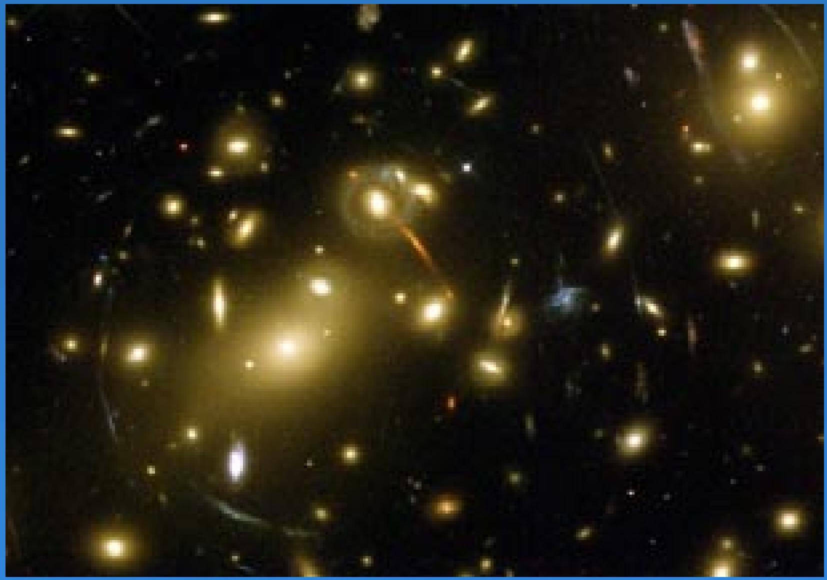


Astronomy 80 B: Light

Lecture 18: color

29 May 2003

Jerry Nelson

Topics for Today

- Research paper is due on or BEFORE 5 June
- List of peoples scores to date
- List of people short on section attendance
- Transit of Mercury
- Last of perspective
- Color and color vision
- Next lecture : ch 12 waves and diffraction
- Final lecture: Review?

Section attendance

- **needs one more (5 needed in total)**
  - Bartley, Davies, Galvan, Hemphill, James, Minolli, Patel, Ponce, Portugal, Prowell, Schwartz, Semana, Wildman, Woodruff
- **needs two**
  - Cambell, Davidoff, Lebus
- **Needs three**
  - Gonzales, Healy, Lawson, Morabito, Rucker
- **Needs 4**
  - Lutzross, Mcvey, Myers
- **Needs 5**
  - Gomez, Horn, Lim, Mottney

Grades, homework and quizes

- **On the table are my grade lists for each of you, ordered by SSN**
  - check that I have all of your homework recorded
  - Check that I have all of your quizes recorded

- **If you disagree with anything, tell me immediately**

Transit of mercury across sun - multiple exposure

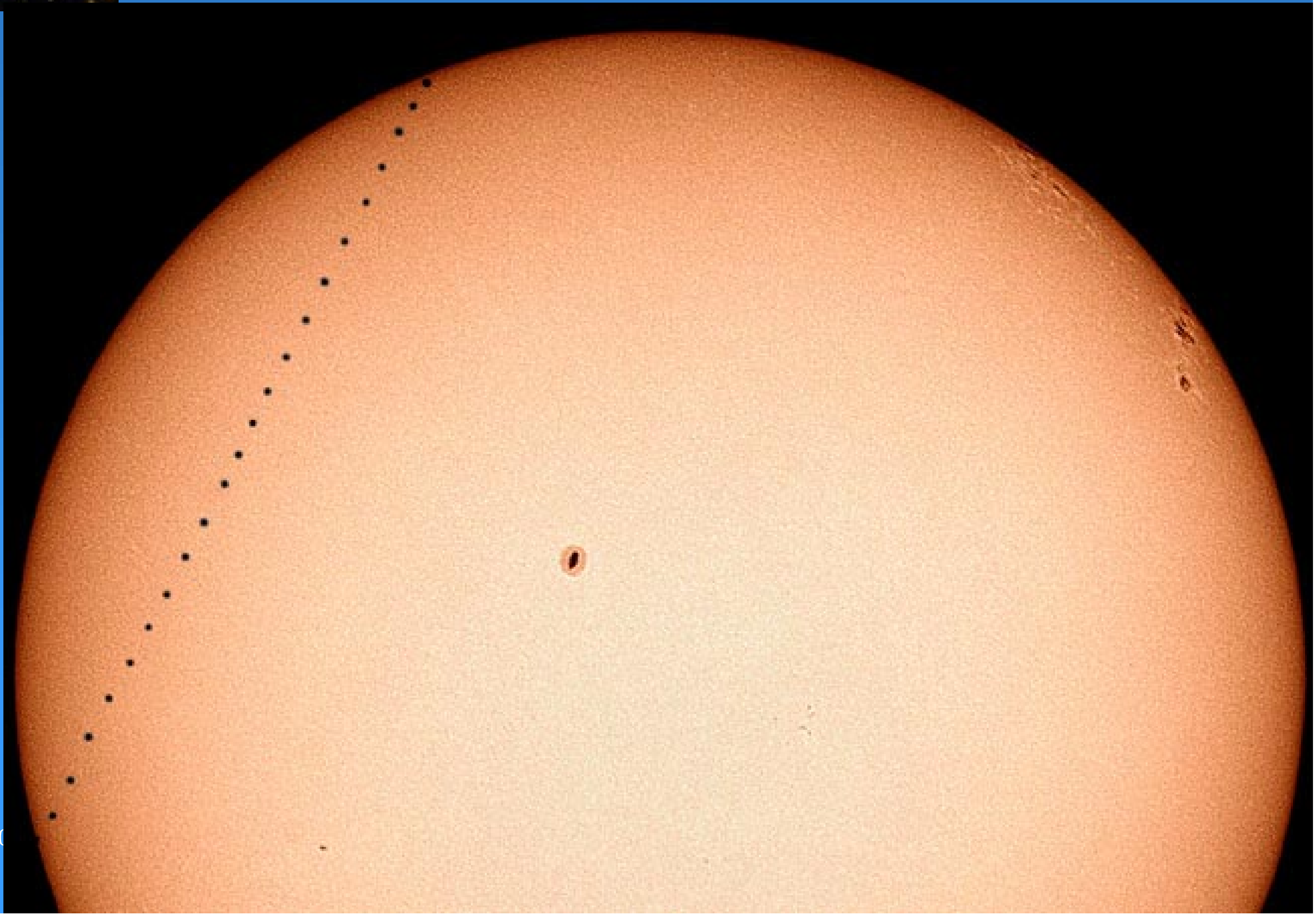
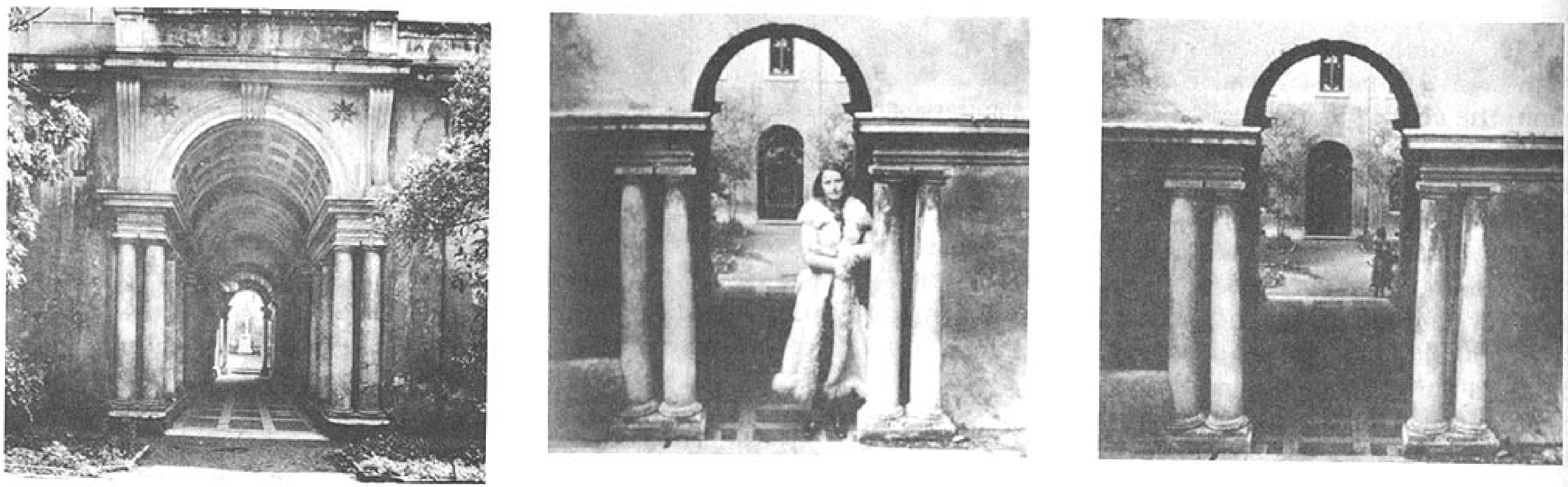


FIGURE 8.25

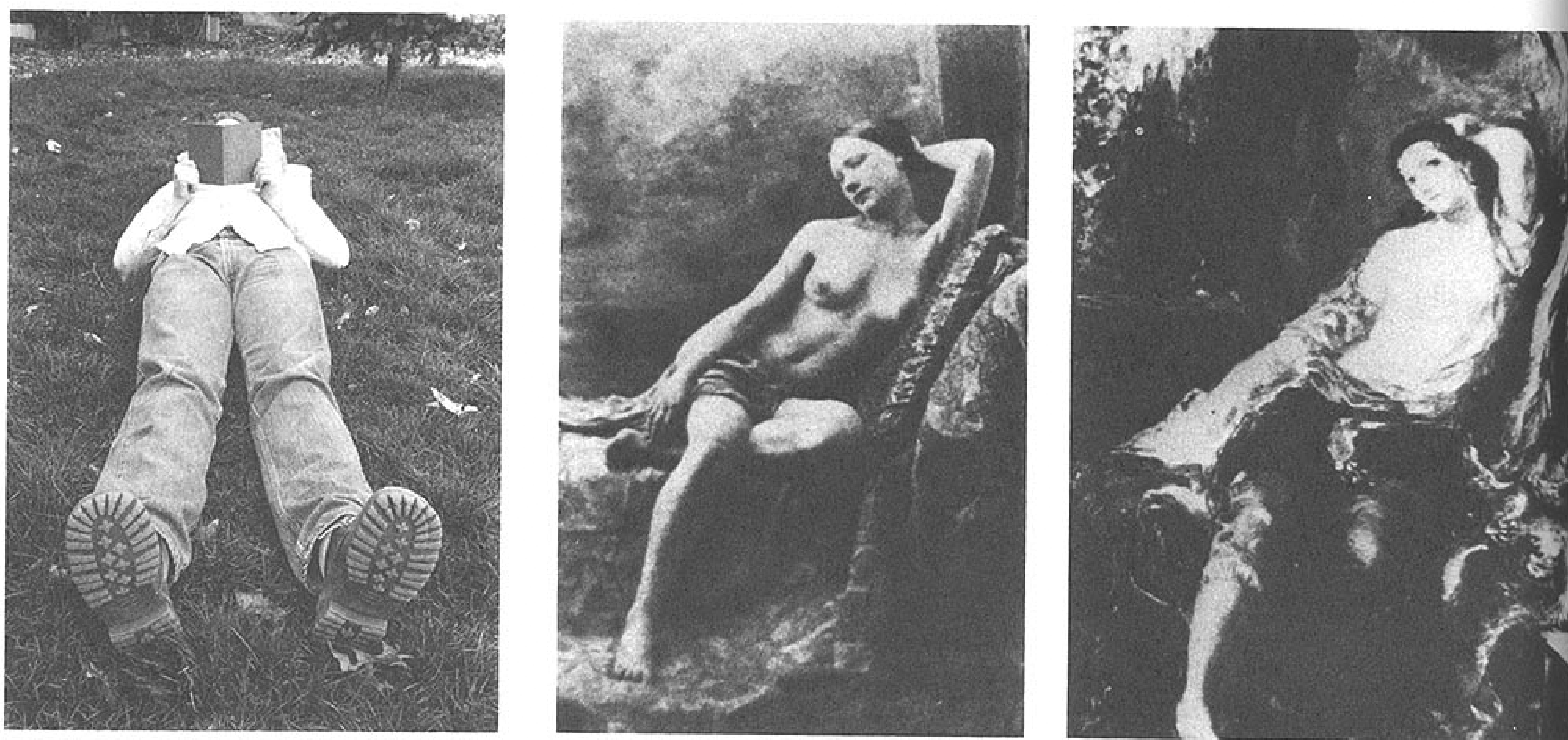
Palazzo Spada, Rome. **(a)** View through colonnade. **(b)** Views from other end of colonnade, showing the deception.



(a) (b)

FIGURE 8.27

(a) Side view of tennis ball and basketball. **(b)** Views of balls as seen from *P* and *Q*. **(c)** View from close up, appears distorted. **(d)** Photograph of nude found in Delacroix's album. **(e)** "Odalisque" by Delacroix (1857).

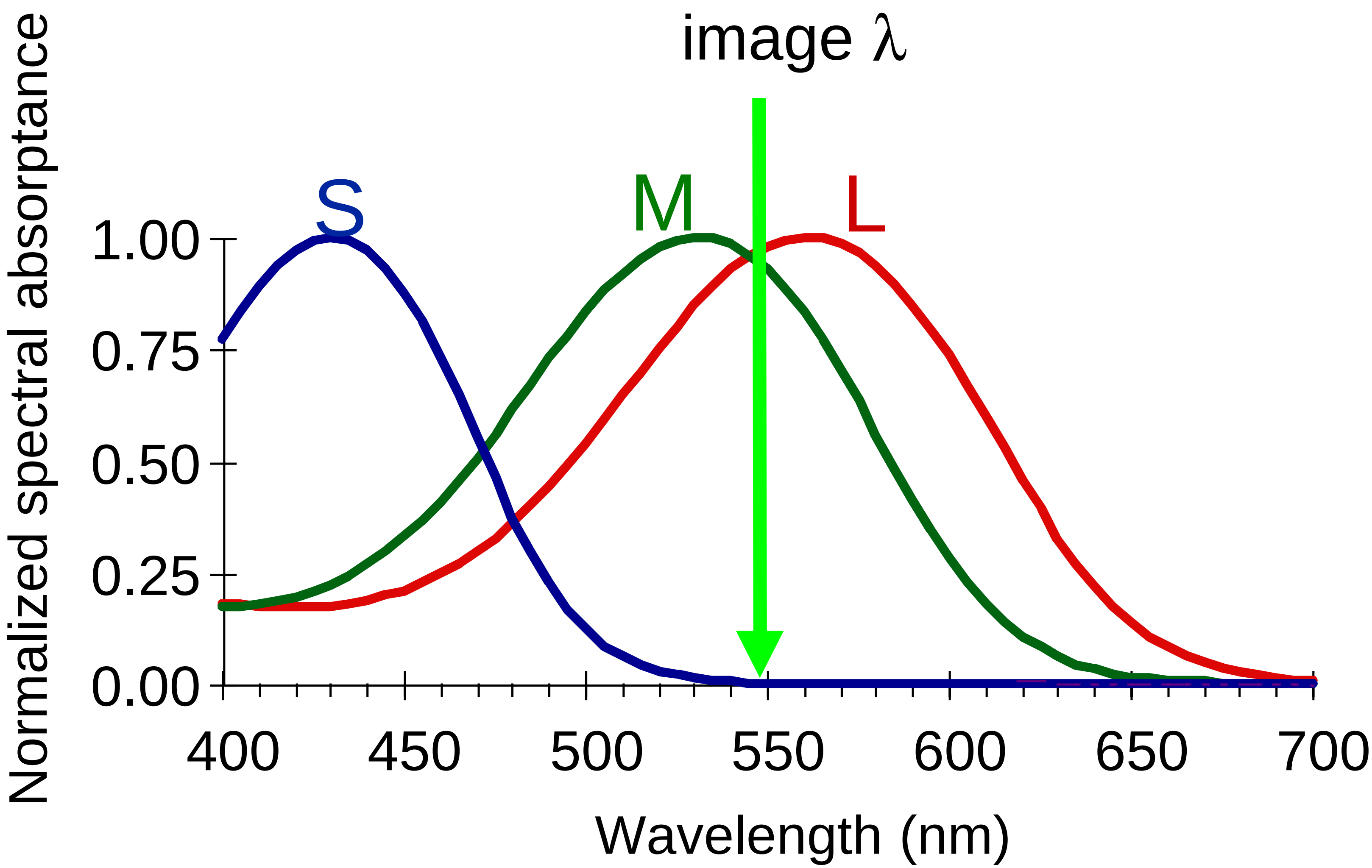


(c) (d) (e)

Color

- **Complex phenomenon**
- **Our visual tools are our three cone receptors**
  - Short wavelength
  - Medium wavelength
  - Long wavelength
- **A variety of light sources can be viewed by us**
- **Nature of source and background determines our perception**
- **Great variety of sources and light mechanisms**

The Trichromatic Cone Mosaic



Color

- **In this section, color is largely a human phenomenon that relates closely to how the retina and brain work**
- **color vs wavelength and non spectral colors**
- **Intensity distribution curves**
- **Three qualities of colored light**
  - Hue
  - Saturation
  - Brightness or Lightness
- **Color tree**

- **Intensity distribution curve**
  - This plot or graph is key tool for understanding color and for representing it
  - This graph is quantitative and thus less ambiguous than words

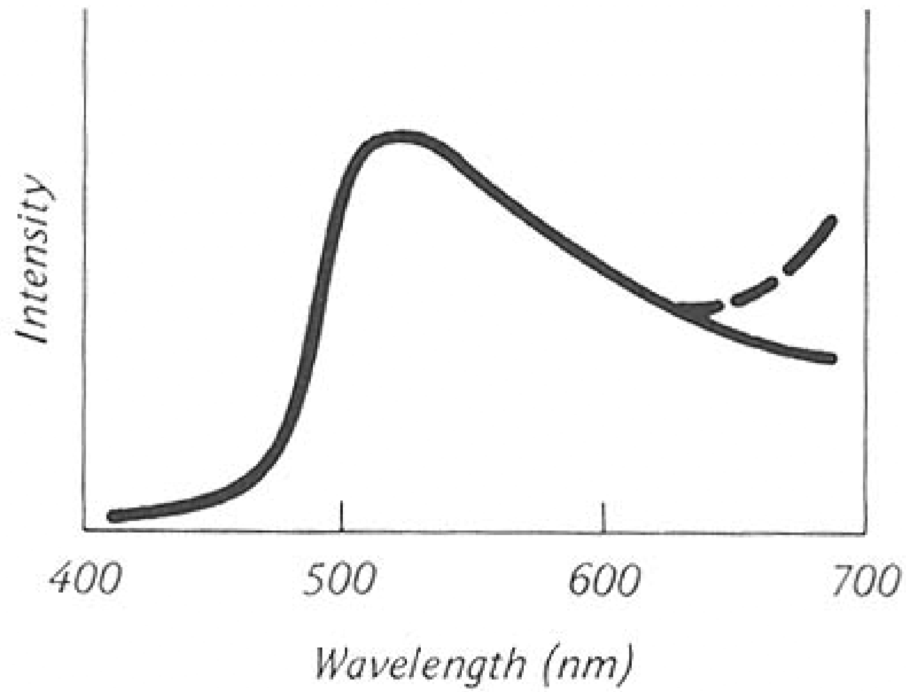


FIGURE 9.2

Intensity-distribution curve. Solid line: the intensity of light, at each visible wavelength, obtained when white light is reflected from a greenish region of Plate 8.4. Dashed line: the same light with a little extra red light mixed in.

Hue

- **Hue**
  - The dominant color or color name
  - This distinguishes one spectral color from another
  - All yellows are different in hue from all blues
  - Defined by the dominant wavelength
    - Actually, this wavelength may be missing from intensity distribution curve

Saturation

- **Saturation is the word that describes the degree to which the light source is monochromatic**

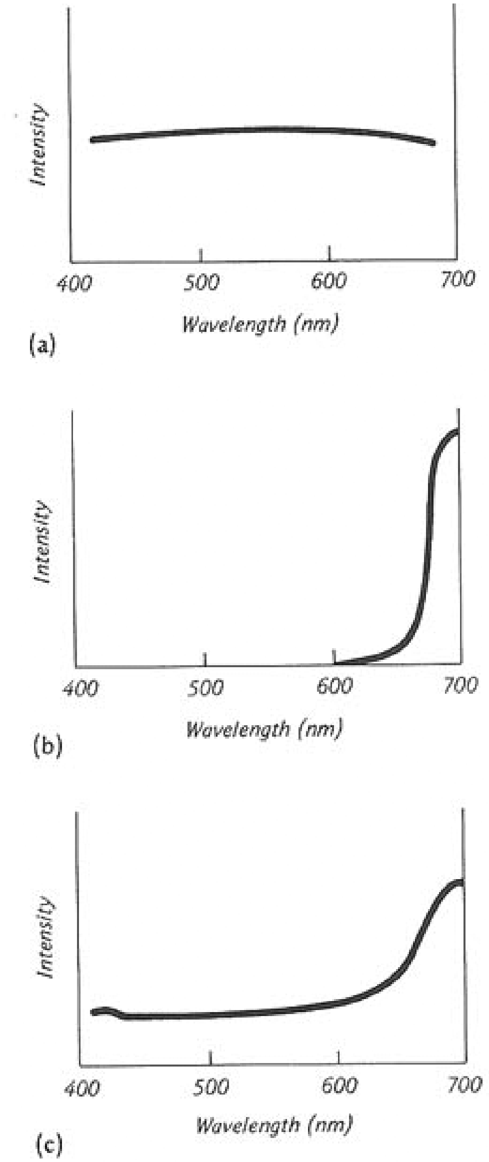


FIGURE 9.3

Saturation. **(a)** White light is completely unsaturated. **(b)** A saturated red light. **(c)** A less saturated red light—pink.

Brightness and Lightness

- **Brightness**
  - Amount of light from light source
- **Lightness**
  - Fraction of light reflected from surface
  - Describes the properties of the reflecting material, not the light source

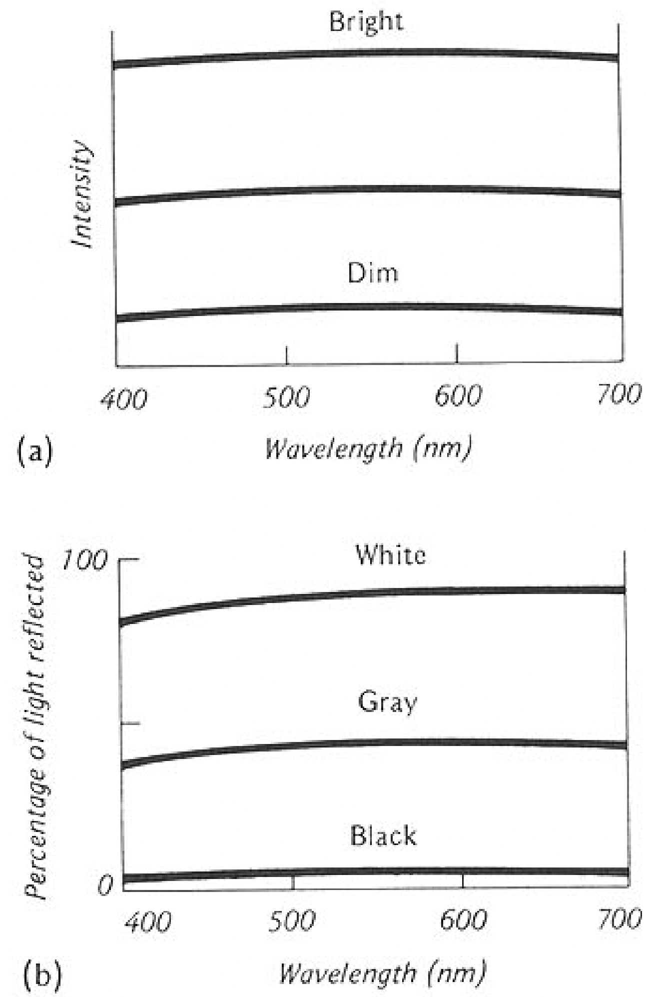
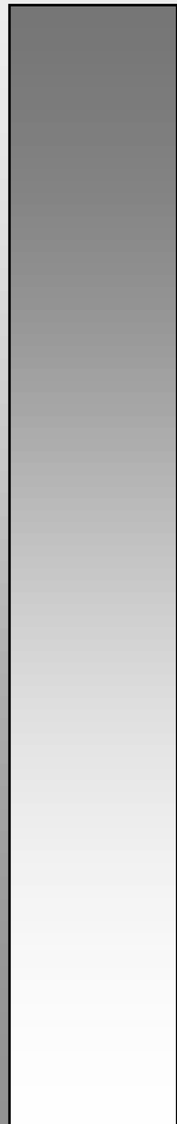
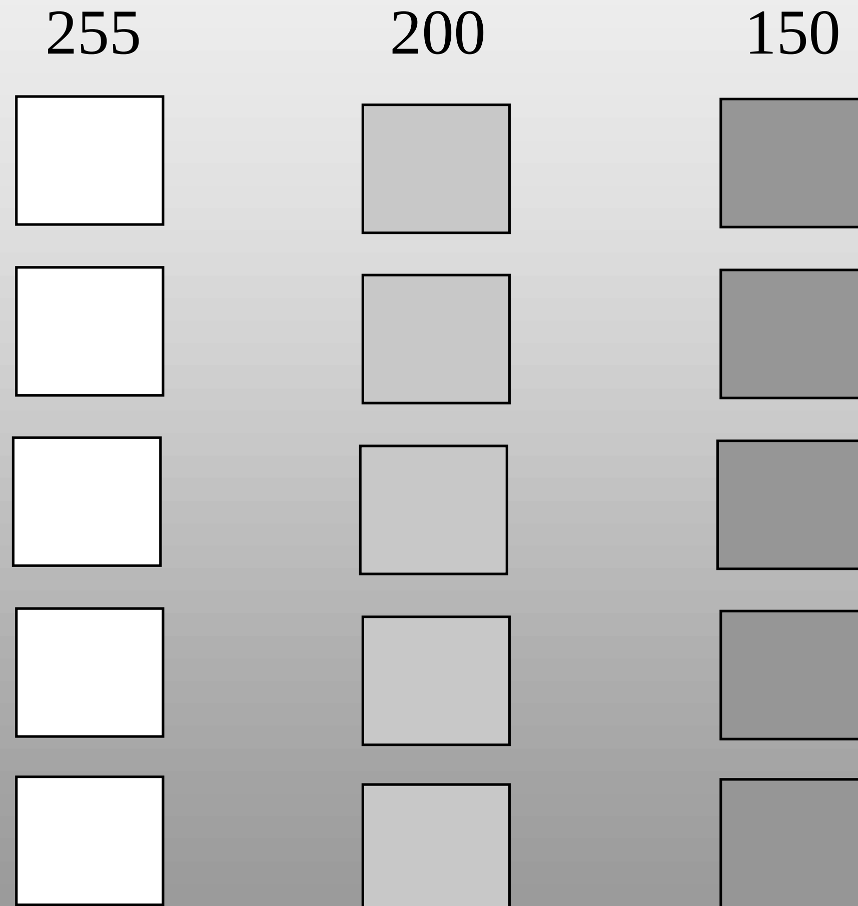


FIGURE 9.4

(a) Brightness of a light. The intensity-distribution curves for three different brightnesses. **(b)** Lightness of a surface. The curves correspond to the percentage of incident light reflected at each wavelength.

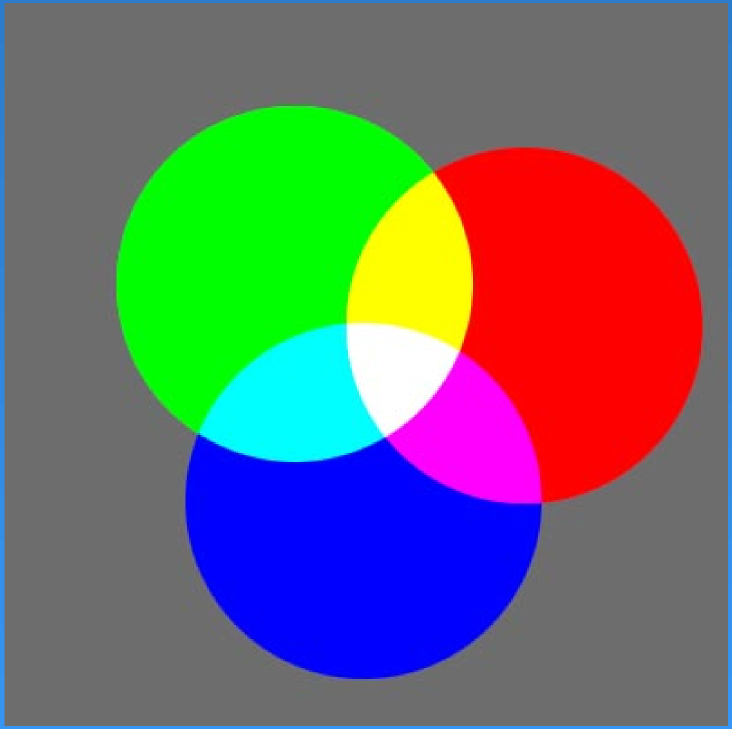
Luminance and lightness





Additive color mixing

- **RGB (red green blue)**
  - R+G+B = W white
  - G + R =Y yellow
  - B + G =C cyan
  - B + R =M magenta
  - follows that
  - B + Y= W
  - R + C = W
  - G + M =W
  - so these are complementary colors



- metamers **are different intensity distribution curves that look identical**

Color tree

- **Color tree represents the three characteristics**
  - Saturation
  - Hue
  - Lightness

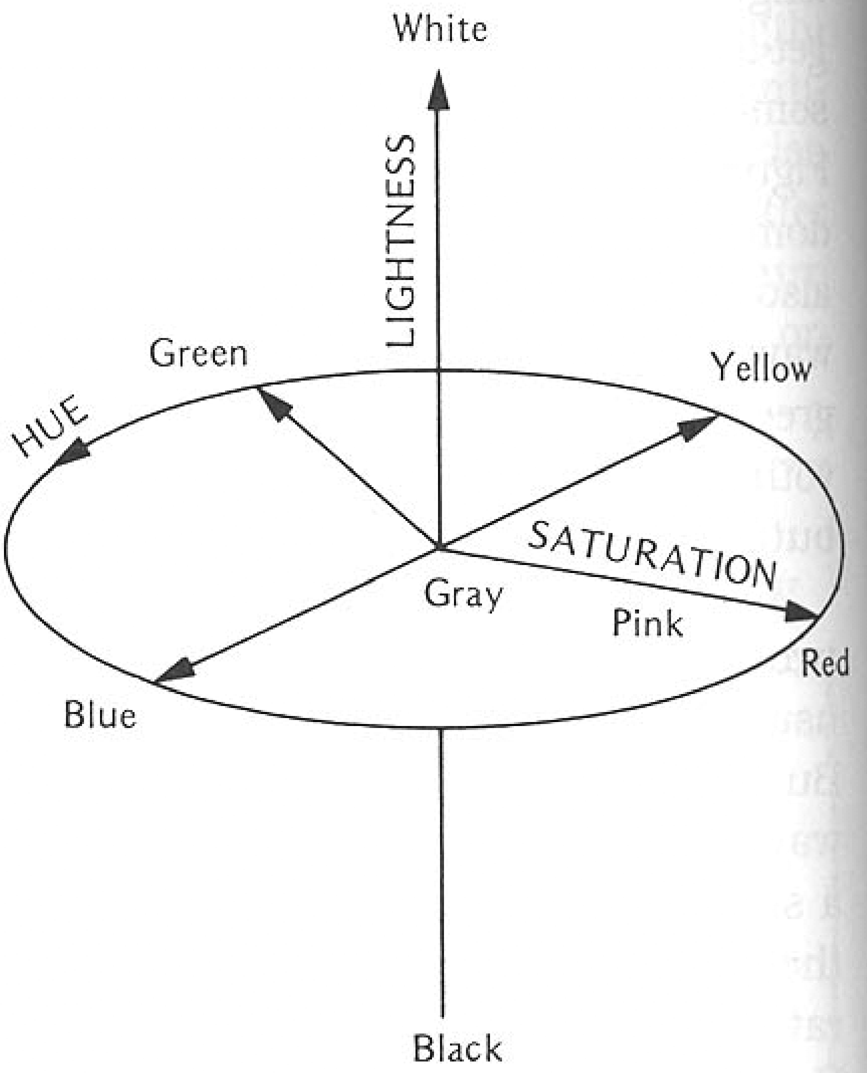


FIGURE 9.5

Schematic drawing of a color tree (compare with Plate 9.1).

- **Intensity plots for additive color mixing**

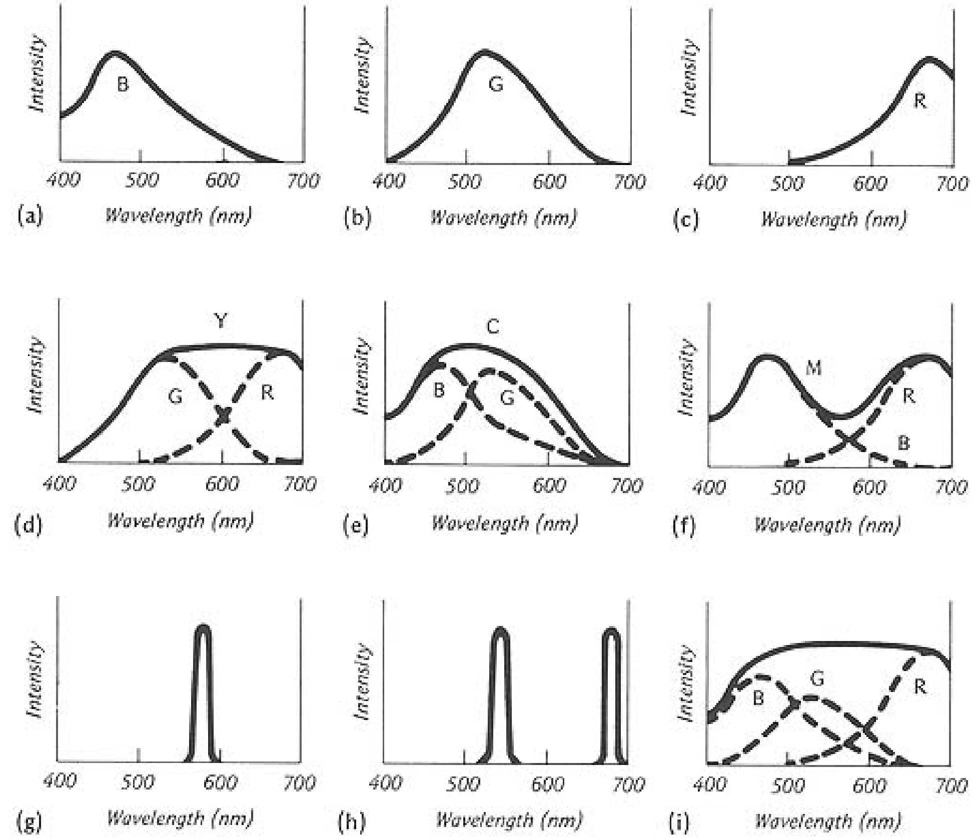


FIGURE 9.6

Additive color mixing. Intensity-distribution curves of **(a)** blue (B), **(b)** green (G), and **(c)** red (R) lights. Intensity-distribution curves of the additive mixtures (in equal amounts) of **(d)** G + R ≡ Yellow (Y), **(e)** B + G ≡ Cyan (C), and **(f)** B + R ≡ Magenta (M). Intensity-distribution curves of **(g)** monochromatic yellow and **(h)** a yellow made of an additive mixture of monochromatic green plus monochromatic red. **(i)** Intensity-distribution curves of the additive mixture of B + G + R ≡ White (W).

- **Additive color mixing "rules"**

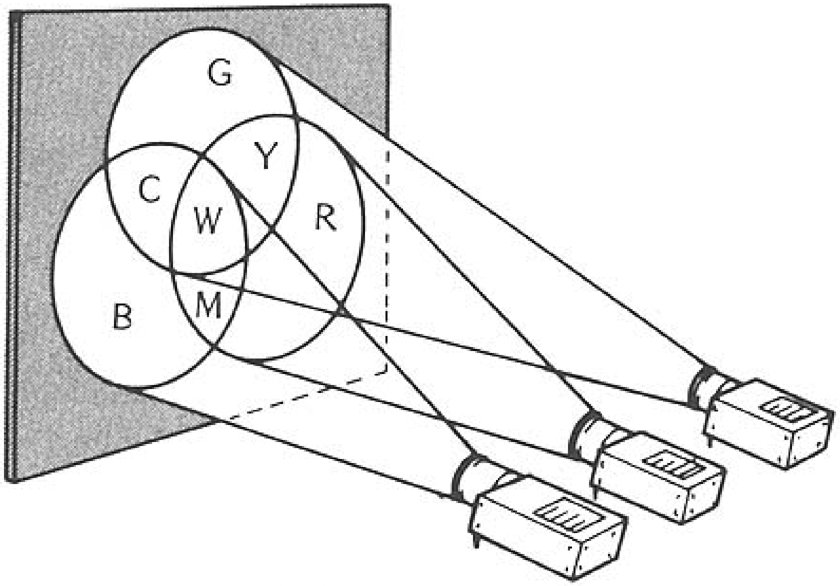


FIGURE 9.7

Simple additive mixing rules. The drawing shows three partially overlapping light beams, which combine additively. B = Blue, G = Green, R = Red, Y = Yellow, C = Cyan, M = Magenta, and W = White:

$$G + R \equiv Y$$
$$B + G \equiv C$$
$$B + R \equiv M$$
$$B + G + R \equiv W$$

Metamers

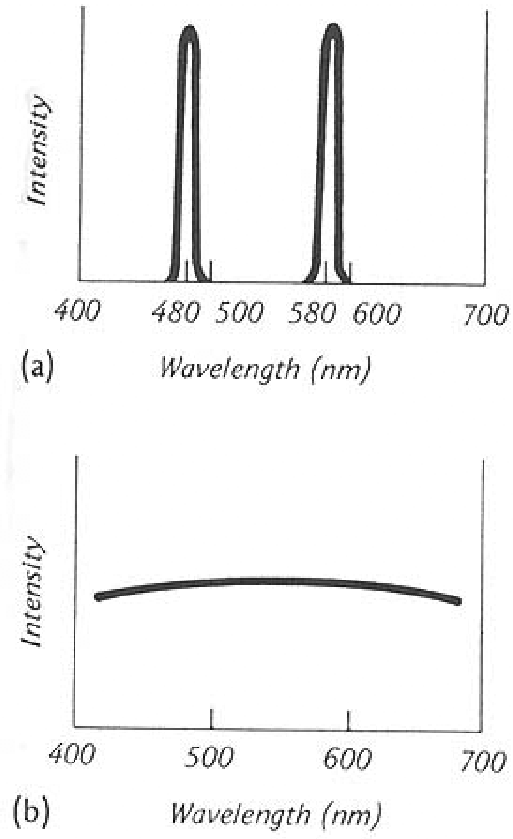


FIGURE 9.8

The lights with these two intensity-distribution curves look alike to your eye, even though one has only two wavelengths present while the other has all visible wavelengths.
(a) Monochromatic blue plus monochromatic yellow. **(b) Broad-band white** (all visible wavelengths).

Complementary colors

- Finding the wavelengths of two complementary colors

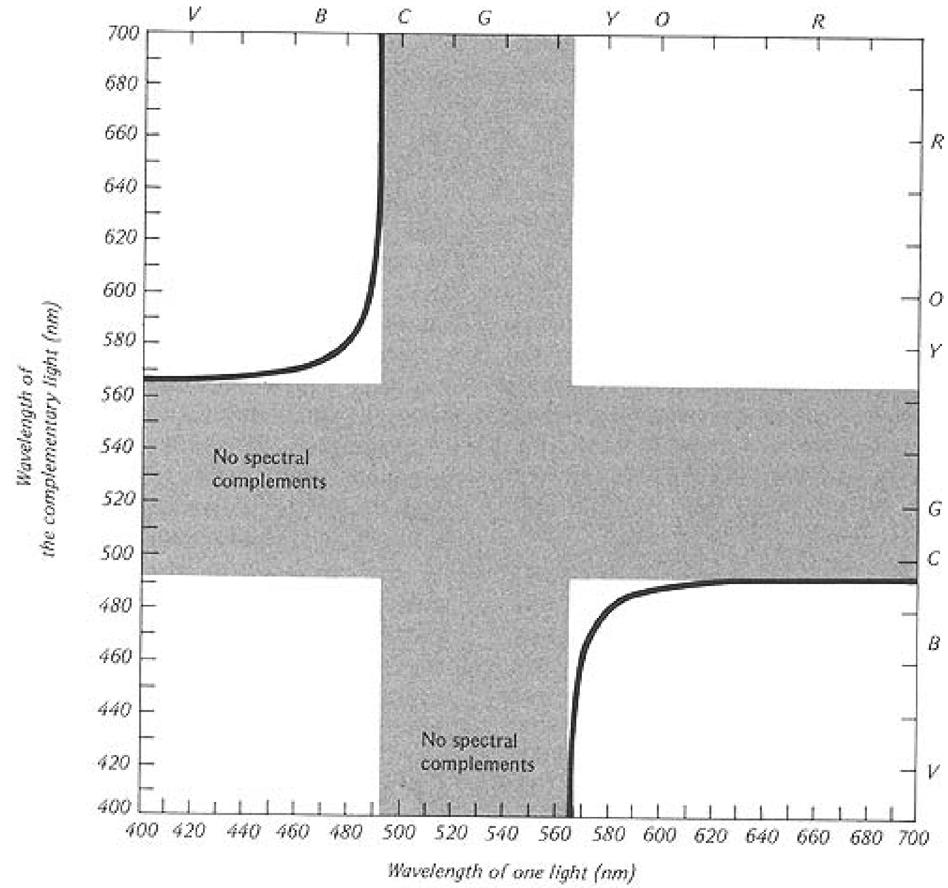


FIGURE 9.9

Wavelengths of complementary pairs of monochromatic colors. To find the complement of a given wavelength, say λ = 600 nm, draw a horizontal line from the 600-nm mark on the vertical axis. Find the point where this line intersects the curve and drop a vertical line from that point to the horizontal axis to determine the wavelength of the complement, λ = 489 nm. Thus, the complement of orange (600 nm) is bluish cyan (489 nm). (V = Violet, B = Blue, C = Cyan, G = Green, Y = Yellow, O = Orange, and R = Red.) The curves depend somewhat on the observer and on the choice of white.

- **Can the sum of 3 colors (RGB) yield any given color?**
  - Almost yes

FIGURE 9.10

The relative amounts of your three colors (460-nm blue, 530-nm green, and 650-nm red) needed to match any monochromatic (spectral) color that we choose. Notice that the required amounts of red and green colors are zero at 460 nm. This is because you can match our 460 nm using only your 460-nm blue. The relative amount of the blue, then, is 100% at that point. Similarly, the blue and red amounts vanish at 530 nm, while the blue and green vanish at 650 nm. (For historical reasons, "equal amounts of blue, green, and red" means that the intensity ratios of blue/green/red are about 1.3/1.0/1.8. The curves shown here and in succeeding figures are standardized; the actual data vary somewhat with observer, intensity of light, etc.)

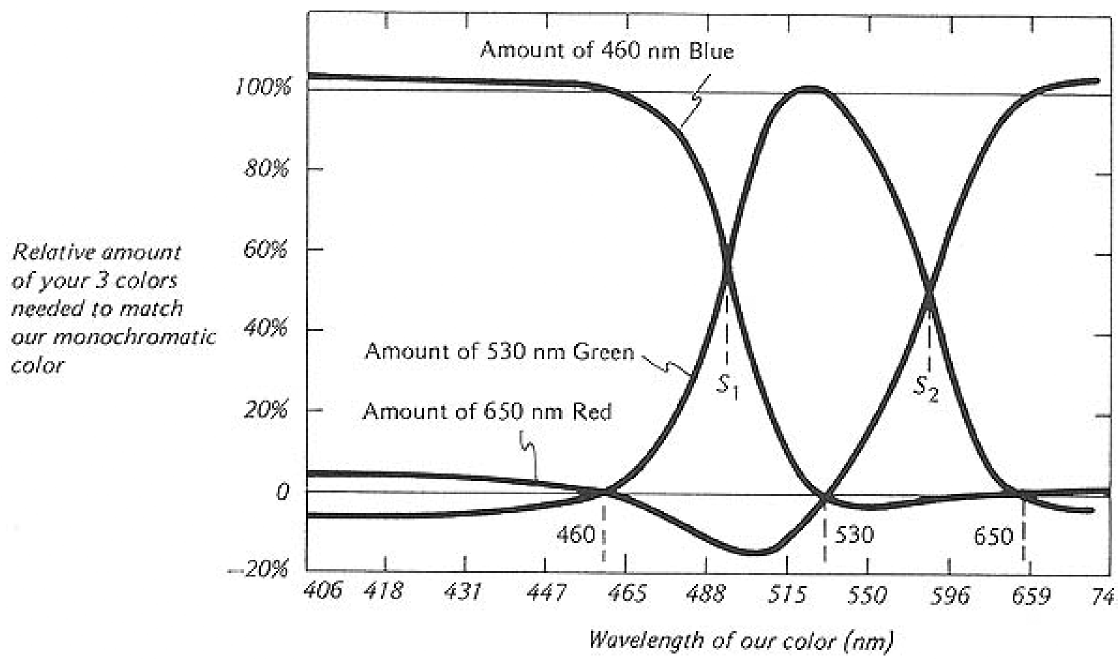
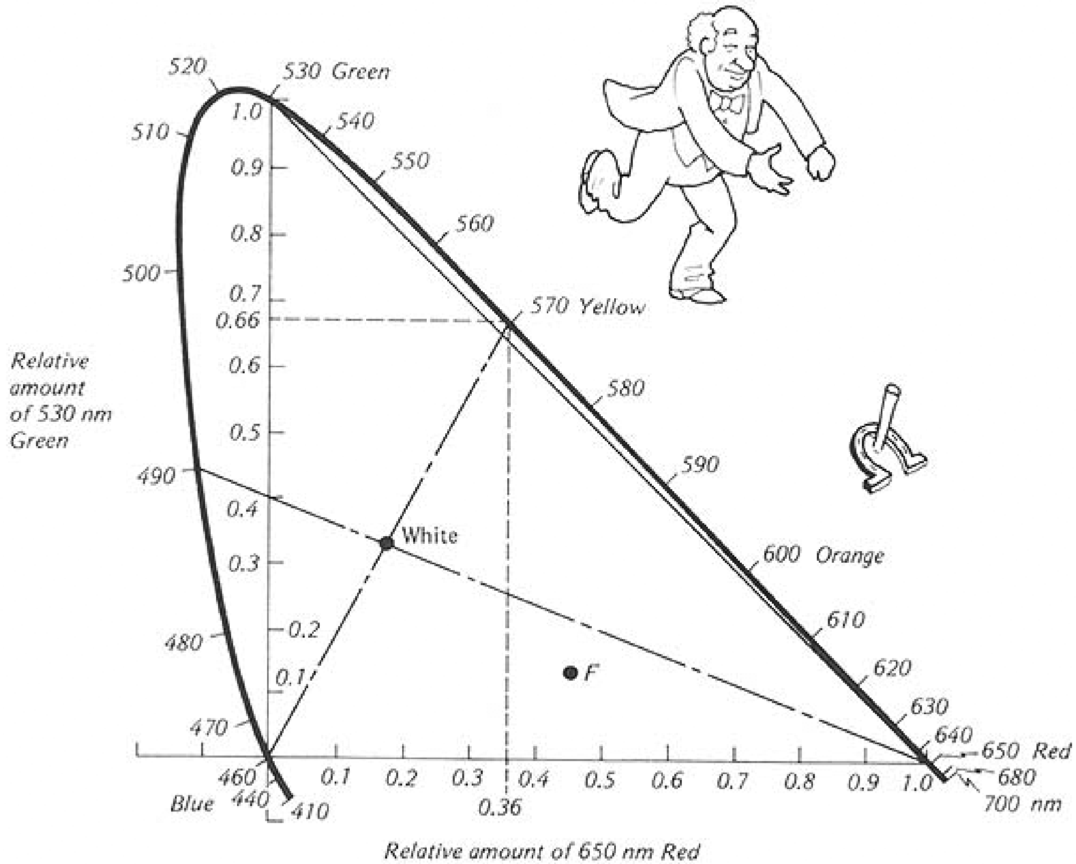


FIGURE 9.11

The relative amounts of 650-nm red and 530-nm green that, along with 460-nm blue, are needed to match any color. The horseshoe curve shows the locations of the spectral color to be matched. To use this, pick a spectral color to be matched, find its location on the horseshoe curve, and read off (by reading down) the amount of red and (by reading across) the amount of green. The amount of blue is determined by subtracting the sum of the green and red from 1.00.



2003 May 29

Chromaticity diagram

- **sum of three colors = 1**
- Horseshoe plot
  - additive mixtures of any two colors lie on a straight line
  - **complement** of any color is found by extending a straight line through white and to the opposite side of horseshoe
  - definition of "**white**"
  - given a color, its **dominant wavelength** can be found by drawing a line from white through the color to the horseshoe.
  - positive addition give everything inside triangle (650, 530, 460), but not everything inside horseshoe.
  - For strictly positive mixing, can invent imaginary colors: tristimulus values X, Y, Z
  - resulting CIE chromaticity diagram, x, y are called the colors **chromaticity**

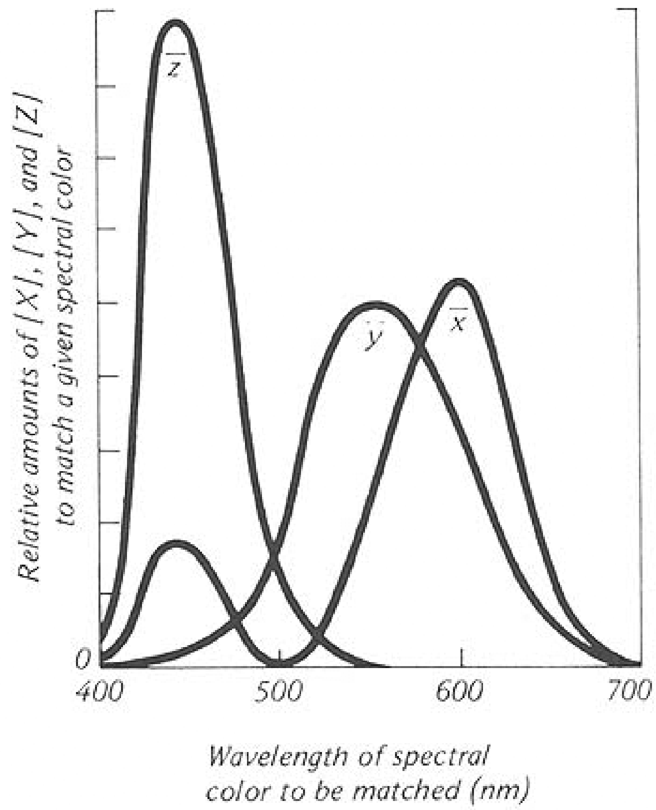


FIGURE 9.12

Tristimulus values: $\bar{x}$, the relative amount of [X], $\bar{y}$, the relative amount of [Y], and $\bar{z}$, the relative amount of [Z], needed to match a given spectral color. The [X], [Y], and [Z] are imaginary primaries, and the curve was not measured but rather was derived mathematically from Figure 9.10 and the definitions of the imaginary primaries.

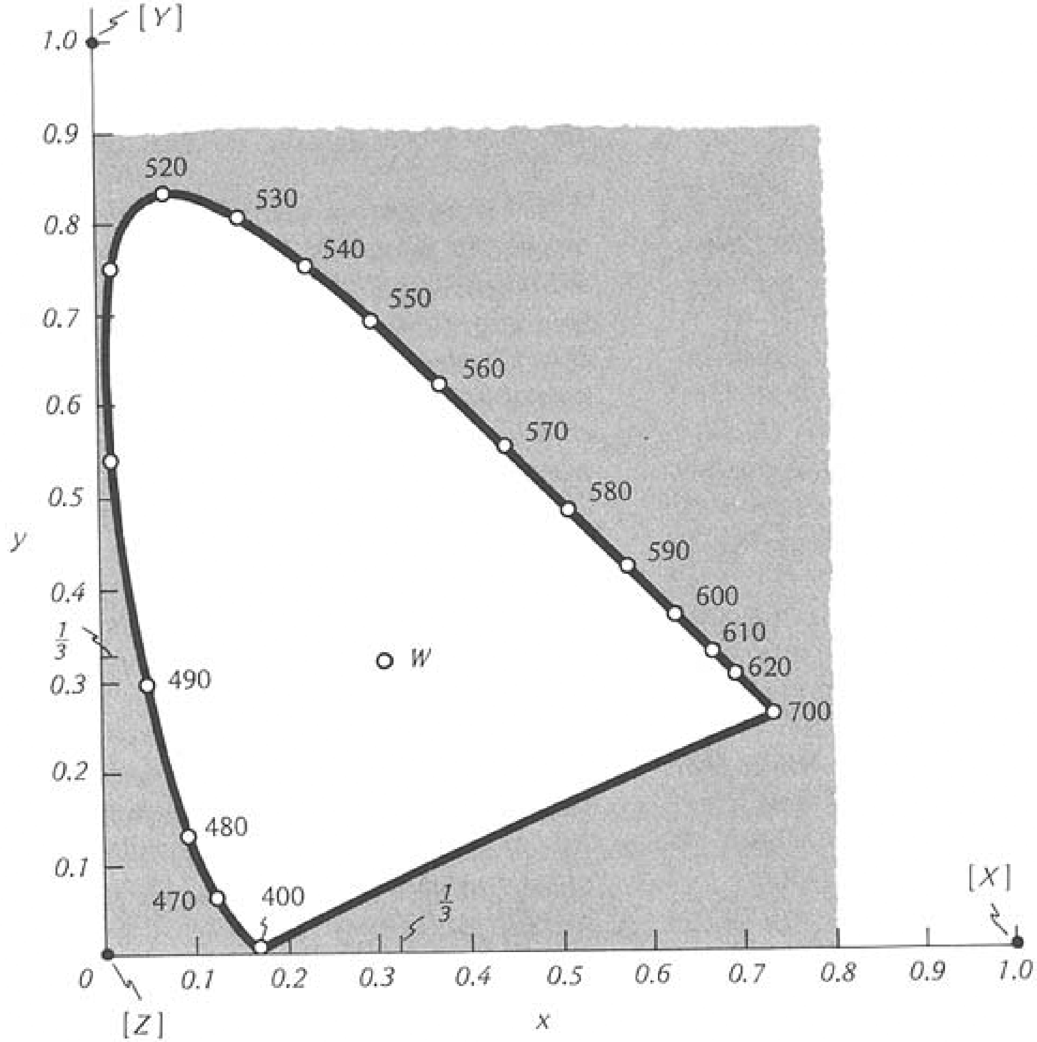


FIGURE 9.13

C.I.E. chromaticity diagram.

filters

- **Properties of filters**
  - Multiply transmission curves to find net transmission

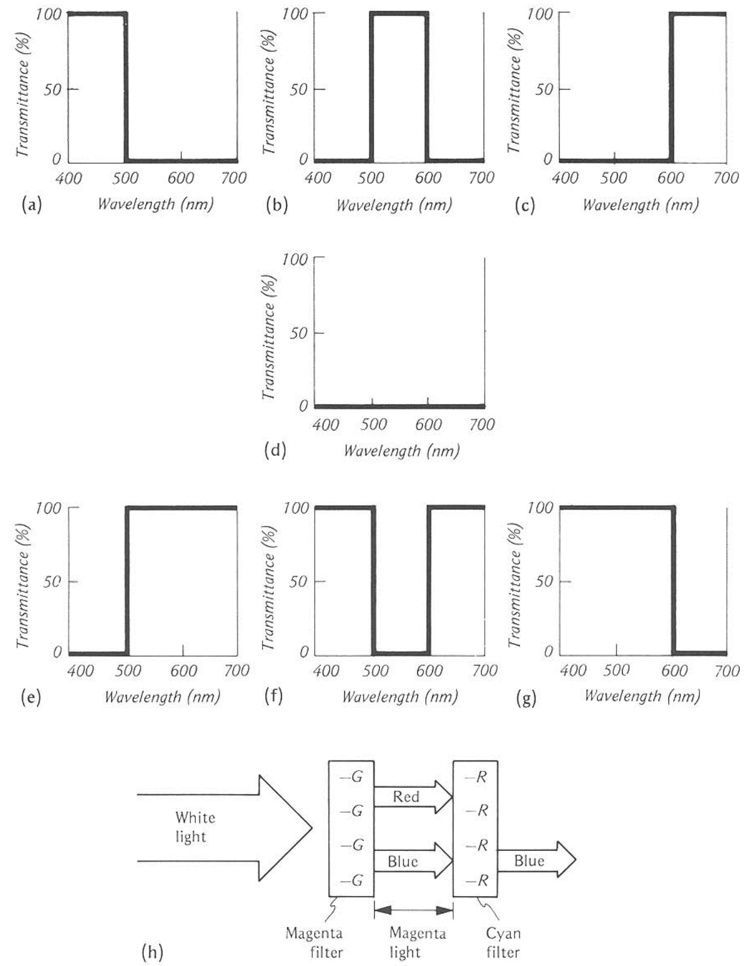


FIGURE 9.14

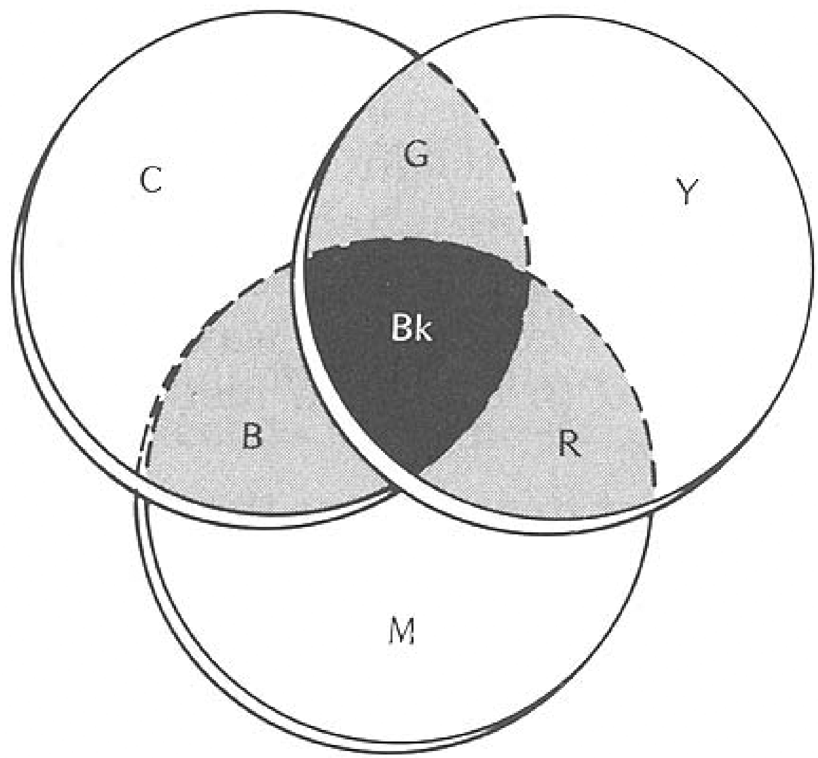
Ideal filters. Transmittance curves of **(a)** an ideal blue filter, **(b)** an ideal green filter, and **(c)** an ideal red filter. **(d)** Result of a subtractive mixture of any two of **(a)**, **(b)**, and **(c)**. Also shown are transmittance curves of filters that transmit the same light as one gets from *additive mixtures of* **(a)**, **(b)**, and **(c)**: **(e)** ideal yellow filter (green plus red ≡ white minus blue), **(f)** ideal magenta filter (blue plus red ≡ white minus green), and **(g)** ideal cyan filter (blue plus green ≡ white minus red). Notice that **(a)**, **(b)**, and **(c)** also give the results of *subtractive* mixtures of **(e)**, **(f)**, and **(g)**. For example, a subtractive mixture of **(f)** and **(g)** gives **(a)**, as shown schematically in **(h)**.

Subtractive colors

FIGURE 9.15

Simple subtractive mixing rules. The drawing shows the effect on white light of three partially overlapping broad-band filters, which produce subtractive mixing:

A subtractive mixture of C and M ≡ B.
A subtractive mixture of C and Y ≡ G.
A subtractive mixture of Y and M ≡ R.
A subtractive mixture of C, Y, and M ≡ Bk (Black).



Color mixing

- **Addition examples:**
  - simple addition: projection TV
  - partitive mixing: regular TV
  - some paintings, some textiles
  - mix in time
- **Subtractive mixing**
  - filters- complex subject in general
  - dyes- substance that absorbs some part of spectrum
  - multiple use of same filter or dye
  - opaque objects get color from absorbed light
  - multiple reflections can change color
    - inside of rose
    - inside of colored cup
  - In general need to multiply the transmittance curves together to find out what happens

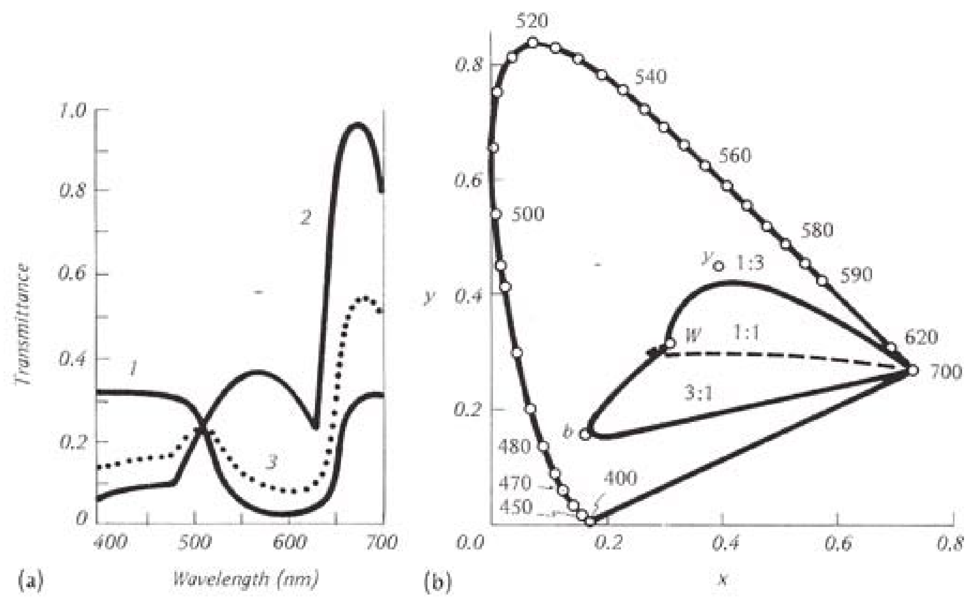
Sources of Illumination

- **Light source can strongly influence the apparent color of an object**
  - To understand what colors will be seen, need to know the intensity distribution curve of the source and the reflecting or transmitting object.
  - Color temperature is useful idea, based on black body appearanc
  - TV studios use 3200° floodlights. Can’t dim them and maintain colors
  - Color film is designed for a given color balance
  - filters on cameras can restore proper color balance when the light source is different than the film is designed for.

dyes

FIGURE 9.17

Subtractive color mixing of two different dyes at various concentrations. **(a)** Transmittance of *(1)* blue and *(2)* yellow dyes at unit concentrations, and *(3)* a one-to-one mixture of the two dyes, also at unit concentration. **(b)** Chromaticity paths as the concentration of mixtures of the two dyes is increased. At very low concentration the dyes are almost transparent, so the illuminating white light passes through unchanged *(W)*. As the concentration is increased, the color becomes more saturated, ultimately becoming red at high concentrations. The path between white and red depends on the ratios of the concentrations of the two dyes. Shown are a one-to-one mixture (1:1), a three-blue-to-one-yellow mixture (3:1), and a one-blue-to-three-yellow mixture (1:3). The points marked *b* and *y* are the colors of the unit concentration dyes shown in **(a)**. Thus, appropriate mixtures of these yellow and blue dyes result in almost any color in the lower half of the chromaticity diagram, but *not* the green one might expect from blue and yellow!



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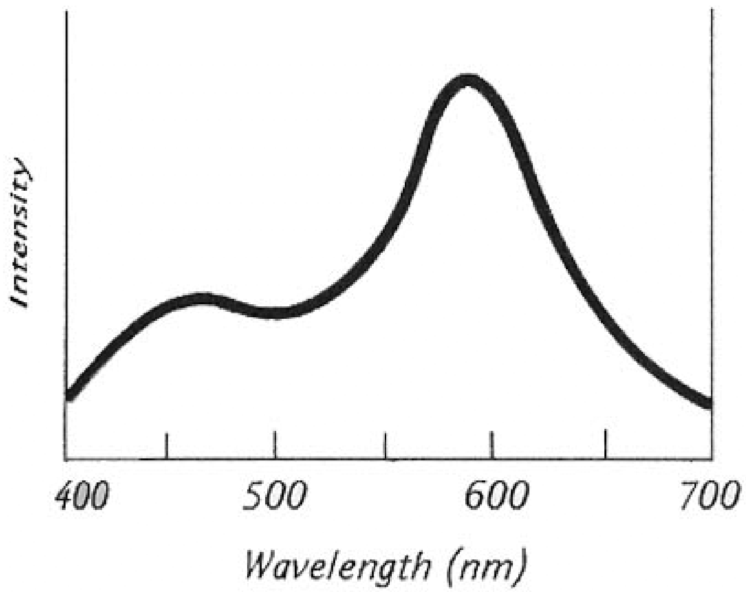
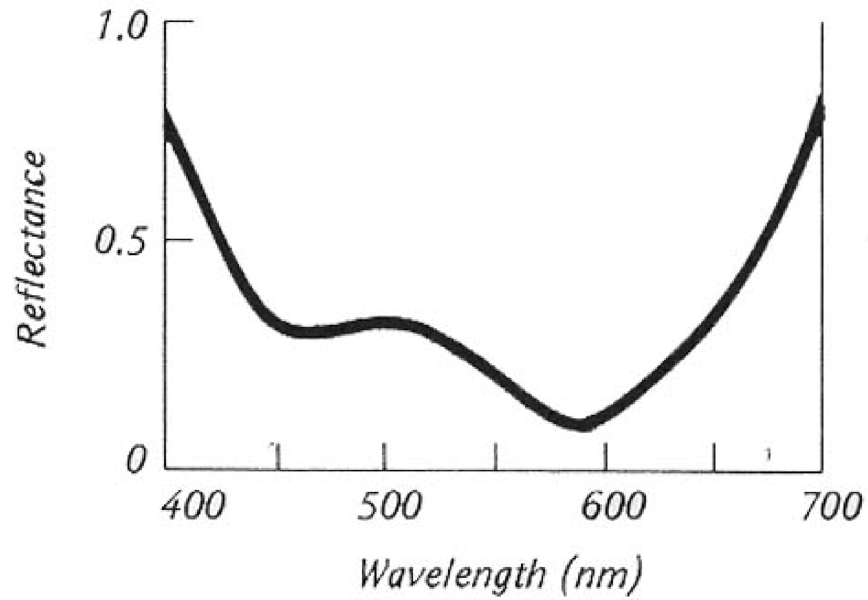
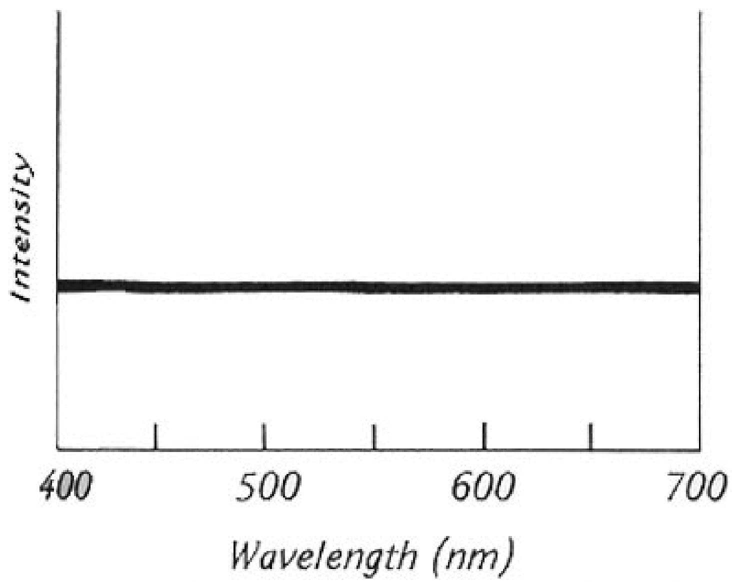


(a)



(b)



(c)

FIGURE 9.18

(a) Intensity-distribution curve of light from a Cool White fluorescent tube. **(b)** Reflectance curve of a magenta object. **(c)** The intensity-distribution curve of the light from that object under Cool White fluorescent illumination is given by the product (at each wavelength) of curves **(a)** and **(b).** Under this illumination, the object loses all hue.

- **Hue and reflectance**

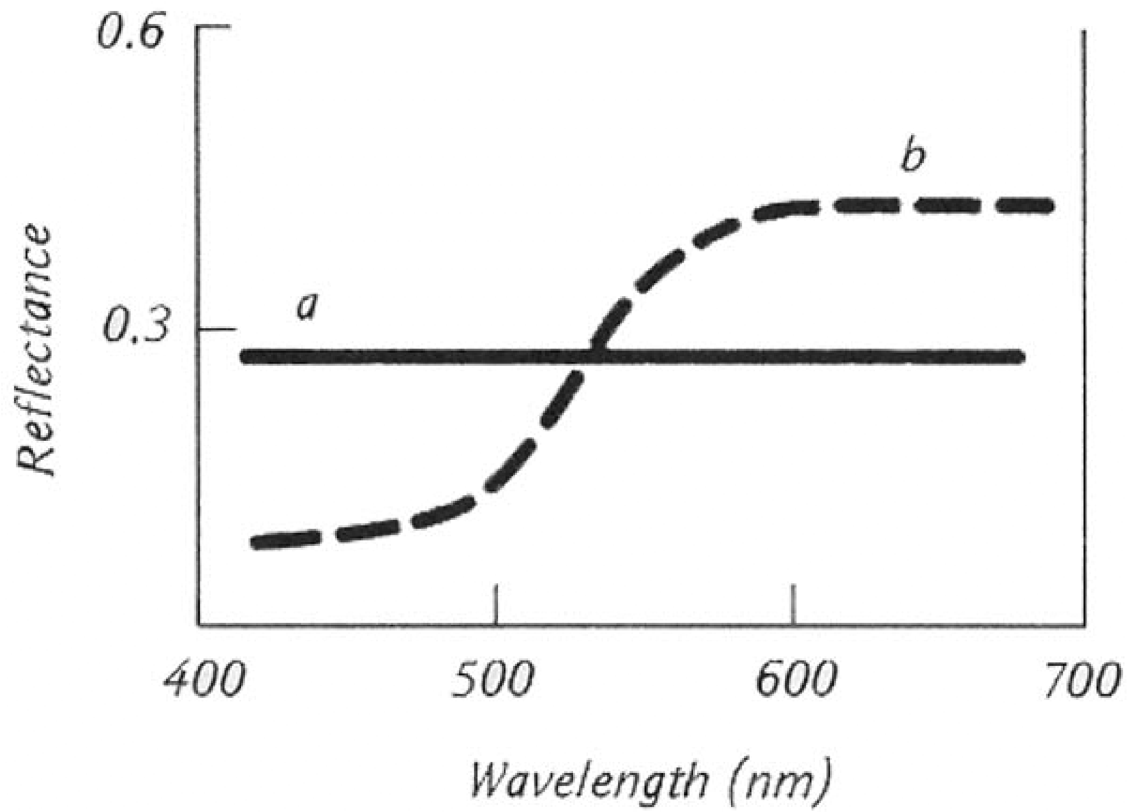


FIGURE 9.19

The reflectance curves of two pieces of cloth. In sunlight, *a* looks gray, *b* looks brown. Under incandescent illumination, which lacks the short-wave end of the spectrum, both have the same hue.

Intensity distribution of light sources

- **Intensity distribution of different light sources**
  - Incandescent bulb
  - Fluorescent tube
  - High intensity discharge lamp

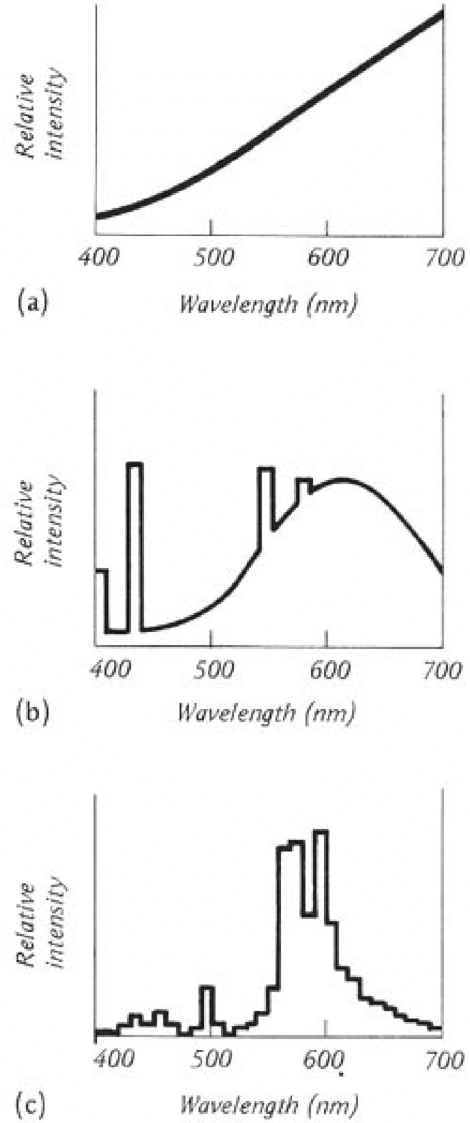


FIGURE 9.20

Intensity-distribution curves of white-light sources: **(a)** 100-W incandescent bulb, **(b)** Delux Warm White fluorescent tube, **(c)** 400-W high-pressure sodium high-intensity discharge lamp.

- **CIE diagram showing black body location**

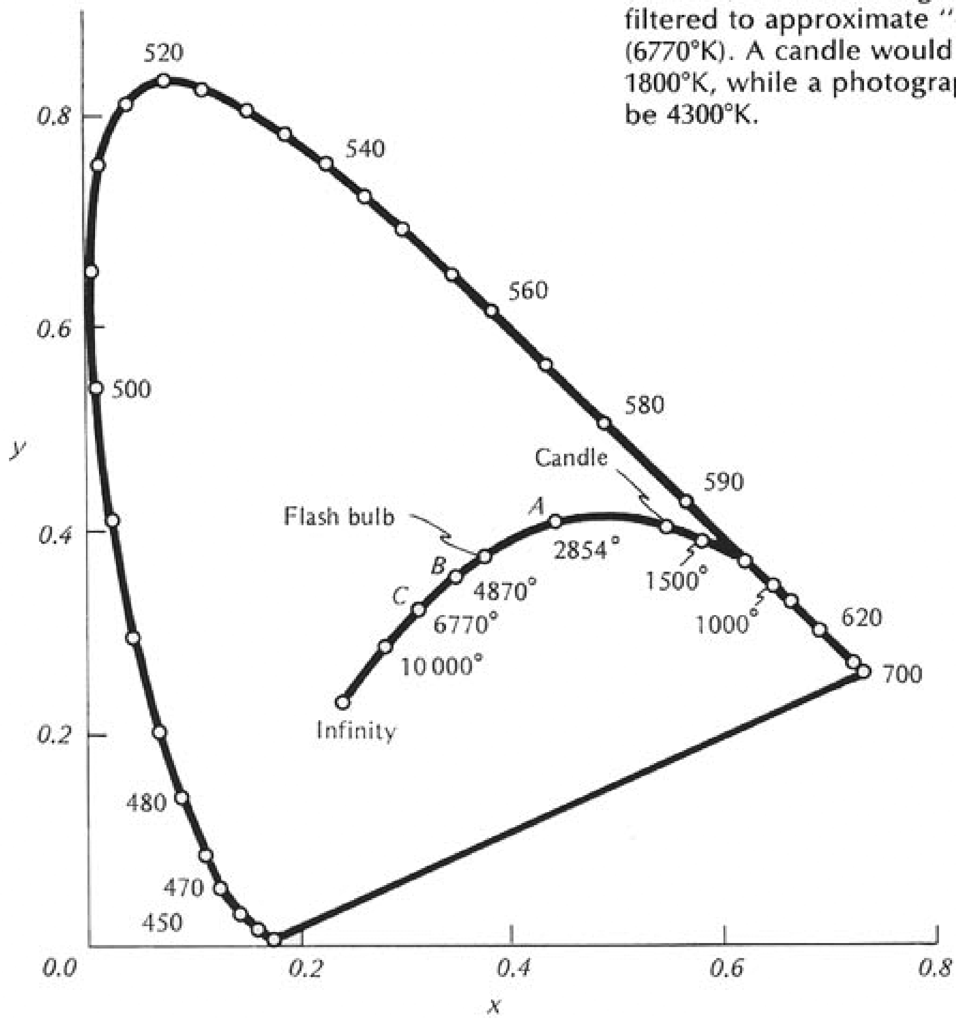
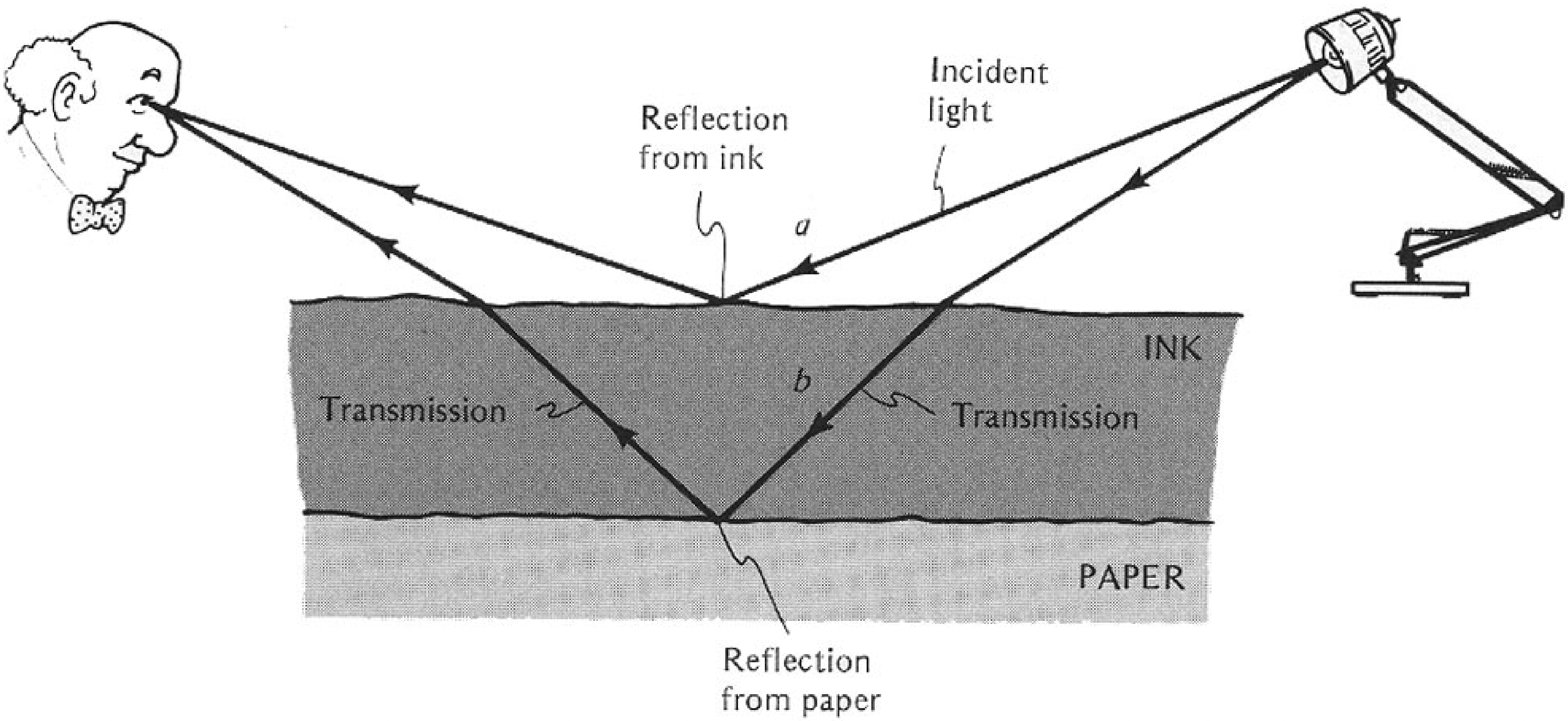


FIGURE 9.21

The location of the color of the light from incandescent sources at various temperatures. The temperature is in **degrees Kelvin (°K),** where °K = °C + 273. Shown are three standard white sources: *A* = tungsten filament (2854°K), *B* = noon sunlight (4870°K), and *C* = tungsten filament filtered to approximate "daylight" (6770°K). A candle would be about 1800°K, while a photographic flash would be 4300°K.

FIGURE 9.22

Color from printer's ink. Ray *a* reflects from the ink. Ray *b* passes through the ink, is reflected by the paper, and passes through the ink again. Each reflection or transmission produces color by a subtractive process, but rays *a* and *b* combine additively (partitive mixing).



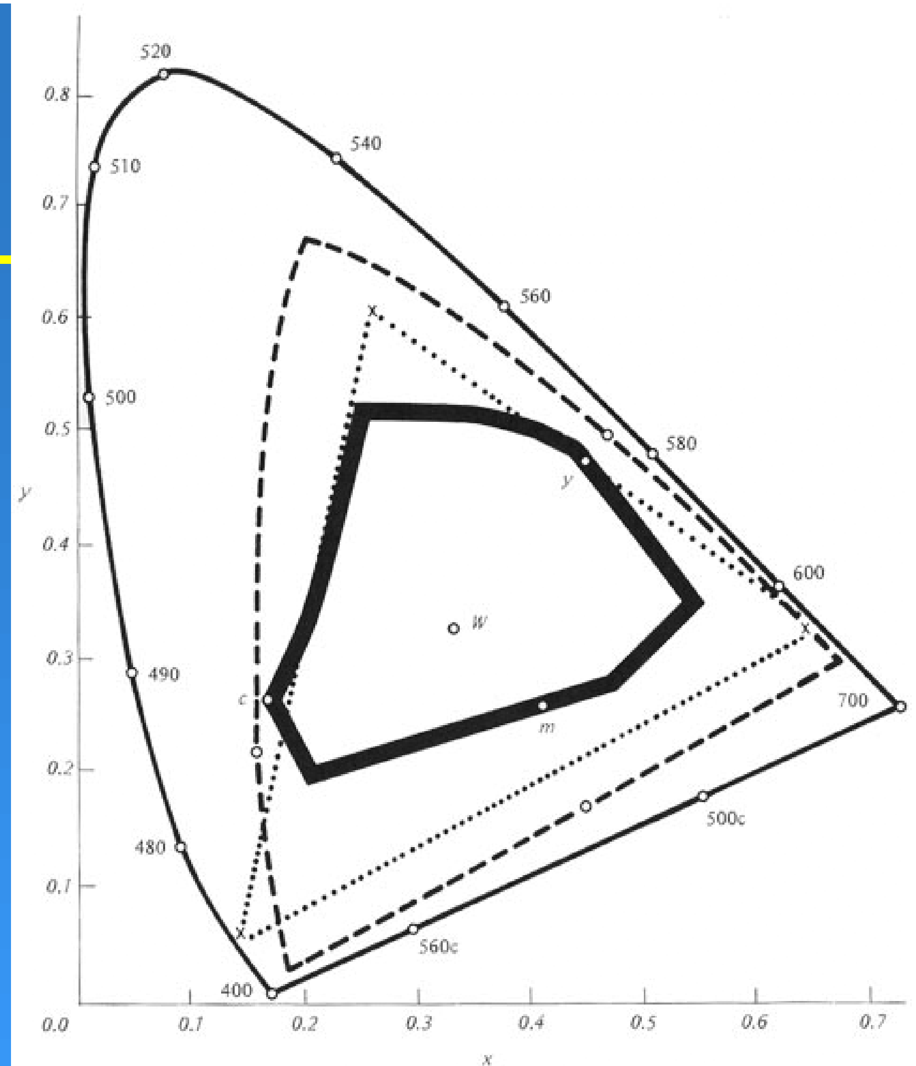


FIGURE 9.23

Media colors. Inside the heavy boundary are the colors that can be printed using the subtractive primaries. The colors of the full-strength inks are indicated: y = yellow, m = magenta, c = cyan. Inside the dotted triangle are the colors available in color TV, with the colors of the three phosphors marked by x's. Inside the dashed curve are the colors available in photographic slides, with the colors of the three dyes marked by small circles.

- **Half tone printing**

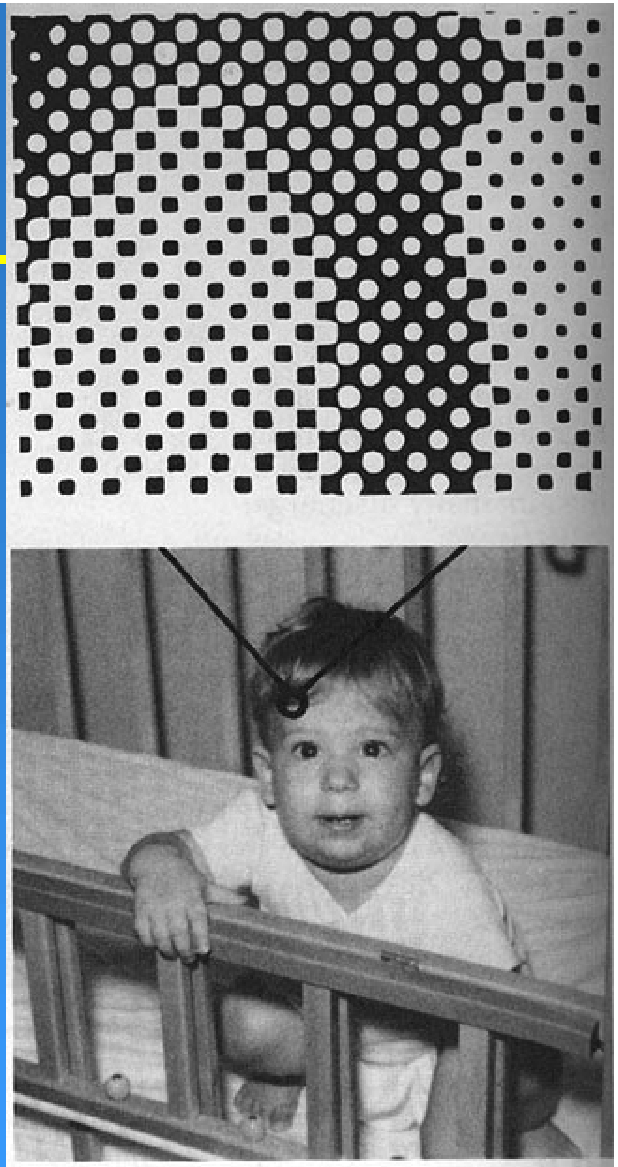
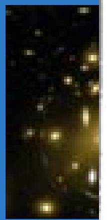


FIGURE 9.24

Close-up of a halftone picture.



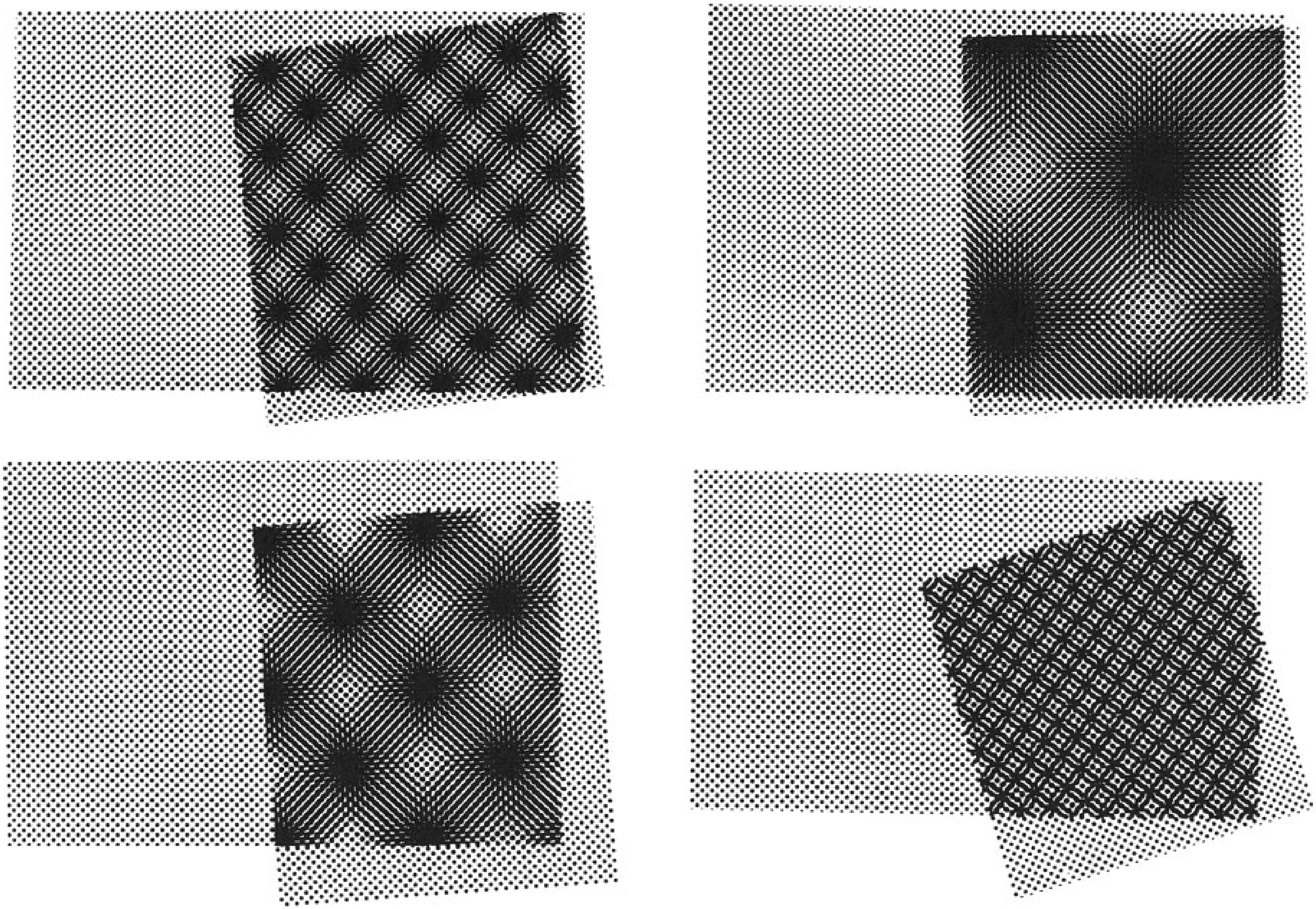


FIGURE 9.25

Halftone arrays at different angles produce different moiré patterns.

Circular halftones

FIGURE 9.26

Dramatic effects of a circular halftone screen.

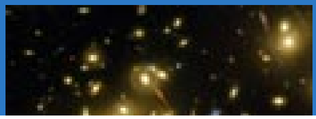


FIGURE 9.30

Some of the processes contributing to the color of paint. Incident light *(I)* strikes the paint, some of it *(1)* is reflected at the surface of the vehicle, some *(2, 3, 4)* continues to a pigment particle. There it may be selectively reflected or transmitted. It may go on to strike the support *(2)*, another pigment particle *(3)*, or go directly to the viewer *(4)*. Each process may impart a different intensity distribution to the light. The successive reflections *(A* and *B)* and the transmission followed by reflection *(C* and *D)* constitute subtractive mixing. The different rays headed toward the viewer *(1, 2, 3,* and *4)* combine additively, if they are close to each other.

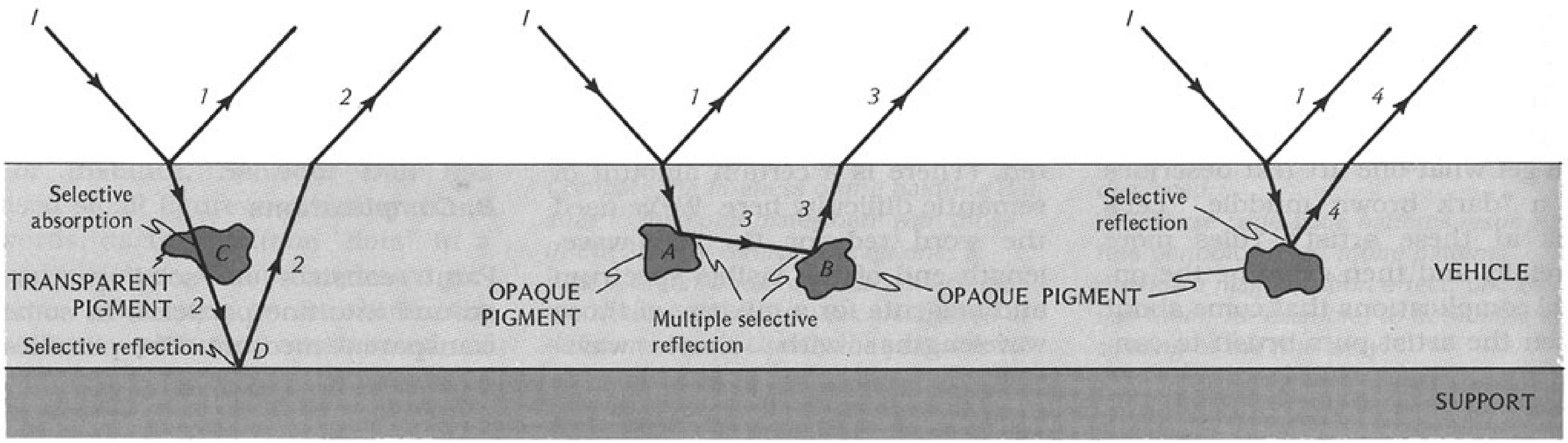
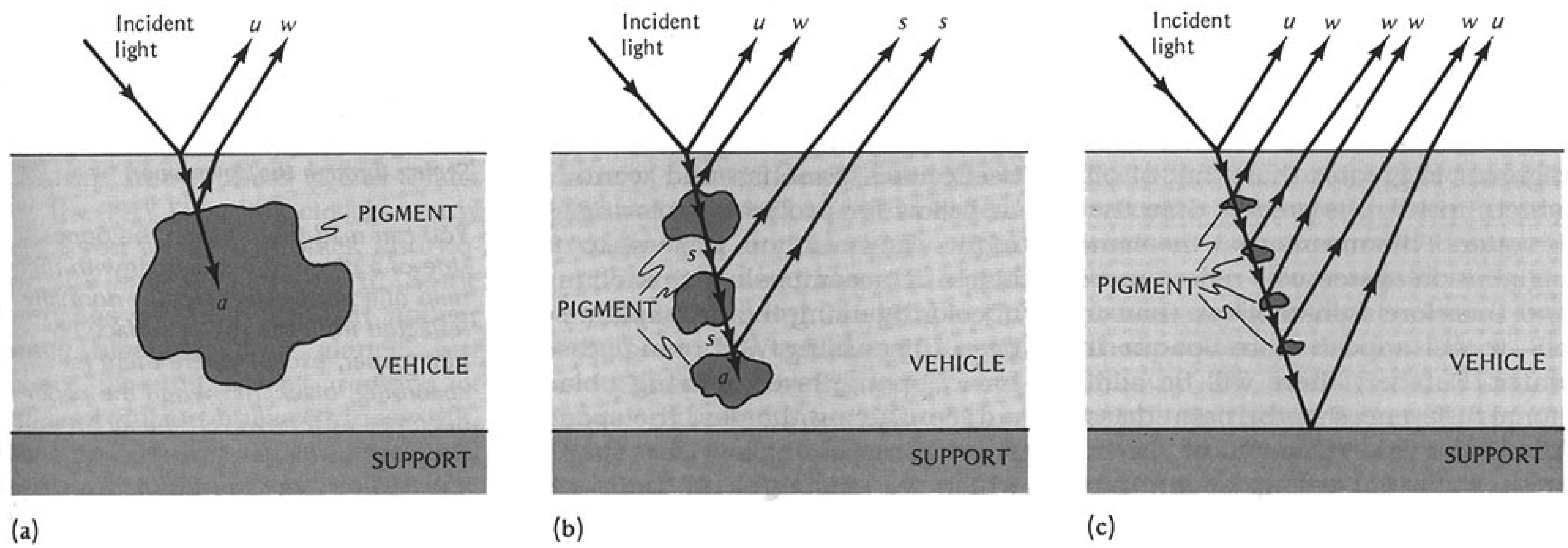


FIGURE 9.31

Dependence of color on the size of the pigment particles. The light reflected from the vehicle is unsaturated *(u)*, and that from the pigment is only weakly saturated *(w)*. Light passing through the pigment is selectively absorbed. After traversing enough pigment, it is all absorbed *(a)*, but if it escapes the pigment, the transmitted beam is saturated *(s)*. All reflected light combines in an additive mixture here. **(a)** Large pigment particles result in a darker, unsaturated color. **(b)** Smaller pigment particles result in a lighter, more saturated color. **(c)** A fine powder gives a still lighter but unsaturated color.



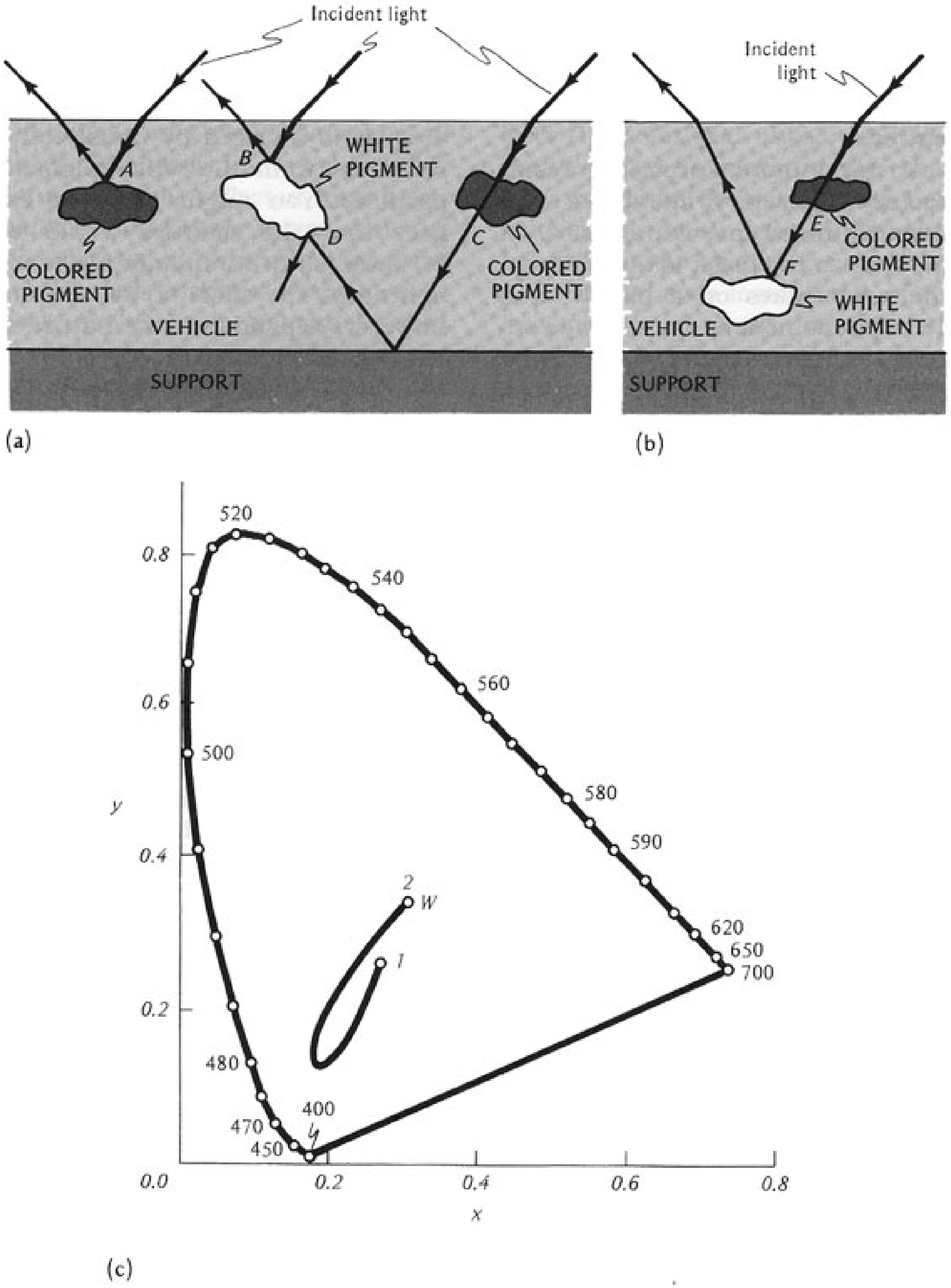


FIGURE 9.32

(a) White pigment mixed with colored pigment of *low* hiding power. The colored reflection, *A*, is weak but selective. The white reflection, *B*, is strong and nonselective, decreasing the saturation. Further, the selective transmission of the colored pigment, *C*, which is reflected by the support, is blocked by the opaque white pigment, *D*, further decreasing the saturation. **(b)** White pigment mixed with colored pigment of *high* hiding power. Here the colored pigment transmits less light than in **(a).** Had the selectively transmitted light, *E*, struck another colored pigment particle, it would have been absorbed. Instead, it strikes the highly reflecting white pigment particle and is reflected, *F*, thus increasing the saturation. **(c)** The path in the chromaticity diagram of the color of a mixture of high hiding power blue paint, *1*, with white paint, *2*, as more and more white is added. First the saturation increases and then it decreases. (Of course, since the lightness increases, this really should not be drawn on one chromaticity diagram.)

Surface reflections and Illumination of object

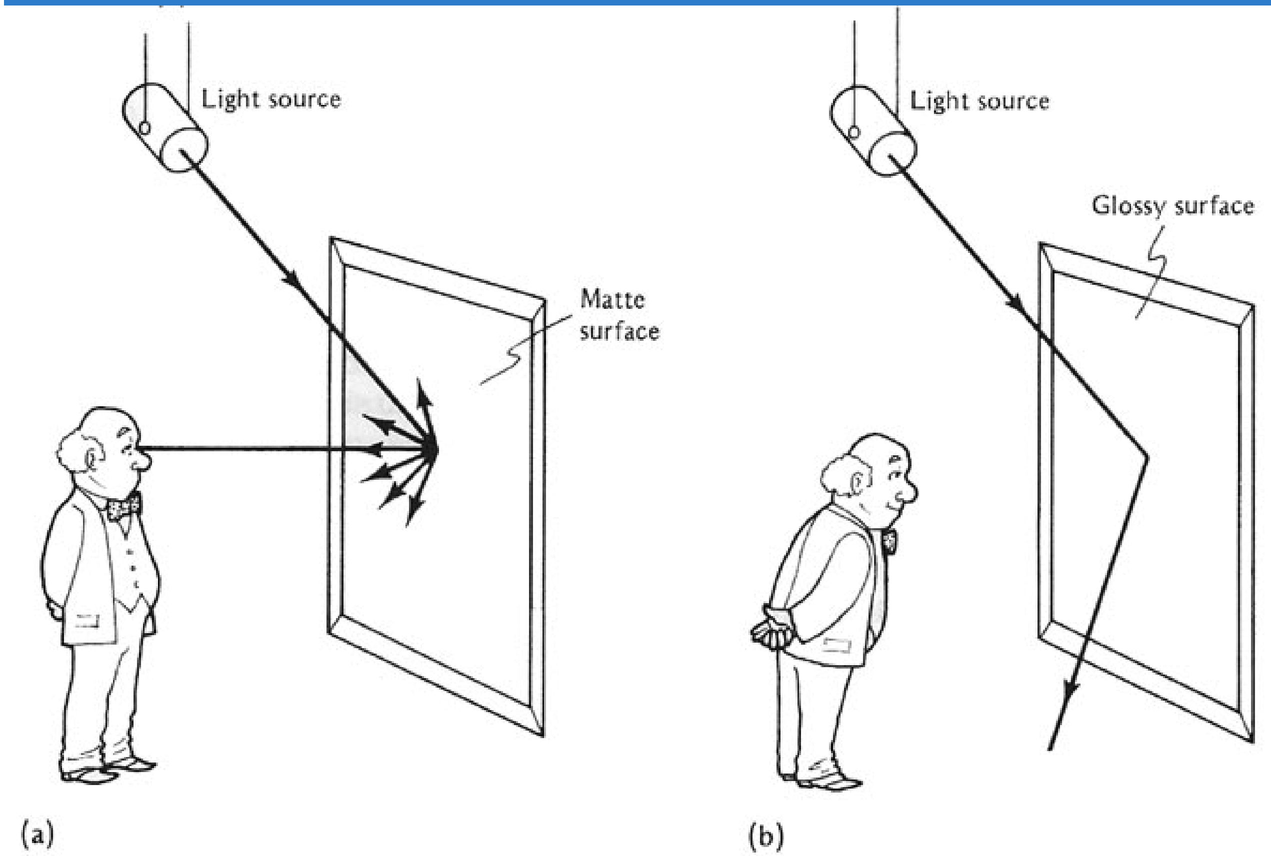


FIGURE 9.33

Surface reflections. **(a)** Diffuse reflections from a matte surface are seen by the viewer no matter where he stands (likewise, he sees the light scattered by the pigment). **(b)** Properly located, the viewer does not see the specular reflections from a glossy surface (but does see the light scattered by the pigment).

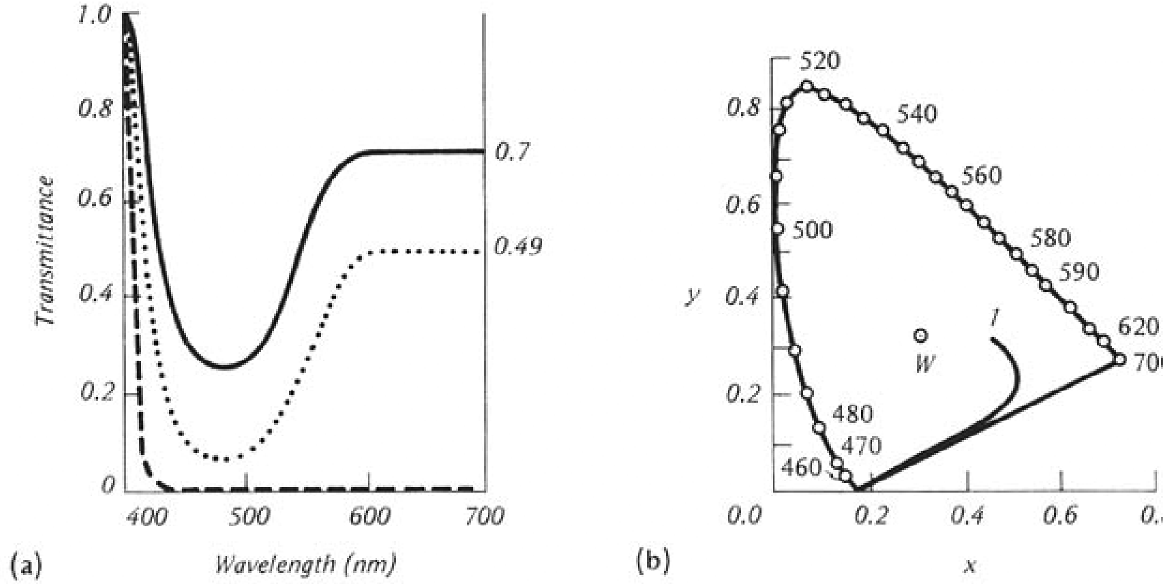


FIGURE 9.16

Subtractive mixing of a color with itself. **(a)** Transmittance curve of one filter (solid line); of two identical such filters, one behind the other (dotted line); and of many identical such filters, one behind the other (dashed line). Here, instead of giving the percentage of incident light transmitted at each wavelength, we give the *fraction* transmitted. That is, we've simply changed from percentage to decimal equivalent. **(b)** Path, in the chromaticity diagram, of the color of the light transmitted as more and more filters are used and the intensity of the incident light is increased proportionally. One filter gives a desaturated orange (the point marked *1*). Several filters give an unsaturated purple. Many filters result in a monochromatic violet.