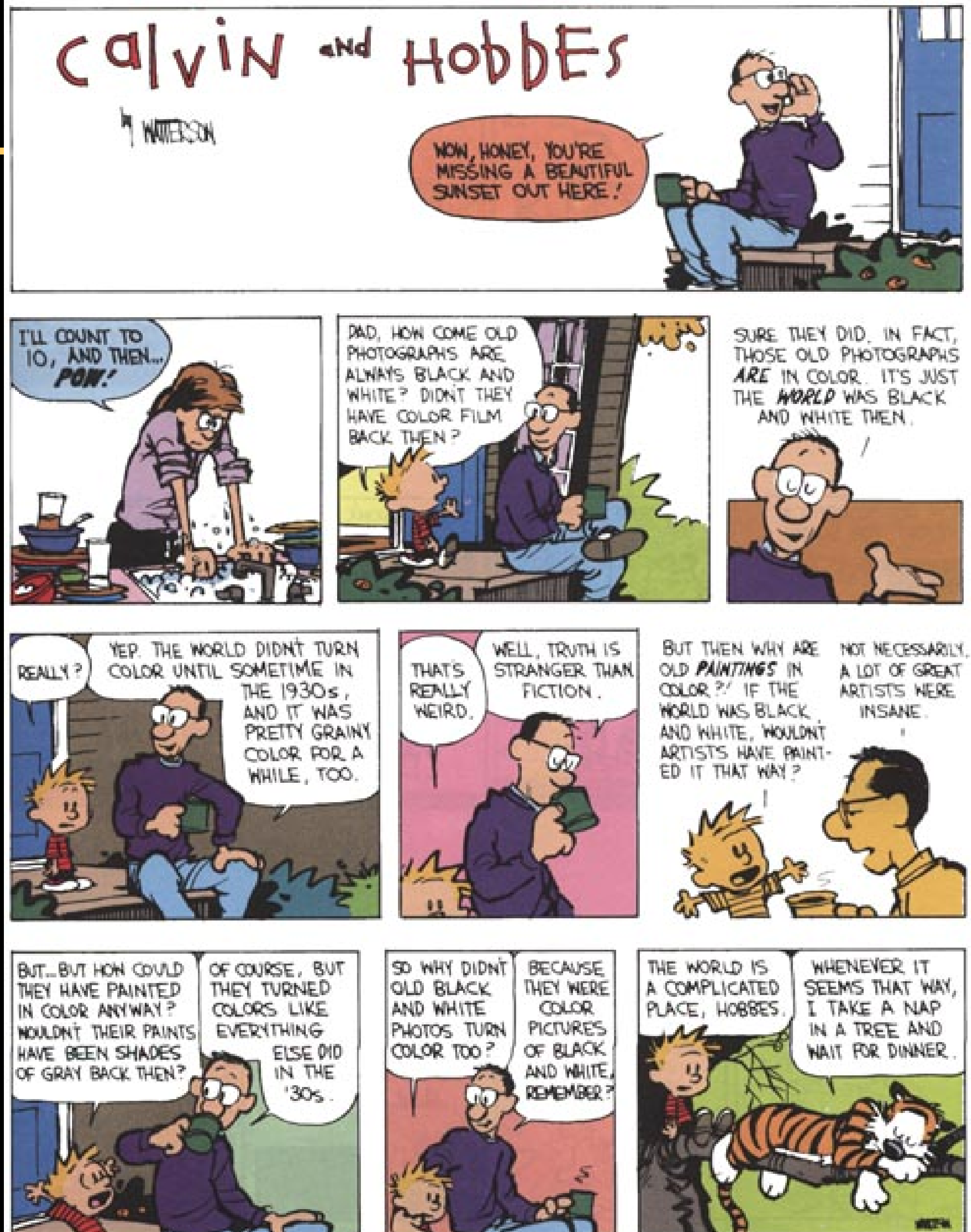
Color


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.

Color

Frédo Durand and Barb Cutler
MIT- EECS

Many slides courtesy of Victor Ostromoukhov and Leonard McMillan

Admin

- Final project due this Friday
  - If you aren't well advanced yet, time to freak out
- Don't forget the final report (~1000 words)
- Submit code, executable, instructions
  (we want to copy-paste command lines)

Review of assignments

- Ray-casting spheres, planes, triangles
- Shadow rays, reflection, refraction
- Phong shading, solid textures
- Grid acceleration
- Supersampling and filtering
- Spline editing, surfaces of revolution, patches
- Particle systems

How to optimize your ray tracer

- Grid insertion: be smart about bbox!
  - Don't check all voxels!
- Precompute values used by intersection
  - E.g. inverse of matrix, square of radius
  - If a value does not change between iterations, cache it!
- Passing parameters as pointers/refs, not value
  - Otherwise you spend a lot of time calling constructors and allocating memory
- In general, avoid memory allocation in inner loops

- But remember, optimization should come last and not at the price of readability
- Trust the compiler for low-level optimizations

Industrial-strength ray tracer

- Usually, one single primitive (triangles)
- Heavily optimize ray-triangle and spatial data structure (recursive grid or kd-tree)
  - Watch memory footprint
- Pluggable shaders (same as your shader class)
- High-quality supersampling (same as you)
- Distribution ray-tracing (soft shadows, glossy, DoF)
- Global illumination (Irradiance caching, photon maps, but only recently used)
- Texture mapping, bump mapping
- Fancy light sources (shaders as well)
- Volumetric effects (fog, dust)
- Data management (although not always done well)

Today: color

Disclaimer:

- Color is both quite simple and quite complex

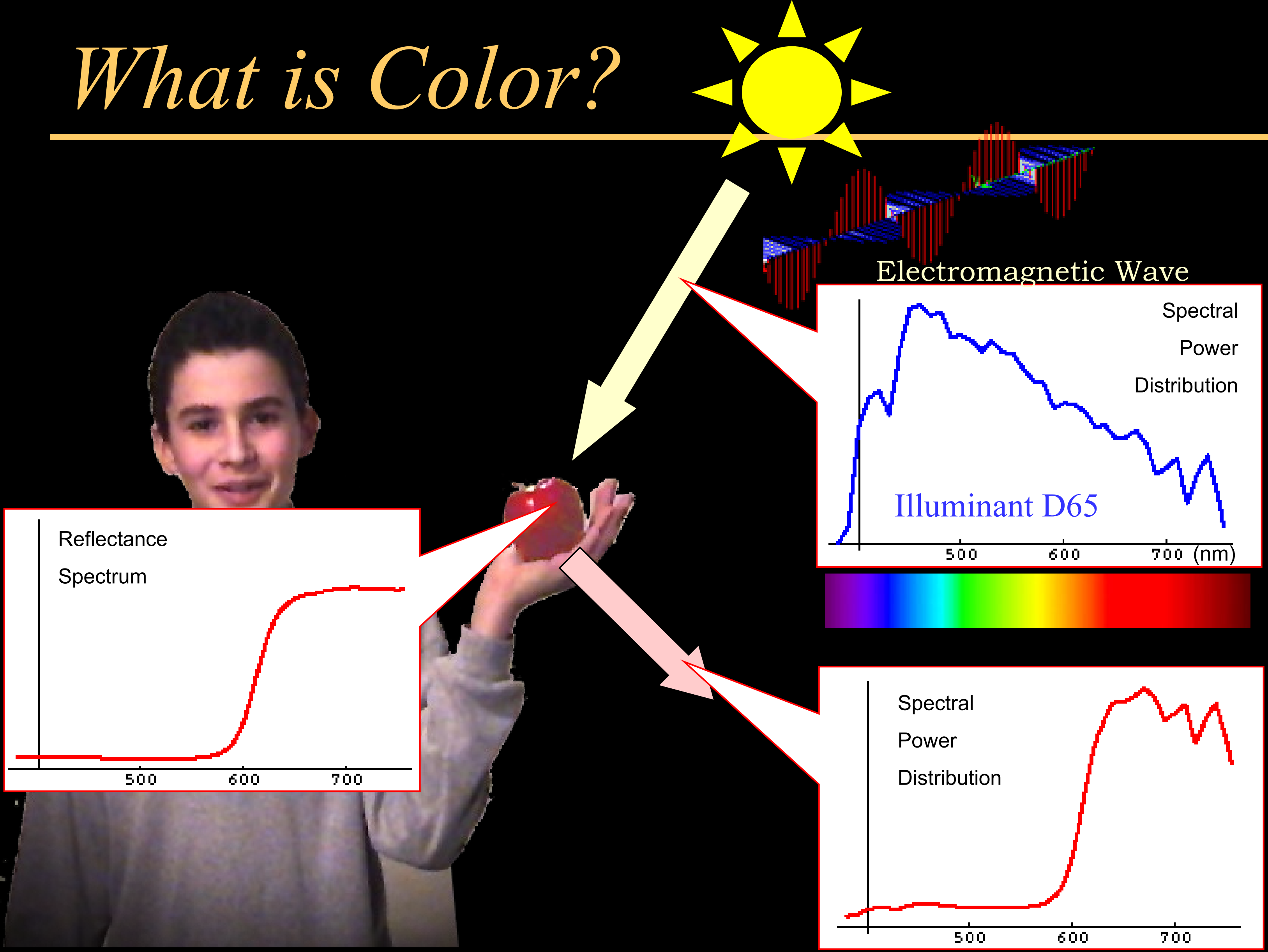
- There are two options to teach color:
  - pretend it all makes sense and it's all simple
  - Expose the complexity and arbitrary choices
- Unfortunately I have chosen the latter
  - Too bad if you believe ignorance is bliss

Plan

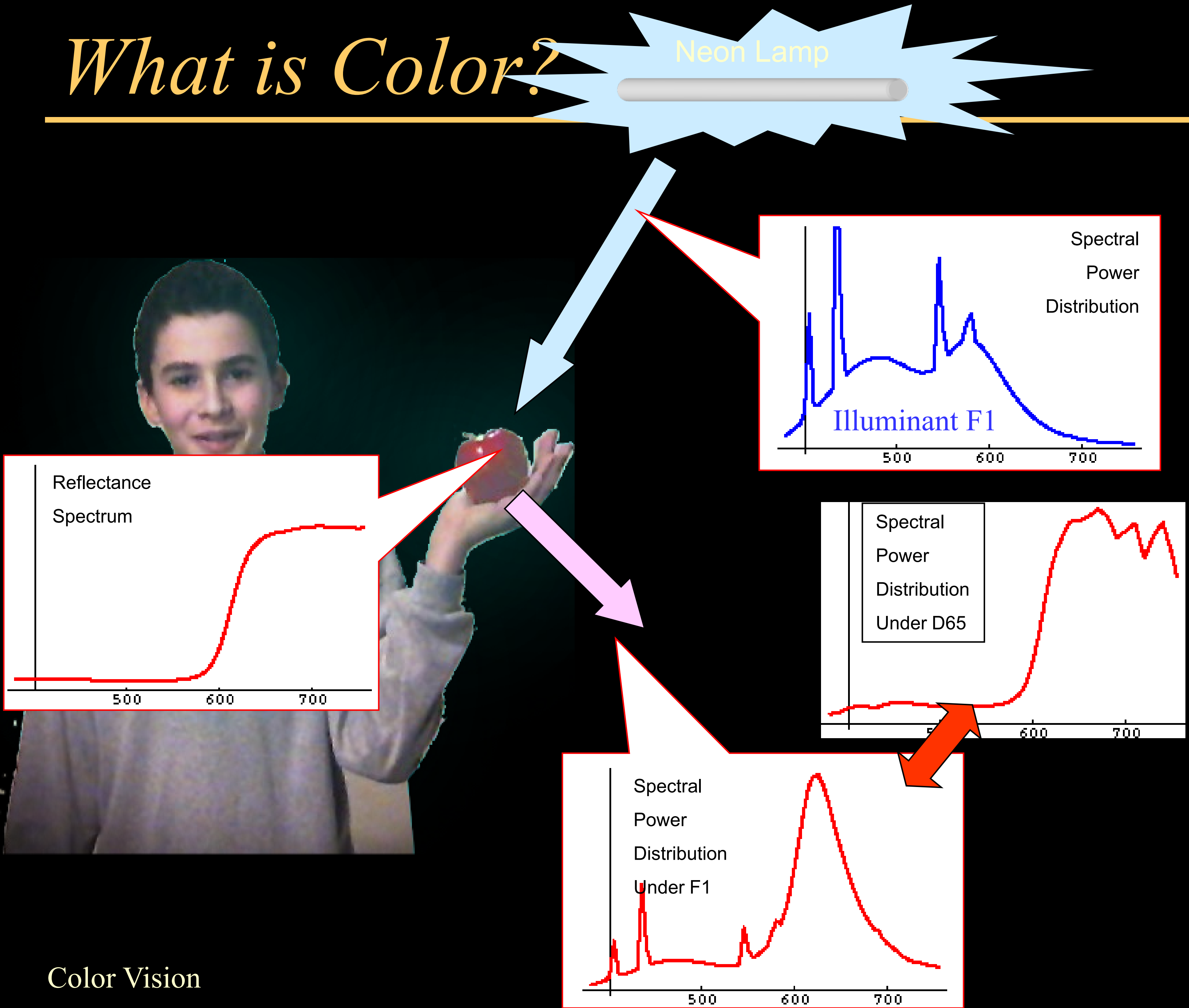
- What is color
- Cones and spectral response
- Color blindness and metamers
- Fundamental difficulty with colors
- Colorimetry and color spaces

- Next time:
  More perception
  Gamma

What is Color?



What is Color?



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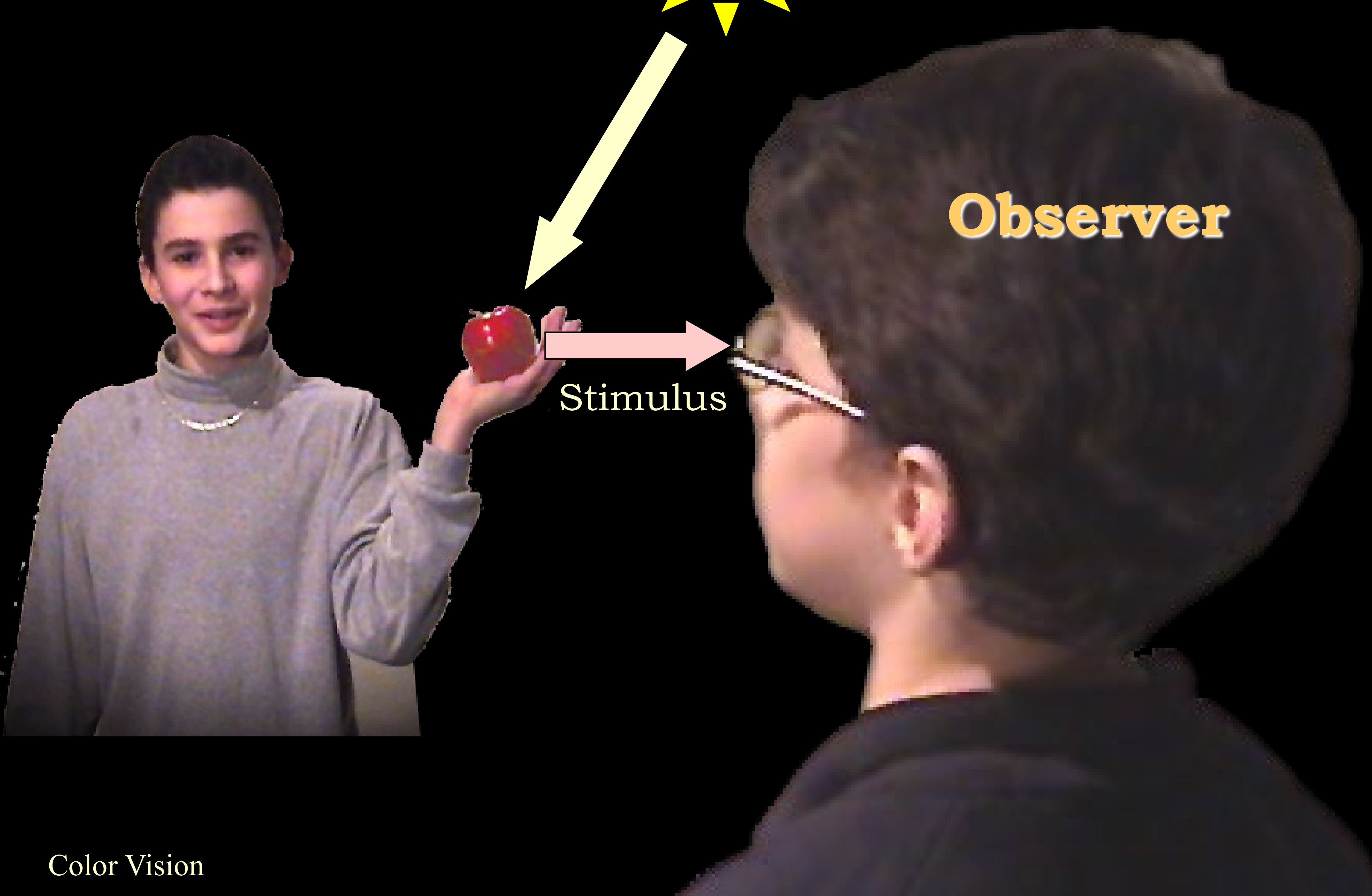

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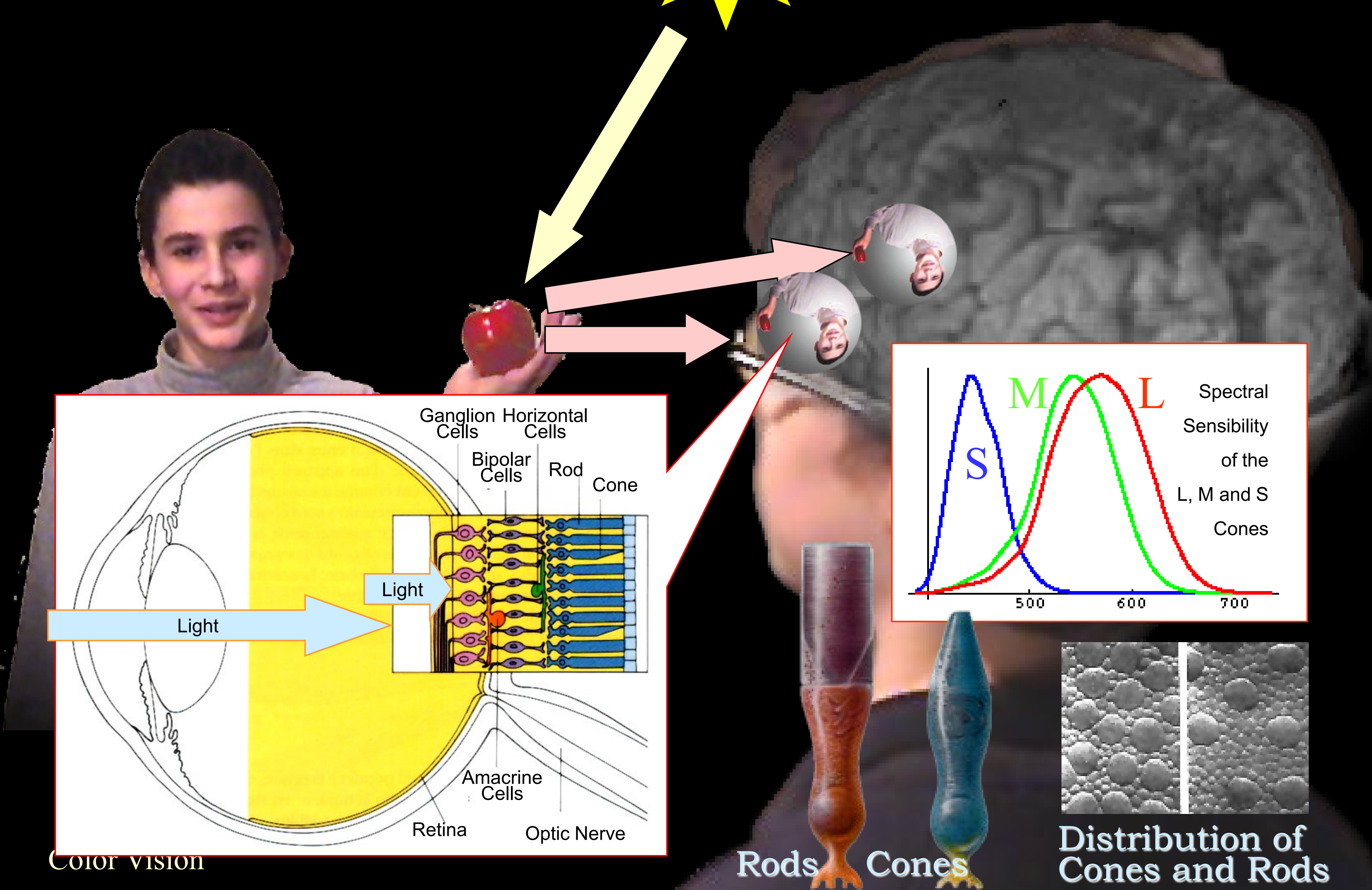
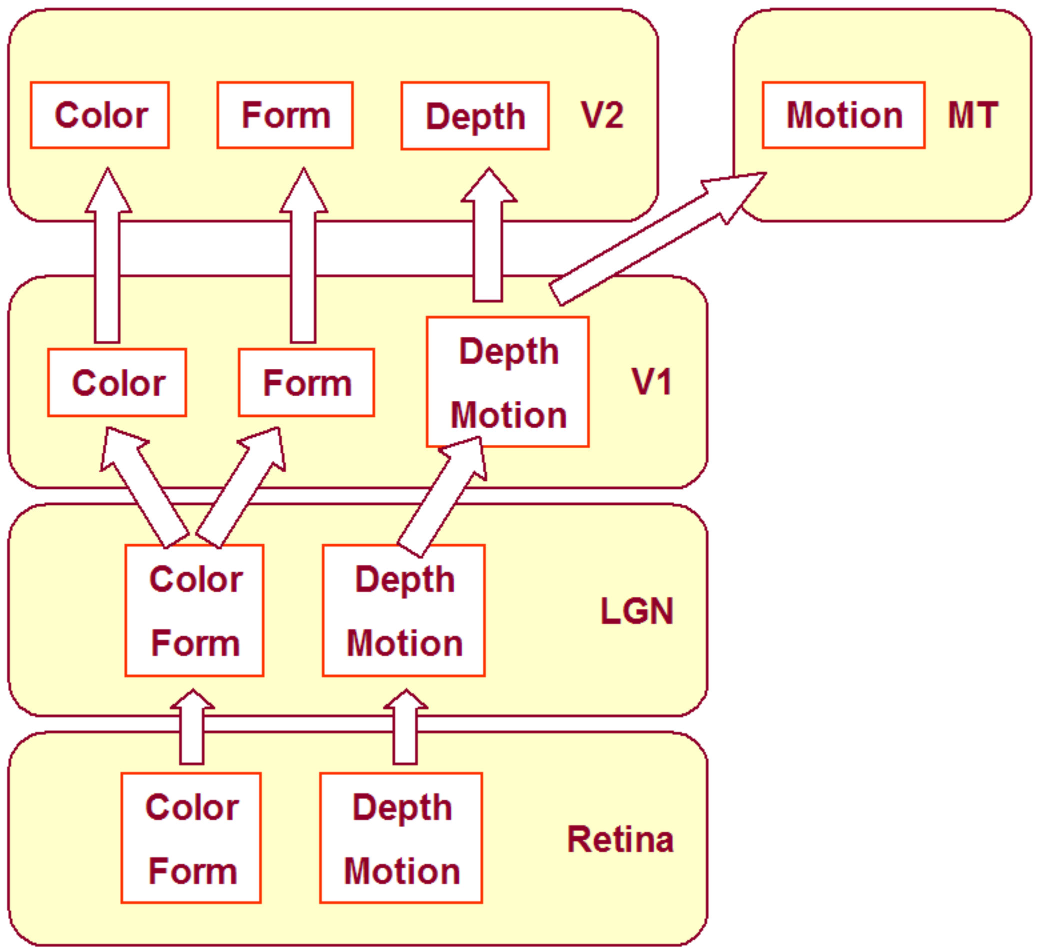
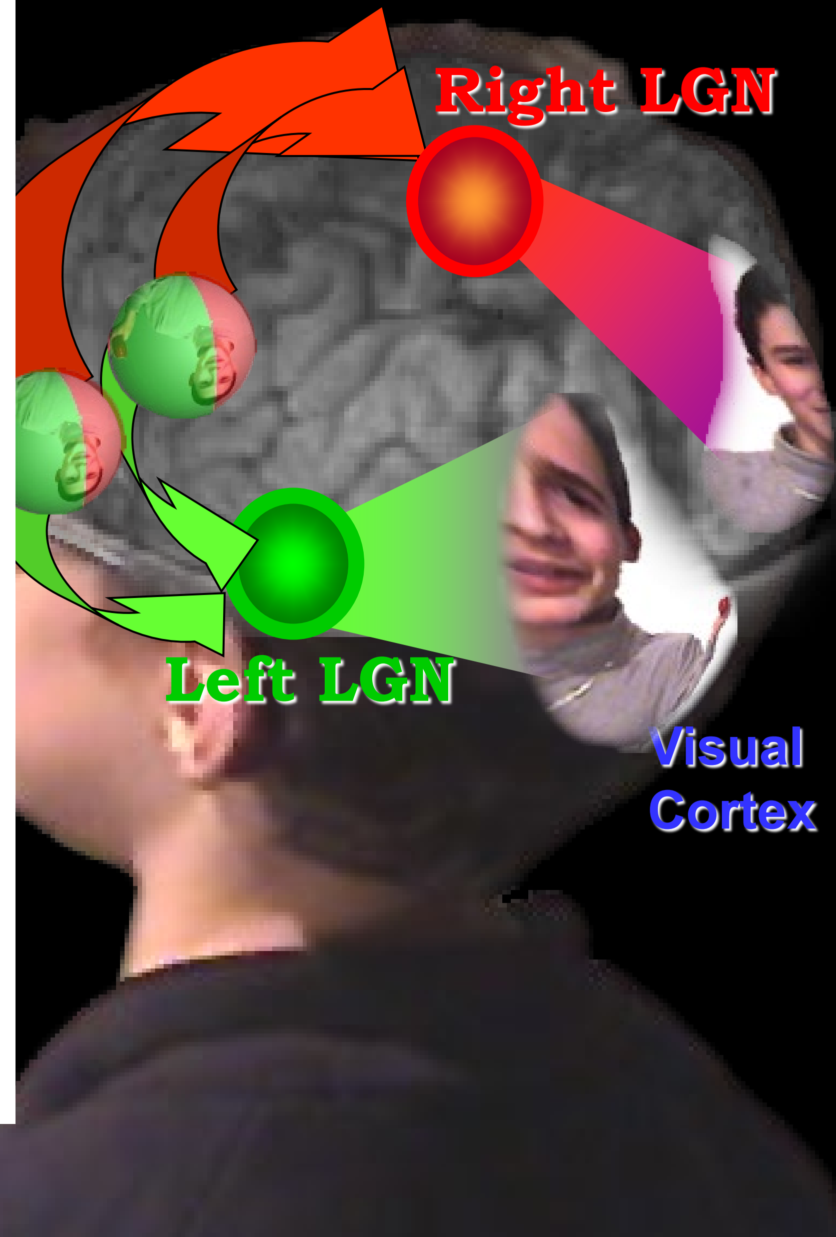


What is Color?

Visual Pathways [Palmer99]





LGN = Lateral Geniculate Nucleus

Questions?

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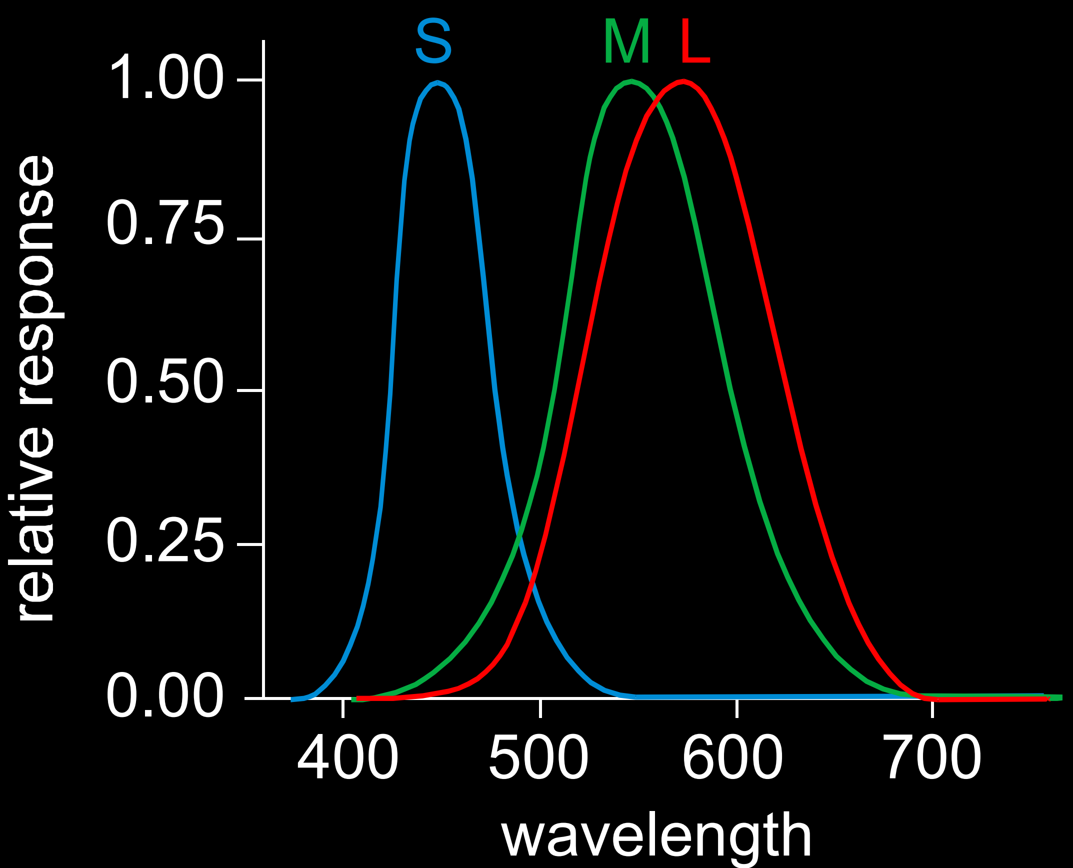
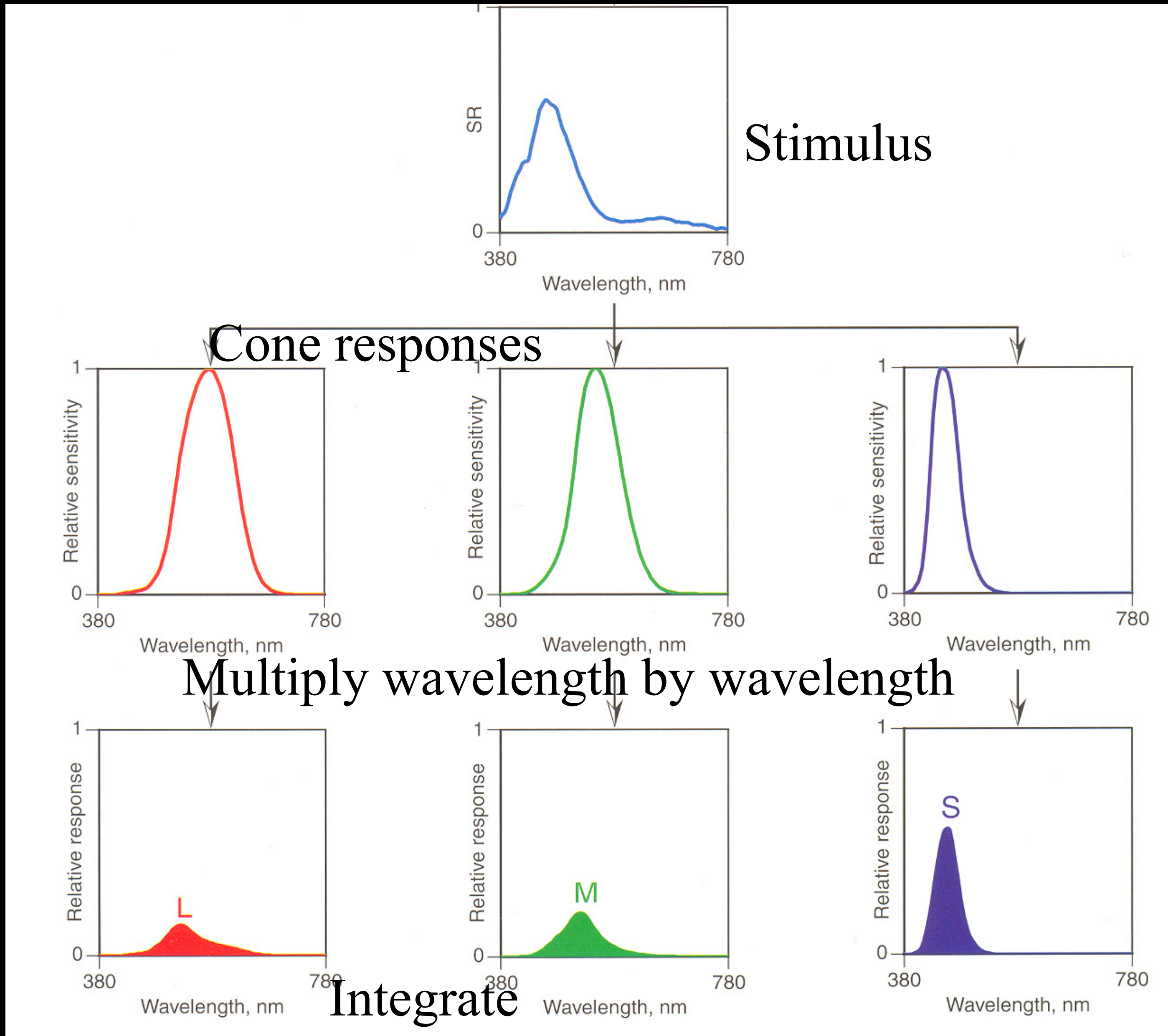
Cone spectral sensitivity

- Short, Medium and Long wavelength
- Response = $\int_{wavelength}$ stimulus(λ) * response(λ) dλ

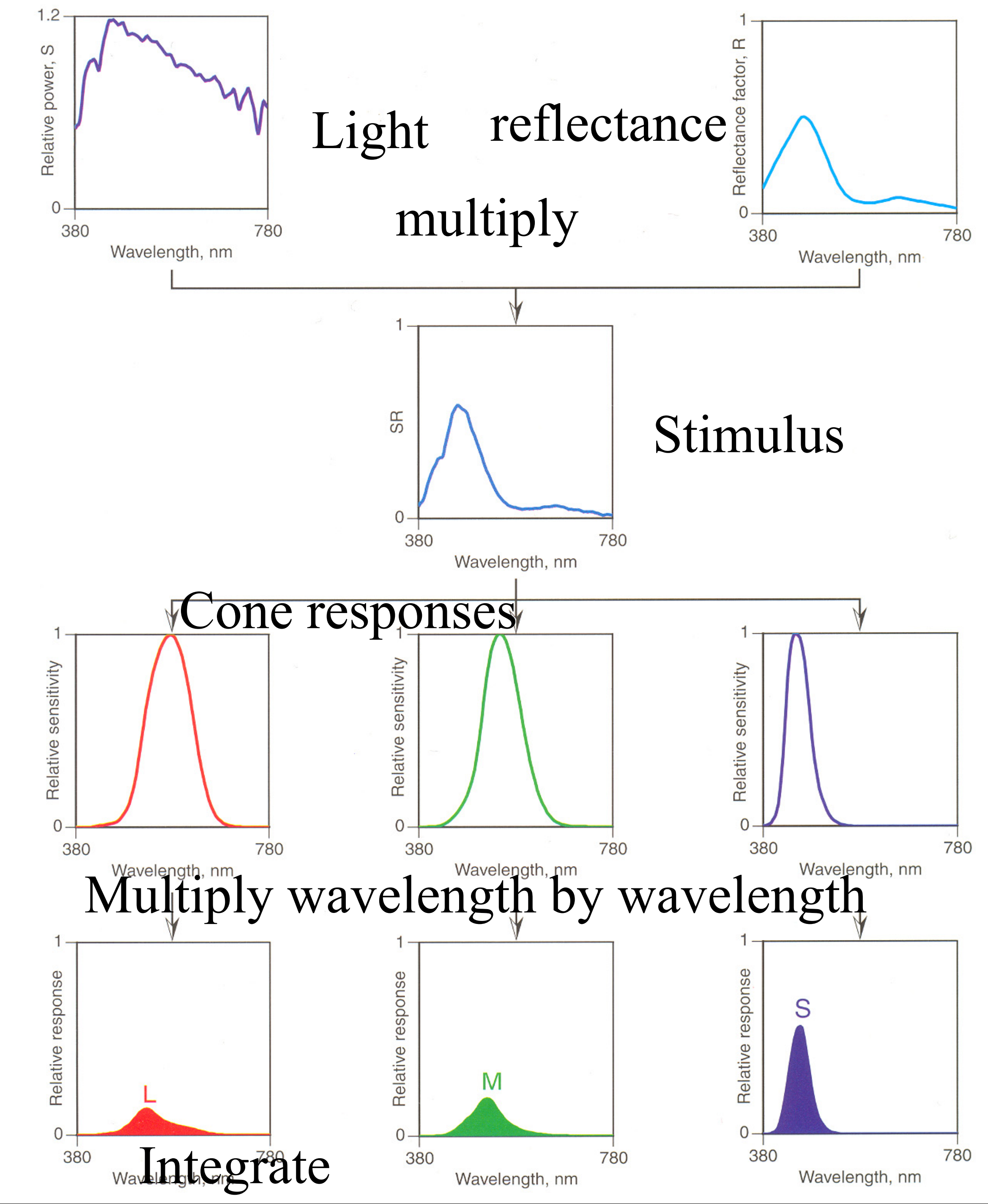


Cone response



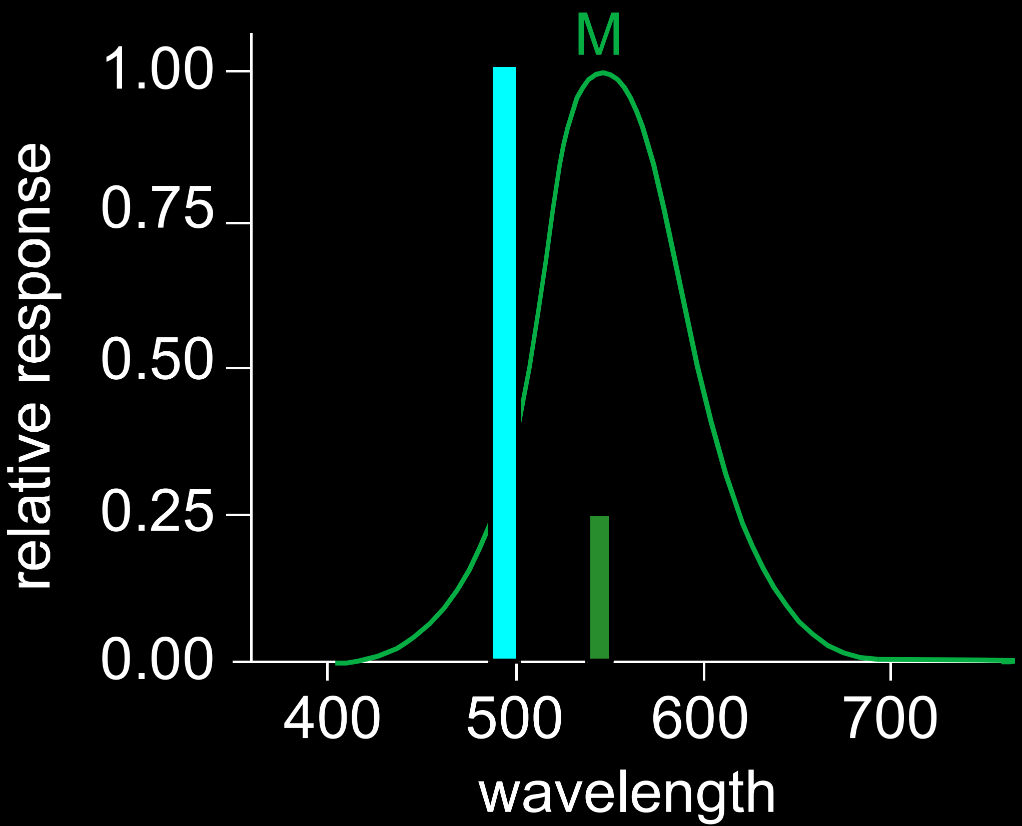
Big picture

- It's all linear!



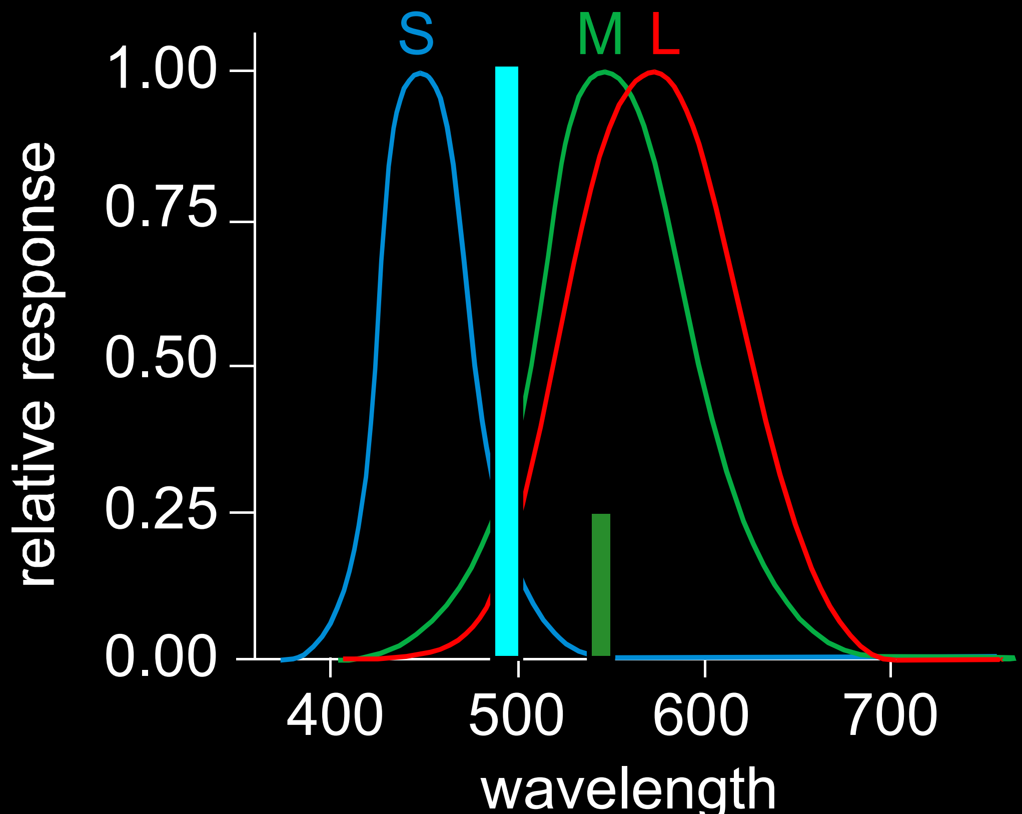
Cones do not "see" colors

- Different wavelength, different intensity
- Same response



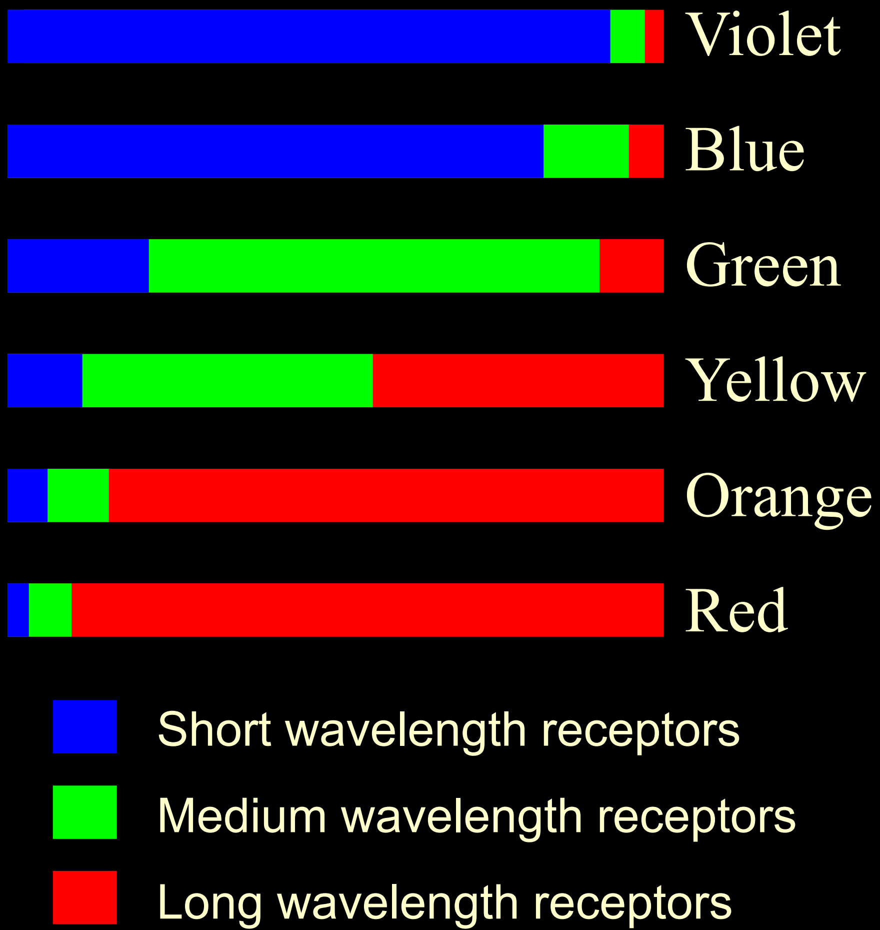
Response comparison

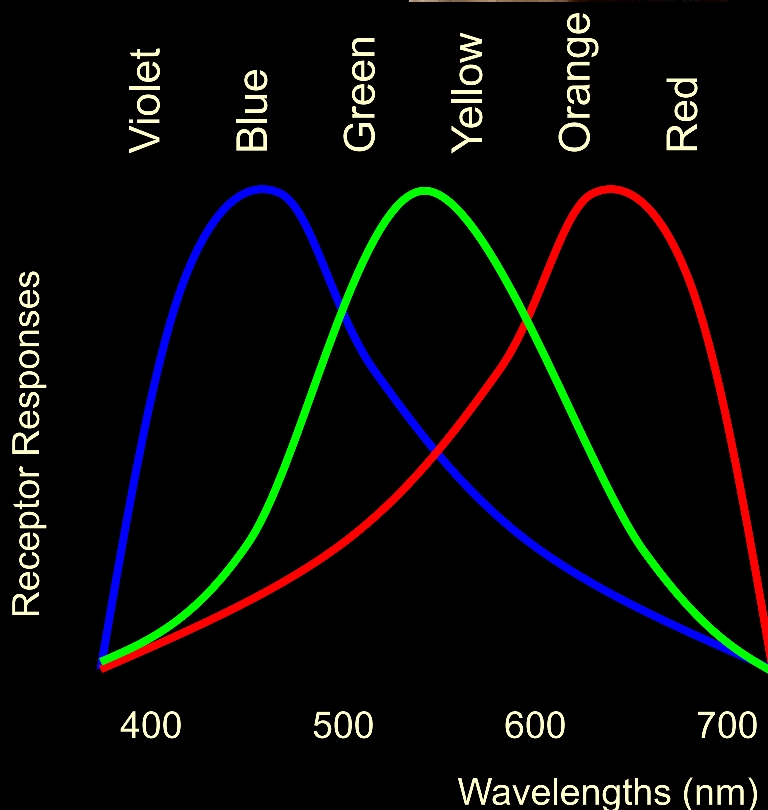
- Different wavelength, different intensity
- But different response for different cones



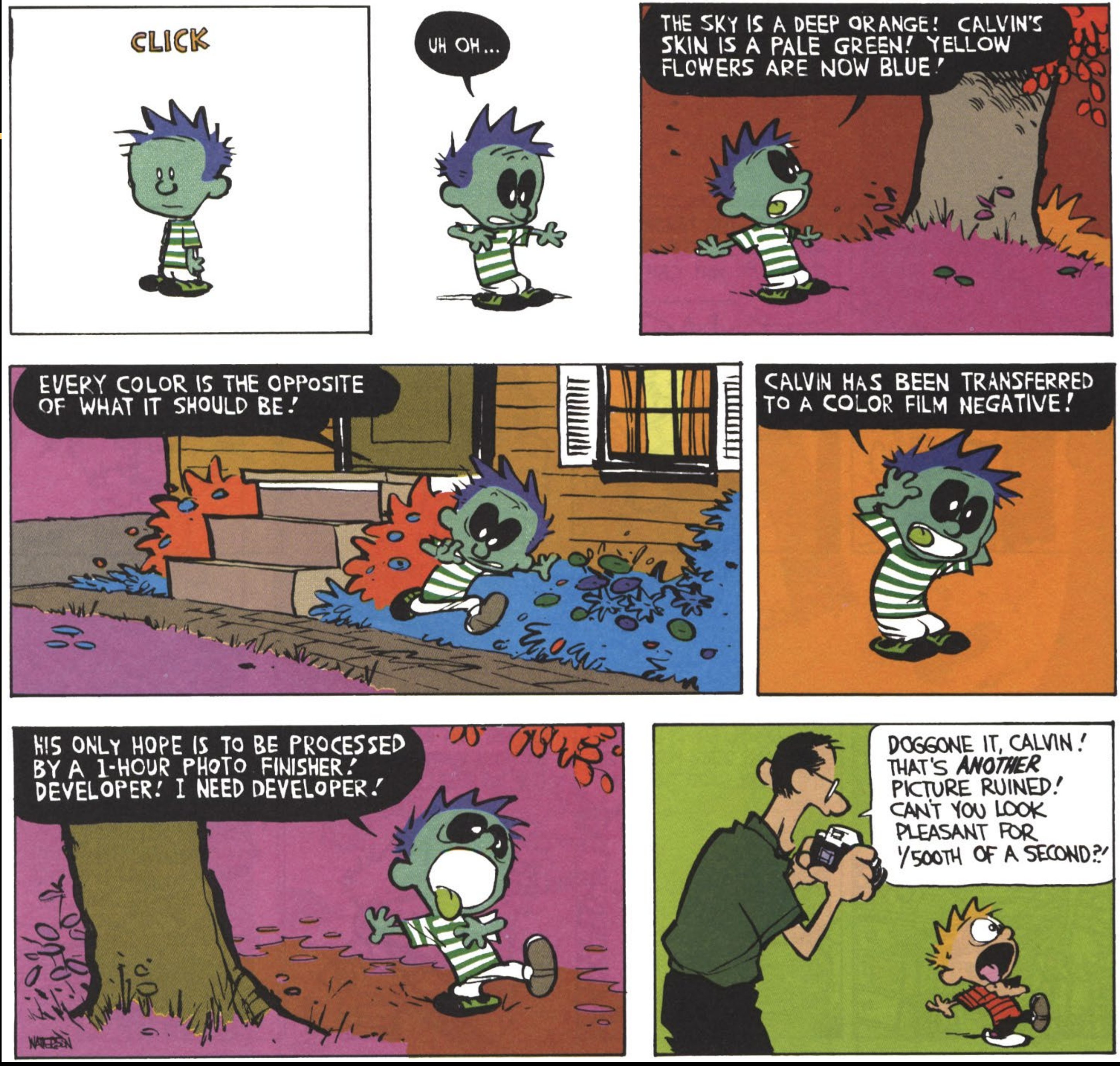
von Helmholtz 1859: Trichromatic theory

- 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?!

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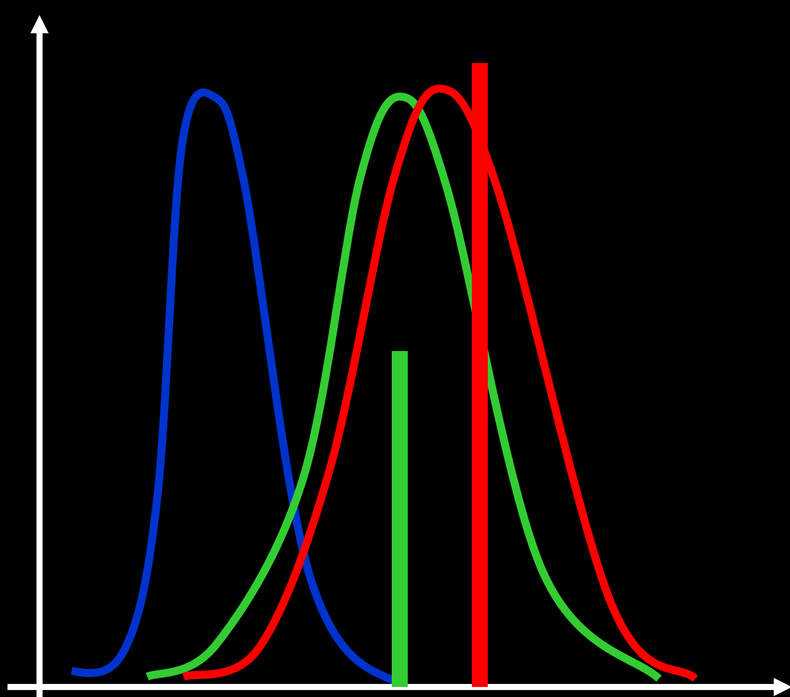
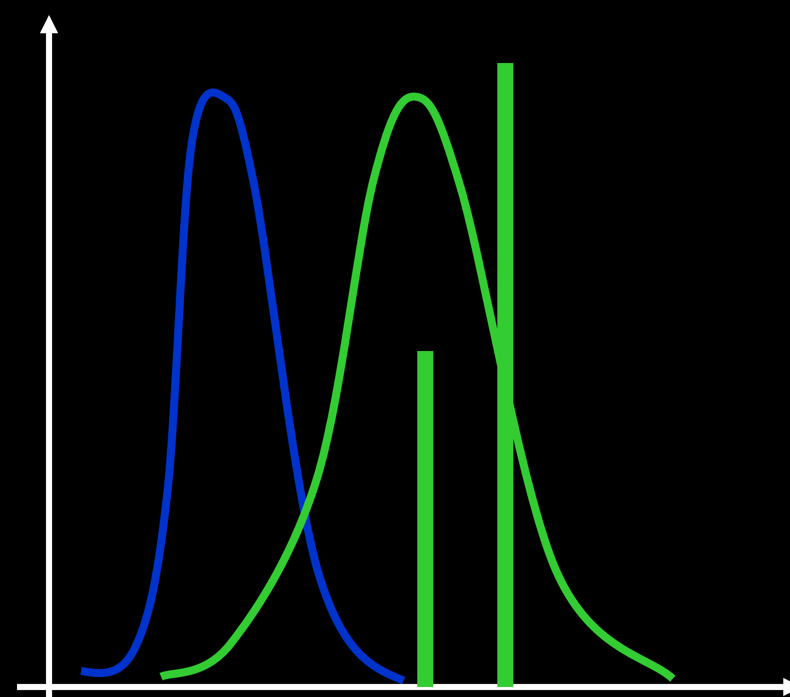
Color blindness

- 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

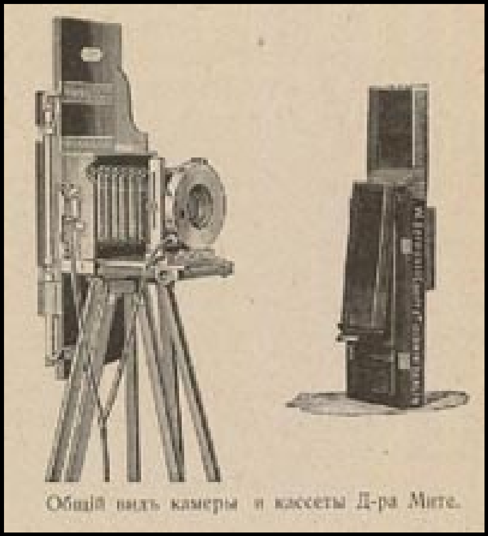
- Metamers under a given light source
- May not be metamers under a different lamp

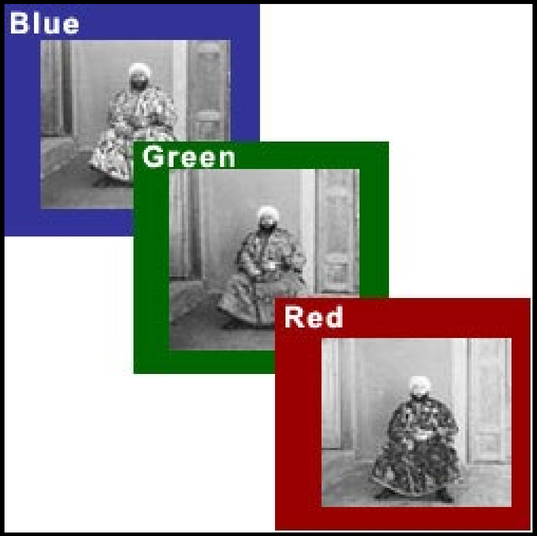
Questions?

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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Playtime: Prokudin-Gorskii

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Warning

Tricky thing with spectra & color:

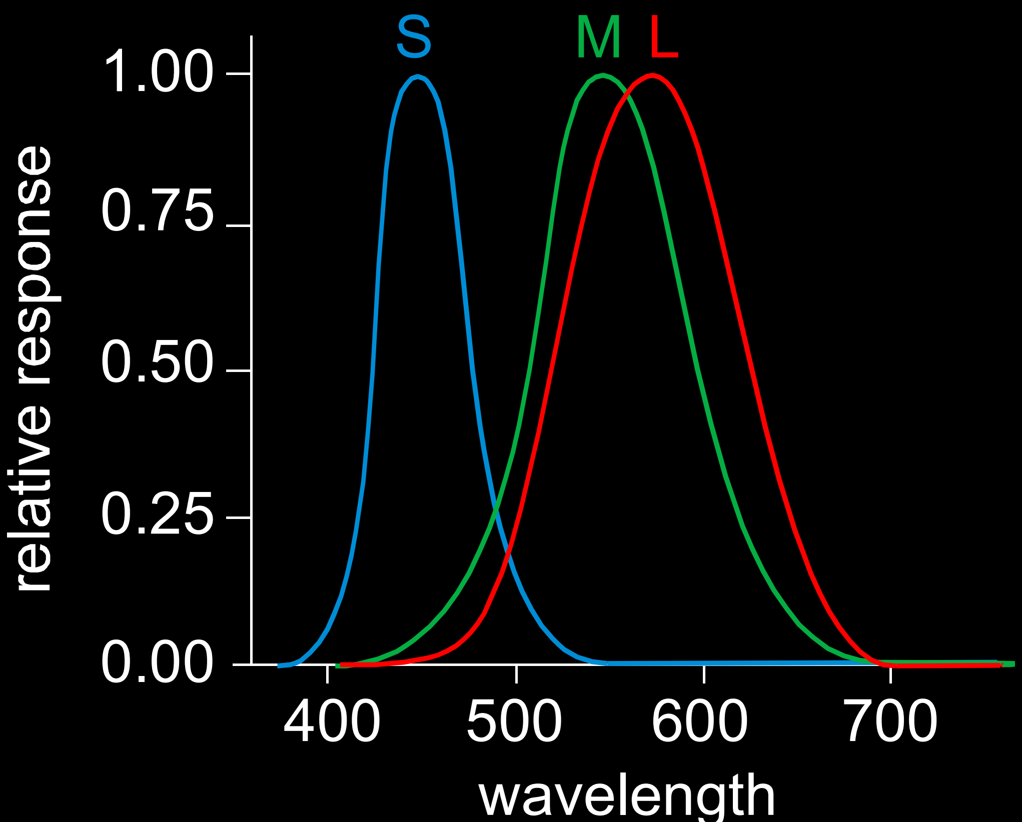
- Spectrum for the stimulus / synthesis
  - Light, monitor, reflectance
- Response curve for receptor /analysis
  - Cones, camera, scanner

They are usually not the same

There are good reasons for this

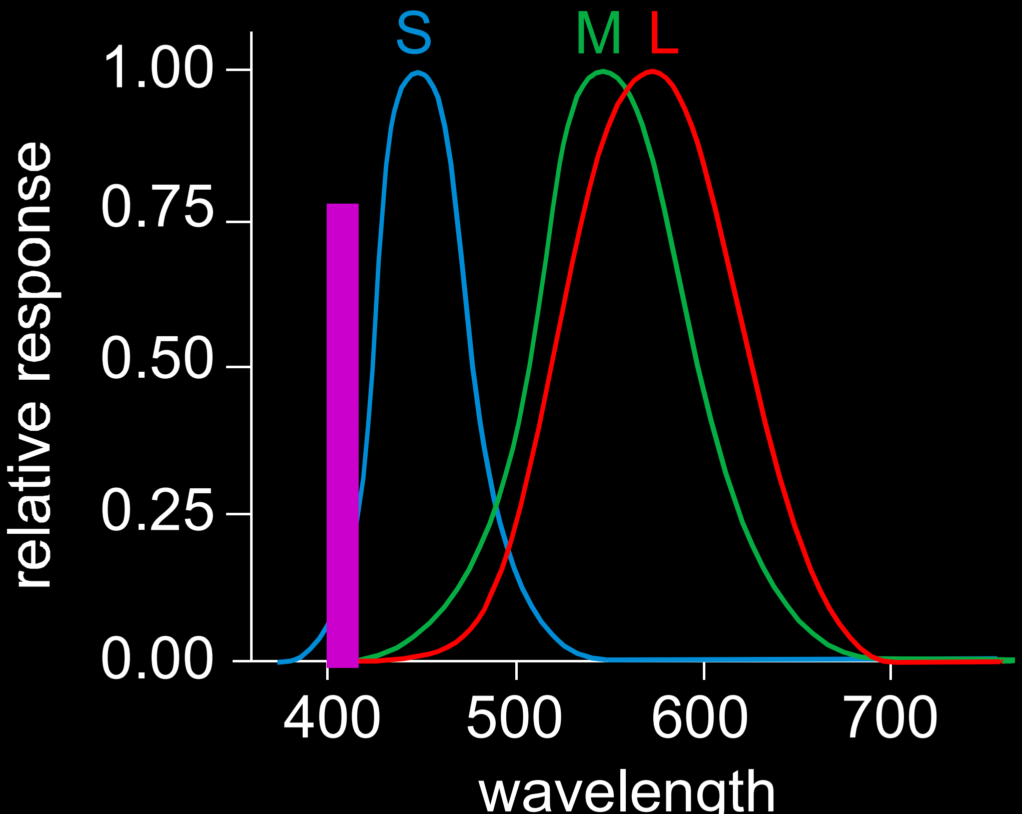
Synthesis

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



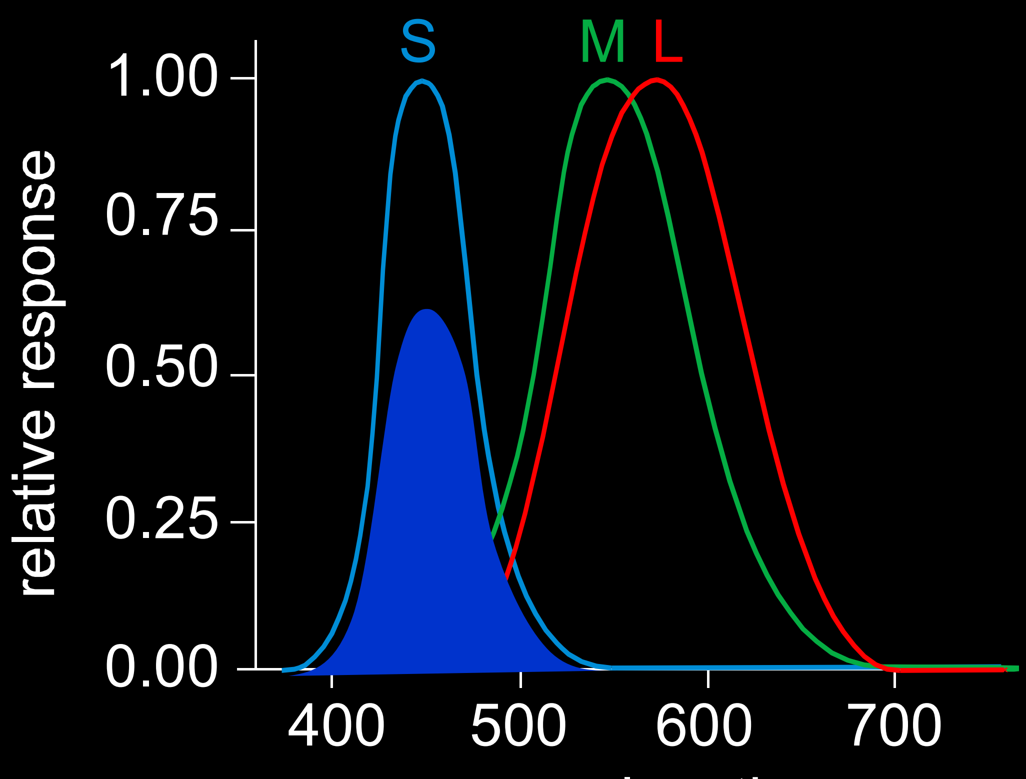
Synthesis

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



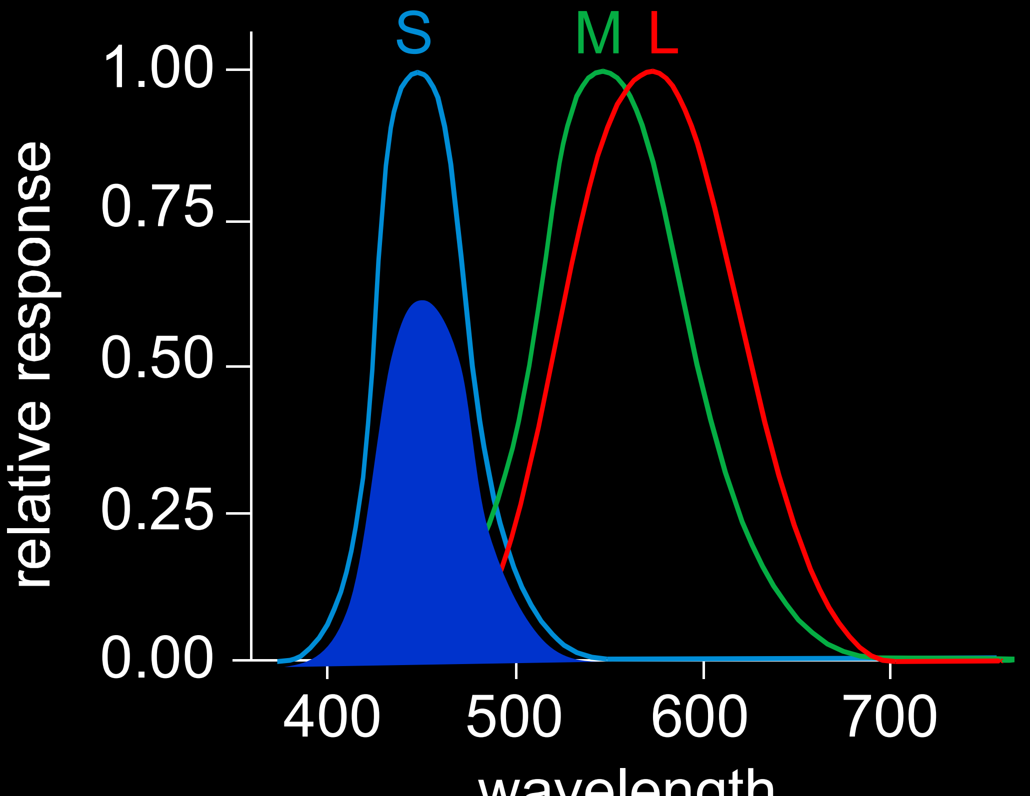
Synthesis

- 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



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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

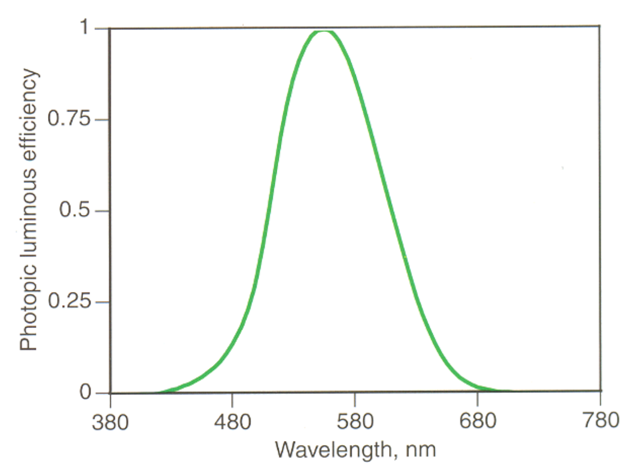
Standard color spaces

- 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

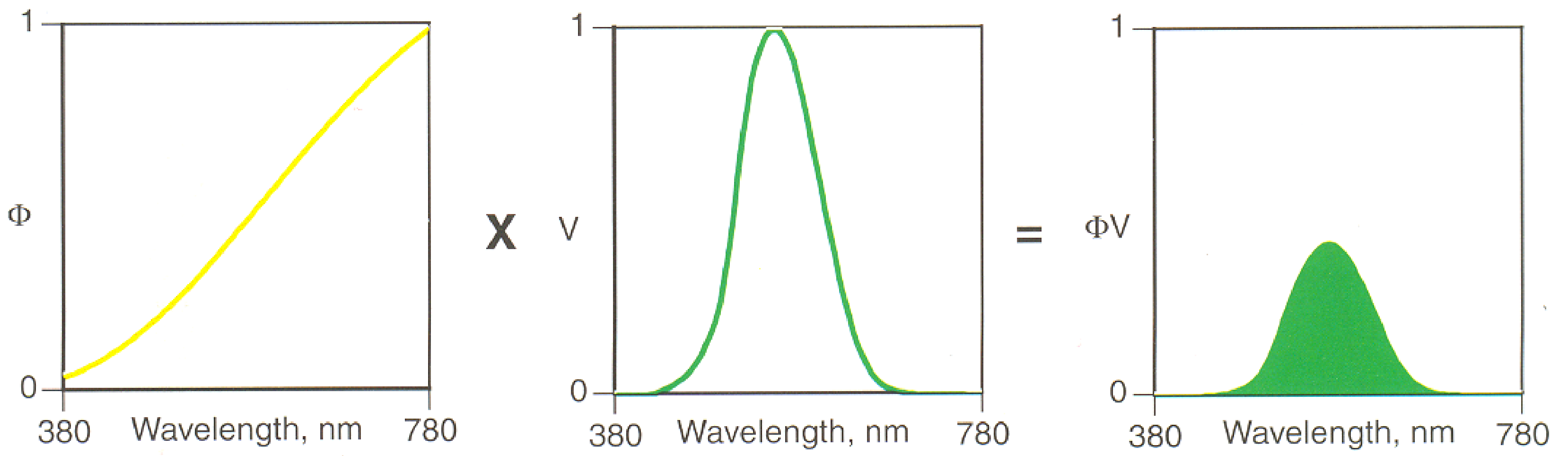
- Commission Internationale de l'Eclairage (International Lighting Commission)
- Circa 1920
- First in charge of measuring brightness for different light chromaticities (monochromatic wavelength)



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, Φ_λ, and the standard photopic observer, V_λ, 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?