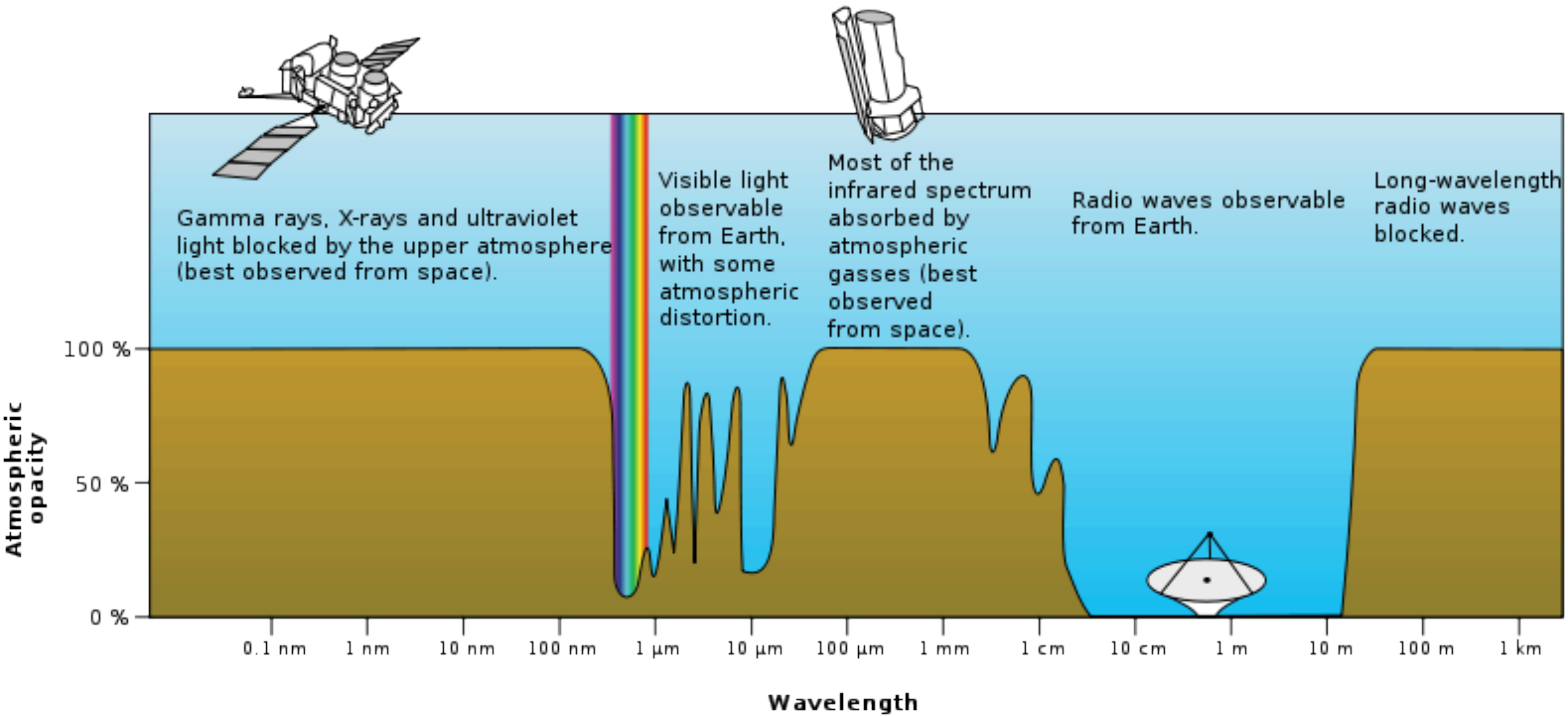
CS6640 Computational Photography

6. Color science for digital photography

What visible light is

- **One octave of the electromagnetic spectrum (380-760nm)**



NASA/Wikimedia Commons

What color is

- **Colors are the sensations that arise from light energy with different wavelength distributions**
- **Color is a phenomenon of human perception; it is not a universal property of light**
- **Roughly speaking, things appear "colored" when they depend on wavelength and "gray" when they do not.**

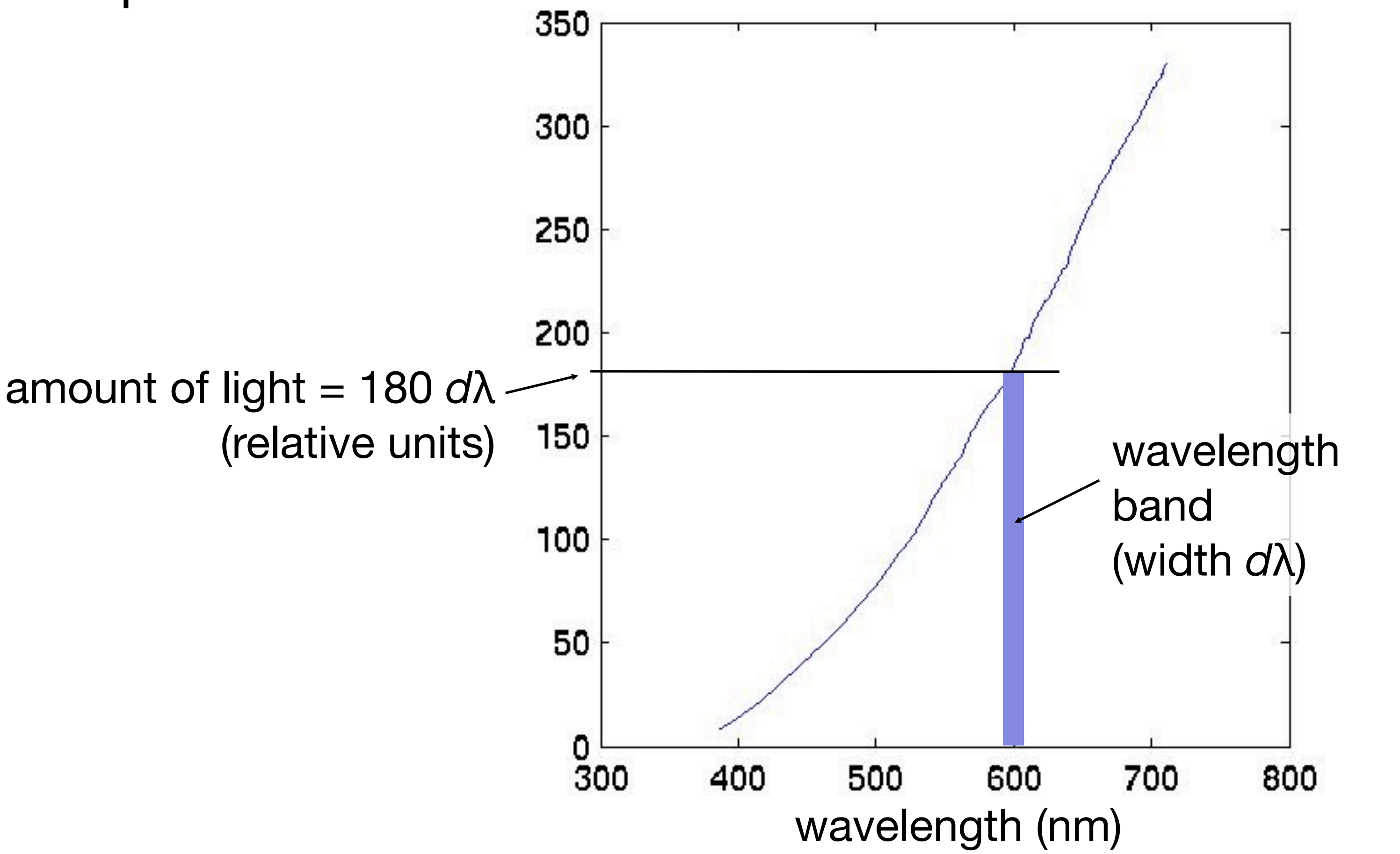
Measuring light

- **Salient property is the *spectral power distribution (SPD)***

  the amount of light present at each wavelength

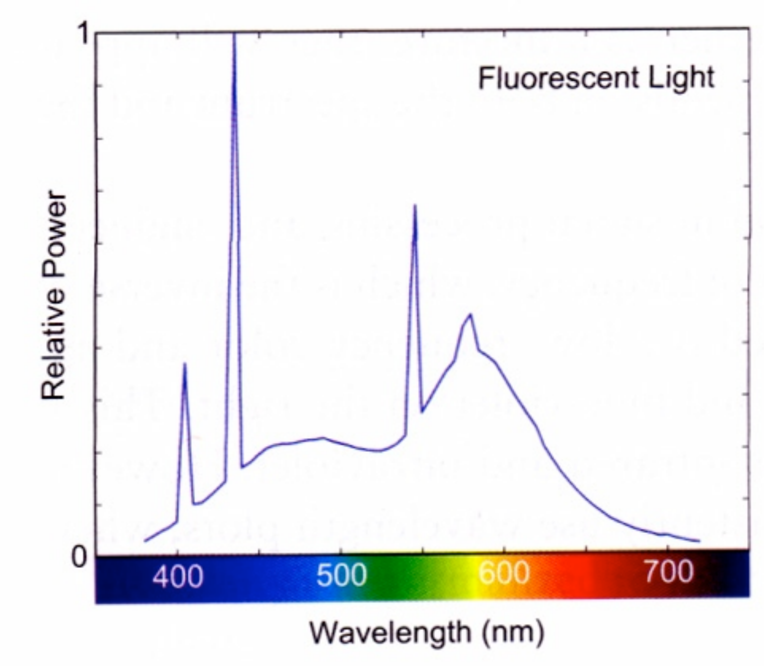
  units: Watts per nanometer (tells you how much power you'll find in a narrow range of wavelengths)

  for color, often use "relative units" when overall intensity is not important



The problem of color science

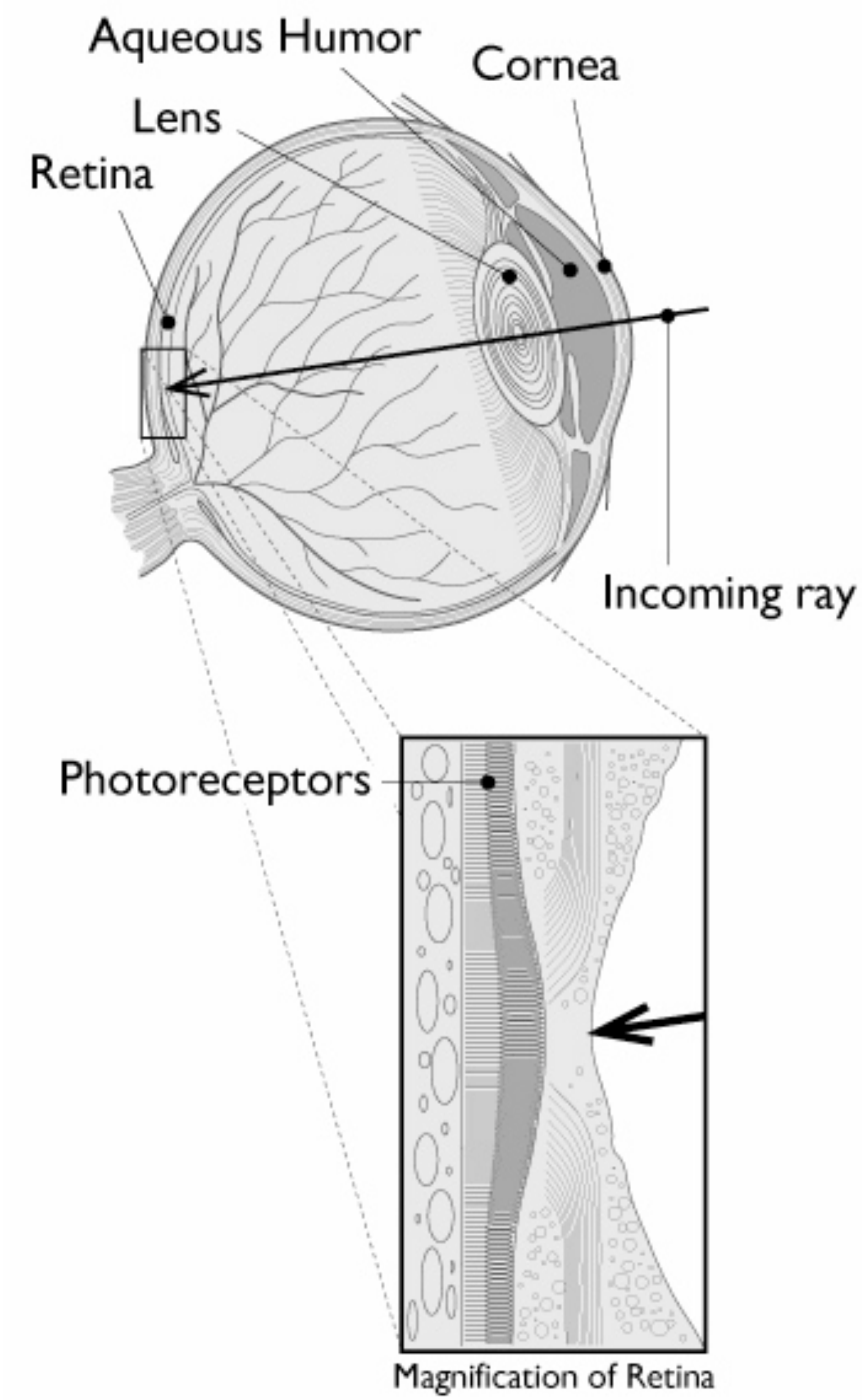
- **Build a model for human color perception**
- **That is, map a *physical light description* to a *perceptual color sensation***



Physical → ? *Perceptual*

[Stone 2003]

The eye as a measurement device



[Greger et al. 1995]

- **We can model the low-level behavior of the eye by thinking of it as a light-measuring machine**

  its optics are much like a camera

  its detection mechanism is also much like a camera

- **Light is measured by the photoreceptors in the retina**

  they respond to visible light

  different types respond to different wavelengths

A simple light detector

- **Produces a scalar value (a number) when photons land on it**

  this value depends strictly on the number of photons detected

  each photon has a probability of being detected that depends on the wavelength

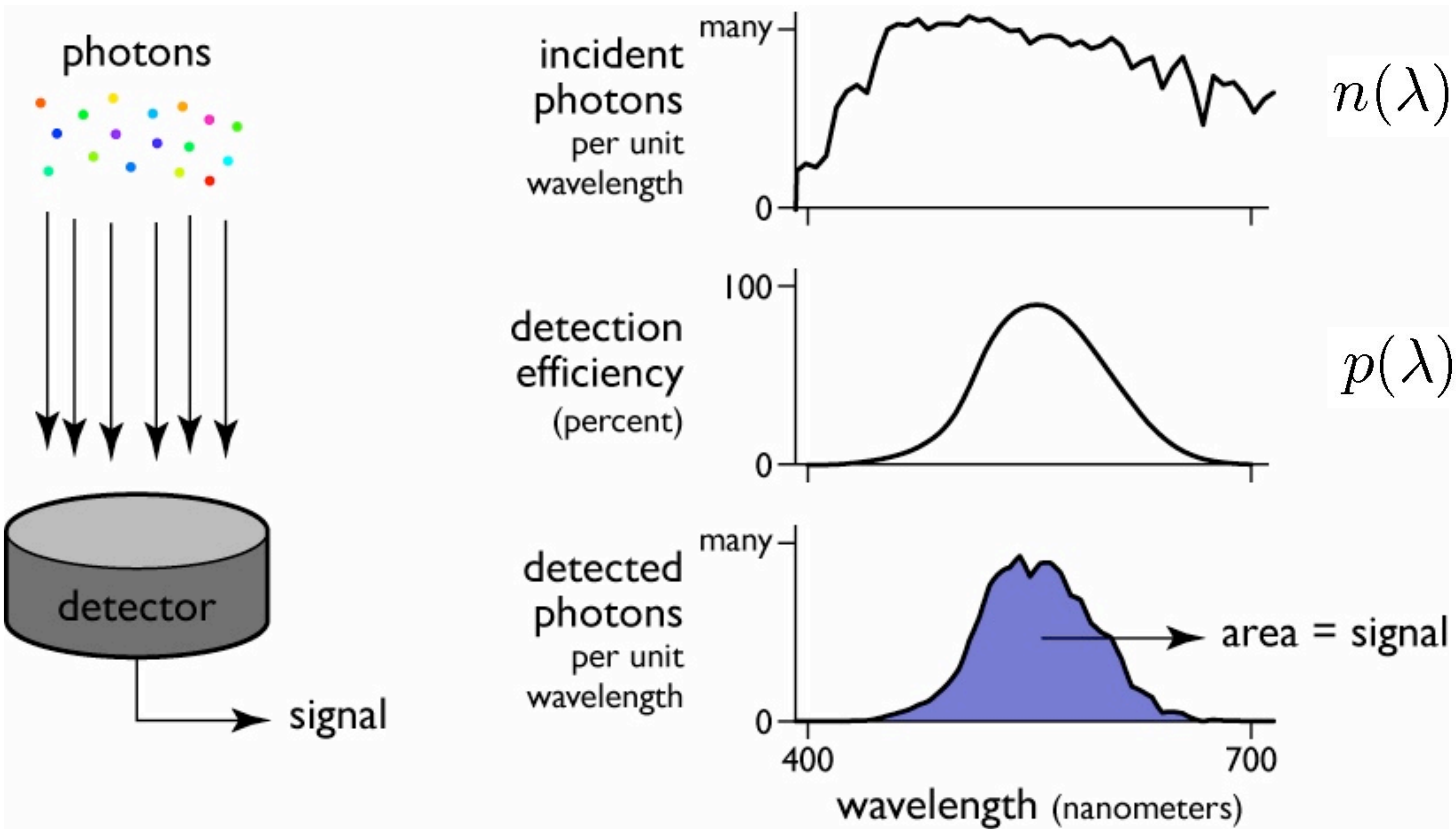
  there is no way to tell the difference between signals caused by light of different wavelengths: there is just a number

- **This model works for many detectors:**

  based on semiconductors (such as in a digital camera)

  based on visual photopigments (such as in human eyes)

A simple light detector



$$X = \int n(\lambda)p(\lambda)\,d\lambda$$

Light detection math

- **Same math carries over to power distributions**

  spectum entering the detector has its spectral power distribution (SPD), $s(\lambda)$

  detector has its *spectral sensitivity* or *spectral response*, $r(\lambda)$

$$X = \int s(\lambda) r(\lambda) \, d\lambda$$

measured signal

detector's sensitivity

input spectrum

Light detection math

$$X = \int s(\lambda) r(\lambda) \, d\lambda \qquad \text{or} \qquad X = s \cdot r$$

- **If we think of *s* and *r* as vectors, this operation is a dot product (aka inner product)**

  in fact, the computation is done exactly this way, using sampled representations of the spectra.

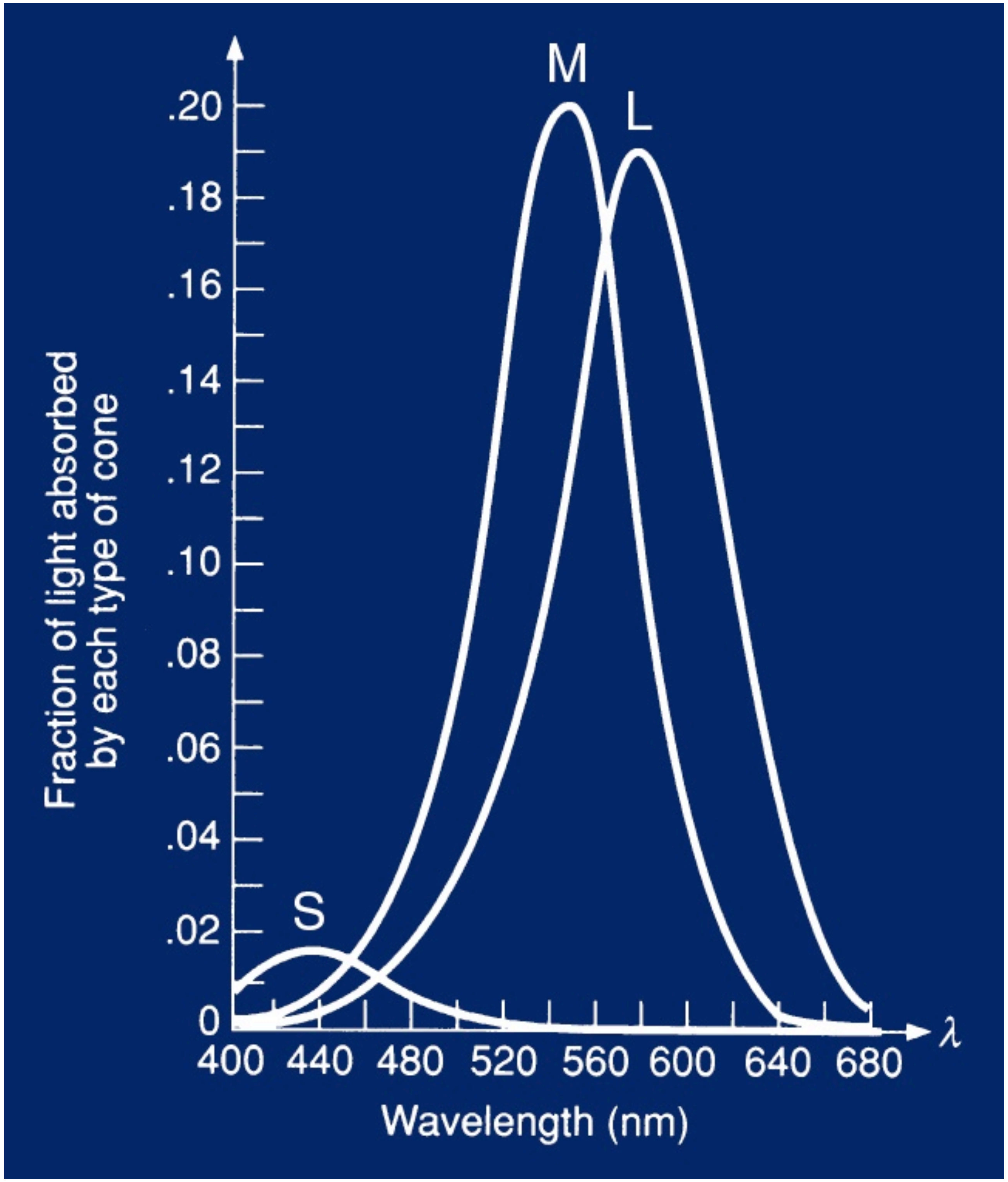
  let λ_i be regularly spaced sample points $\Delta\lambda$ apart; then:

$$\tilde{s}[i] = s(\lambda_i); \tilde{r}[i] = r(\lambda_i)$$

  this sum is very clearly a dot product

$$\int s(\lambda) r(\lambda) \, d\lambda \approx \sum_i \tilde{s}[i] \tilde{r}[i] \, \Delta\lambda$$

Cone Responses



- **S,M,L cones have broadband spectral sensitivity**
- **S,M,L neural response is integrated w.r.t. λ**

  we'll call the response functions

  r_S, r_M, r_L
- **Results in a trichromatic visual system**
- **S, M, and L are *tristimulus values***

[source unknown]

Cone responses to a spectrum *s*

$$S = \int r_S(\lambda) s(\lambda)\, d\lambda = r_S \cdot s$$

$$M = \int r_M(\lambda) s(\lambda)\, d\lambda = r_M \cdot s$$

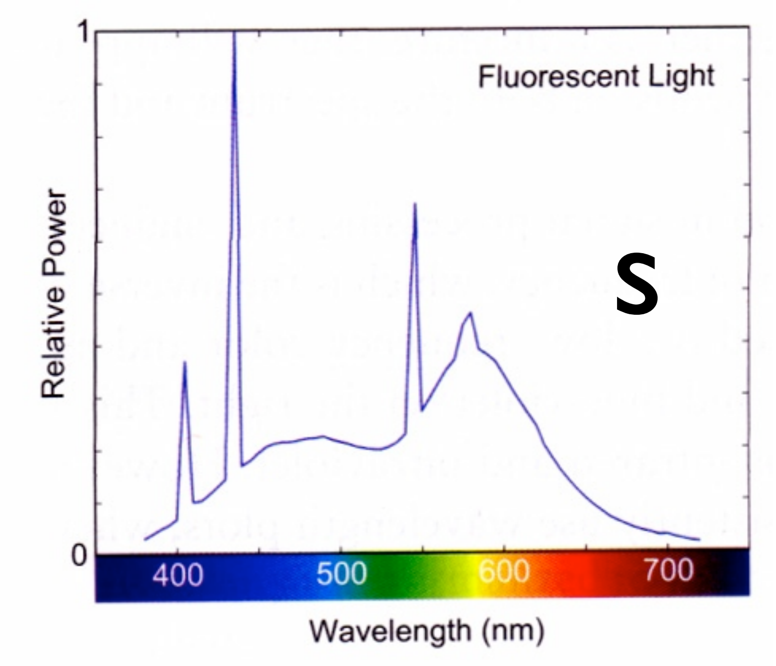
$$L = \int r_L(\lambda) s(\lambda)\, d\lambda = r_L \cdot s$$

Colorimetry: an answer to the problem

- **Wanted to map a *physical light description* to a *perceptual color sensation***
- **Basic solution was known and standardized by 1930**

  Though not quite in this form—more on that in a bit

[Stone 2003]



s

$$S = r_S \cdot s$$
$$M = r_M \cdot s$$
$$L = r_L \cdot s$$

Physical → *Perceptual*

Basic fact of colorimetry

- **Take a spectrum (which is a function)**
- **Eye produces three numbers**
- **This throws away a lot of information!**

  Quite possible to have two different spectra that have the same S, M, L tristimulus values

  Two such spectra are *metamers*

Pseudo-geometric interpretation

- **A dot product is a projection**
- **We are projecting a high dimensional vector (a spectrum) onto three vectors**

  differences that are perpendicular to all 3 vectors are not detectable

- **For intuition, we can imagine a 3D analog**

  3D stands in for high-D vectors

  2D stands in for 3D

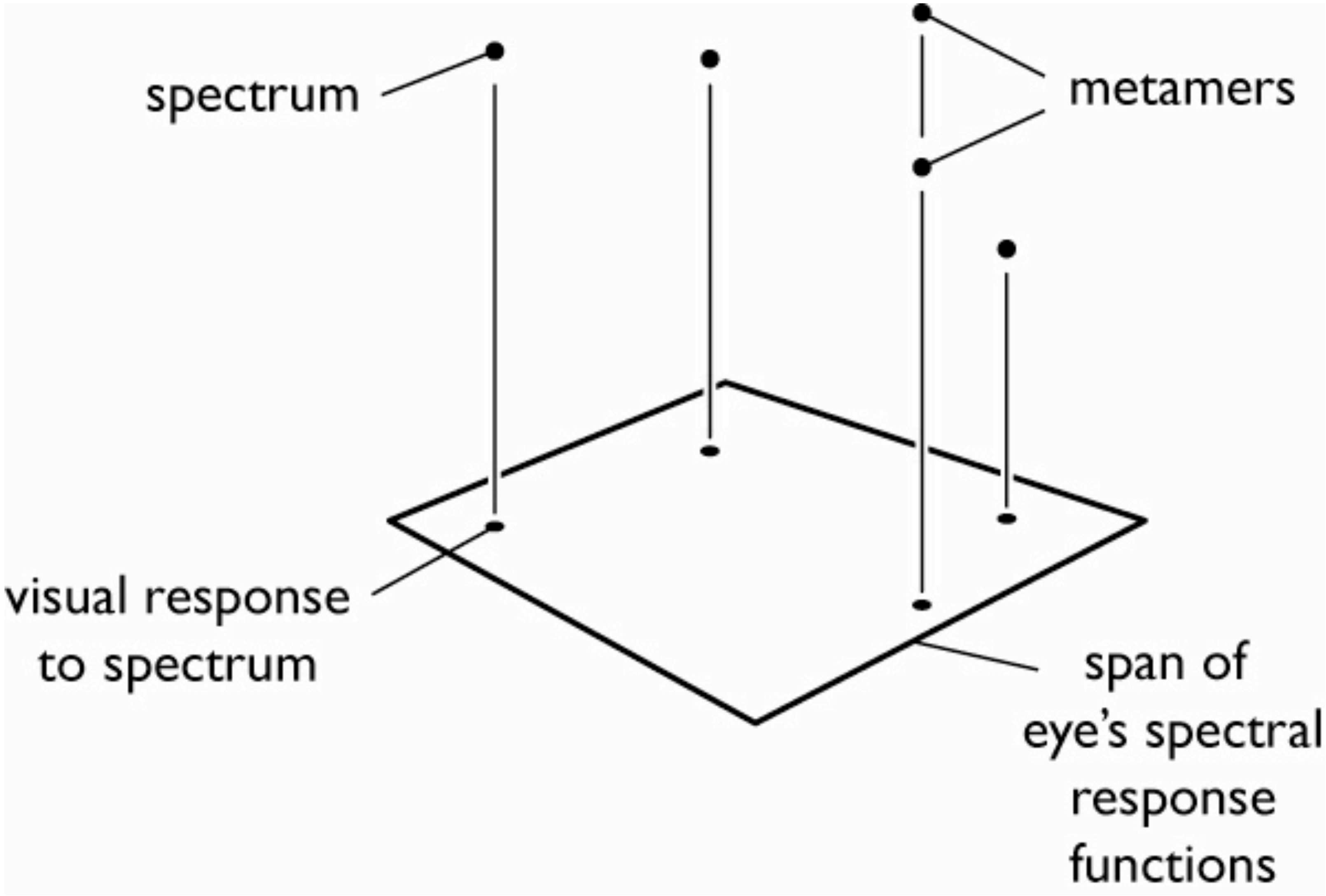
  Then vision is just projection onto a plane

Pseudo-geometric interpretation

- **The information available to the visual system about a spectrum is three values**

  this amounts to a loss of information analogous to projection on a plane

- **Two spectra that produce the same response are metamers**



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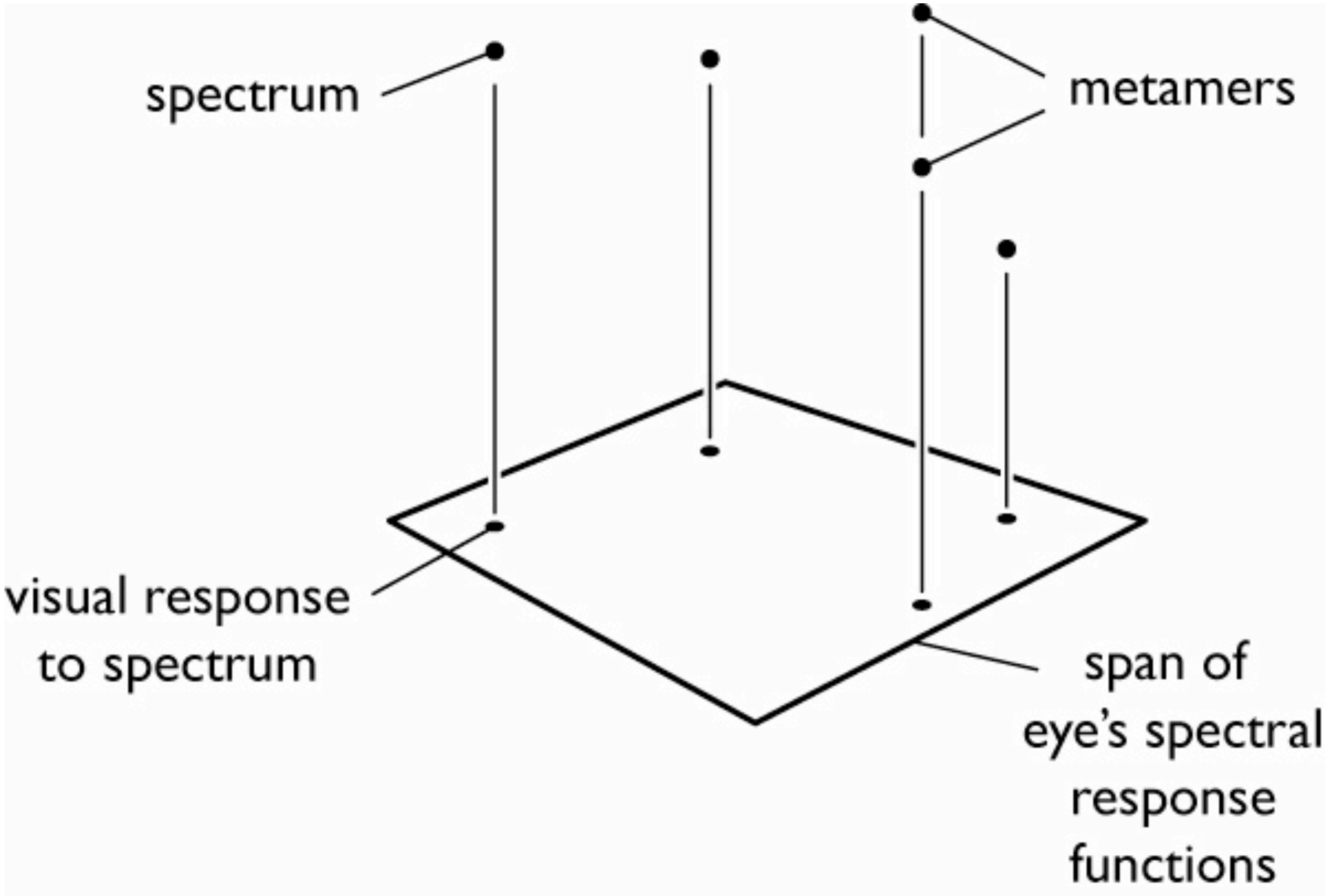


Questions?

Basic colorimetric concepts

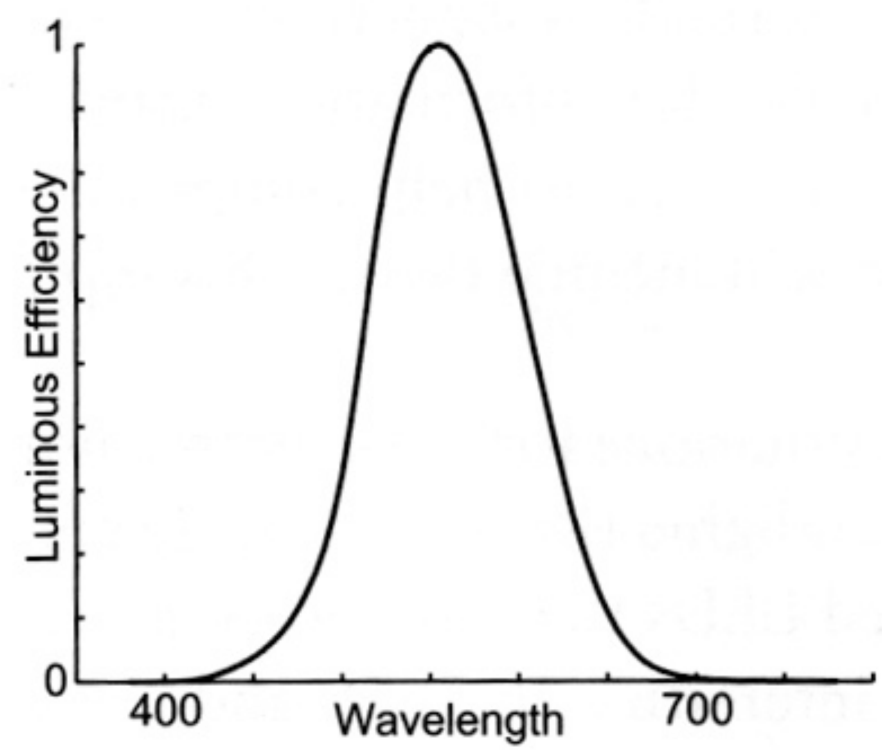
- **Luminance**

  the overall magnitude of the the visual response to a spectrum (independent of its color)

  corresponds to the everyday concept "brightness"

  determined by product of SPD with the *luminous efficiency function* V_λ that describes the eye's overall ability to detect light at each wavelength

  e.g. lamps are optimized to improve their luminous efficiency (tungsten vs. fluorescent vs. sodium vapor)



[Stone 2003]

Luminance, mathematically

- **Y just has another response curve (like *S*, *M*, and *L*)**

$$Y = r_Y \cdot s$$

  - r_Y is really called "V_λ"

- V_λ **is a linear combination of *S*, *M*, and *L***

  Has to be, since it's derived from cone outputs

More basic colorimetric concepts

- **Chromaticity**

  what's left after luminance is factored out (the color without regard for overall brightness)

  scaling a spectrum up or down leaves chromaticity alone

- **Dominant wavelength**

  many colors can be matched by white plus a spectral color

  correlates to everyday concept "hue"

- **Purity**

  ratio of pure color to white in matching mixture

  correlates to everyday concept "colorfulness" or "saturation"

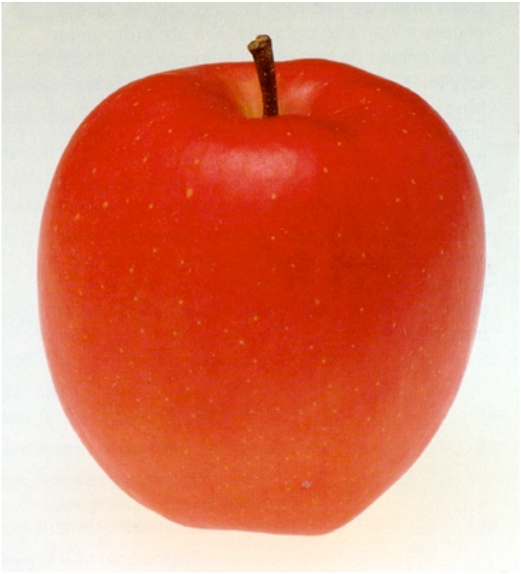
Color reproduction

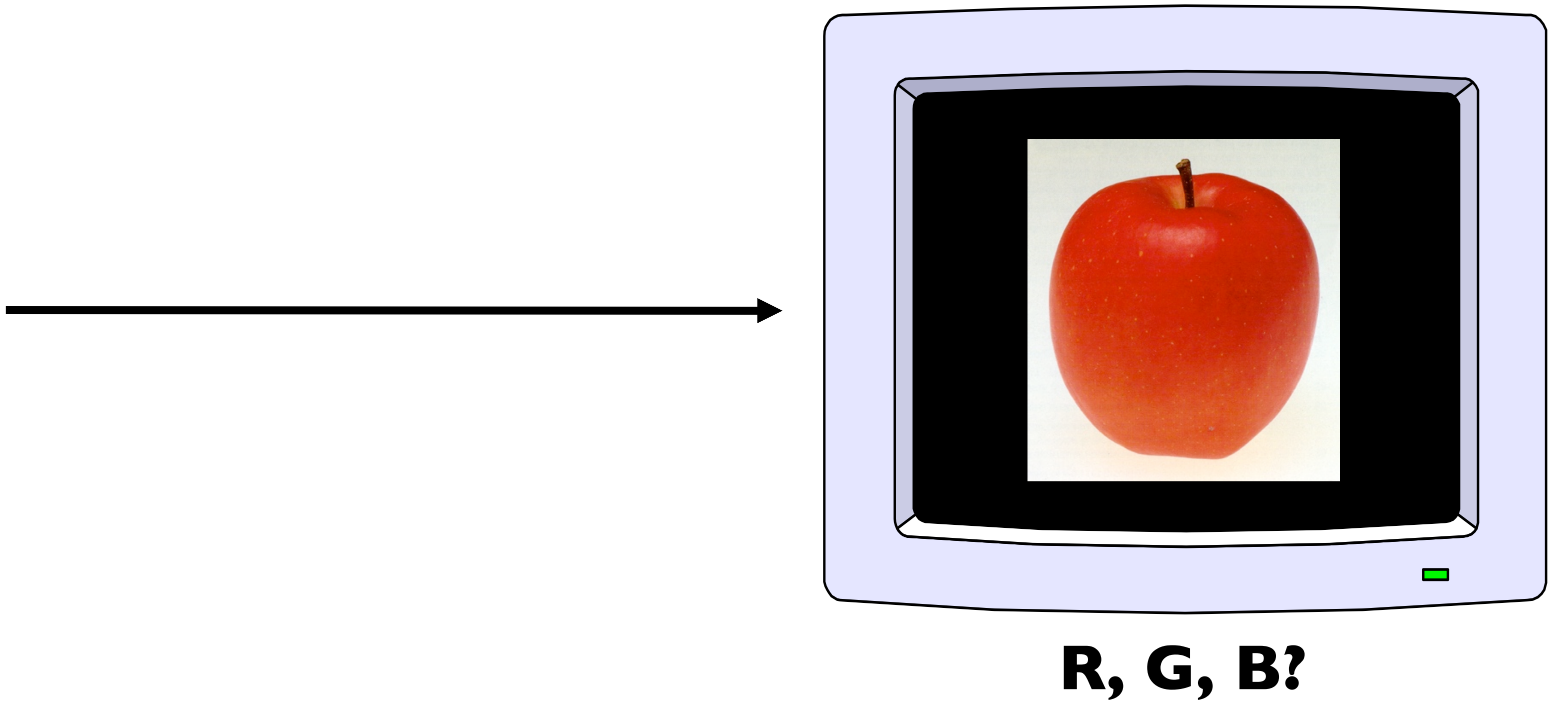
- **Have a spectrum *s*; want to match on RGB monitor**

  "match" means it looks the same

  any spectrum that projects to the same point in the visual color space is a good reproduction

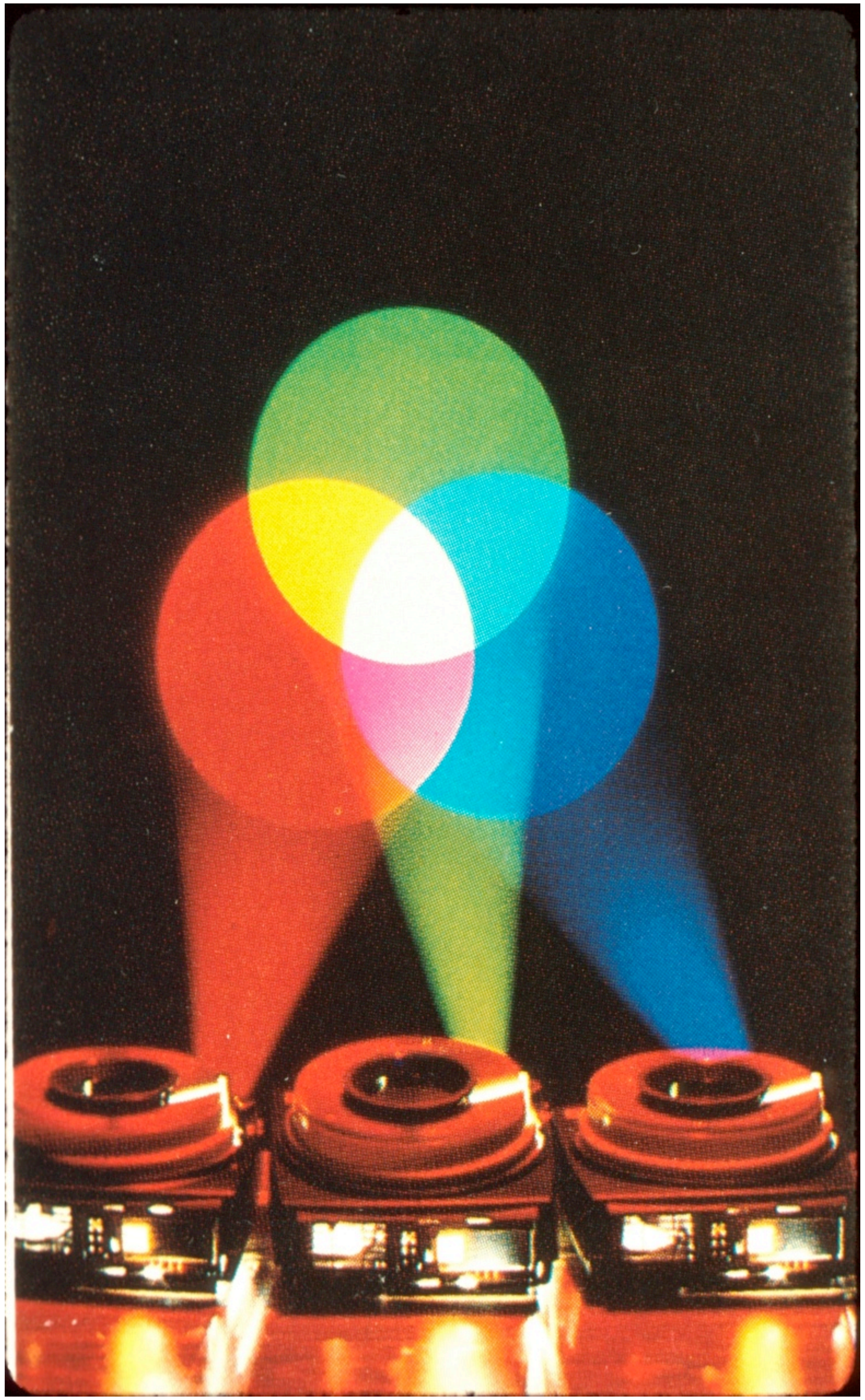
- **Must find a spectrum that the monitor *can* produce that is a metamer of *s***





[cs417—Greenberg]

Additive Color



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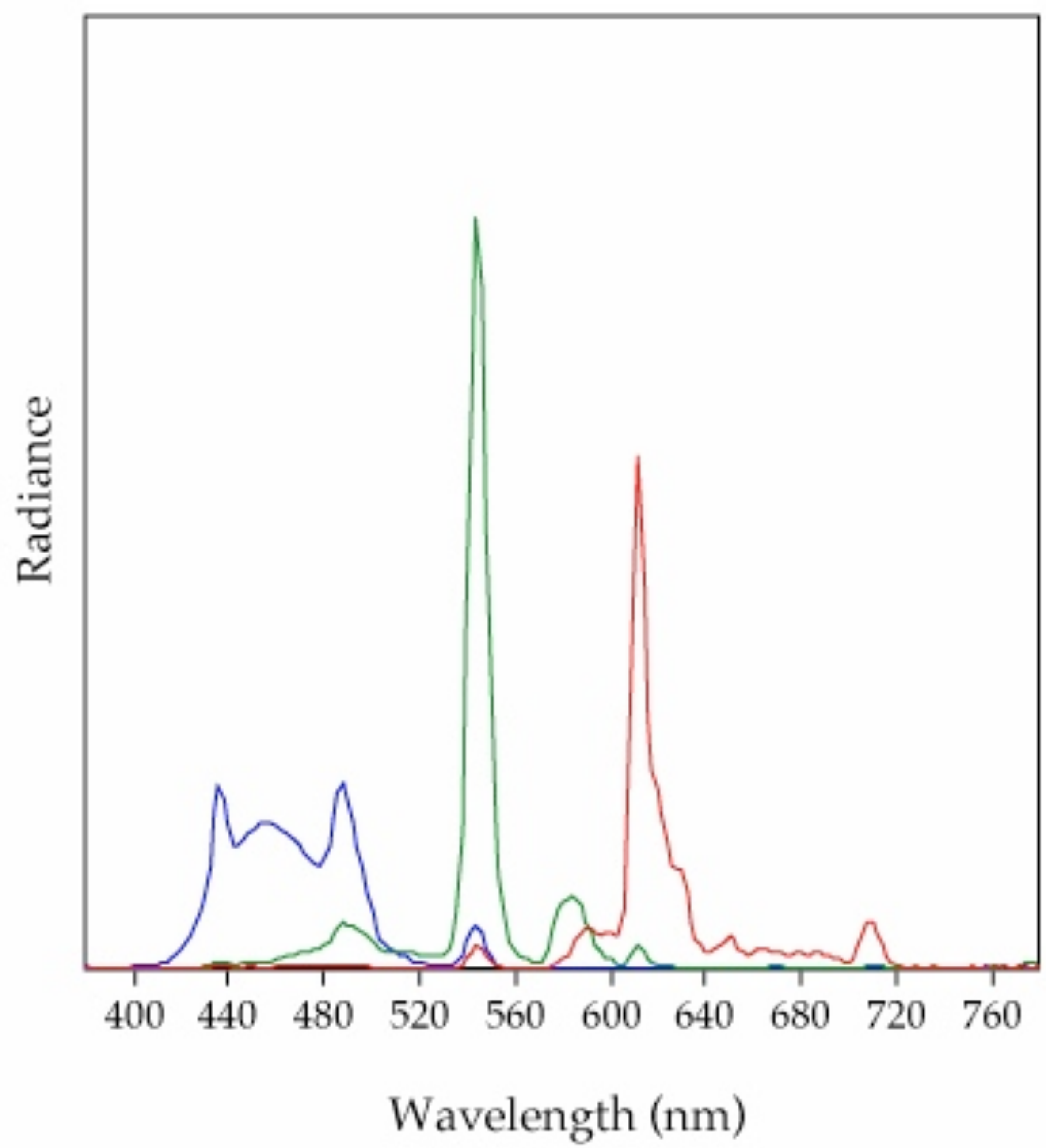
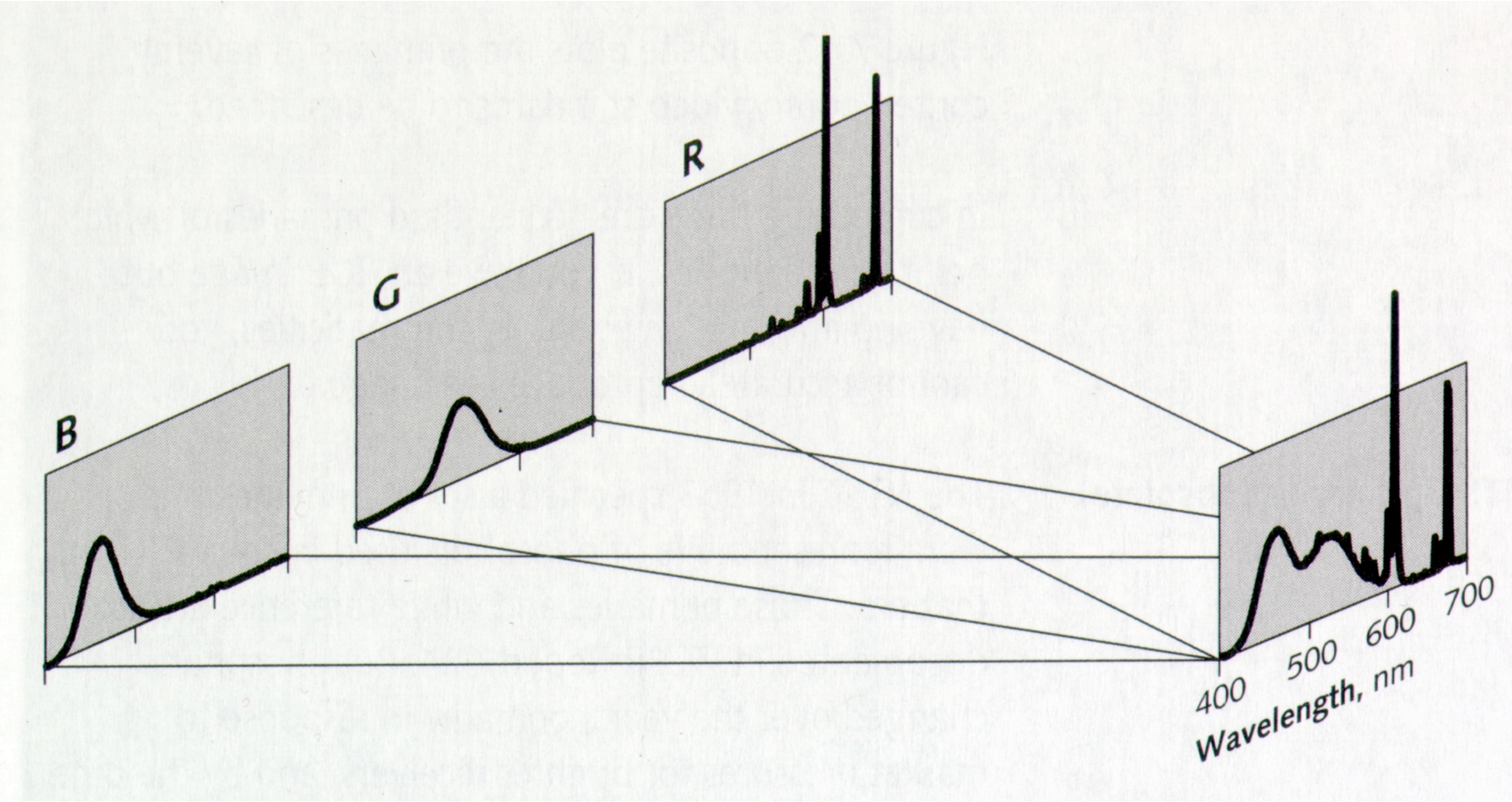
LCD display primaries



[Fairchild 97]

Curves determined by (fluorescent or LED) backlight and filters

Spatial integration



[source unknown]

Color reproduction

- **Say we have a spectrum *s* we want to match on an RGB monitor**

  "match" means it looks the same

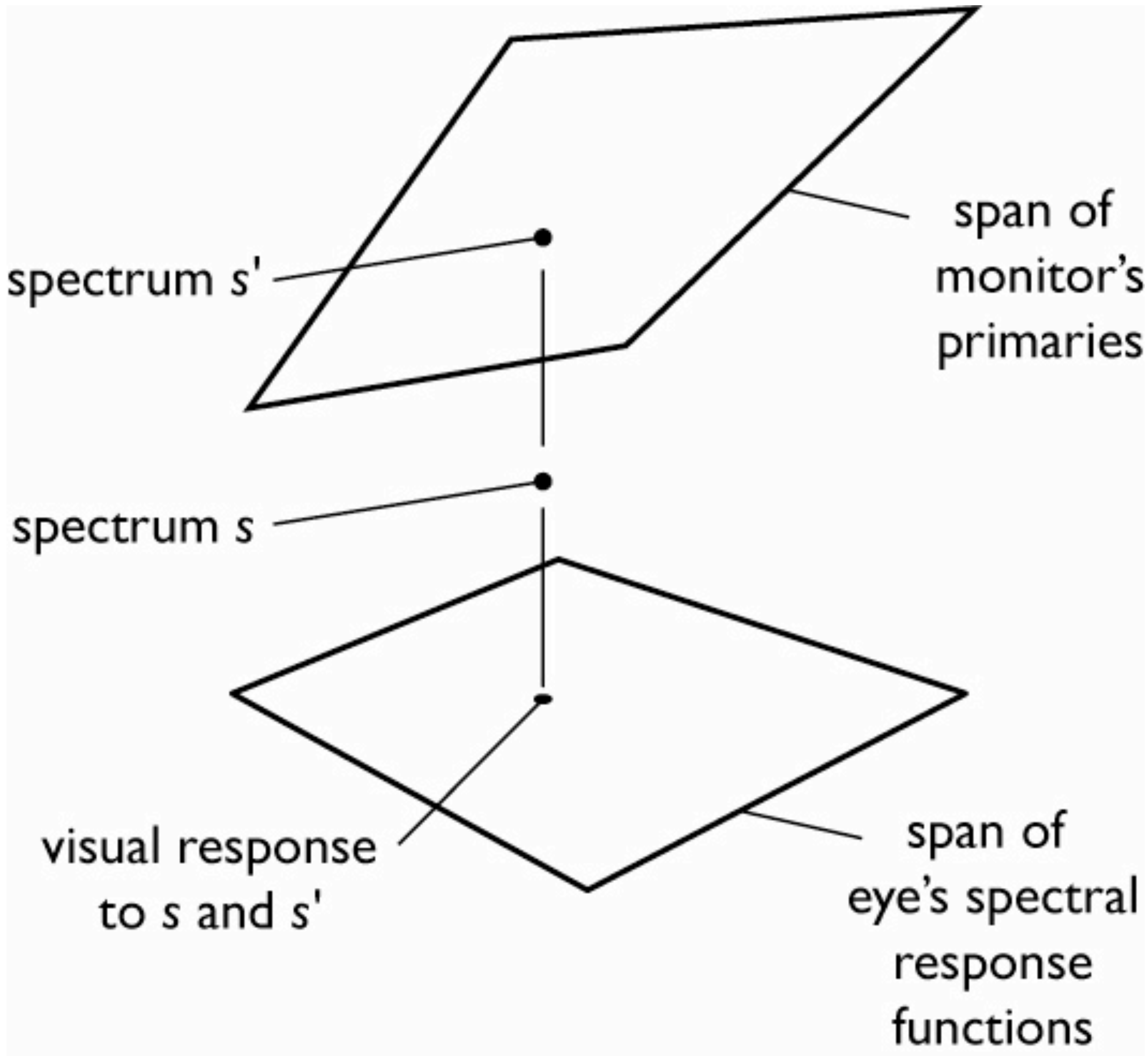
  any spectrum that projects to the same point in the visual color space is a good reproduction

- **So, we want to find a spectrum that the monitor can produce that matches *s***

  that is, we want to display a metamer of *s* on the screen

Color reproduction

- **We want to compute the combination of R, G, B that will project to the same visual response as *s*.**



Color reproduction as linear algebra

- **The projection onto the three response functions can be written in matrix form:**

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} — \; r_S \; — \\ — \; r_M \; — \\ — \; r_L \; — \end{bmatrix} \begin{bmatrix} | \\ s \\ | \end{bmatrix}$$

or,

$$V = M_{SML}\, s.$$

Color reproduction as linear algebra

- **The spectrum that is produced by the monitor for the color signals *R*, *G*, and *B* is:**

$$s_a(\lambda) = Rs_r(\lambda) + Gs_g(\lambda) + Bs_b(\lambda).$$

- **Again the discrete form can be written as a matrix:**

$$\begin{bmatrix} | \\ s_a \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_R & s_G & s_B \\ | & | & | \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} =$$

or,

$$s_a = M_{RGB}\, C.$$

Color reproduction as linear algebra

- **What color do we see when we look at the display?**

  Feed *C* to display

  Display produces s_a

  Eye looks at s_a and produces *V*

$$V = M_{SML} M_{RGB} C$$

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} r_S \cdot s_R & r_S \cdot s_G & r_S \cdot s_B \\ r_M \cdot s_R & r_M \cdot s_G & r_M \cdot s_B \\ r_L \cdot s_R & r_L \cdot s_G & r_L \cdot s_B \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Color reproduction as linear algebra

- **Goal of reproduction: visual response to *s* and s_a is the same:**

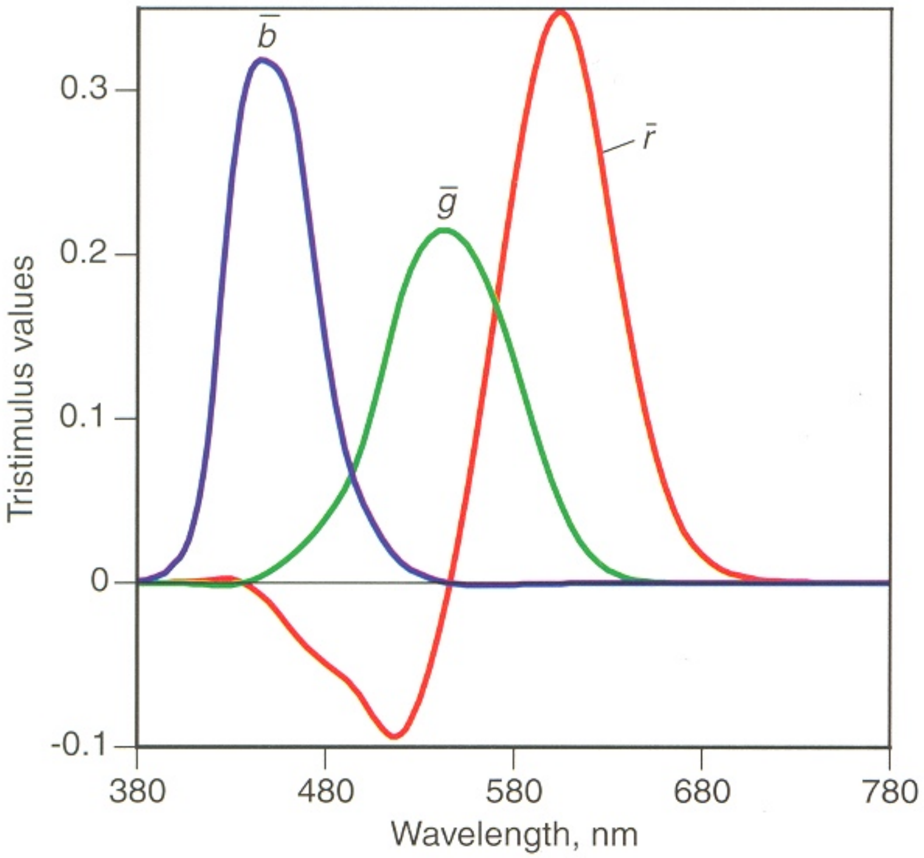
$$M_{SML}\,\tilde{s} = M_{SML}\,\tilde{s}_a.$$

- **Substituting in the expression for s_a,**

$$M_{SML}\,\tilde{s} = M_{SML} M_{RGB}\,C$$

$$C = \underbrace{(M_{SML} M_{RGB})^{-1} M_{SML}}\,\tilde{s}$$

color matching matrix for RGB



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.

[source unknown]

Recap

- **We now know how to match any color from the real world on a display**
- **We don't need to know the whole spectrum, only the projections onto S, M, and L response functions**
- **There is then a simple linear procedure to work out the combination of any 3 primaries to match the color**

Recap

- **We now know how to match any color from the real world on a display**
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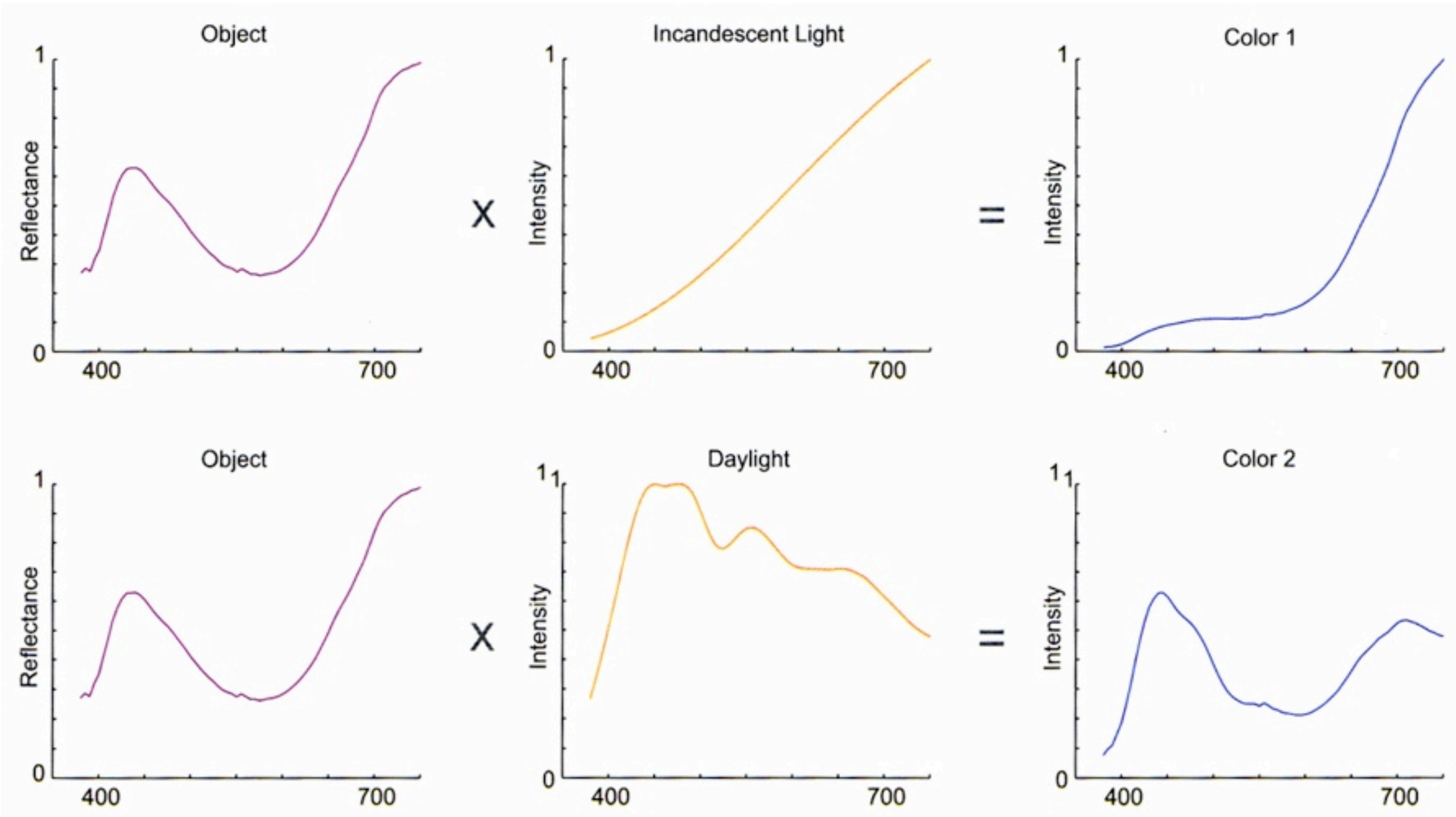
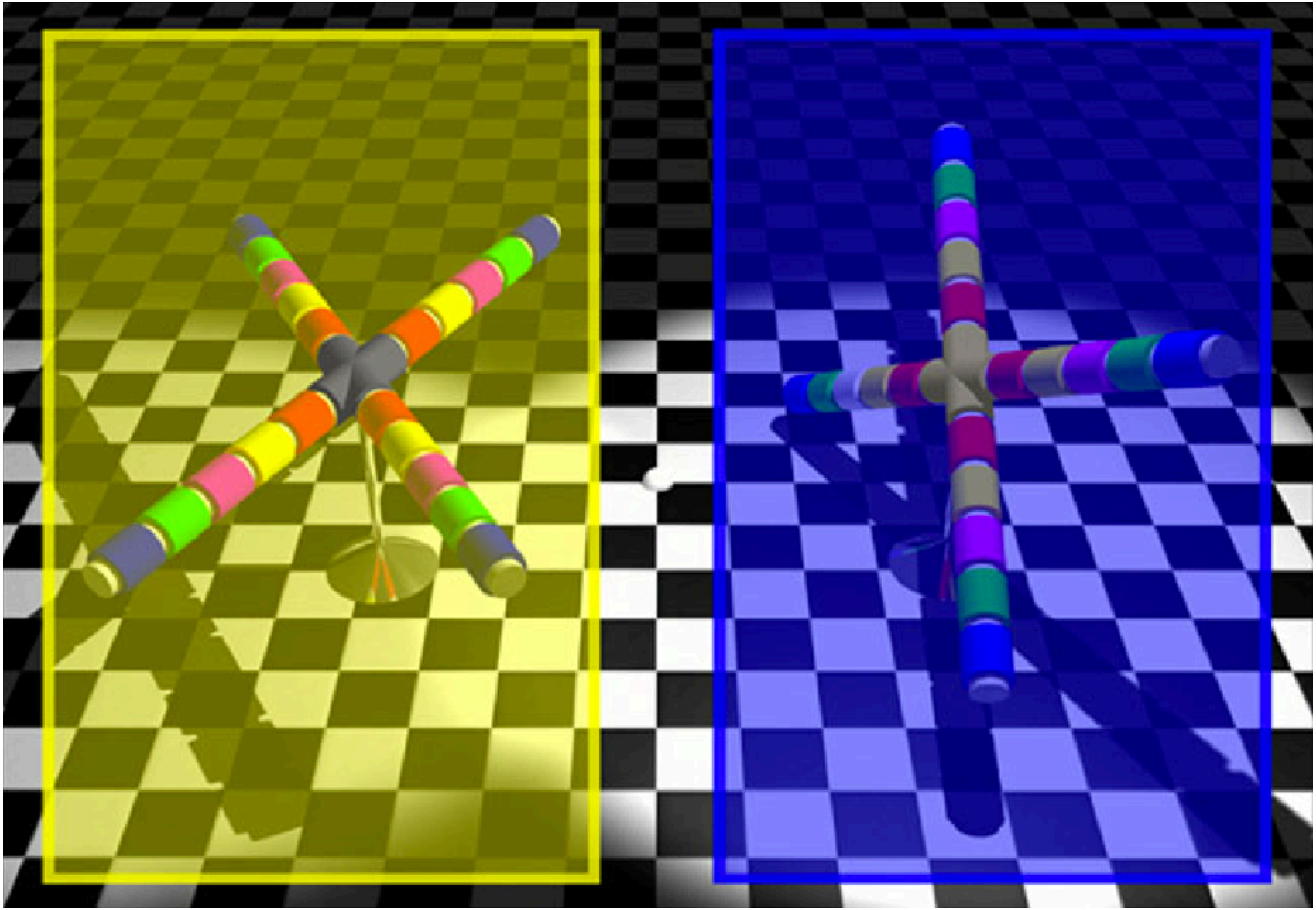
Questions?

Reflection from colored surface



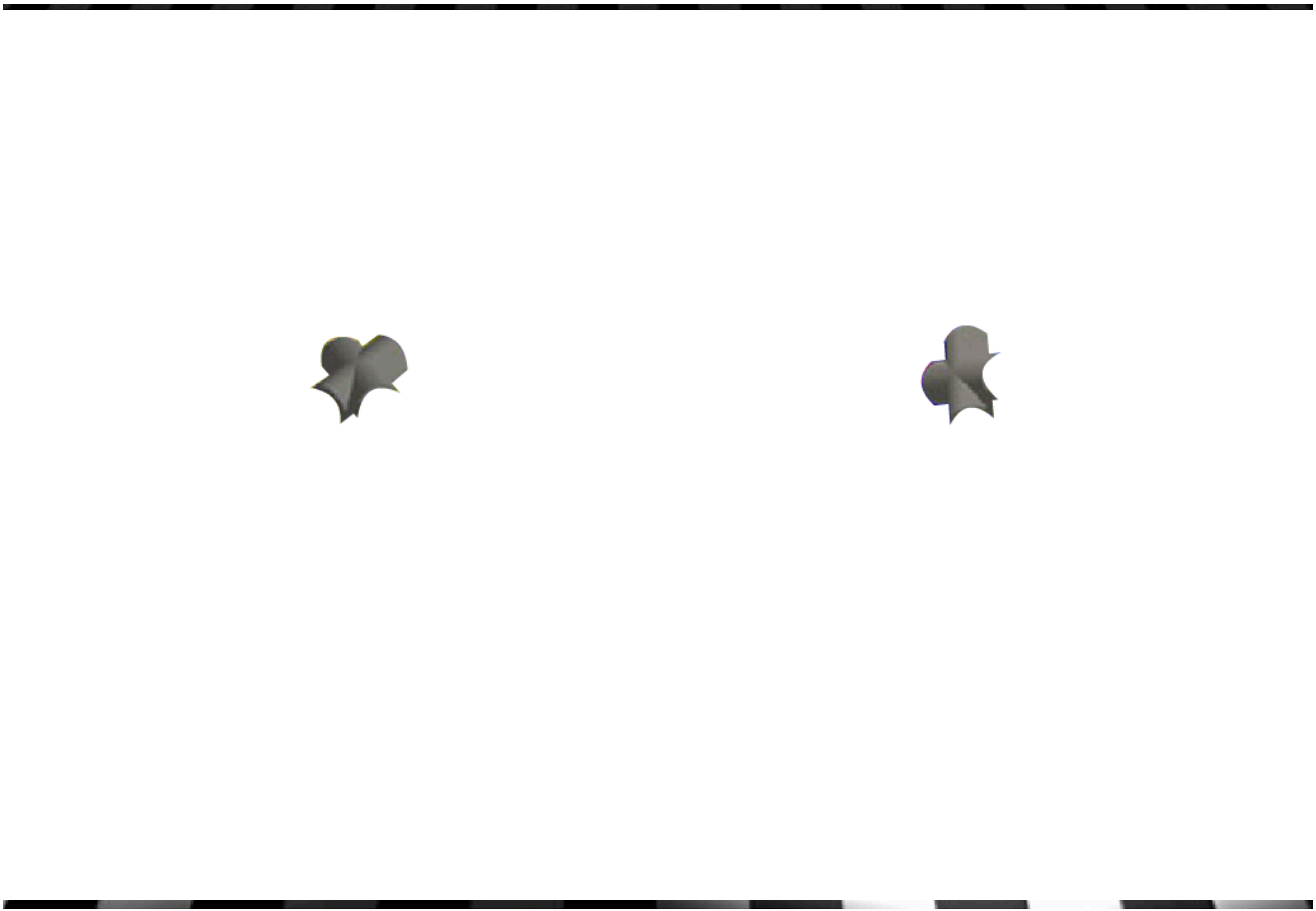
[Stone 2003]

Color constancy



R. Beau Lotto

Color constancy



R. Beau Lotto

Chromatic adaptation

- **Objects have different spectra under different illuminants**

  …but your brain has no problem recognizing them anyway

- **The human visual system automatically detects the illuminant color and adjusts for it**

  so the same object (usually) looks (roughly) the same color under a wide range of illumination conditions

  this happens at a low level so you don't even notice

- **But color constancy is not perfect**

  …and indeed can't be, with just 3 color receptors

  examples: sweater looks nice with pants in your closet, then looks different once you get out in the daylight

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Questions?

Color spaces

- **Need three numbers to specify a color**

  but what three numbers?

  a *color space* is an answer to this question

- **Stored numbers often map nonlinearly to intensity of primary**

  enables nonuniform quantization (smaller quantization steps in dark)

  common scheme is $R = (n_R/255)^\gamma$

- **Common example: monitor RGB**

  define colors by what *R*, *G*, *B* signals will produce them on your monitor

  (in math, $s = R\mathbf{R} + G\mathbf{G} + B\mathbf{B}$ for some spectra **R**, **G**, **B**)

  device dependent (depends on gamma, phosphors, gains, …)

  if I choose RGB by looking at my monitor and send it to you, you may not see the same color

  also leaves out some colors (limited *gamut*), e.g. vivid yellow

Standard color spaces

- **Standardized RGB (sRGB)**

  makes a particular monitor RGB standard

  standard quantization curve is almost gamma = 2.2

  other color devices simulate that monitor by calibration

  sRGB is usable as an interchange space; widely adopted today

  gamut is still limited

- **Other RGB spaces**

  Adobe RGB (more saturated primaries than sRGB—wider gamut)

A universal color space: XYZ

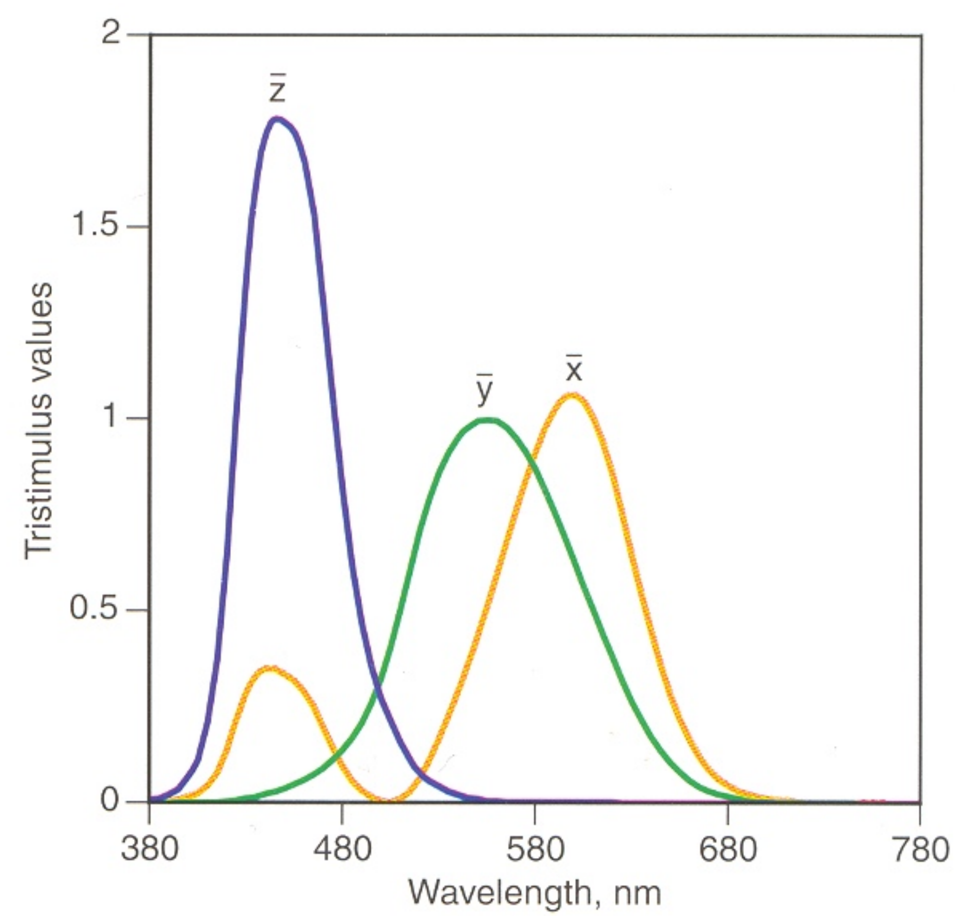
- **Standardized by CIE (*Commission Internationale de l'Eclairage*, the standards organization for color science)**
- **Based on three "imaginary" primaries X, Y, and Z**

(in math, $s = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}$)

imaginary = only realizable by spectra that are negative at some wavelengths

any stimulus can be matched with positive *X*, *Y*, and *Z*

separates out luminance: **X**, **Z** have zero luminance, so *Y* tells you the luminance by itself



The 1931 standard observer, as it is usually shown.

[source unknown]

Separating luminance, chromaticity

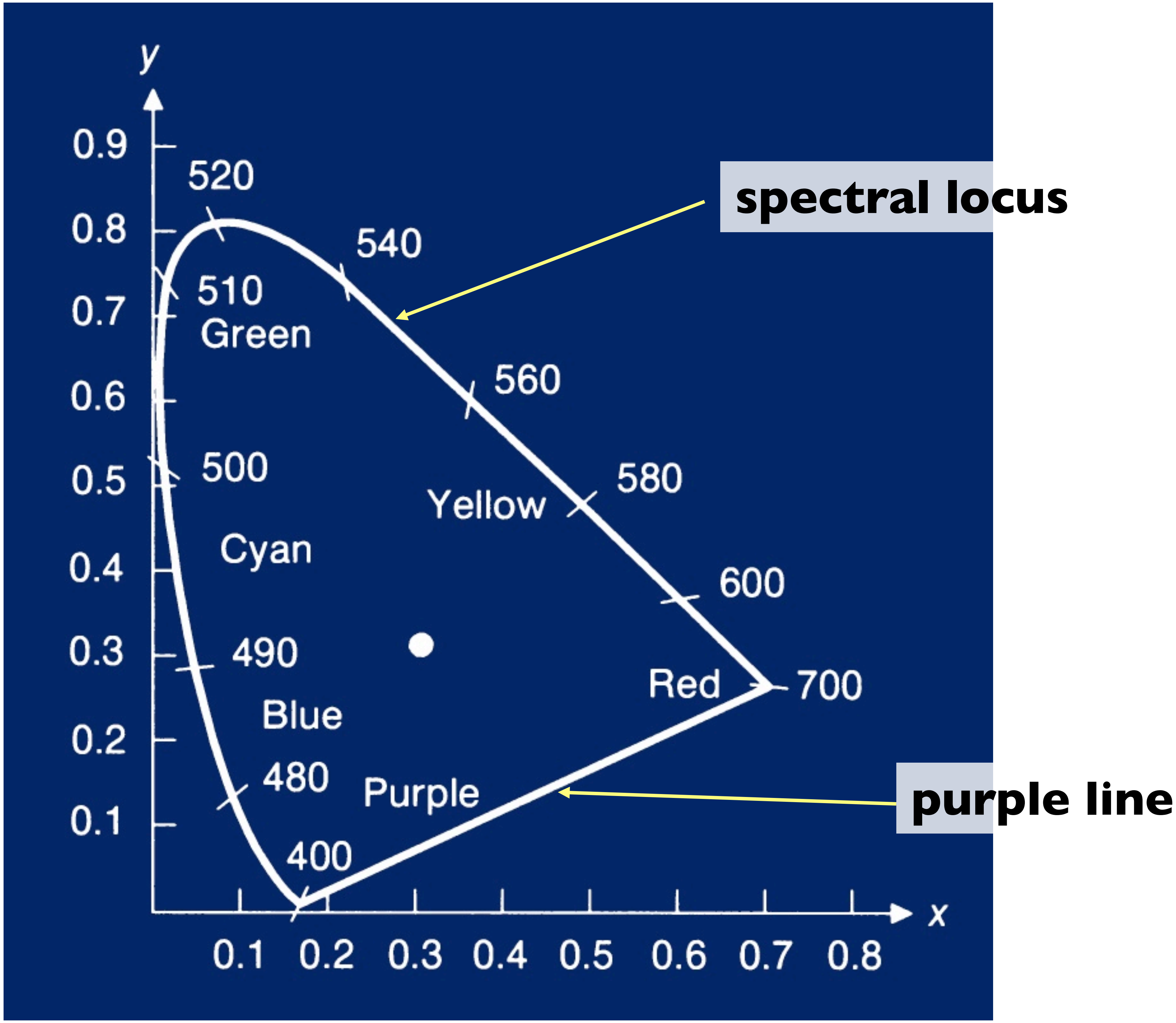
- **Luminance:** Y
- **Chromaticity:** x**,** y**,** z**, defined as**

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

since $x + y + z = 1$, we only need to record two of the three

usually choose x and y, leading to (x, y, Y) coords

Chromaticity Diagram



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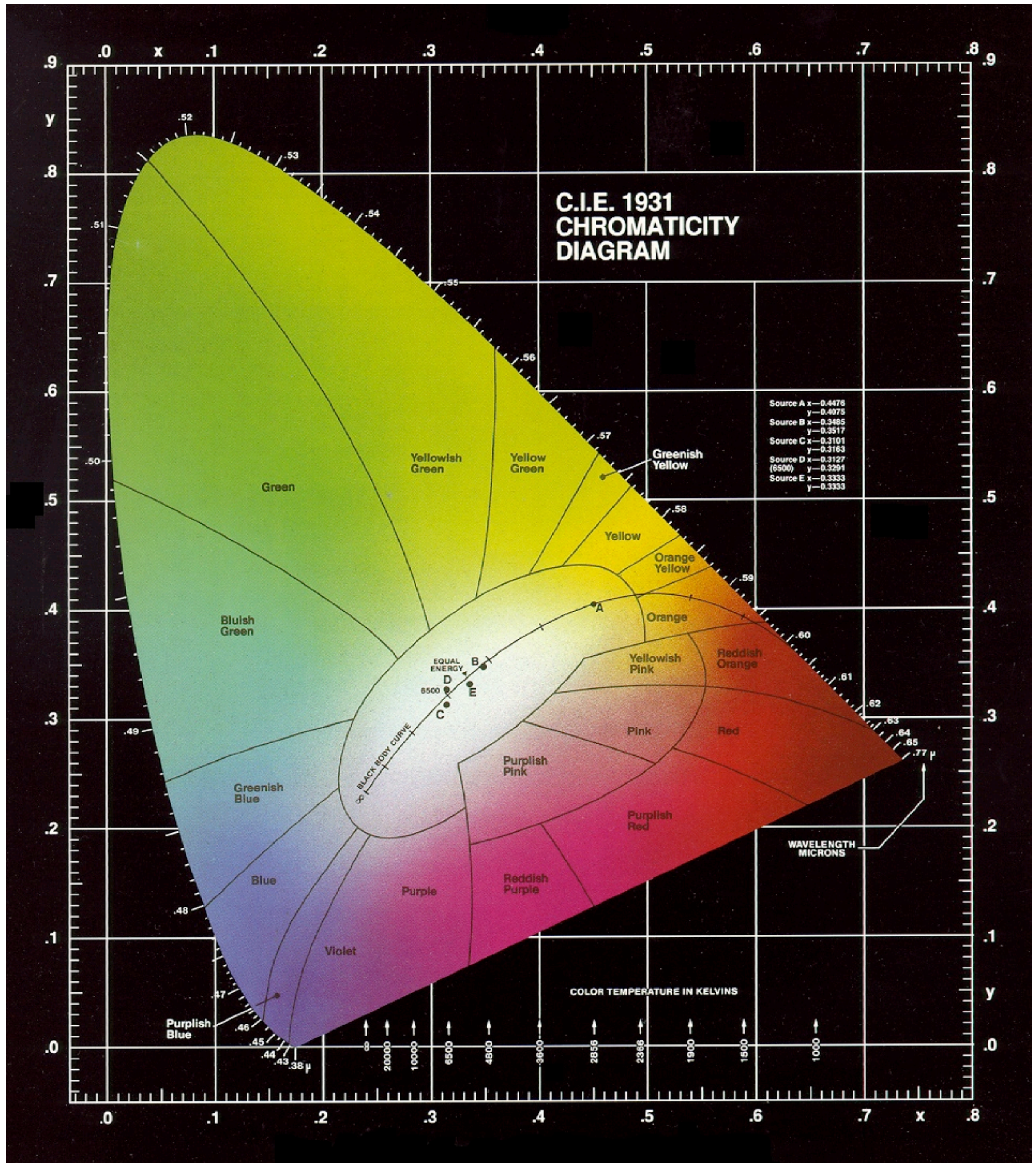
Chromaticity Diagram



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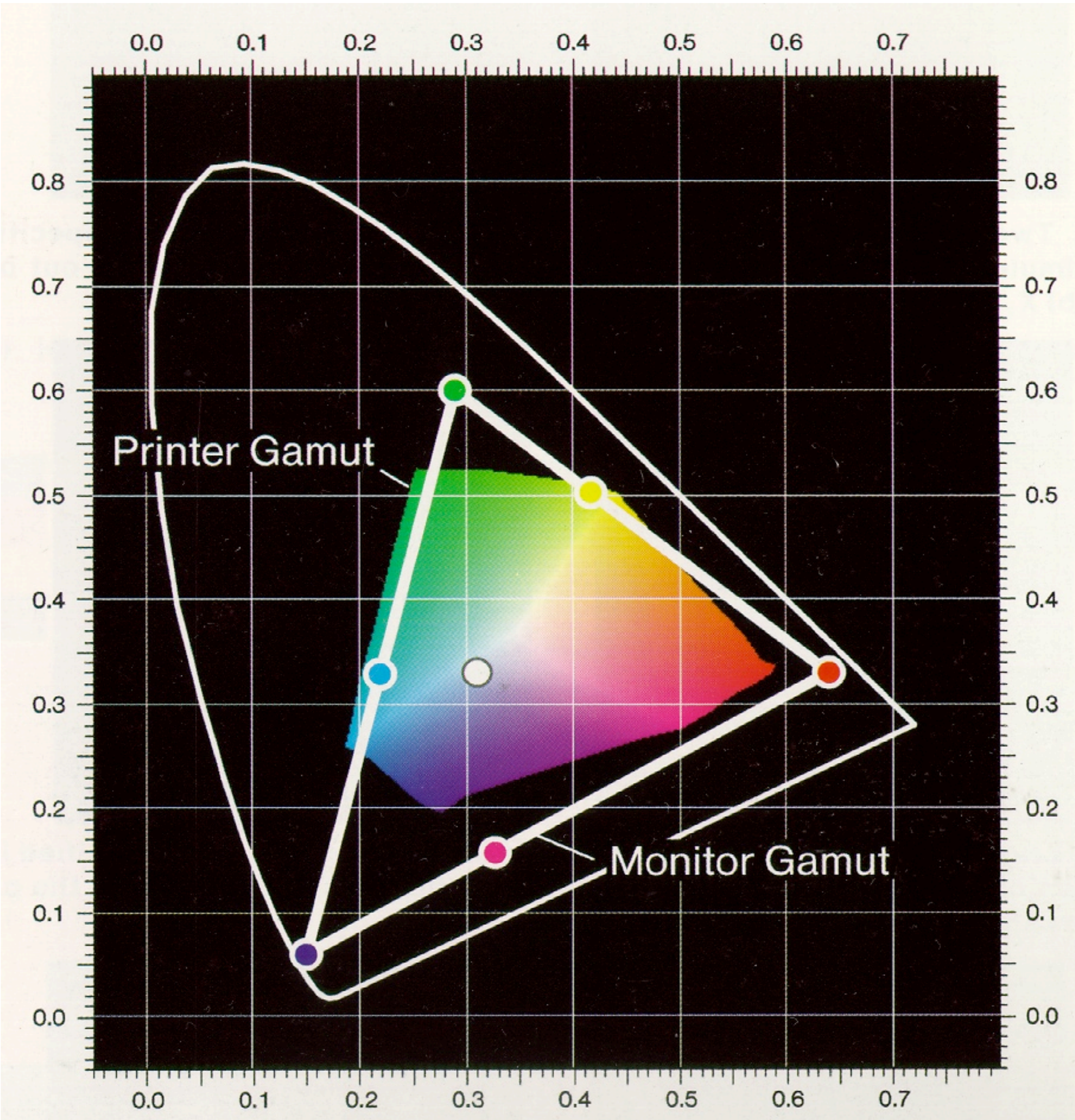
Color Gamuts

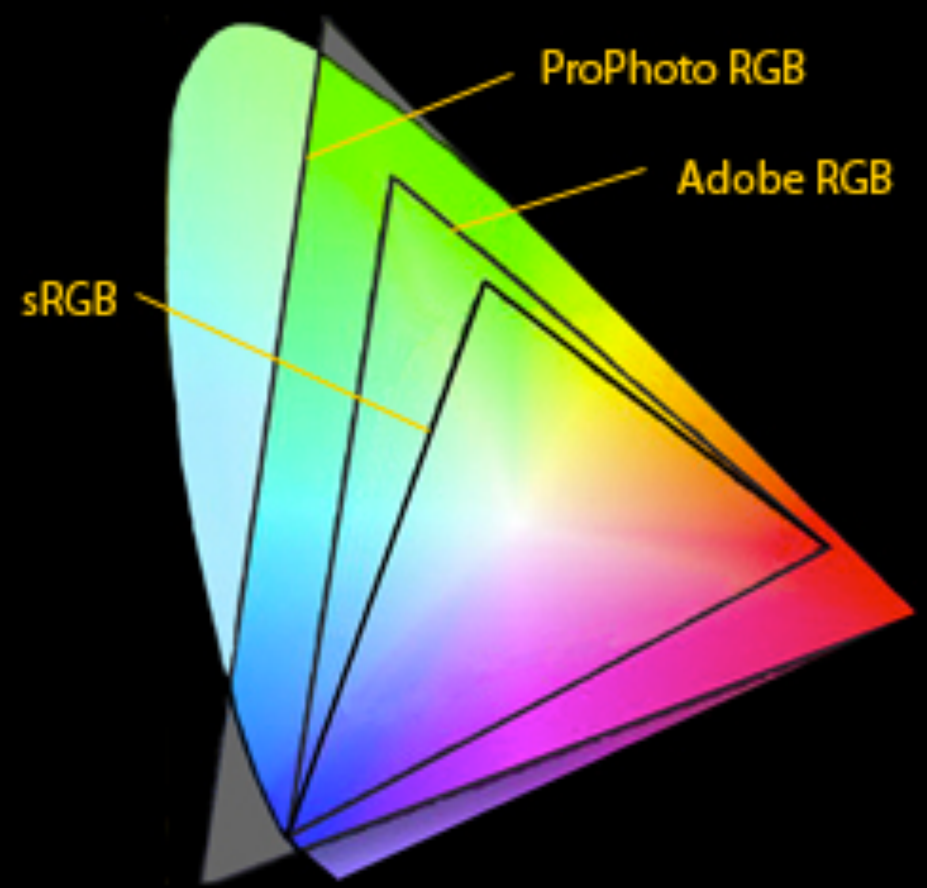


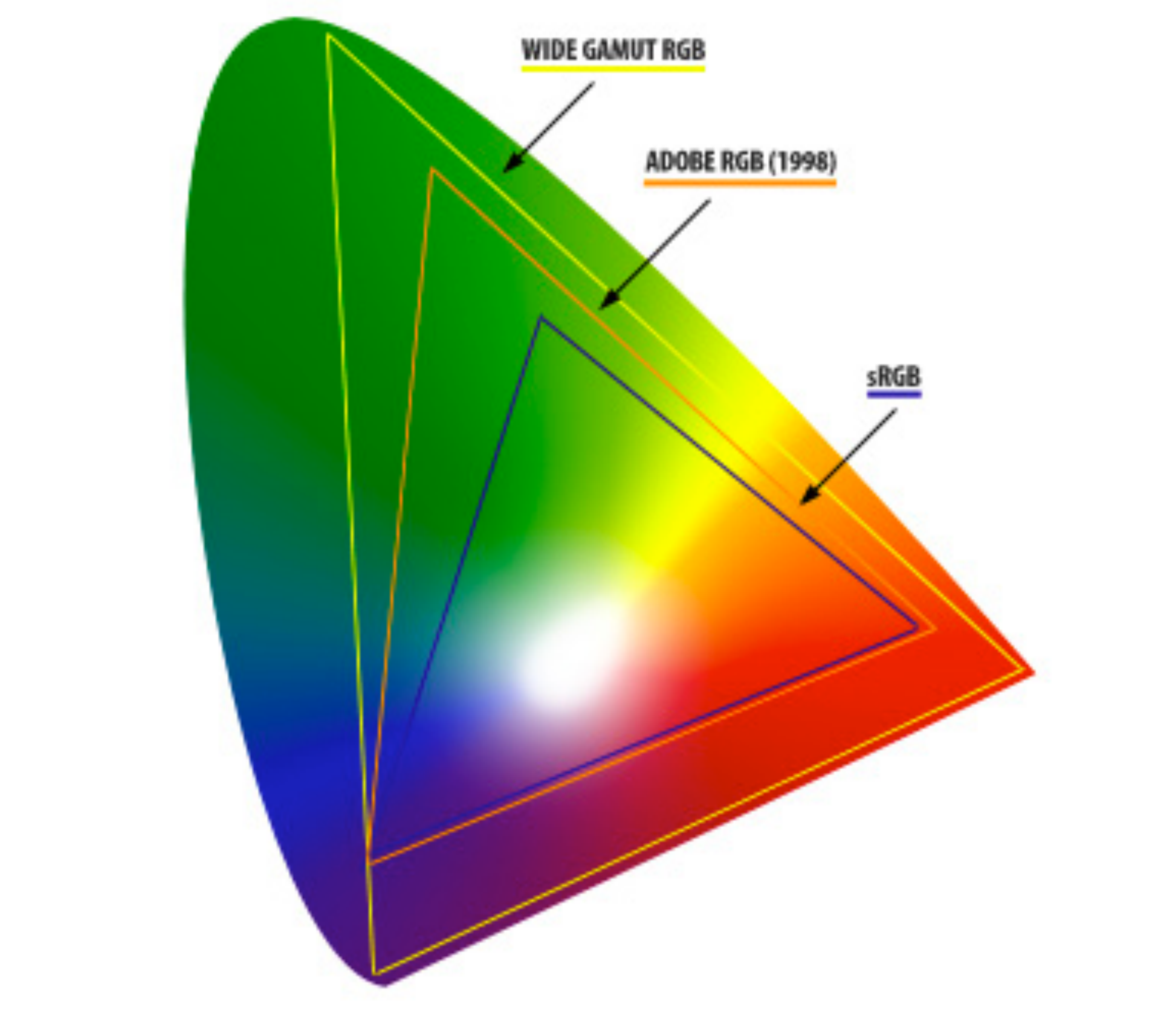
[source unknown]

- **Monitors/printers can't produce all visible colors**
- **Reproduction is limited to a particular domain**
- **For additive color (e.g. monitor) gamut is the triangle defined by the chromaticities of the three primaries.**

RGB limitations

- http://dba.med.sc.edu/price/irf/Adobe_tg/manage/images/gamuts.jpg
- http://www.petrvodnakphotography.com/Articles/ColorSpace.htm





slide by Frédo Durand, MIT

Color sensing

- **Sensor is like eye**

  gives you projection onto a 3D (or >3D) space

  but it is the wrong space!

- **Problems with measured data**

  we have RGB, but not the right RGB

  projection onto sensitivities, not coefficients for primaries (always)

  projection onto wrong space (always in practice)

  results depend strongly on illuminant (help!)

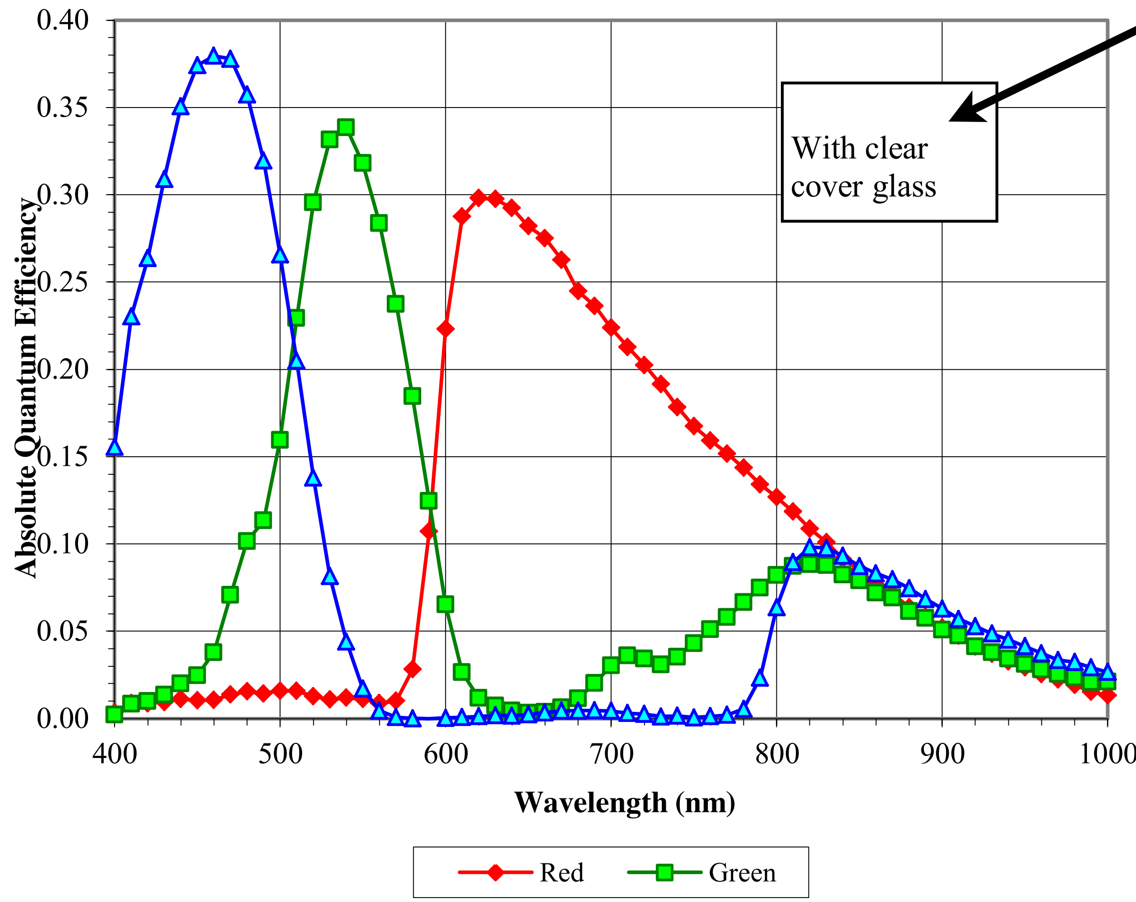
Sensor color properties

- **Like eye, key property is the spectral sensitivity curves**

TRUESENSE imaging, inc.

KAI-2093 Image Sensor

COLOR WITH MICROLENS QUANTUM EFFICIENCY

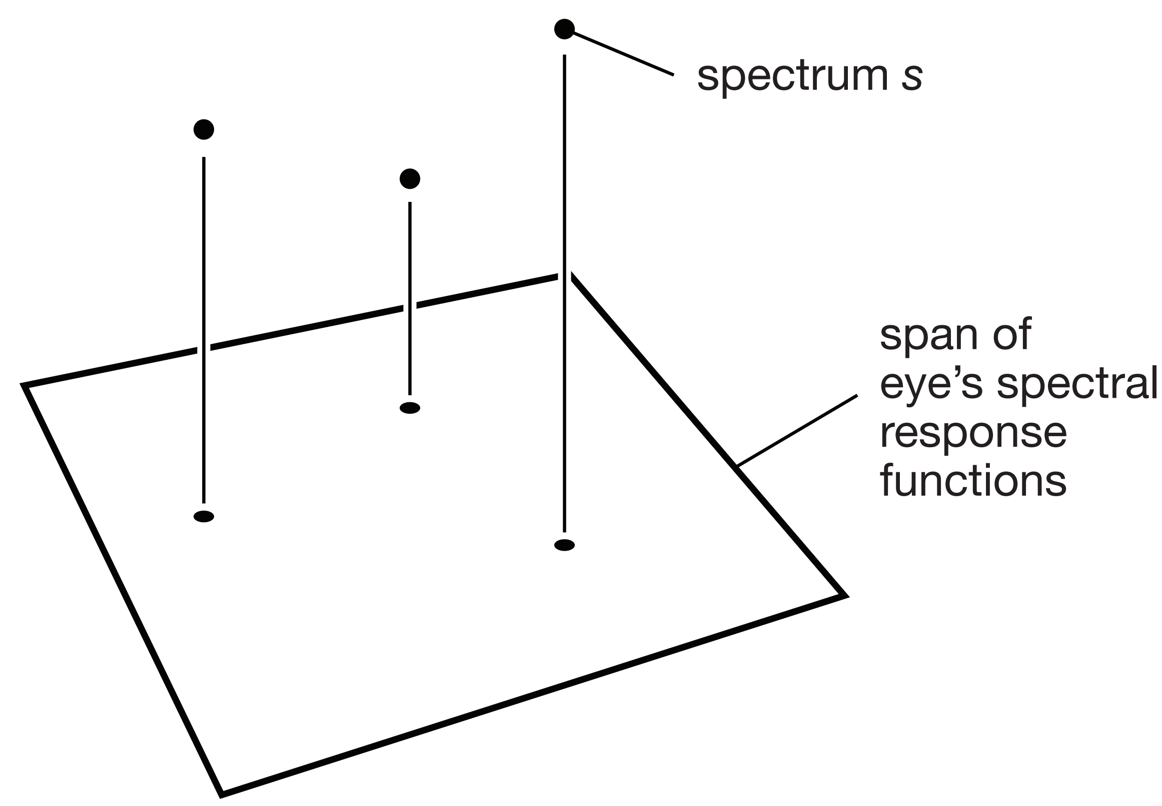


In a real camera, there will be a filter to block infrared

Figure 5: Quantum Efficiency Spectrum for Color Filter Array Sensors

Camera color problem

- **Given camera response, determine corresponding visual response**
- **This guess has to involve assumptions about which reflectance spectra are more likely**
- **Mathematical approach: assume spectra in fixed subspace**
- **Or, more often, just derive a transformation empirically**



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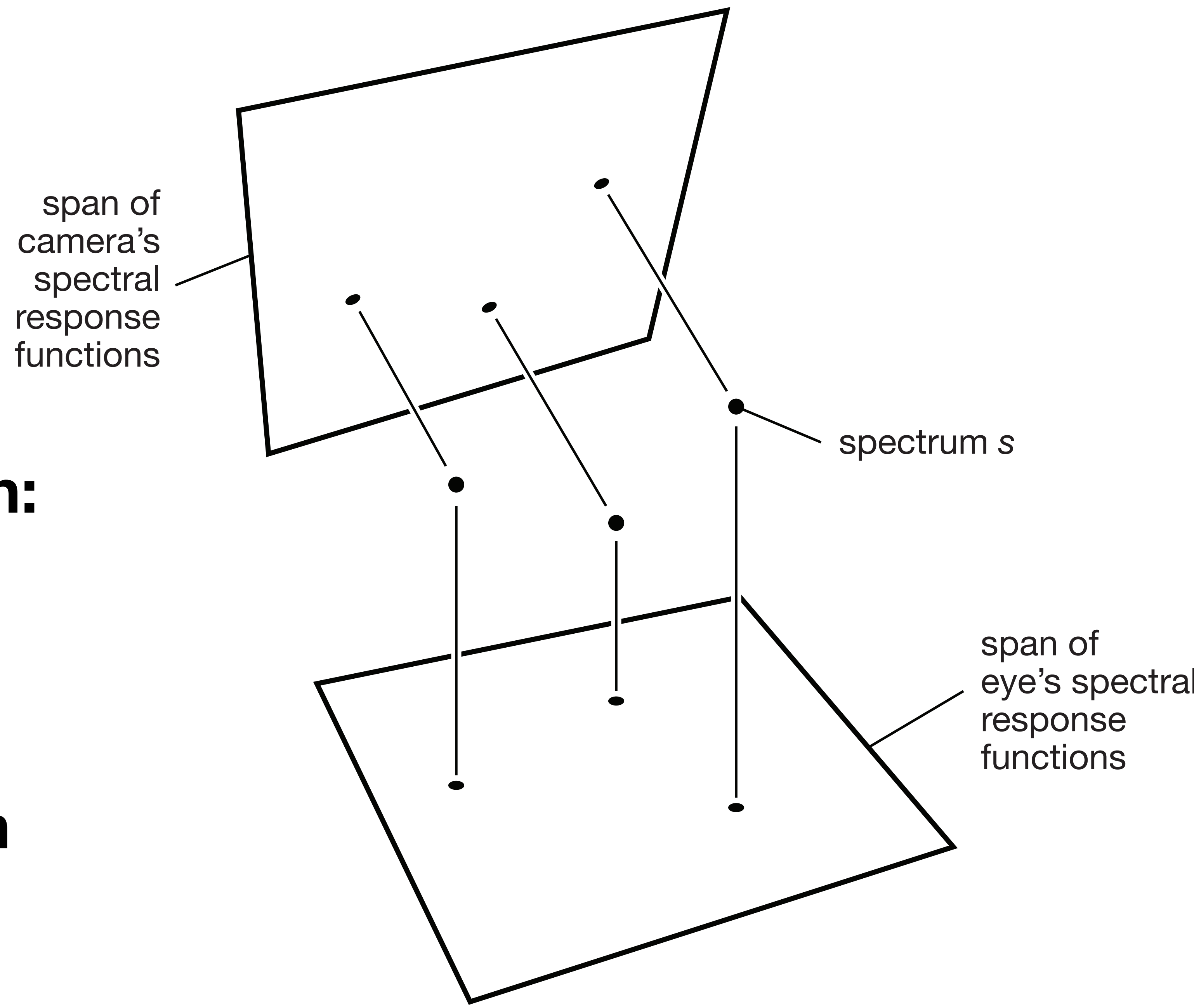

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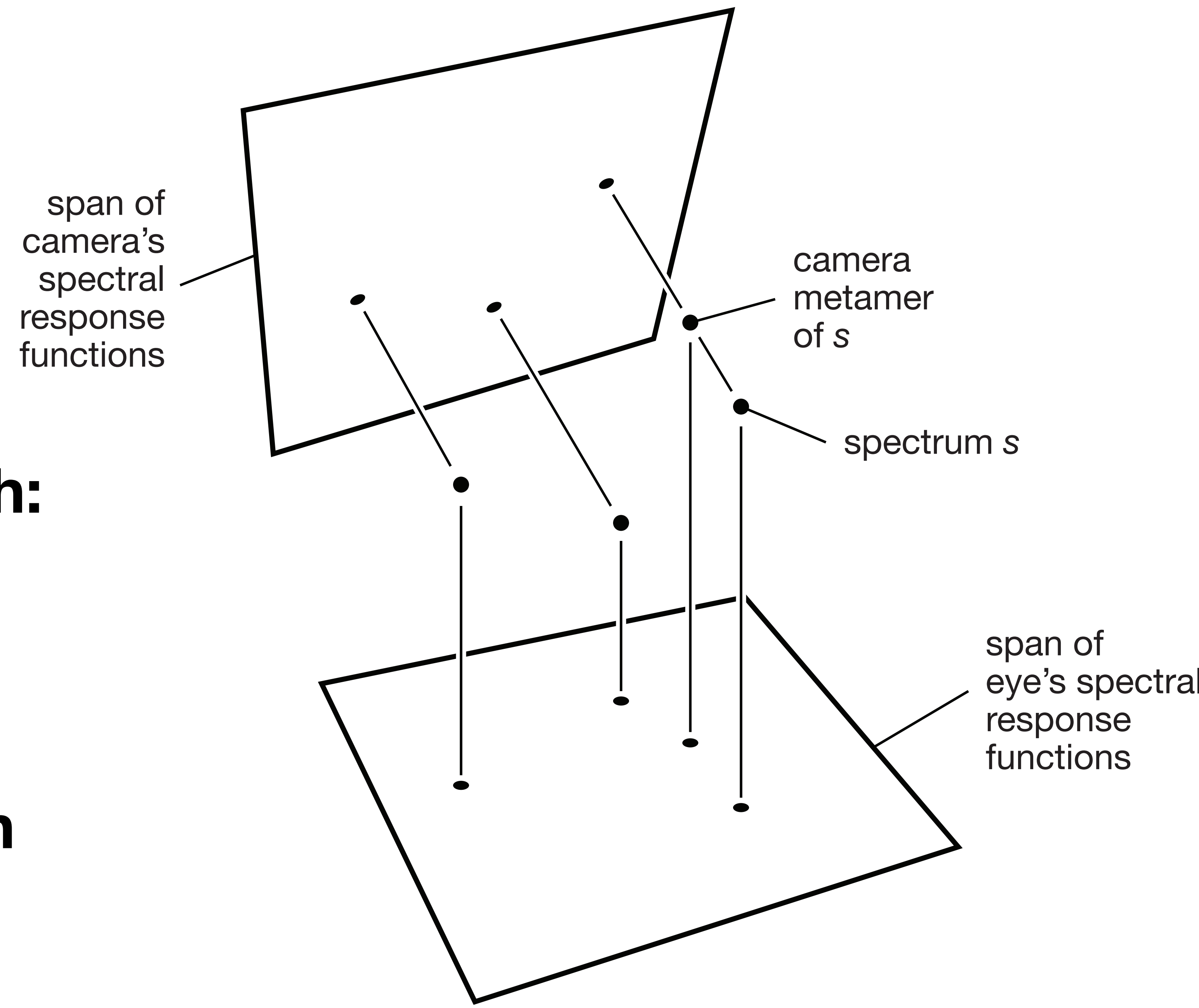

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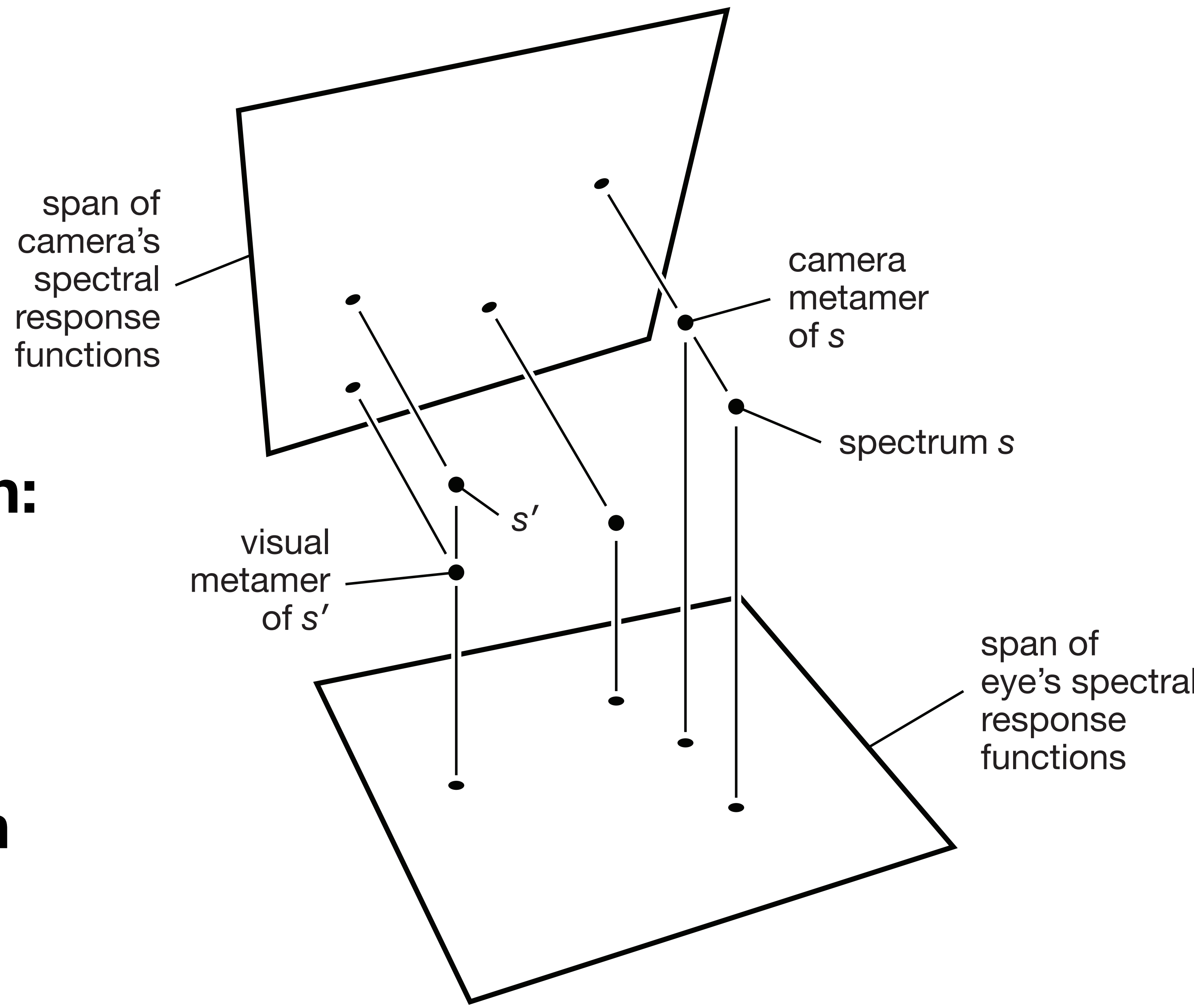

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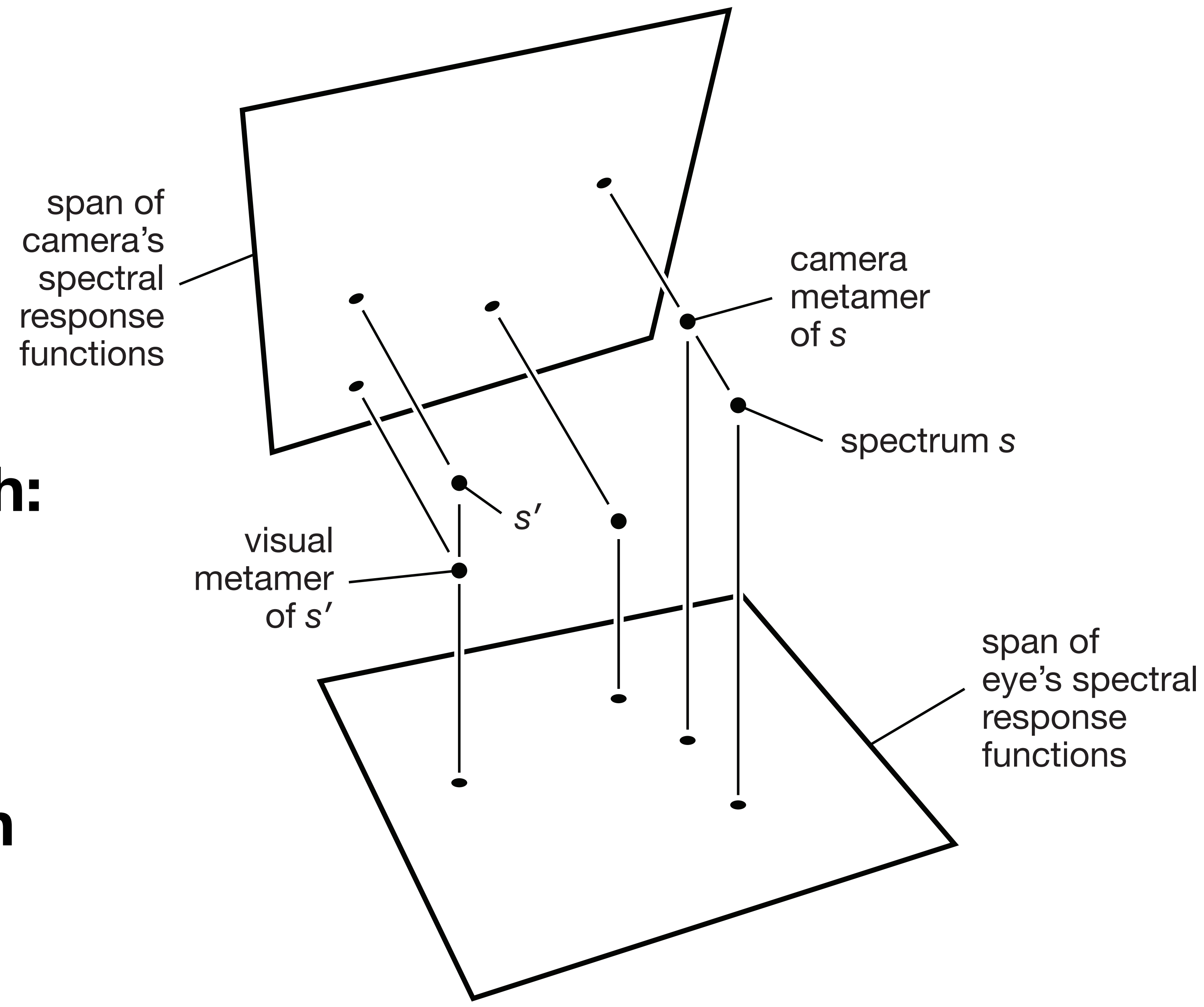


Camera color rendering via subspace

- **Assume spectrum *s* is a combination of three spectra**

$$\begin{bmatrix} | \\ s \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

- **Work out what combination it is**

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \left(\begin{bmatrix} — & r_R & — \\ — & r_G & — \\ — & r_B & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \right) \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

same math as additive color matching

- **Project that combination onto visual response**

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} — & r_S & — \\ — & r_M & — \\ — & r_L & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \left(\begin{bmatrix} — & r_R & — \\ — & r_G & — \\ — & r_B & — \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \right)^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Camera color rendering via subspace

- **Assume spectrum *s* is a combination of three spectra**

$$\begin{bmatrix} | \\ s \\ | \end{bmatrix} = \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$$

- **Work out what combination it is**

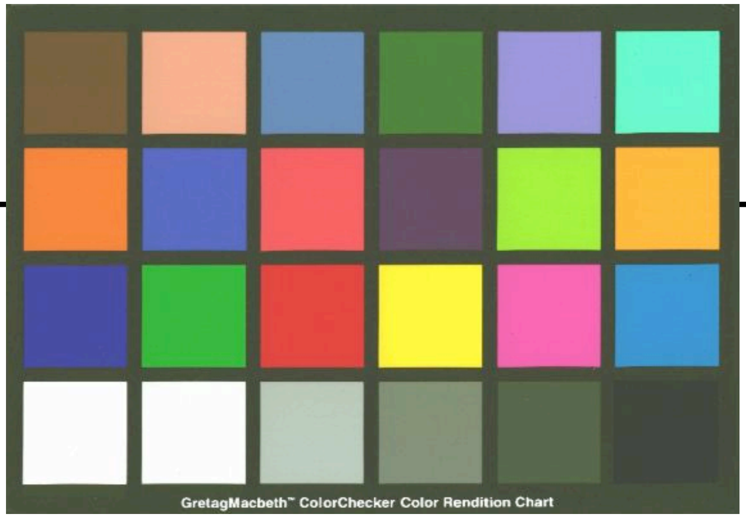
$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \left(\begin{bmatrix} - & r_R & - \\ - & r_G & - \\ - & r_B & - \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \right)^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

same math as additive color matching

- **Project that combination onto visual response**

$$\begin{bmatrix} S \\ M \\ L \end{bmatrix} = \begin{bmatrix} - & r_S & - \\ - & r_M & - \\ - & r_L & - \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \left(\begin{bmatrix} - & r_R & - \\ - & r_G & - \\ - & r_B & - \end{bmatrix} \begin{bmatrix} | & | & | \\ s_1 & s_2 & s_3 \\ | & | & | \end{bmatrix} \right)^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Empirical color transformation



- **Baseline method: use Macbeth Color Checker**

  a set of square patches of known color

  (these days you buy the MCC from X-Rite)

- **Procedure**

  1. Photograph the color checker under uniform illumination
  2. Measure the camera-RGB values of the 24 squares
  3. Look up the XYZ colors of the 24 squares
  4. Use linear least squares to find a 3x3 matrix that approximately maps the camera responses to the correct answers

$$\min_M \|C_{\text{macbeth}} - M C_{\text{camera}}\|$$

3 × 24   3 × 3   3 × 24

White balancing

- **Problem with previous slide**

  the camera-RGB colors depend on the illuminant

  the matrix *M* only works for the illuminant that was used to calibrate

- **Solutions?**

  calibrate separately for every illuminant?

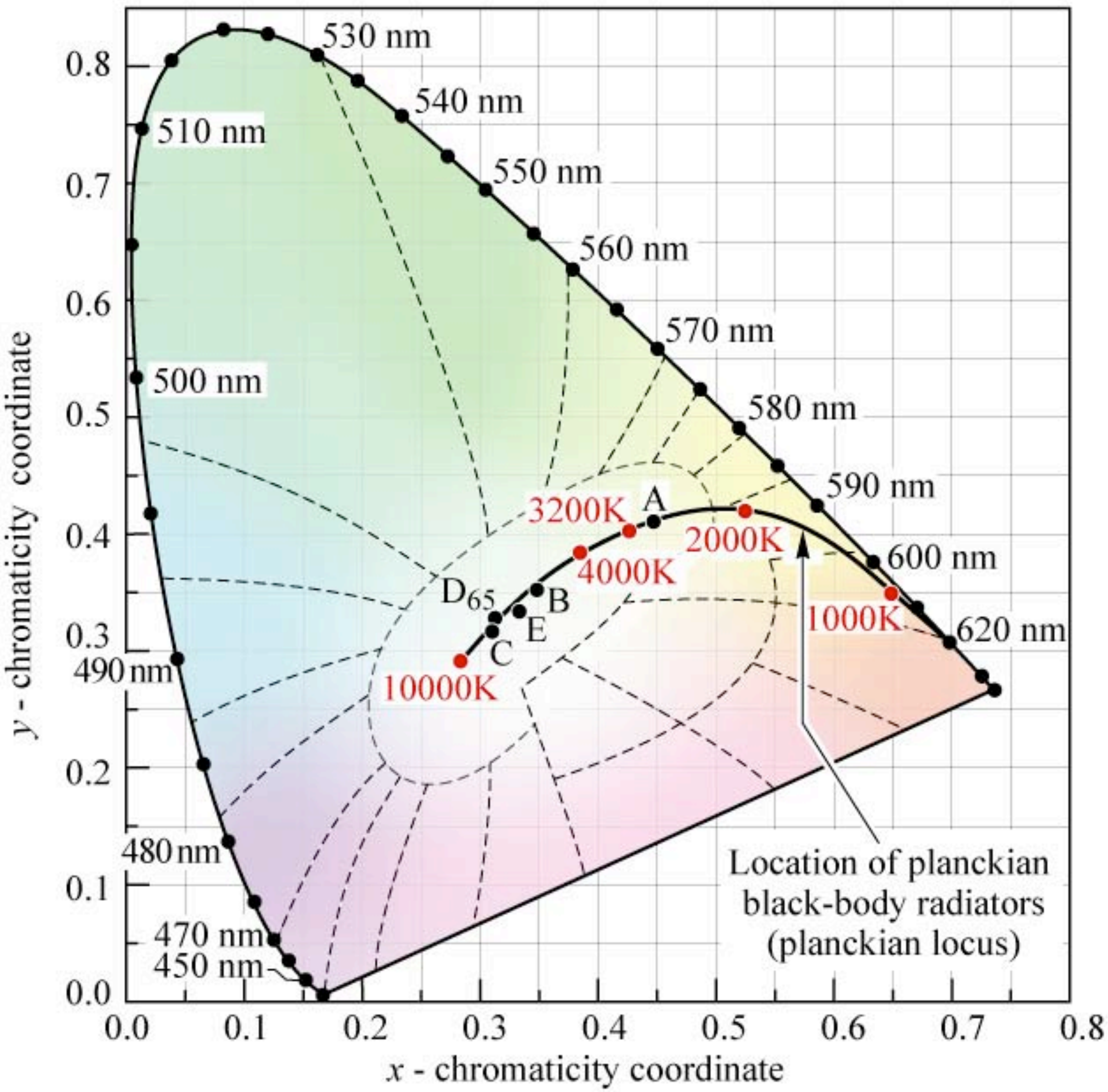
  correct for illuminant first, then apply matrix!

- **Hypothesis of von Kries: eye accounts for illuminant by simply scaling the three cone signals separately**

  some evidence this is a reasonable model for the eye

  leads to “von Kries transform”: multiply by a diagonal matrix

Range of illuminants



Illuminant A
$(x, y) = (0.4476, 0.4074)$
(Incandescent source, $T = 2856$ K)

Illuminant B
$(x, y) = (0.3484, 0.3516)$
(Direct sunlight, $T = 4870$ K)

Illuminant C
$(x, y) = (0.3101, 0.3162)$
(Overcast source, $T = 6770$ K)

Illuminant D_{65}
$(x, y) = (0.3128, 0.3292)$
(Daylight, $T = 6500$ K)

Illuminant E (equal-energy point)
$(x, y) = (0.3333, 0.3333)$

Fig. 18.3. Chromaticity diagram showing planckian locus, the standardized white Illuminants A, B, C, D_{65}, and E, and their color temperature (after CIE, 1978).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

White balancing steps

1. Determine the camera RGB of the illuminant (up to scale)

professional/studio setting: photograph a gray card

poor man's version: find something gray in the image

alternative: let user tell the camera (tungsten, daylight, …)

practical solution: Auto White Balance software guesses

2. Divide all the pixel values by the illuminant RGB

undetermined scale factor

maybe fix luminance to 1

maybe scale lowest channel of illuminant to 1

- **Now neutral colors are neutral!**

  this is unbelievably important for getting nice color

Putting it together: color processing

- **Calibrate your color matrix using a carefully white-balanced image**

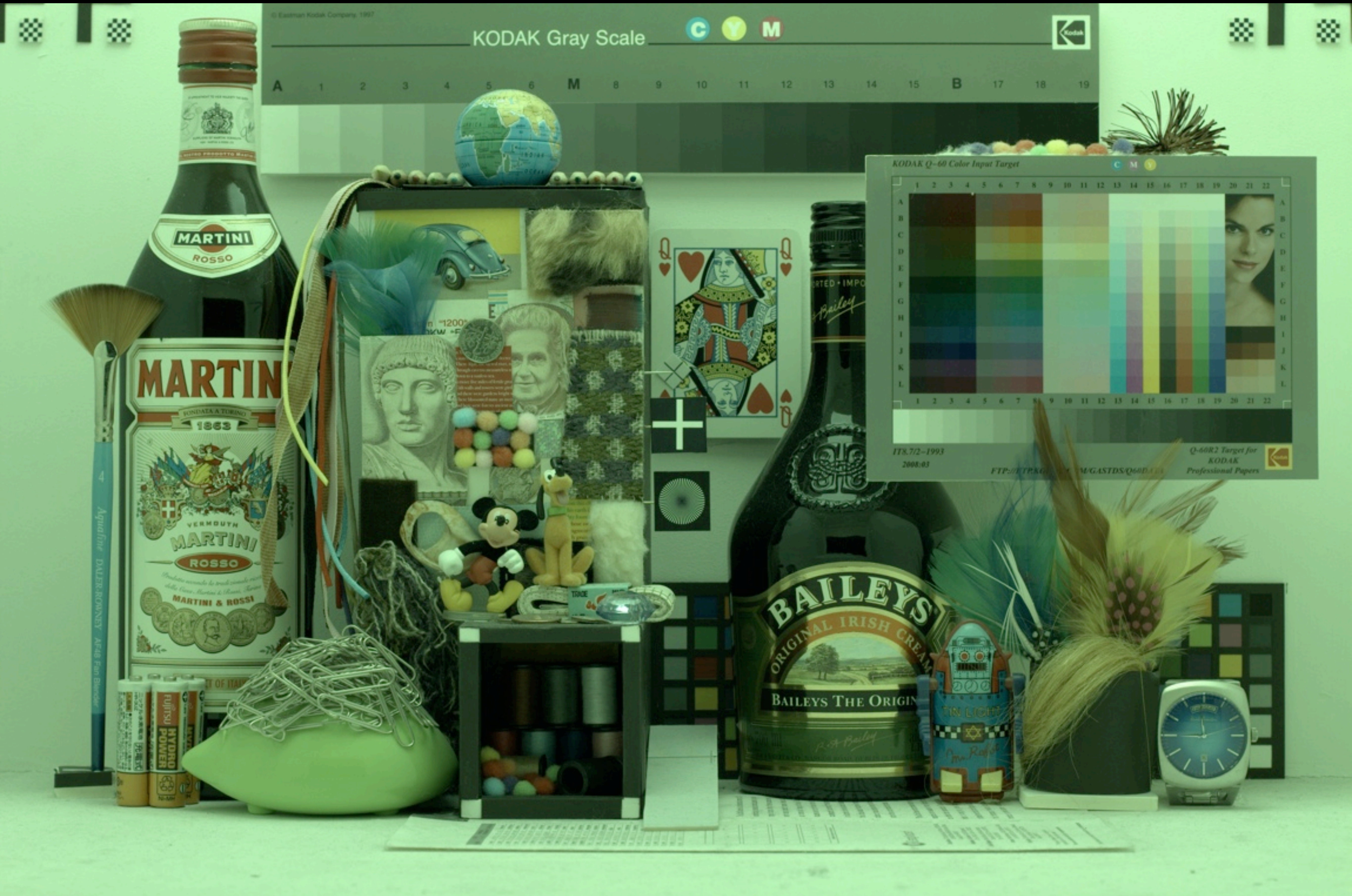
  when solving for *M*, constrain to ensure rows sum to 1

  (then *M* will leave neutral colors exactly alone)

- **For each photograph:**

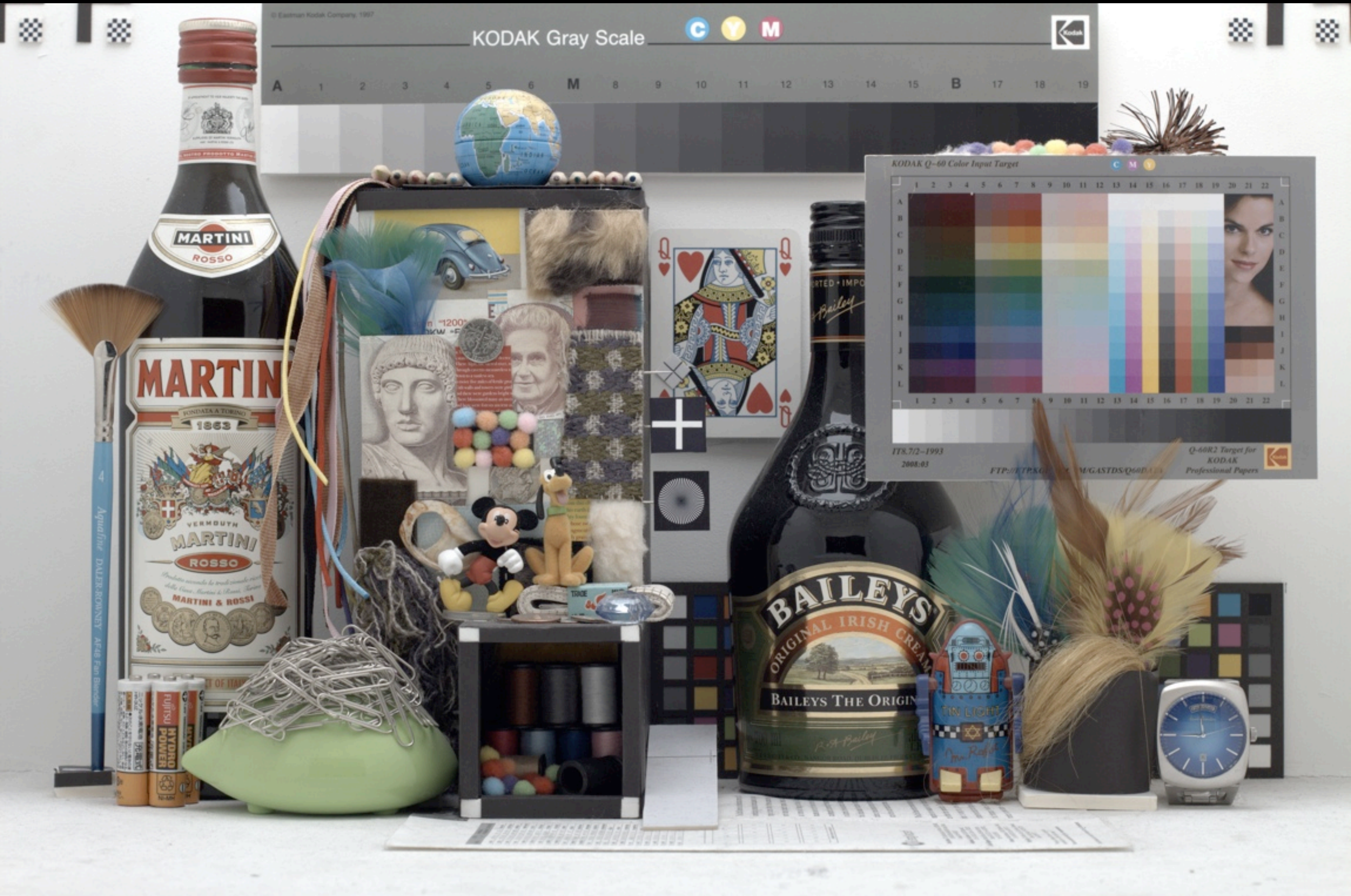
1. determine illuminant
2. apply von Kries
3. apply color matrix
4. apply any desired nonlinearity
5. display the image!

raw sensor color



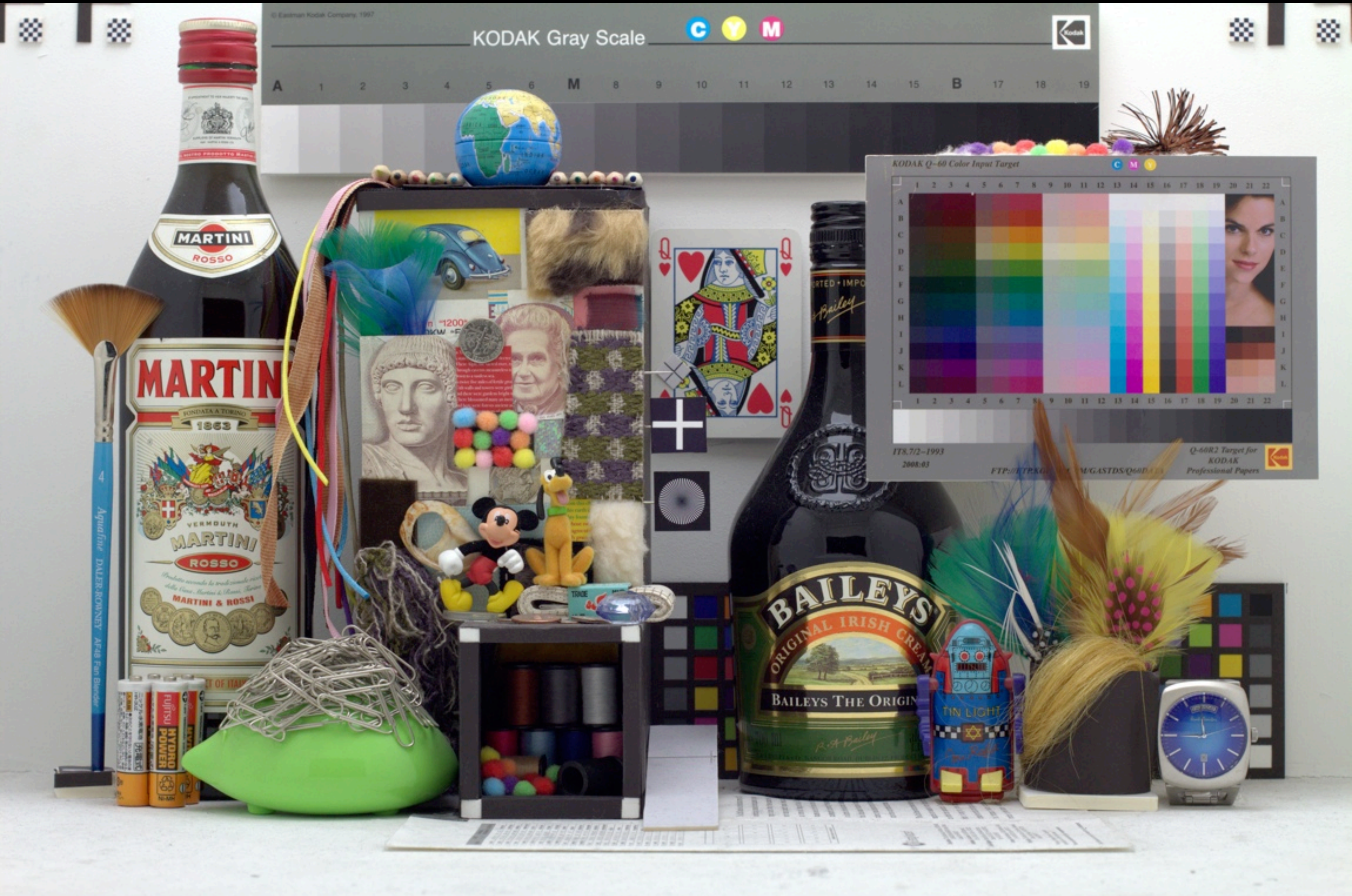
test image for Canon EOS 650D (Rebel T4i) from dpreview.com

white balanced raw sensor color



test image for Canon EOS 650D (Rebel T4i) from dpreview.com

white balanced and matrixed to sRGB



test image for Canon EOS 650D (Rebel T4i) from dpreview.com