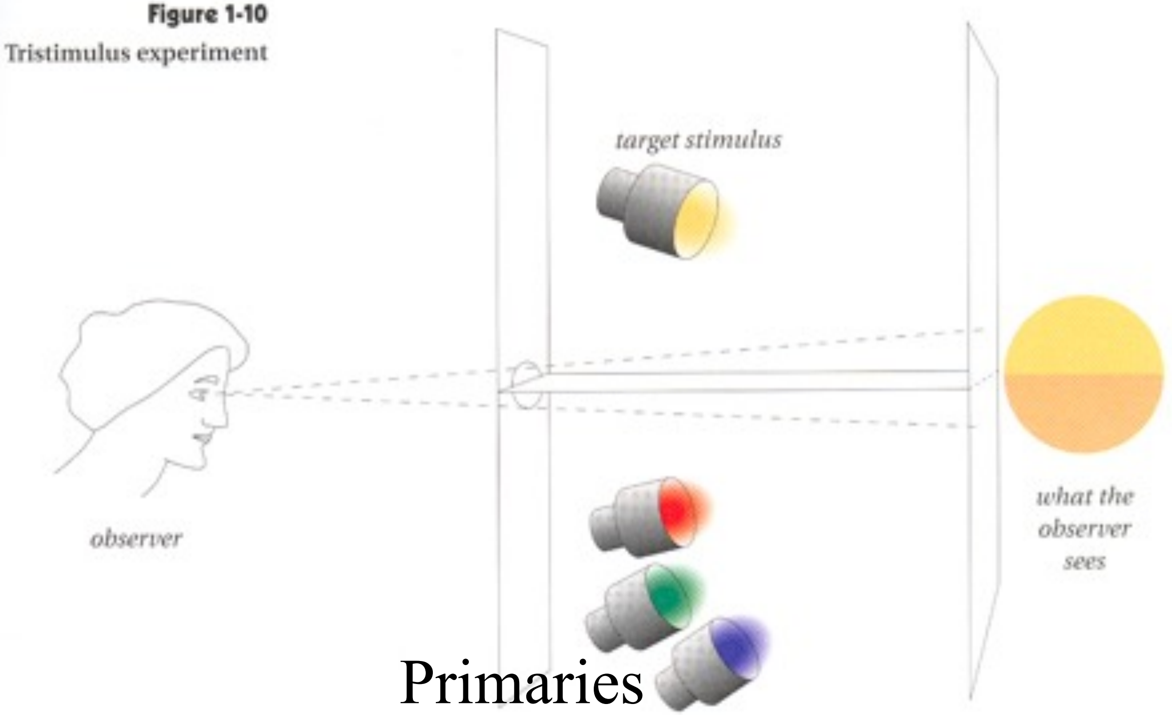
- Less directly measurable
  - electrode in photoreceptor?
  - not available when color spaces were defined
- Most directly available measurement:
  - notion of metamers
  - color matching

CIE color matching

- Choose 3 synthesis primaries
- Seek to match any monochromatic light (400 to 700nm)
  - Record the 3 values for each wavelength
- By linearity, this tells us how to match any light

Figure 1-10

Tristimulus experiment



The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

CIE color matching

- Primaries (synthesis) at 435.8, 546.1 and 700nm
  - Chosen for robust reproduction, good separation in red-green
- Resulting 3 numbers for a wavelength are called tristimulus values

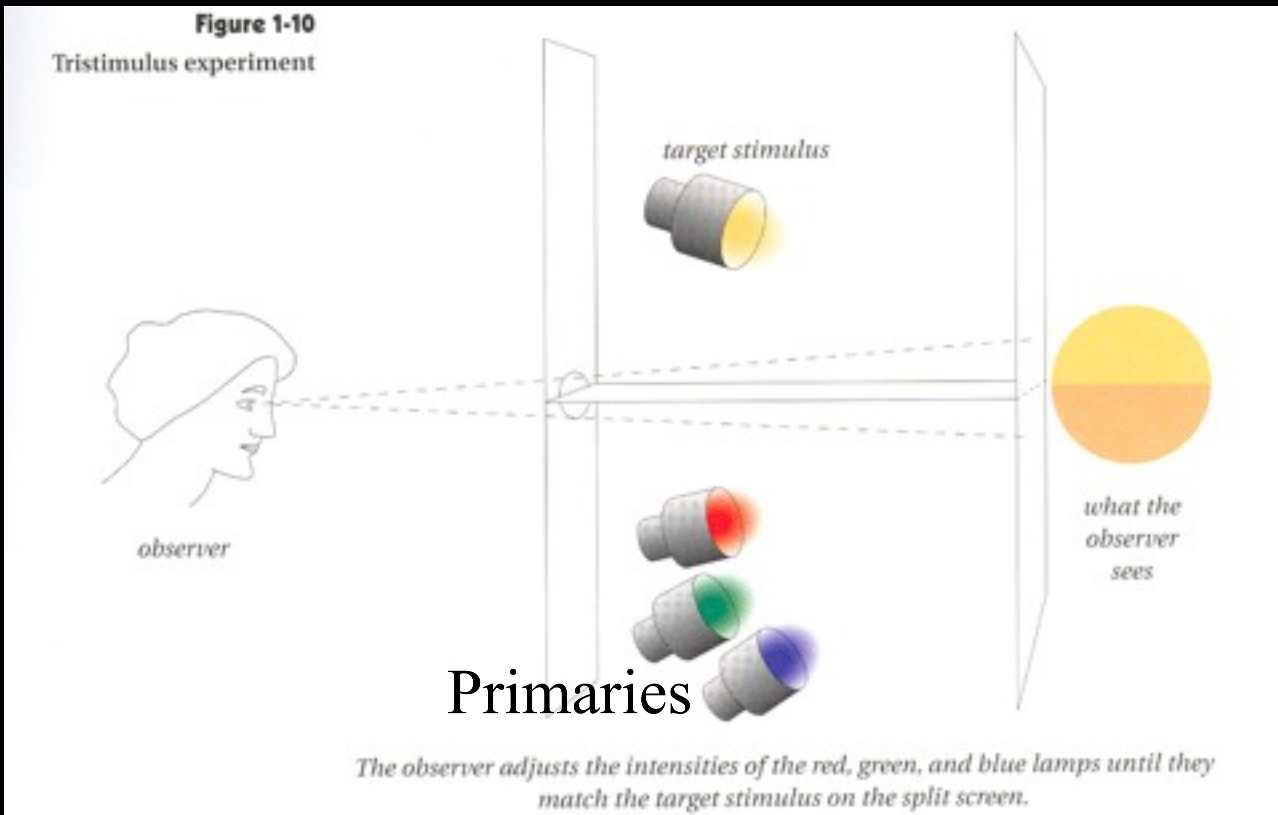
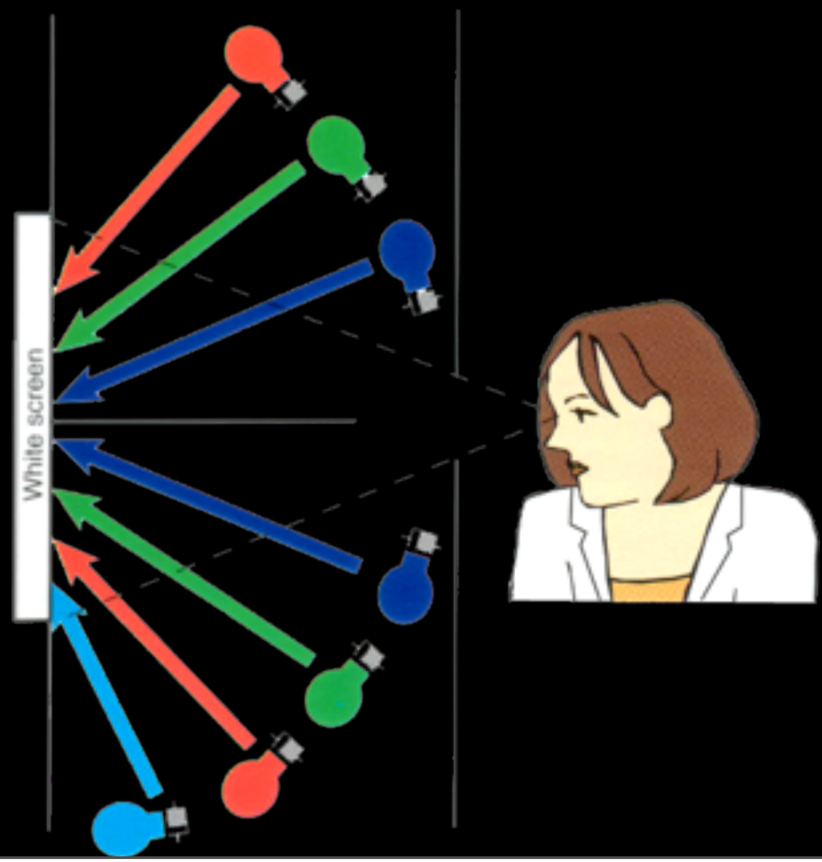


Figure 1-10
Tristimulus experiment

The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

Color Matching Problem

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

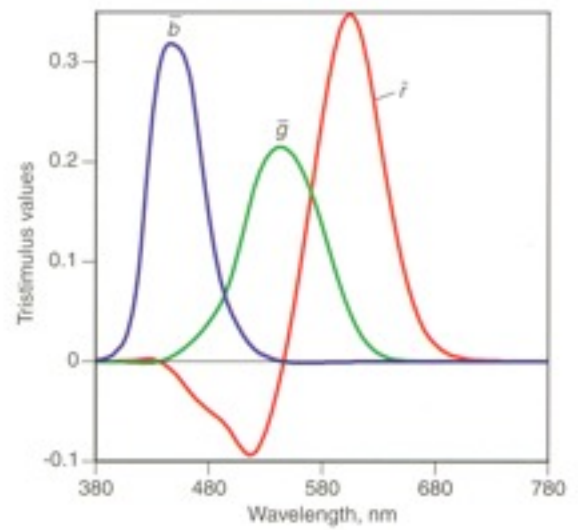


CIE color matching

- Meaning of these curves: a monochromatic wavelength λ can be reproduced with
  b(λ) amount of the 435.8nm primary,
  +g(λ) amount of the 546.1 primary,
  +r(λ) amount of the 700 nm primary

- This fully specifies the color perceived by a human

- Careful: this is not your usual rgb, note the bars

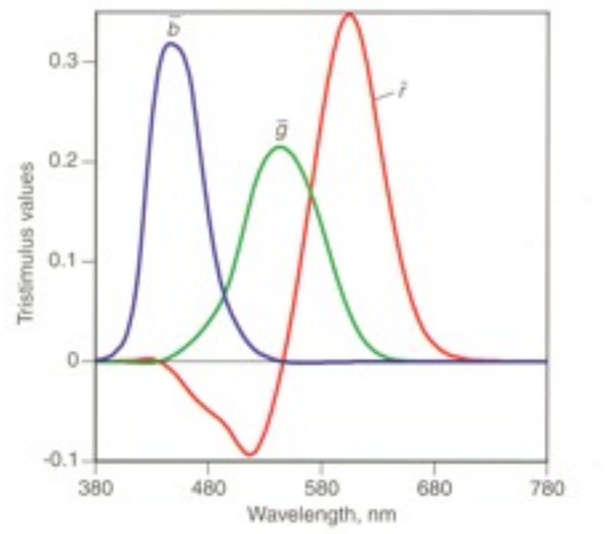


These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

CIE color matching

- Meaning of these curves: a monochromatic wavelength λ can be reproduced with b(λ) amount of the 435.8nm primary, +g(λ) amount of the 546.1 primary, +r(λ) amount of the 700 nm primary

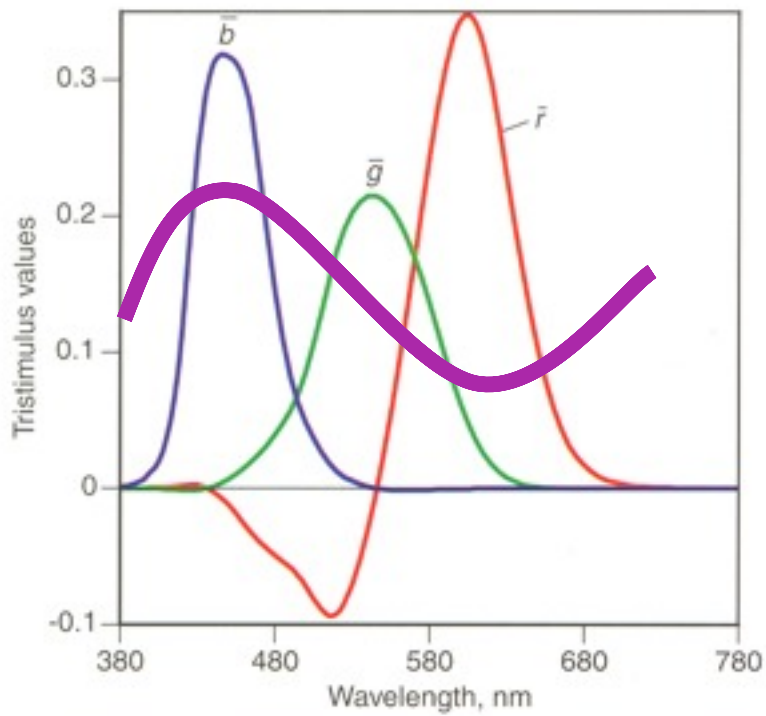
- This fully specifies the color perceived by a human
- However, note that one of the responses can be negative
  - Those colors cannot be reproduced by those 3 primaries.



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?

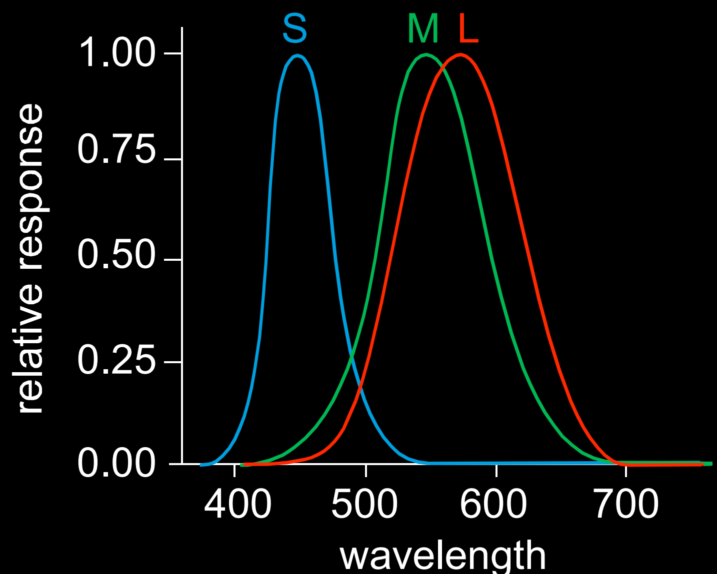
- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)

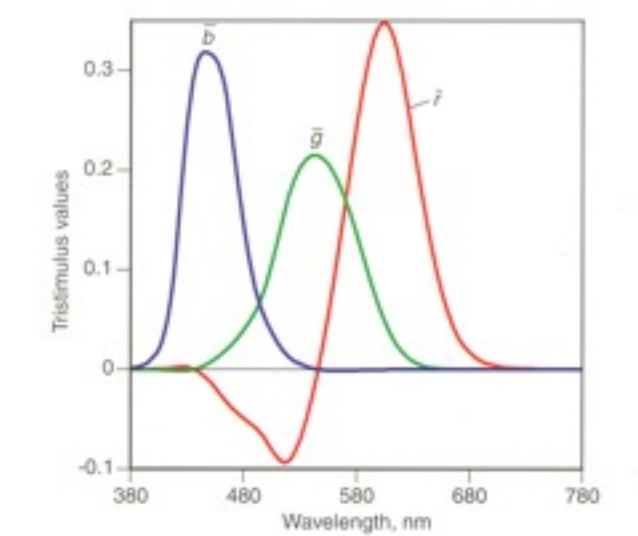


These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

Relation to cone curves

- Project to the same subspace
  - b, g, and r are linear combinations of S, M and L
- Related by 3x3 matrix.
- Unfortunately unknown at that time. This would have made life a lot easier!





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.

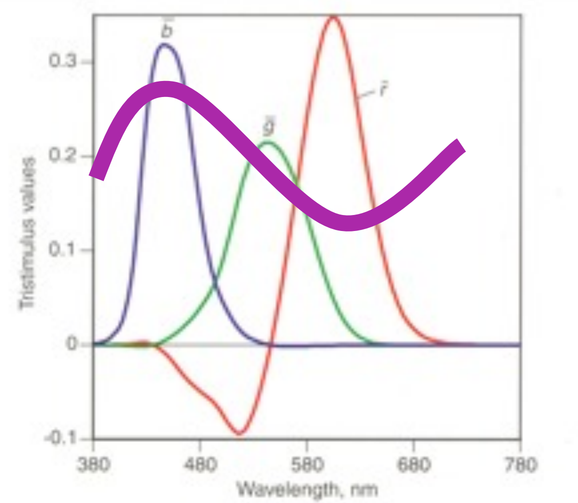
Recap

- Spectra : infinite dimensional
- Cones: 3 spectral responses
- Metamers: spectra that look the same (same projection onto cone responses)
- CIE measured color response:
  - chose 3 primaries
  - tristimulus curves to reproduce any wavelength

- Questions?

How to build a measurement device?

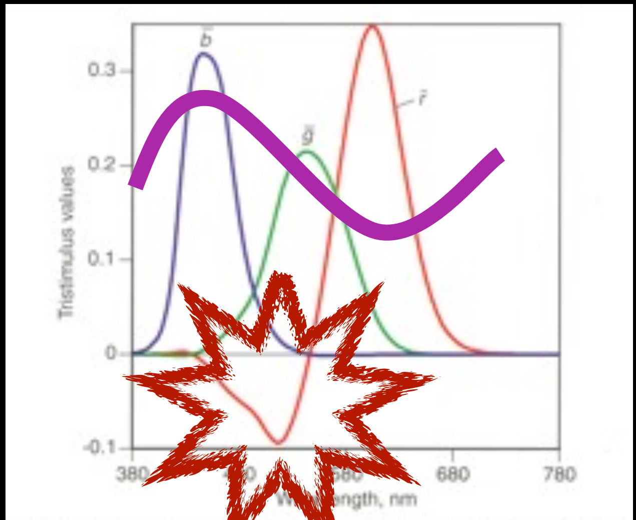
- Idea:
  - Start with light sensor sensitive to all wavelength
  - Use three filters with spectra b, r, g
  - measure 3 numbers
- This is pretty much what the eyes do!



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's problem

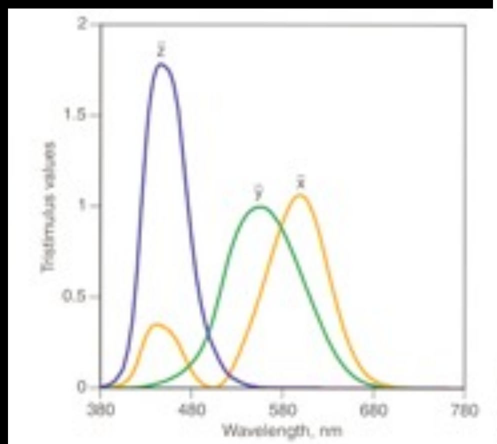
- Idea:
  - Start with light sensor sensitive to all wavelength
  - Use three filters with spectra b, r, g
  - measure 3 numbers
- But for those primaries, we need negative spectra
  -



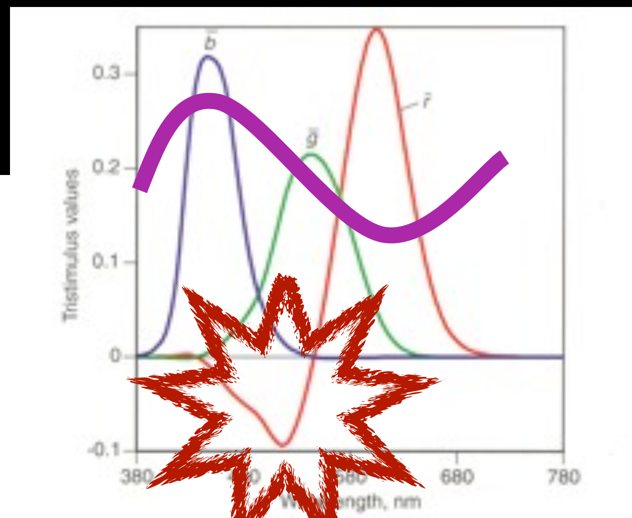
These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.

CIE's problem

- Obvious solution:
  use cone response!
  - but unknown at the time
- =>new set of tristimulus curves
  - linear combinations of b, g, r
  - pretty much add enough b and g until r is positive



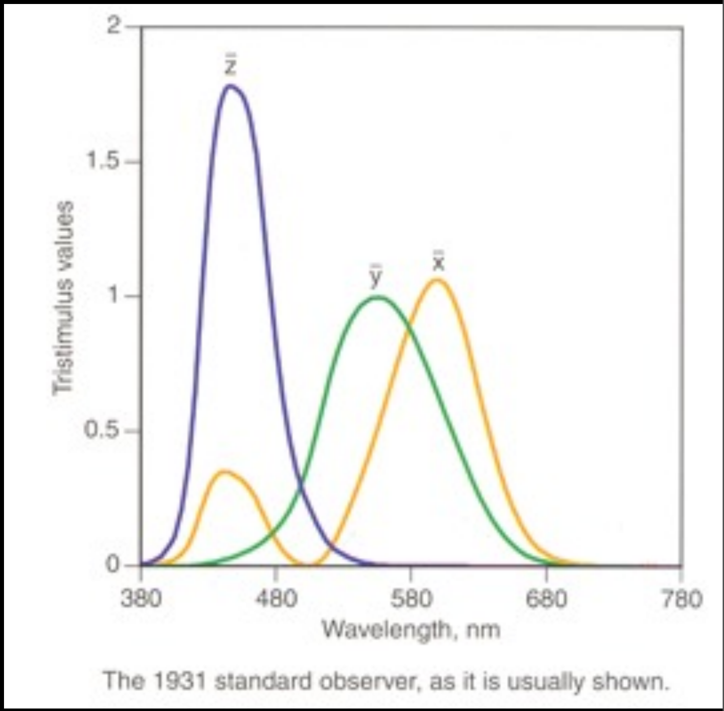
The 1931 standard observer, as it is usually shown.



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 XYZ

- The most widely recognized color space
- Linear transform of the original tristimuls curves
- 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)

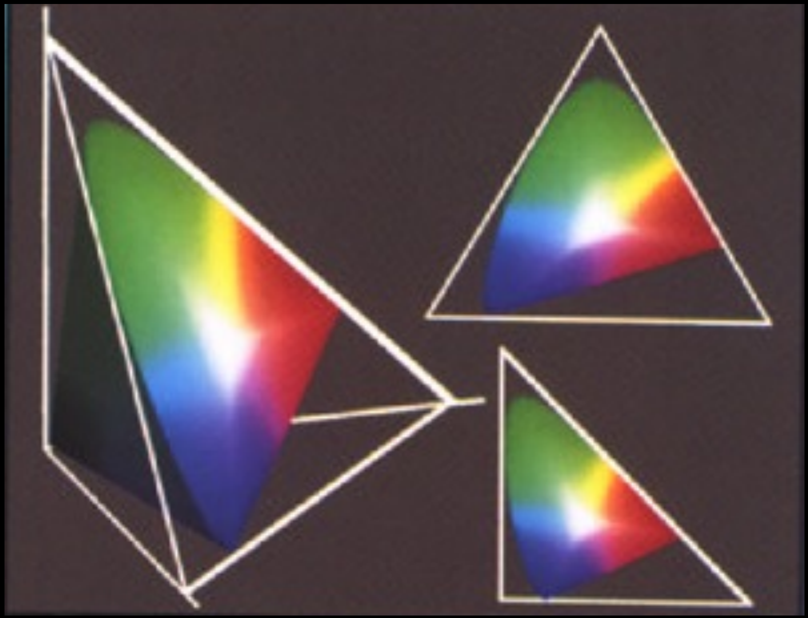


CIE color space

- 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)

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

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



In summary

- It’s all about linear algebra
  - Projection from infinite-dimensional spectrum to a 3D response
  - Then any space based on color matching and metamerism can be converted by 3x3 matrix
- Complicated because
  - Projection from infinite-dimensional space
  - Non-orthogonal basis (cone responses overlap)
  - No negative light

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MIT Press; ISBN: 0262161834
760 pages (May 7, 1999)

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by Roy S. Berns, Fred W. Billmeyer, Max Saltzman
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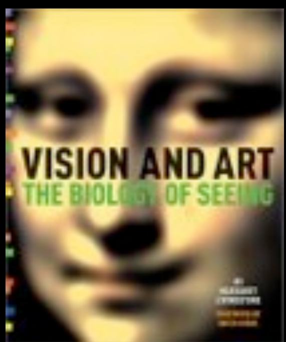

Vision and Art : The Biology of Seeing
by Margaret Livingstone, David H. Hubel
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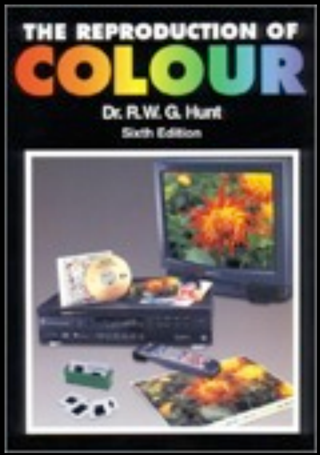

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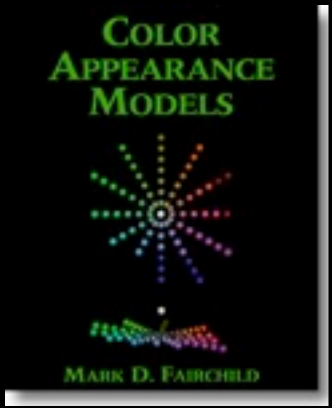
Fountain Press, 1995



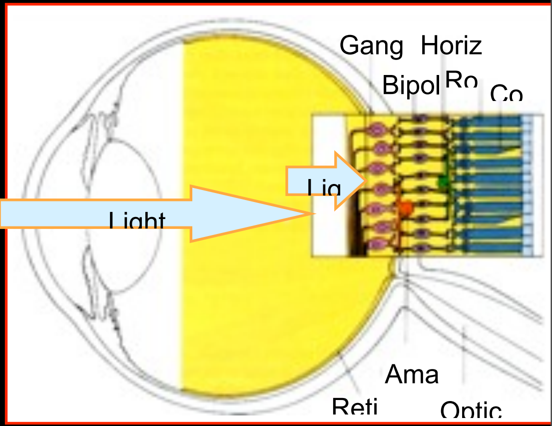
Color Appearance Models
by Mark Fairchild
Addison Wesley, 1998

Questions?

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

Explanation for inverted eye

- Thanks Quinn!
- Allows photoreceptors to be closer to oxygen & nutrient supply, waste management, etc.



- Layer of cells in front of receptors act as fiber optics
  - http://www.pnas.org/cgi/content/short/104/20/8287
  - http://www.pnas.org/cgi/content/short/104/20/8287
  - http://books.google.com/books?id=_4Waro_peuMC&pg=PA77&lpg=PA77&dq=photoreceptor+waveguide&source=web&ots=2jpmEB9F2Y&sig=mnYwGPKLWjeoQFNKNsukyX8VmTY#PPA77,M1
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