Visual Imaging and the Electronic Age

Color Science

Grassman's Experiments & Trichromacy

Lecture #5

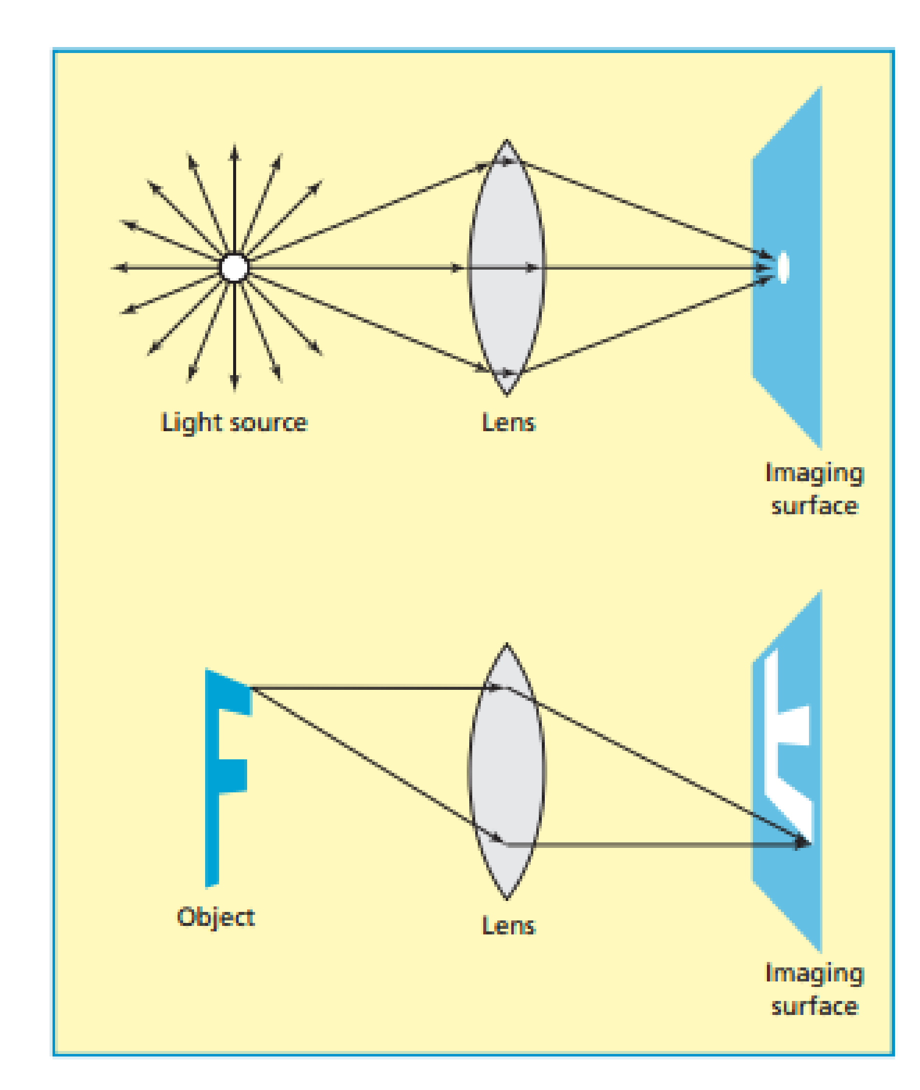
September 17, 2020

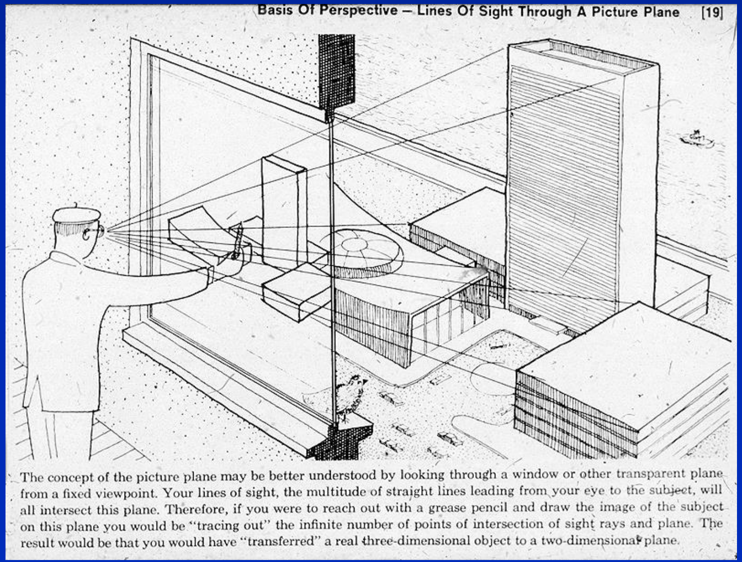
Prof. Donald P. Greenberg

- Required Reading:
- Roy S. Berns. “Principles of Color Technology,” 2000 John Wiley & Sons, Inc., Chapter 1. PDF
- None
- References:

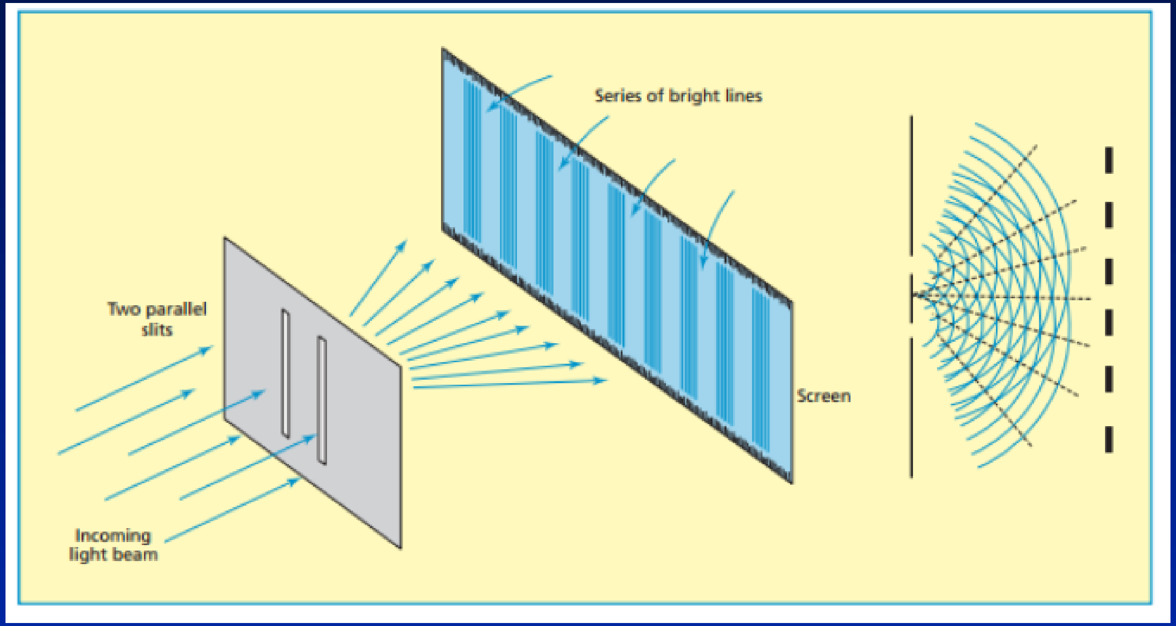
- Foundations of Color Science Lecture.
- S. Deleniv. "The Basic Neurobiology Behind the Recently Famous 12-Dot Illusion." September 17, 2016. The Neurosphere.
- R.C. Dougal. "Maxwell's First Coloured Light Sources: Artists' Pigments," Colour in Art, Design and Nature, WIT Press, 2011
- Holland Cotter. "Harmony, Harder than it Looks," The New York Times, July 27, 2012. The New York Times
- Dr. R.W.G. Hunt. "The Reproduction of Colour," 1995, Fifth Edition, Fountain Press.
- Gunter Wyszecki & W.S. Stiles. "Color Science," 1967 John Wiley & Sons, Inc.
- Tom N. Cornsweet. "Visual Perception," 1970, Academic Press.

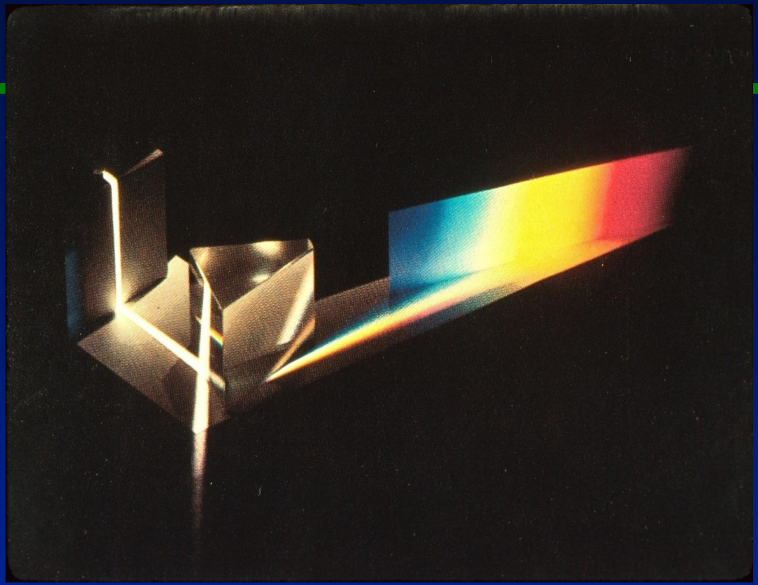
Light as Rays

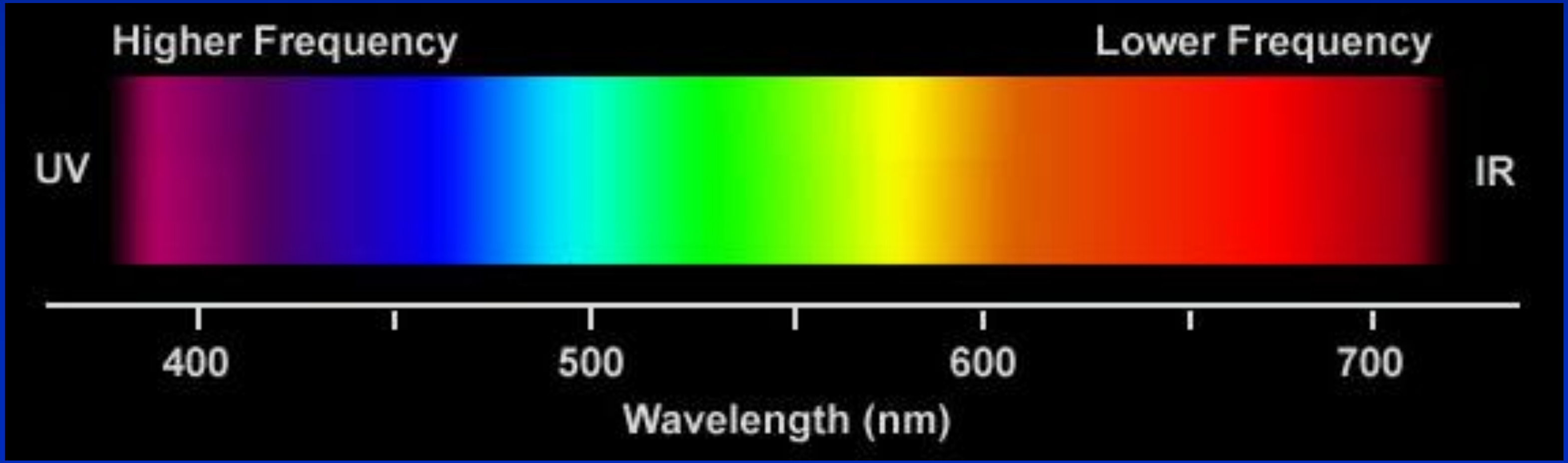




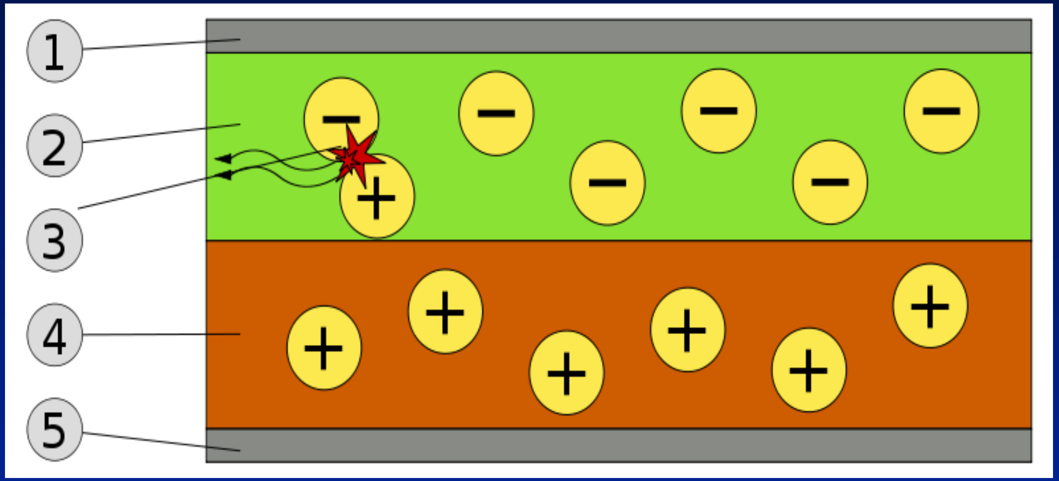
Light as Waves

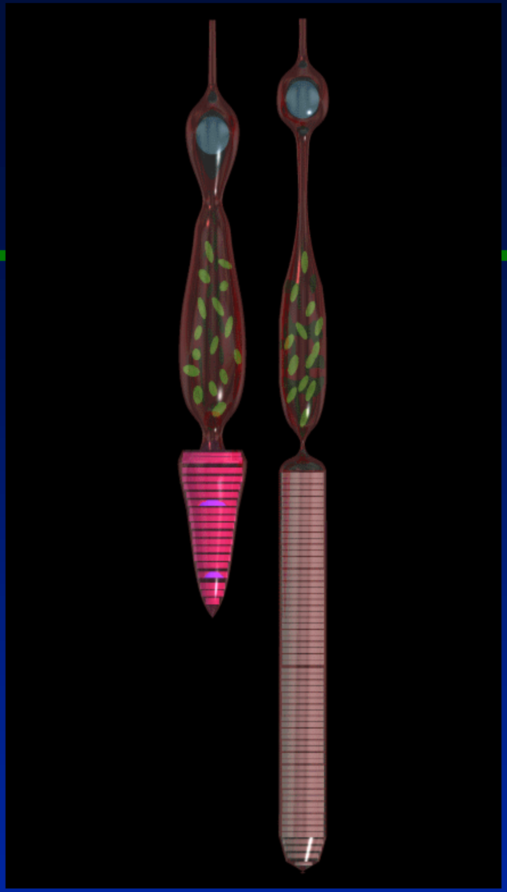


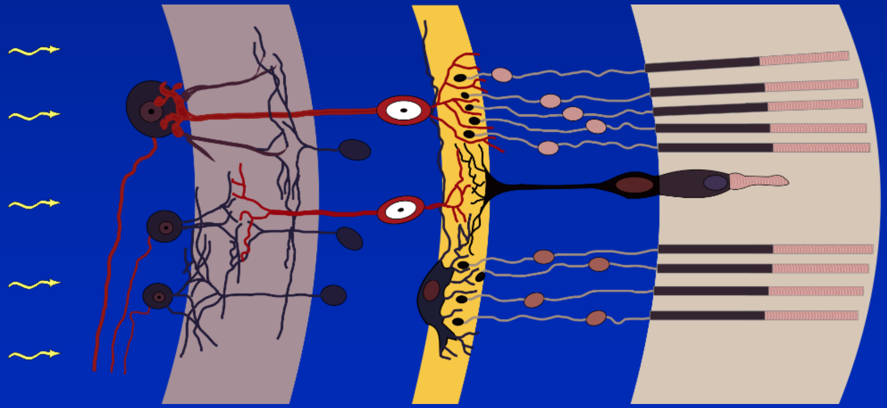


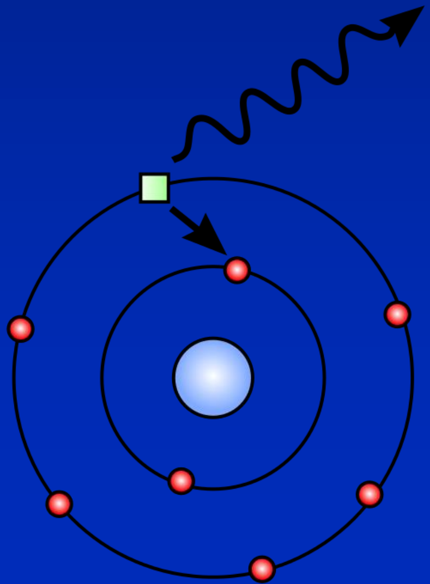


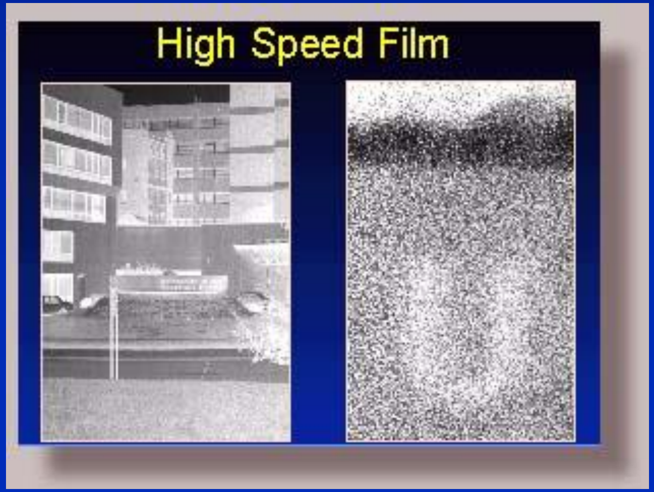
Light as Photons



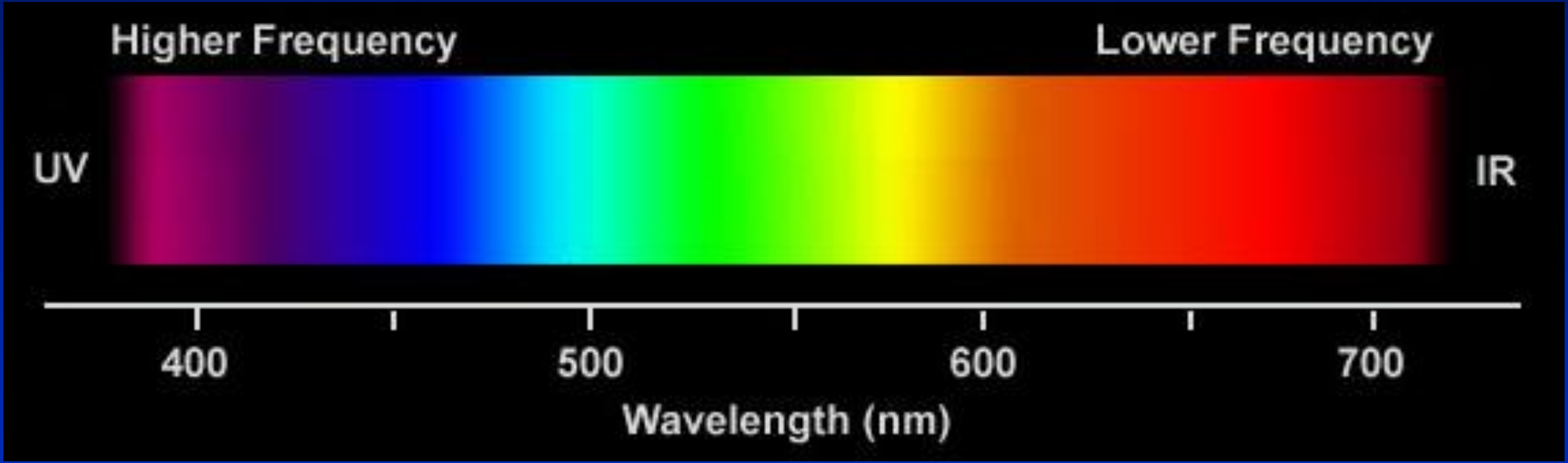




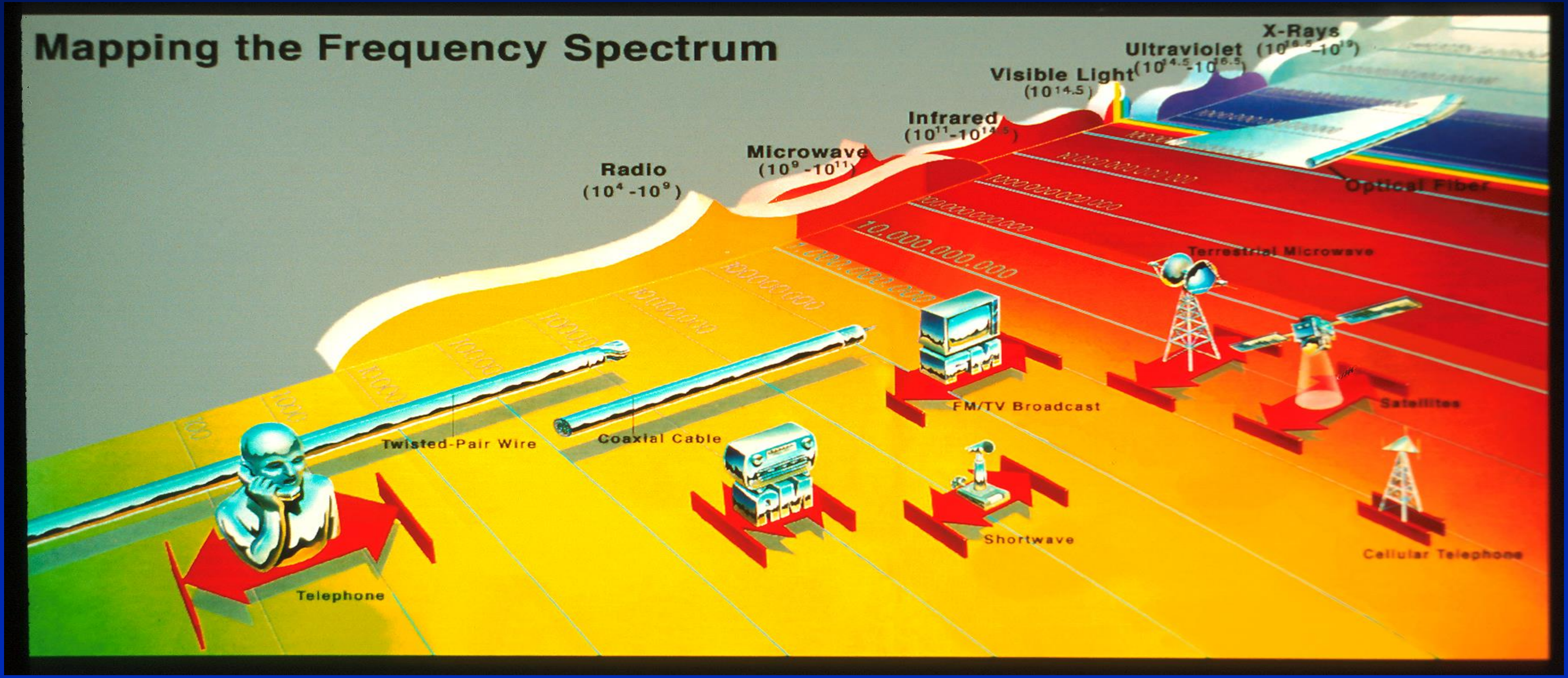




Visible Light Spectrum



Frequency Spectrum



What is Color Science?

- Quantifying the physical energy which reaches the eye (physical)
- Determining the information which is sent from the retina (rods and cones) through the optic nerve to the human visual system (physiological stimuli)
- How does the brain interpret this information? (cognitive)

What is Color Science?

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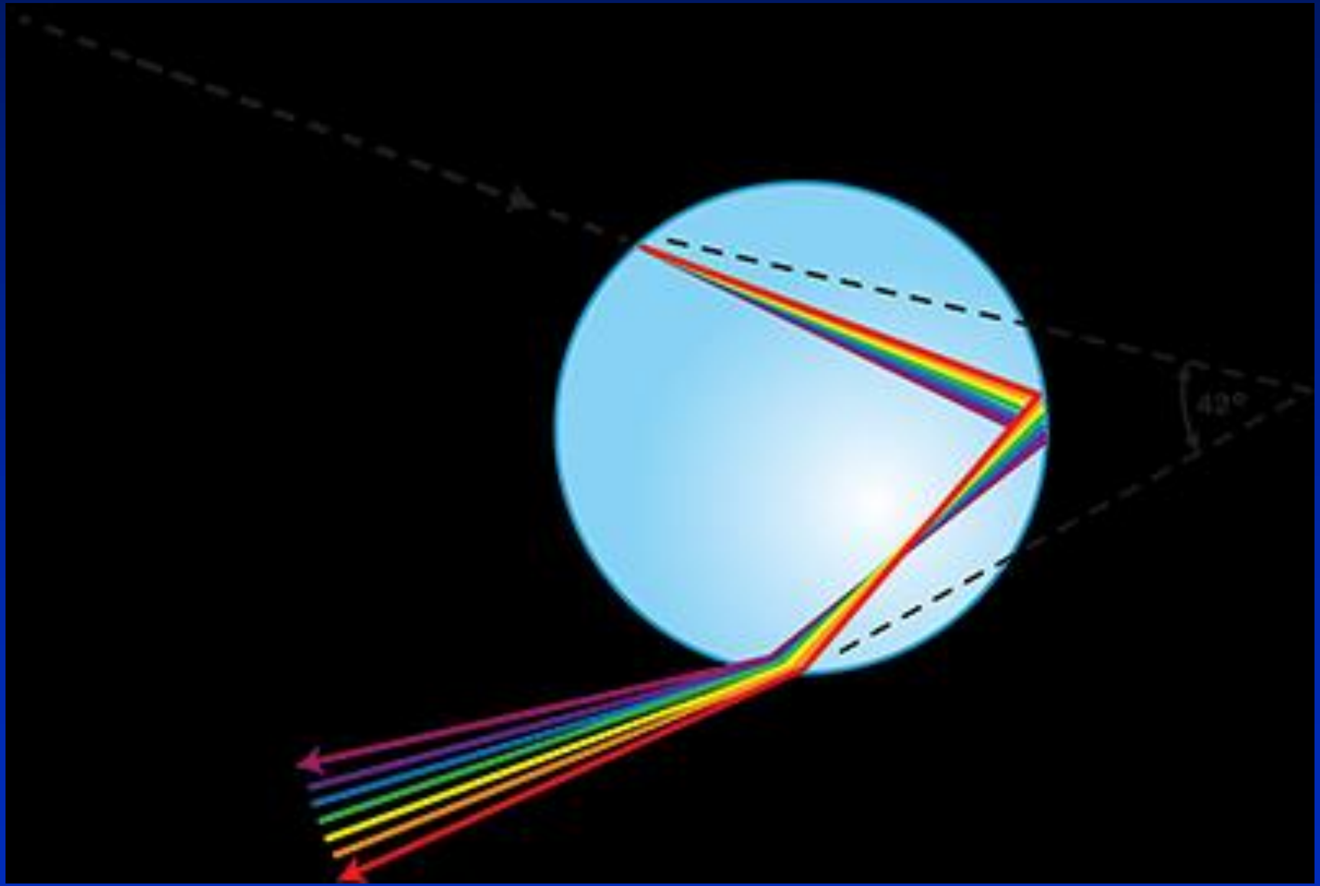
Color

Rainbow over London.

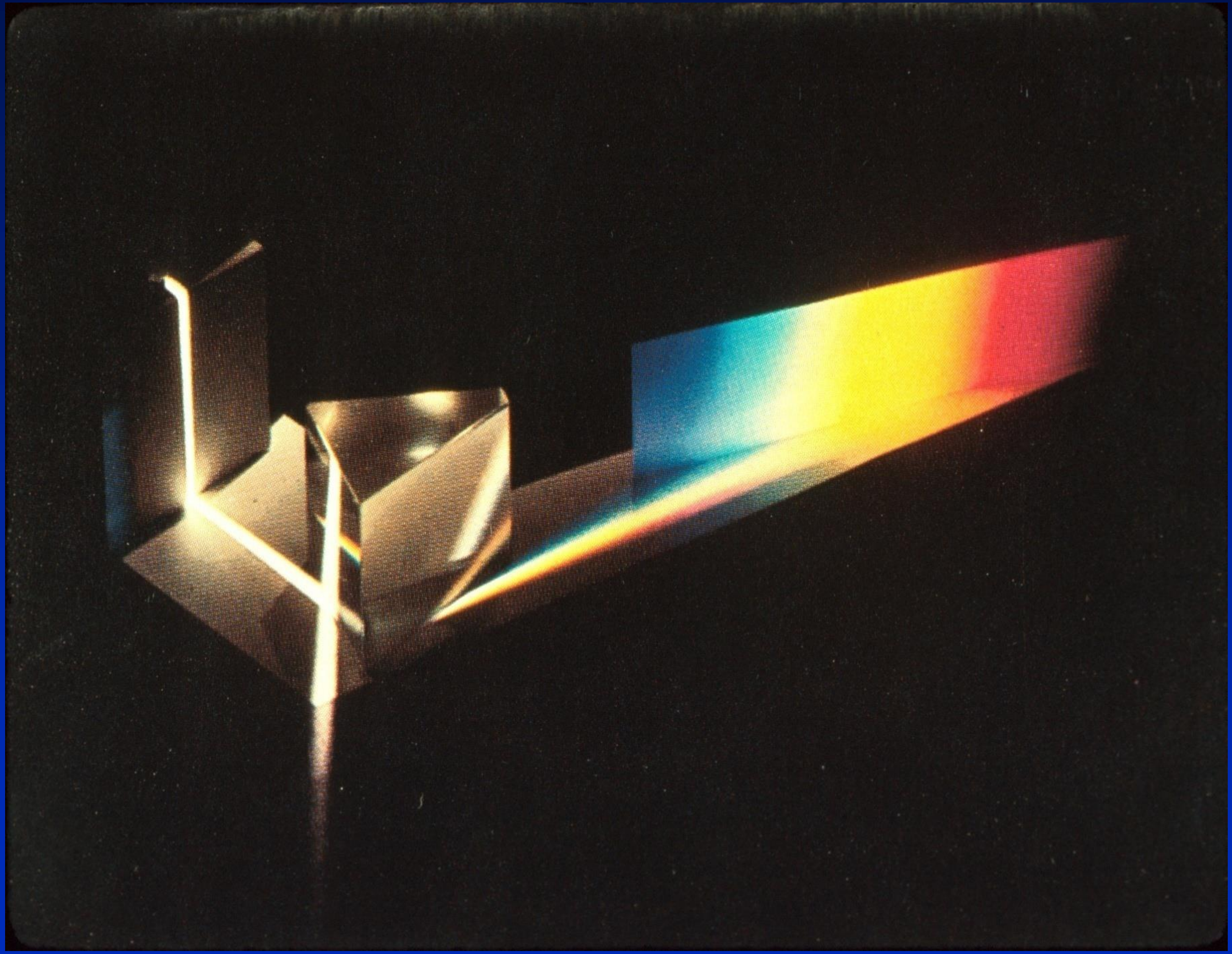
What Causes the Colors of the Rainbow?



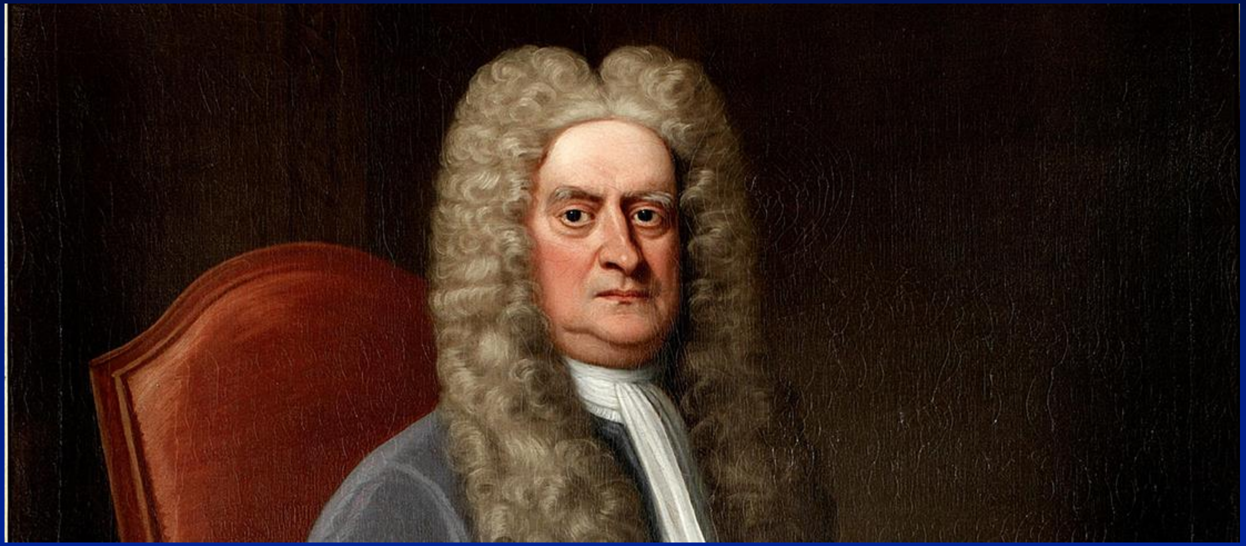
Water droplet

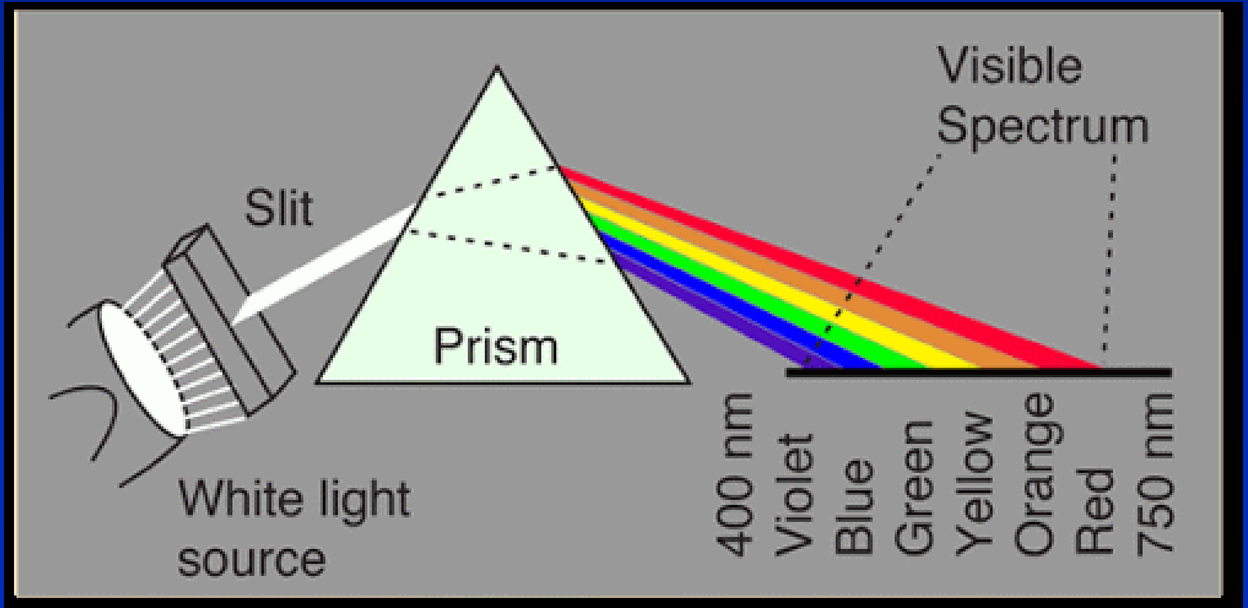
https://scijinks.gov/rainbow/

Color

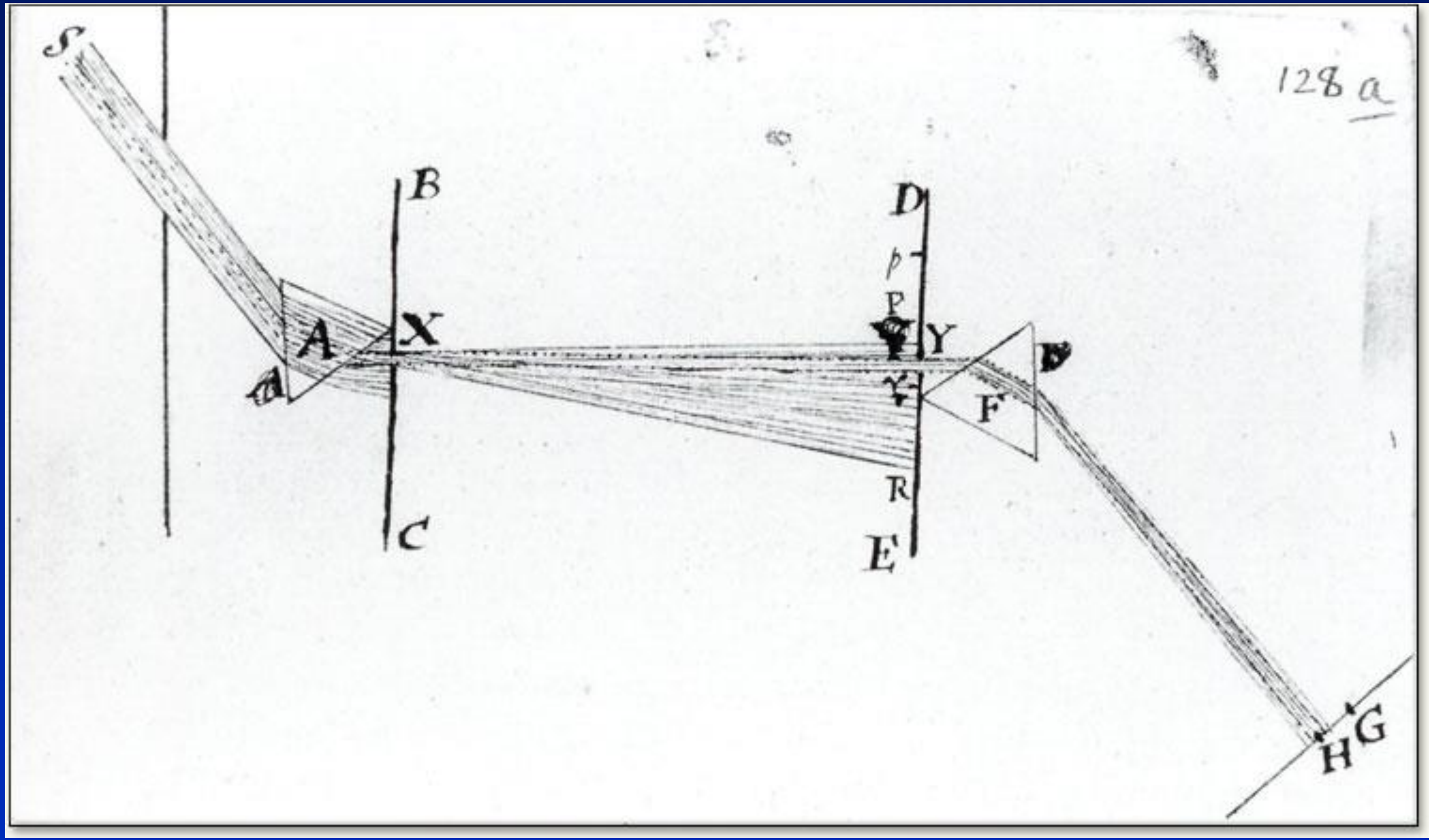


Newton's Color Spectrum

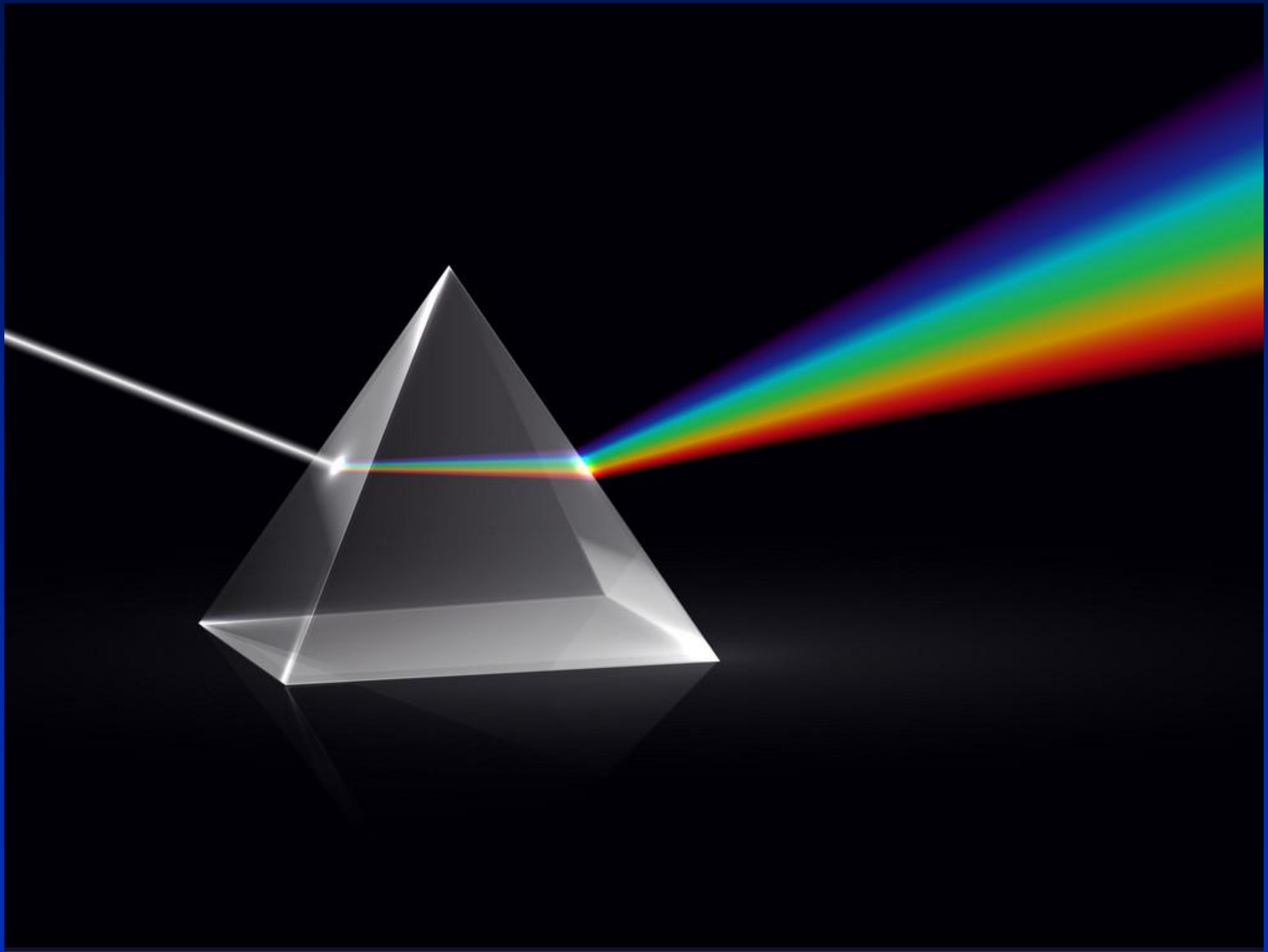




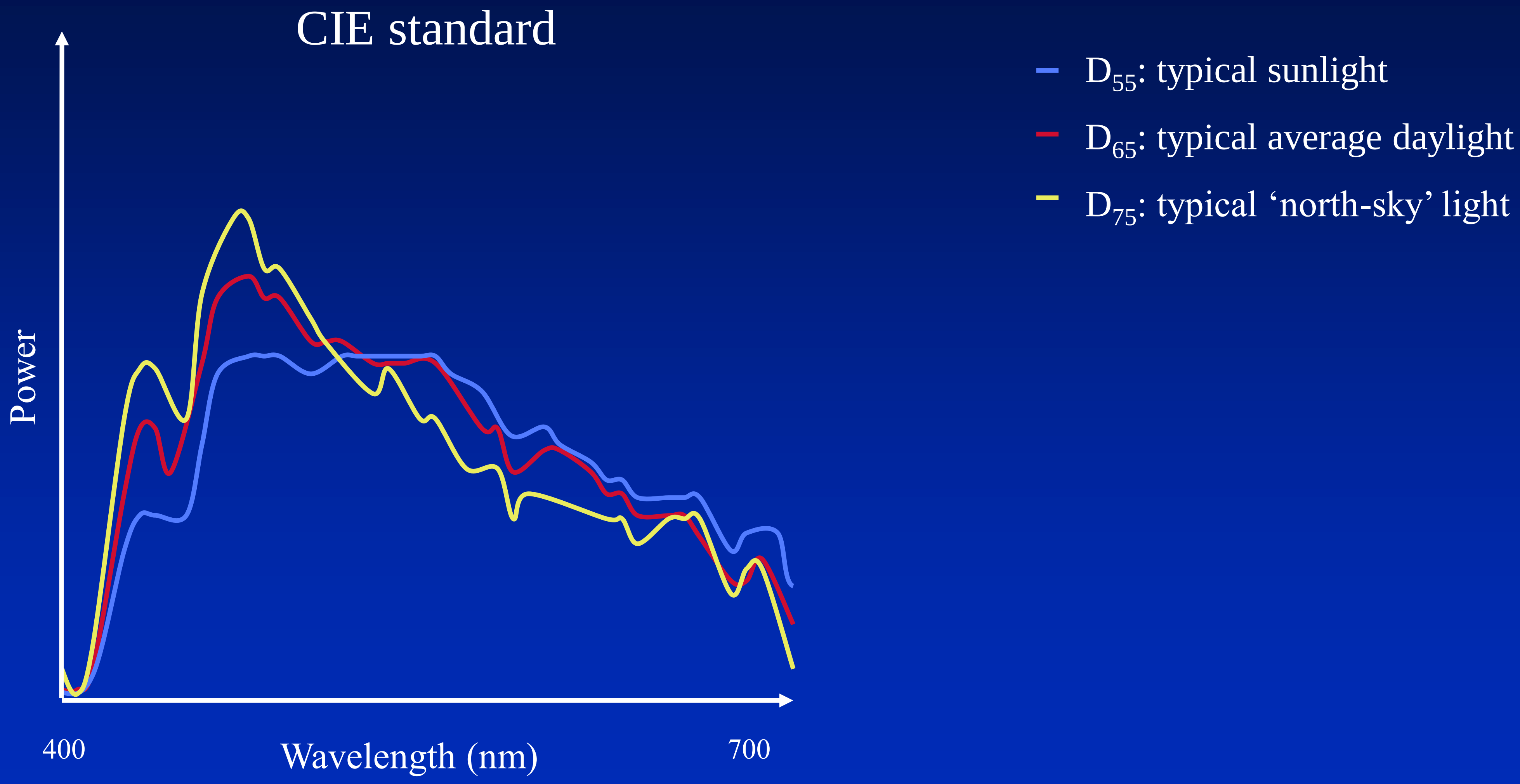
Newton and the Color Spectrum 1672



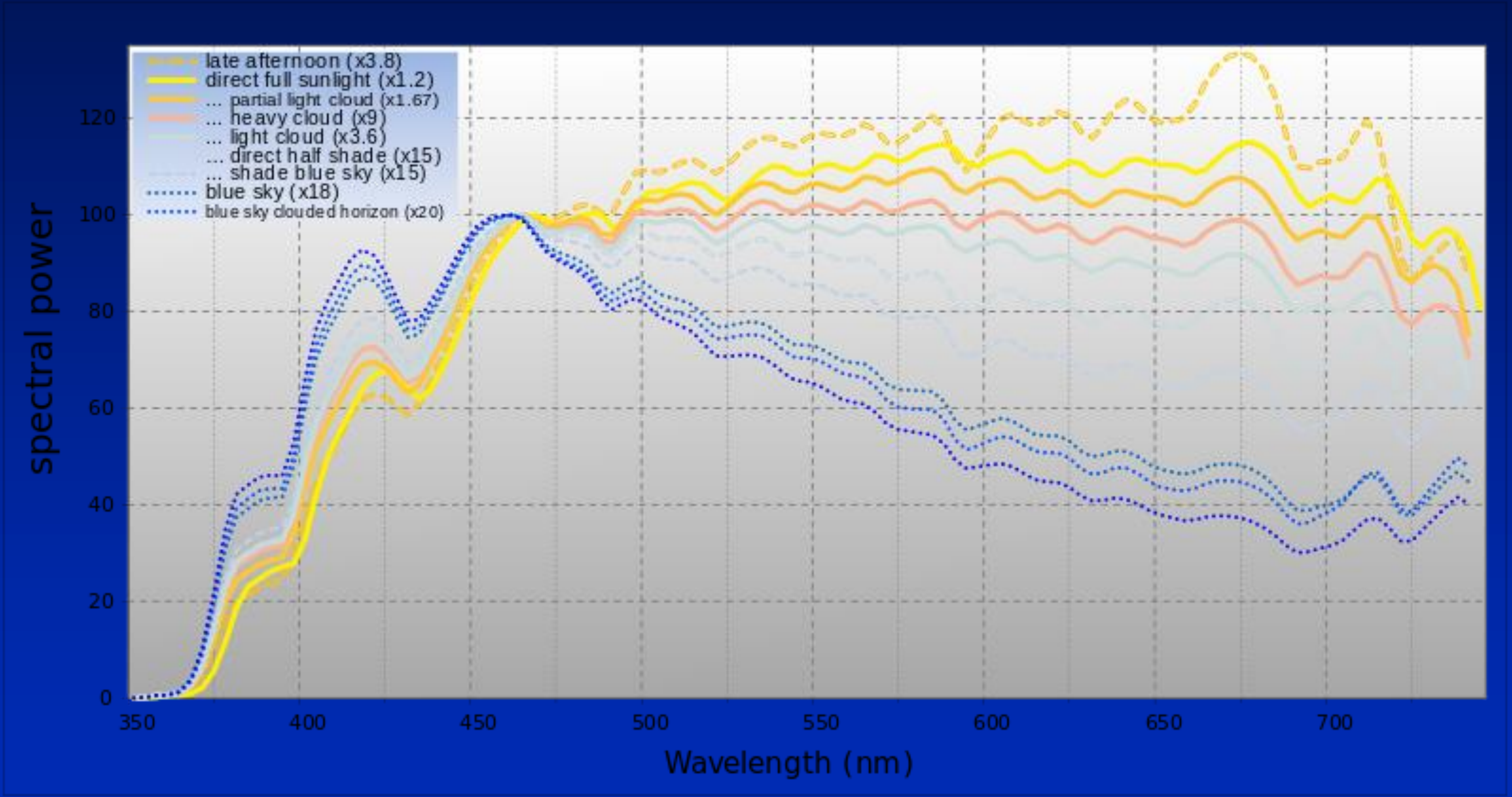
http://www.webexhibits.org/colorart/bh.html



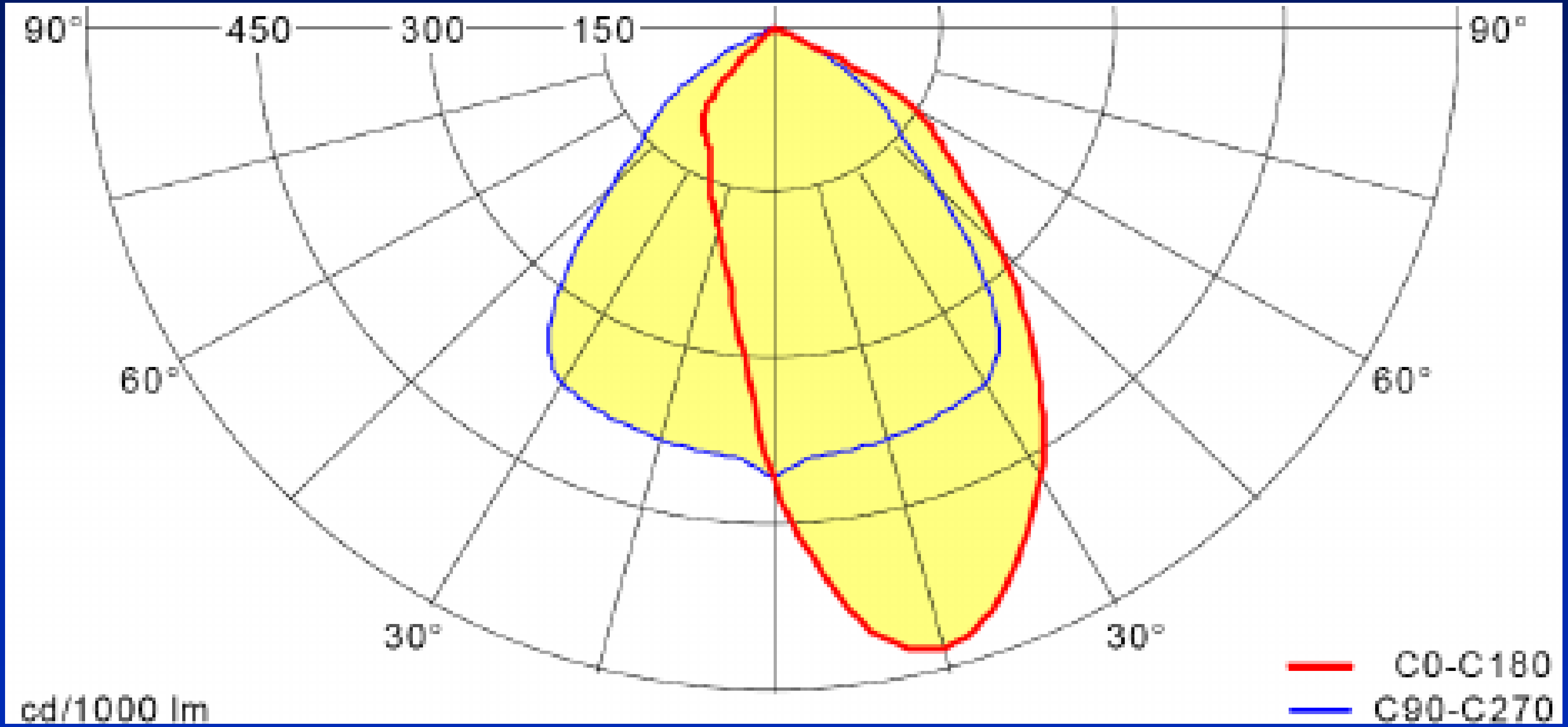
Spectral Distributions of Natural Outdoor Light Sources



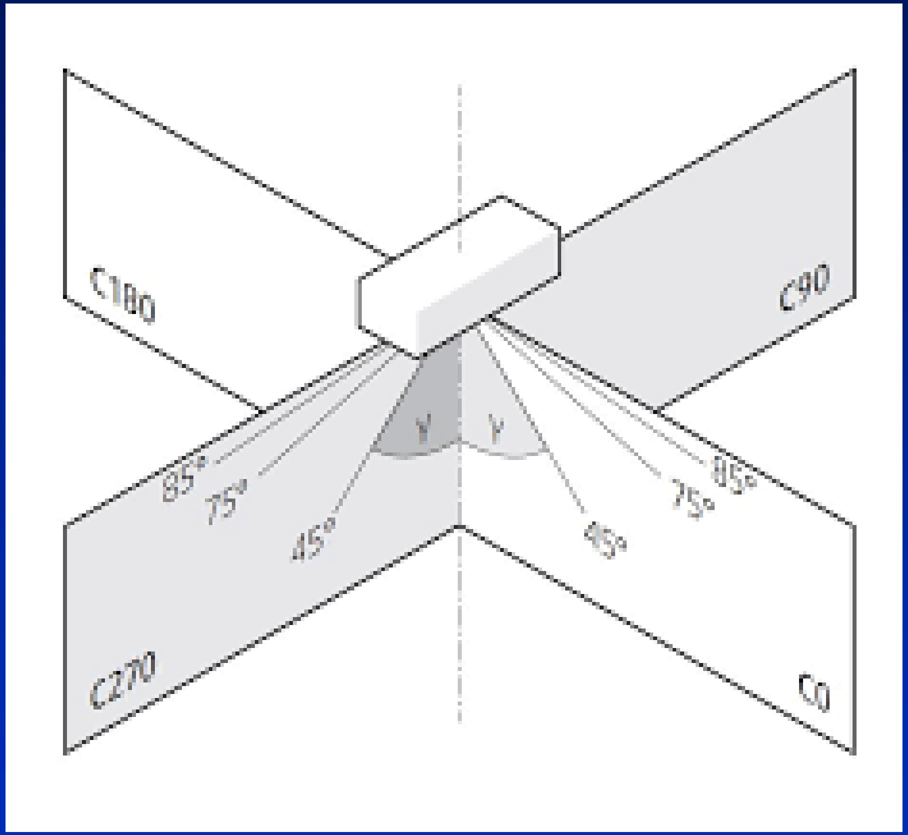
Spectral Distributions of Natural Outdoor Light Sources



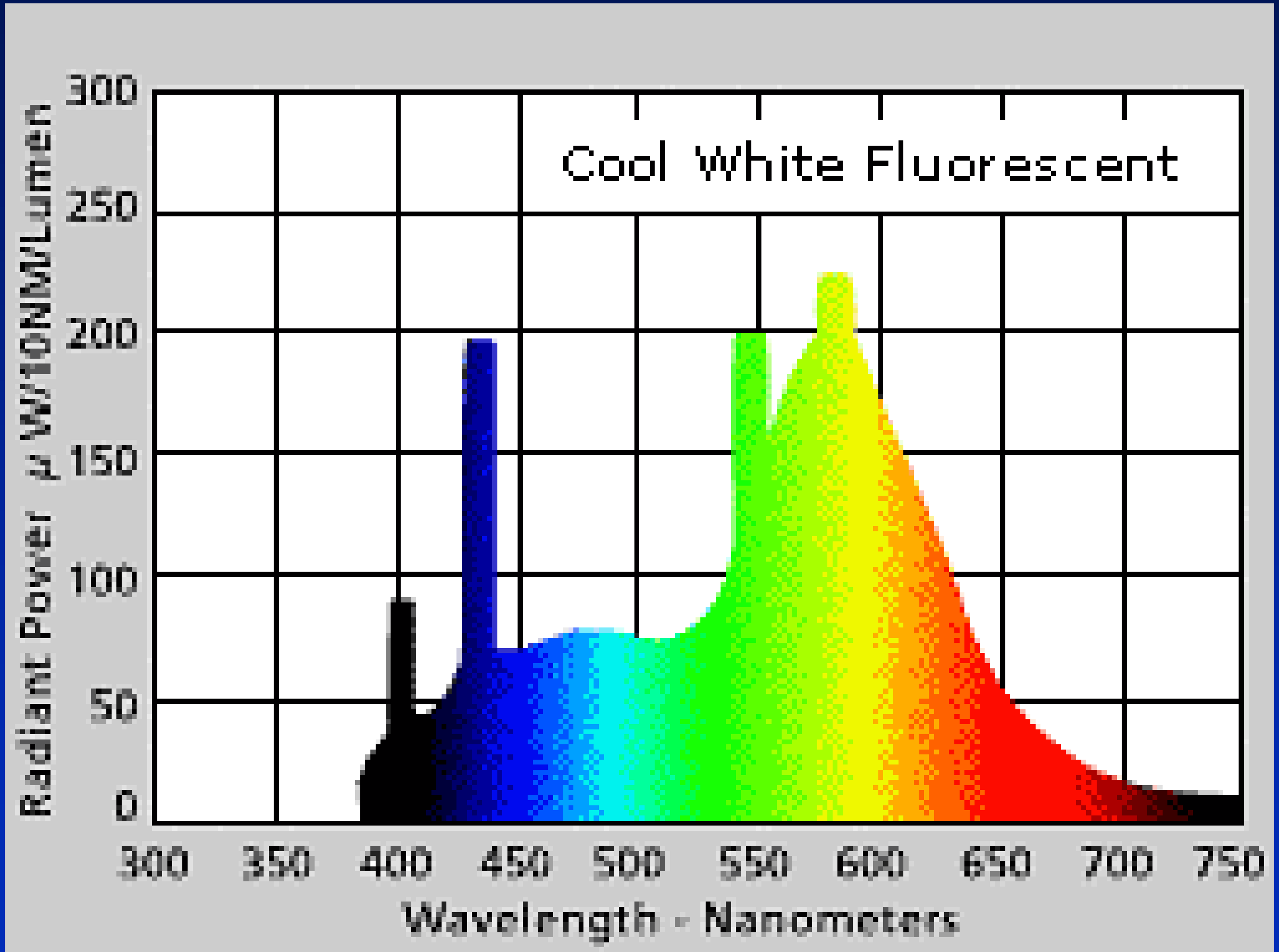
Indoor Light Source Goniometric Diagram



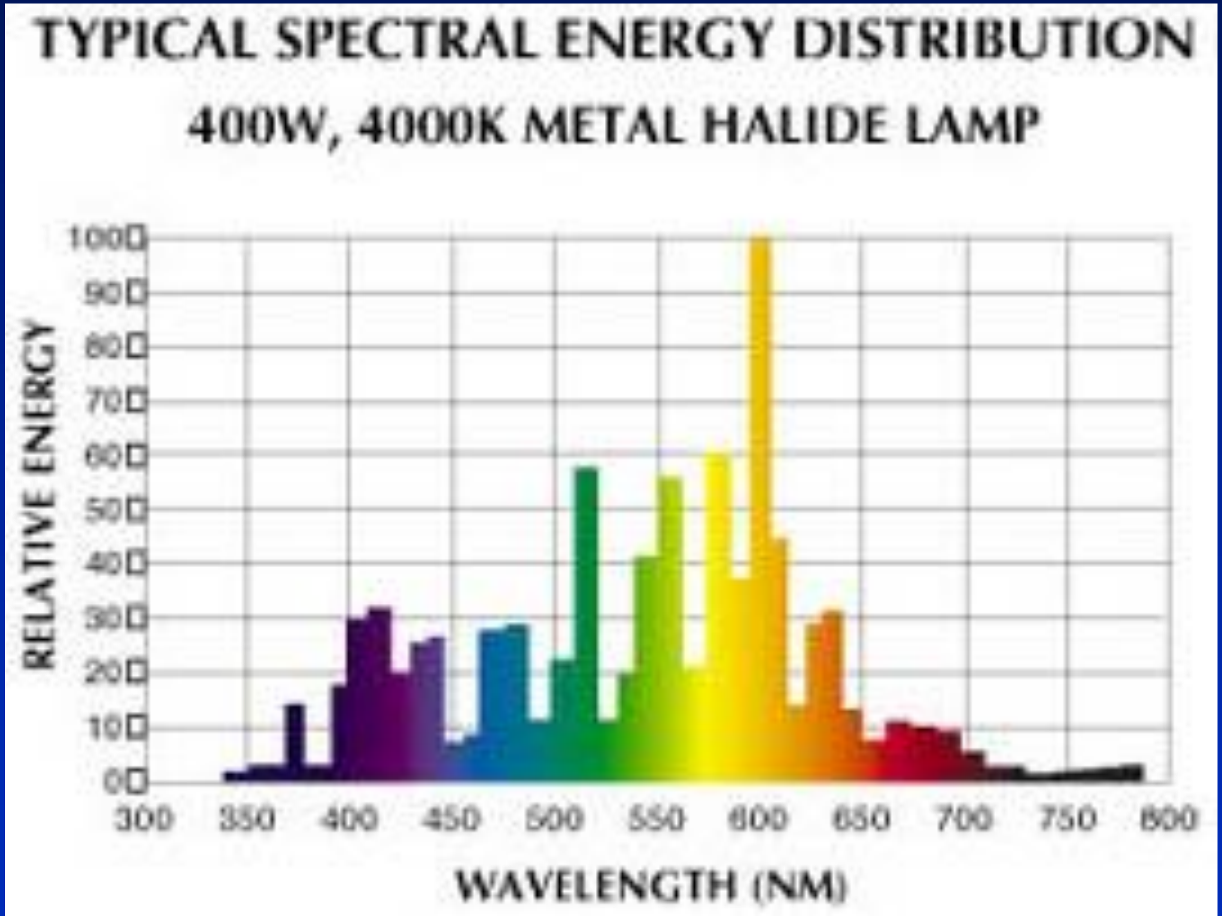
Indoor Light Source Goniometric Diagram



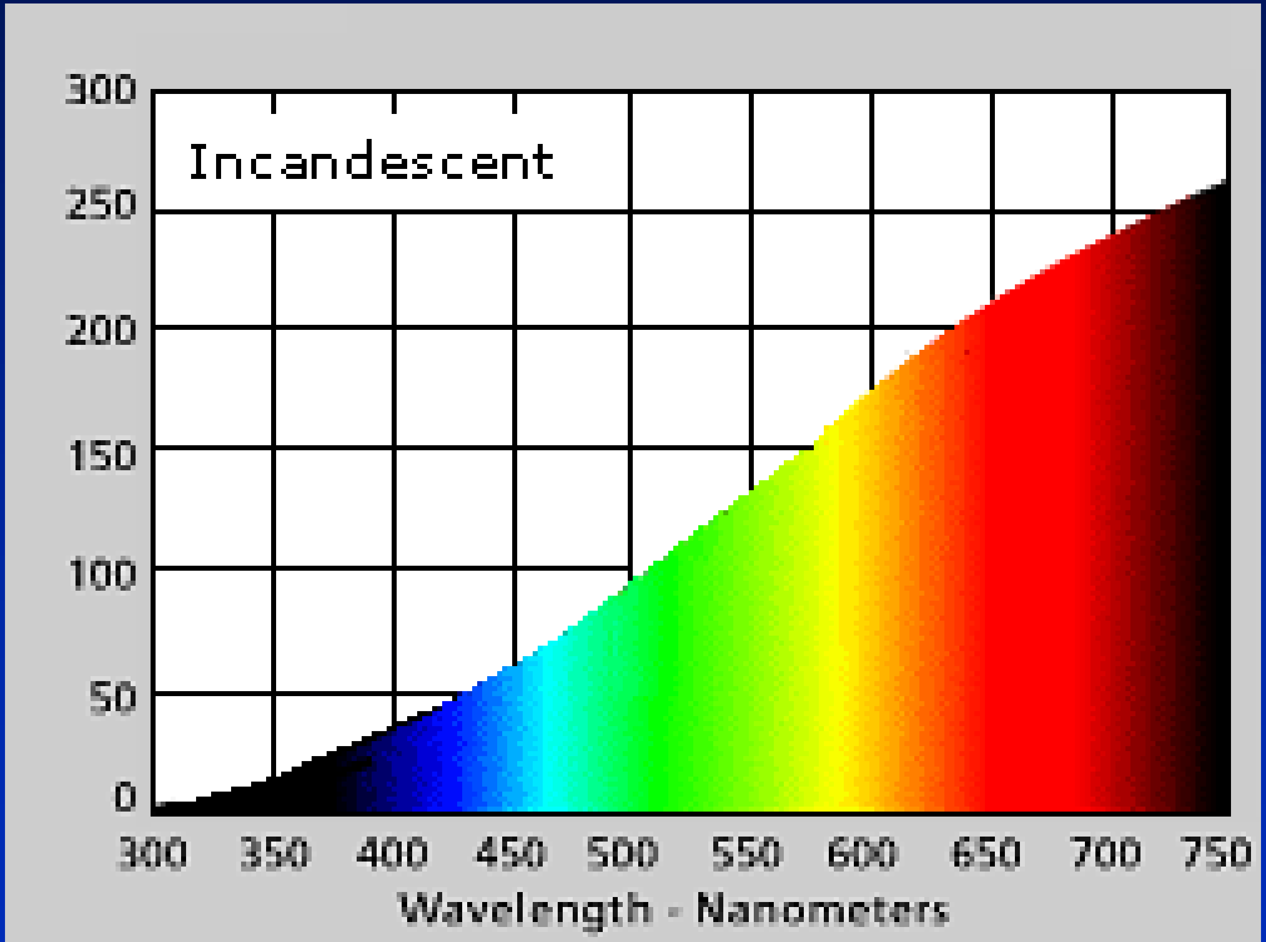
Spectral Distribution Fluorescent Light



Spectral Distribution Metal Halide Lamp

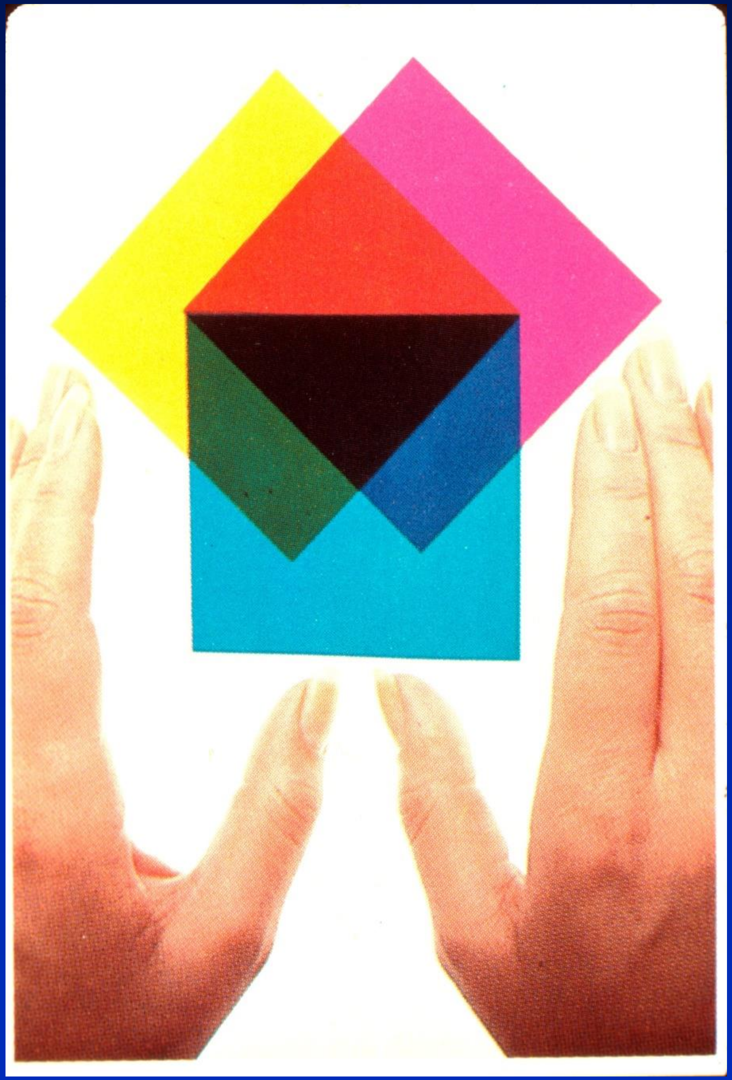


Spectral Distribution Incandescent Light



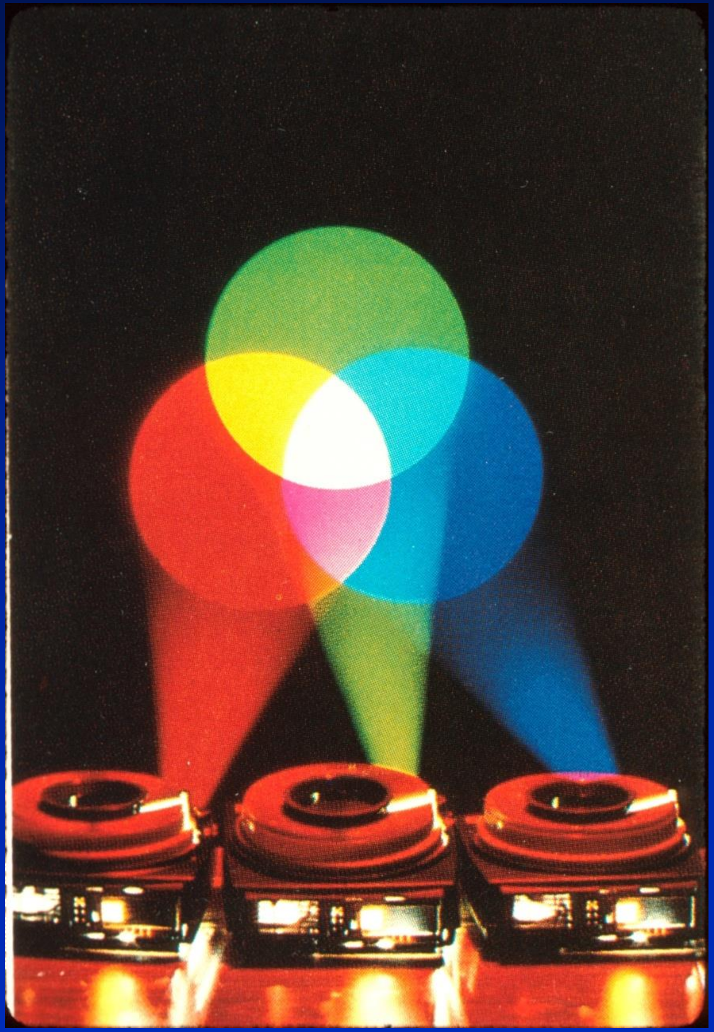
Additive Color

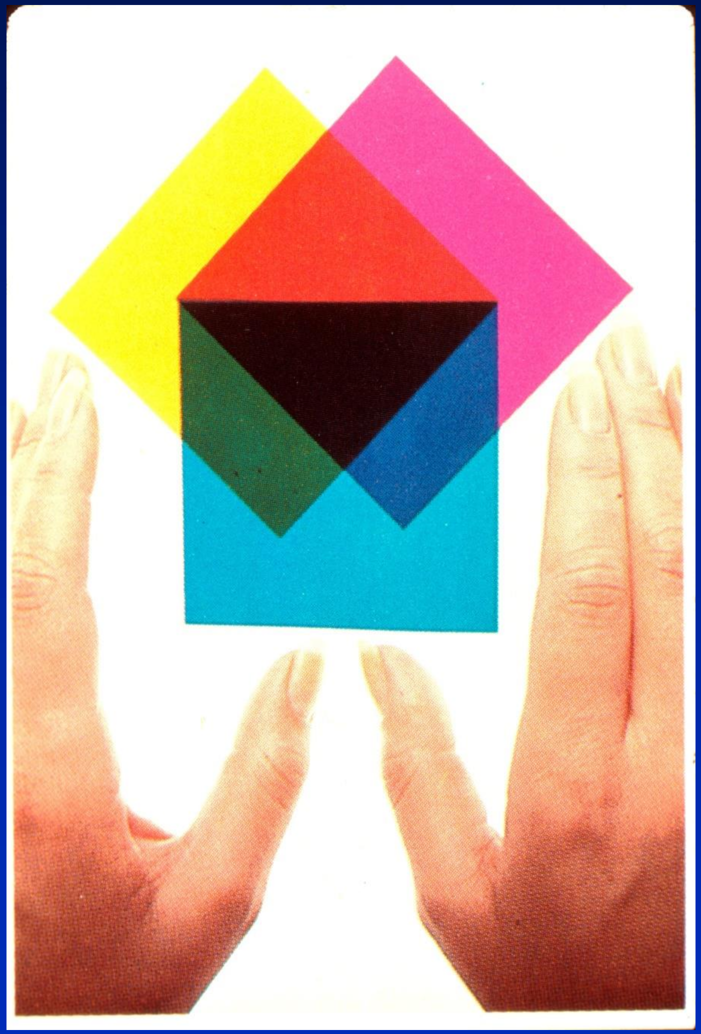
Subtractive Color



Additive & Subtractive Color Spaces

RGB



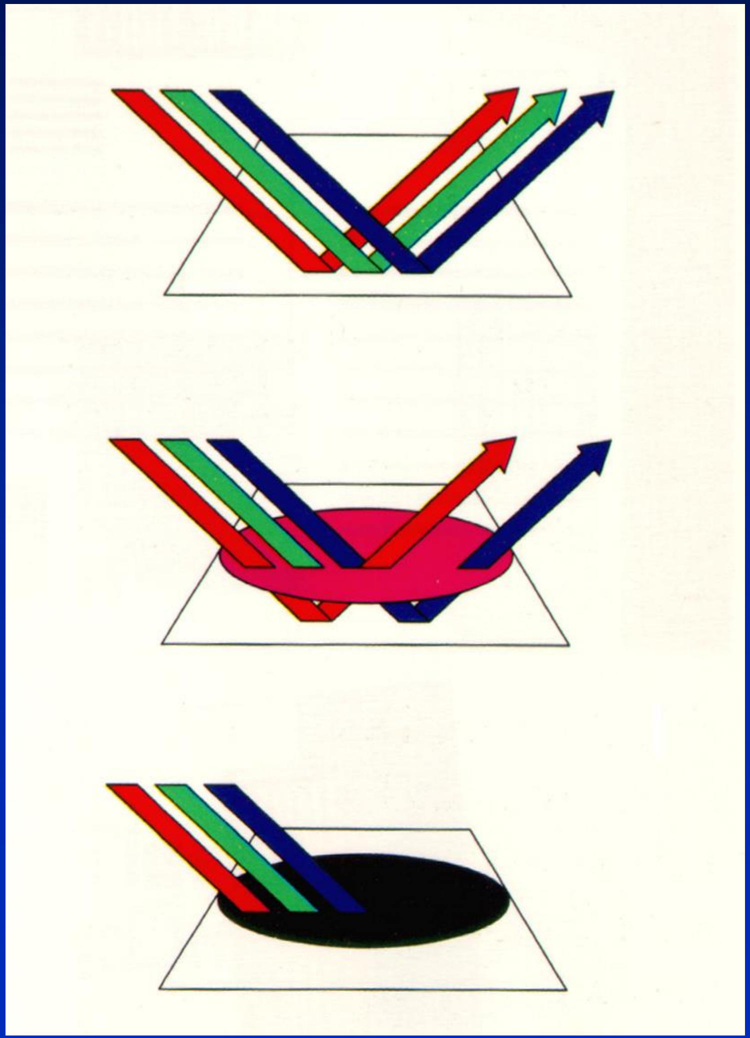


CMY

Printer Inks

Black Cyan Magenta Yellow

Subtractive Reflection Processes



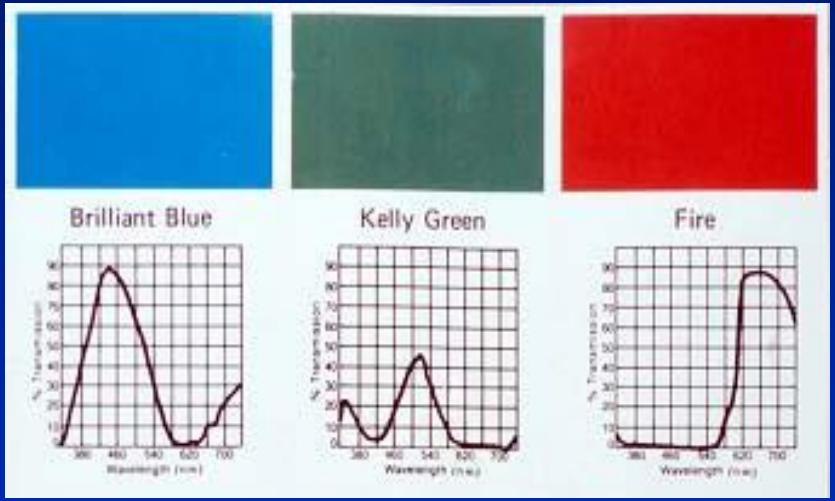
Emitted Light

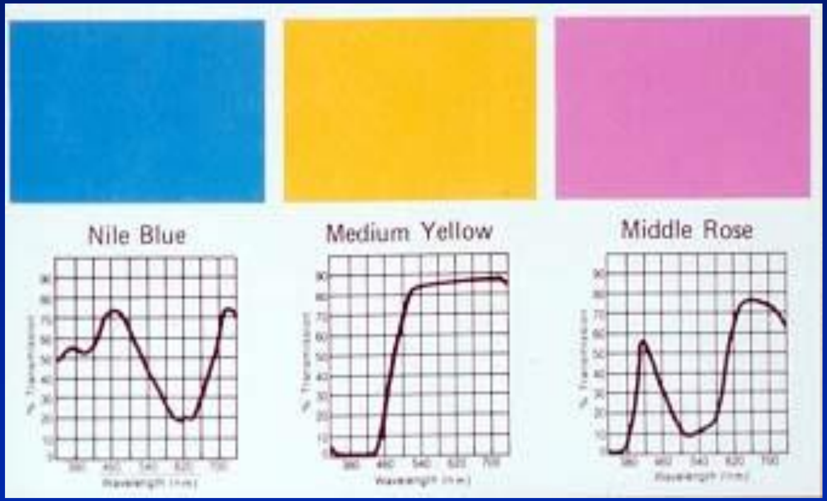
$$P = \sum_{\lambda} E_{\lambda} \qquad P = \int_{390}^{700} E_{\lambda}\, d\lambda$$

$P =$ energy reaching the eye at all wavelengths

$E_{\lambda} =$ emitted light energy at each wavelength

Spectral Distributions of Reflective Colors





Reflected Light

$$P = \sum_{\lambda} E_{\lambda} \qquad \text{(Emitted Light)}$$

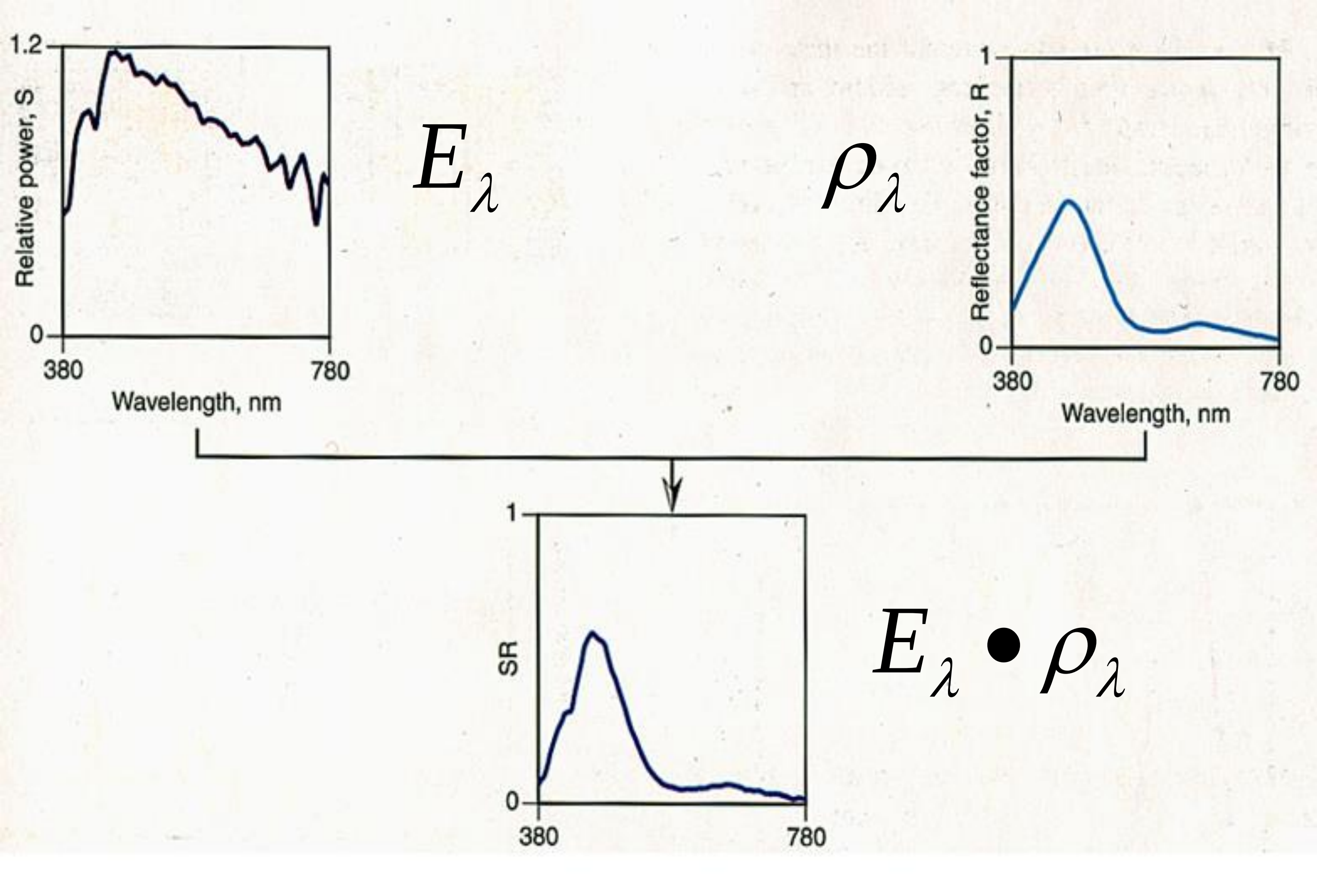
$$P = \sum_{\lambda} E_{\lambda} \bullet \rho_{\lambda} \qquad \mathrm{P} = \int_{390}^{700} E_{\lambda} \cdot \rho\lambda \, d\lambda$$

$P =$ energy reaching the eye at all wavelengths

$E_{\lambda} =$ emitted light energy at each wavelength

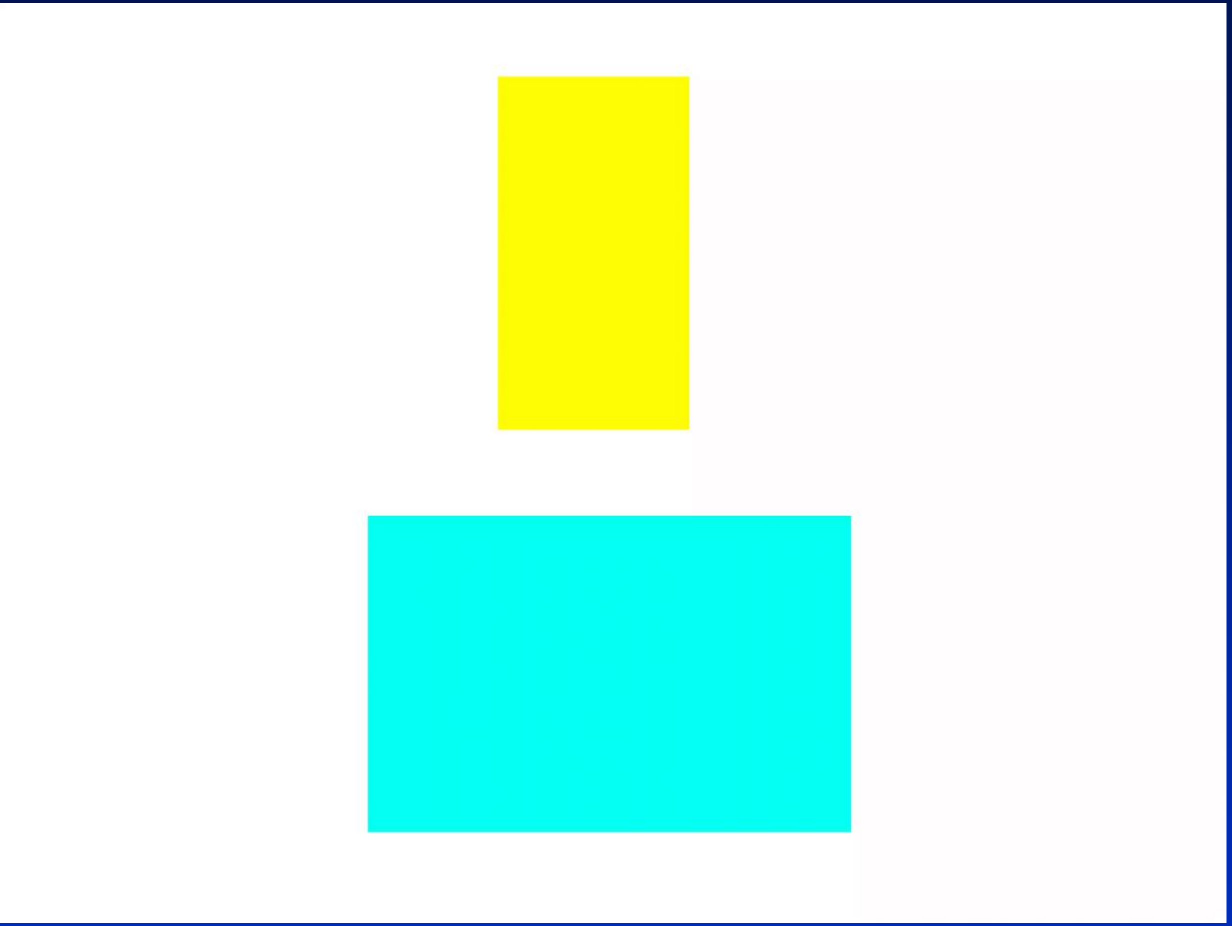
$\rho_{\lambda} =$ reflected light energy at each wavelength

Reflected Light



Roy S. Berns. "Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 15.

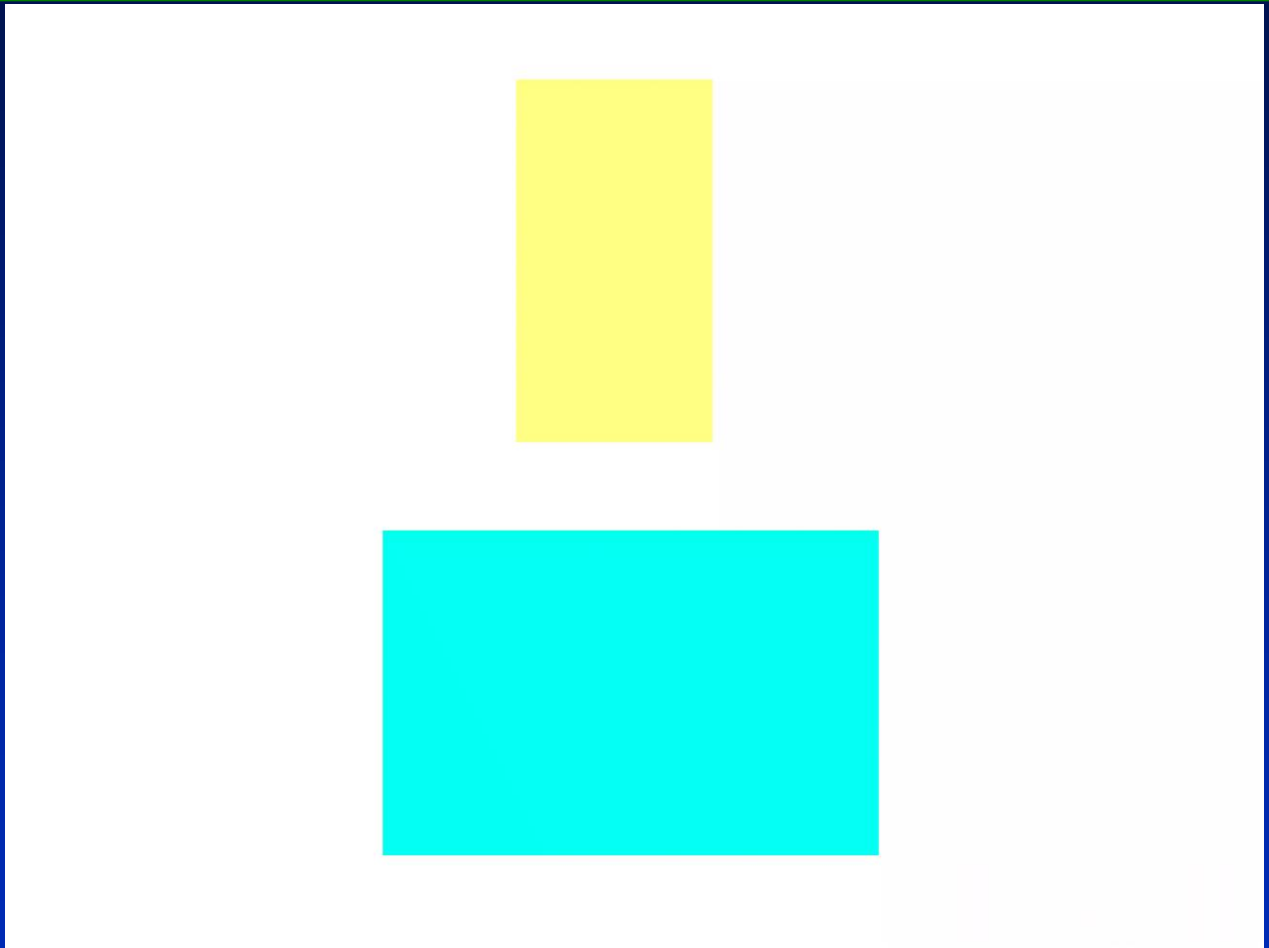
Opaque Video



α_{yellow} = 1

$$C_o = \alpha_a \cdot C_a + (1 - \alpha_a) \cdot C_b$$

Transparency Video



α_{yellow} = 0.5

$$C_o = \alpha_a \cdot C_a + (1 - \alpha_a) \cdot C_b$$

Transmitted Light

$$P = \int_{390}^{700} E_\lambda \cdot d_\lambda$$

$$P = \int_{390}^{700} E_\lambda \cdot p_\lambda \cdot d_\lambda$$

$$P = \int_{390}^{700} E_\lambda \cdot t_\lambda \cdot d_\lambda$$

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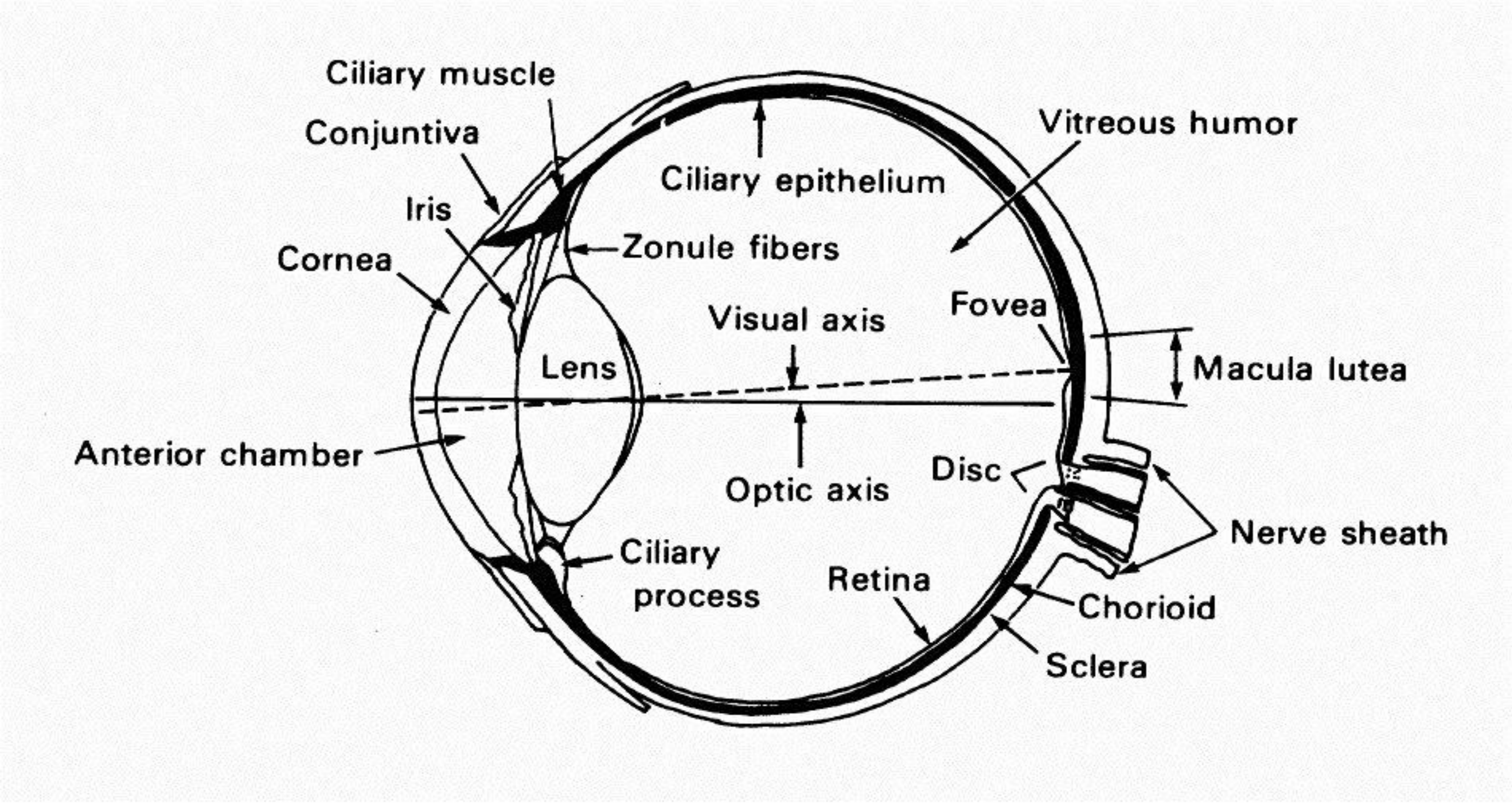
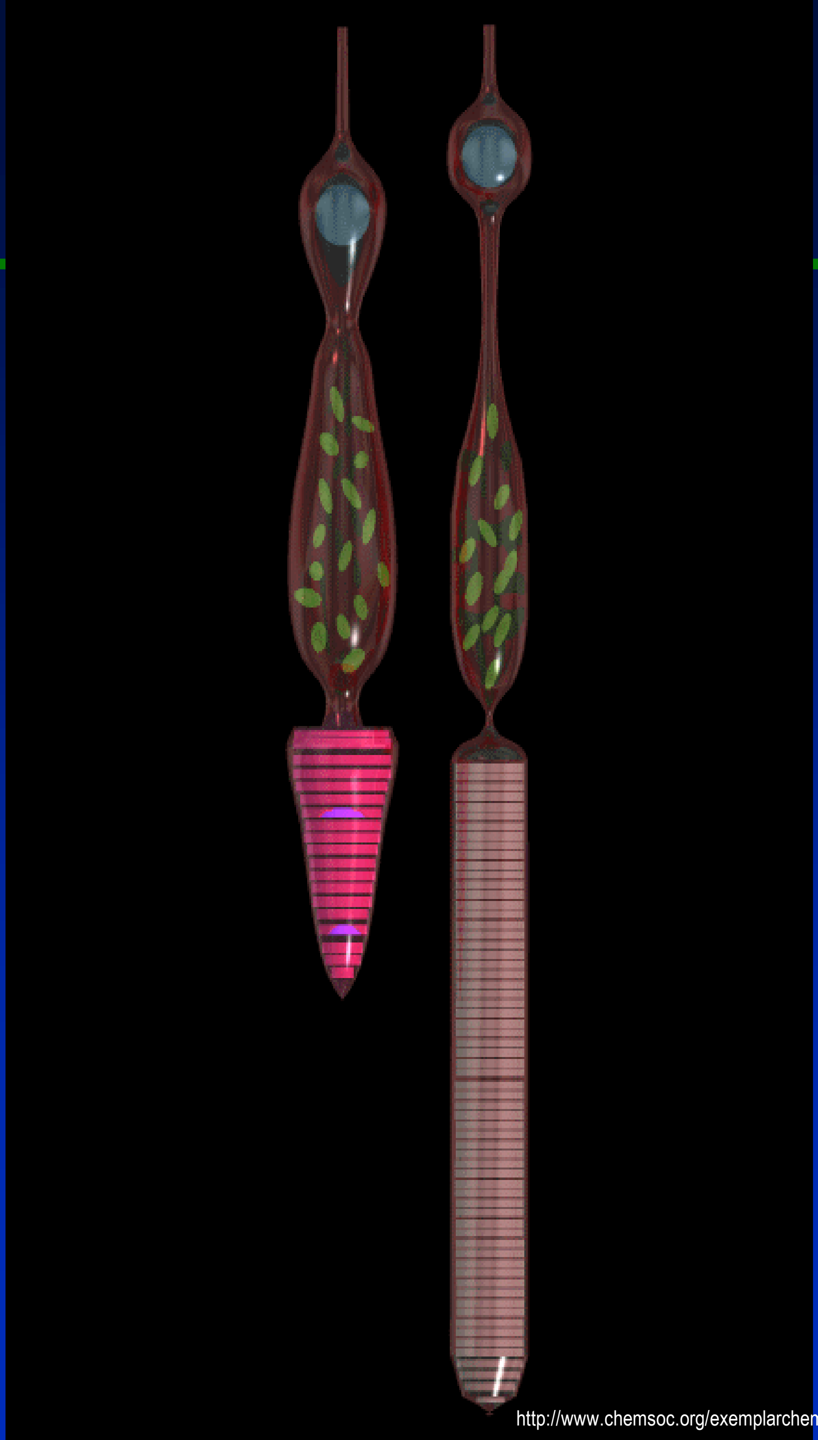
Cross Section of Eye & Retina



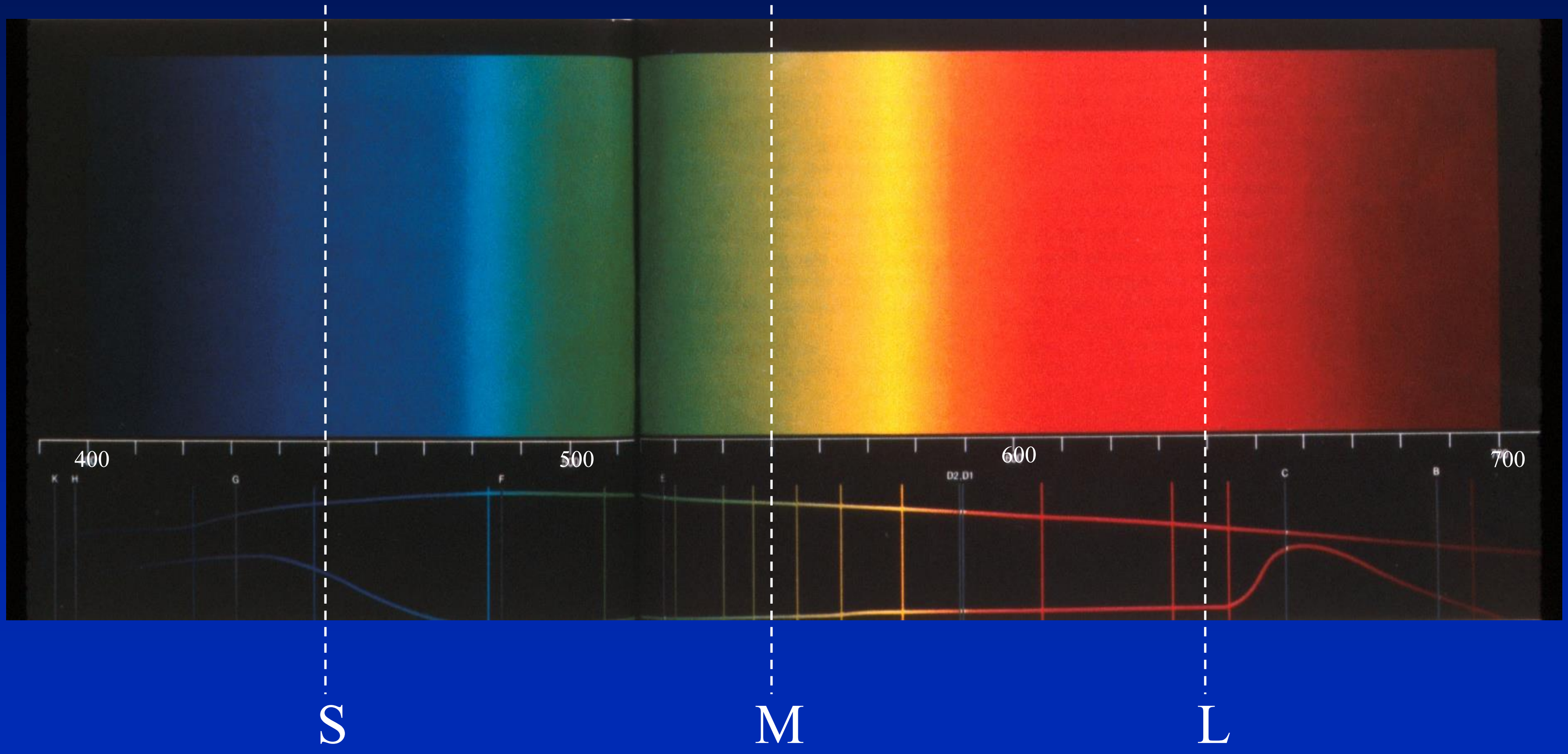
Rods & Cones

Comparison of a rod cell (right) and cone cell (left). This shows how each cell acquired its name from its shape.



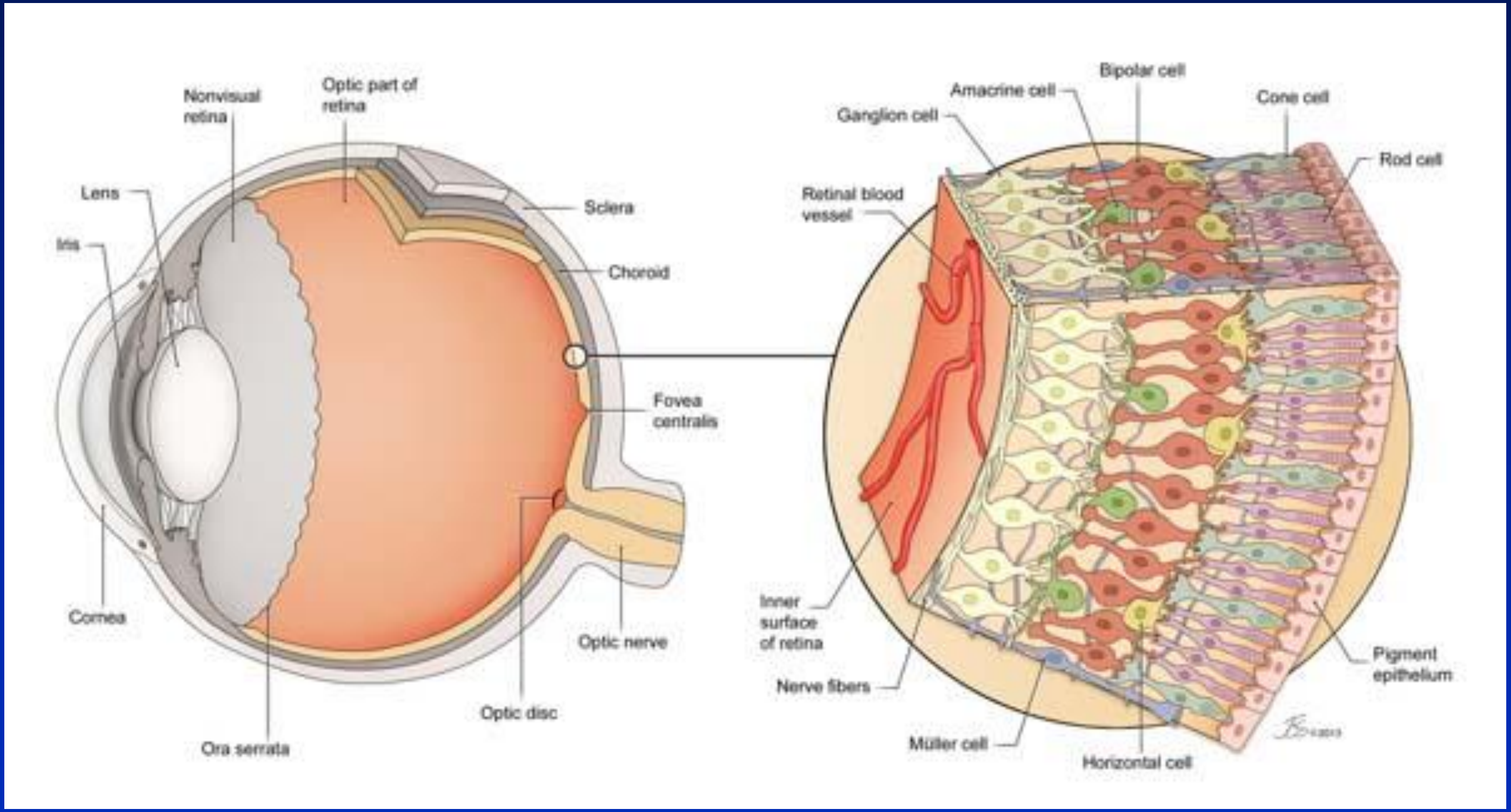
http://www.chemsoc.org/exemplarchem/entries/2002/upton/cones.htm

Visible Light Spectrum

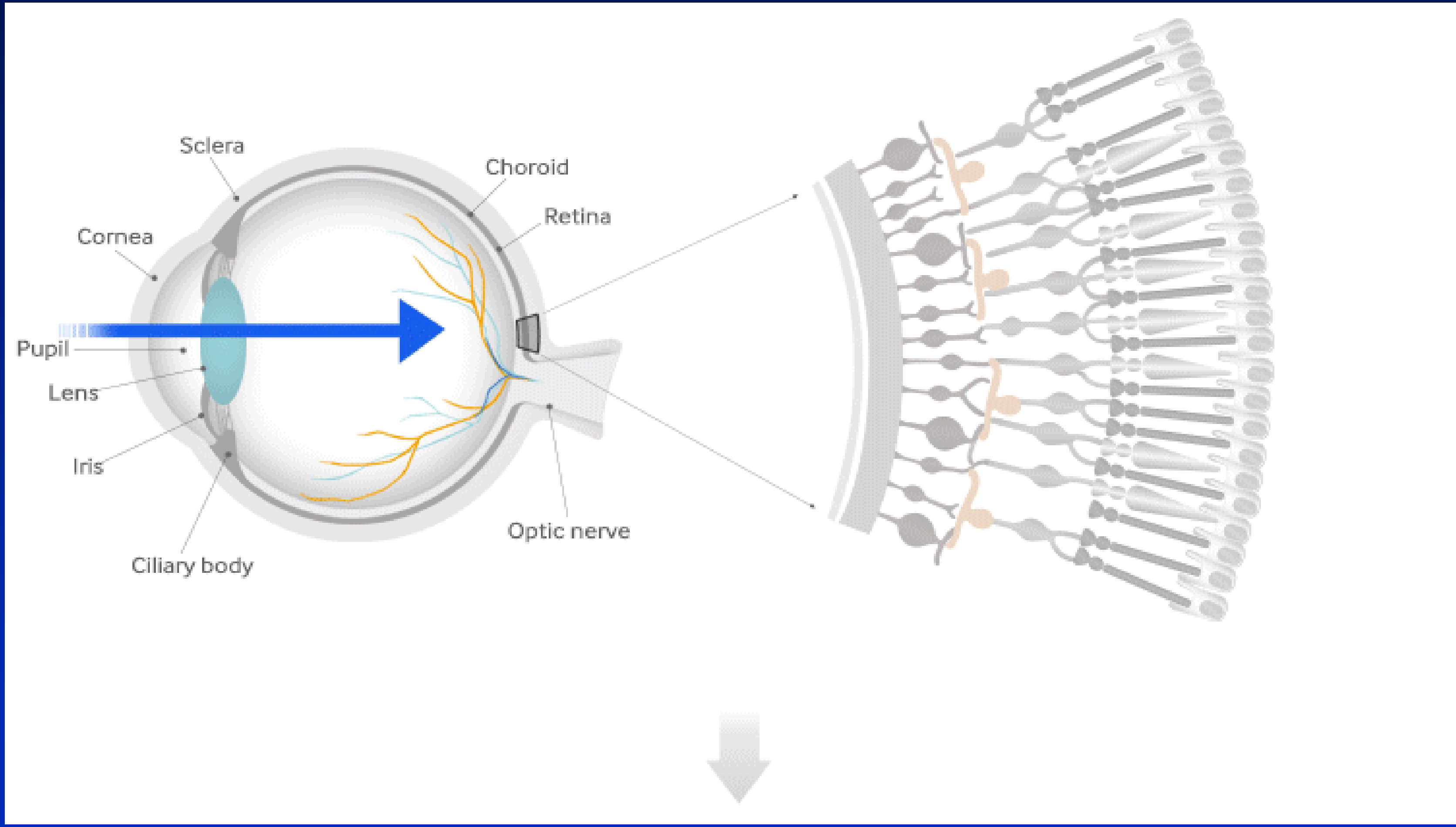


Dominant wavelengths of the cones of the human receptor system

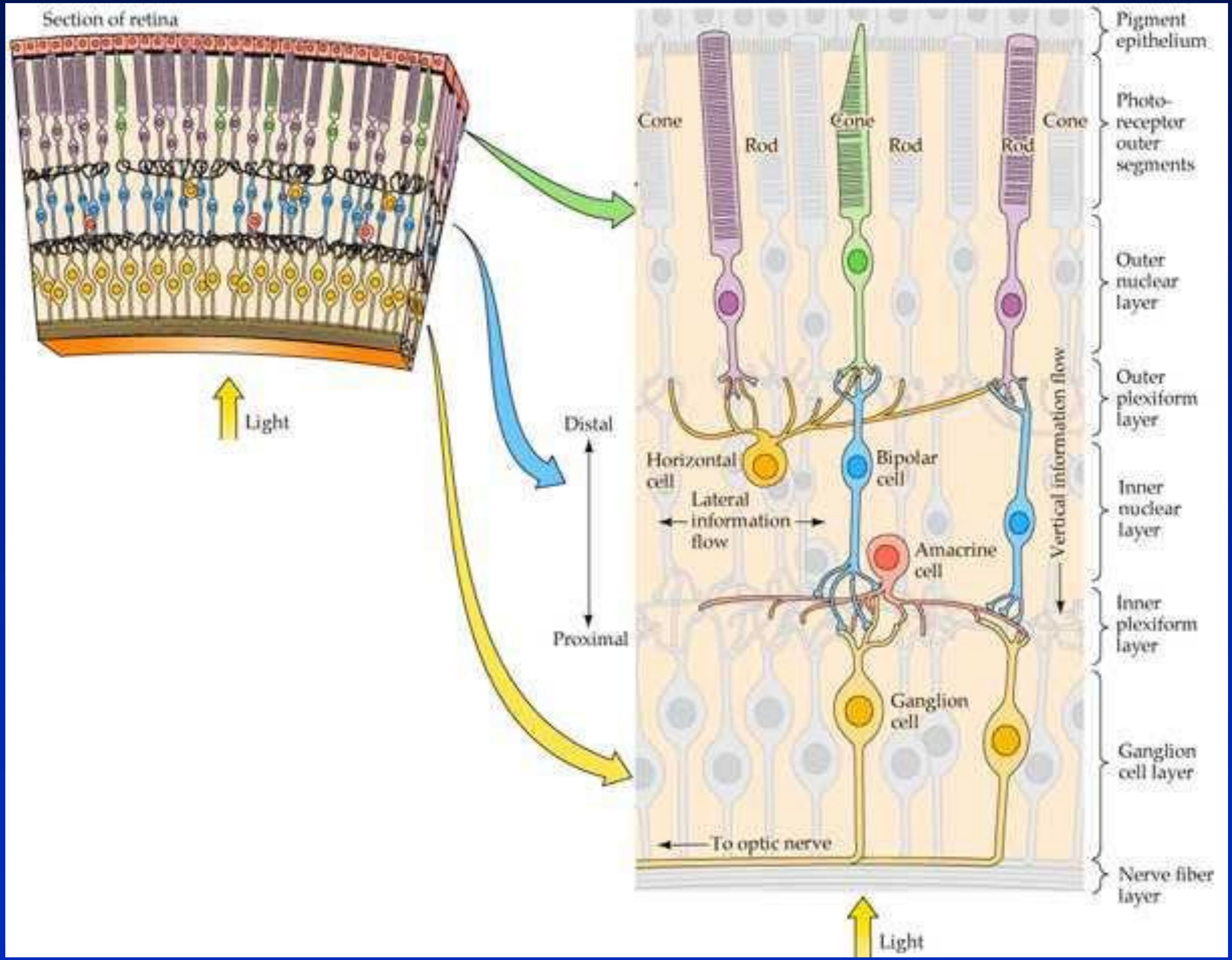
Rods and Cones



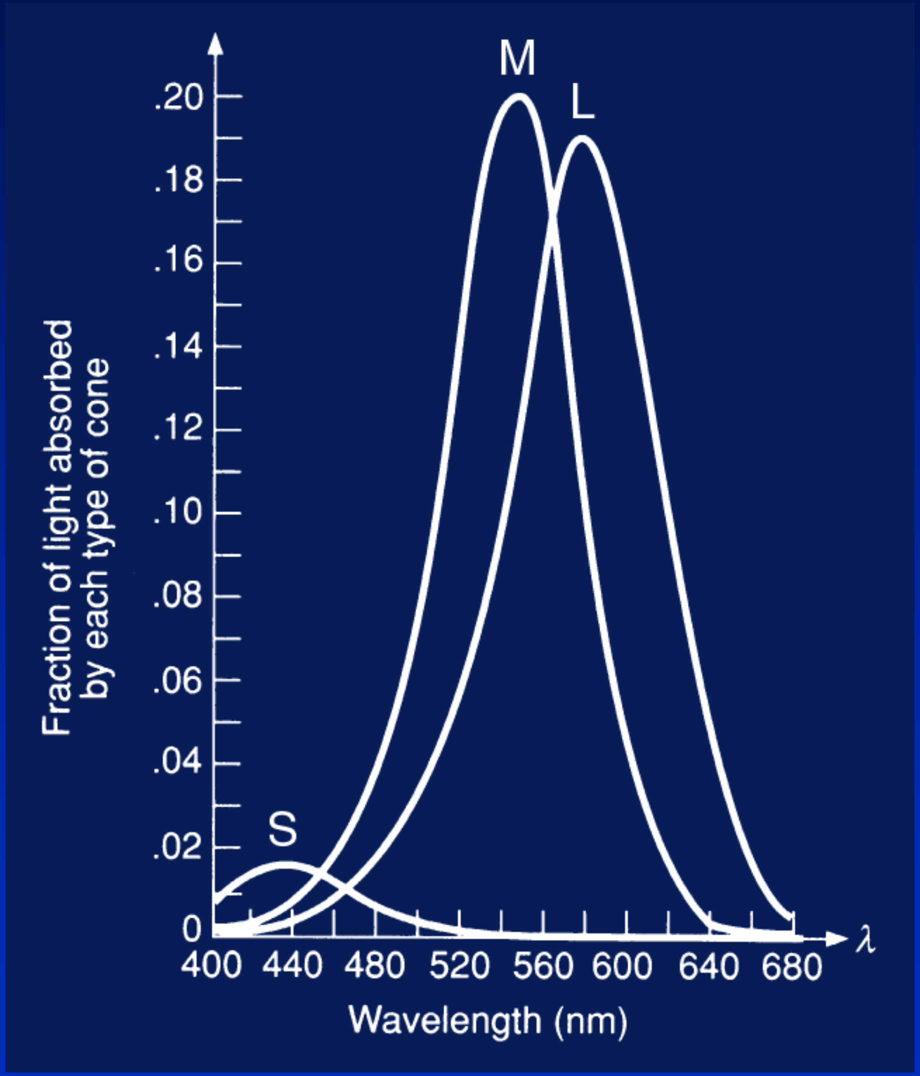
Color Receptors in the Eye



Rods and Cones



Cone Responses



- S,M,L cones have broadband spectral sensitivity
- S,M,L neural response is integrated with respect to λ
- results in a trichromatic visual system

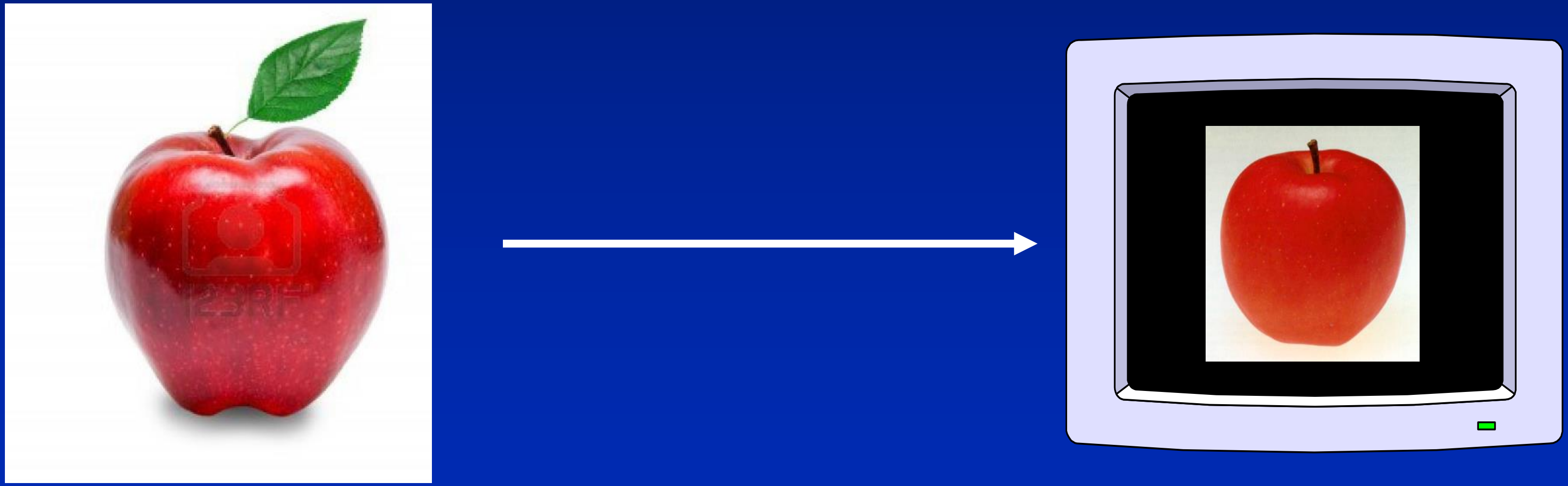
Question?

- How can we map a *Physical light description* to a *Perceptual color sensation?*

Physical *Perceptual*

Question?

- How can a TV display reproduce (almost) every color sensation that we can experience using only 3 color phosphors?



R,G,B ?

Question?

- How can a printer reproduce (almost) every color sensation that we can experience using only 3 color inks?

CMY ?

Question?

How can we reproduce such a vast range of color using two completely different sets of three primary colors?

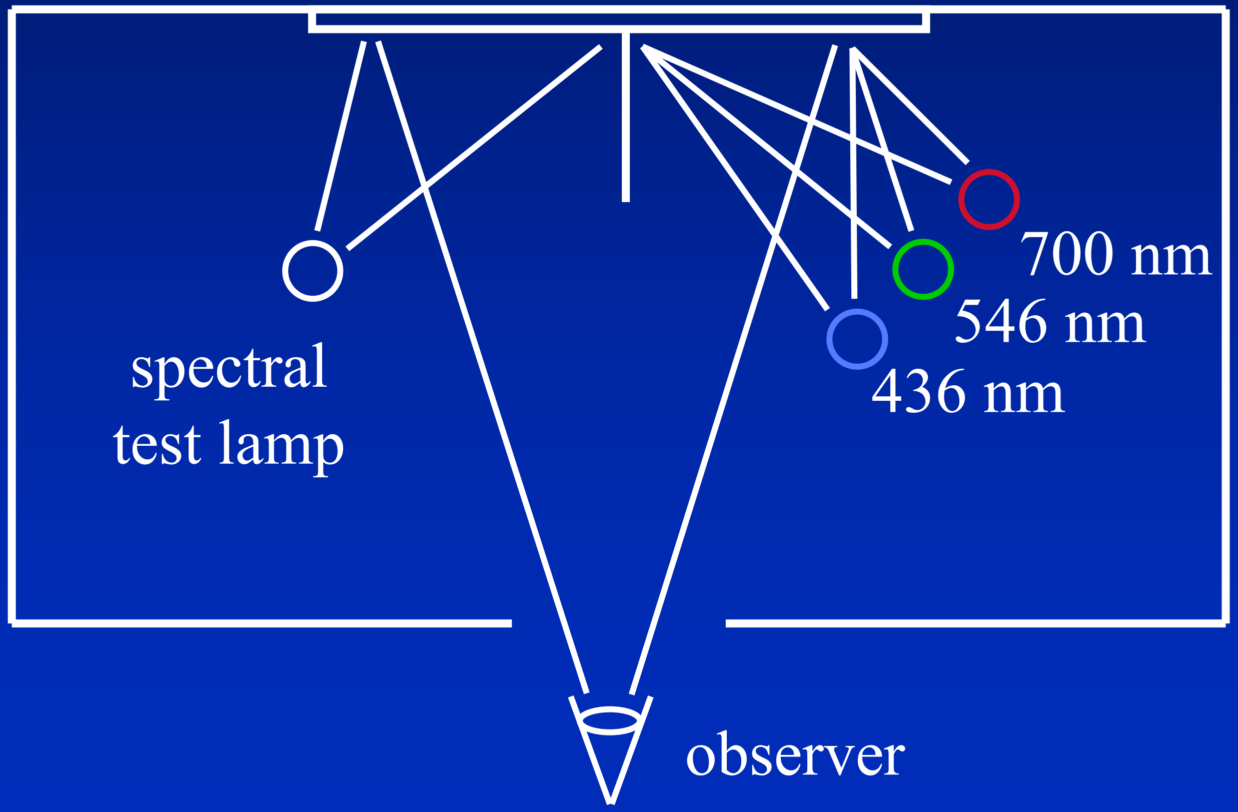
R G B vs C M Y

Grassmann's Color Matching Experiments (1853)

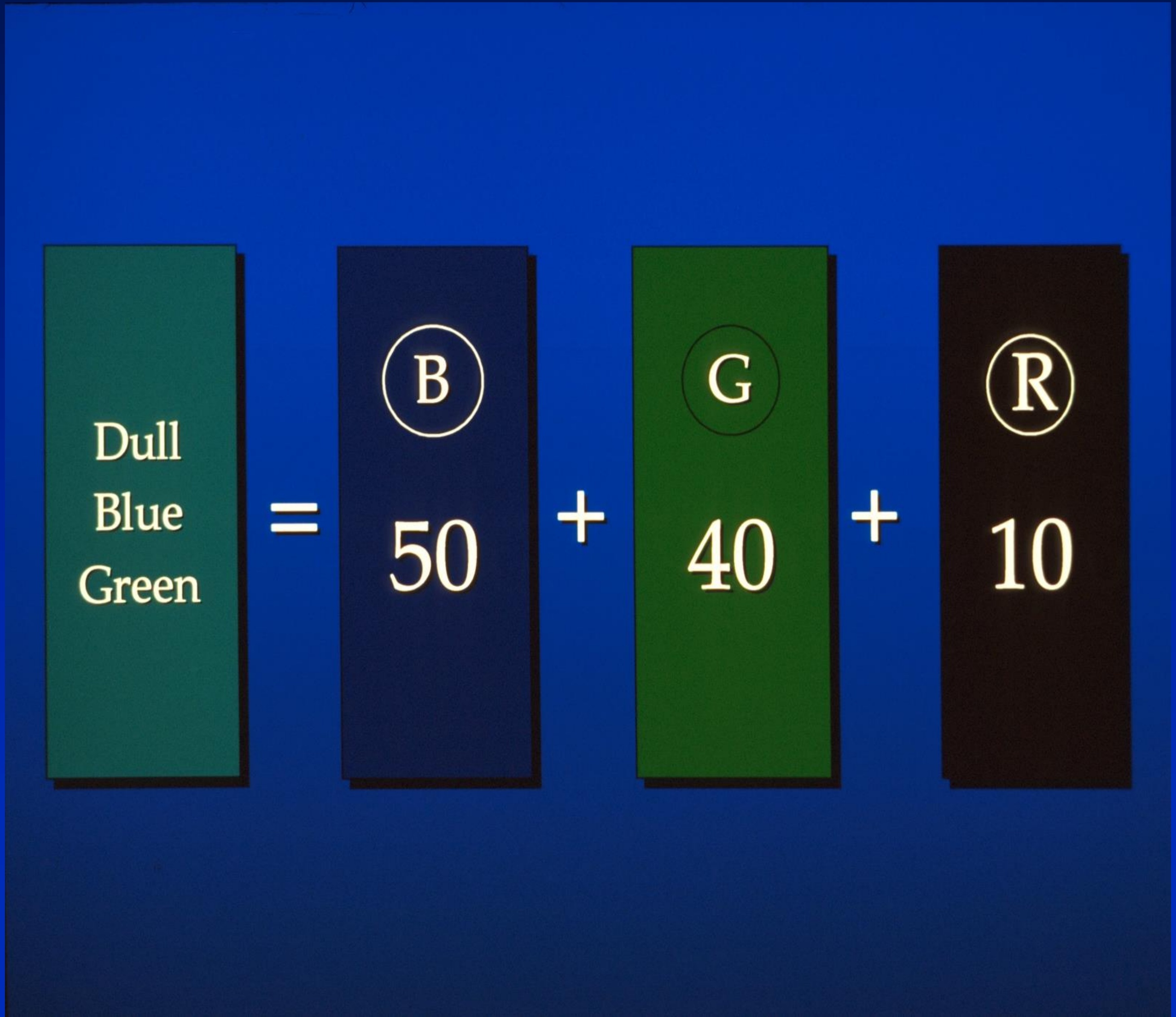
- Roy. S. Berns. Billmeyer and Saltzman's PRINCIPLES OF COLOR TECHNOLOGY, 2000 John Wiley & Sons, Inc.

Matching a Test Lamp with 3 Primary Lights

- We can match a color sensation from *any* spectrum using only 3 primary colors (R,G,B)

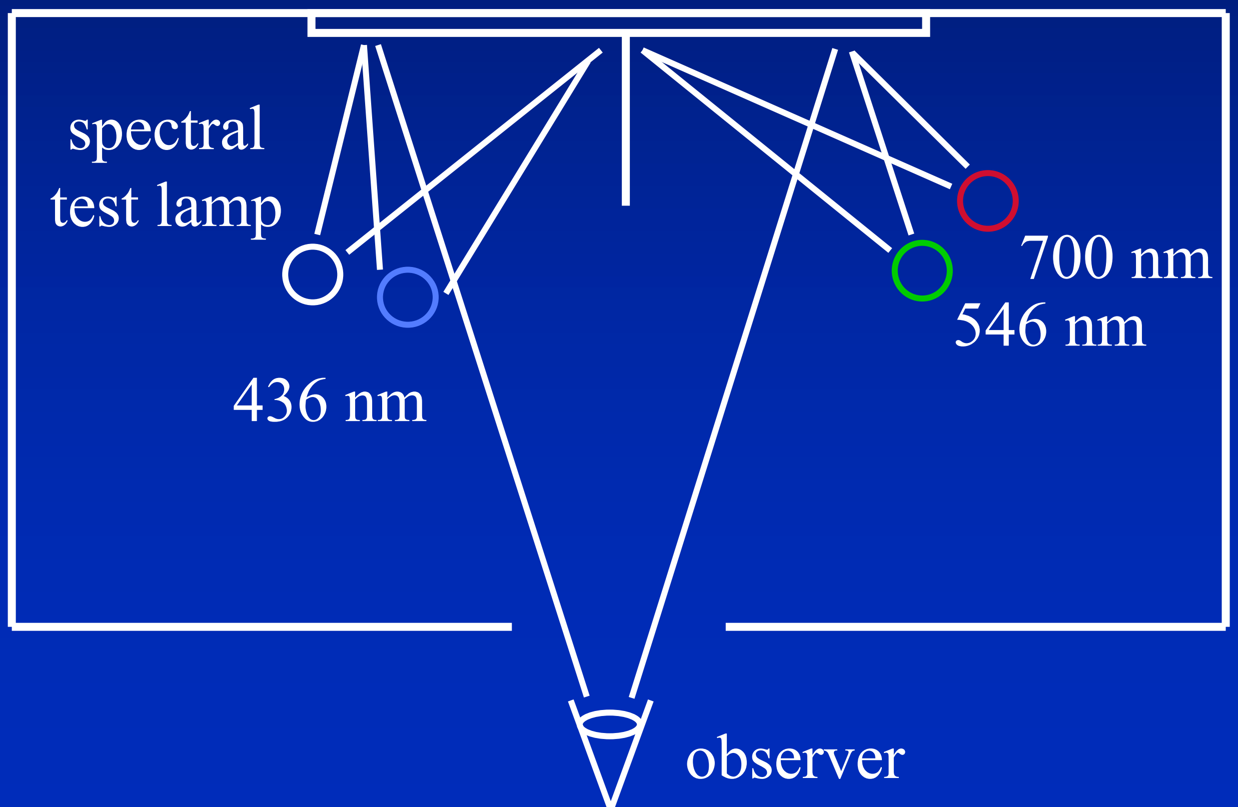


Matching a Test Lamp with 3 Primary Colors

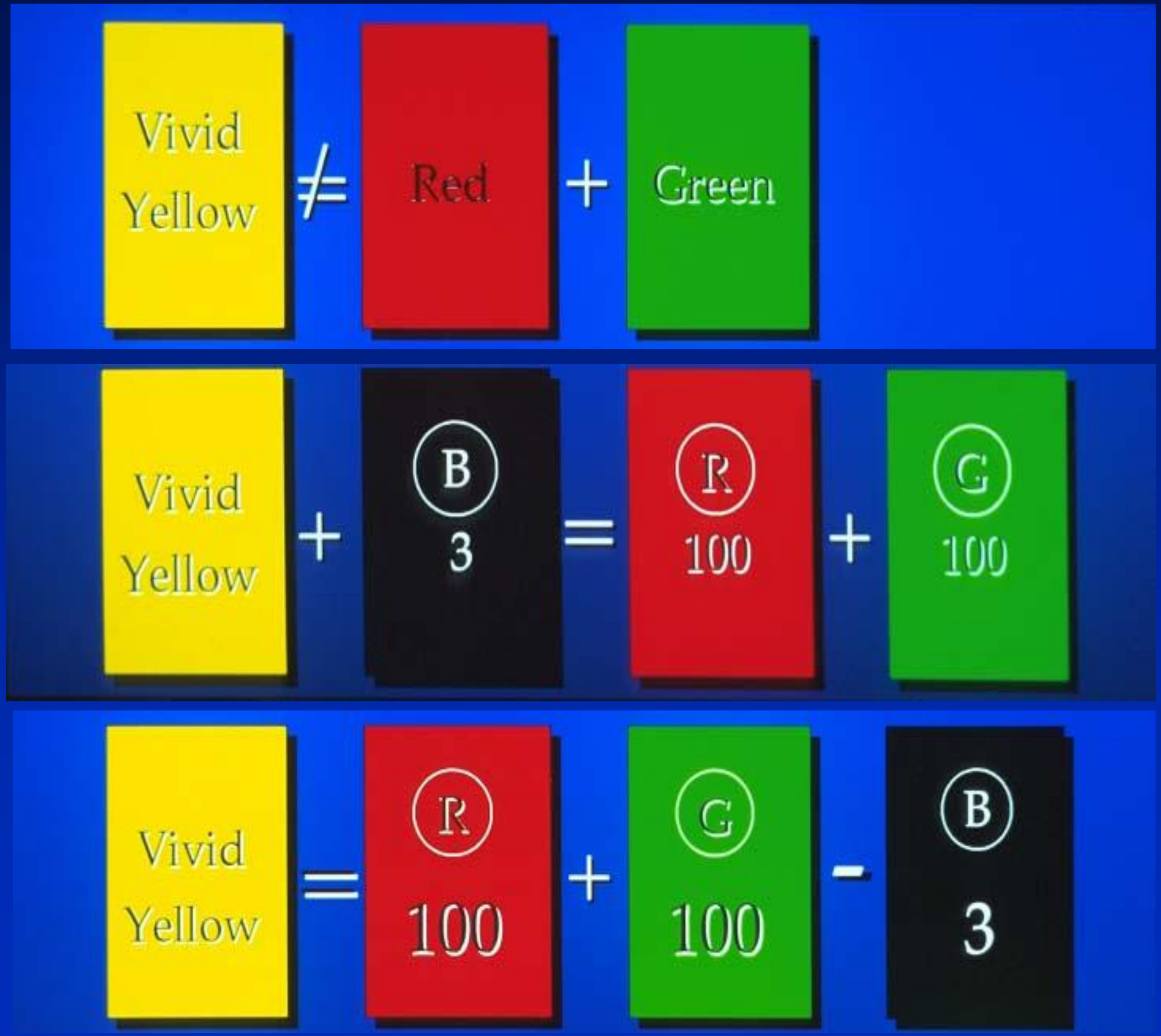


Matching a Test Lamp with 3 Primary Lights

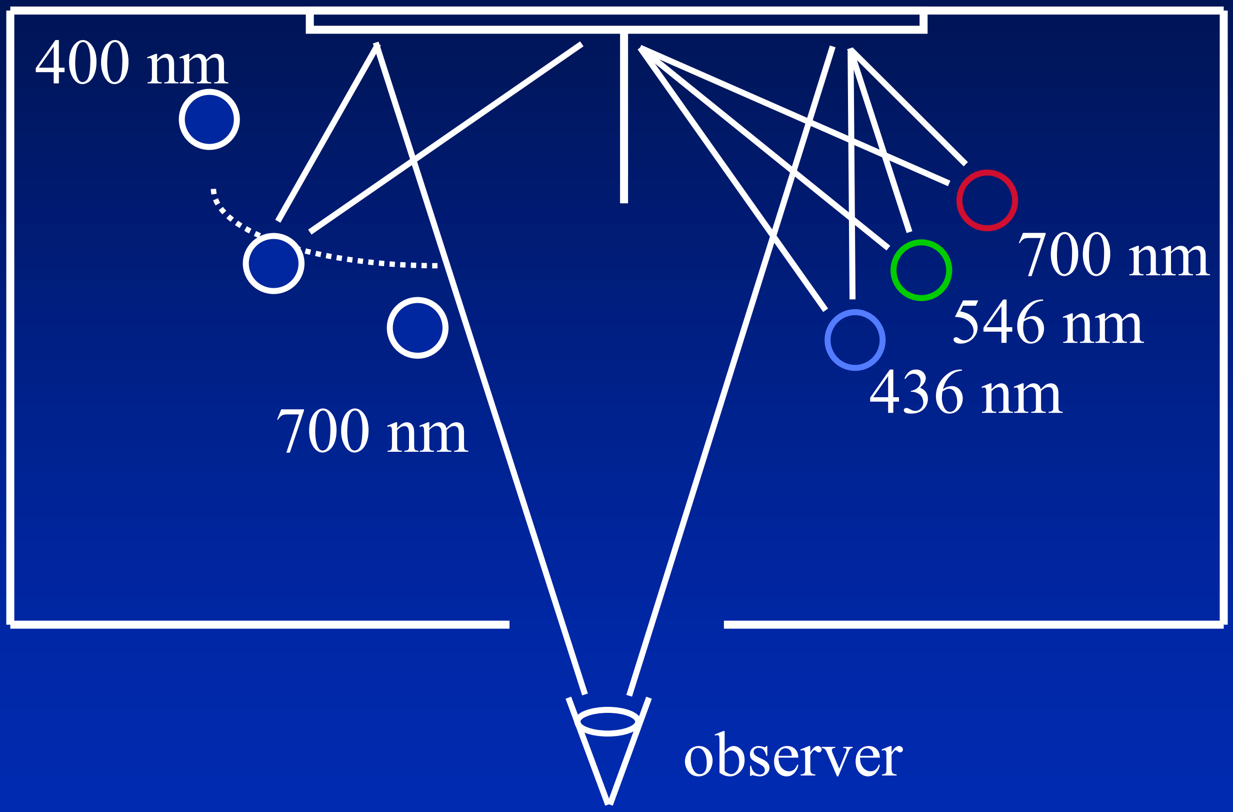
- Need to allow "negative light"
  - Can't match a bright yellow (Y) light with R,G,B.
  - But can match Y + B with R + G.



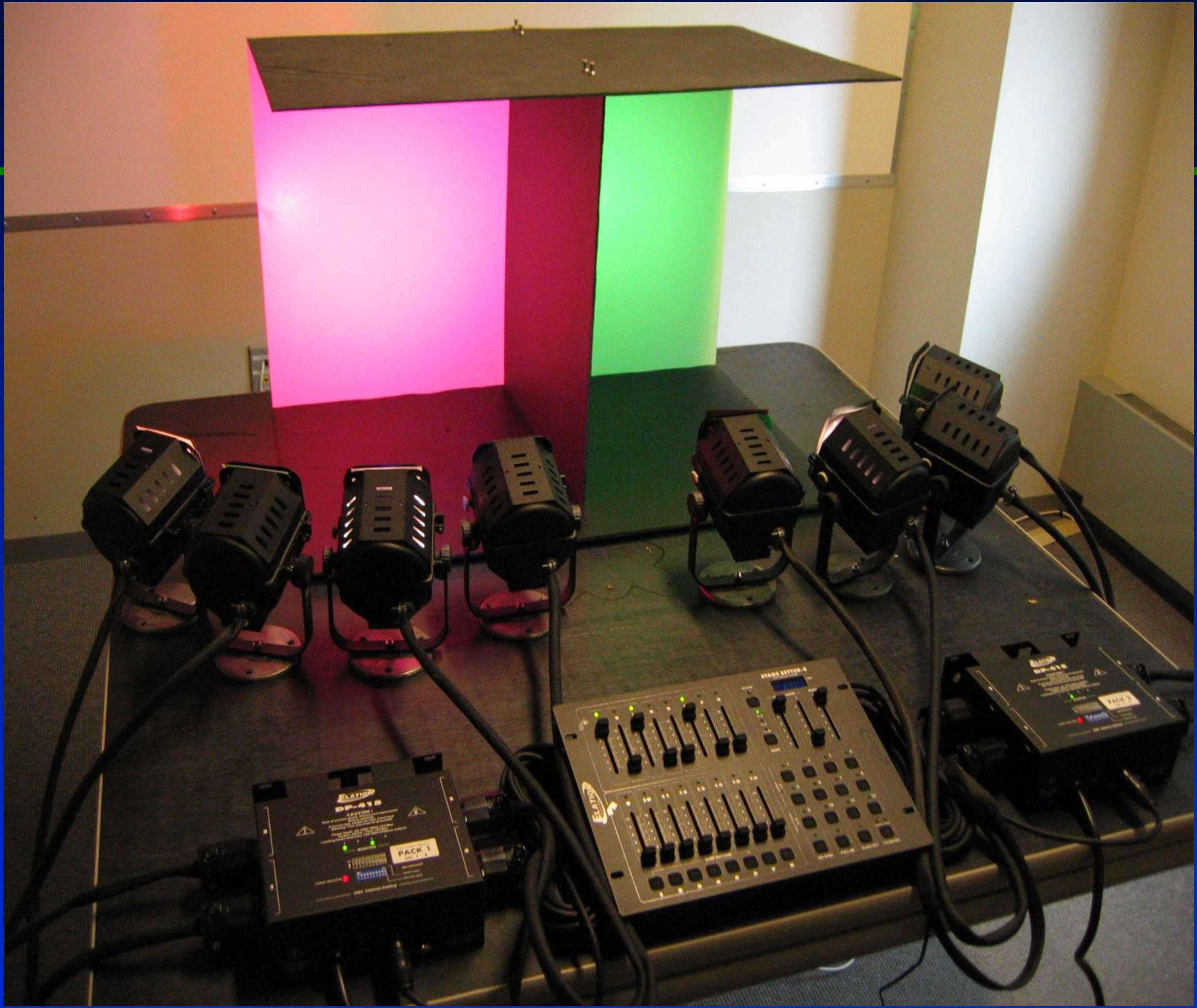
Matching a Test Color (Lamp) with 3 Primary Colors



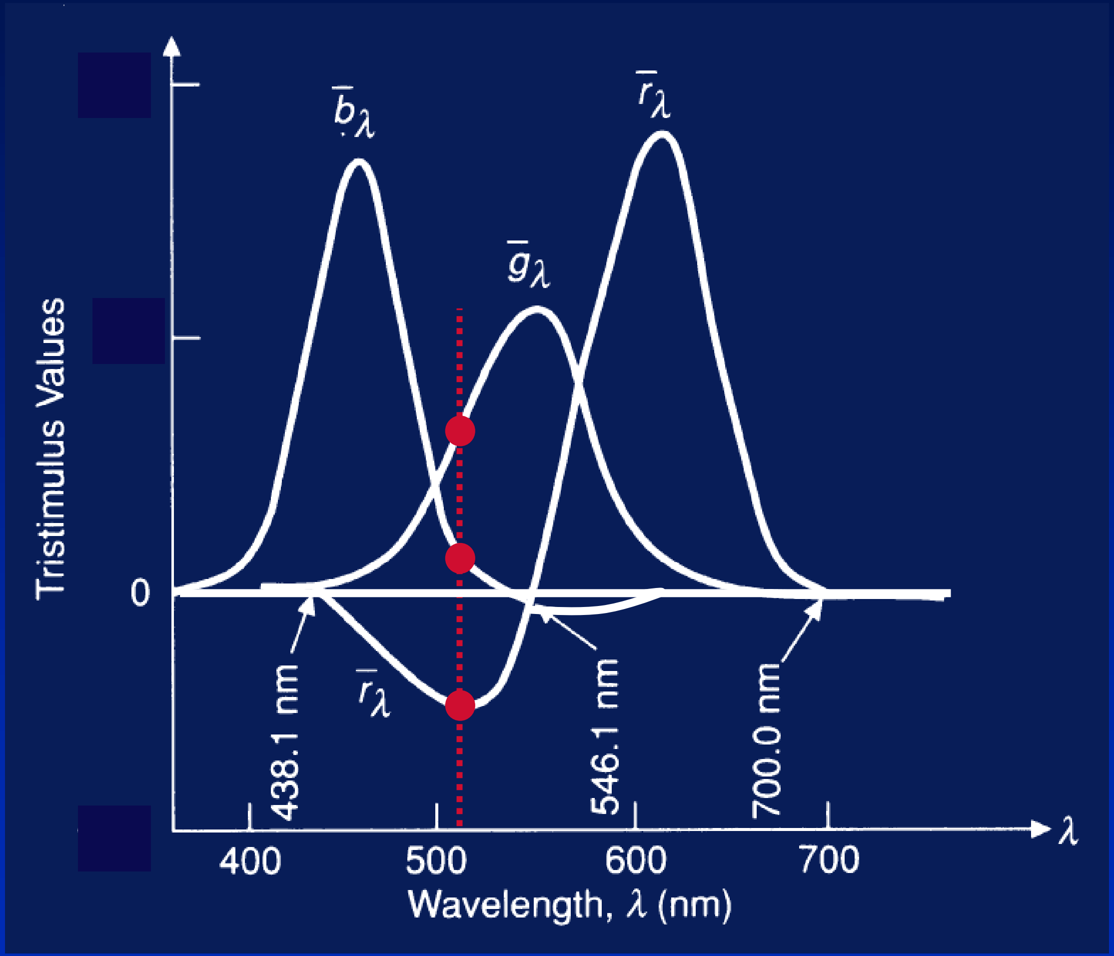
Experiment to Determine the Response Matching Functions of the Average Human Observer



Individually match the RGB primary lights to the unit values of each of the spectral lamps.


ELATION
DP-415
CAUTION
PACK 1

Response Matching Functions of the Average Human Observer



These are the response matching functions of the average human observer for these three primary lights.

Trichromatic Generalization

- Many colors can be matched by additive mixtures of suitable amounts of three fixed primary colors.
- Others have to be mixed with a suitable amount of one before it can be matched by the other two.
- All the colors can be matched in one of these two ways:
  - The restriction is that none of the primary colors can be matched by an additive mixture of the other two.

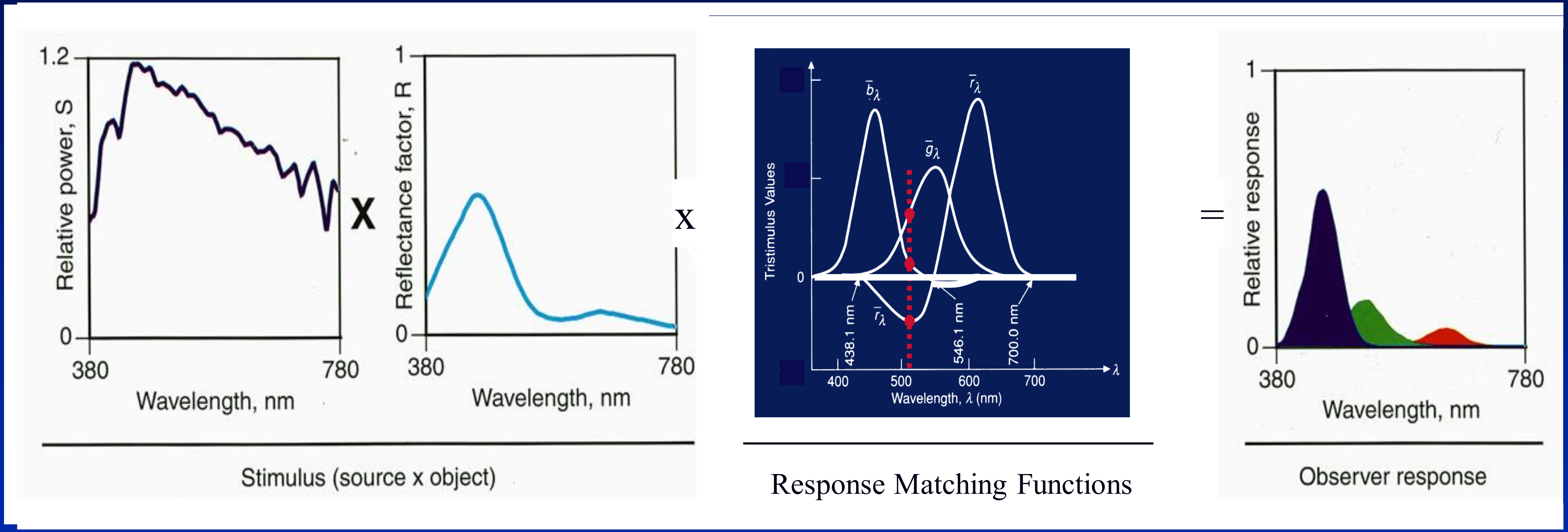
Trichromatic Generalization

– Proportionality and additivity are valid over a large range of observing conditions.

Proportionality - If A=B, then kA=kB

Additivity- If A=B, and C=D, the A+C=B+D

Observer Response



Roy S. Berns. "Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 46.

Computing Tristimulus Values with the Response Matching Functions

- For each test lamp we can compute the equivalent RGB tristimulus values using the color matching functions

$$R = \int P(\lambda)\bar{r}(\lambda)d\lambda$$

$$G = \int P(\lambda)\bar{g}(\lambda)d\lambda$$

$$B = \int P(\lambda)\bar{b}(\lambda)d\lambda$$

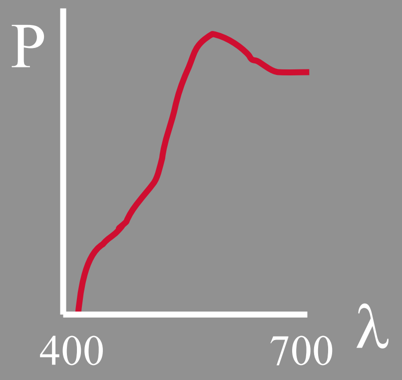
Comments on Response Matching Functions

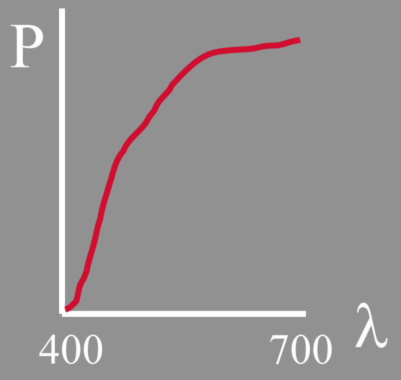
- Note that knowing the spectral distributions of the primary light sources and the response matching functions of the average human observer, we can then represent a large range of colors with any three primary light sources. (Monitors, cell phones, and printers).
- Perhaps most important, is the fact that these are perceptual spaces because a human observer is within the experimental testing loop.
- All of these tests have been conducted in a dark room and thus do not consider the effect of the illumination within the external environment.

Metamer

A metamer is a phenomenon
in which two spectrally different stimuli
match to a given observer.

Metamers

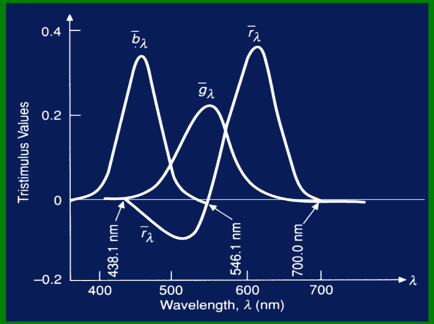


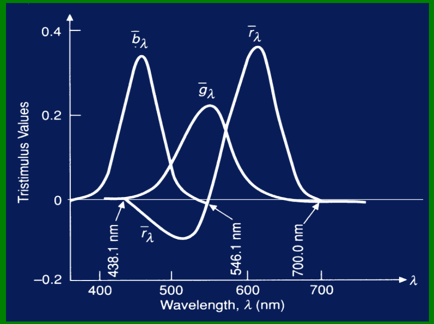


Physically different

×

×





Perceptual filter

↓ ↓

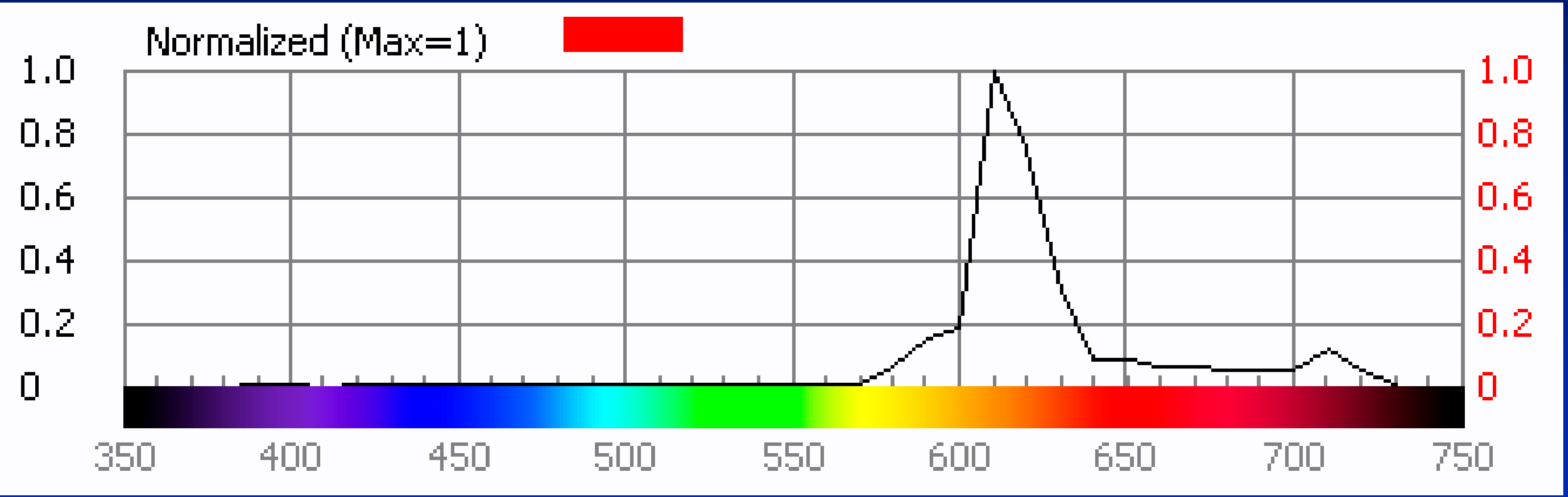
R,G,B = *R,G,B*

Perceptually equal

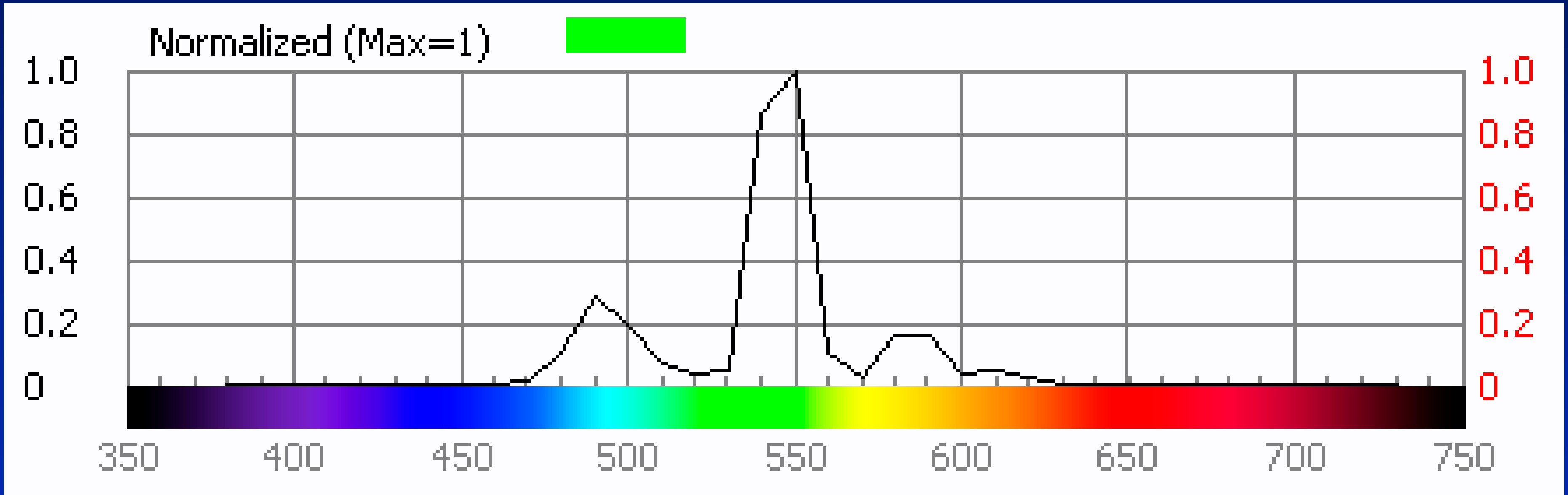
Metamers

- Trichromacy, perhaps the most important property of the visual system, leads to metamerism. (Grassman 1853)
- Metamerism is a phenomenon in which spectrally different stimuli match to a given observer.
- Because of metamerism, color reproduction is possible.
- Stimuli do not have to have identical spectral properties in order to have a perceptual color match.

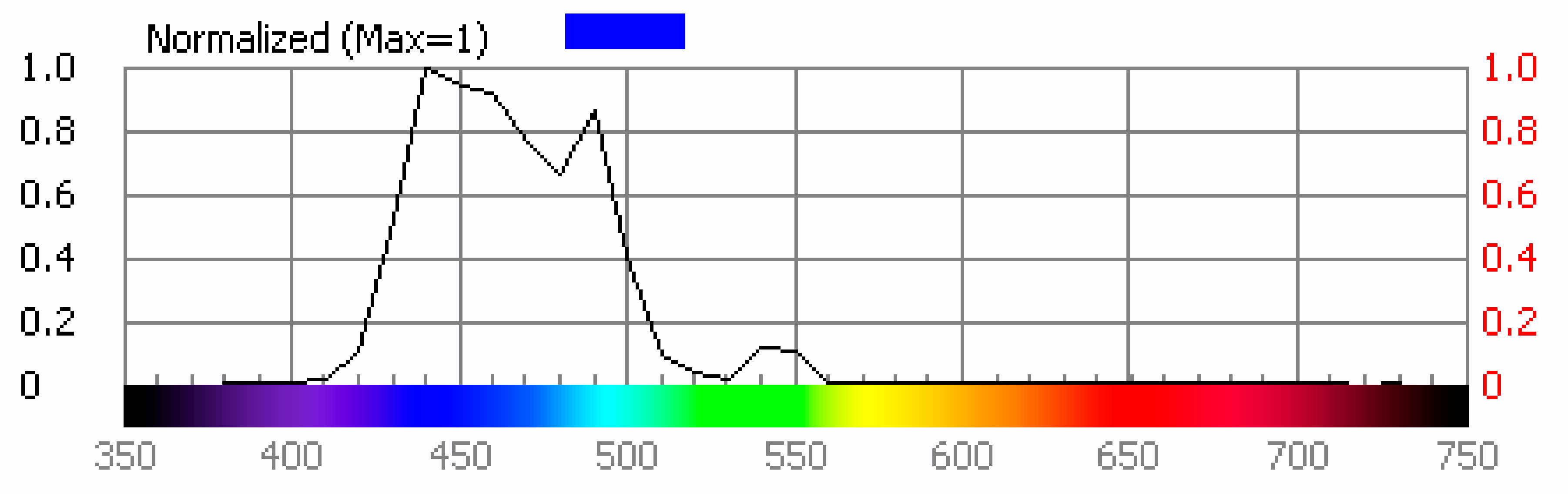
Typical LCD spectral radiance distribution



Typical LCD spectral radiance distribution



Typical LCD spectral radiance distribution



Typical LCD spectral radiance distribution

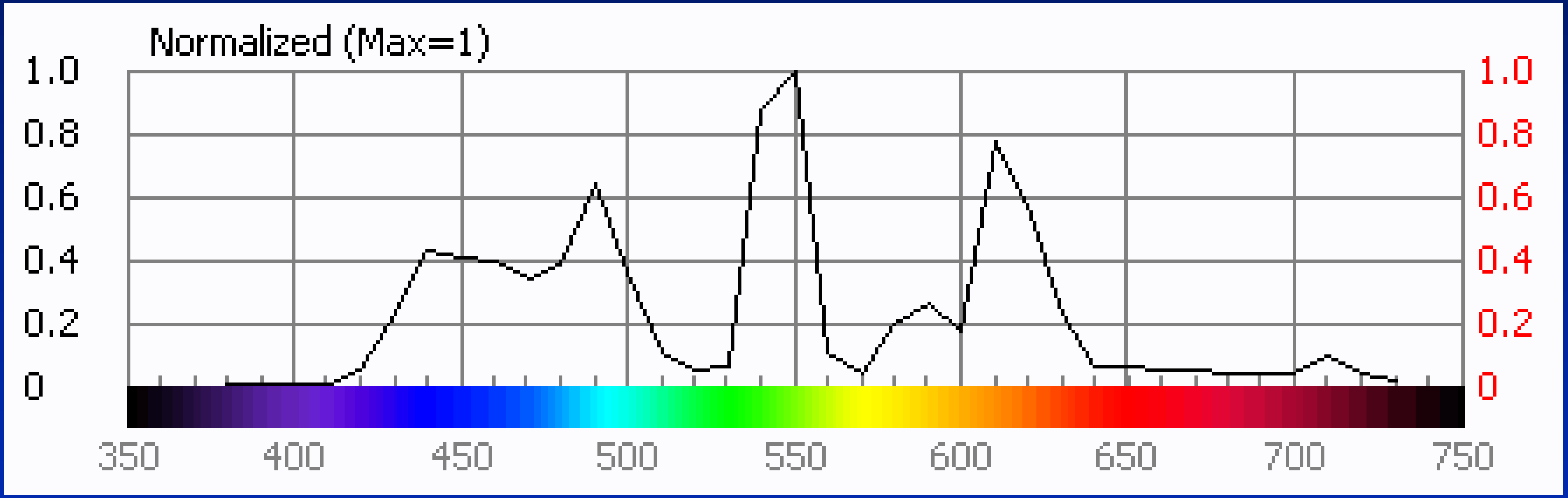
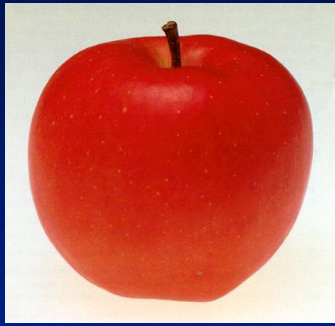
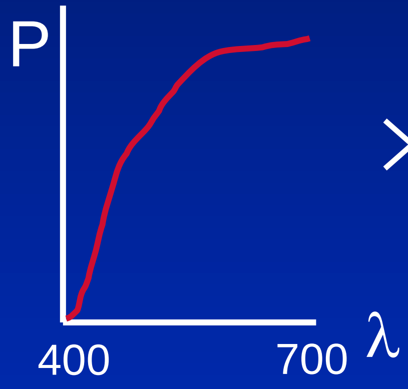


Figure #3 -- http://www.marcelpatek.com/LCD.html

Taking Advantage of Metamers





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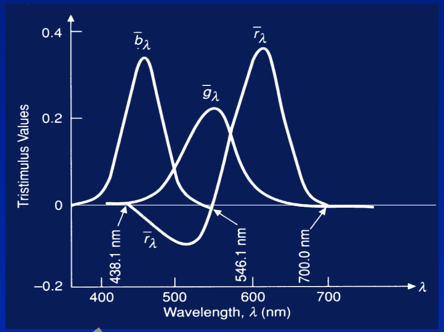

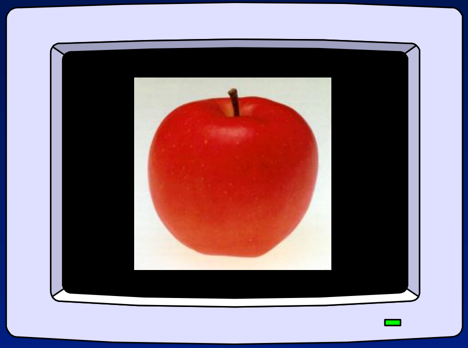

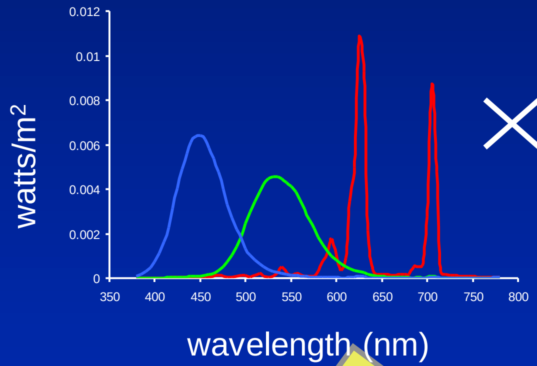

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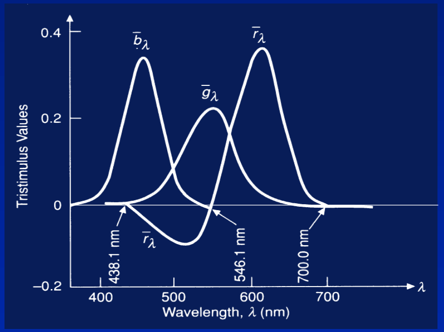


$$R,G,B \quad = \quad R,G,B$$

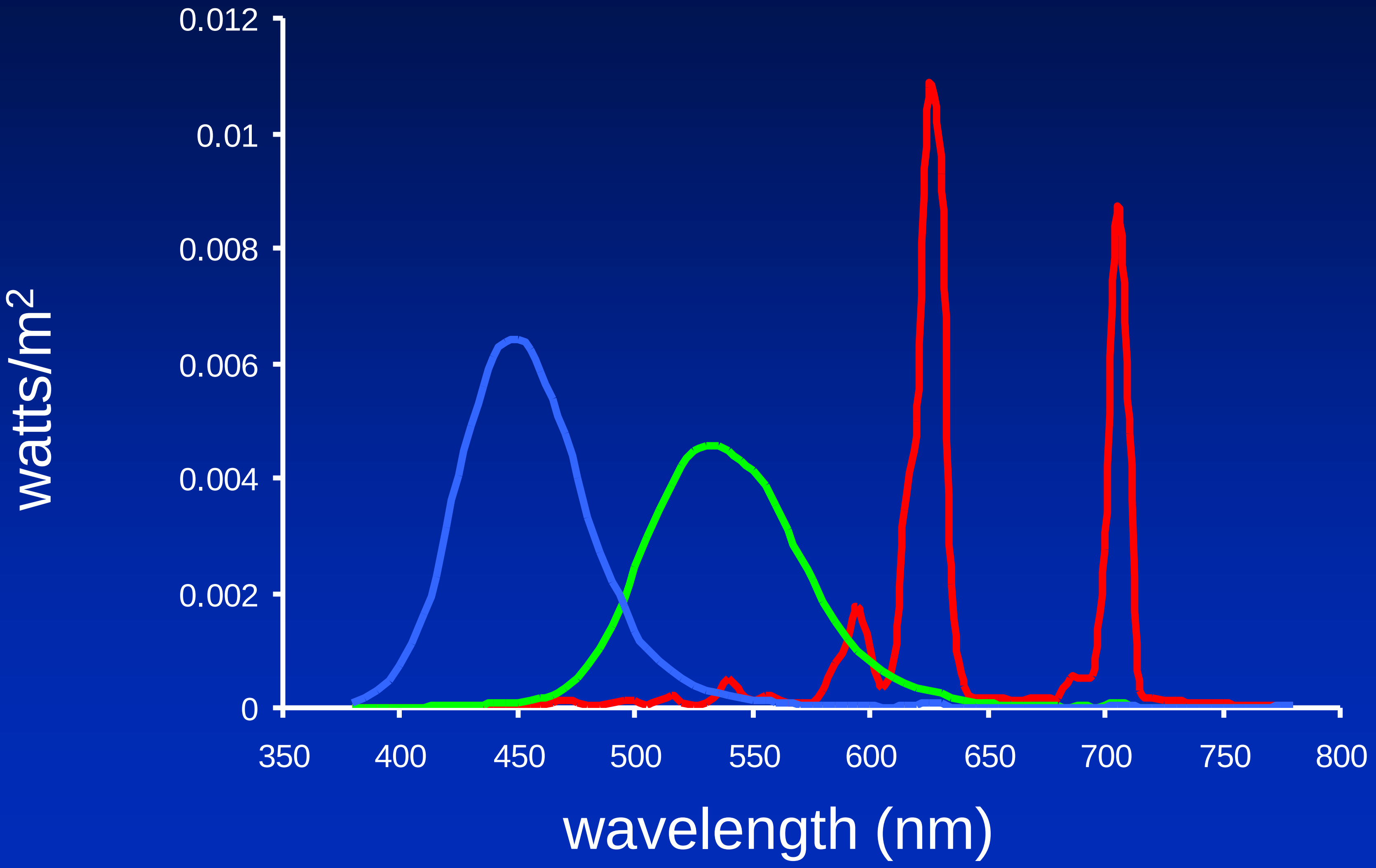
Visual match

Color Vision 2

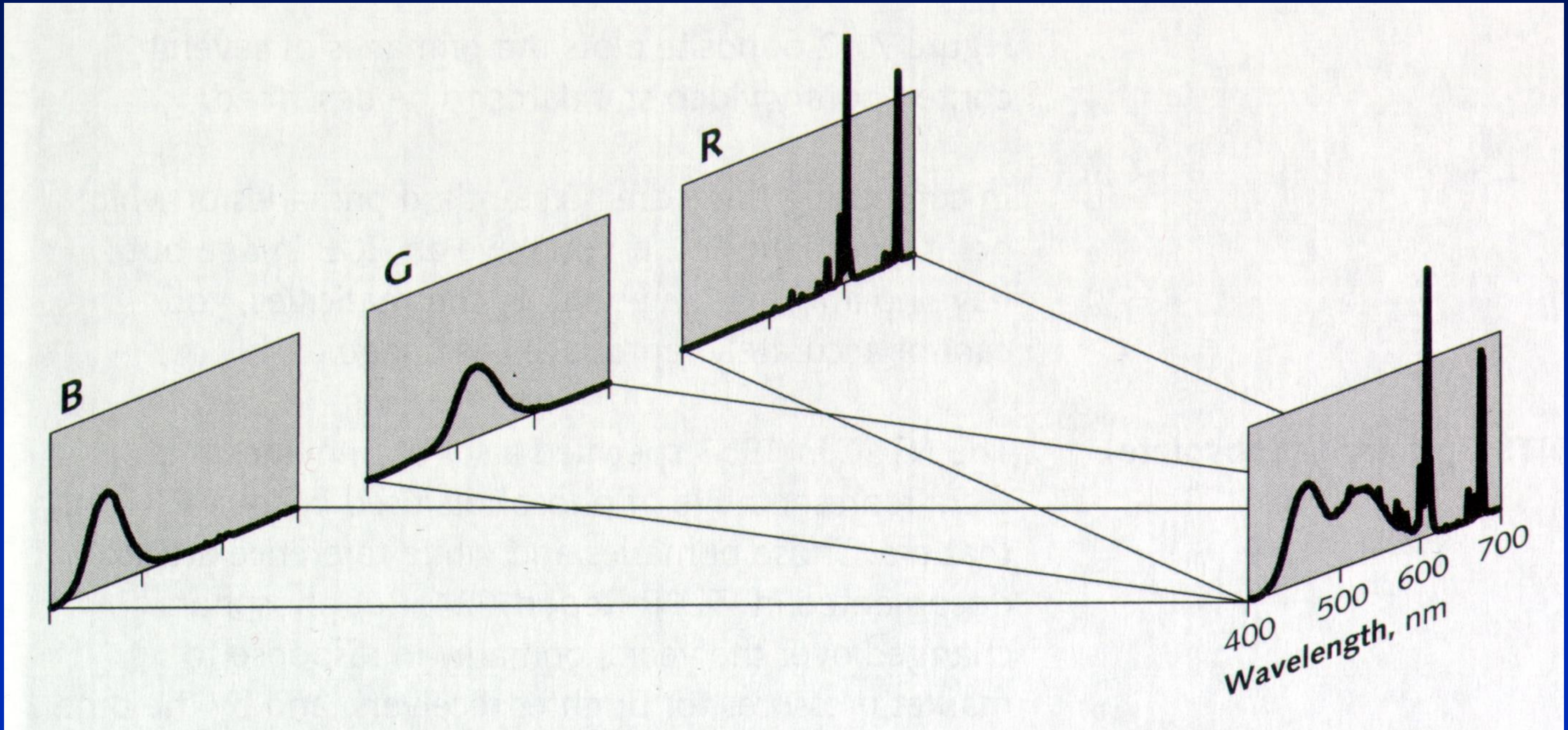
https://www.youtube.com/watch?v=82ItpxqPP4I

End. . .

Vacuum Tube Monitor Phosphors

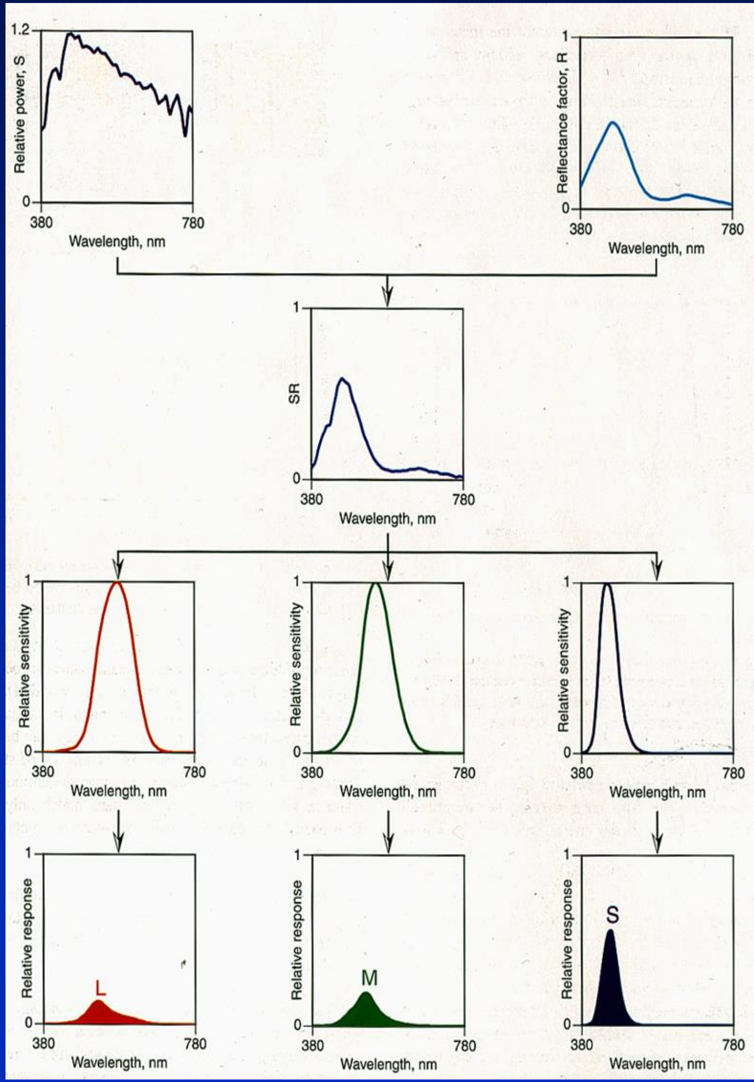


Combining Monitor Phosphors with Spatial Integration



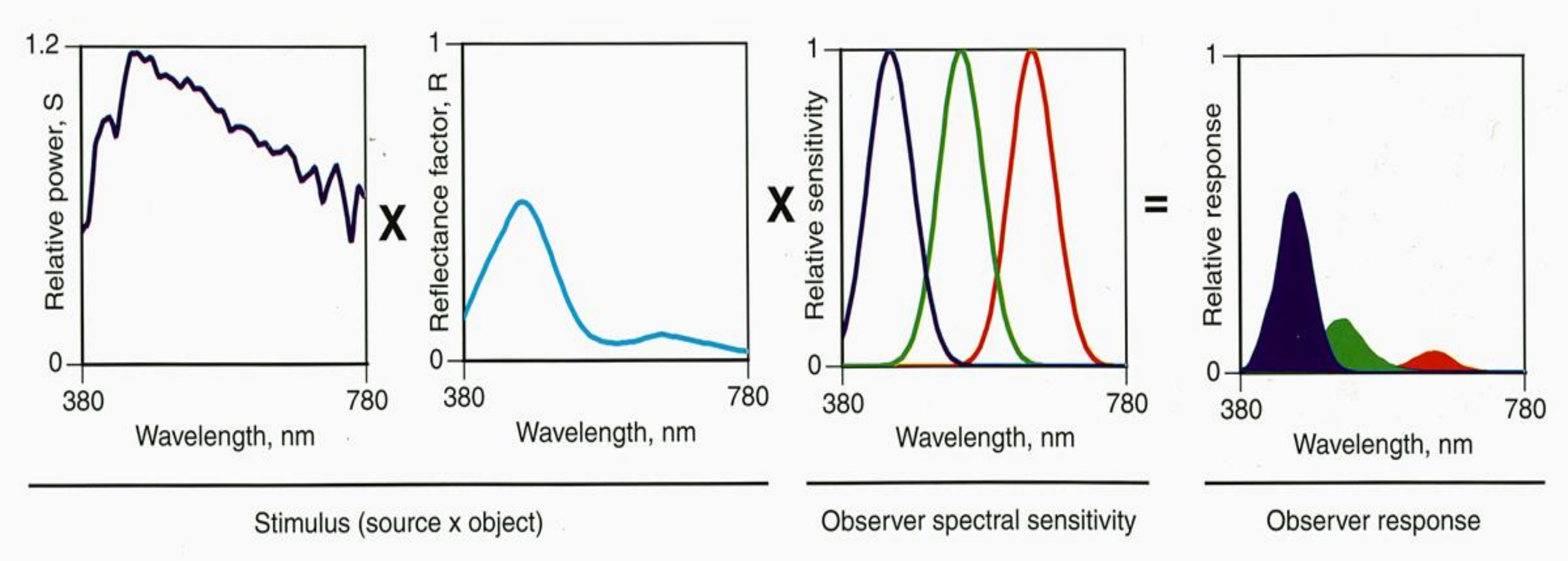
Observer Response

The integrated L, M, and S responses that result from the light entering the eye from an illuminated object. This can be calculated as the product of the spectral properties of the light source, the object, and the observer's sensitivities, followed by integration over wavelength, essentially, calculating the areas under the last row of curves.



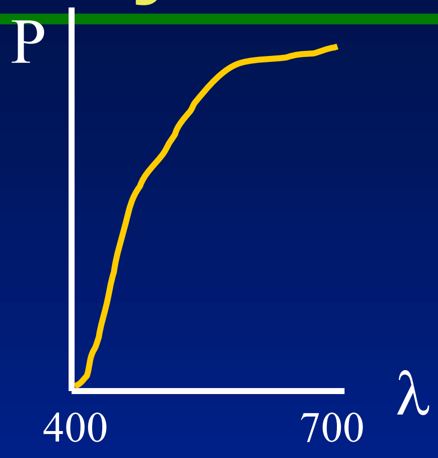
Roy S. Berns. "Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 15.

Observer Response

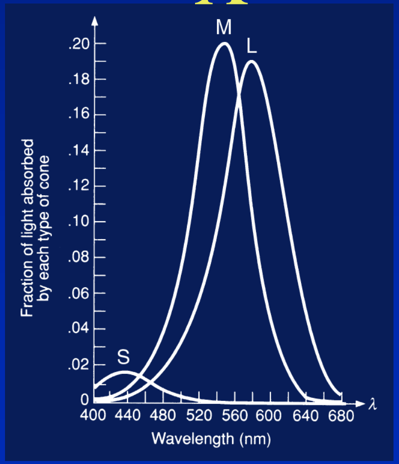


Roy S. Berns. “Billmeyer and Saltzman’s Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 46.

Trichromacy



X



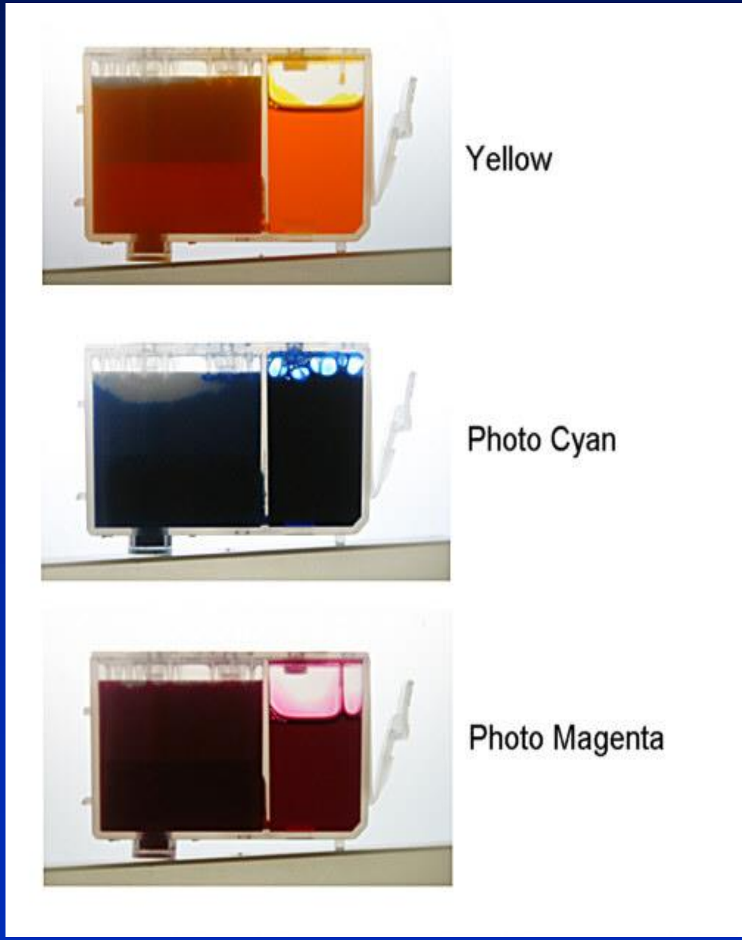
S, M, L

$$S = \int P(\lambda) s(\lambda) d\lambda$$

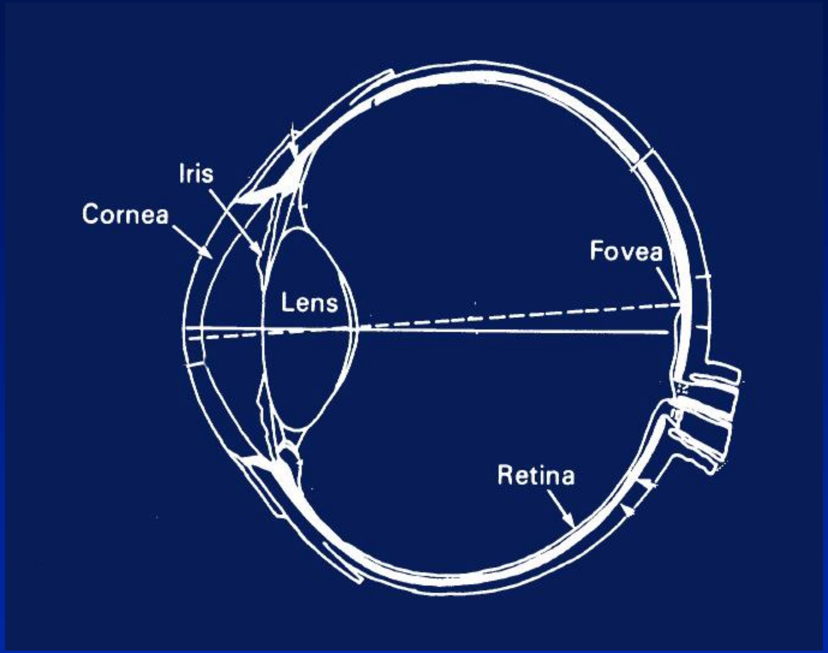
$$M = \int P(\lambda) m(\lambda) d\lambda$$

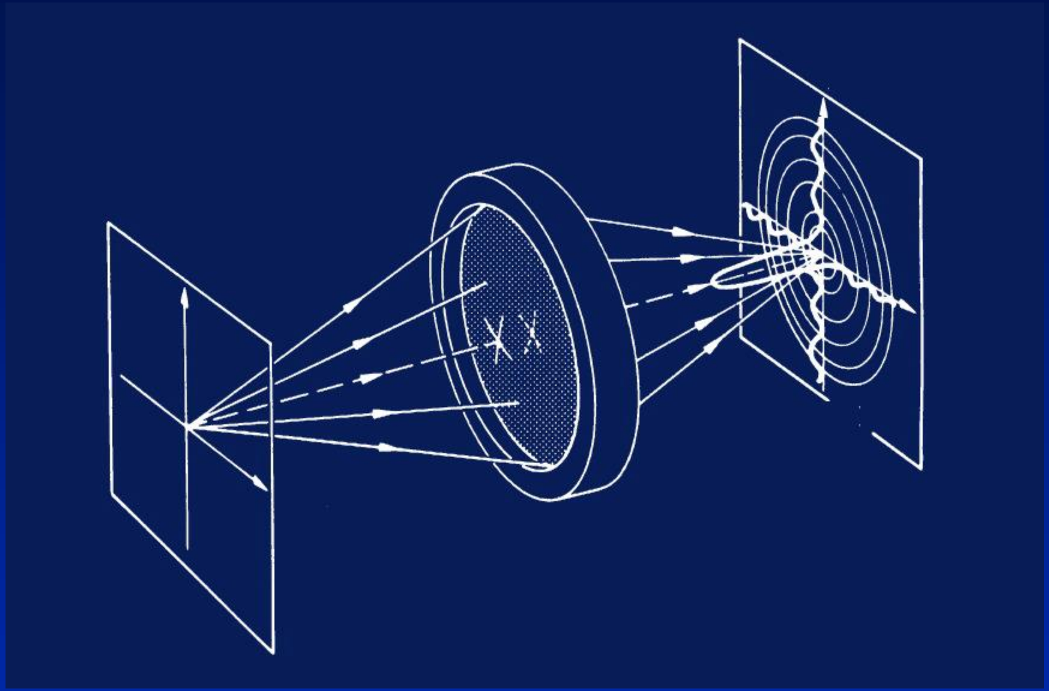
$$L = \int P(\lambda) l(\lambda) d\lambda$$

Printer Inks



Formation of the Retinal Image

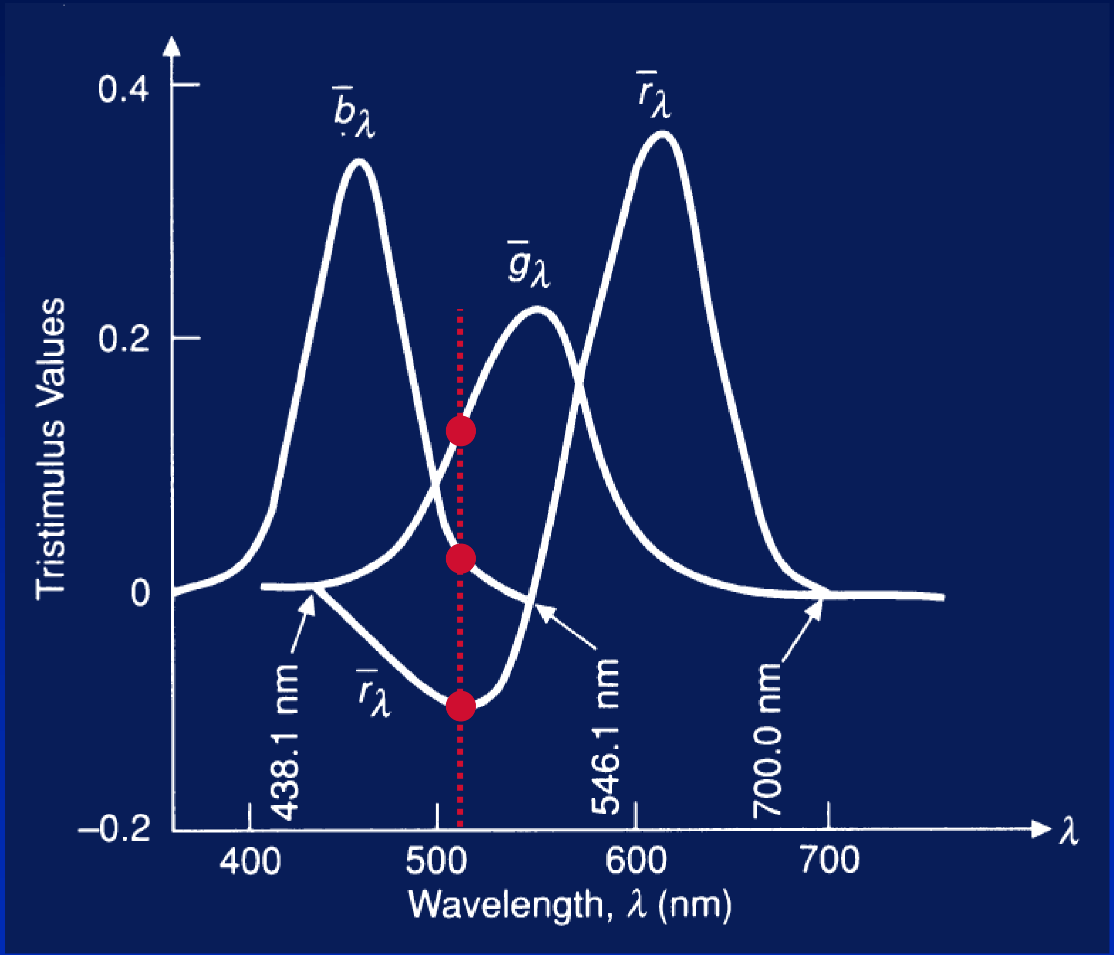




- point spread function (PSF): luminance distribution produced by imaging a point source

Left figure adapted from: Atkinson, Steven's Handbook of Experimental Psychology © Wiley 1988.
Right figure adapted from: Hecht, Optics © Addison-Wesley 1974.

Response Matching Functions



These are the response matching functions of the average human observer for these three primary lights.

Emitted Light

$$P = \sum_{\lambda} E_{\lambda}$$

$P =$ energy reaching the eye at all wavelengths

$E_{\lambda} =$ emitted light energy at each wavelength

Reflected Light

$$P = \sum_{\lambda} E_{\lambda}$$ (Emitted Light)

$$P = \sum_{\lambda} E_{\lambda} \bullet \rho_{\lambda}$$

$P =$ energy reaching the eye at all wavelengths

$E_{\lambda} =$ emitted light energy at each wavelength

$\rho_{\lambda} =$ reflected light energy at each wavelength

Transmitted Light

$$P = \sum_{\lambda} E_{\lambda}$$ (Emitted Light)

$$P = \sum_{\lambda} E_{\lambda} \bullet \rho_{\lambda}$$ (Reflected Light)

$$P = \sum_{\lambda} E_{\lambda} \bullet T_{\lambda}$$ (Transmitted Light)

T_{λ} = transmitted light energy at each wavelength

Computing Tristimulus Values with the Response Matching Functions

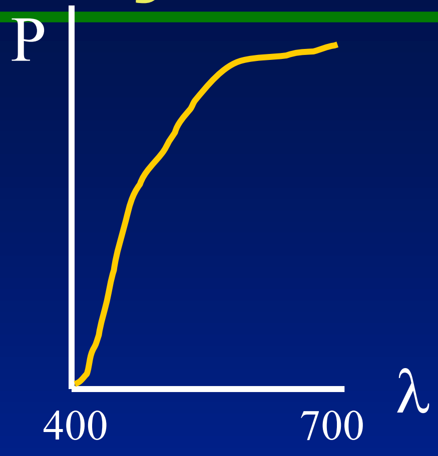
- For each test lamp we can compute the equivalent RGB tristimulus values using the color matching functions

$$R = \int P(\lambda)\bar{r}(\lambda)d\lambda$$

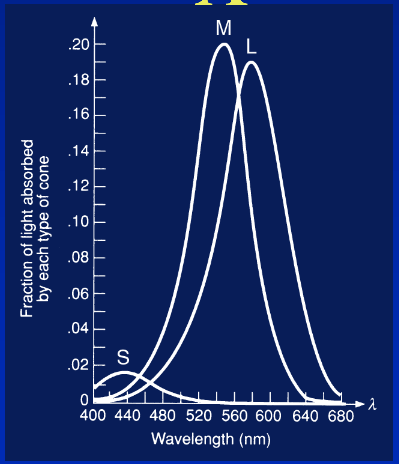
$$G = \int P(\lambda)\bar{g}(\lambda)d\lambda$$

$$B = \int P(\lambda)\bar{b}(\lambda)d\lambda$$

Trichromacy



X



S,M,L

$$S = \int P(\lambda)s(\lambda)d\lambda$$

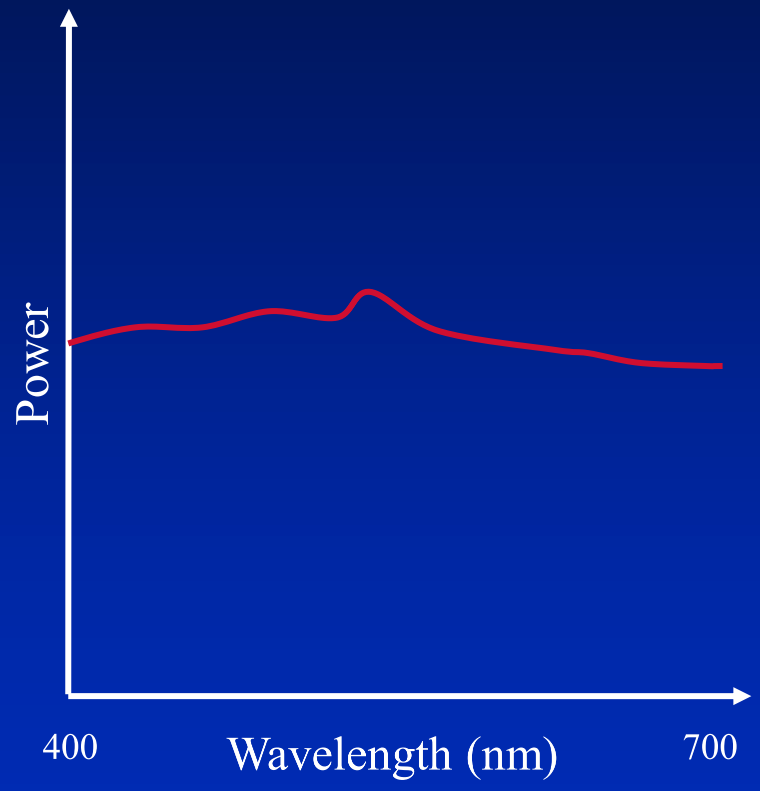
$$M = \int P(\lambda)m(\lambda)d\lambda$$

$$L = \int P(\lambda)l(\lambda)d\lambda$$

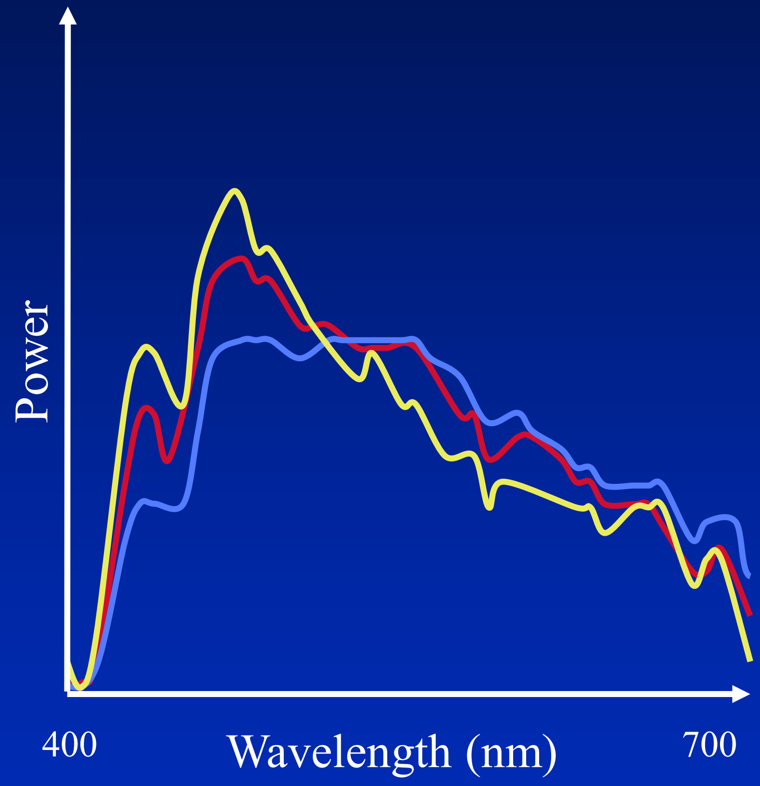
- produces metamers

Spectral Distributions (Wavelengths) of Emissive Light Sources

Test lamp

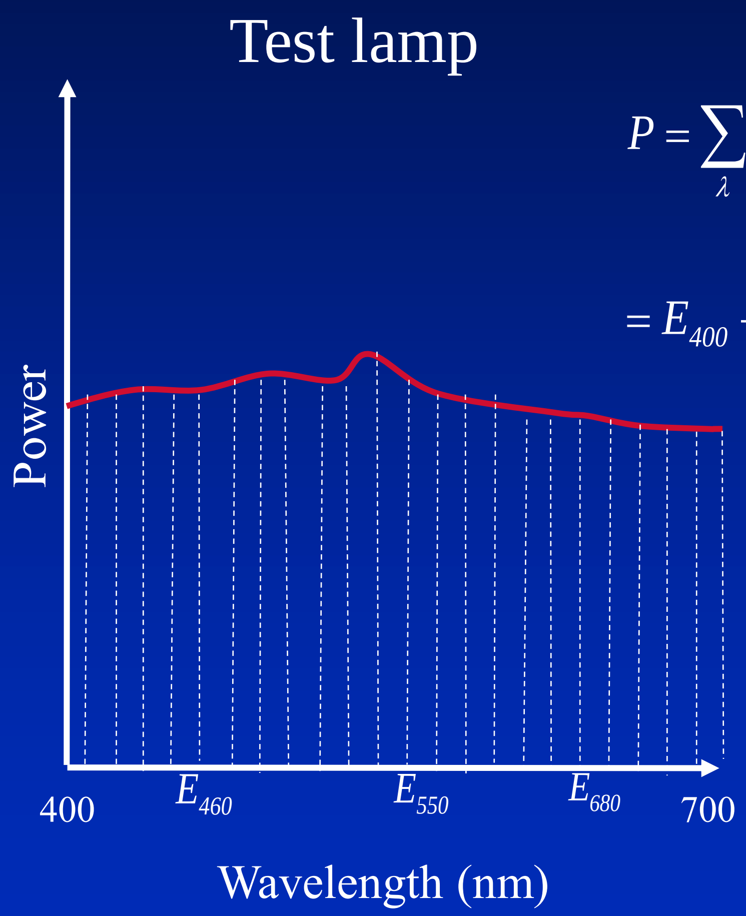


CIE standard



- D_{55}: typical sunlight
- D_{65}: typical average daylight
- D_{75}: typical 'north-sky' light

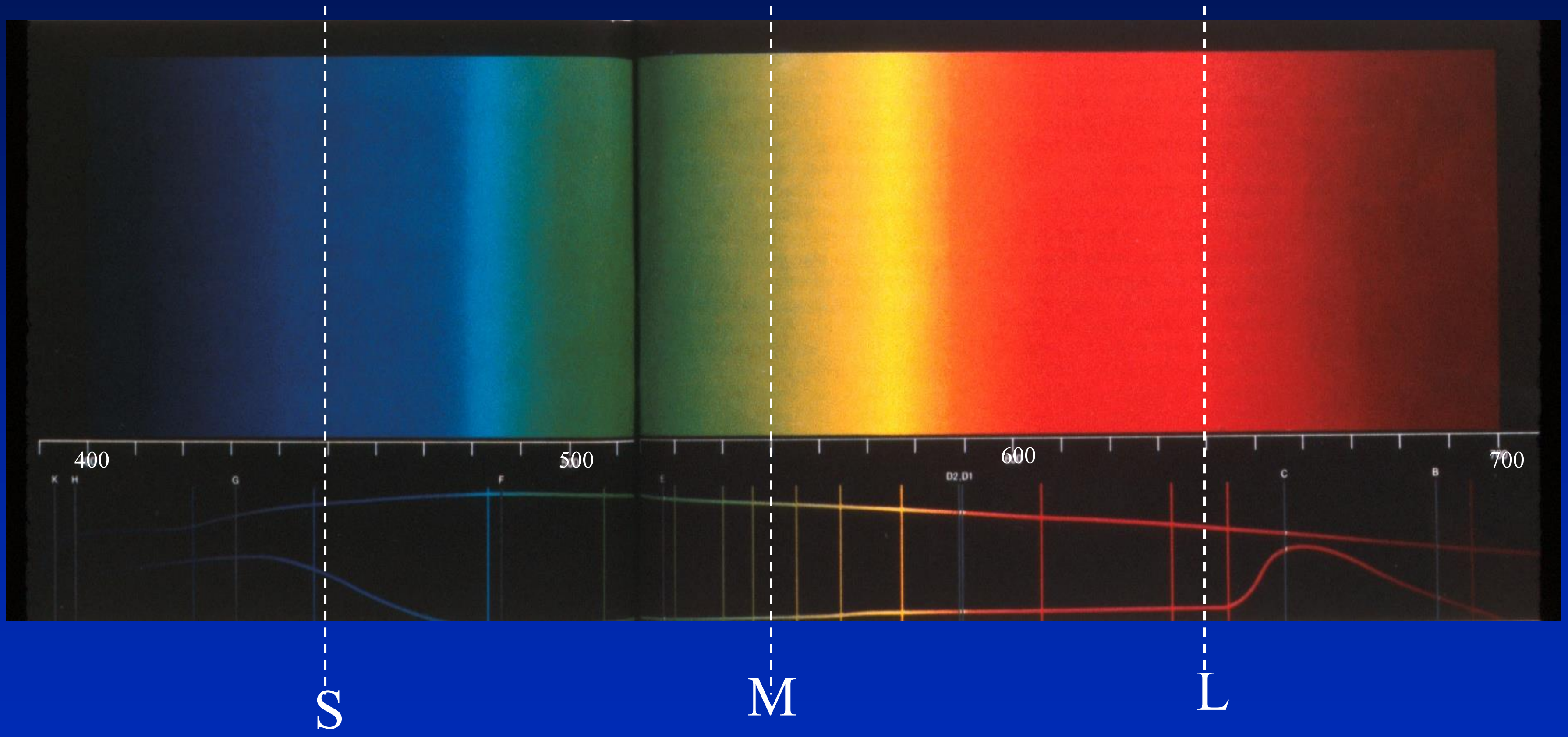
Spectral Distributions of Emissive Light Sources



$$P = \sum_{\lambda} E_{\lambda}$$

$$= E_{400} + E_{410} + E_{420} + E_{430} + + +$$

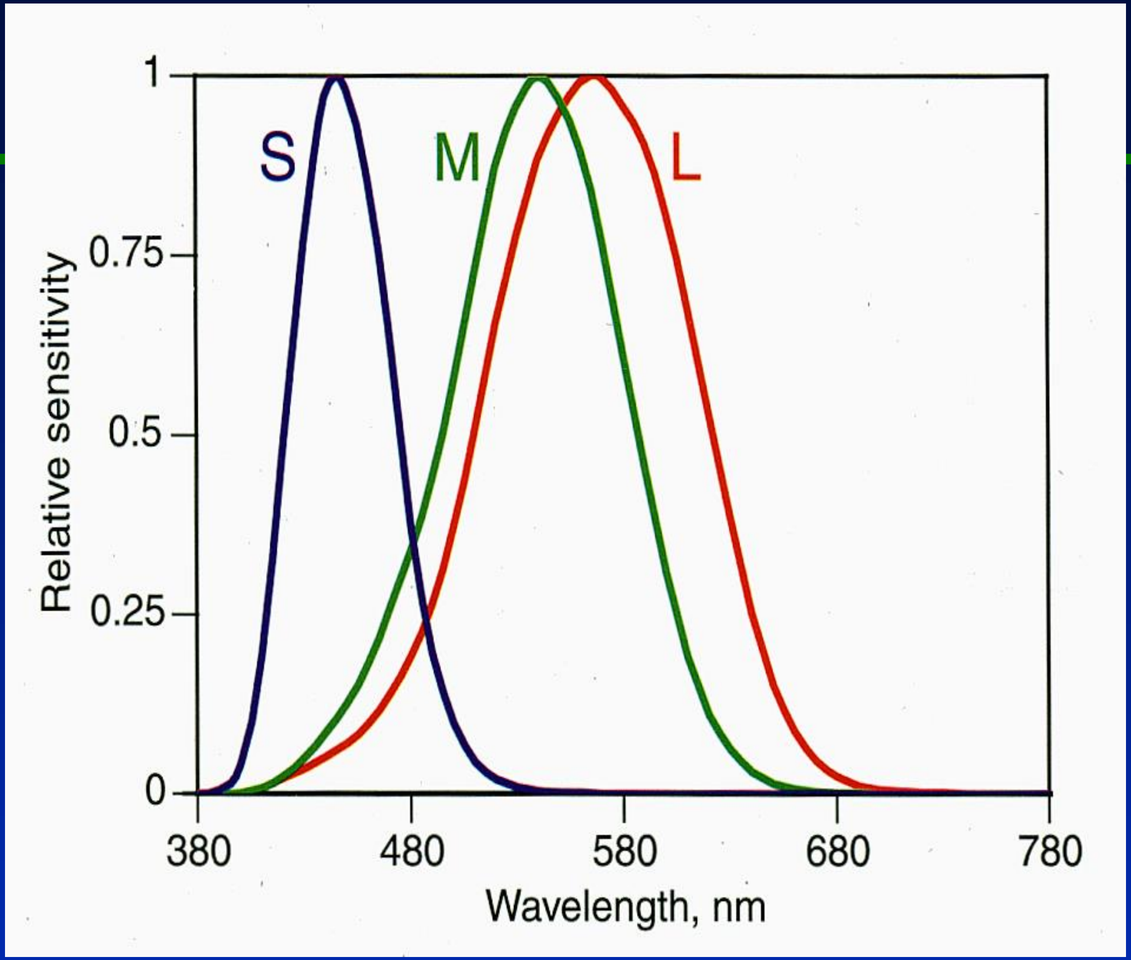
Visible Light Spectrum



Dominant wavelengths of human receptor system

The above are also frequently represented as BGR

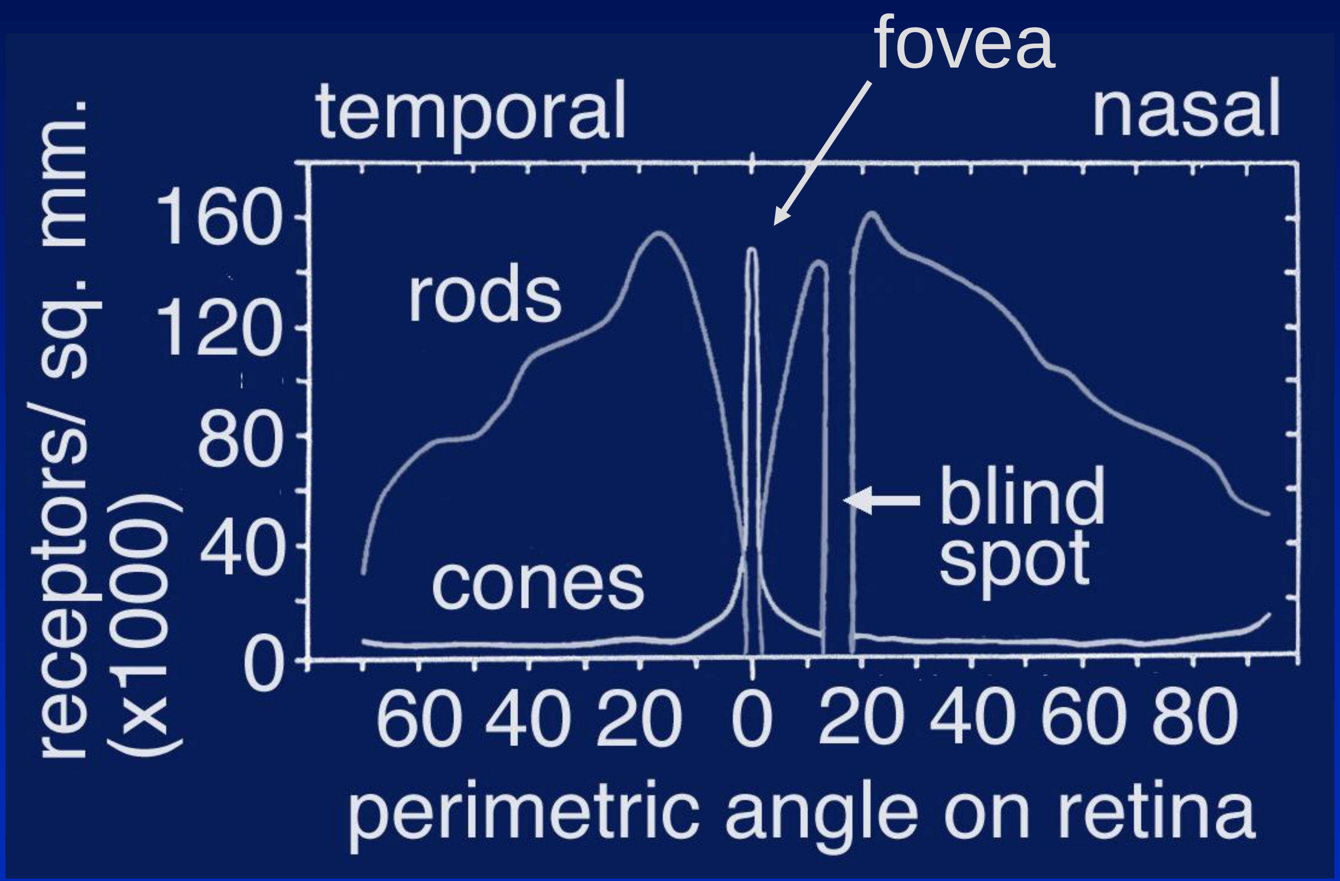
Relative Spectral Sensitivity (normalized)



The relative spectral sensitivity of the L, M, and S cones (Stockman 1993). These spectral sensitivities are based on measurements in front of the eye rather than of isolated photoreceptors. Strictly speaking, these are called cone fundamentals.

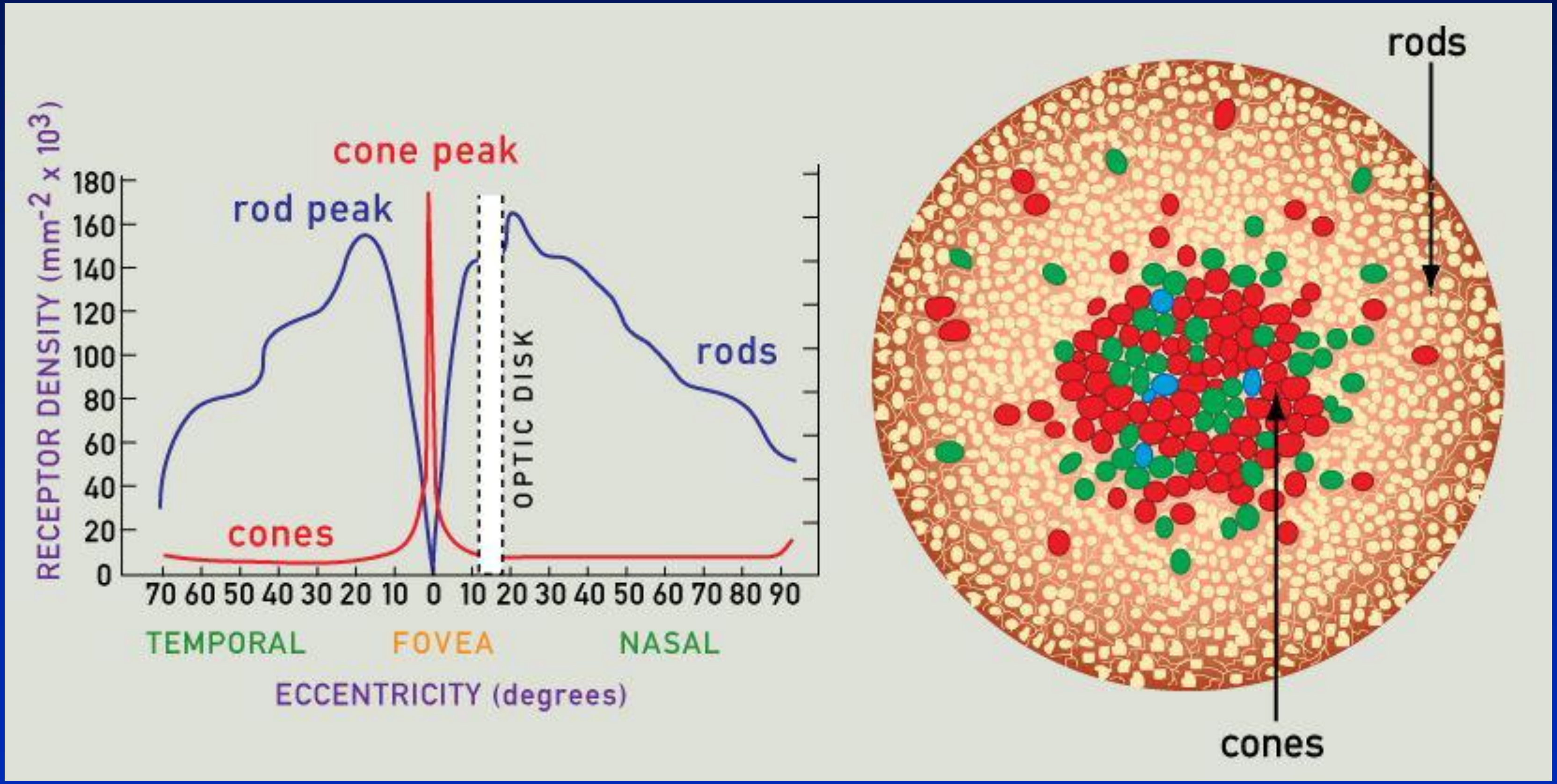
Roy S. Berns. "Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed. 2000, John Wiley & Sons, Inc. p. 14.

Receptor Distribution

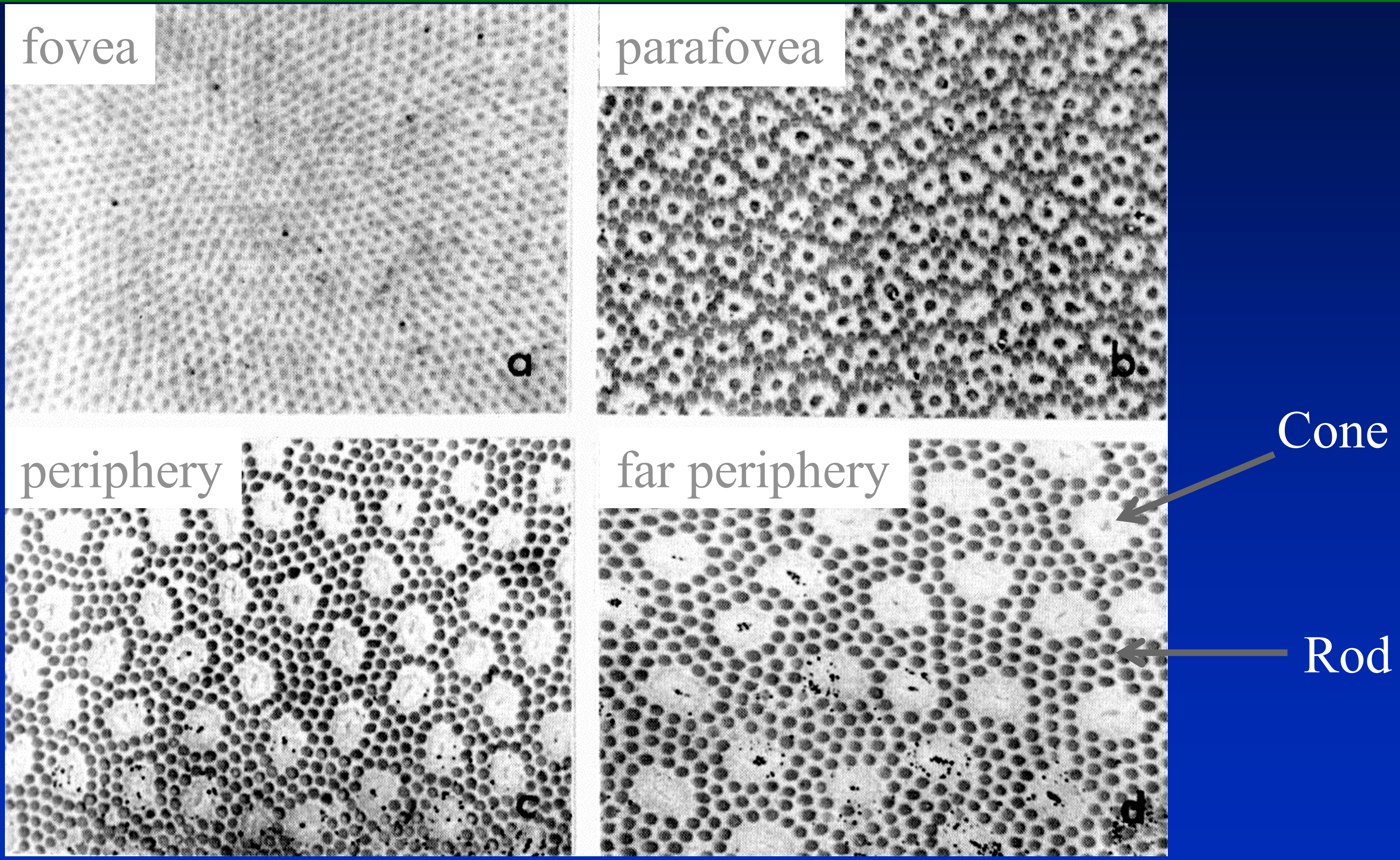


Adapted from Levine, Vision in Man and Machine © McGraw-Hill, 1985.

Receptor Distribution

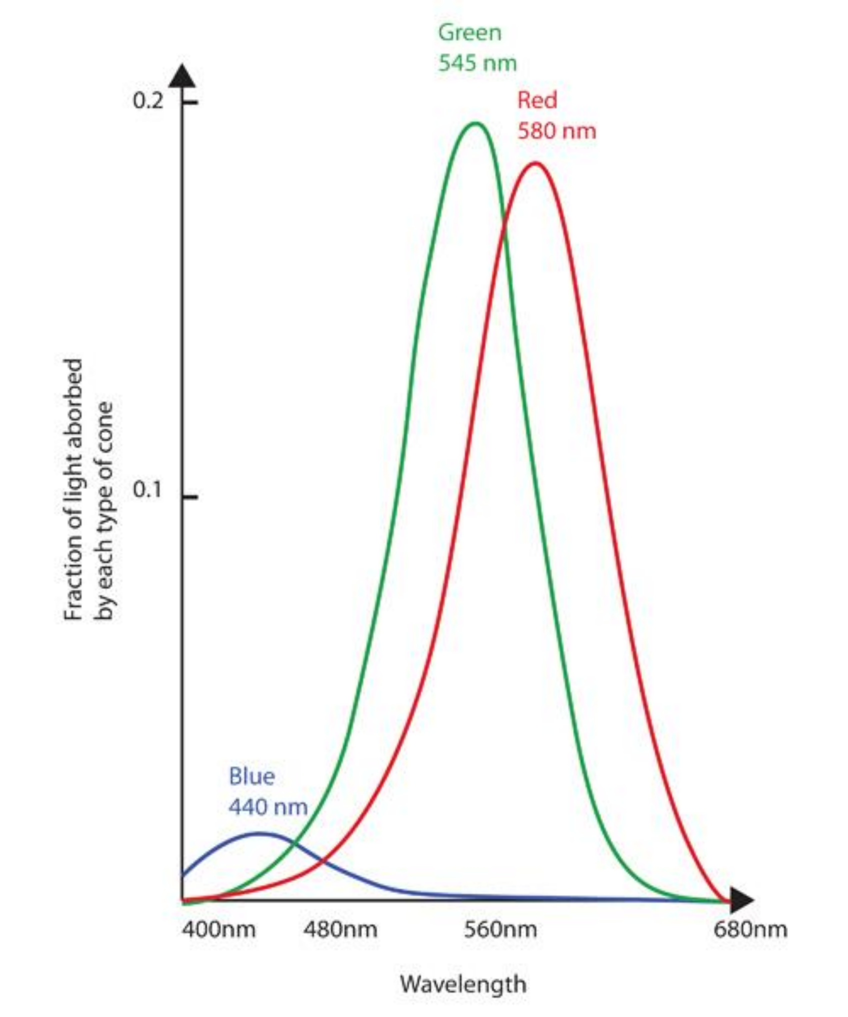


Receptor Distribution



Adapted from Levine, Vision in Man and Machine © McGraw-Hill, 1985.

Why RGB?


Green
545 nm
Red
580 nm
0.2
0.1
Fraction of light aborbed
by each type of cone
Blue
440 nm
400nm
480nm
560nm
680nm
Wavelength