

# Color: Physics and Effects

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# Color

- The sensation of color occurs in the brain.
- One way to get it is the response of the eye to the presence/absence of light at various wavelengths.
  - others:
    - Dreaming, hallucination, etc.
    - Pressure on the eyelids
- Different amounts at different wavelengths because:
  - wavelengths absent (flourescent light vs. incandescent light)
  - differentially reflected - e.g. paint on a surface
  - differentially refracted - e.g. Newton's prism
  - wavelength dependent specular reflection (most metals).
  - Flourescence -
    - invisible wavelengths absorbed and reemitted at visible wavelengths.
  - Phosphorescence (ditto, energy, longer timescale)

XXXXX

BLUE

YELLOW

XXXXX

GREEN

BLUE

XXXXX

RED

GREEN

XXXXX

YELLOW

RED

XXXXX

BLUE

YELLOW

XXXXX

RED

GREEN

XXXXX

GREEN

BLUE

XXXXX

BLUE

YELLOW

XXXXX

YELLOW

RED

XXXXX

RED

GREEN

# Stroop effect

- Color perception affects all sorts of other perceptual phenomena
- You name colors slowly IF the word is a different color name!

# Monochromatic light

- Use:
  - a prism
  - a refraction grating (CD, DVD)
  - an oil film
  - etc
- to produce light at “a single” wavelength
- You will see colors

# Photopic sensitivity

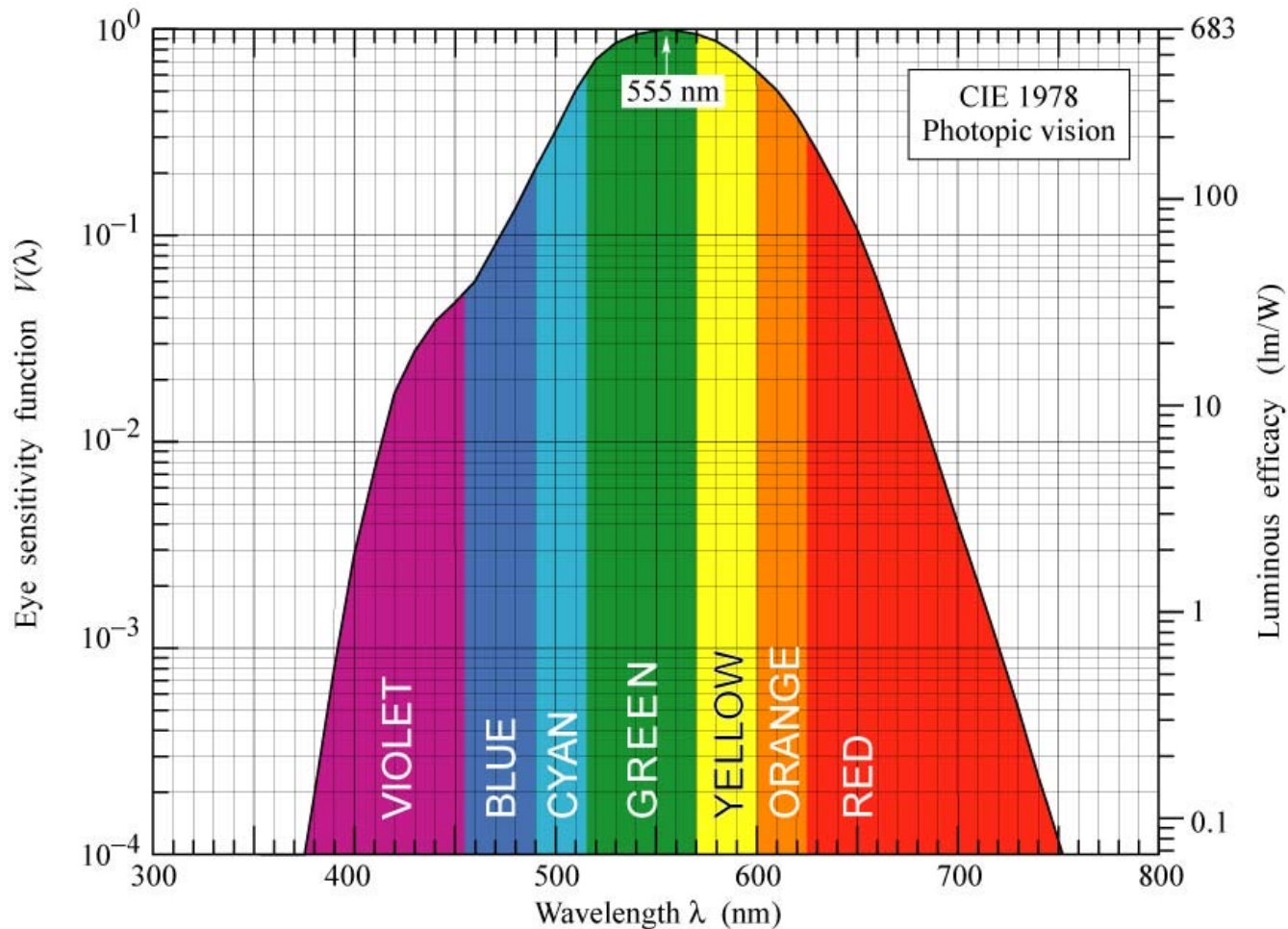


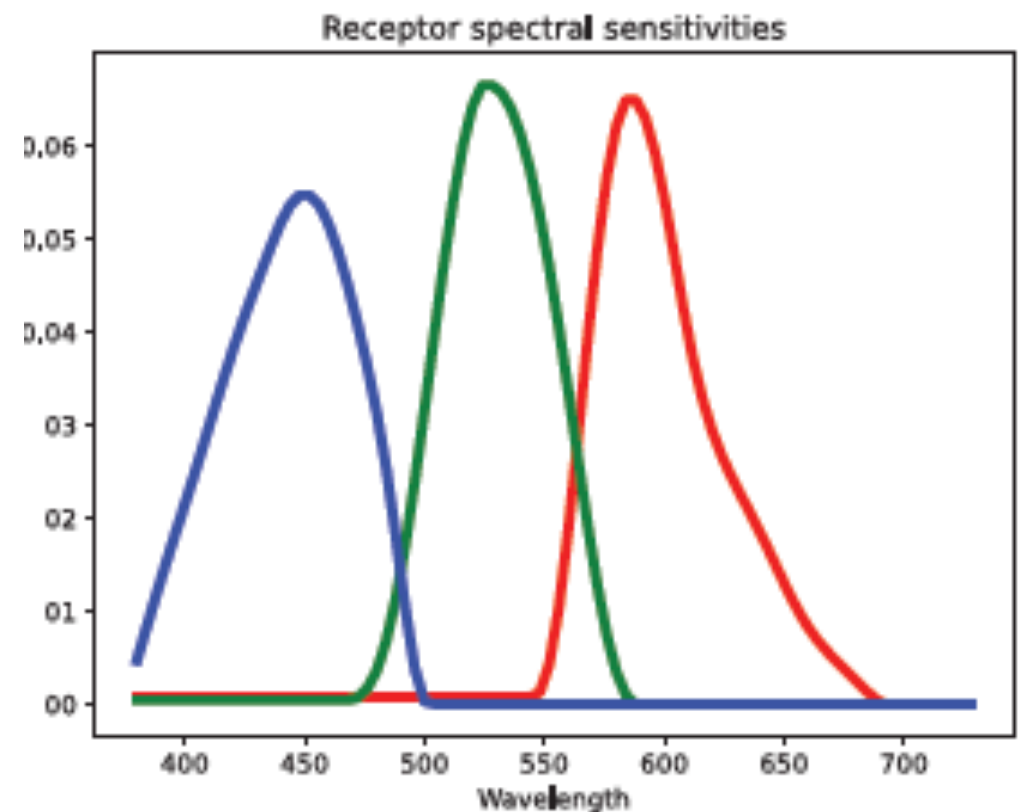
Fig. 16.7. Eye sensitivity function,  $V(\lambda)$ , (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate).  $V(\lambda)$  is greatest at 555 nm. Also given is a polynomial approximation for  $V(\lambda)$  (after 1978 CIE data).

# Receptors

- Principle of univariance
  - receptor response at different wavelengths is
    - of the same kind
    - in different amounts

Response to P over Delta t is:

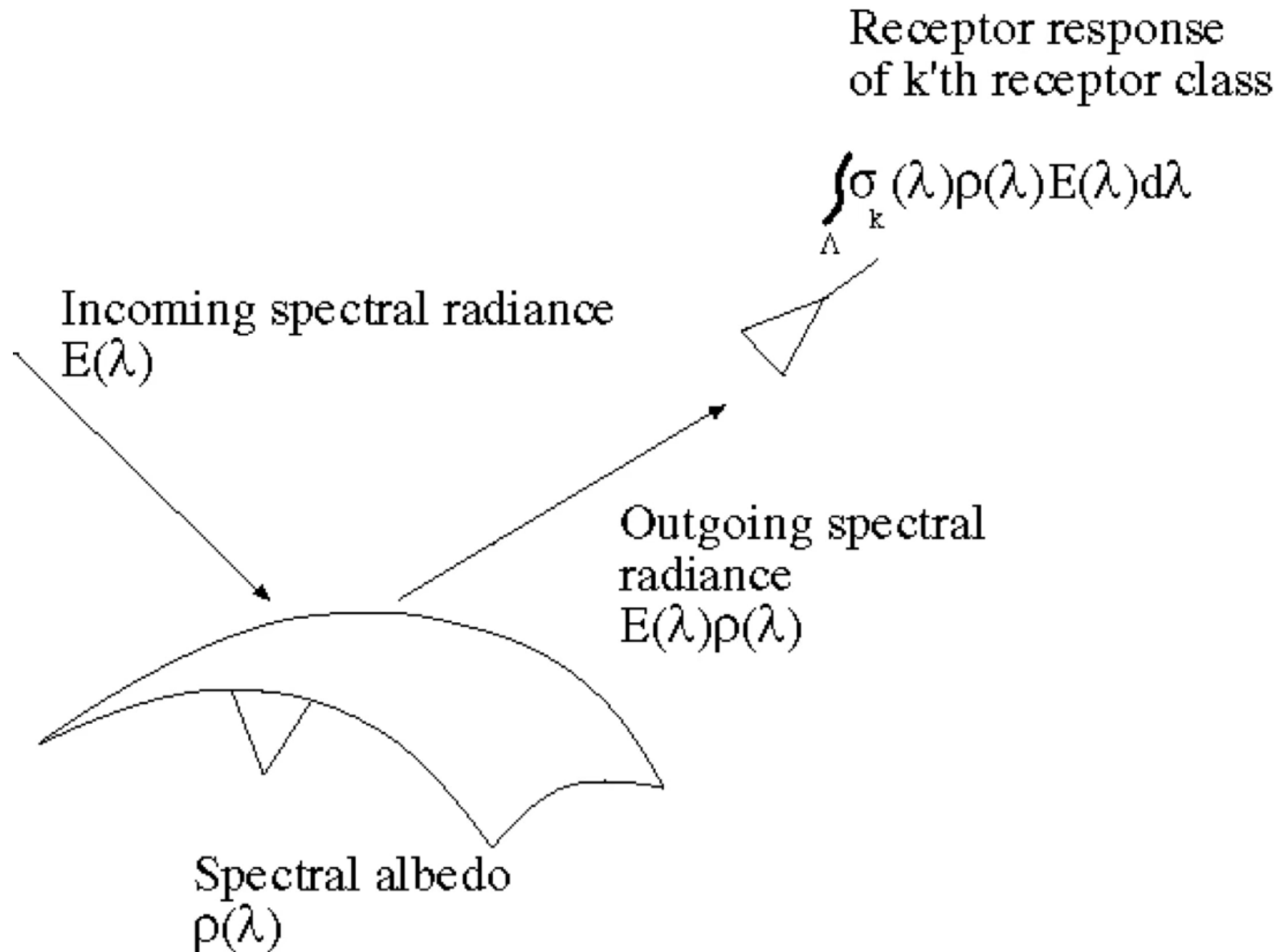
$$\int_{\text{wavelength}} P(\mathbf{X} \rightarrow \mathbf{x}, \lambda) \sigma_k(\lambda) d\lambda \Delta_t$$



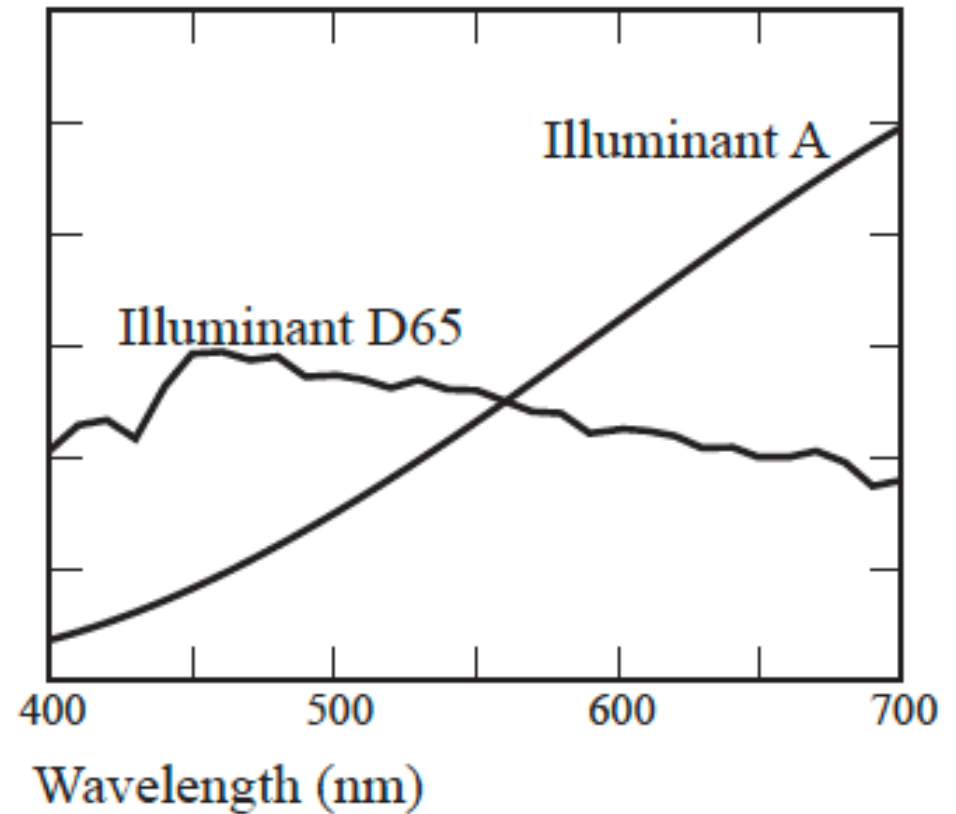
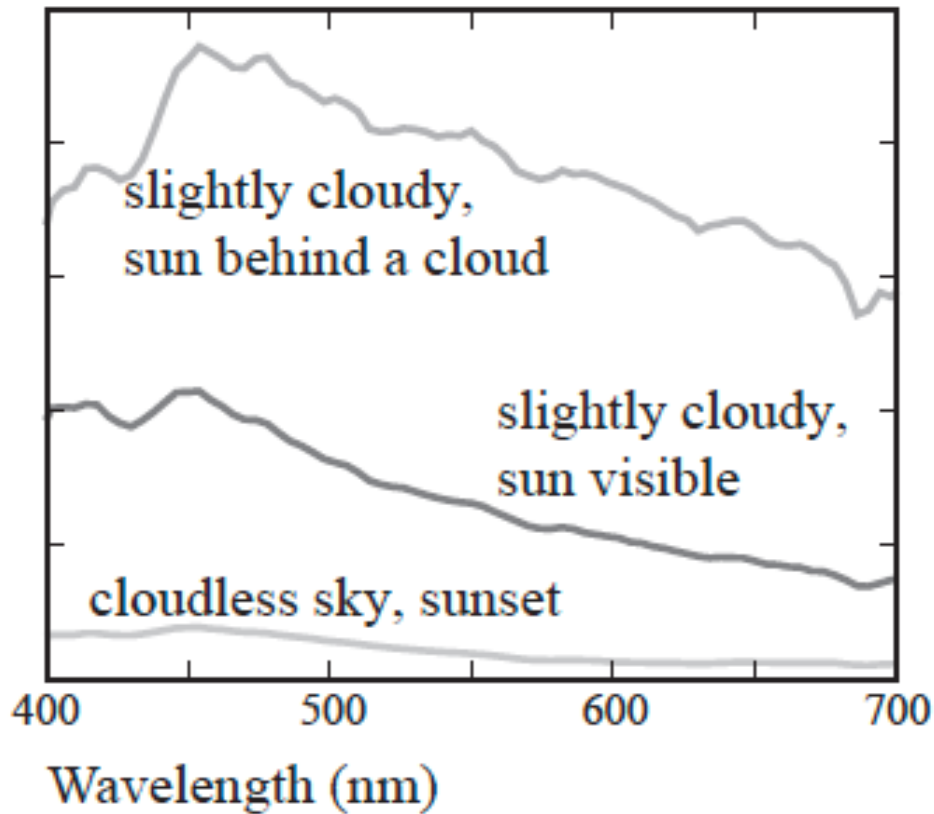
Violet

Red

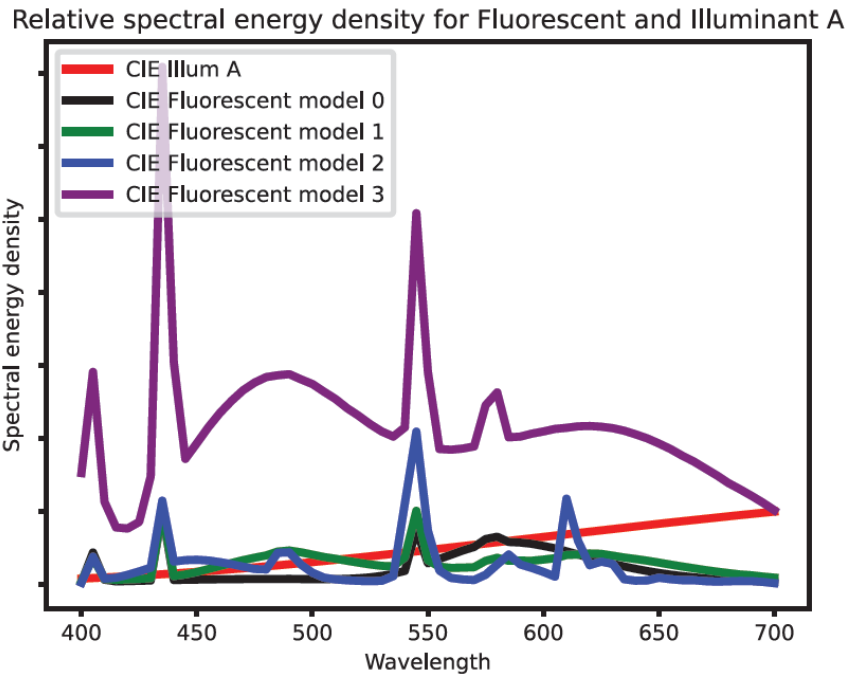
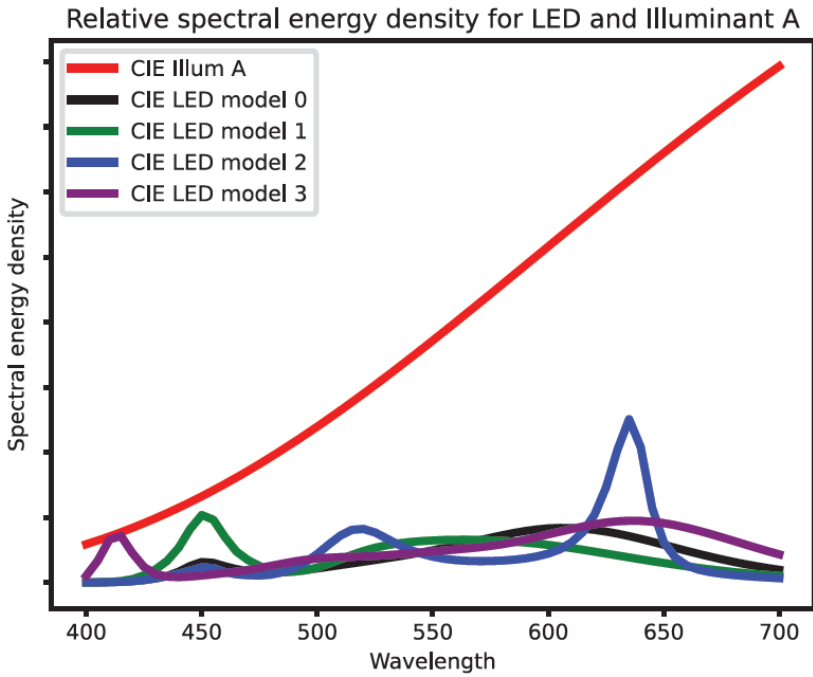
# Color in camera receptors



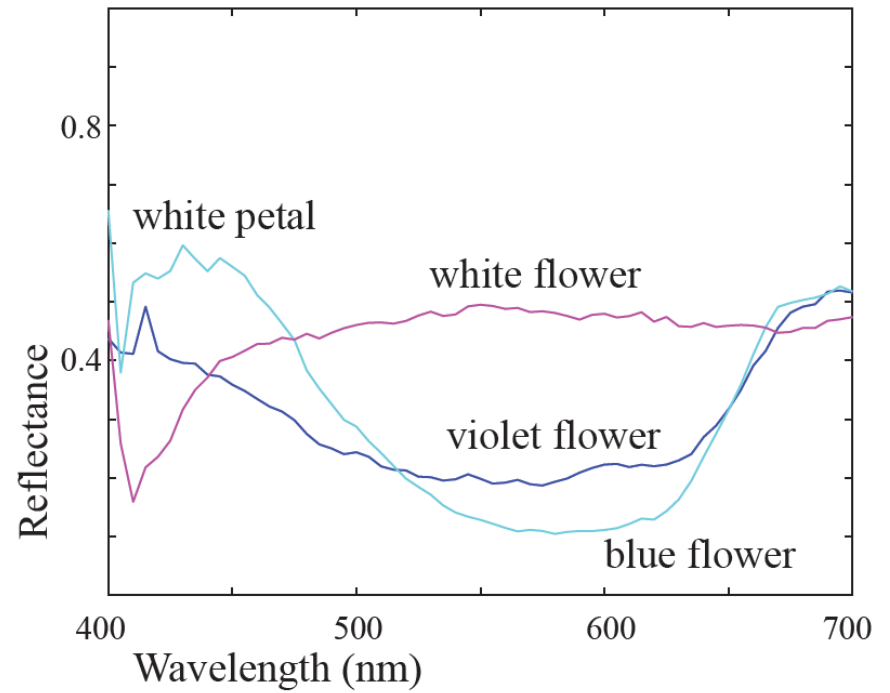
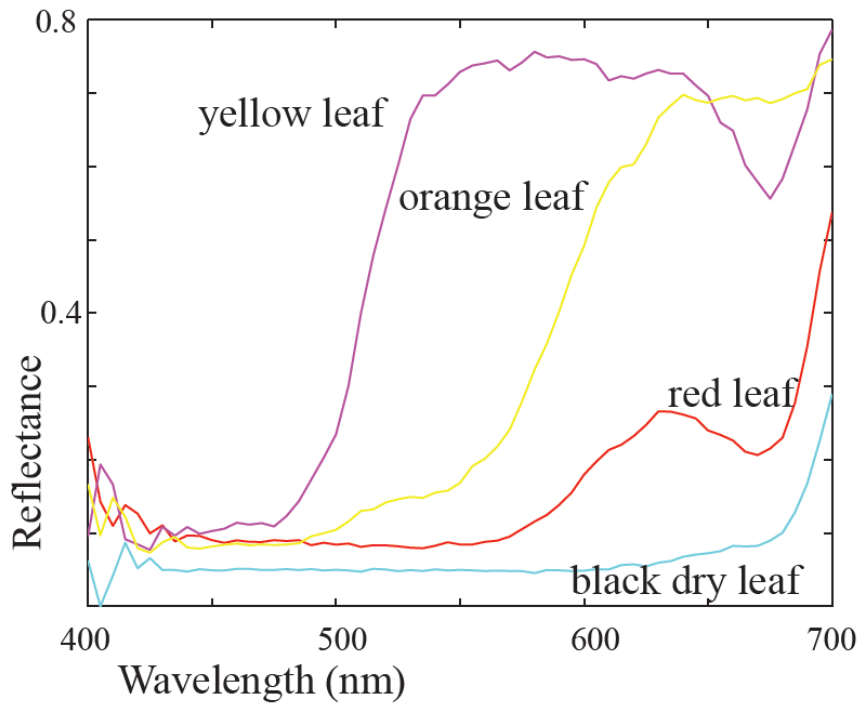
# Outdoor light spectra



# Indoor light spectra



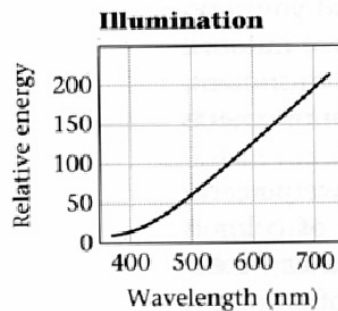
# Spectral albedoes



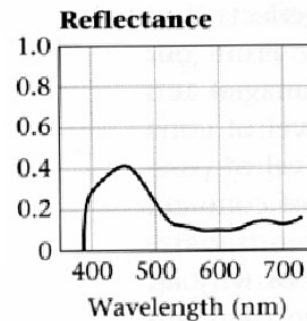
# Interaction of light and surfaces



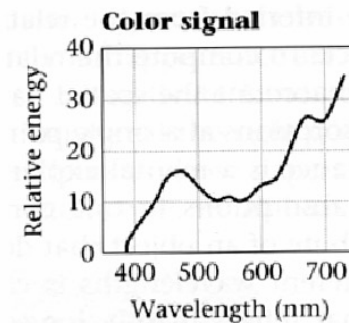
- Reflected color is the result of interaction of light source spectrum with surface reflectance



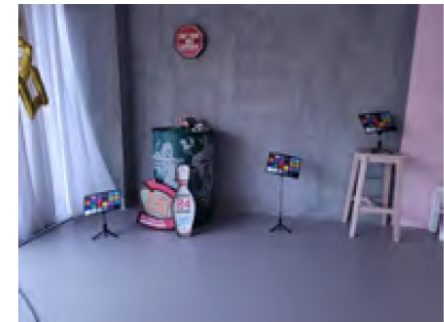
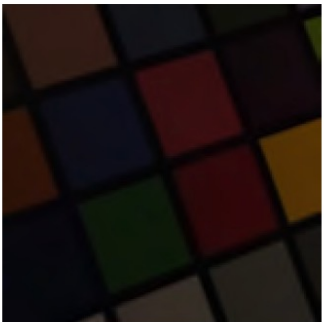
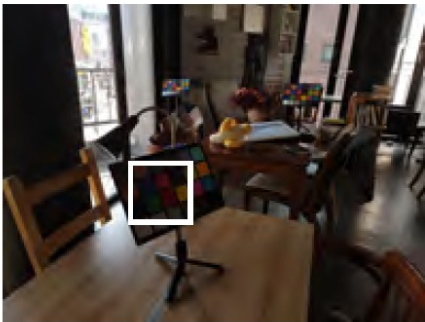
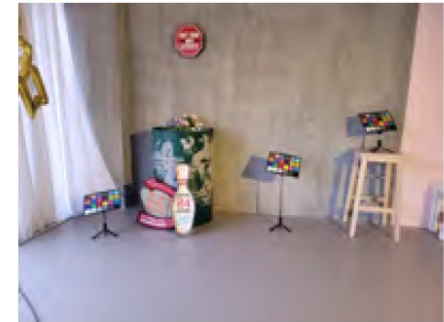
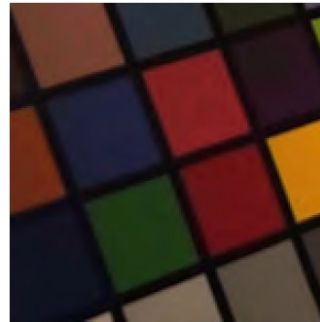
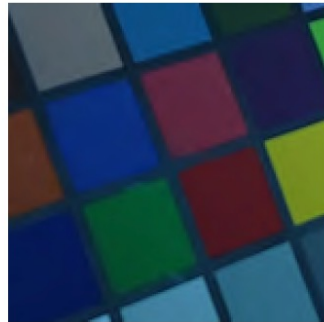
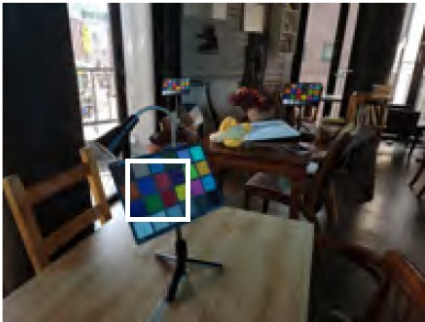
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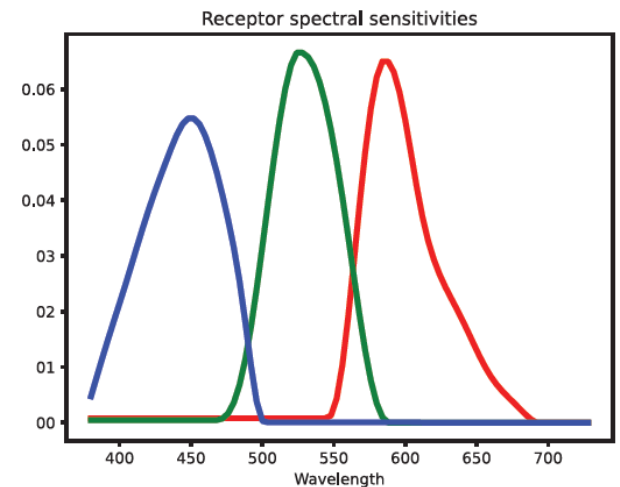
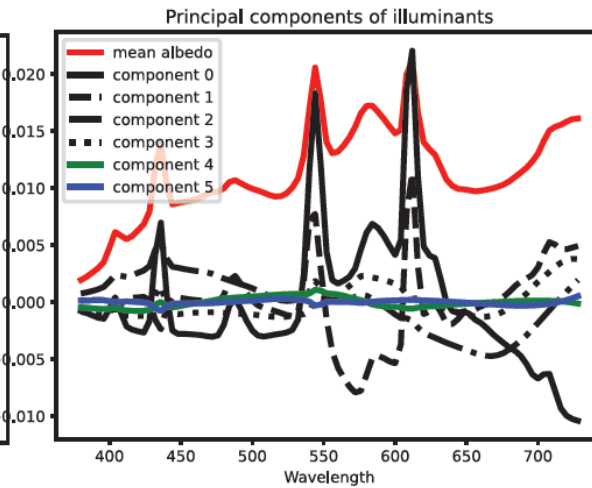
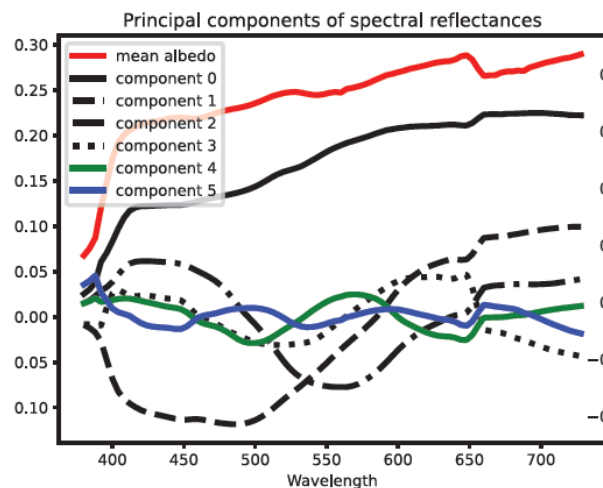
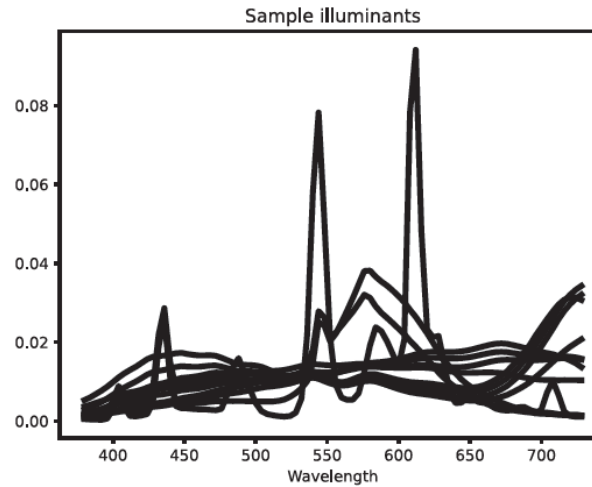
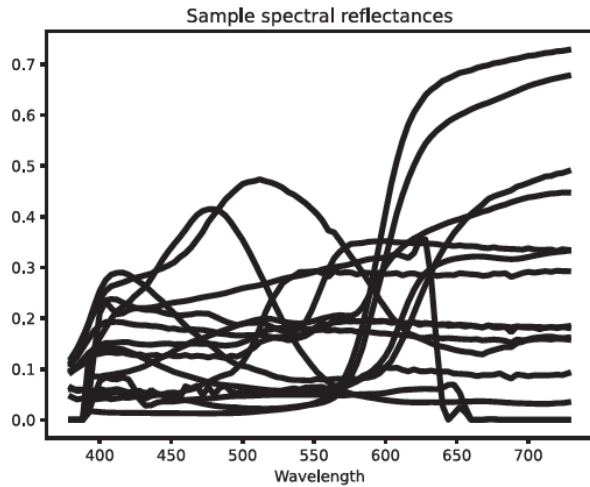


# Light and surface interactions



$$E(\lambda) = \rho_{dh}(\lambda)S(\lambda) \times \text{geometric terms} + \text{specular term}$$

# PCA models of light and surface



# Pixel color model - I

(where  $g_c$  is the gain constant of the linear camera). Now assume: that all power arriving at  $\mathbf{x}$  comes from  $\mathbf{X}$  in the scene; all reflection is diffuse; the scene is illuminated by light of one spectral energy density  $E(\lambda)$ ; and there are no interreflections.

Write  $\rho(\mathbf{X}, \lambda)$  for the spectral albedo at  $\mathbf{X}$ . Then

$$p_k(\mathbf{x}) = g_c E_k(\mathbf{x}) = \int_{\text{wavelength}} g(\mathbf{X}) \rho(\mathbf{X}, \lambda) \sigma_k(\lambda) E(\lambda) d\lambda \Delta_t$$

where  $g(\mathbf{X})$  is a term due to geometric effects (as in Section 21.3). Assume the camera gain and the time interval are known and so can be ignored. Finally, assume that both spectral albedo and spectral energy density can be written as a weighted sum of basis functions, so that

$$\rho(\mathbf{X}, \lambda) = \sum_i r_i(\mathbf{X}) \phi_i(\lambda) \text{ and } E(\lambda) = \sum_j e_j \psi_j(\lambda).$$

This assumption is sound for quite a small basis (Figure 29.8). As the figure suggests, the basis functions for albedo and for spectral energy density may be different.

# Pixel color model -III

$$g_{ijk} = \int \phi_i(\lambda)\psi_j(\lambda)\sigma_k(\lambda)d\lambda,$$

and obtain

$$p_k(\mathbf{x}) = g(\mathbf{x}) \sum_{ijk} e_i r_j(\mathbf{x}) g_{ijk}$$

or

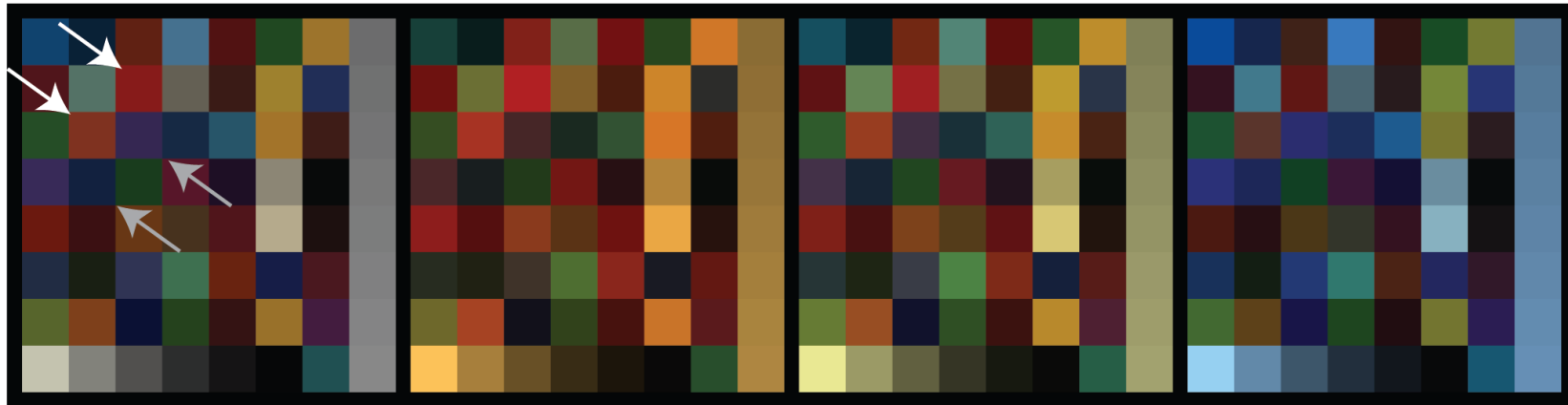
$$\mathbf{p}(\mathbf{x}) = g(\mathbf{x})\mathcal{A}_e\mathbf{r}(\mathbf{x}).$$

(where the responses of different types of receptor have been stacked into a vector  $\mathbf{p}$ , the vector  $\mathbf{r}$  represents the reflectance coefficients, the  $\mathbf{e}$  represents the color of the illuminant, and  $\mathcal{A}_e$  is the matrix whose  $u, v$ 'th element is  $\sum_i e_i g_{ivu}$ . A model of this form is known as a *finite dimensional linear model*. Usually,  $g_{ijk}$  are known or can be calibrated.

# Color mapping

The map  $\mathcal{A}_e$  is quite strongly affected by  $e$ . This experimental fact is most easily observed by looking at the collection of all pixel values in the image – its *gamut*. As Figure 29.14 shows, if the illuminant is orange in color, then the colors in the image shift toward orange; if it is blue, they shift to blue. Because  $\mathcal{A}_e$  changes when  $e$  changes its kernel may change. In turn, if the basis for spectral reflectances has more than three dimensions, there may be pairs of surfaces that have different colors under one light and the same color under another light (exercises). This occurs in practice (Figure 29.14) and such pairs of surfaces are known as *metamers*.

# Metamerism and gamuts



Gamut 0

Gamut 1

Gamut 2

Gamut 3

