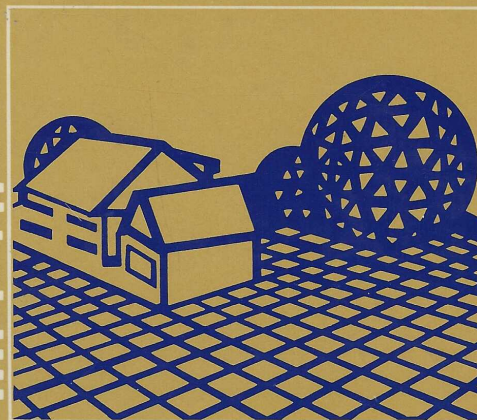
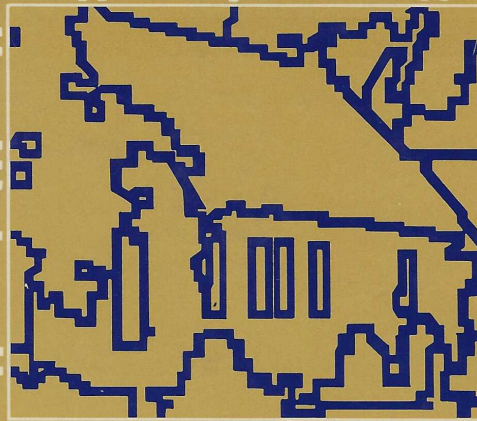


COMPUTER VISION

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2.2.5 Color

Not all images are monochromatic; in fact, applications using multispectral images are becoming increasingly common (Section 2.3.2). Further, human beings intuitively feel that color is an important part of their visual experience, and is useful or even necessary for powerful visual processing in the real world. Color vision provides a host of research issues, both for psychology and computer vision. We briefly discuss two aspects of color vision: color spaces and color perception. Several models of the human visual system not only include color but have proven useful in applications [Granrath 1981].

Color Spaces

Color spaces are a way of organizing the colors perceived by human beings. It happens that weighted combinations of stimuli at three principal wavelengths are sufficient to define almost all the colors we perceive. These wavelengths form a natural basis or coordinate system from which the color measurement process can be described. Color perception is not related in a simple way to color measurement, however.

Color is a perceptual phenomenon related to human response to different wavelengths in the visible *electromagnetic spectrum* [400 (blue) to 700 nanometers (red); a nanometer (nm) is 10^{-9} meter]. The sensation of color arises from the sensitivities of three types of neurochemical sensors in the retina to the visible spectrum. The relative response of these sensors is shown in Fig. 2.6. Note that each sensor responds to a range of wavelengths. The illumination source has its own spectral composition $f(\lambda)$ which is modified by the reflecting surface. Let $r(\lambda)$ be this reflectance function. Then the measurement R produced by the “red” sensor is given by

$$R = \int f(\lambda) r(\lambda) h_R(\lambda) d\lambda \quad (2.32)$$

So the sensor output is actually the integral of three different wavelength-dependent components: the source f , the surface reflectance r , and the sensor h_R .

Surprisingly, only weighted combinations of three delta-function approximations to the different $f(\lambda) h(\lambda)$, that is, $\delta(\lambda_R)$, $\delta(\lambda_G)$, and $\delta(\lambda_B)$, are necessary to

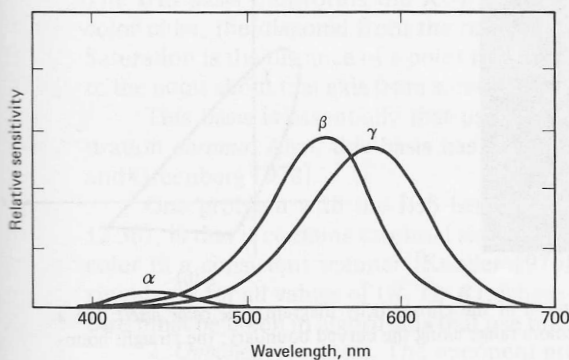


Fig. 2.6 Spectral response of human color sensors.

produce the sensation of nearly all the colors. This result is displayed on a *chromaticity diagram*. Such a diagram is obtained by first normalizing the three sensor measurements:

$$\begin{aligned} r &= \frac{R}{R + G + B} \\ g &= \frac{G}{R + G + B} \\ b &= \frac{B}{R + G + B} \end{aligned} \quad (2.33)$$

and then plotting perceived color as a function of any two (usually red and green). Chromaticity explicitly ignores intensity or brightness; it is a section through the three-dimensional color space (Fig. 2.7). The choice of $(\lambda_R, \lambda_G, \lambda_B) = (410, 530, 650) \text{ nm}$ maximizes the realizable colors, but some colors still cannot be realized since they would require negative values for some of r , g , and b .

Another more intuitive way of visualizing the possible colors from the *RGB* space is to view these measurements as Euclidean coordinates. Here any color can be visualized as a point in the unit cube. Other coordinate systems are useful for different applications; computer graphics has proved a strong stimulus for investigation of different color space bases.

Color Perception

Color perception is complex, but the essential step is a transformation of three input intensity measurements into another basis. The coordinates of the new

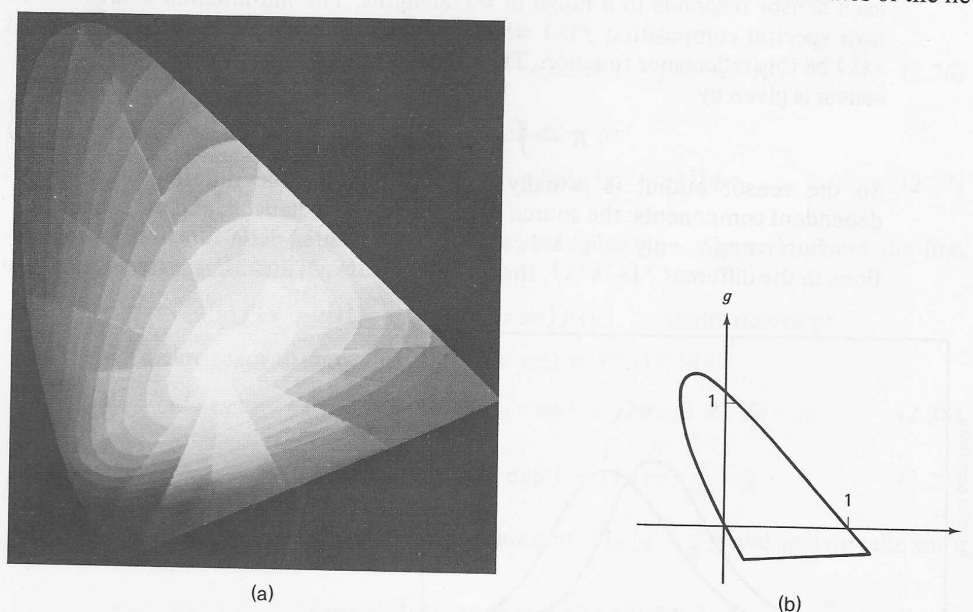


Fig. 2.7 (a) An artist's conception of the chromaticity diagram—see color insert; (b) a more useful depiction. Spectral colors range along the curved boundary; the straight boundary is the line of purples.

basis are more directly related to human color judgments.

Although the *RGB* basis is good for the acquisition or display of color information, it is not a particularly good basis to explain the perception of colors. Human vision systems can make good judgments about the relative surface reflectance $r(\lambda)$ despite different illuminating wavelengths; this reflectance seems to be what we mean by surface color.

Another important feature of the color basis is revealed by an ability to perceive in "black and white," effectively deriving intensity information from the color measurements. From an evolutionary point of view, we might expect that color perception in animals would be compatible with preexisting noncolor perceptual mechanisms.

These two needs—the need to make good color judgments and the need to retain and use intensity information—imply that we use a transformed, non-*RGB* basis for color space. Of the different bases in use for color vision, all are variations on this theme: Intensity forms one dimension and color is a two-dimensional subspace. The differences arise in how the color subspace is described. We categorize such bases into two groups.

1. *Intensity/Saturation/Hue (IHS)*. In this basis, we compute intensity as

$$\text{intensity} = R + G + B \quad (2.34)$$

The saturation measures the lack of whiteness in the color. Colors such as "fire engine" red and "grass" green are saturated; pastels (e.g., pinks and pale blues) are desaturated. Saturation can be computed from *RGB* coordinates by the formula [Tenenbaum and Weyl 1975]

$$\text{saturation} = 1 - \frac{3 \min(R, G, B)}{\text{intensity}} \quad (2.35)$$

Hue is roughly proportional to the average wavelength of the color. It can be defined using *RGB* by the following program fragment:

$$\text{hue} = \cos^{-1} \left\{ \frac{\{1/2[(R - G) + (R - B)]\}}{\sqrt{(R - G)^2 + (R - B)(G - B)}} \right\} \quad (2.36)$$

If $B > G$ then $\text{hue} = 2\pi - \text{hue}$

The *IHS* basis transforms the *RGB* basis in the following way. Thinking of the color cube, the diagonal from the origin to (1, 1, 1) becomes the intensity axis. Saturation is the distance of a point from that axis and hue is the angle with regard to the point about that axis from some reference (Fig. 2.8).

This basis is essentially that used by artists [Munsell 1939], who term saturation *chroma*. Also, this basis has been used in graphics [Smith 1978; Joblove and Greenberg 1978].

One problem with the *IHS* basis, particularly as defined by (2.34) through (2.36), is that it contains essential singularities where it is impossible to define the color in a consistent manner [Kender 1976]. For example, hue has an essential singularity for all values of (R, G, B) , where $R = G = B$. This means that special care must be taken in algorithms that use hue.

2. *Opponent processes*. The opponent process basis uses Cartesian rather than