Digital Image Processing

Color

Outline

- Color and electromagnetic spectrum
- Primary colors(原色)
- Chromaticity diagram(色度图)
- Color models
  - RGB model
  - CMY model
  - HSI model
- Color Image

Color spectrum(色谱)

- When passing through a prism(棱镜), a beam of sunlight is decomposed into a spectrum of colors : violet, blue, cyan, green, yellow, orange, red

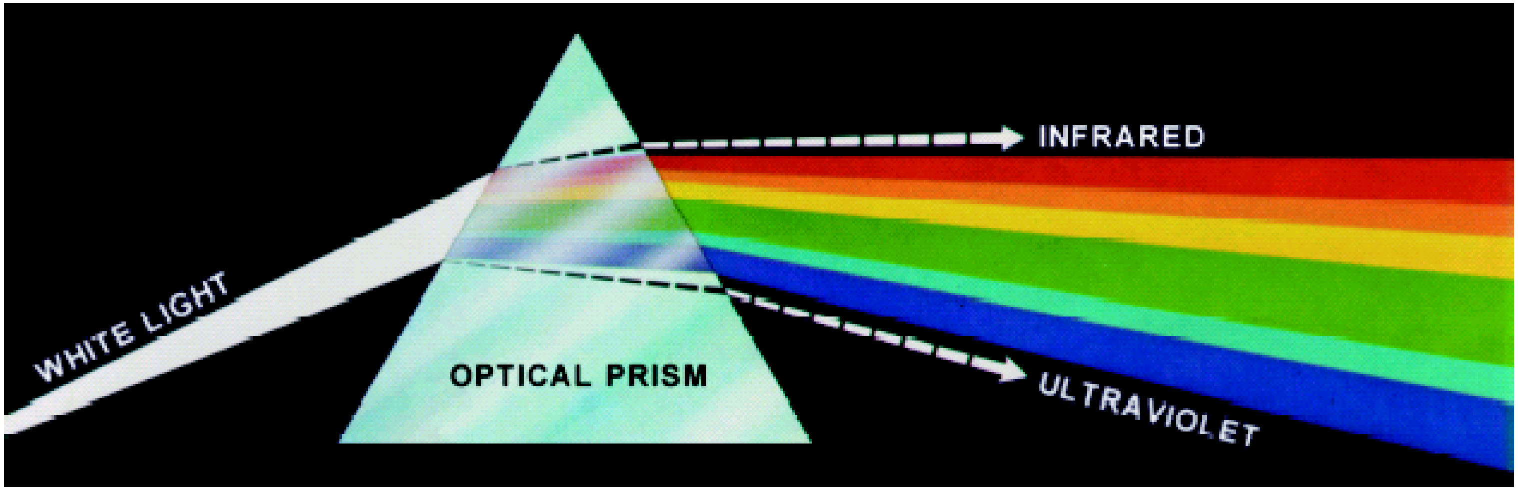


FIGURE 6.1 Color spectrum seen by passing white light through a prism. (Courtesy of the General Electric Co., Lamp Business Division.)

Electromagnetic spectrum(电磁波谱)

- Ultraviolet(紫外) – visible light(可见) – infrared(红外)
- The longer the wavelength (meter), the lower the frequency (Hz),

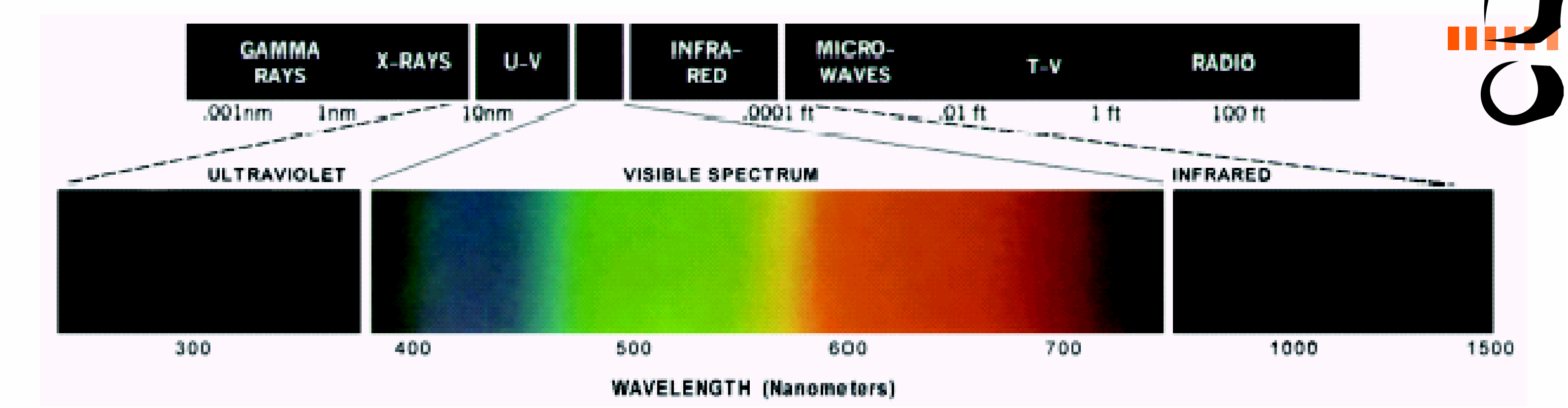


FIGURE 6.2 Wavelengths comprising the visible range of the electromagnetic spectrum. (Courtesy of the General Electric Co., Lamp Business Division.)

Questions

- What does it mean when we say an object is in certain color?
- Why the primary colors of human vision are red, green, and blue?
- Is it true that different portions of red, green, and blue can produce all the visible color?
- What kind of color model is the most suitable one to describe the human vision?

Light

- Light is the electromagnetic radiation that stimulates human visual systems which respond to EM wave of $\lambda \in [350nm, 780nm]$.
- The power density(辐射度) of light $c(\lambda)$ from an object can be measured by *radiometric units(辐射度单位)* such as radiant flux, irradiance or watt/m3.
- The light intensity(光强) perceived by human or illuminationcan be measured by the basic *photometric unit* lux or lumen/m2.

Human perception of color

- Retina(视网膜) contains photo receptors
  - Rods(视杆细胞): night vision, perceive brightness only
  - Cones(视锥细胞) : day vision, can perceive color tone
  - Cones are divided into three sensible categories
    - 65 % percent of cones are sensible to red light
    - 33 % percent of cones are sensible to green light
    - 2% percent of cones are sensible to blue light
  - Different cones have different frequency responses
  - Tri-receptor theory of color vision: the perceived color depends only on three numbers, Cr, Cg, Cb, rather than the complete light spectrum.

Color Processing

requires some knowledge of how we see colors

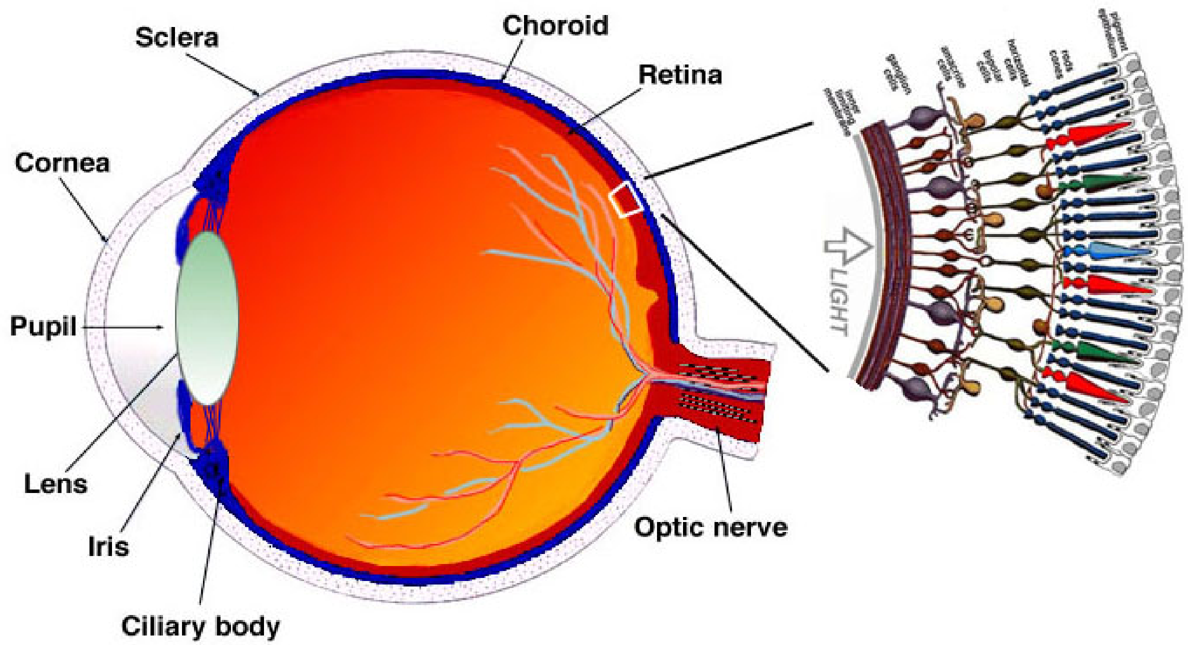
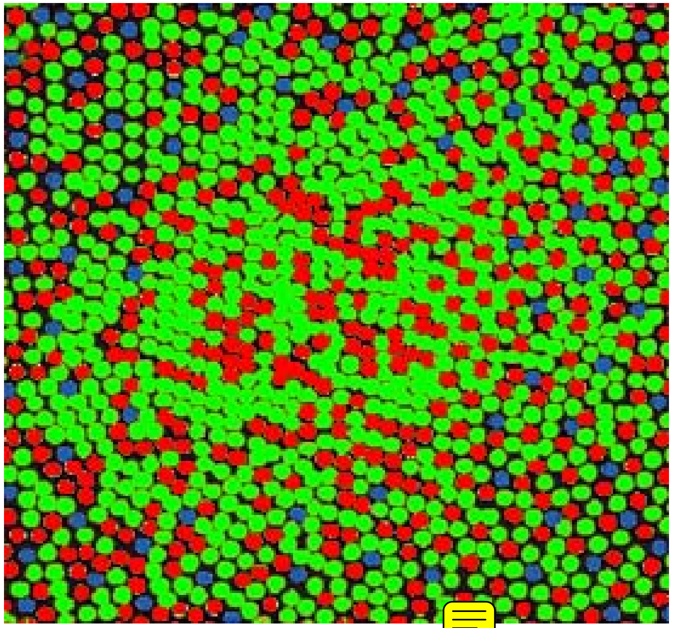


Fig. 1.1. A drawing of a section through the human eye with a schematic enlargement of the retina.

Eye’s Light Sensors

cone density near fovea (中央凹)



#(blue) << #(red) < #(green)

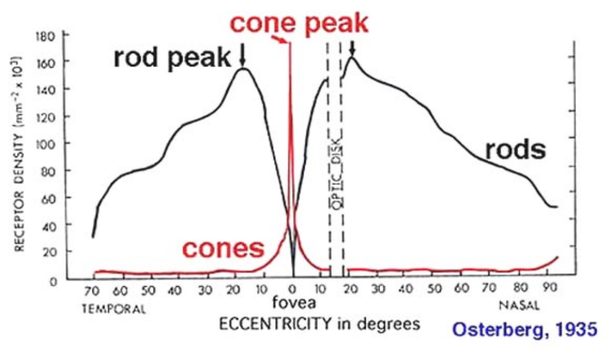


Fig. 20. Graph to show rod and cone densities along the horizontal meridian.

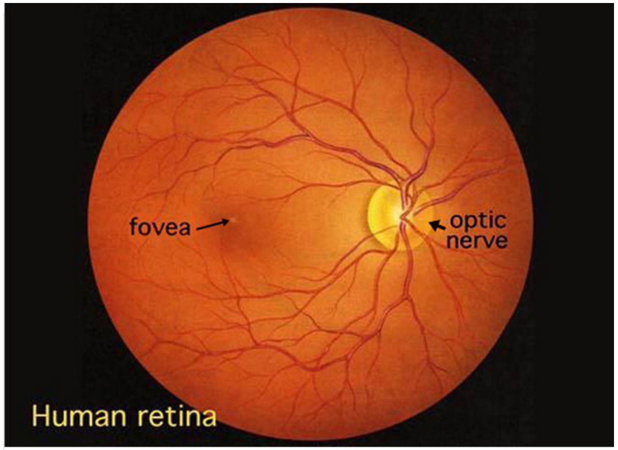
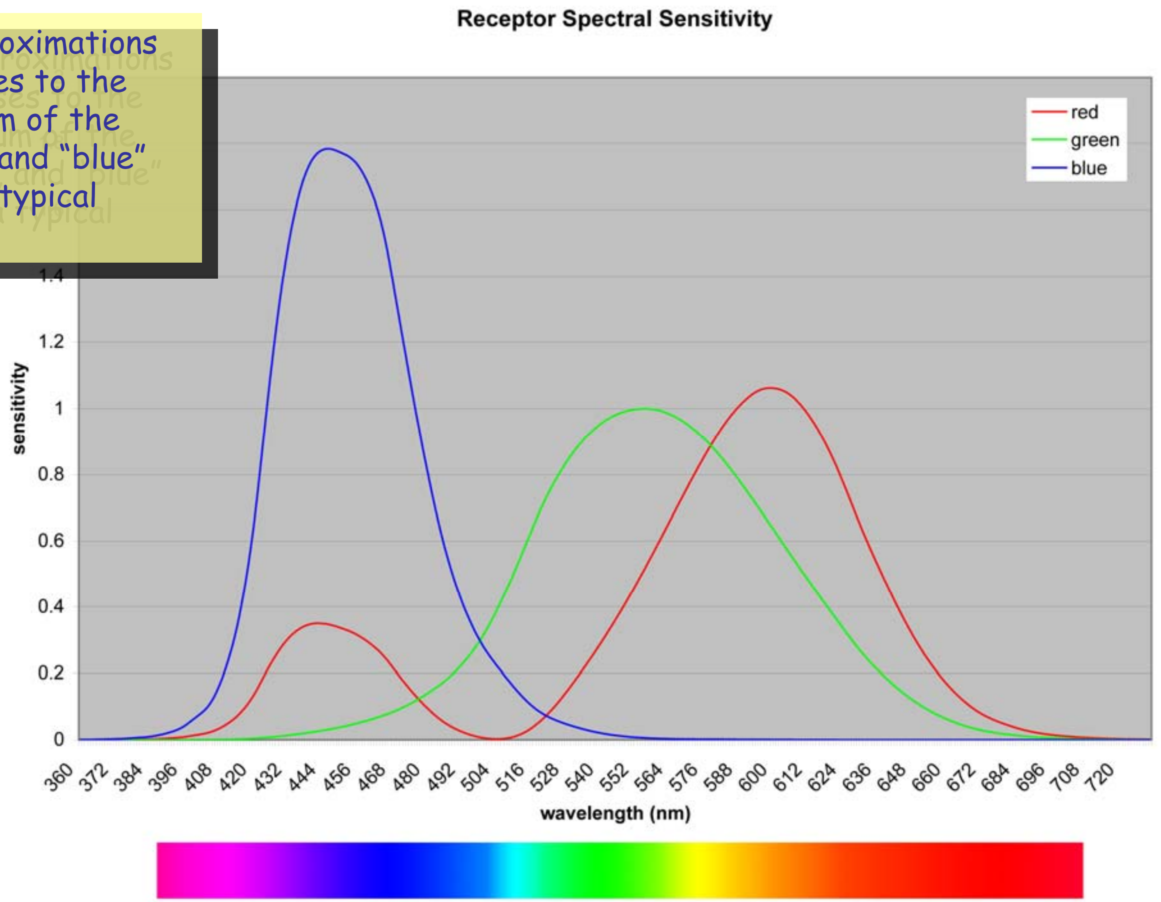


Fig. 1. Human retina as seen through an opthalmoscope.

Color Sensing / Color Perception

These are approximations of the responses to the visible spectrum of the "red", "green", and "blue" receptors of a typical human eye.



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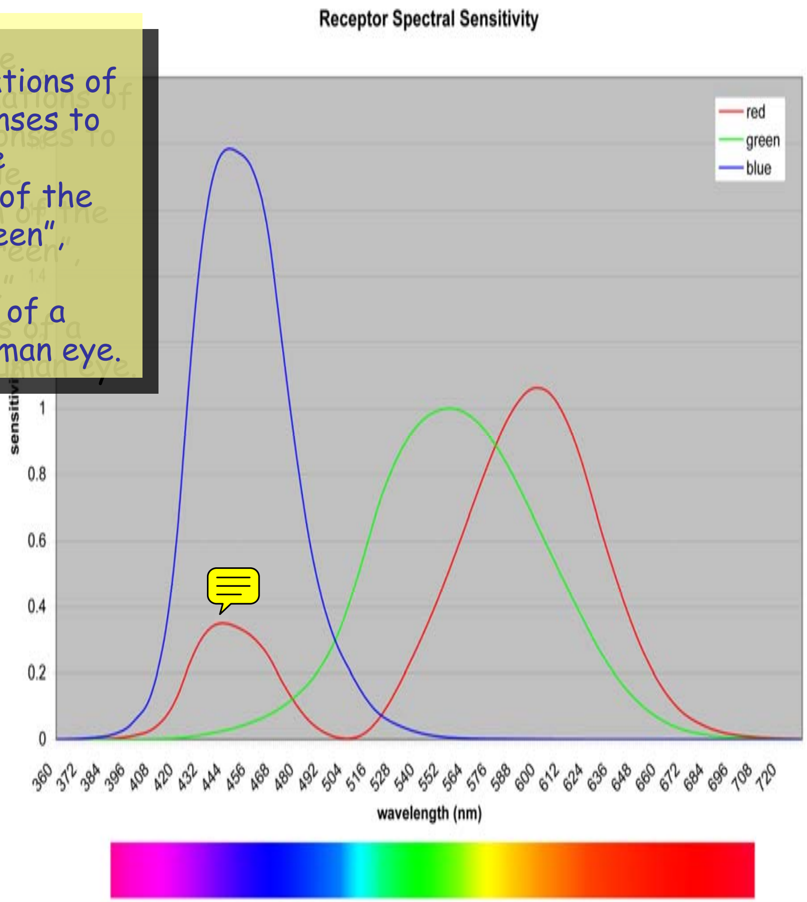
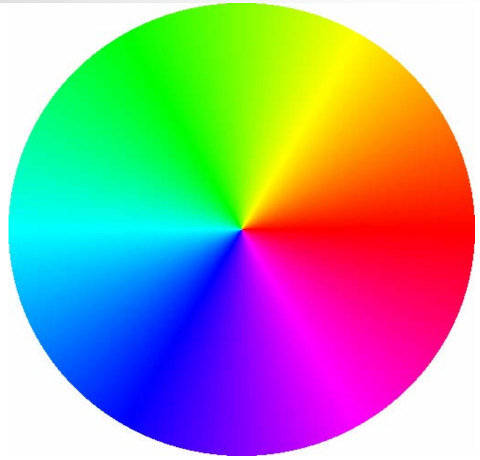
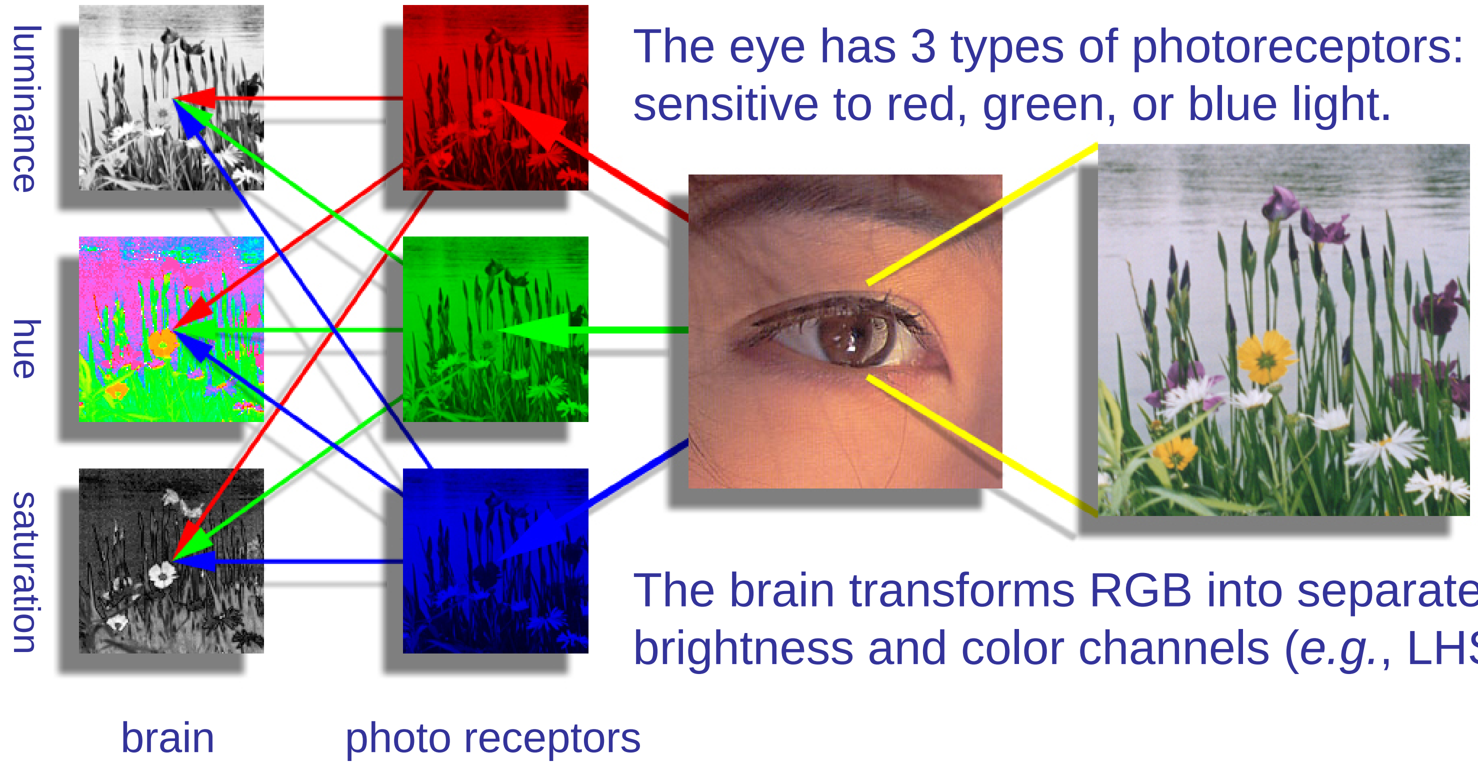




The simultaneous red + blue response causes us to perceive a continuous range of hues on a circle. No hue is greater than or less than any other hue.

Color Sensing / Color Perception



The eye has 3 types of photoreceptors: sensitive to red, green, or blue light.

The brain transforms RGB into separate brightness and color channels (*e.g.*, LHS).

Primary colors of human vision

- For this reason, red, green, and blue are referred to as the primary colors of human vision. CIE (the international Commission on Illumination, "Commission International d'Eclairage") standard designated three specific wavelength to these three colors in 1931.
  - Red : 700 nm
  - Green : 546.1 nm
  - Blue : 435.8 nm

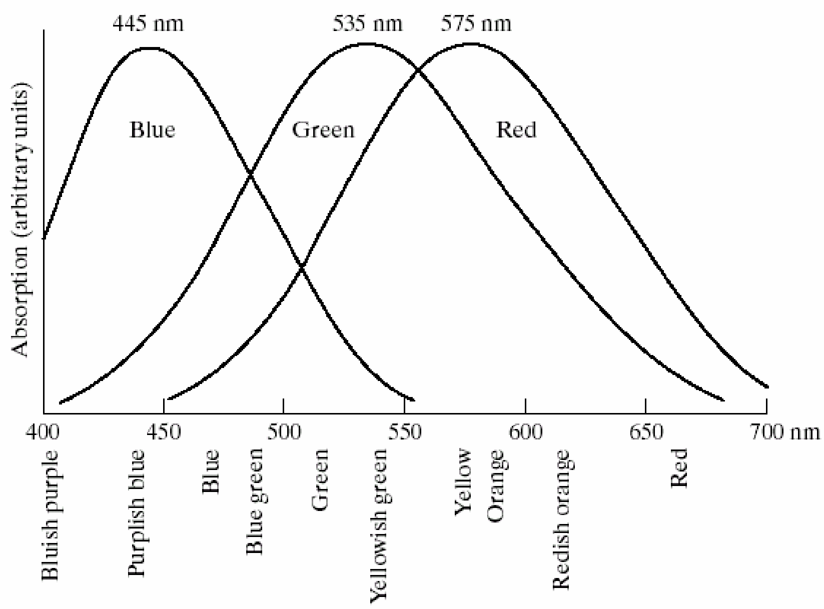


FIGURE 6.3 Absorption of light by the red, green, and blue cones in the human eye as a function of wavelength.

Chromaticity (色度)

- Chromaticity = hue + saturation
- Tristimulus(三色激励) : the amount of R, G, and B needed to form any color (R, G, B)
- Trichromatic coefficients : x, y, z

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

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

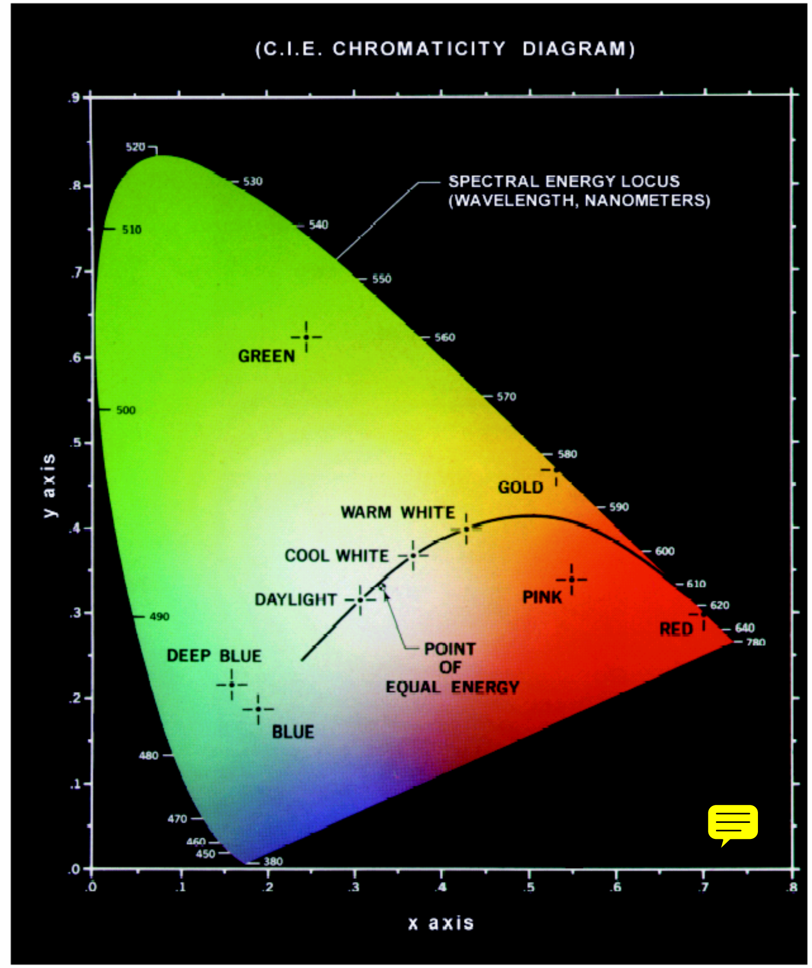
$$z = \frac{Z}{X+Y+Z}$$

$$x + y + z = 1$$

Chromaticity diagram

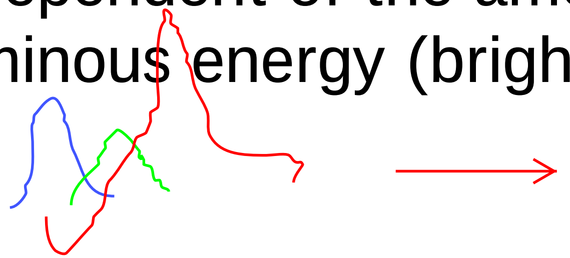
- CIE standard (1931)
- Shows all the possible colors
- Questions
  - Can different portions of R, G, and B create all the possible colors?
  - Where is the brown in the diagram?

FIGURE 6.5 Chromaticity diagram. (Courtesy of the General Electric Co., Lamp Business Division.)



Answers

- A triangle can never cover the horse-shoe shape diagram
- The fixed primary colors can not produce all the visible colors.
- Chromaticity diagram only shows dominant wavelengths and the saturation, and is independent of the amount of luminous energy (brightness)



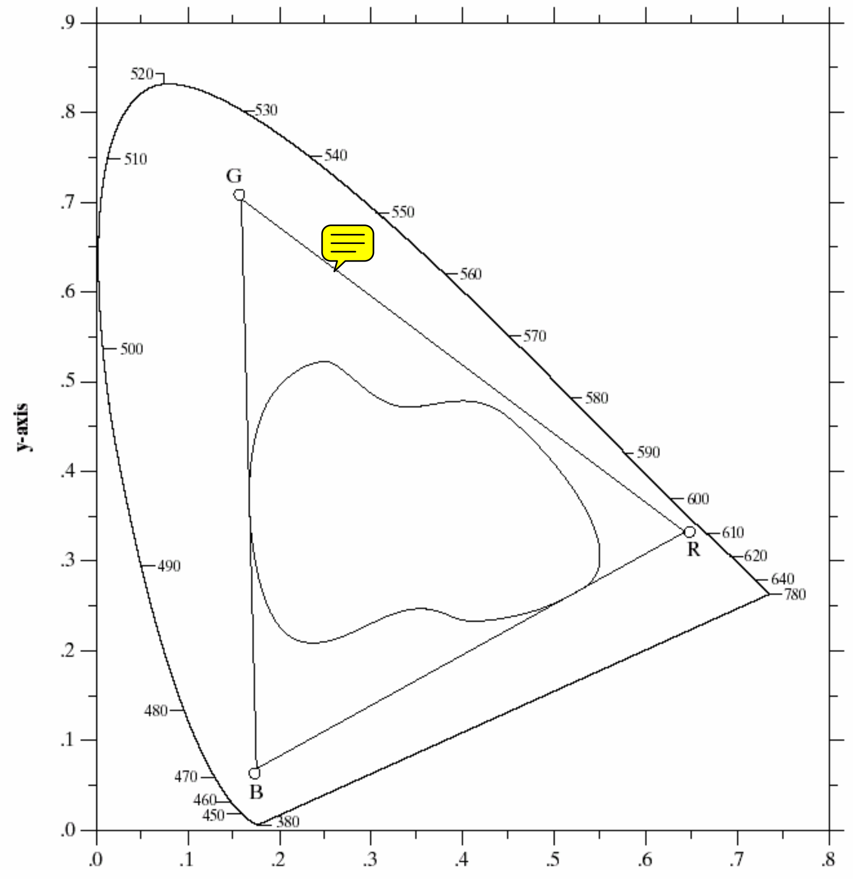
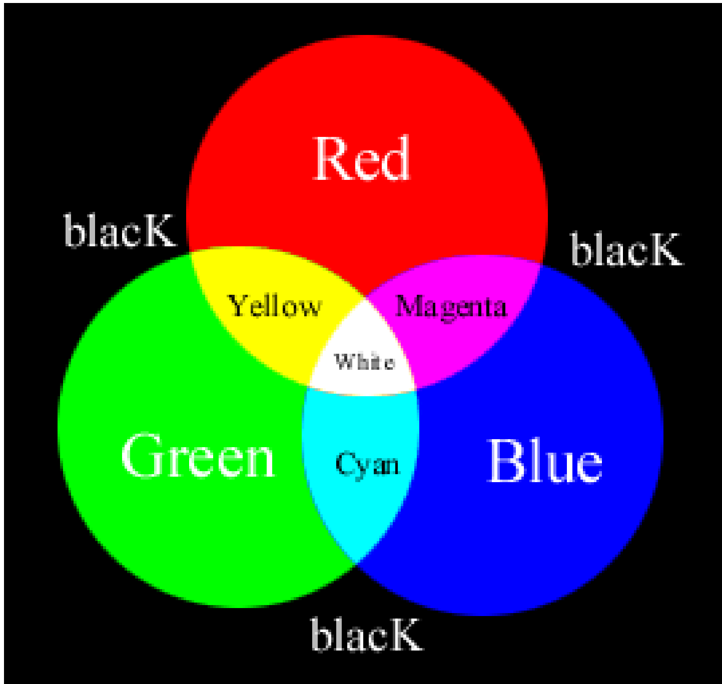


FIGURE 6.6 Typical color gamut of color monitors (triangle) and color printing devices (irregular region).

Additive Primaries: RGB
加法三原色

- Illuminating sources (Display monitor…)
  - Emit light (发射光)(e.g. the sun, light bulb, TV monitors)
  - Perceived color depends on the emitted frequency.
  - Follows additive rule: R+G+B = White

Magenta=(Red+Blue) =(White-Green)
Cyan =(Green+Blue) =(White-Red)
Yellow =(Red+Green) =(White-Blue)



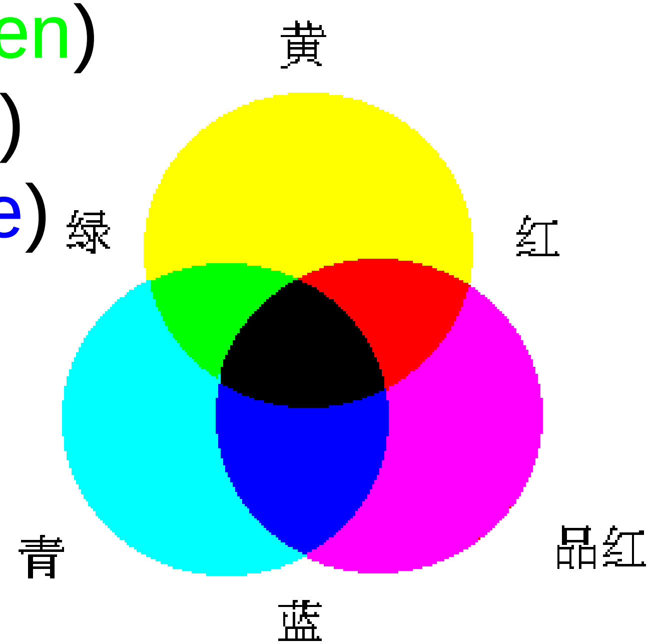
Subtractive Primaries: CMY
减法三原色

- Reflecting sources (Printer)
  - Reflect an incident light(入射光) (e.g. the color dye, matte surface, cloth)
  - Perceived color depends on reflected frequent (=incident – absorbed)
  - Follows subtractive rule: C+M+Y = Black

Magenta=(Red+Blue) =(White-Green)

Cyan =(Green+Blue) =(White-Red)

Yellow =(Red+Green) =(White-Blue)



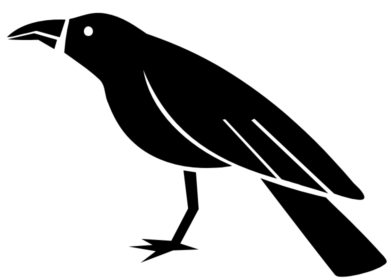
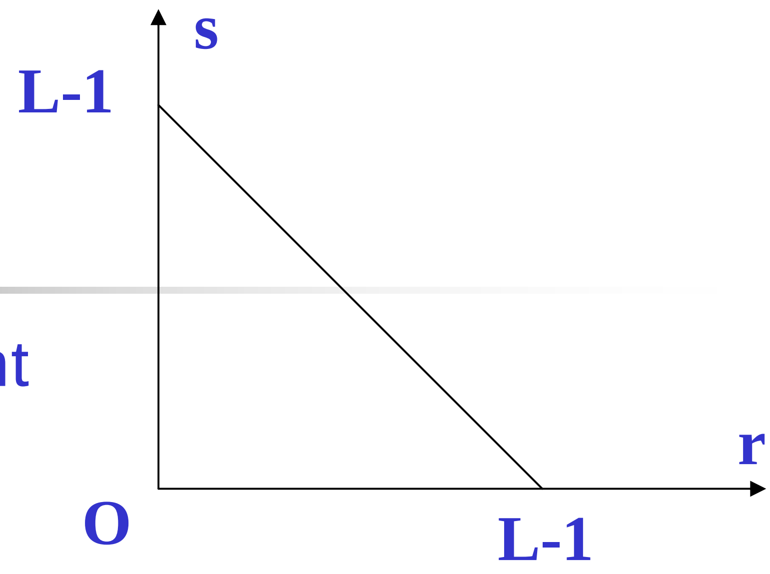
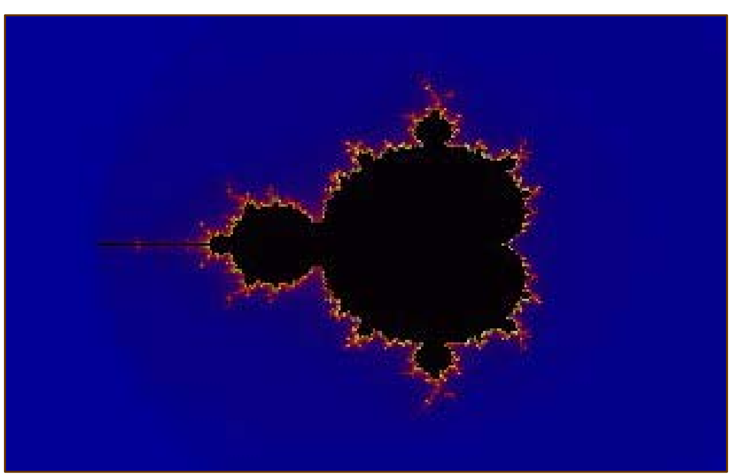
A fairy tale about  ...

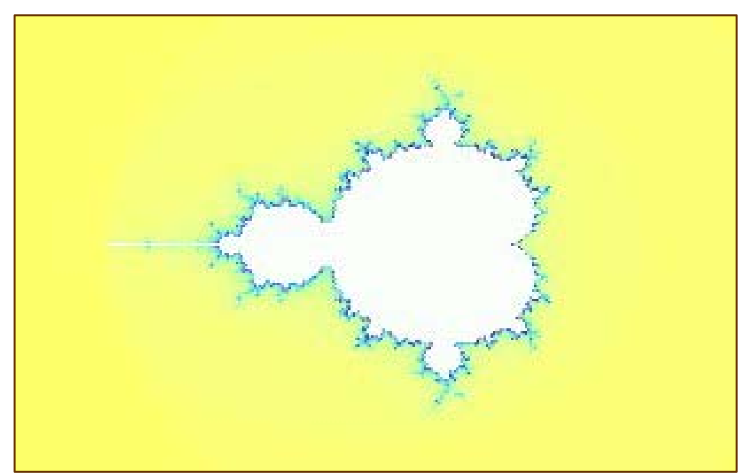
Image Negative

- Convert the color to its complement



$$s=(L-1)-r$$





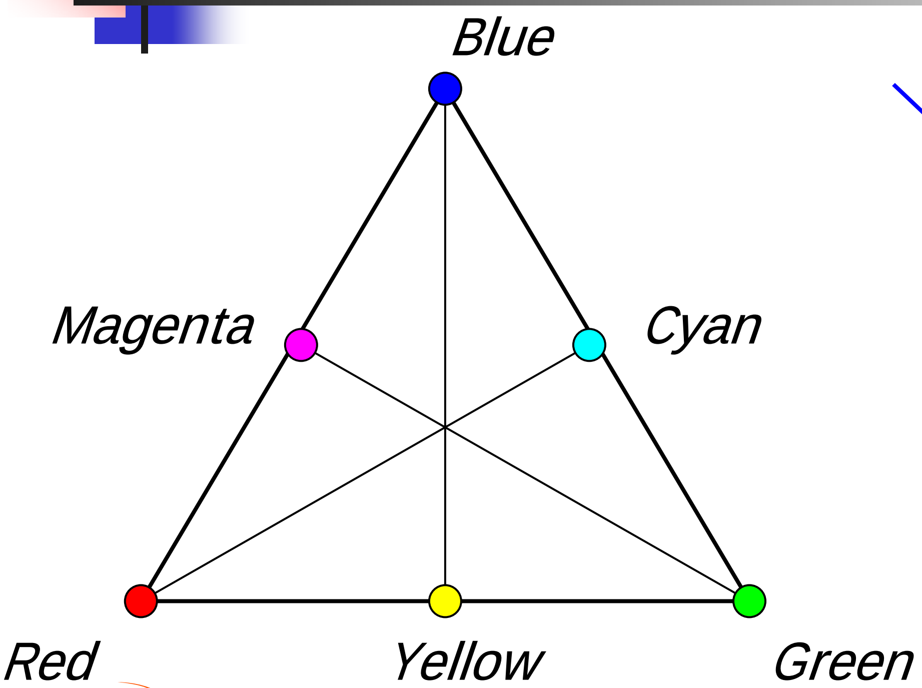
CMY or RYB ?

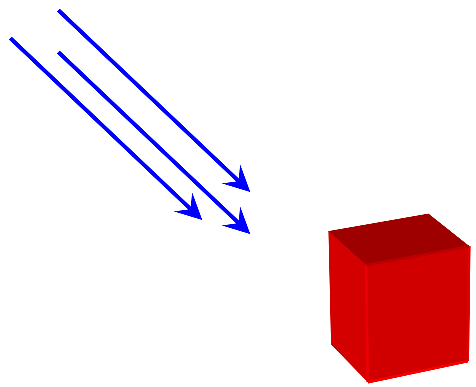
- Traditional opinion of subtractive primaries: Red, Yellow, Blue.
- A comparison

Violet = (Red + Blue)
Green = (Yellow + Blue)
Orange = (Red + Yellow)

Red = (Magenta + Yellow)
Green = (Yellow + Cyan)
Blue = (Cyan + Magenta)

Color triangle





- What is the color of a red object illuminated by blue light?
- What is the color of a red object observed through blue glasses ?

Color characterization

- Brightness(亮度)：chromatic notion of intensity
- Hue(色调)：dominant color (dominant wavelength in a mixture of light waves)
- Saturation(饱和度)：relative purity of the amount of white mixed with a hue

- When we call an object red, orange, etc., we refer to its hue.

Color models

- RGB model
  - Color monitor, color video cameras
- CMY model
  - Color printer
- HSI/HSV model
  - Color image manipulation
- XYZ (CIE standard, Y directly measures the luminance)
- YUV (used in PAL color TV)
- YIQ (used in NTSC color TV)
- YC_bC_r (used in digital color TV standard BT.601)

RGB model

- Color monitors, color video cameras
- Pixel depth : number of bits used to represent each pixel
- suitable for imaging and display

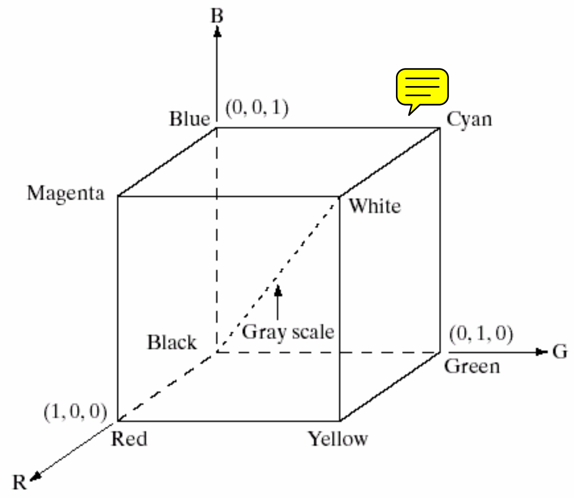


FIGURE 6.7 Schematic of the RGB color cube. Points along the main diagonal have gray values, from black at the origin to white at point (1, 1, 1).

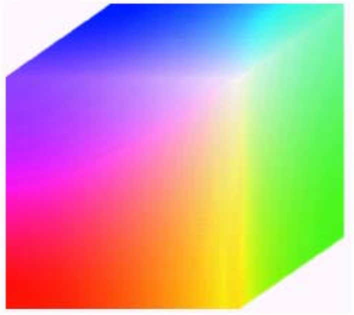


FIGURE 6.8 RGB 24-bit color cube.

CMY model

- Color printer and copier
- Deposit colored pigment on paper
- Relationship with RGB model

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = 1 - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

HSI model

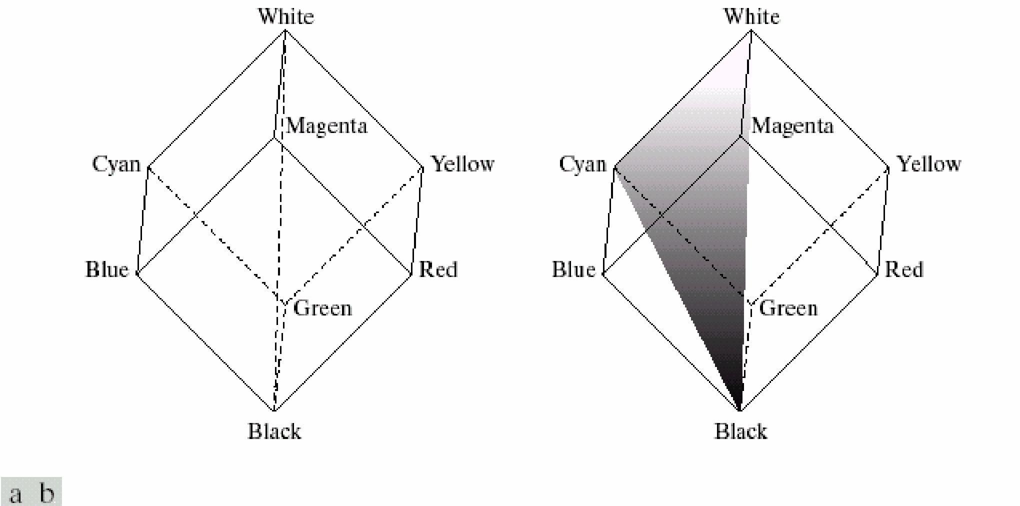
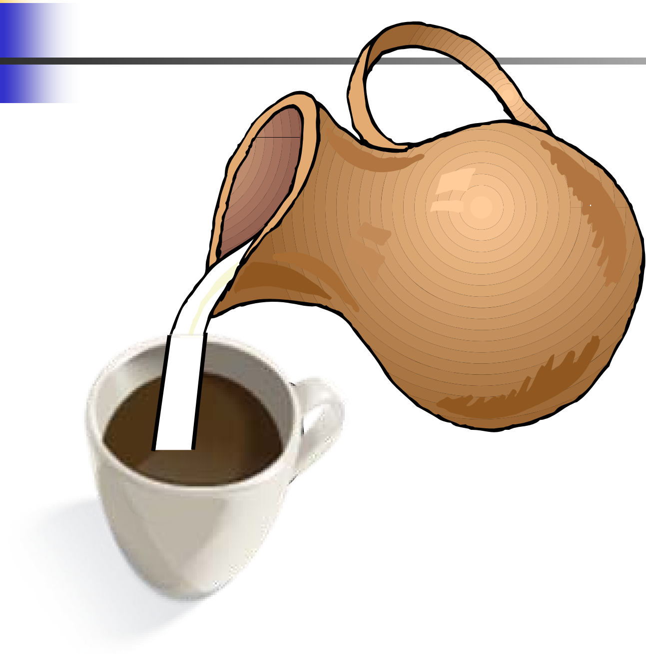
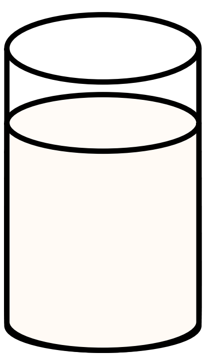


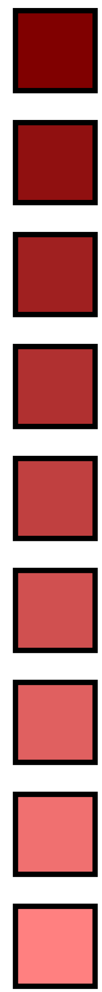
FIGURE 6.12 Conceptual relationships between the RGB and HSI color models.

- Hue represents dominant color as perceived by an observer. It is an attribute associated with the dominant wavelength.
- Saturation refers to the relative purity or the amount of white light mixed with a hue. The pure spectrum colors are fully saturated. Pink and lavender are less saturated.
- Intensity reflects the brightness.

HSI model – Saturation(饱和度)







(128,0,0)

(144,16,16)

(160,32,32)

(176,48,48)

(192,64,64)

(208,80,80)

(224,96,96)

(240,112,112)

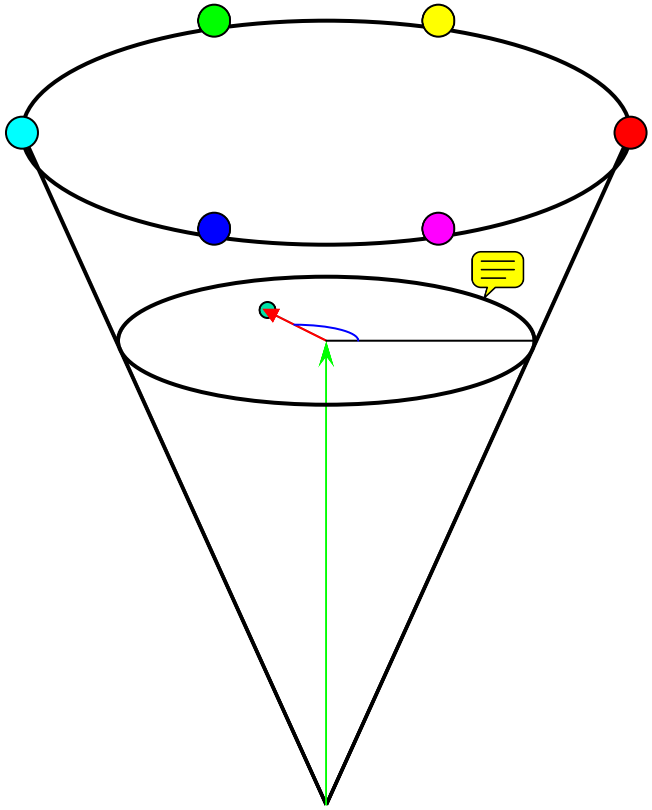
(255,127,127)

HSI/HSV model

Hue

Saturation

Value



HSI/HSV model (cont')

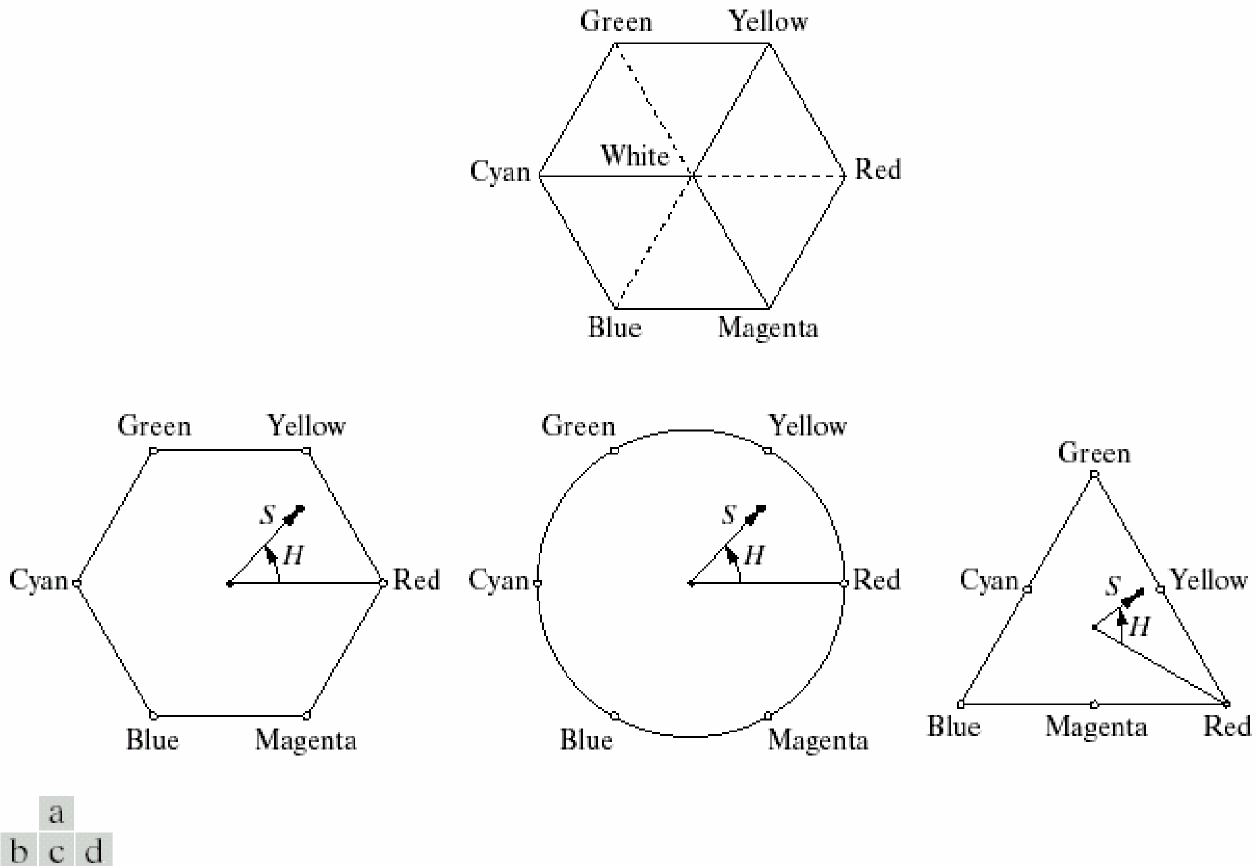
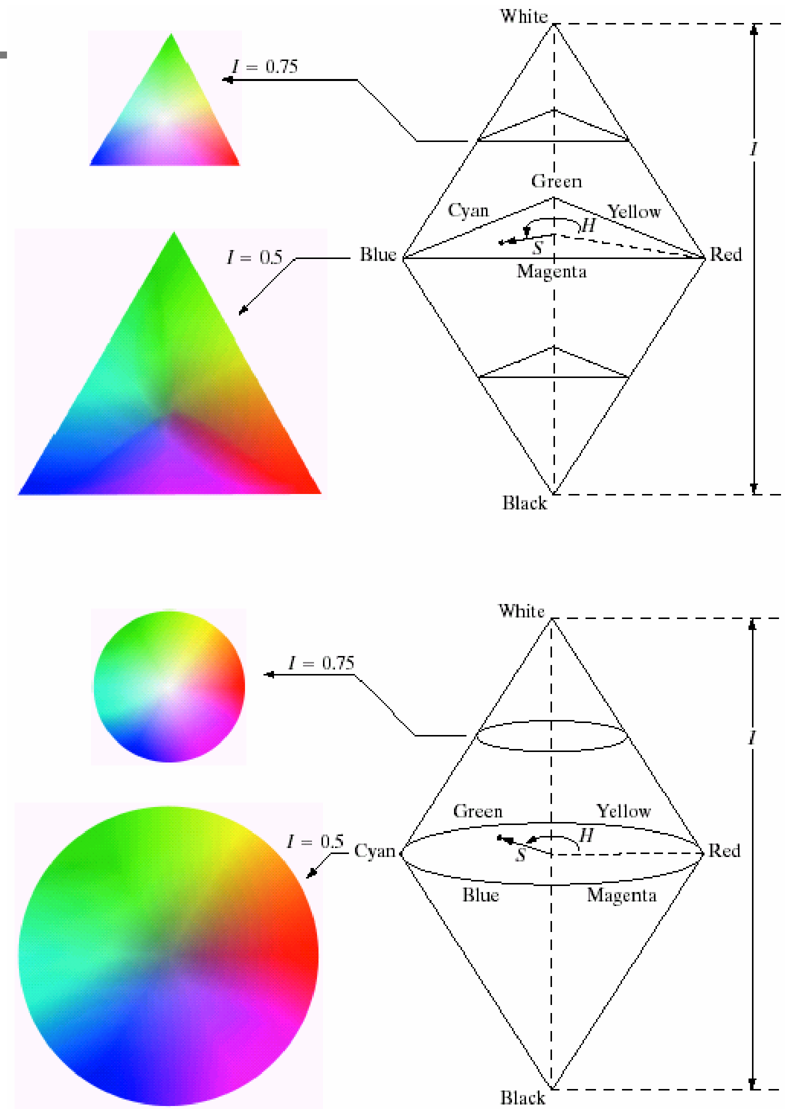


FIGURE 6.13 Hue and saturation in the HSI color model. The dot is an arbitrary color point. The angle from the red axis gives the hue, and the length of the vector is the saturation. The intensity of all colors in any of these planes is given by the position of the plane on the vertical intensity axis.

HSI/HSV model (cont')



Model conversion between RGB and HSI

- Converting from RGB to HSI

$$H = \begin{cases} \theta & \text{if } B \le G \\ 360 - \theta & \text{if } B > G \end{cases}, \quad \theta = \cos^{-1}\left\{ \frac{\frac{1}{2}\left[(R-G)+(R-B)\right]}{\left[(R-G)^2+(R-B)(G-B)\right]^{1/2}} \right\}$$

$$S = 1 - \frac{3}{(R+G+B)}\left[\min(R,G,B)\right]$$

$$I = \frac{1}{3}(R+G+B)$$

  - S is determined by the fraction or white component
  - The saturation of the complement color cannot be uniquely determined by that of the original color.

Model conversion between RGB and YCbCr

$$\begin{bmatrix} Y \\ Cb \\ Cr \end{bmatrix} = \begin{bmatrix} 0.257 & 0.504 & 0.098 \\ -0.148 & -0.291 & 0.439 \\ 0.439 & -0.368 & -0.071 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} 16 \\ 128 \\ 128 \end{bmatrix}$$

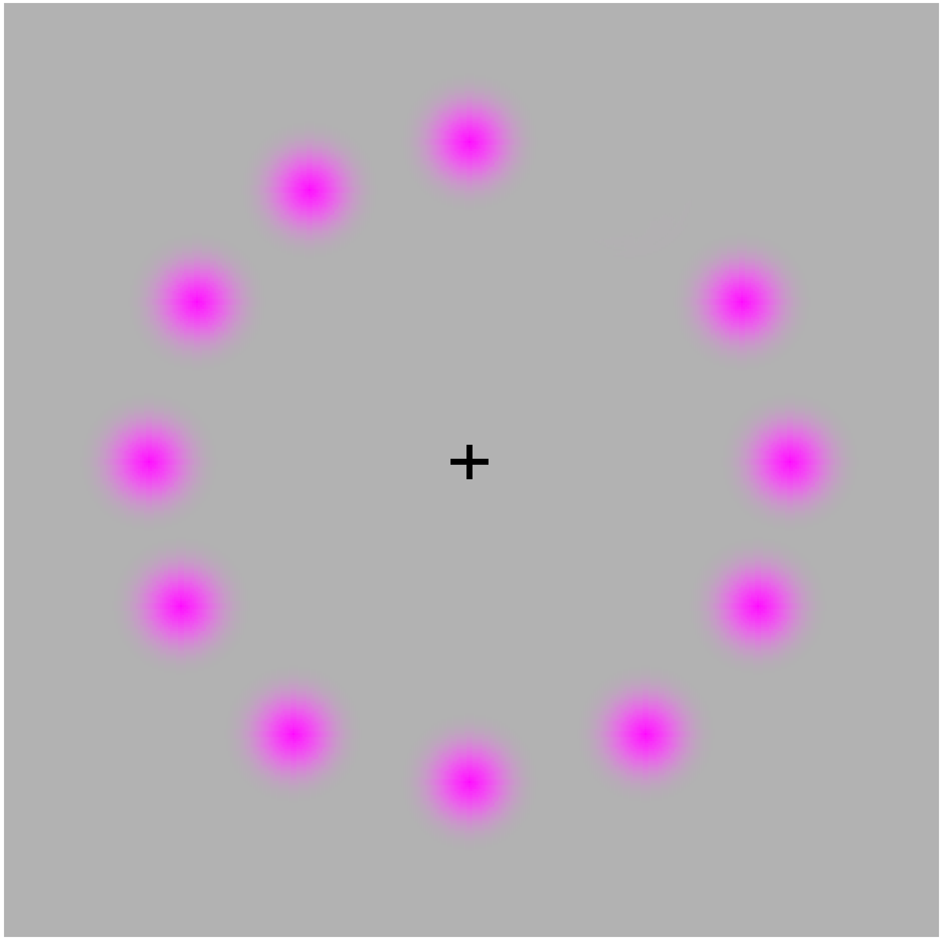
$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.164 & 0.000 & 1.598 \\ 1.164 & -0.329 & -0.813 \\ 1.164 & 2.017 & 0.000 \end{bmatrix} \begin{bmatrix} Y-16 \\ Cb-128 \\ Cr-128 \end{bmatrix}$$

$$Y \in [16,235], Cb, Cr \in [16-240]$$

Why so many color models?

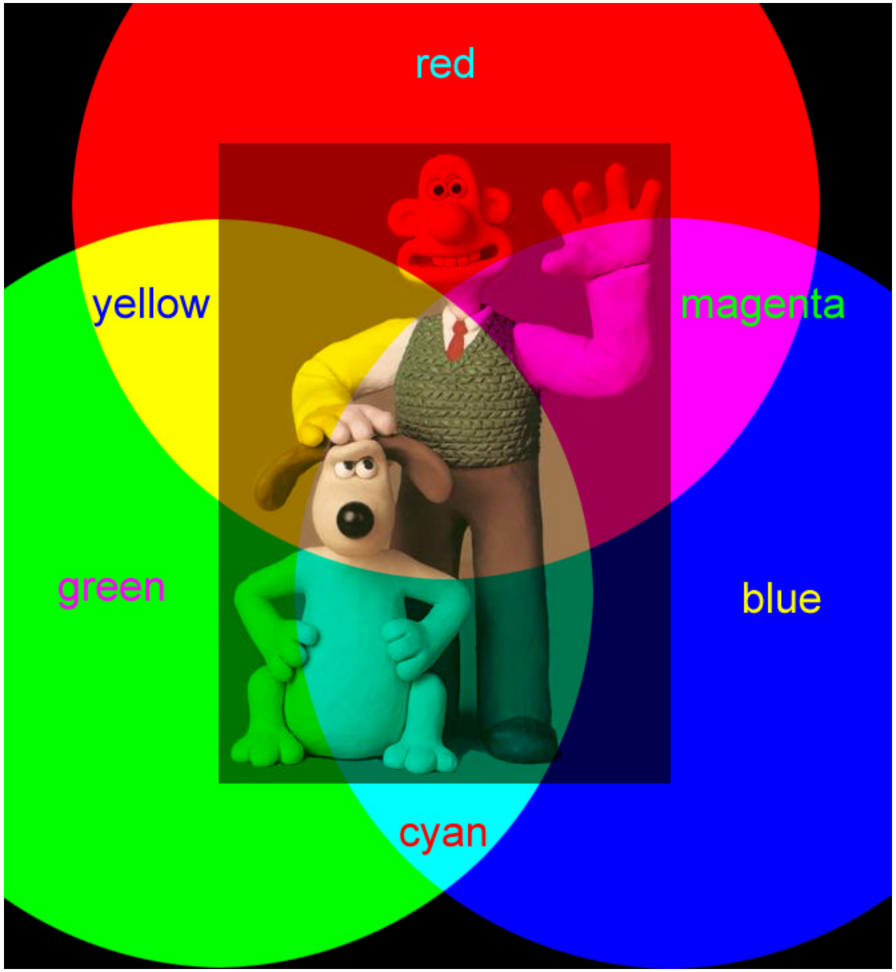
- Historical reasons
- For particular purposes or facilitating the implementation under certain framework
- transform between different color systems

Color fun

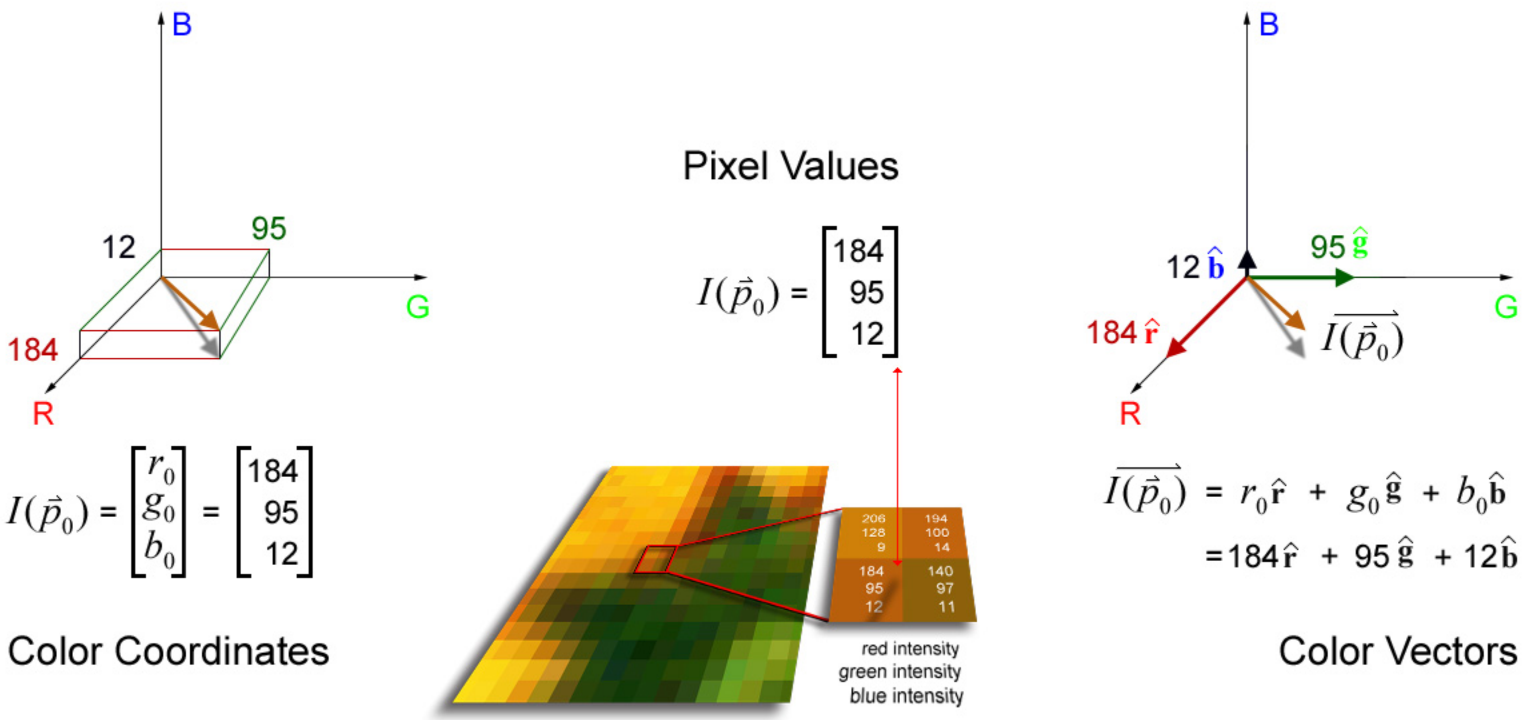


Color Images

- Are constructed from three overlaid intensity maps.
- Each map represents the intensity of a different "primary" color.
- The actual hues of the primaries do not matter as long as they are distinct.
- The primaries are 3 vectors (or axes) that form a "basis" of the color space.



Vector-Valued Pixels



Each color corresponds to a point in a 3D vector space

Color Space

for standard digital images

- primary image colors red, green, and blue
  - correspond to R,G, and B axes in color space.
- 8-bits of intensity resolution per color
  - correspond to integers 0 through 255 on axes.
- no negative values
  - color “space” is a cube in the first octant of 3-space.
- color space is discrete
  - 256^3 possible colors = 16,777,216 elements in cube.

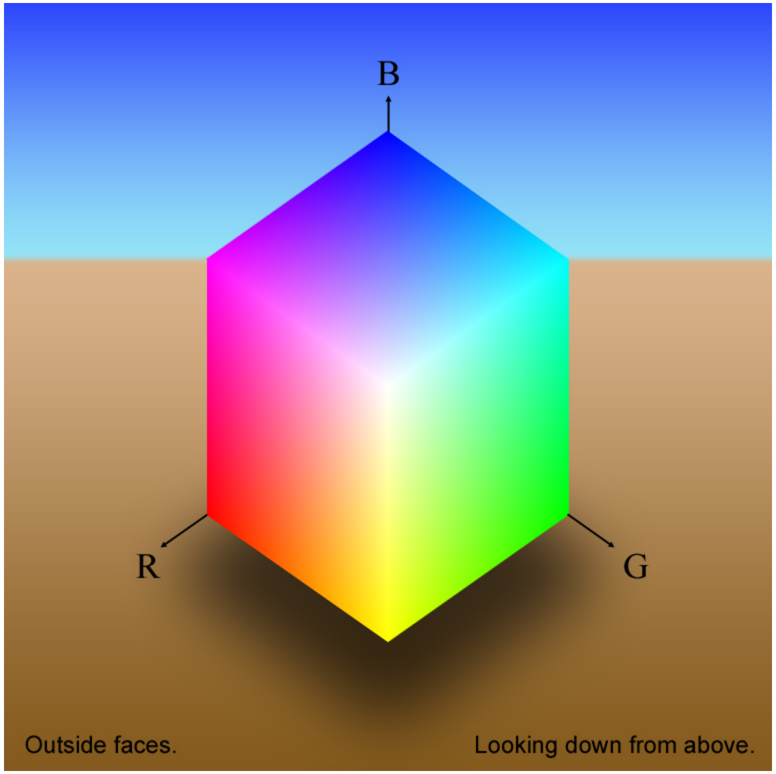
Some Exercises

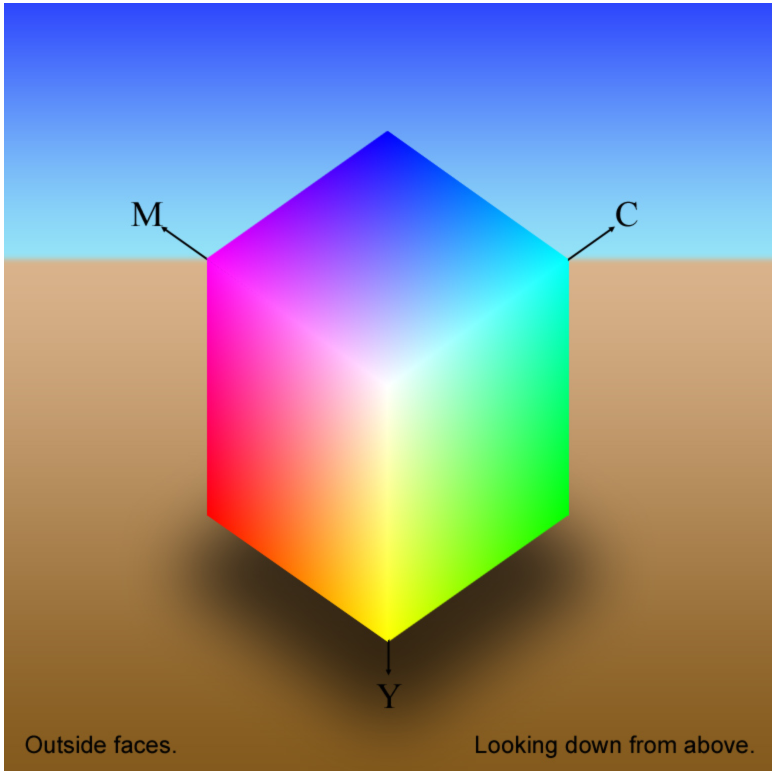
- The complement of (0,255,0) ? (255,0,255)
- The Intensity of (40,60,200) ? 100
- The Hue of (0,255,255) ? 0.5/180º(Cyan)
- The Saturation of (255,128,0) ? 1.0
- The Saturation of (25,25,50) ? 0.25
- The Saturation of (0,0,0) ? NaN ?

$$I = \frac{1}{3}(R + G + B)$$

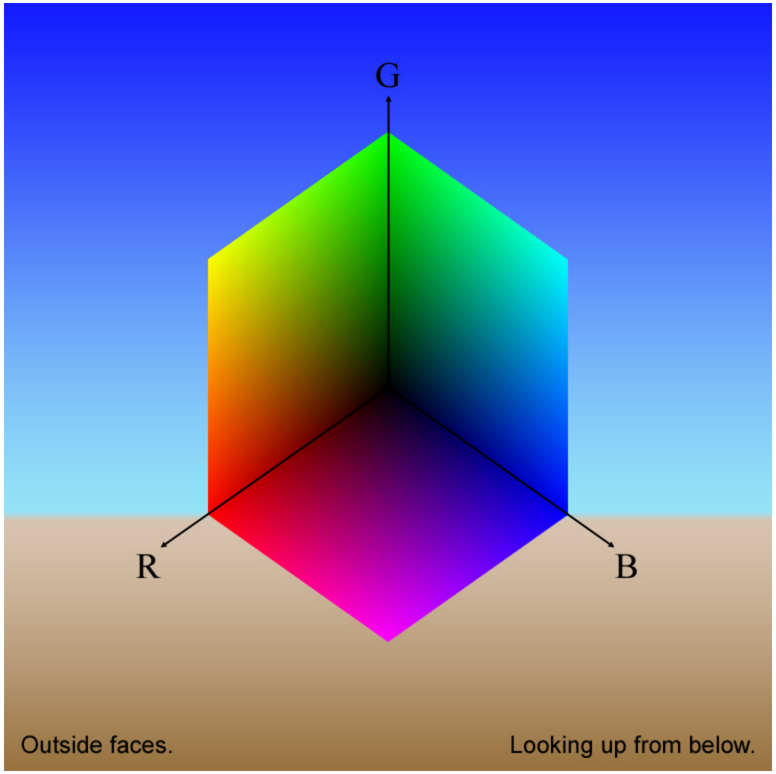
$$S = 1 - \frac{3}{(R + G + B)}\left[\min(R, G, B)\right]$$

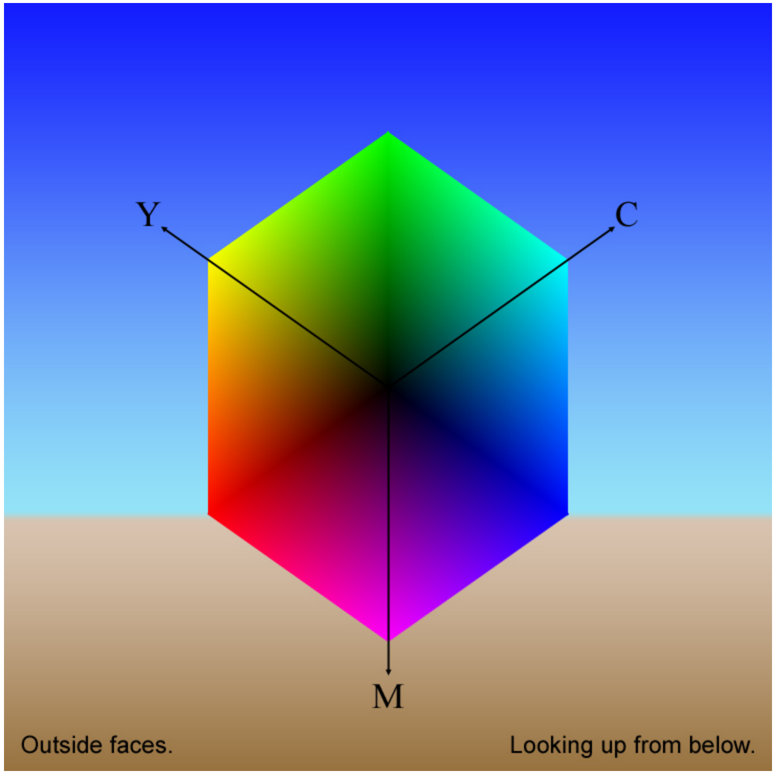
Color Cube: Faces (outer)



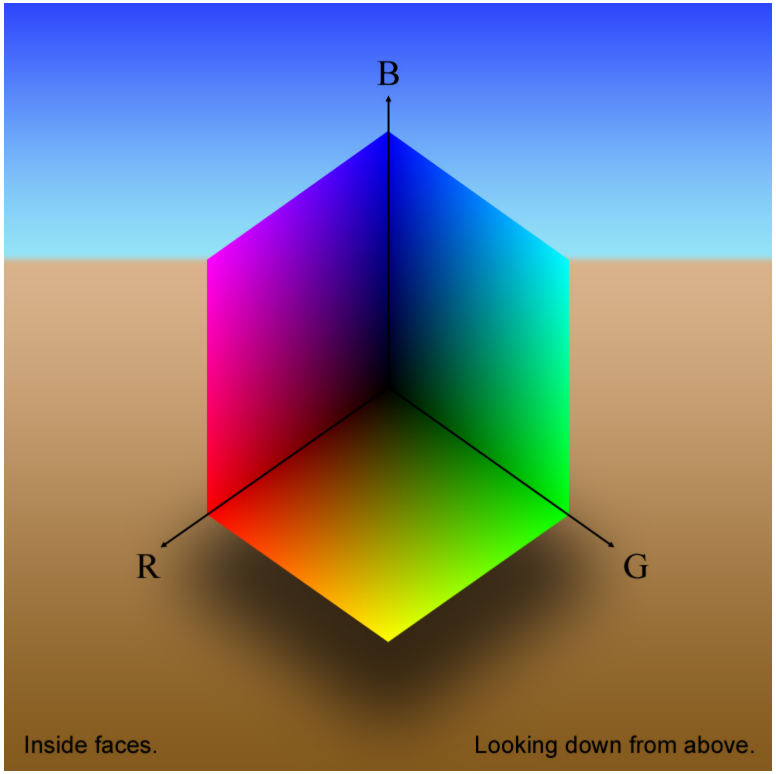


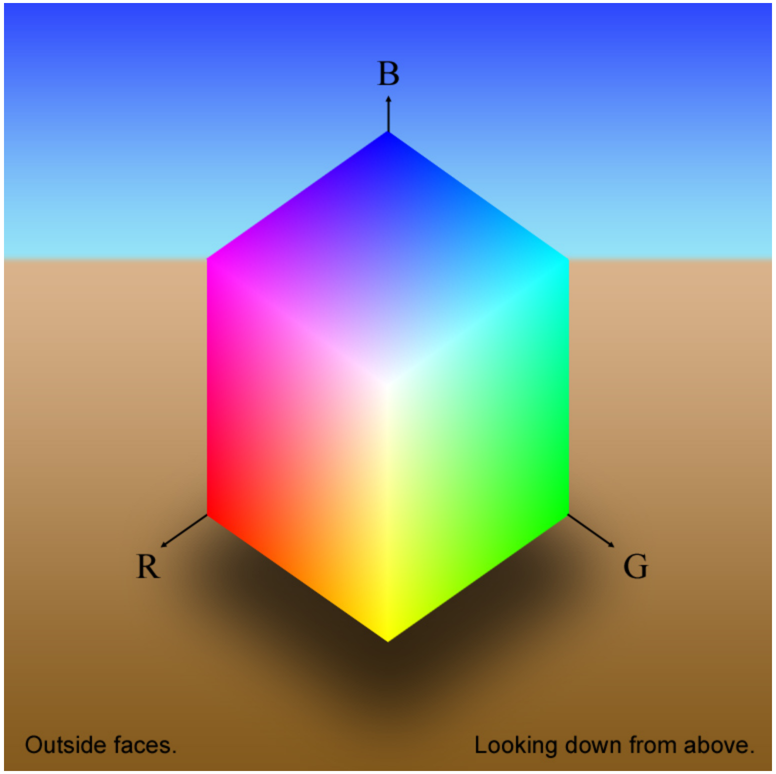
Color Cube: Faces (inner)



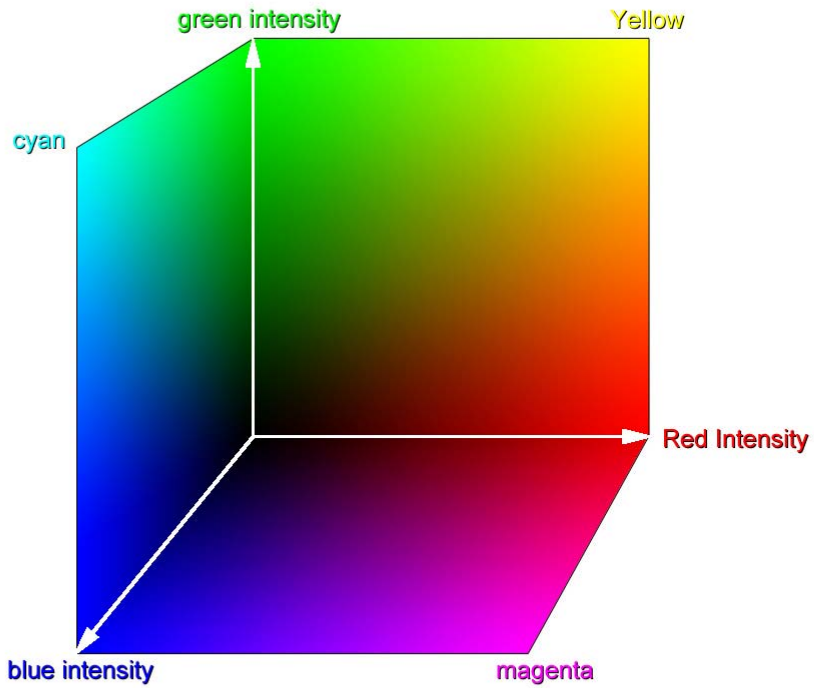


Color Cube: Faces (inner and outer)

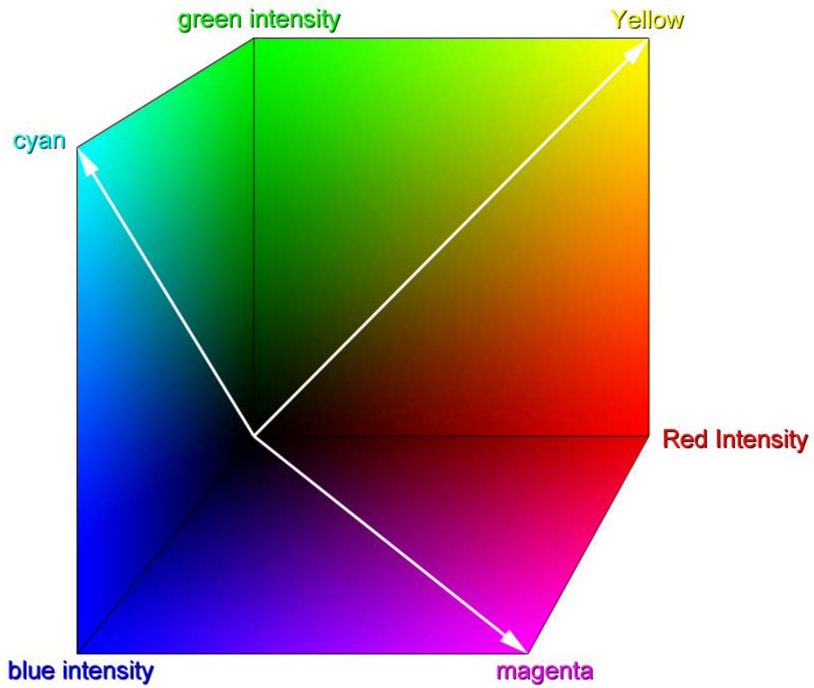




Different Axis Sets in Color Space

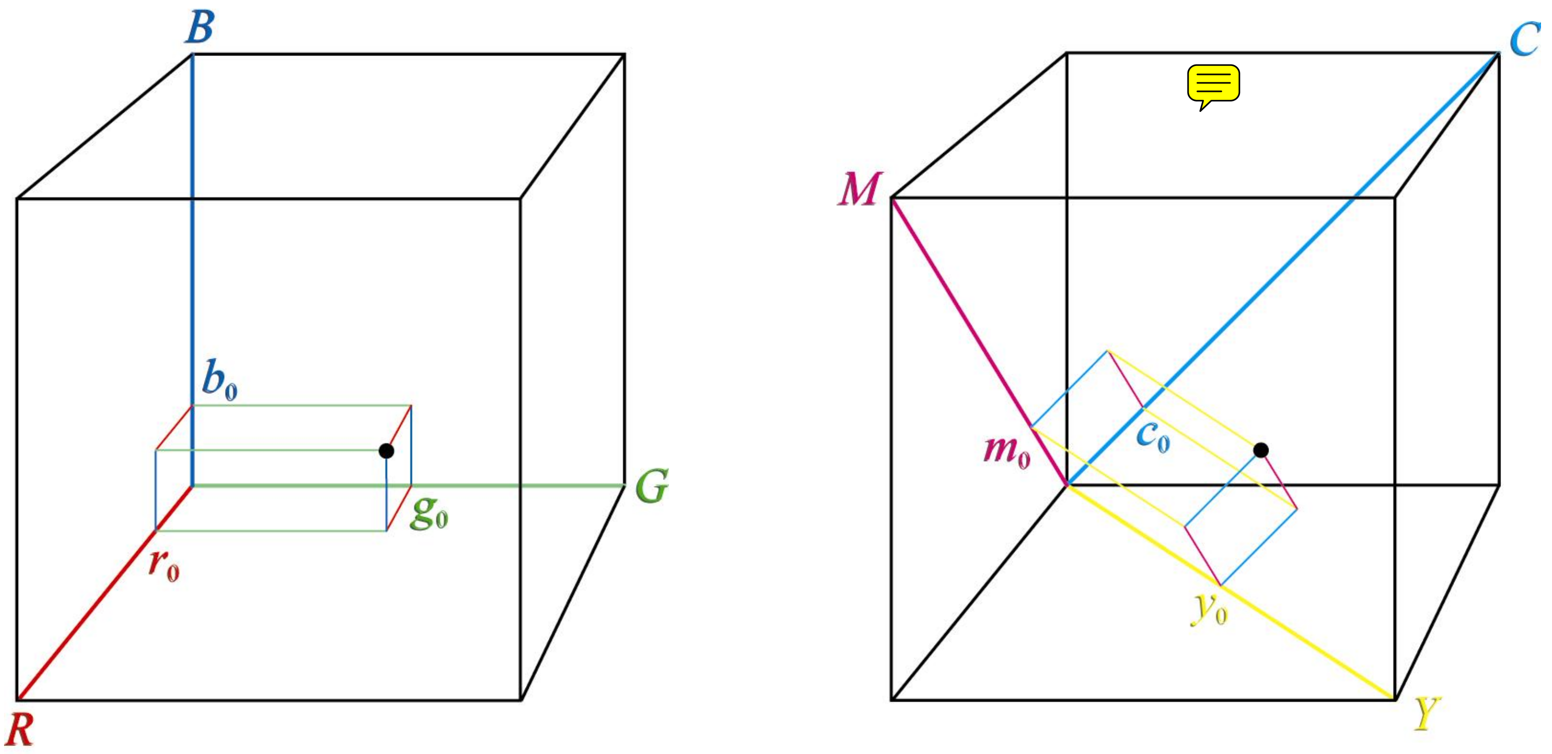


RGB axes



CMY axes

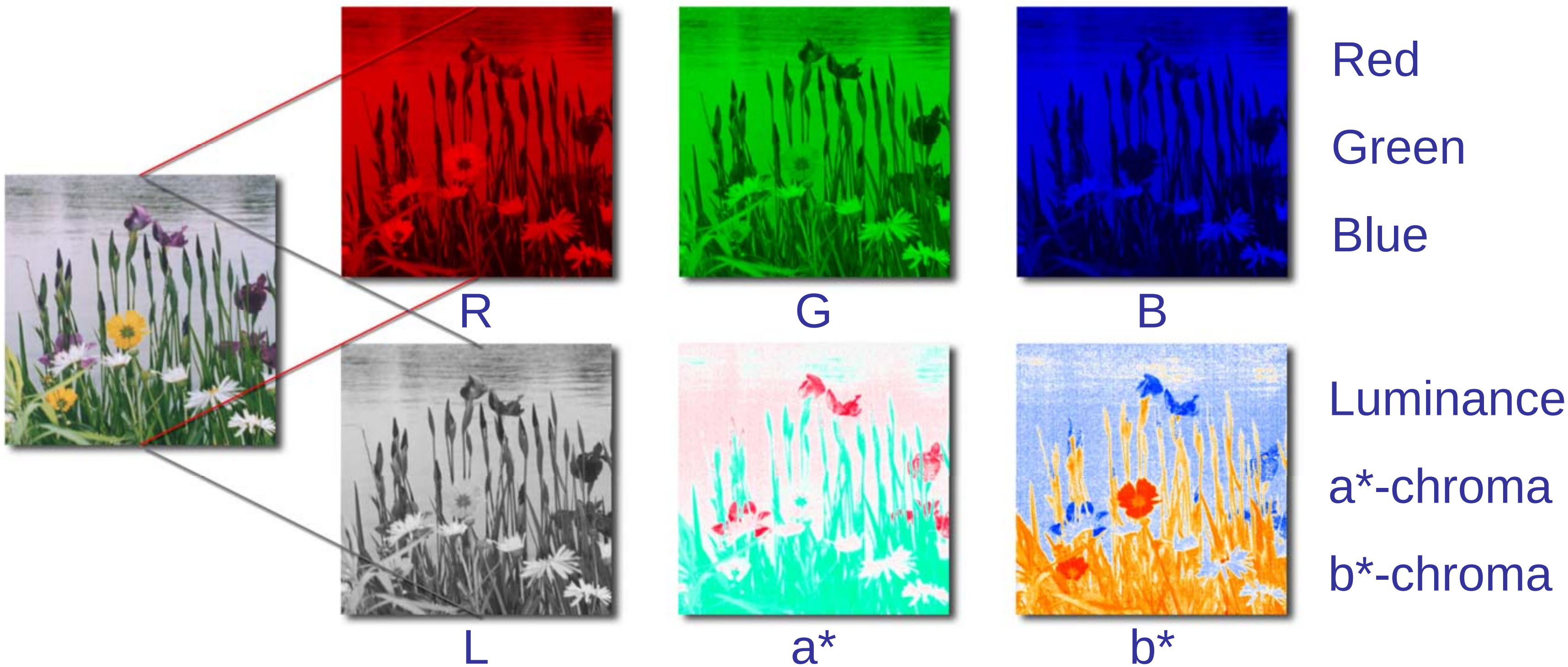
Color With Respect To Different Axes



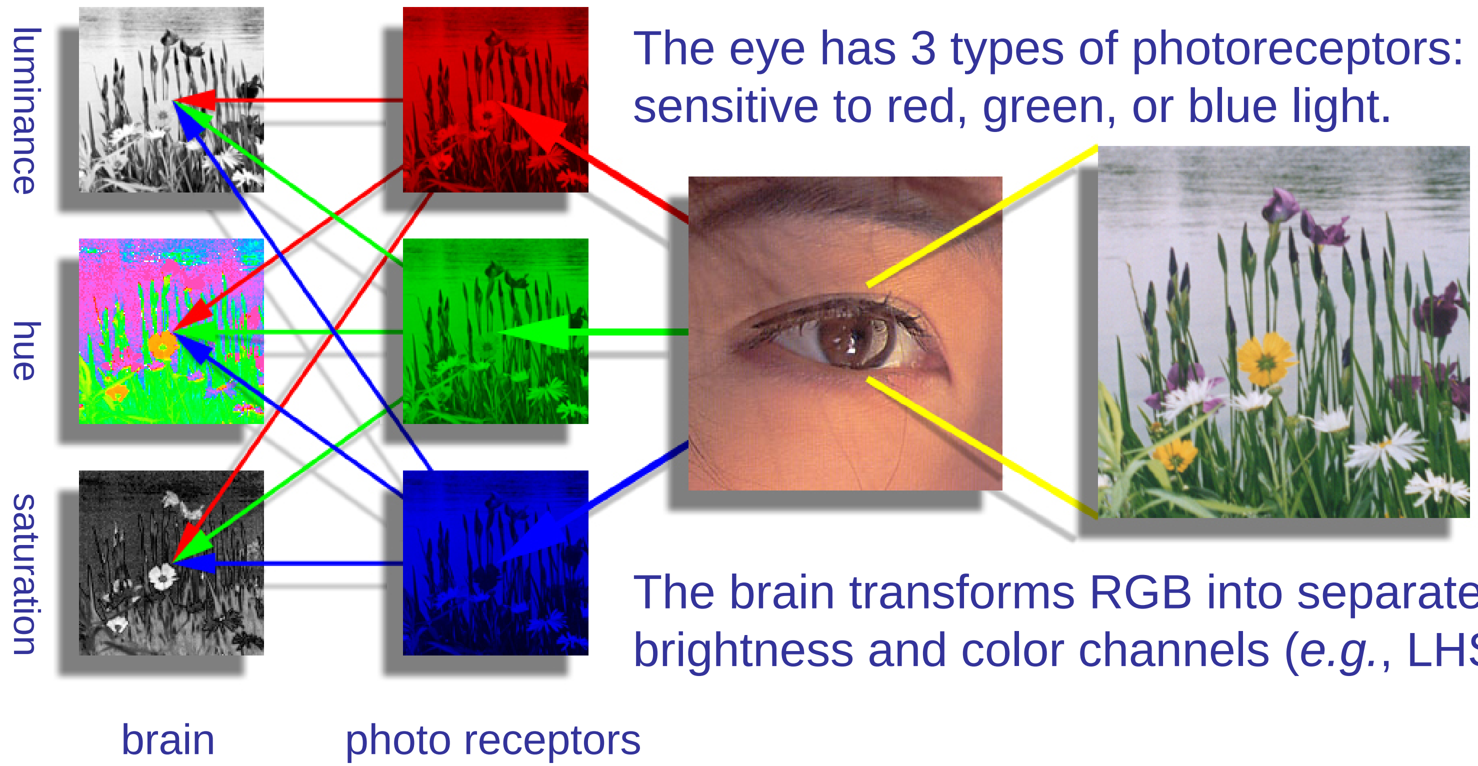
The same color has different RGB and CMY coordinates.

Color Images

are represented by three bands (not uniquely) *e.g.*, R, G, & B or L, a*, & b*.



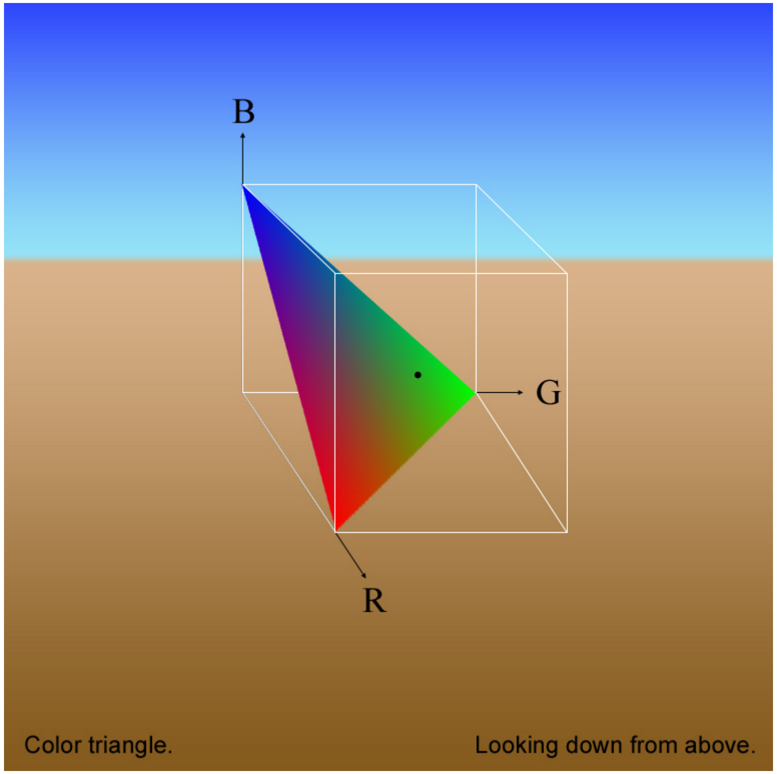
RGB to LHS: A Perceptual Transformation



The eye has 3 types of photoreceptors: sensitive to red, green, or blue light.

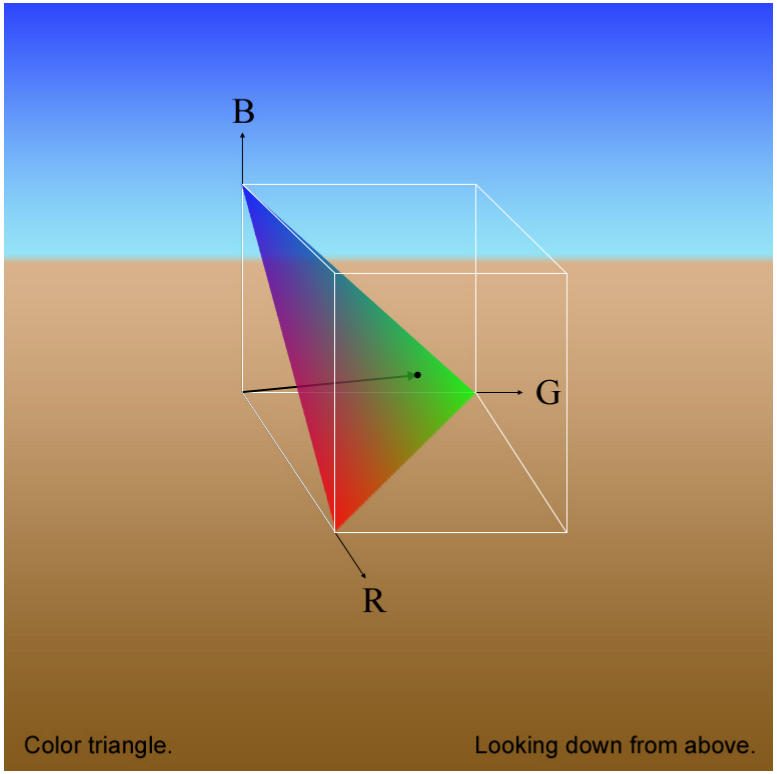
The brain transforms RGB into separate brightness and color channels (*e.g.*, LHS).

Color Point on Equivalue Triangle (等值三角形)

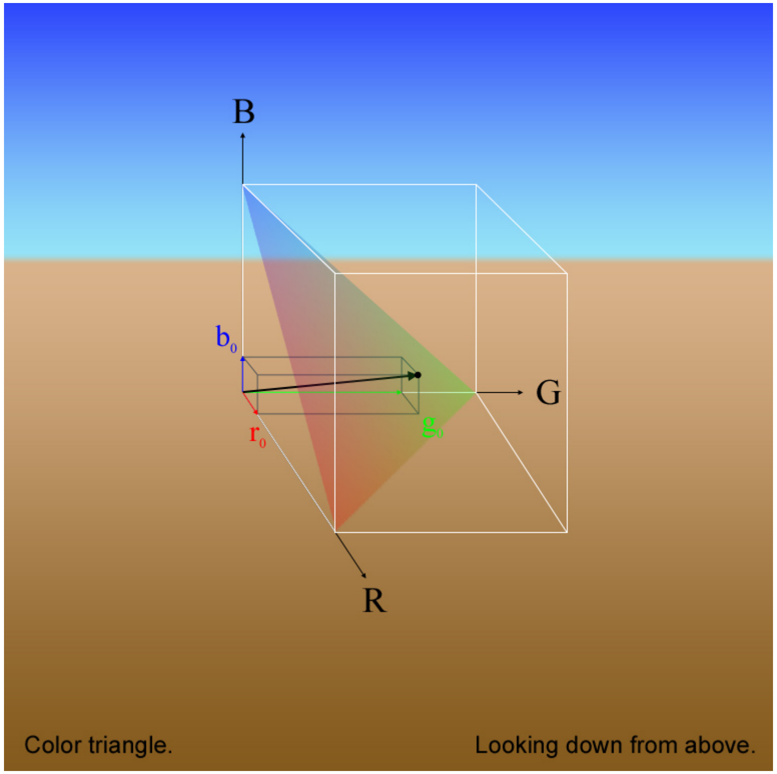


What is the equation of the equivalue plane?

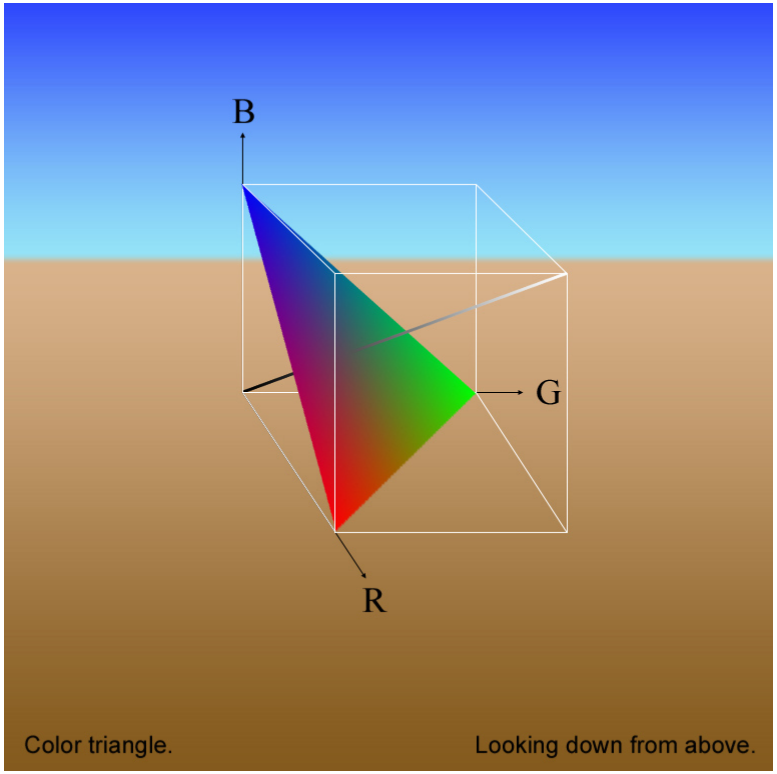
Color Vector Associated with Point



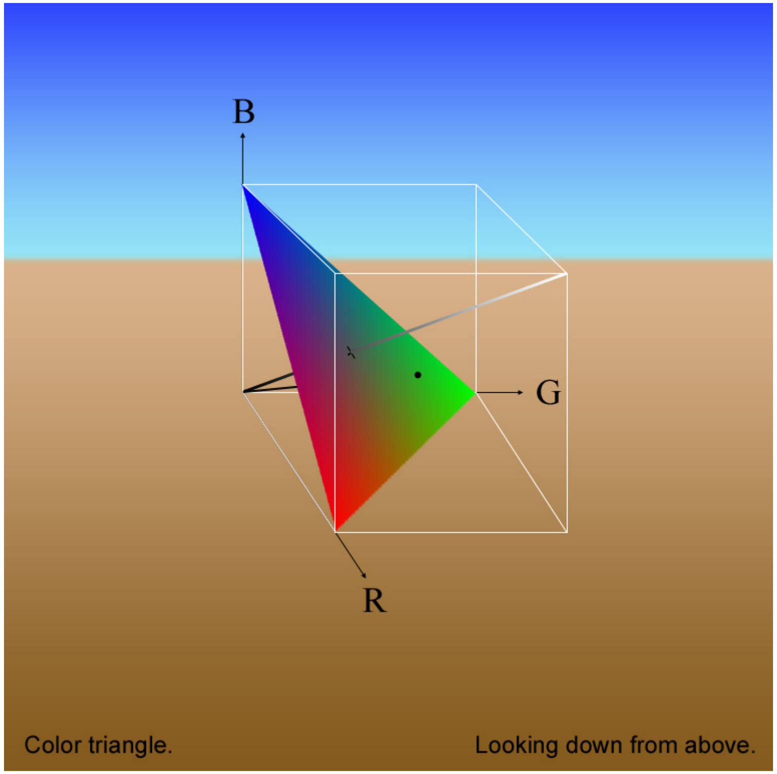
Color Coordinates and Component Vectors



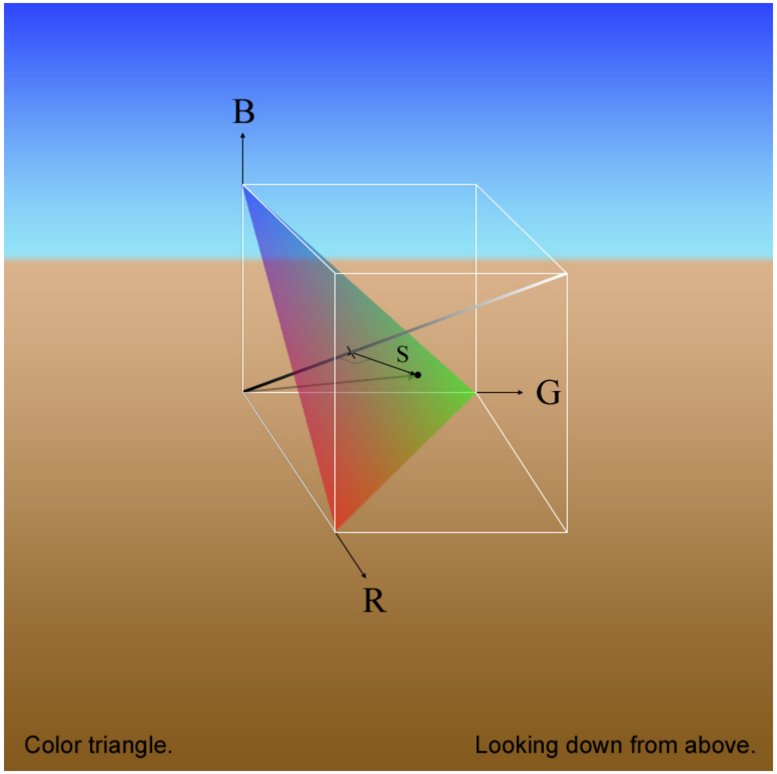
Color Cube, Equivalue Triangle, & Gray Line



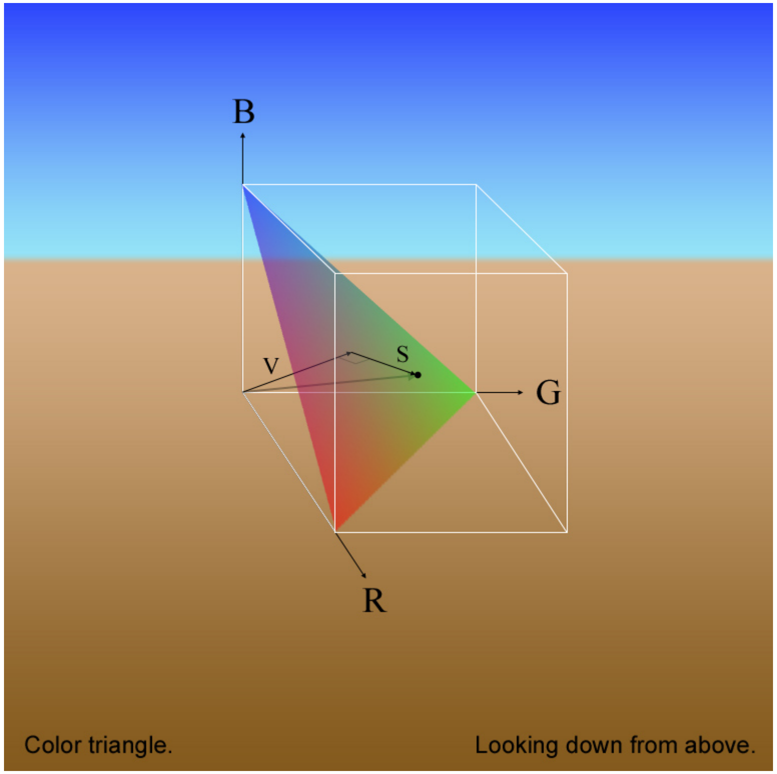
Color Point and Gray Line



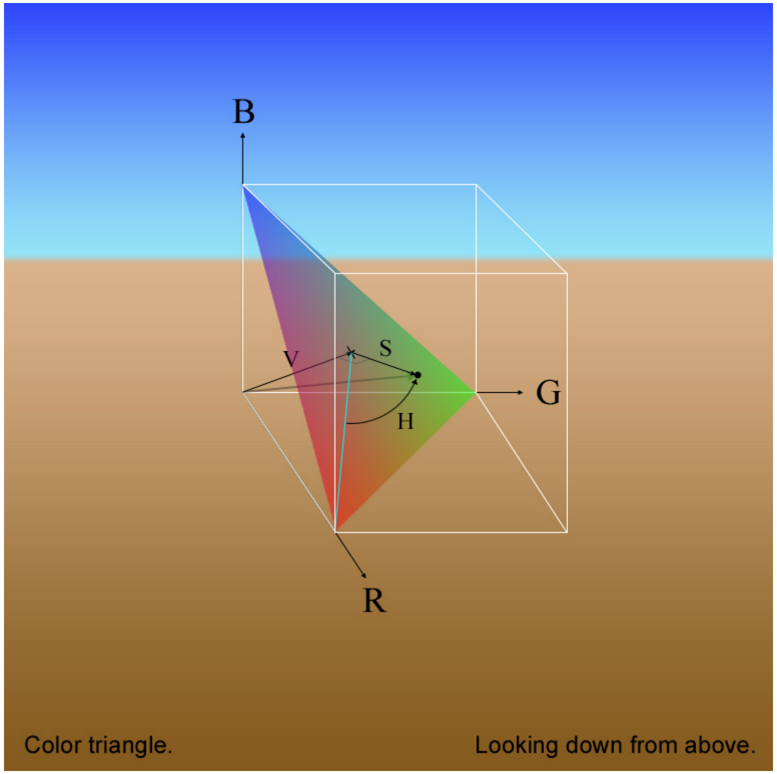
Saturation Component of Color Vector



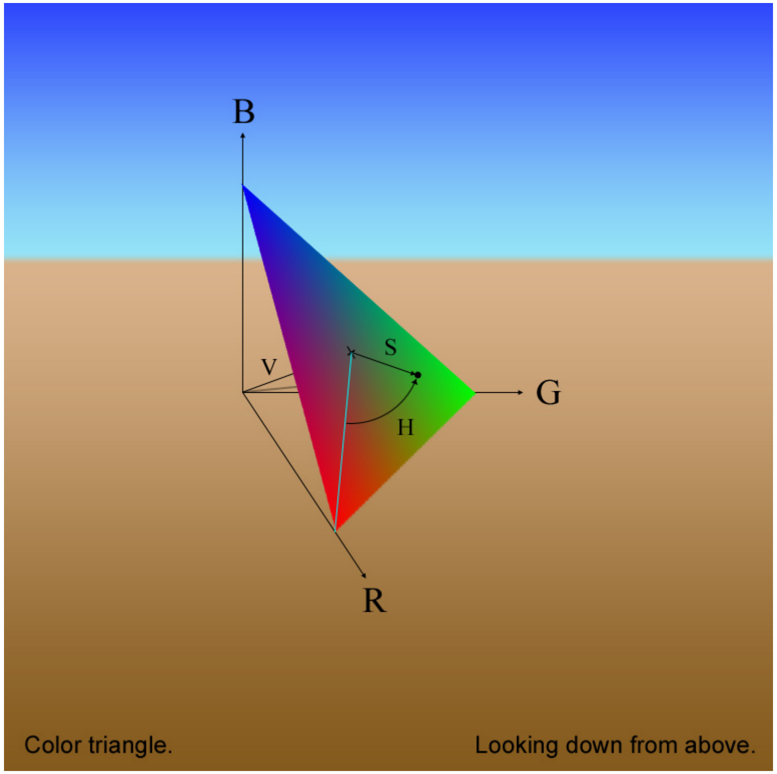
Saturation and Value Components of Color Vector



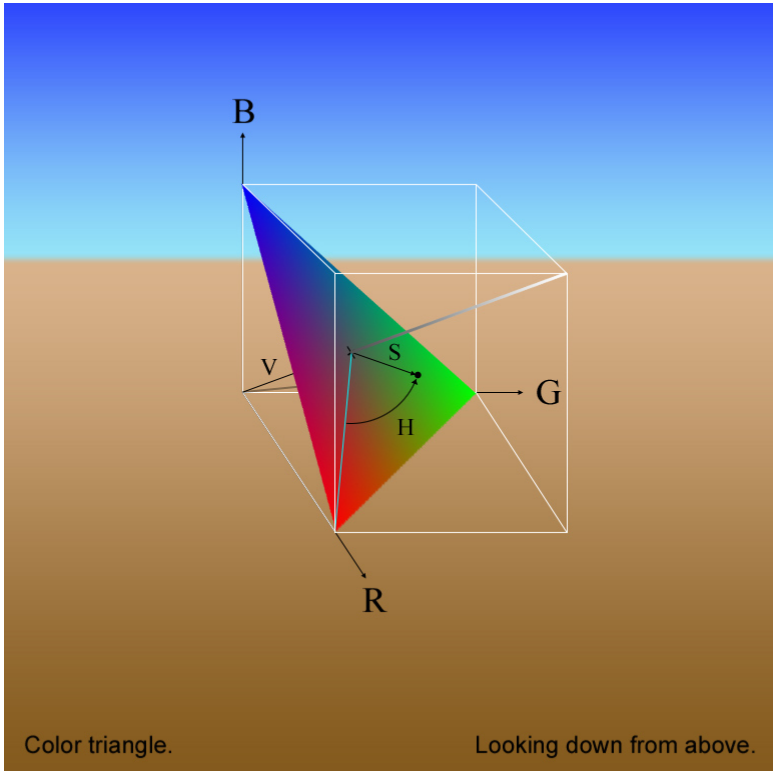
Hue, Saturation, and Value



Hue and Saturation on Equivalue Plane



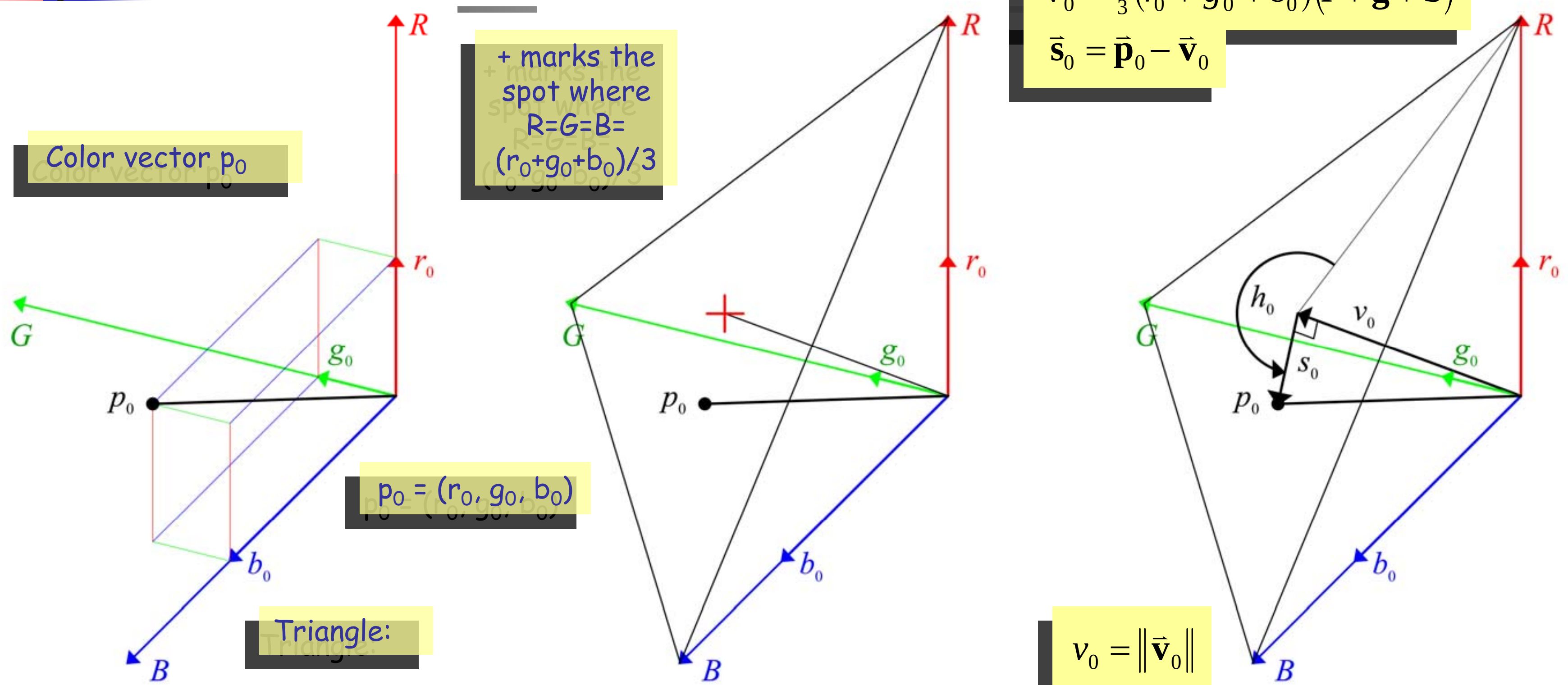
Hue, Saturation, and Value with Gray Line



HSV Color Representation

Color vector p_0

+ marks the spot where R=G=B=$(r_0+g_0+b_0)/3$



$p_0 = (r_0, g_0, b_0)$

Triangle:

lies in plane $R+G+B=(r_0+g_0+b_0)$,

intersects R, G, & B at $r_0+g_0+b_0$, and contains p_0.

$$\vec{\mathbf{v}}_0 = \tfrac{1}{3}(r_0 + g_0 + b_0)(\hat{\mathbf{r}} + \hat{\mathbf{g}} + \hat{\mathbf{b}})$$

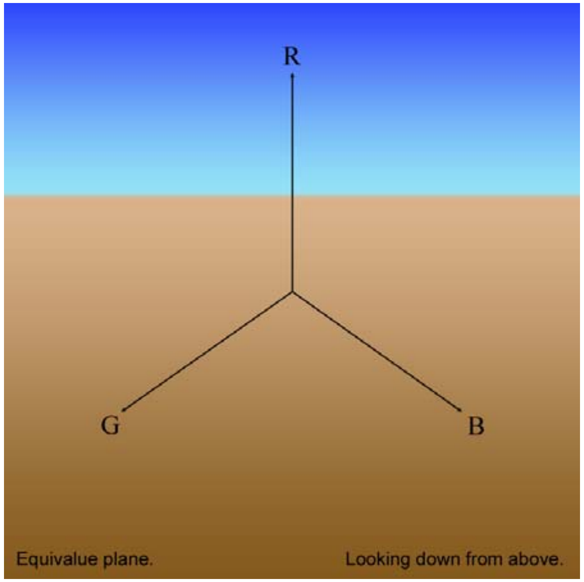
$$\vec{\mathbf{s}}_0 = \vec{\mathbf{p}}_0 - \vec{\mathbf{v}}_0$$

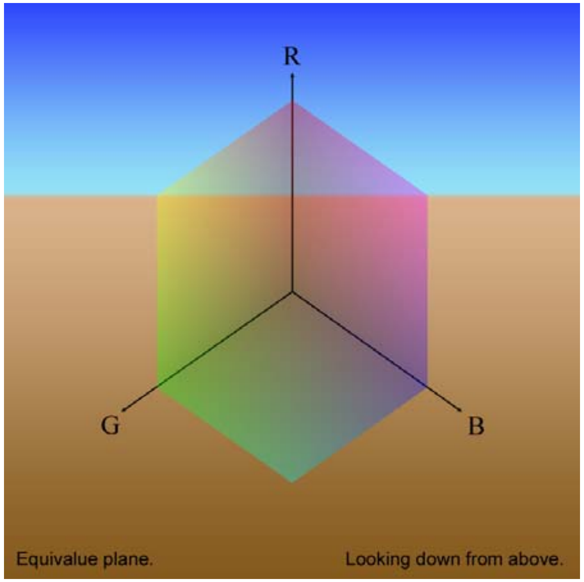
$$v_0 = \|\vec{\mathbf{v}}_0\|$$

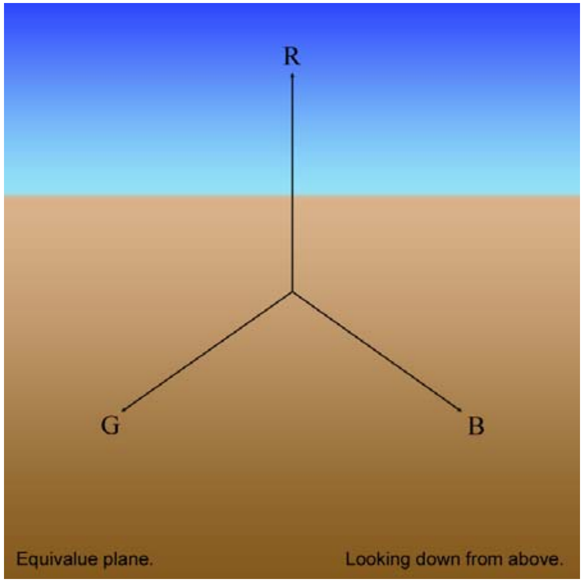
$$s_0 = \|\vec{\mathbf{s}}_0\|$$

$$h_0 = \angle\{[(r_0 + g_0 + b_0)\hat{\mathbf{r}} - \vec{\mathbf{v}}_0], \vec{\mathbf{s}}_0\}$$

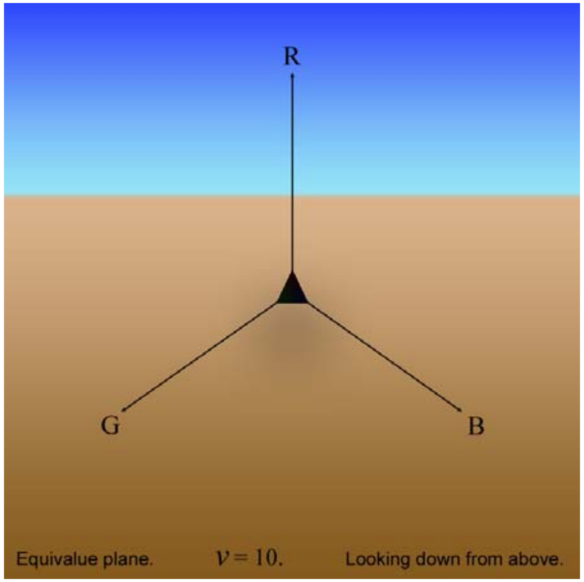
Equivalue Plane Intersecting Color Cube

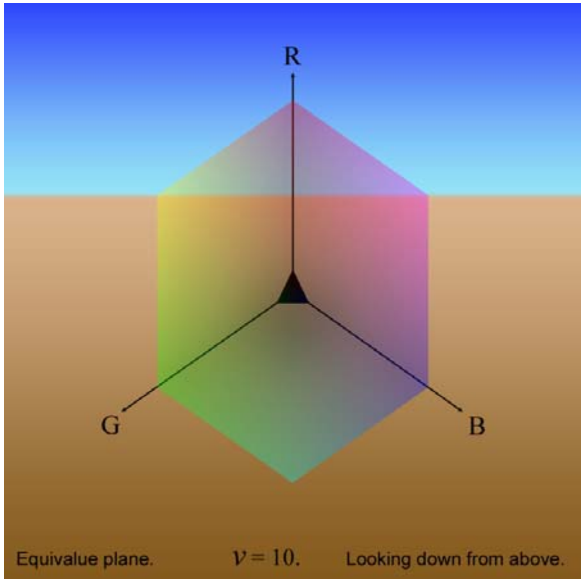


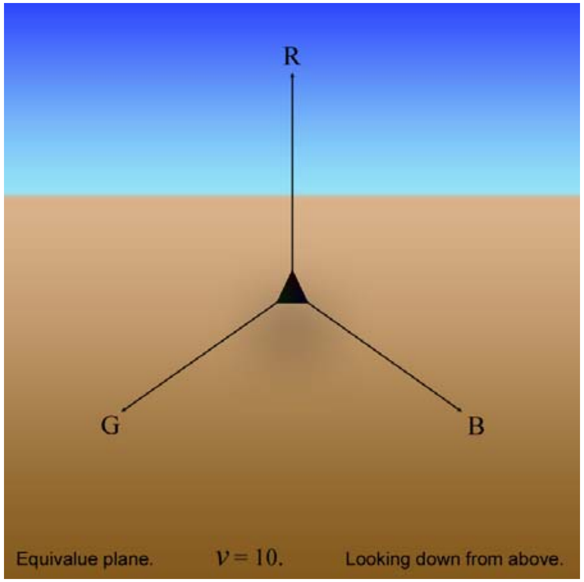




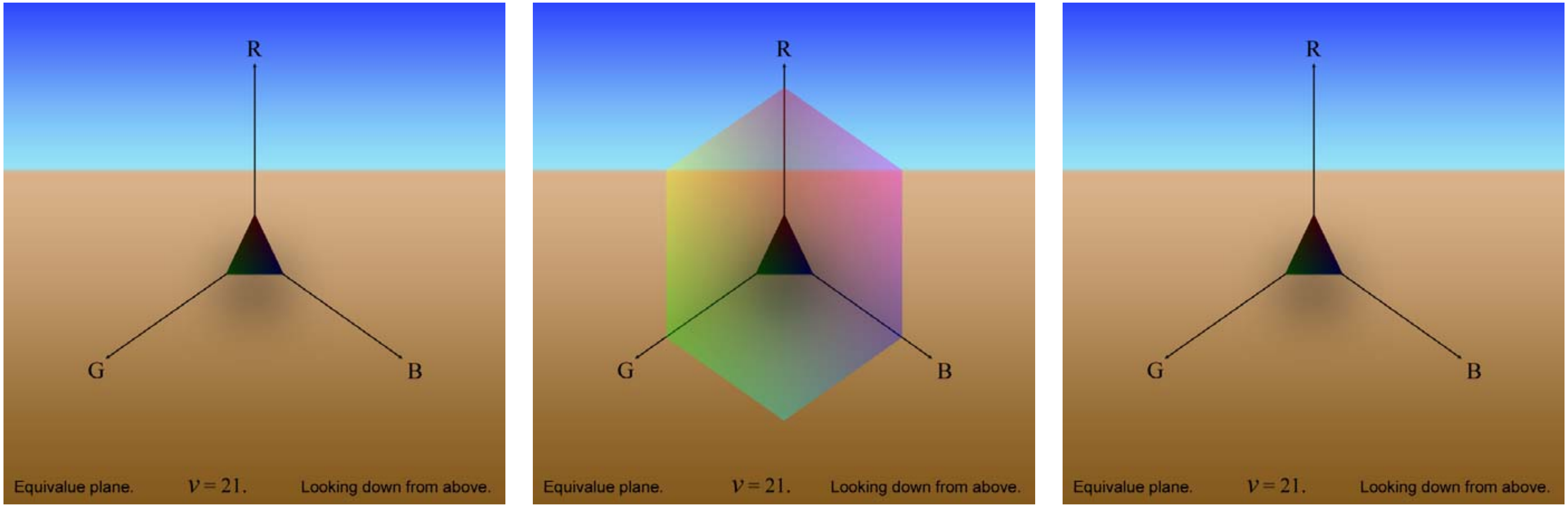
Equivalue Plane Intersecting Color Cube



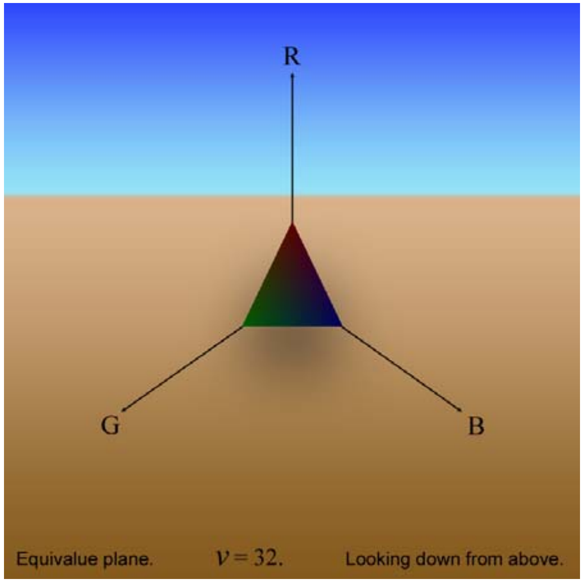


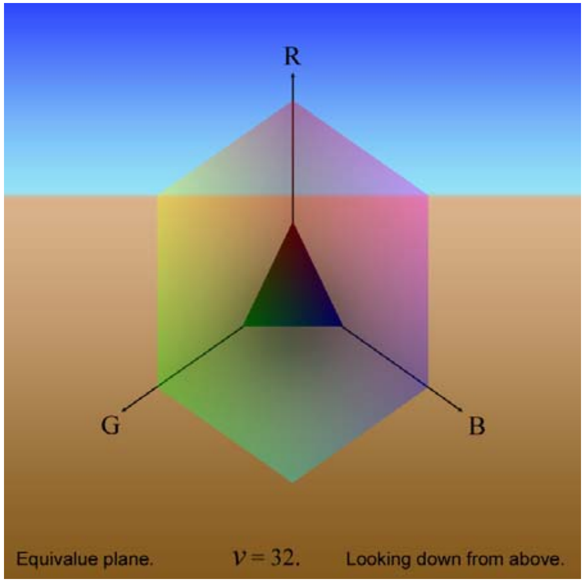


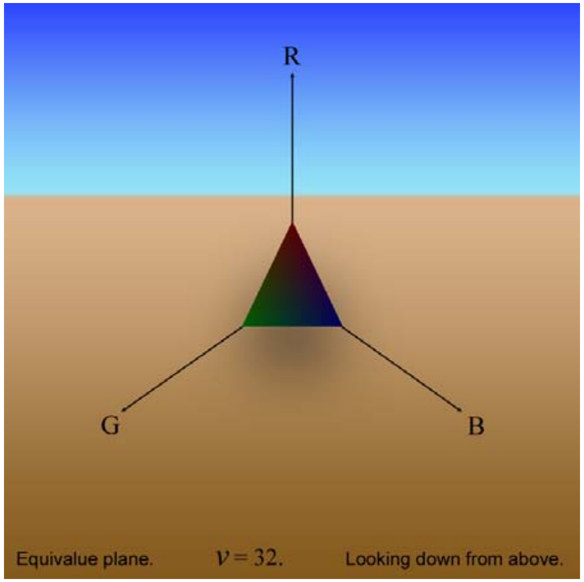
Equivalue Plane Intersecting Color Cube



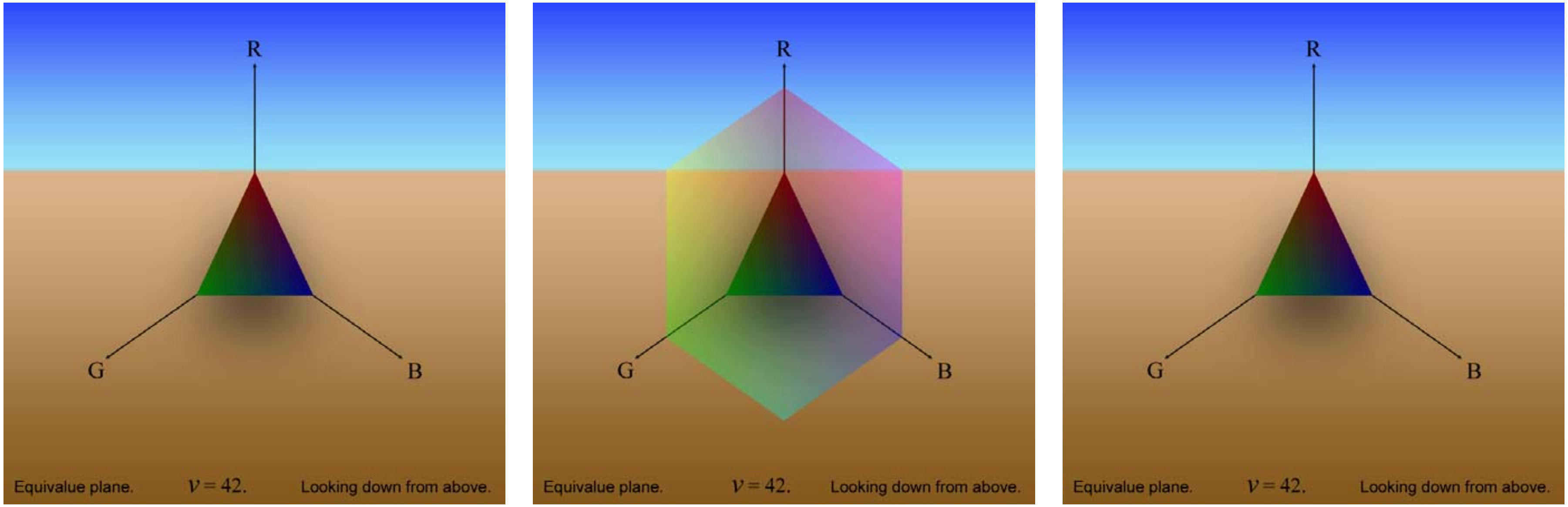
Equivalue Plane Intersecting Color Cube



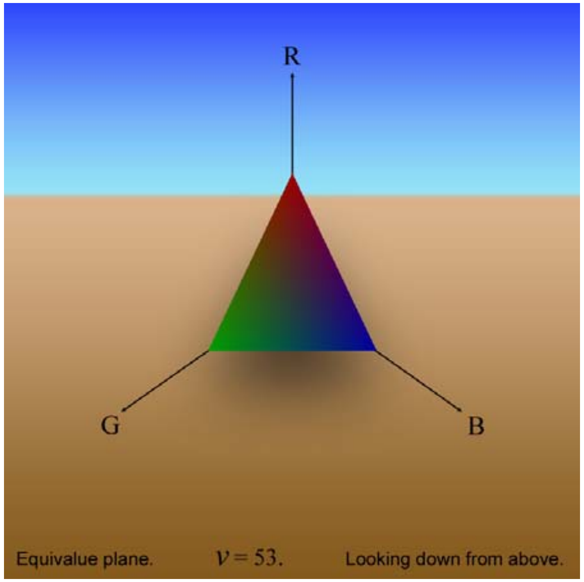


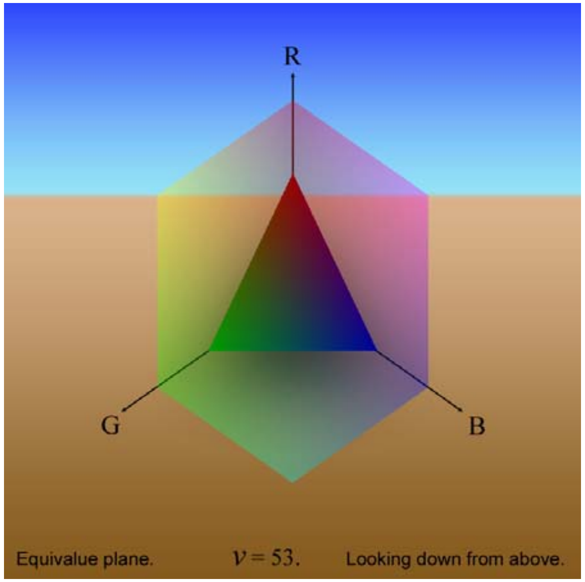


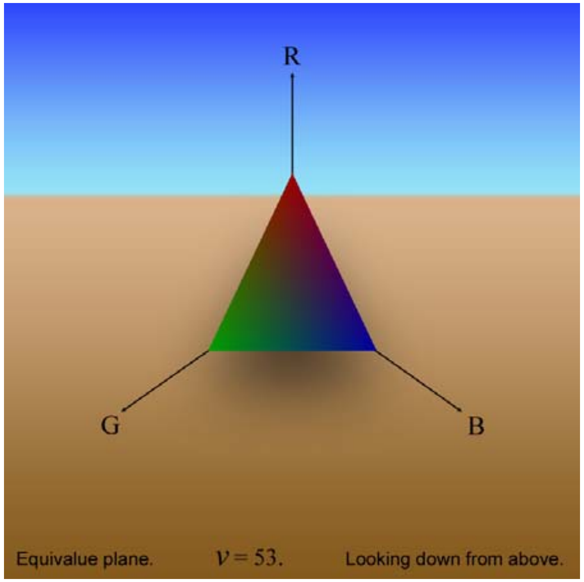
Equivalue Plane Intersecting Color Cube



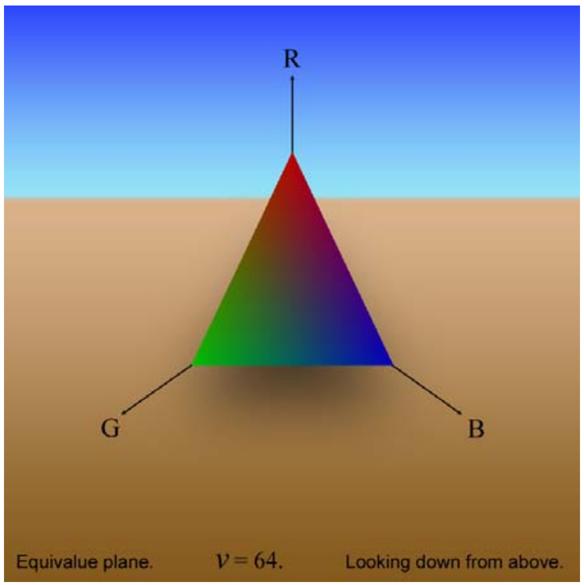
Equivalue Plane Intersecting Color Cube

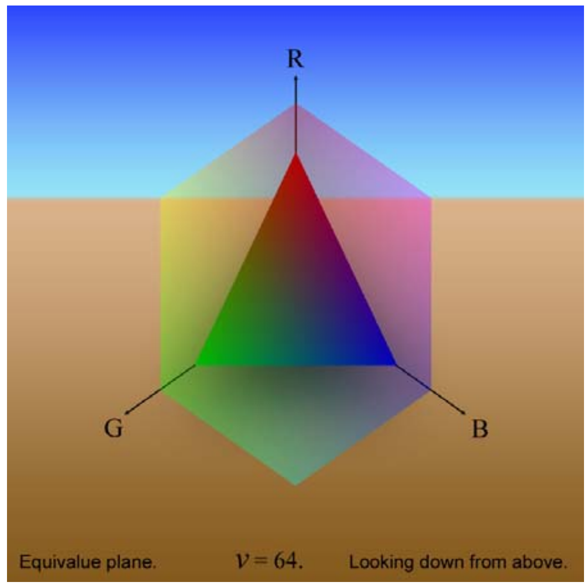


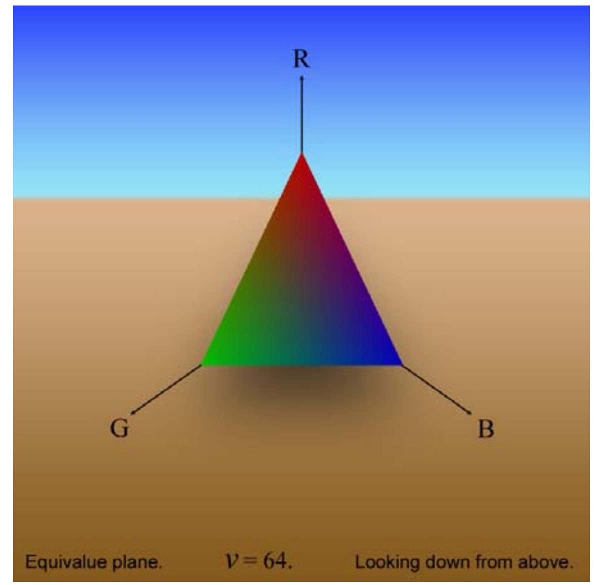




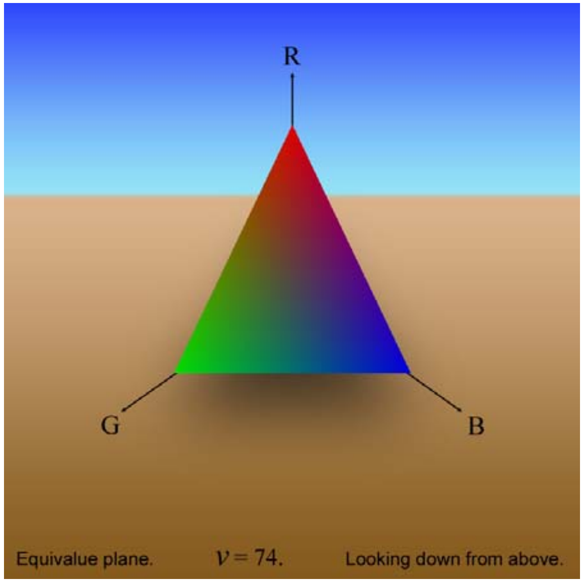
Equivalue Plane Intersecting Color Cube

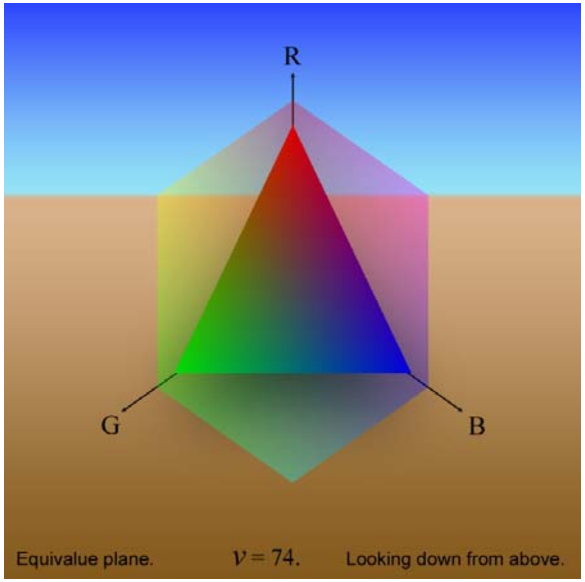


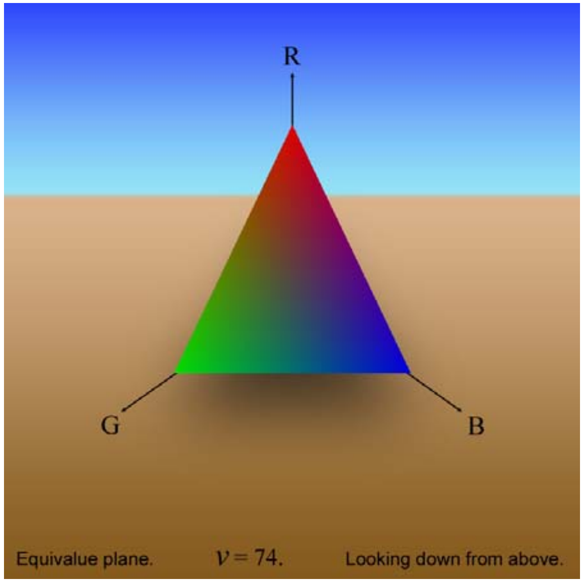




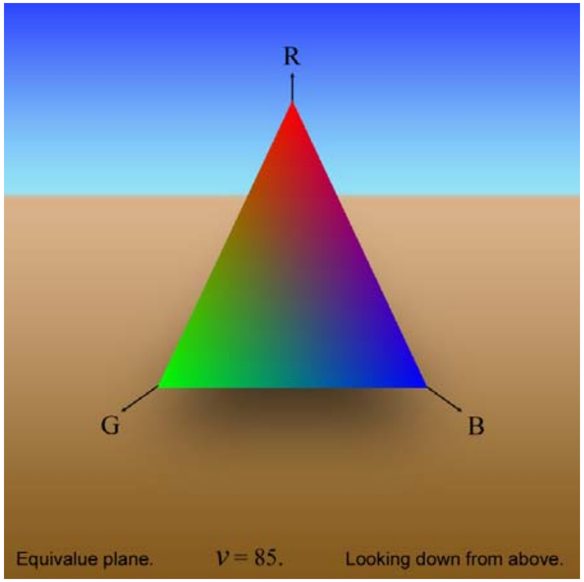
Equivalue Plane Intersecting Color Cube

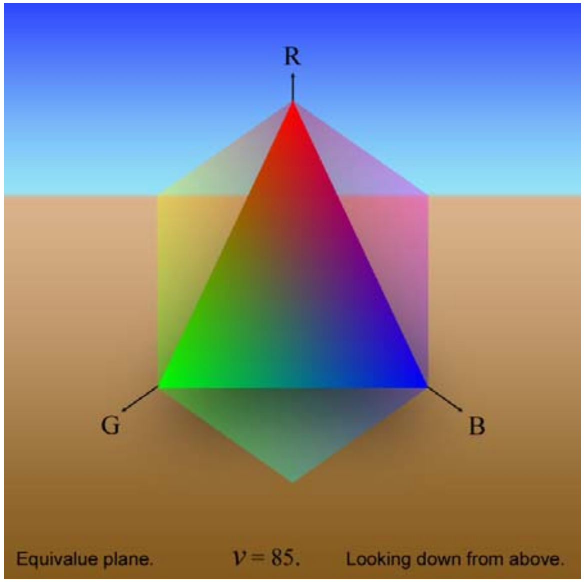


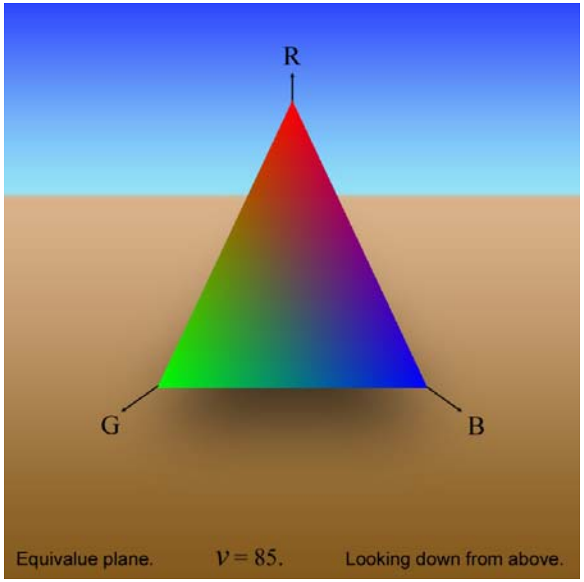




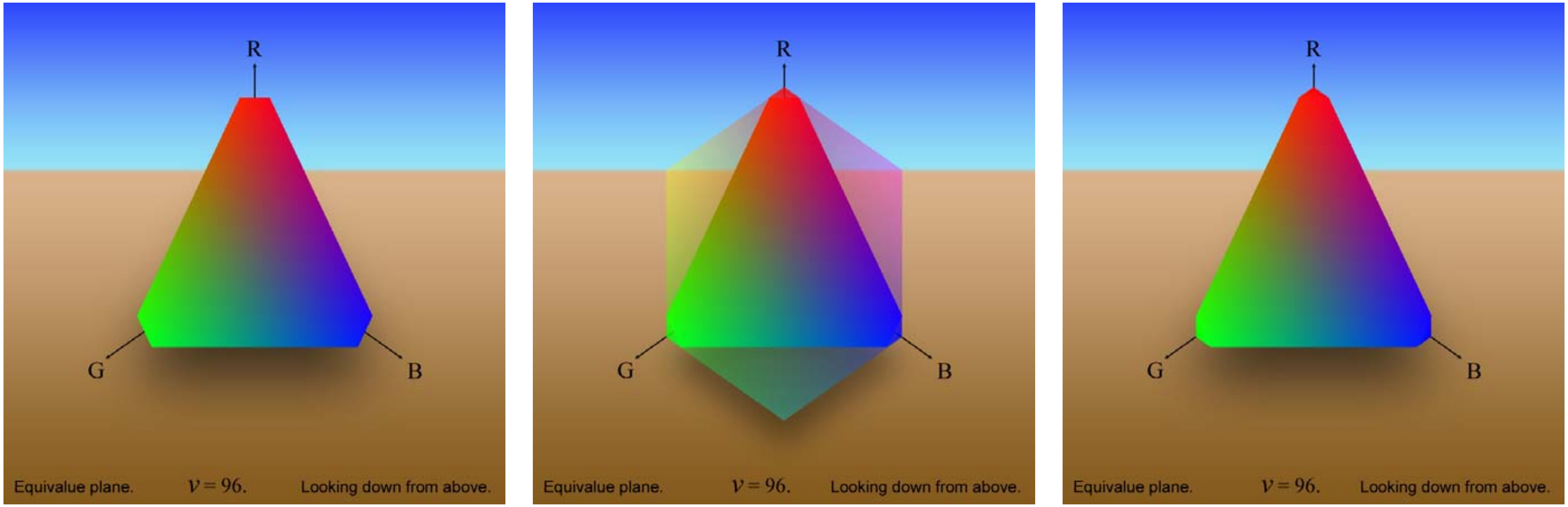
Equivalue Plane Intersecting Color Cube



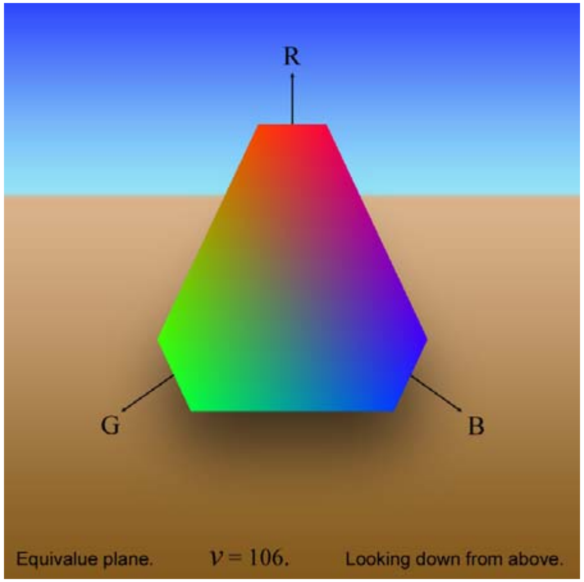


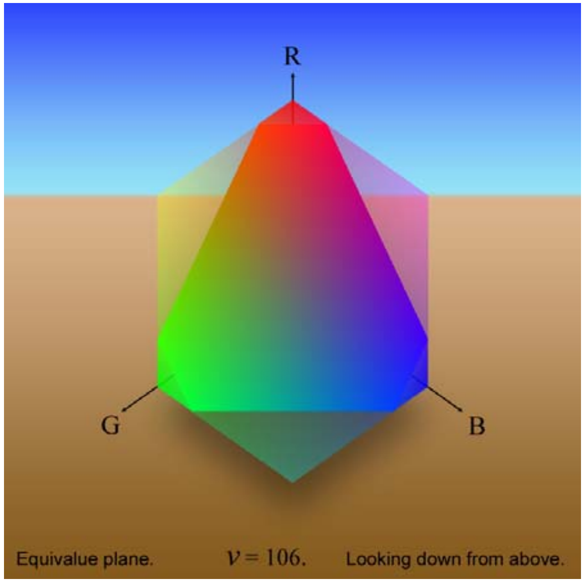


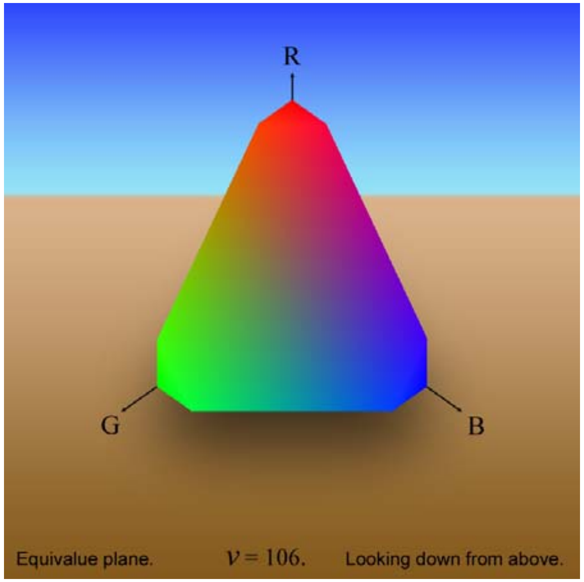
Equivalue Plane Intersecting Color Cube



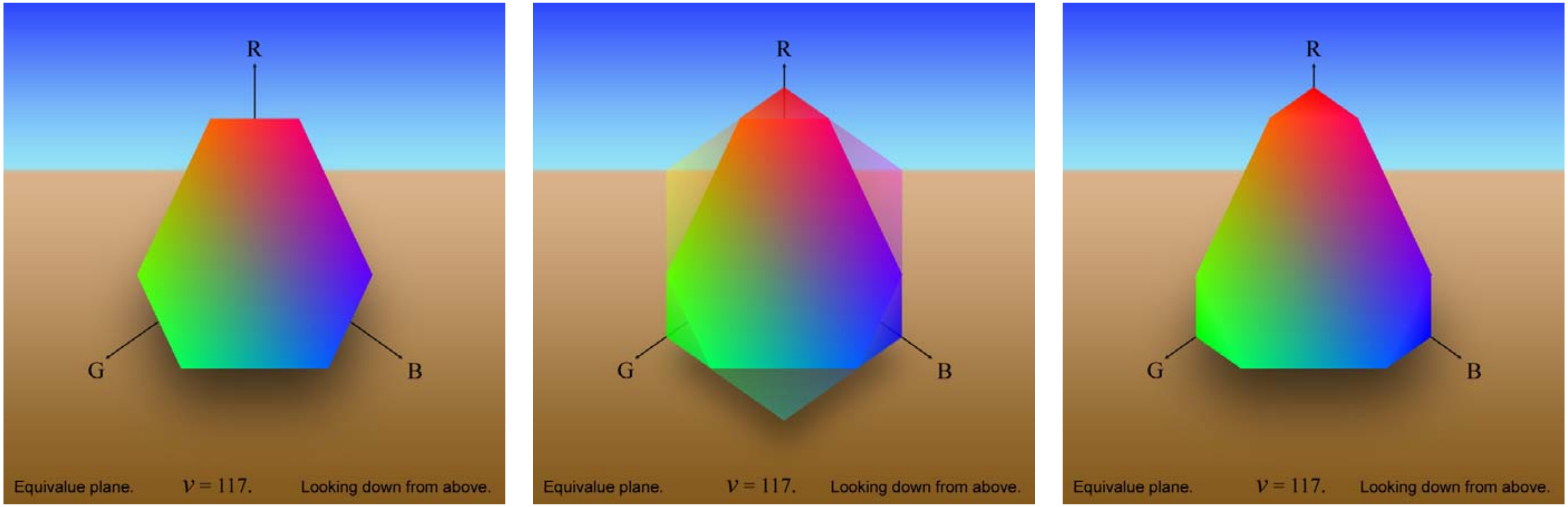
Equivalue Plane Intersecting Color Cube



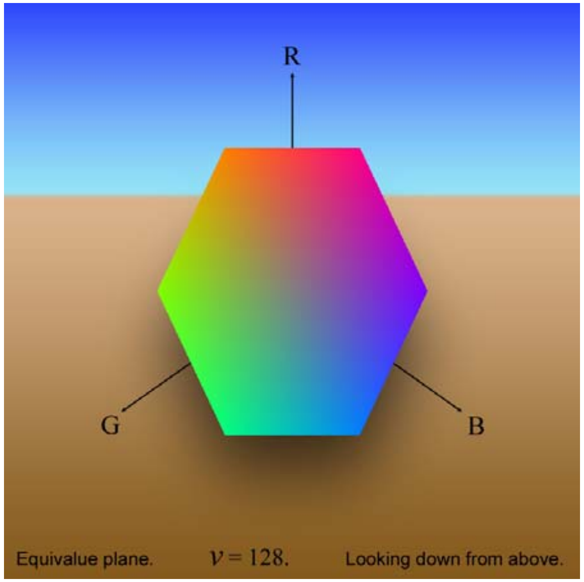


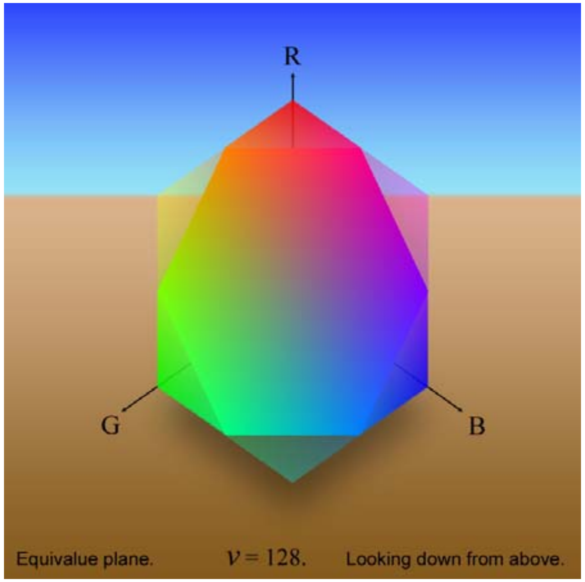


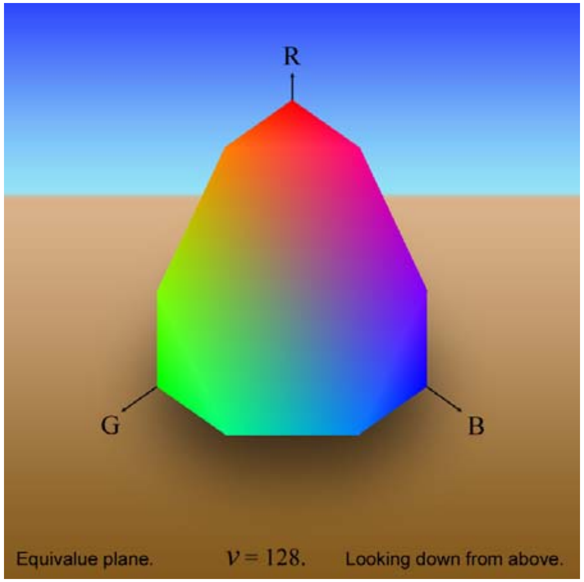
Equivalue Plane Intersecting Color Cube



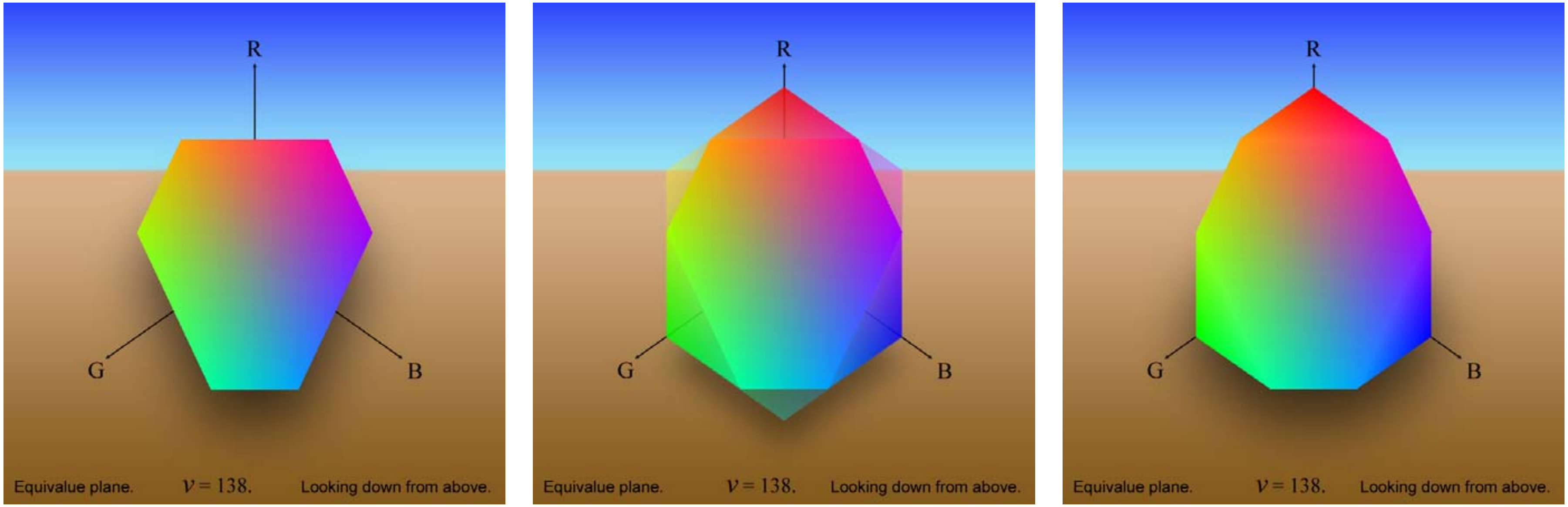
Equivalue Plane Intersecting Color Cube



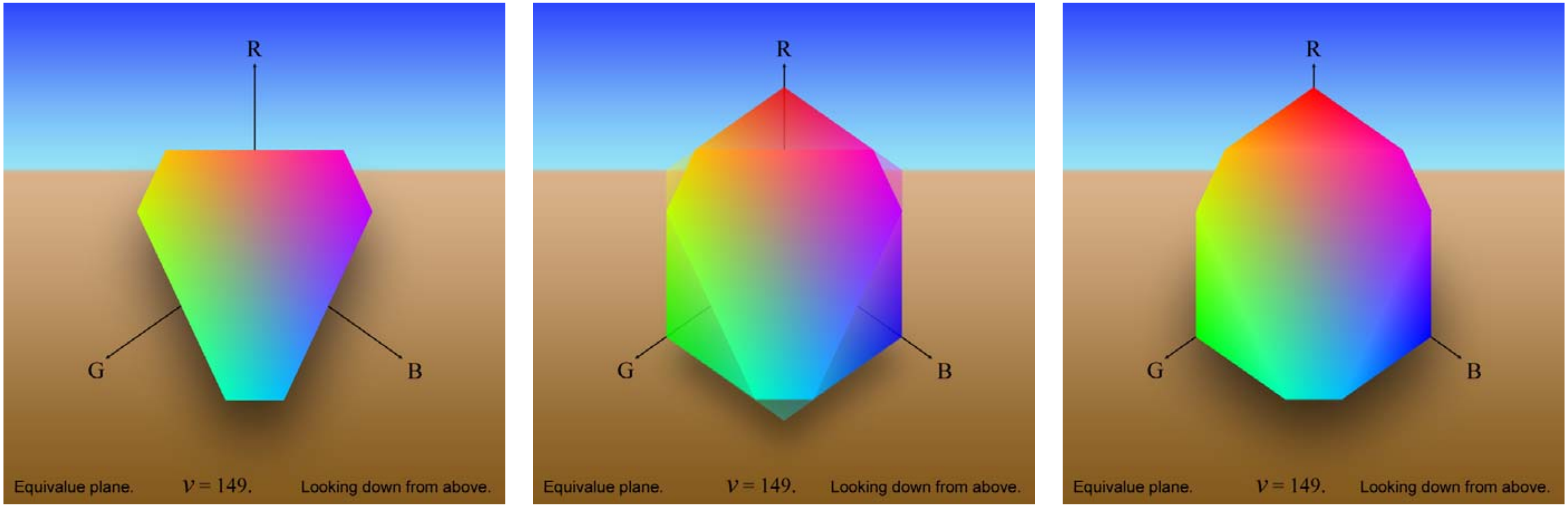




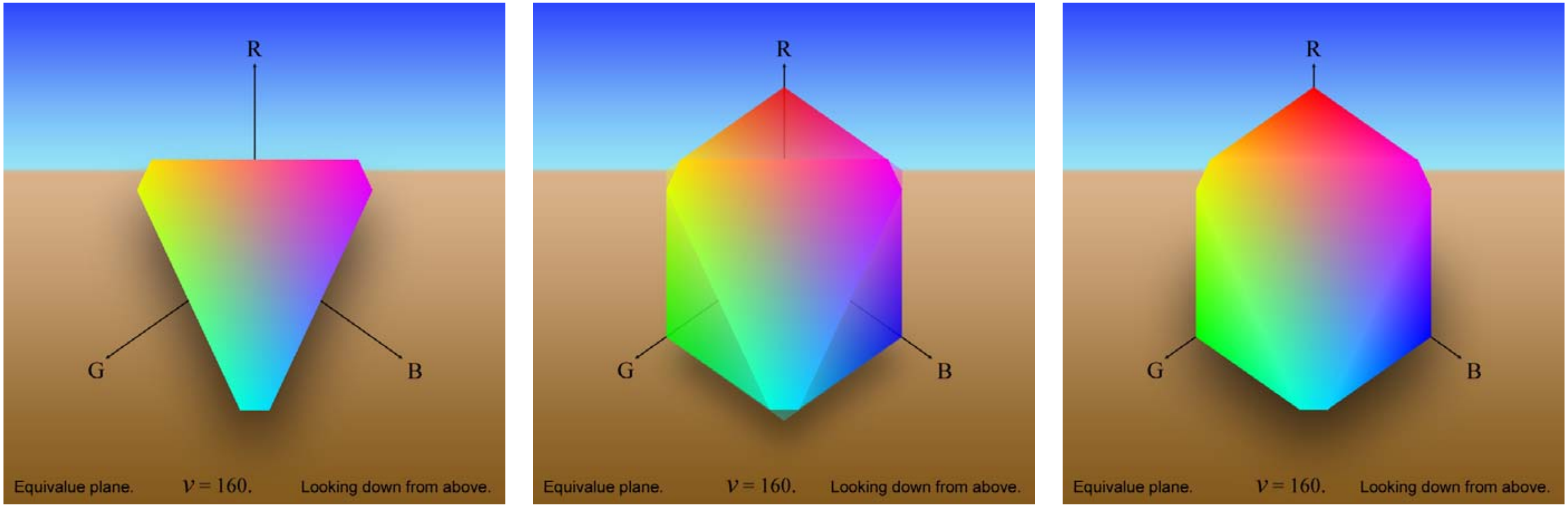
Equivalue Plane Intersecting Color Cube



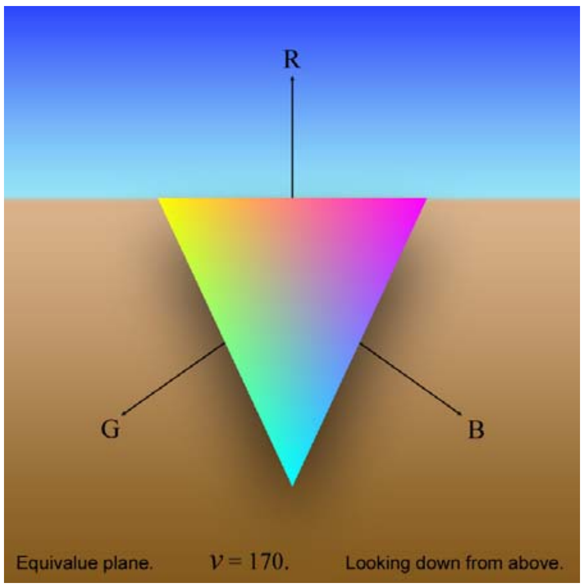
Equivalue Plane Intersecting Color Cube

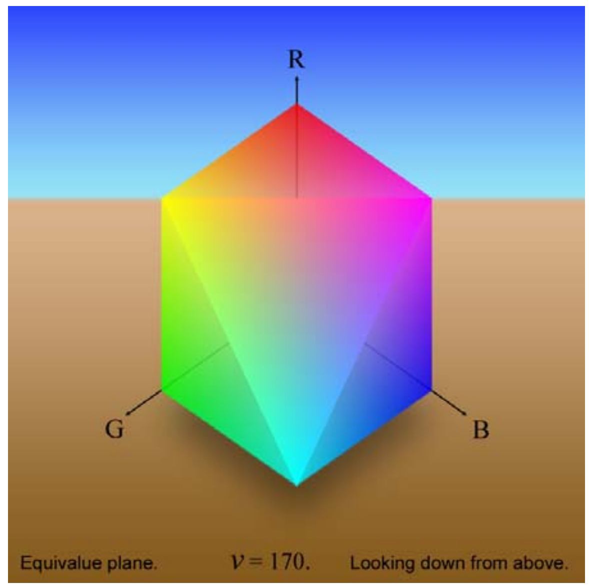


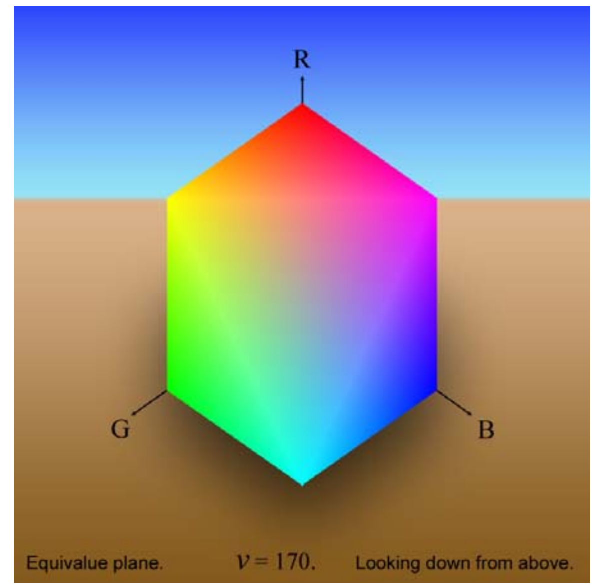
Equivalue Plane Intersecting Color Cube



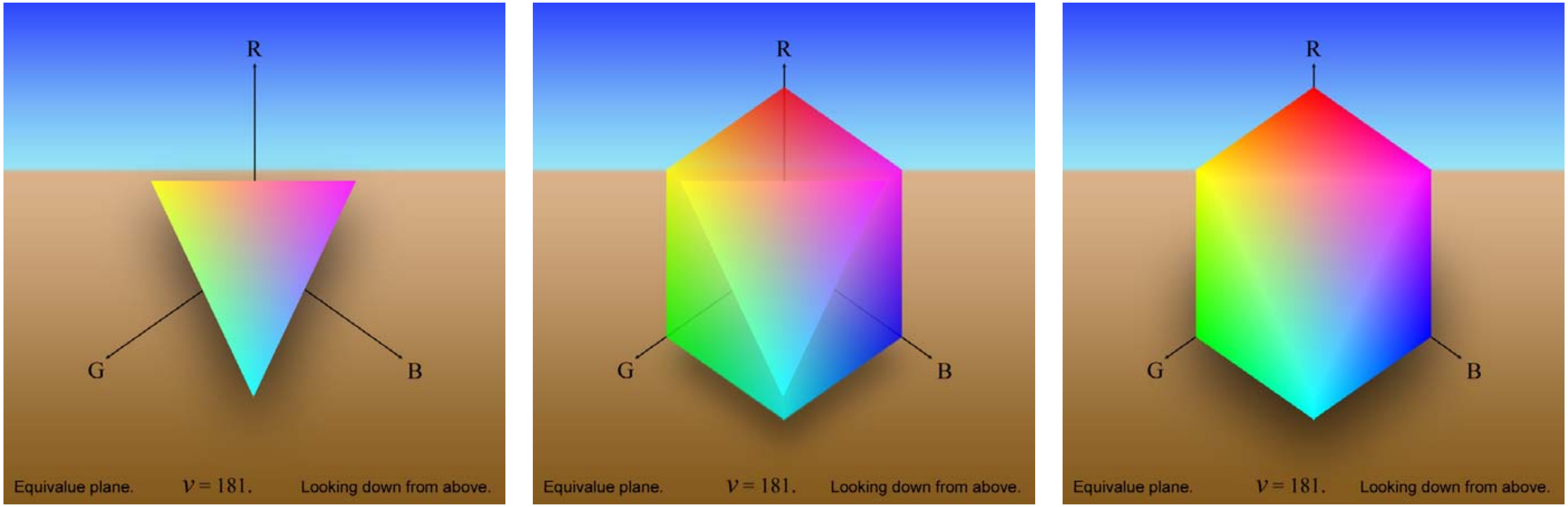
Equivalue Plane Intersecting Color Cube



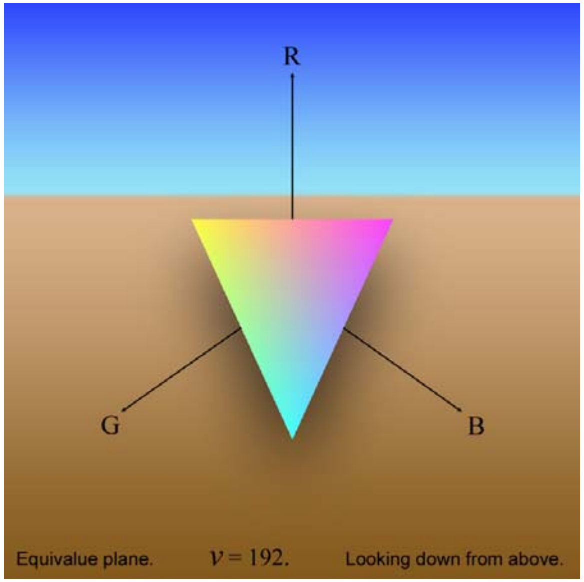


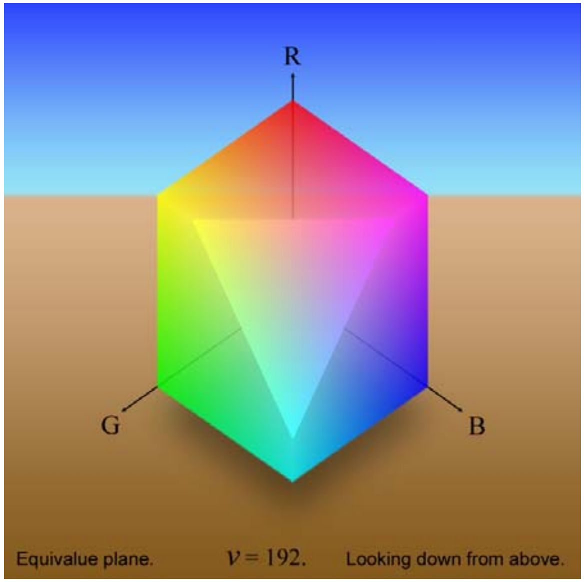


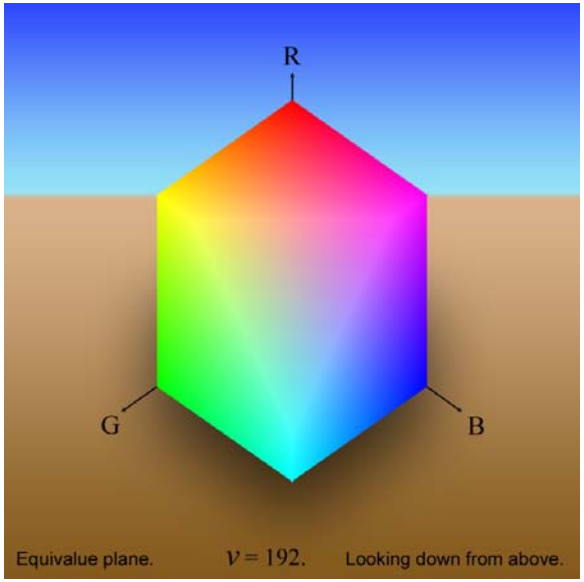
Equivalue Plane Intersecting Color Cube



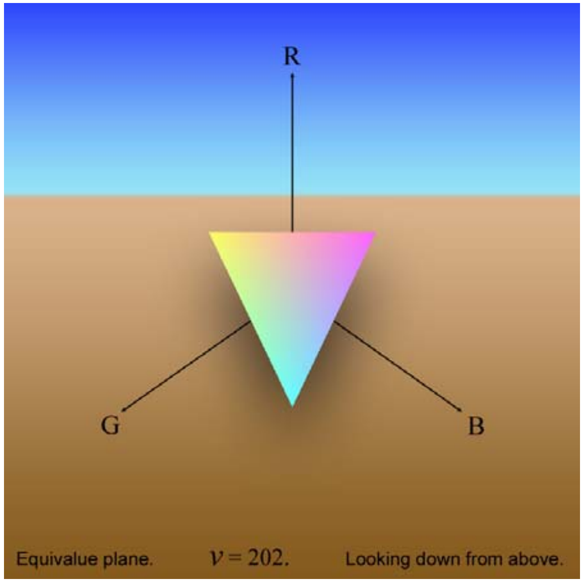
Equivalue Plane Intersecting Color Cube

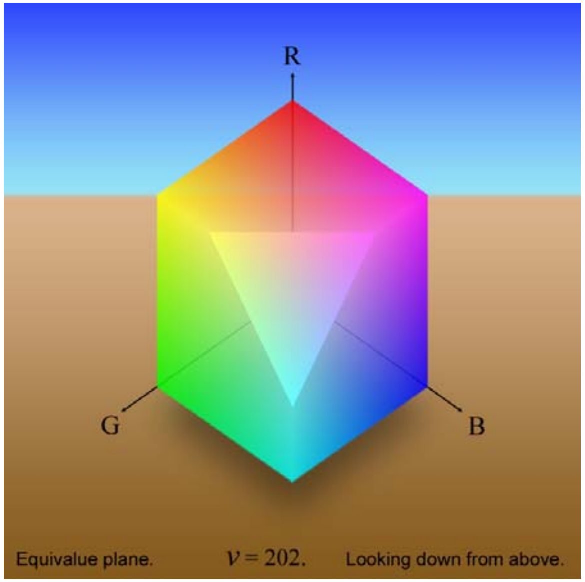


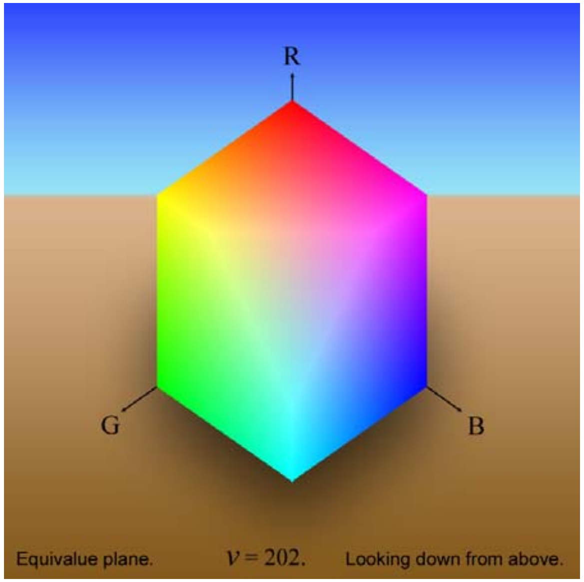




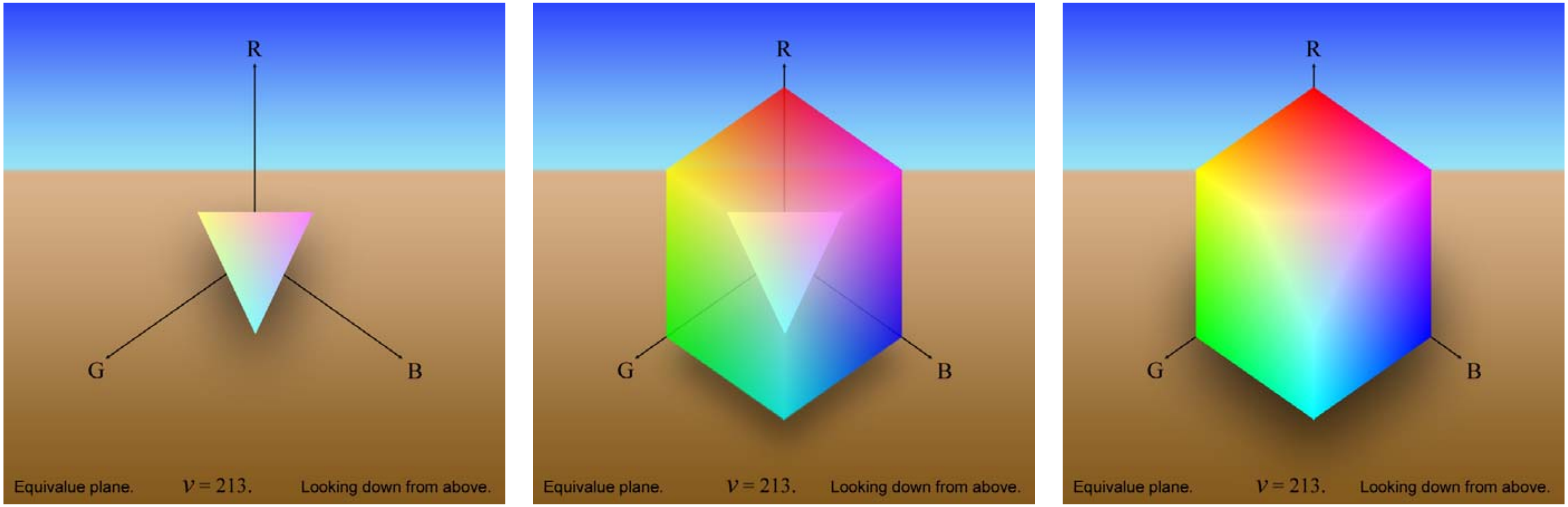
Equivalue Plane Intersecting Color Cube



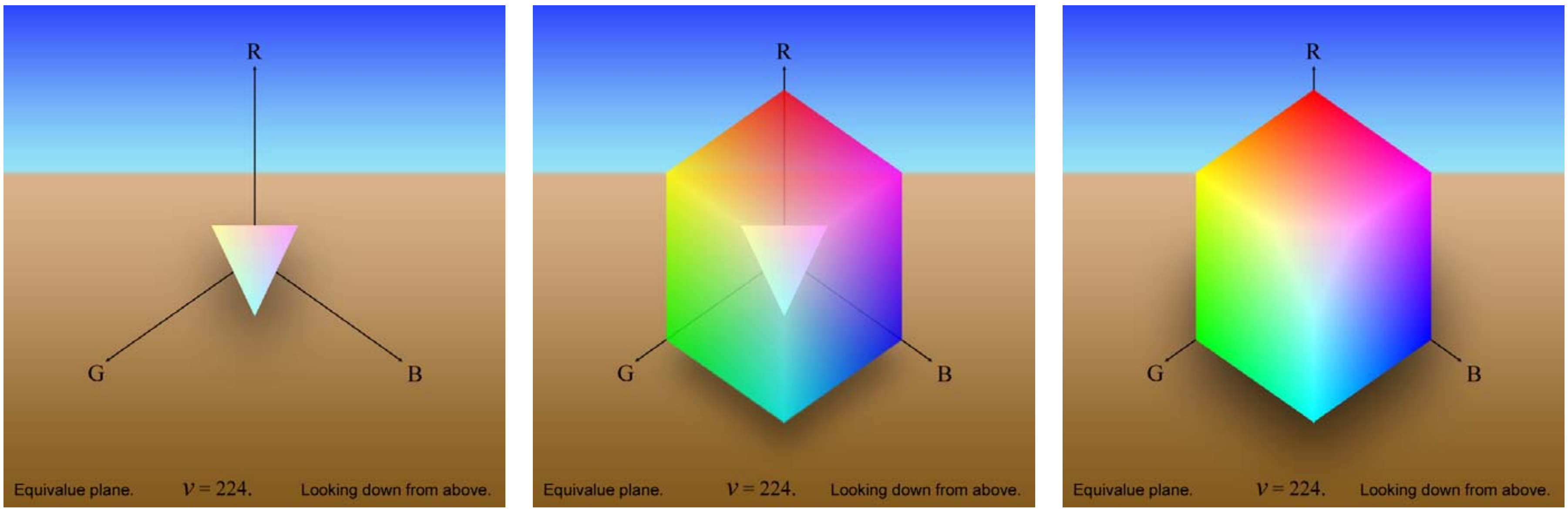




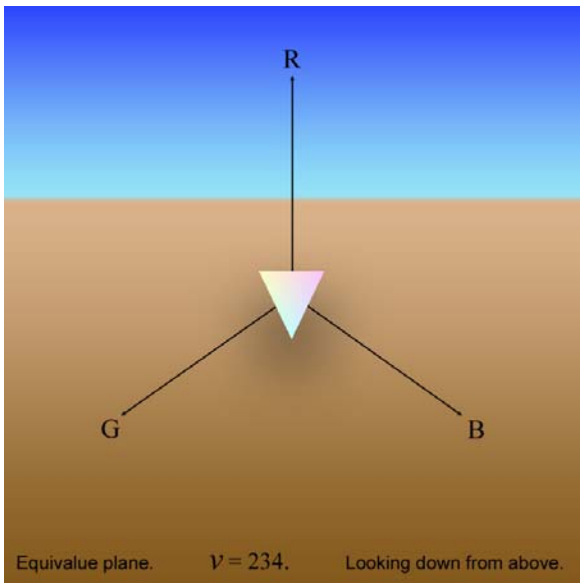
Equivalue Plane Intersecting Color Cube

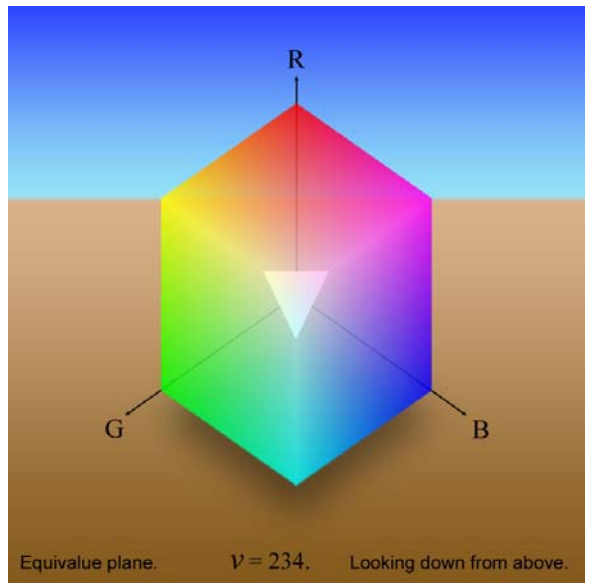


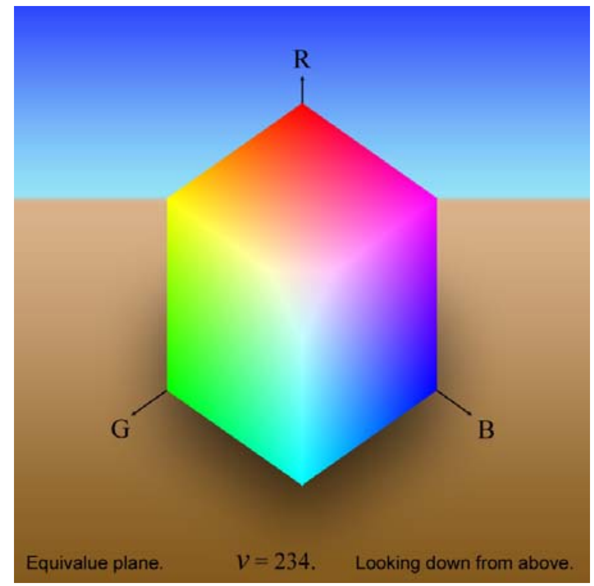
Equivalue Plane Intersecting Color Cube



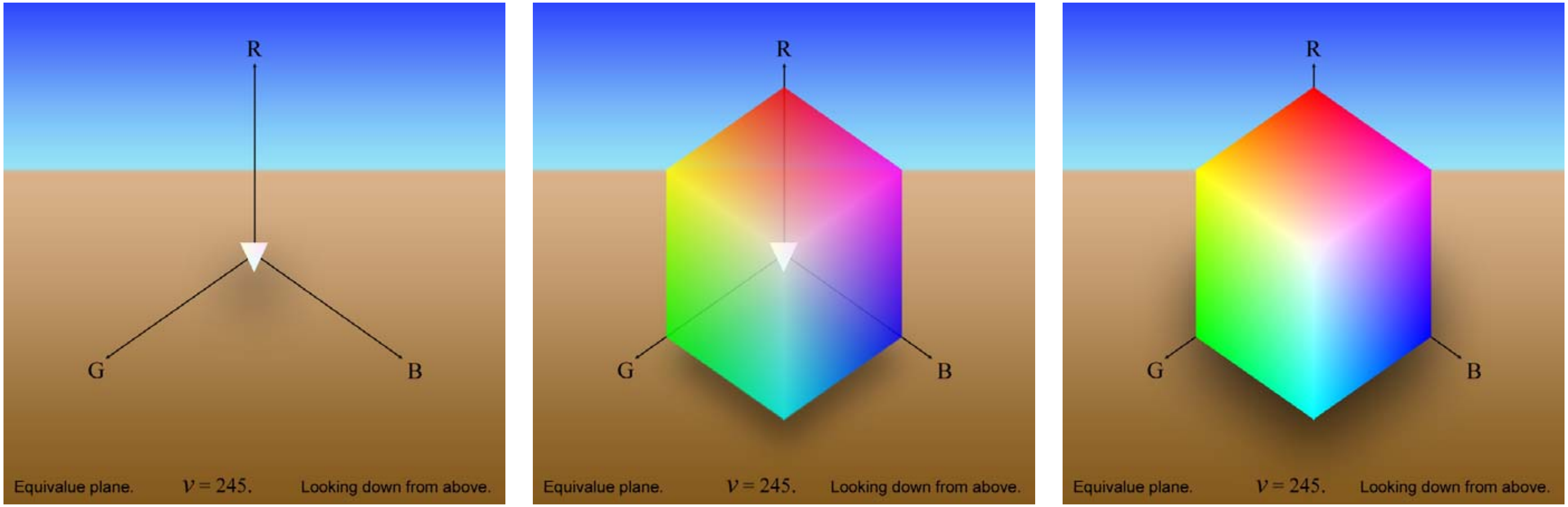
Equivalue Plane Intersecting Color Cube



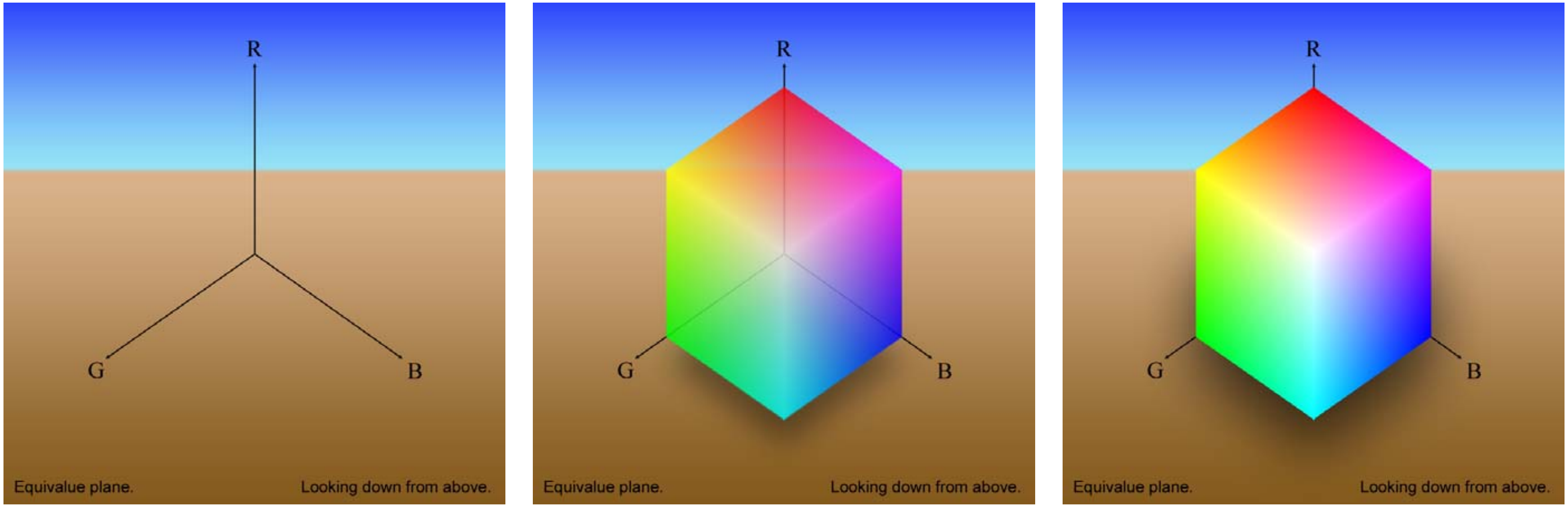




Equivalue Plane Intersecting Color Cube



Equivalue Plane Intersecting Color Cube



RGB to HSV Conversion

In summary,

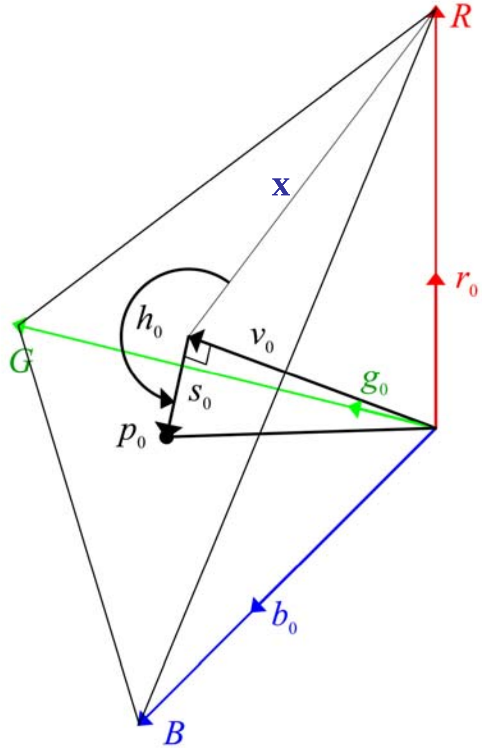
$$v_0 = \tfrac{1}{3}c, \;\text{ or }\; v_0 = \left\|\mathbf{v}_0\right\| = \tfrac{\sqrt{3}}{3}c,$$

where $c = r_0 + g_0 + b_0$,

$$s_0 = \sqrt{\left(r_0 - \tfrac{1}{3}c\right)^2 + \left(g_0 - \tfrac{1}{3}c\right)^2 + \left(b_0 - \tfrac{1}{3}c\right)^2},$$

and

$$h_0 = \cos^{-1}\left(\frac{\mathbf{s}_0 \cdot \mathbf{x}}{\left\|\mathbf{s}_0\right\|\left\|\mathbf{x}\right\|}\right).$$



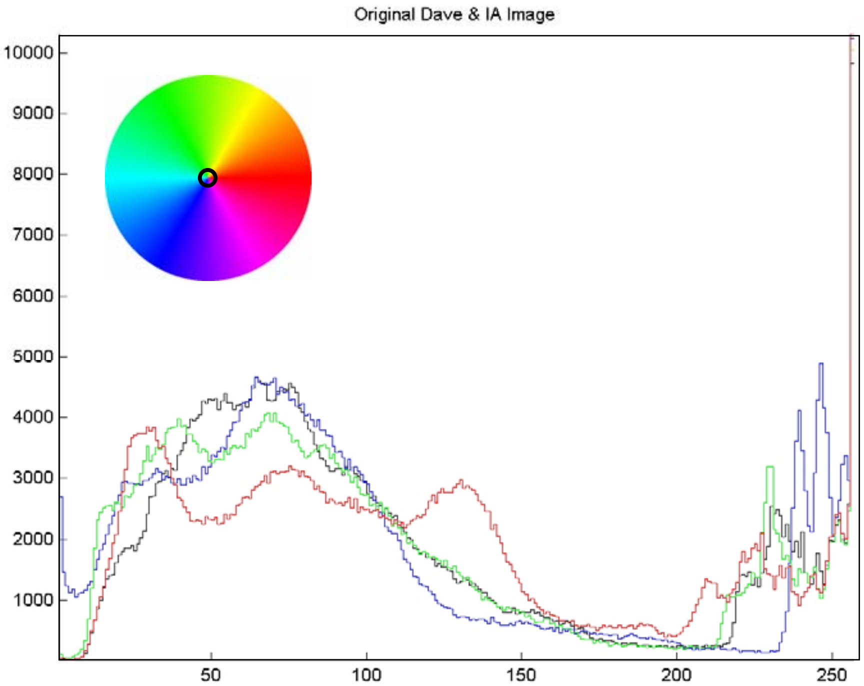
Parse the conversion formula of Matlab function rgb2hsv()

Color Correction

Global changes in the coloration of an image to alter its tint, its hues or the saturation of its colors with minimal changes to its luminant features

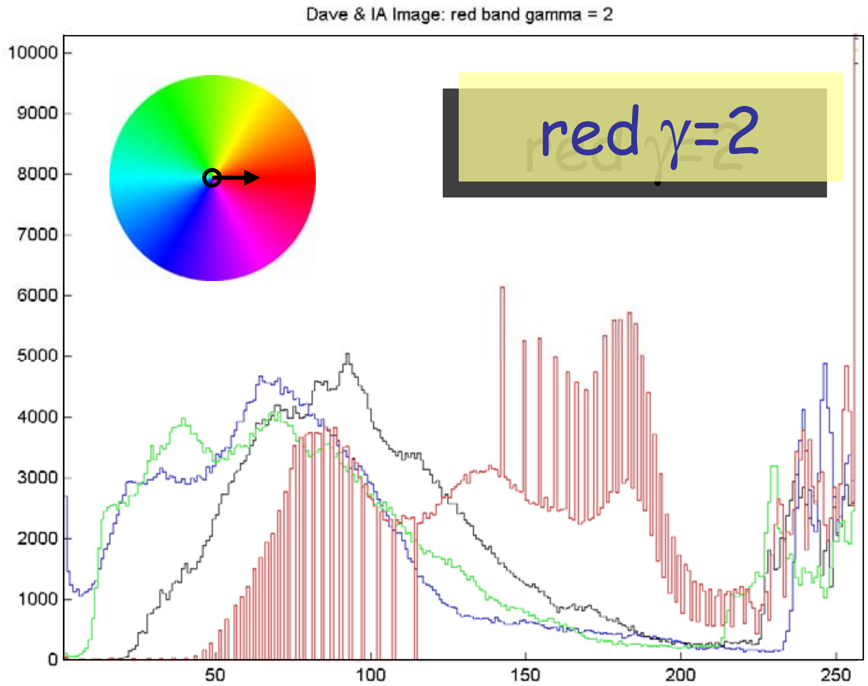
Gamma Adjustment of Color Bands

original



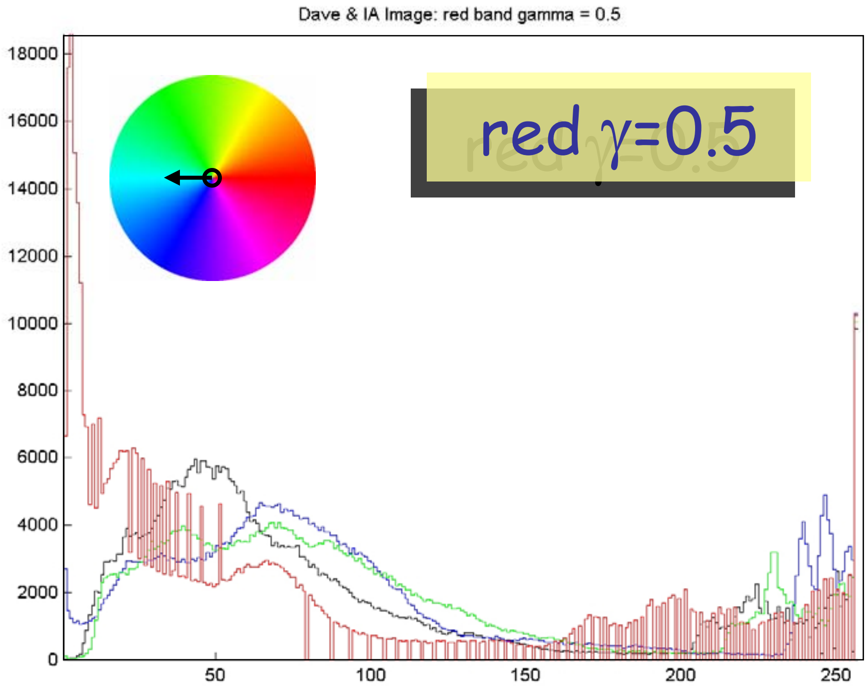
David Peters, producer, and representatives of the IA, The International Alliance of Theatrical Stage Employees, Moving Picture Technicians, Artists and Allied Crafts, on the set of *Frozen Impact* (PorchLight Entertainment, 2003).

Gamma Adjustment of Color Bands



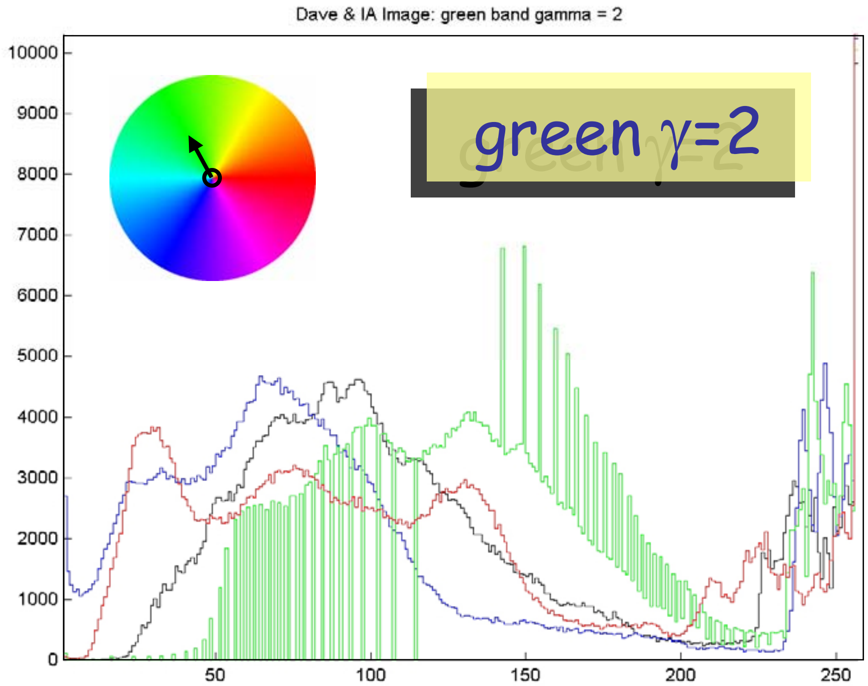
$$J = 255 \cdot \left(I / 255 \right)^{1/\gamma}$$

Gamma Adjustment of Color Bands

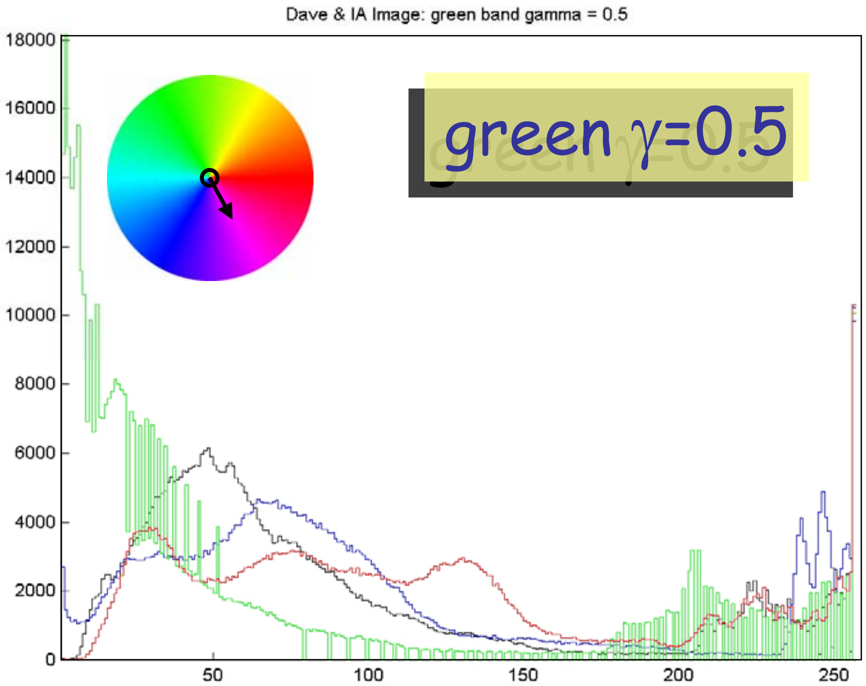


reduced red = increased cyan

Gamma Adjustment of Color Bands



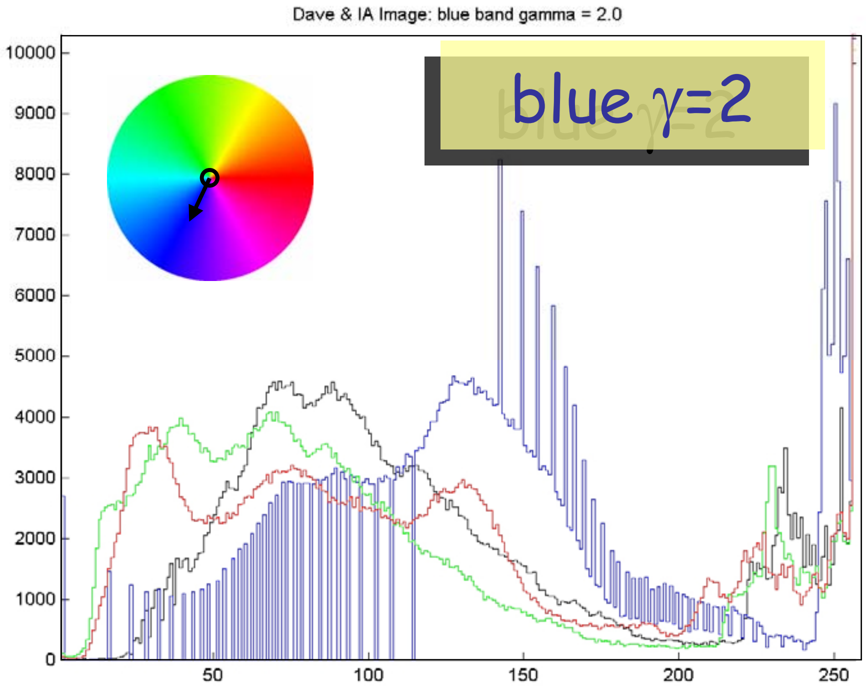
Gamma Adjustment of Color Bands



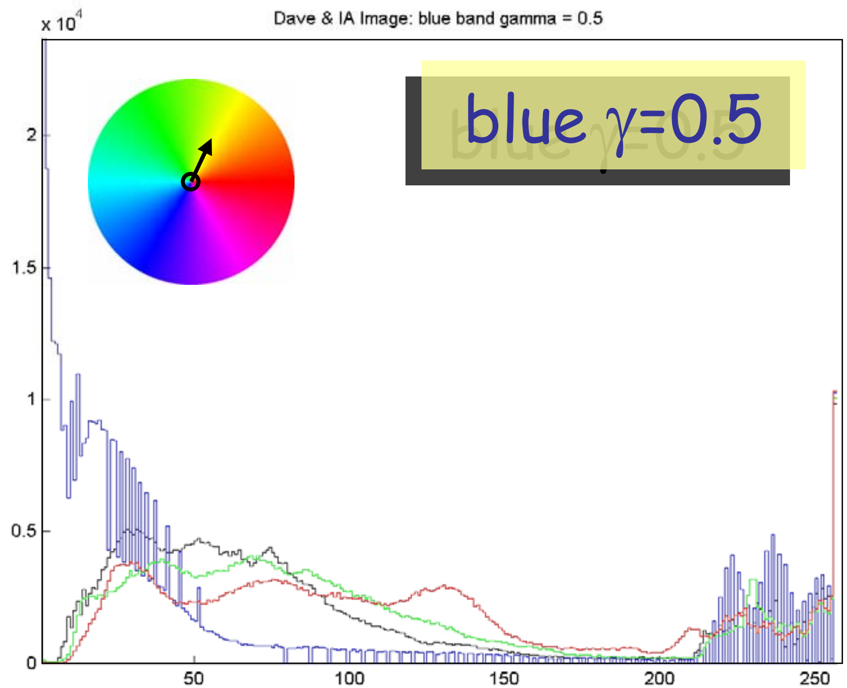
green γ=0.5

reduced green = incr. magenta

Gamma Adjustment of Color Bands



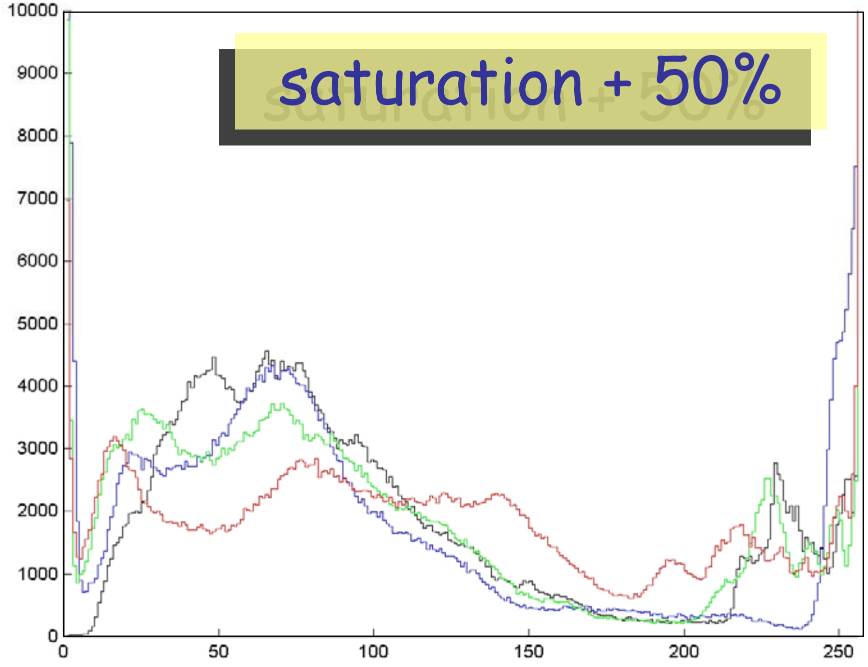
Gamma Adjustment of Color Bands



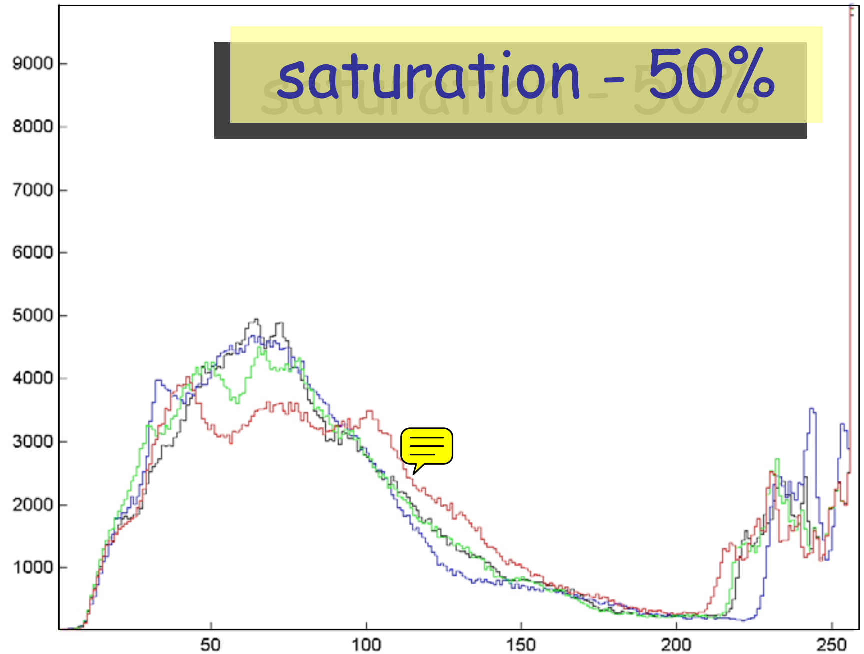
blue γ=0.5

reduced blue = incr. yellow

Saturation Adjustment

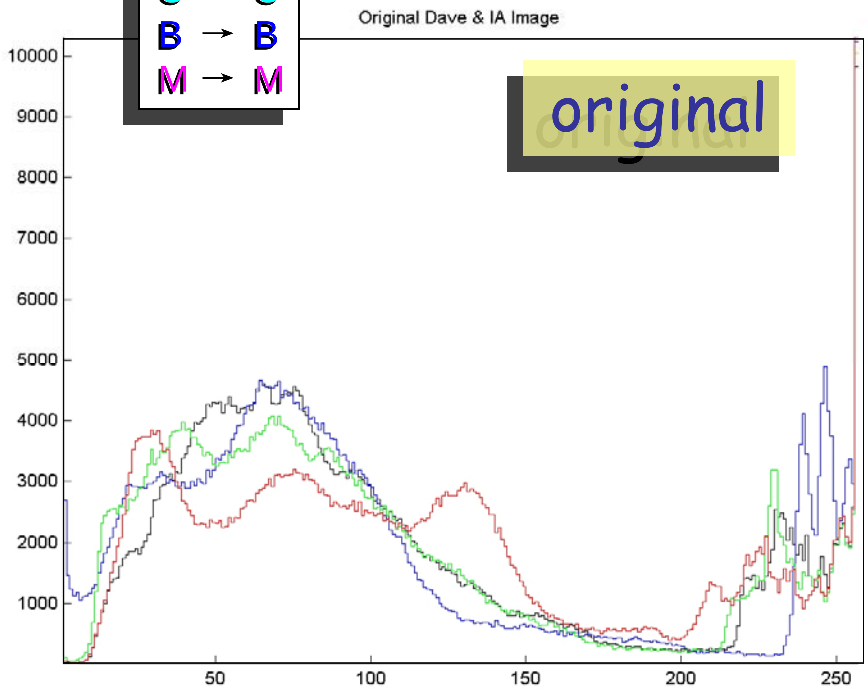


Saturation Adjustment



Hue Shifting

R	→	R
Y	→	Y
G	→	G
C	→	C
B	→	B
M	→	M

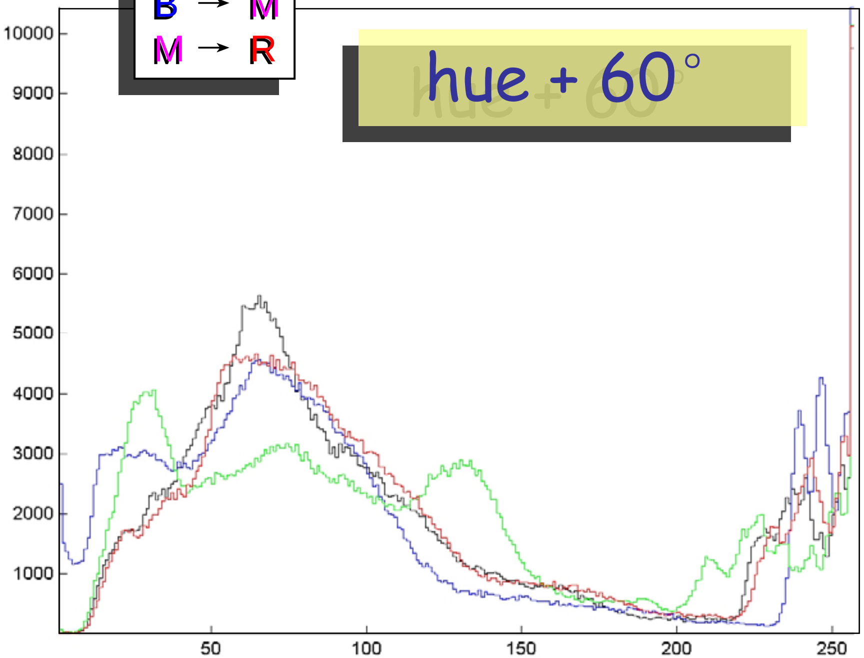


original

Hue Shifting

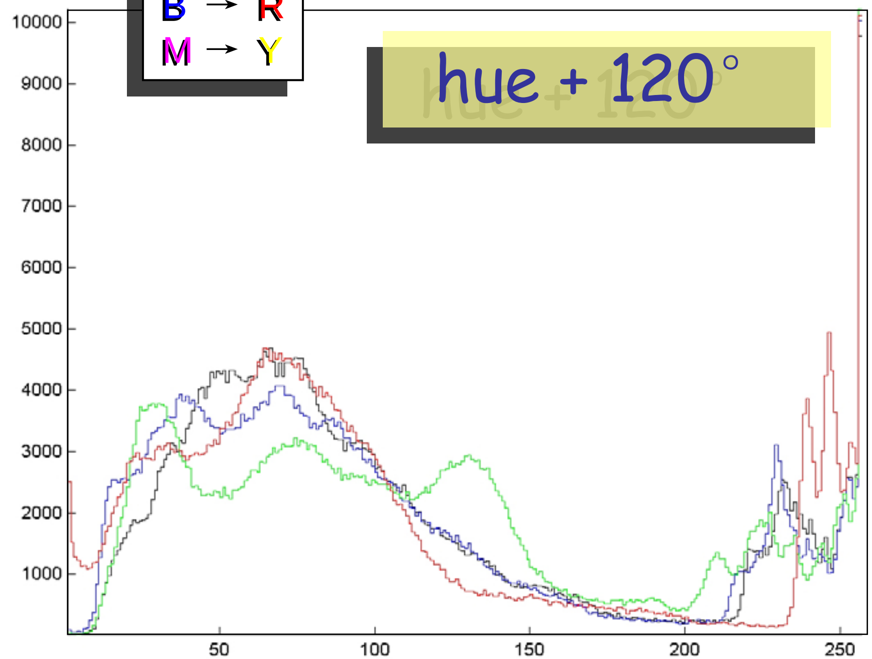
R → Y
Y → G
G → C
C → B
B → M
M → R

hue + 60°



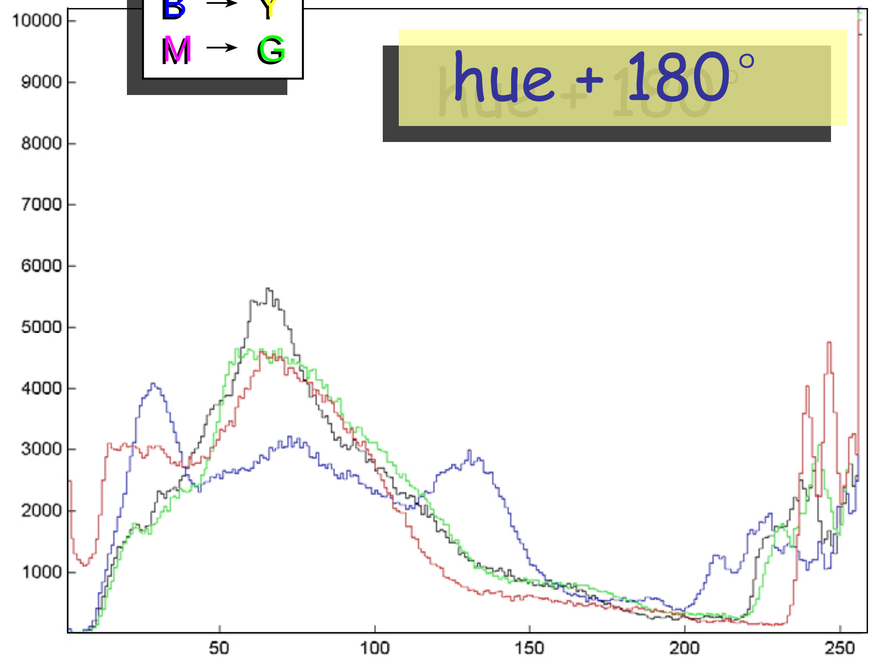
Hue Shifting

- R → G
- Y → C
- G → B
- C → M
- B → R
- M → Y



Hue Shifting

R → C
Y → B
G → M
C → R
B → Y
M → G

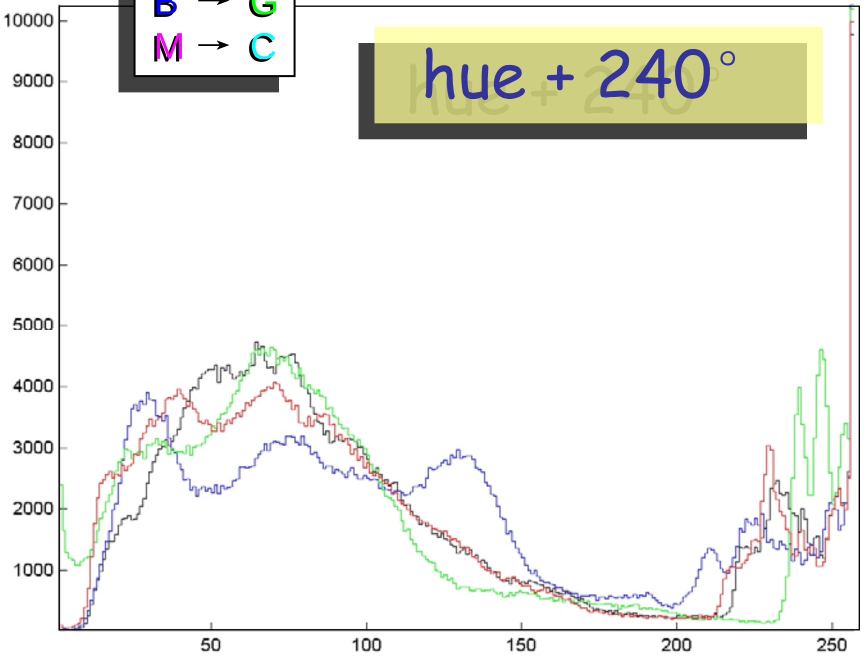


hue + 180°

Hue Shifting

R	→	B
Y	→	M
G	→	R
C	→	Y
B	→	G
M	→	C

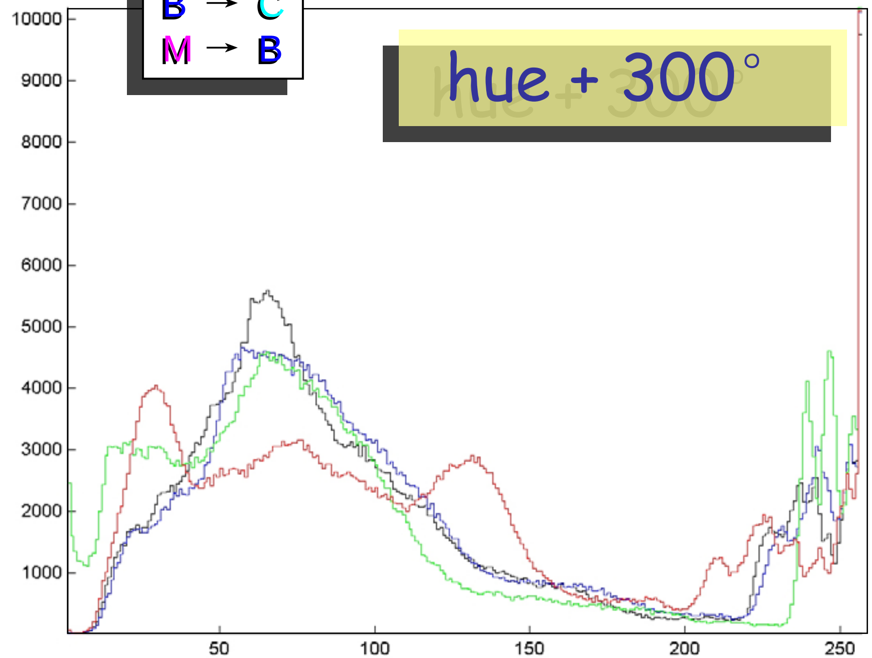
hue + 240°



Hue Shifting

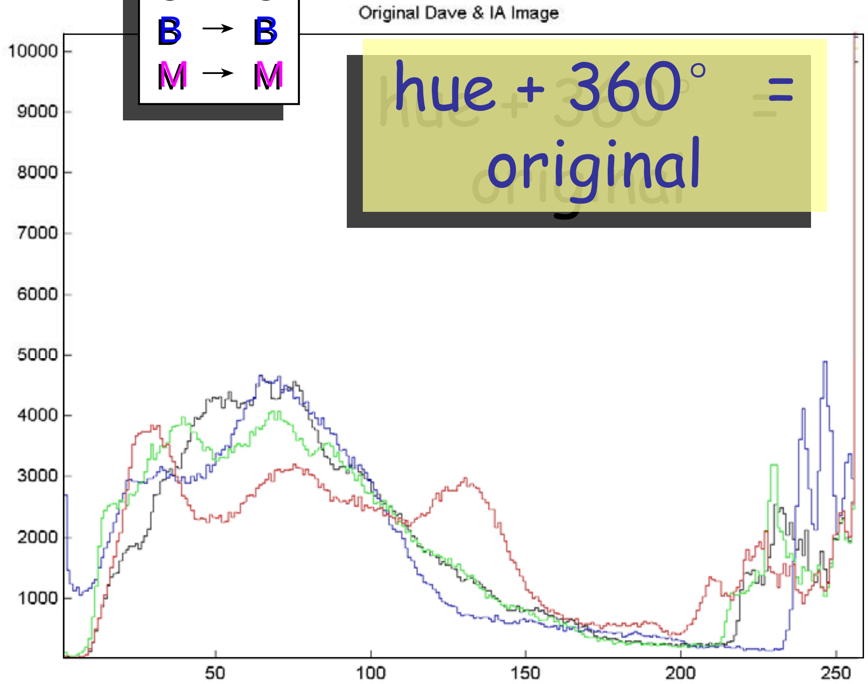
R → M
Y → R
G → Y
C → G
B → C
M → B

hue + 300°



Hue Shifting

R → R
Y → Y
G → G
C → C
B → B
M → M



hue + 360° = original

Color Correction Via Transformation

- is a point process; the transformation is applied to each pixel as a function of its color alone.

$$J(r,c) = \Phi[I(r,c)] \quad \forall (r,c) \in \text{supp}(I)$$

- Each pixel is vector valued, therefore the transformation is a vector space operator.

$$I(r,c) = \begin{bmatrix} R_I(r,c) \\ G_I(r,c) \\ B_I(r,c) \end{bmatrix} \qquad J(r,c) = \begin{bmatrix} R_J(r,c) \\ G_J(r,c) \\ B_J(r,c) \end{bmatrix} = \Phi\{I(r,c)\} = \Phi\left\{ \begin{bmatrix} R_I(r,c) \\ G_I(r,c) \\ B_I(r,c) \end{bmatrix} \right\}$$

Linear Transformation of Color

Color Vector Space Operators

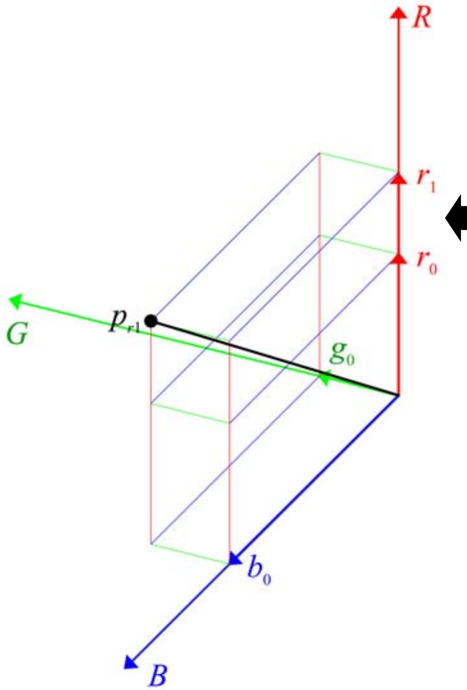
Linear operators are matrix multiplications

$$\begin{bmatrix} r_1 \\ g_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix}$$

$$\begin{bmatrix} r_1 \\ g_1 \\ b_1 \end{bmatrix} = 255 \cdot \begin{bmatrix} (r_0 / 255)^{1/\gamma_r} \\ (g_0 / 255)^{1/\gamma_g} \\ (b_0 / 255)^{1/\gamma_b} \end{bmatrix}$$

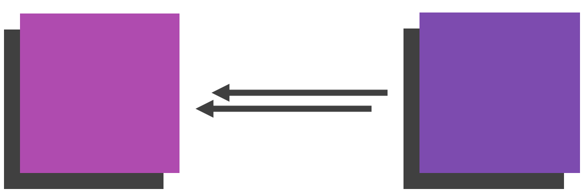
Example of a nonlinear operator: gamma correction

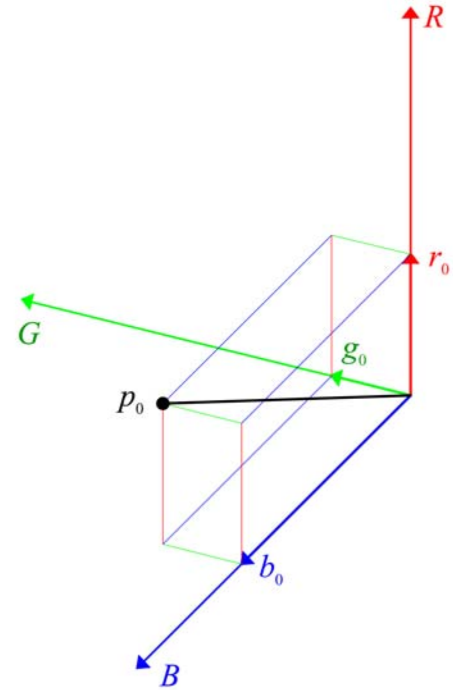
Linear Transformation of Color



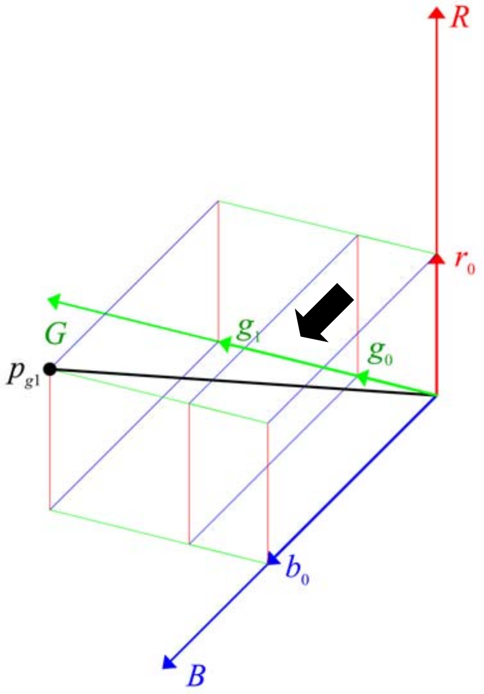
$$\begin{bmatrix} r_1 \\ g_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} s_r & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix}$$

$$\begin{bmatrix} 175 \\ 75 \\ 175 \end{bmatrix} \Longleftarrow \begin{bmatrix} 125 \\ 75 \\ 175 \end{bmatrix}$$



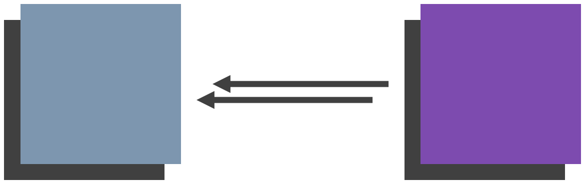


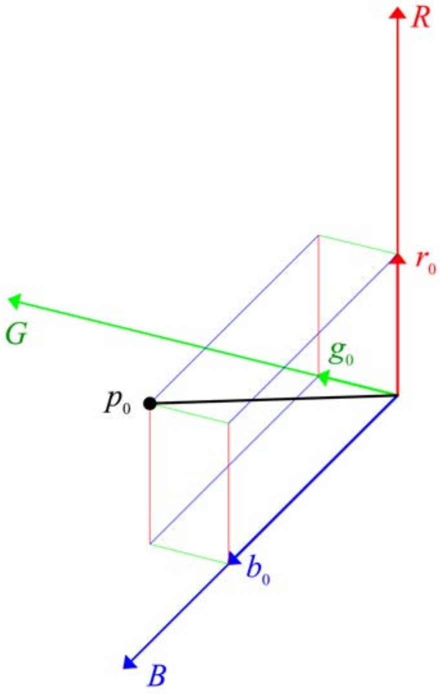
Linear Transformation of Color



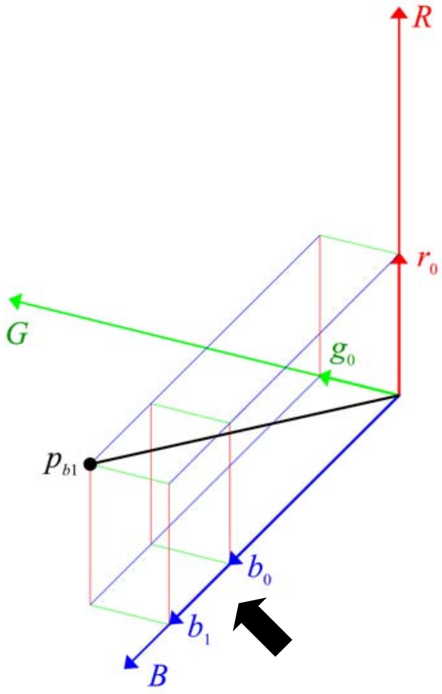
$$\begin{bmatrix} r_0 \\ g_1 \\ b_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & s_g & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix}$$

$$\begin{bmatrix} 125 \\ 150 \\ 175 \end{bmatrix} \Longleftarrow \begin{bmatrix} 125 \\ 75 \\ 175 \end{bmatrix}$$



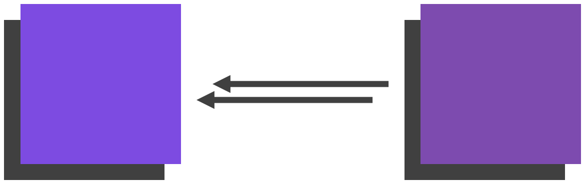


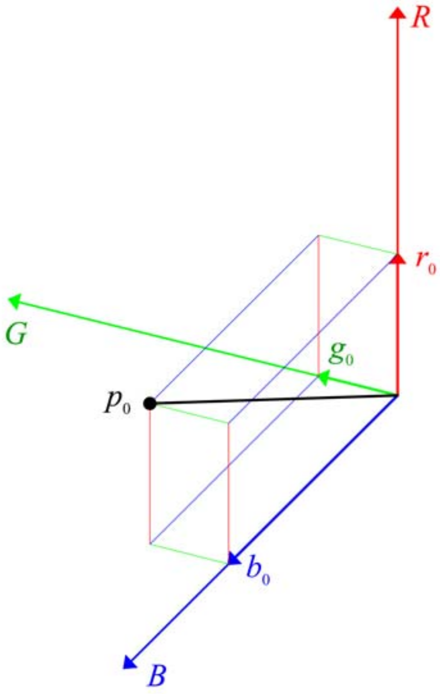
Linear Transformation of Color



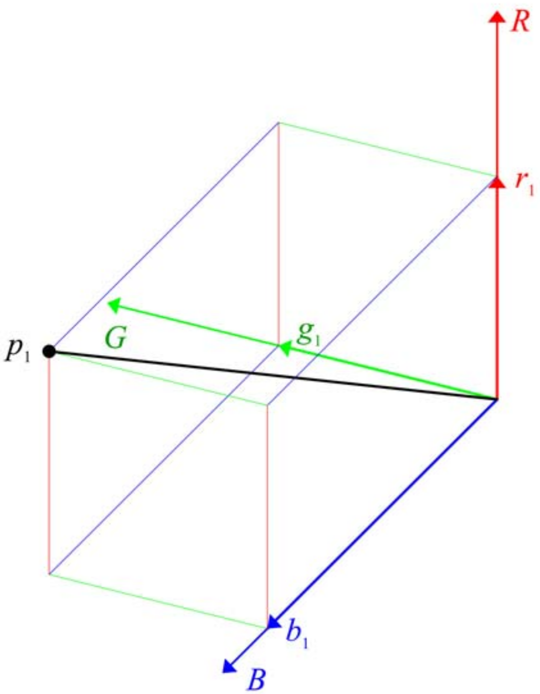
$$\begin{bmatrix} r_0 \\ g_0 \\ b_1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & s_b \end{bmatrix} \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix}$$

$$\begin{bmatrix} 125 \\ 75 \\ 225 \end{bmatrix} \leftleftarrows \begin{bmatrix} 125 \\ 75 \\ 175 \end{bmatrix}$$



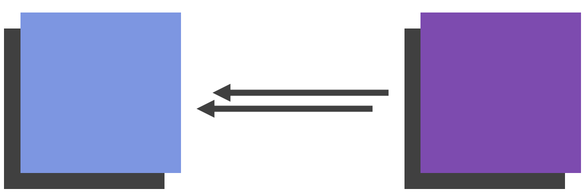


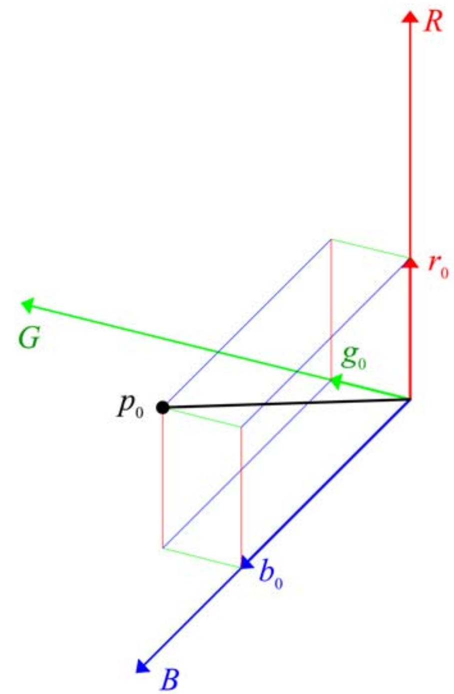
Linear Transformation of Color



$$\begin{bmatrix} r_1 \\ g_1 \\ b_1 \end{bmatrix} = \begin{bmatrix} s_r & 0 & 0 \\ 0 & s_g & 0 \\ 0 & 0 & s_b \end{bmatrix} \begin{bmatrix} r_0 \\ g_0 \\ b_0 \end{bmatrix}$$

$$\begin{bmatrix} 175 \\ 150 \\ 225 \end{bmatrix} \Longleftarrow \begin{bmatrix} 125 \\ 75 \\ 175 \end{bmatrix}$$





Color Transformation

Assume J is a discolored version of image I such that $J = \Phi[\ I\ ]$. If Φ is linear then it is represented by a 3×3 matrix, A:

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}.$$

Then $J = AI$ or, more accurately, $J(r,c) = AI(r,c)$ for all pixel locations (r,c) in image I.

Color Transformation

If at pixel location (r,c),

image $I(r,c)=\begin{bmatrix}\rho_I\\ \gamma_I\\ \beta_I\end{bmatrix}$ and

image $J(r,c)=\begin{bmatrix}\rho_J\\ \gamma_J\\ \beta_J\end{bmatrix}$,

then $J(r,c)=AI(r,c)$, or

$$\begin{bmatrix}\rho_J\\ \gamma_J\\ \beta_J\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12} & a_{13}\\ a_{21} & a_{22} & a_{23}\\ a_{31} & a_{32} & a_{33}\end{bmatrix}\begin{bmatrix}\rho_I\\ \gamma_I\\ \beta_I\end{bmatrix}$$

$$=\begin{bmatrix}a_{11}\rho_I & + & a_{12}\gamma_I & + & a_{13}\beta_I\\ a_{21}\rho_I & + & a_{22}\gamma_I & + & a_{23}\beta_I\\ a_{31}\rho_I & + & a_{32}\gamma_I & + & a_{33}\beta_I\end{bmatrix}.$$

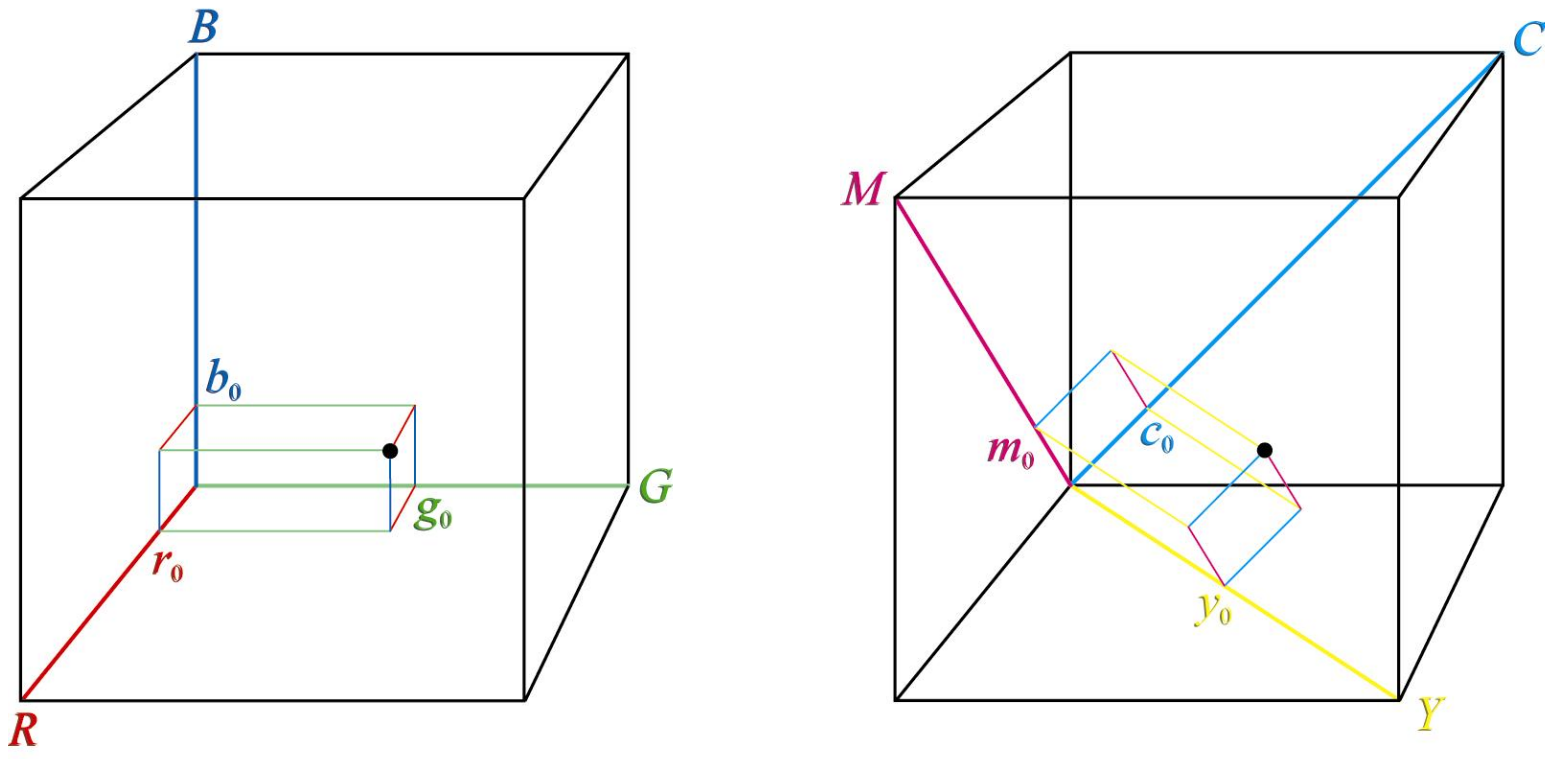
Color Transformation

The inverse transform Φ^{-1} (if it exists) maps the discolored image, *J*, back into the correctly colored version, *I*, *i.e.*, $I = \Phi^{-1}[\, J \,]$. If Φ is linear then it is represented by the inverse of matrix *A*:

$$A^{-1} = \left(a_{11}a_{22}a_{33} - a_{11}a_{23}a_{32} - a_{12}a_{21}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32} - a_{13}a_{22}a_{31}\right)^{-1} \cdot \begin{bmatrix} a_{22}a_{33} - a_{23}a_{32} & a_{13}a_{32} - a_{12}a_{33} & a_{12}a_{23} - a_{13}a_{22} \\ a_{23}a_{31} - a_{21}a_{33} & a_{11}a_{33} - a_{13}a_{31} & a_{13}a_{21} - a_{11}a_{23} \\ a_{21}a_{32} - a_{22}a_{31} & a_{12}a_{31} - a_{11}a_{32} & a_{11}a_{22} - a_{12}a_{21} \end{bmatrix}.$$

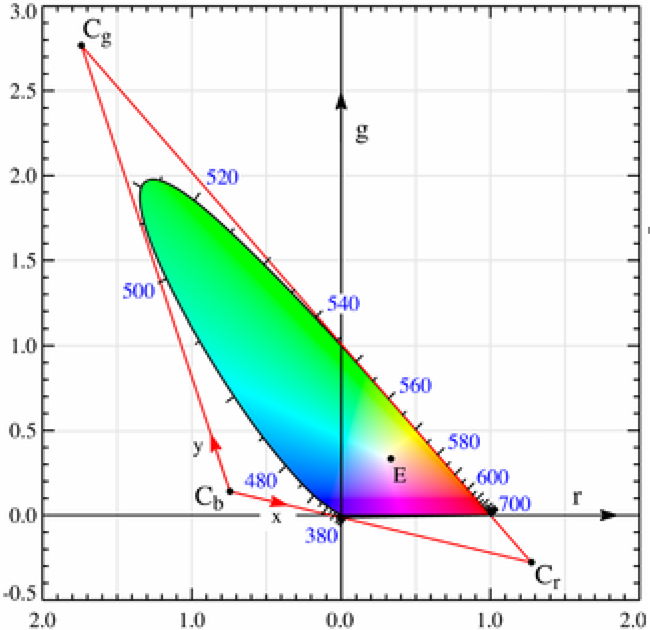
勘误:

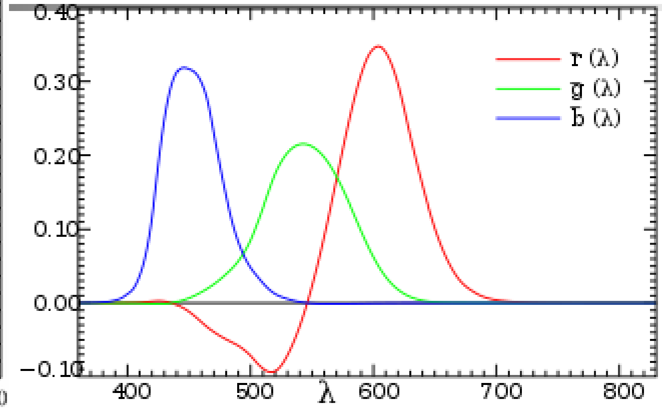
Color With Respect To Different Axes

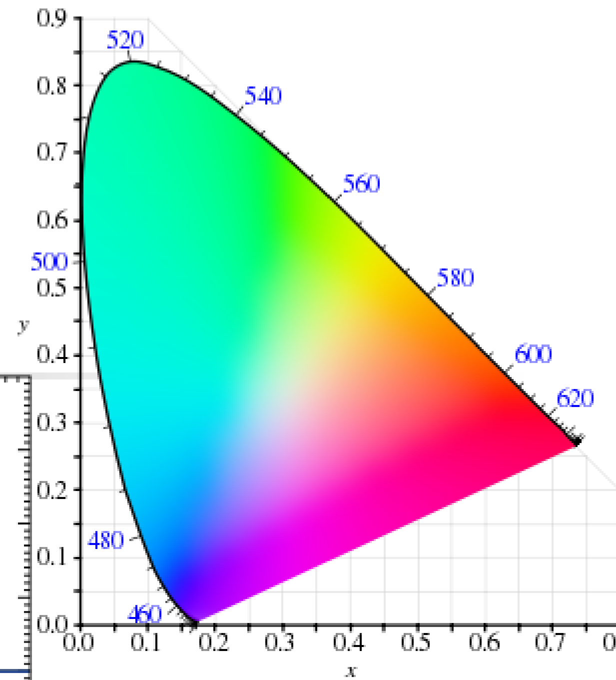


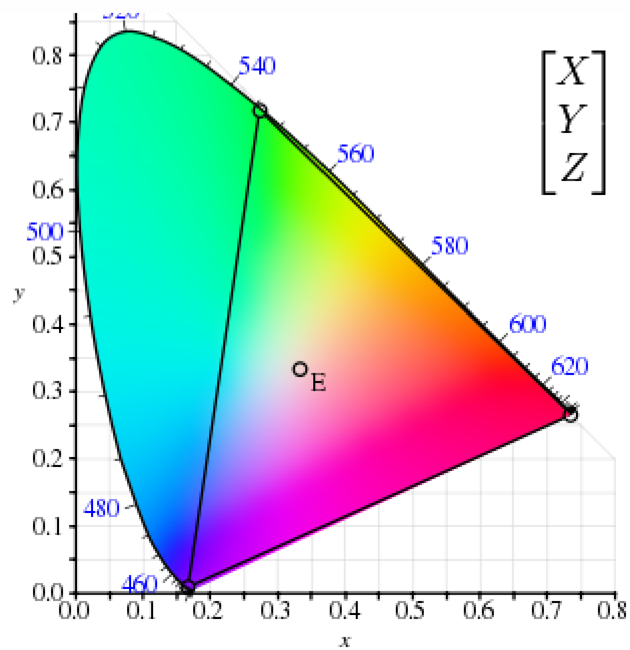
The same color has different RGB and CMY coordinates.

CIE-XYZ color space

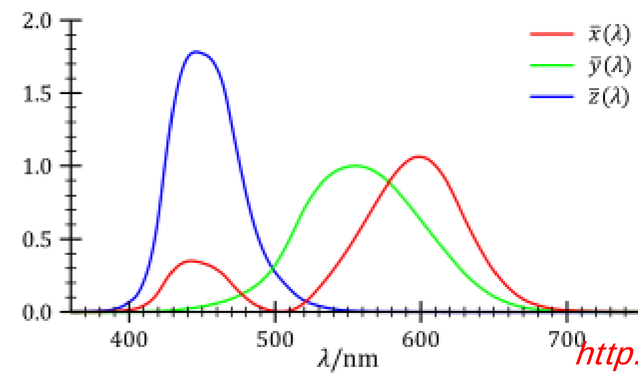








$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



Red：700 nm

Green：546.1 nm

Blue：435.8 nm

http://zh.wikipedia.org/wiki/CIE1931色彩空间

Linear Color Correction

NASA Summer Faculty Fellows at Ellington Air Force Base, Houston, TX, July 2002. Airplane is a T-38.

Original Image

“Aged” Image

Color Transformation

If at pixel location (r,c),

image $I(r,c) = \begin{bmatrix} \rho_I \\ \gamma_I \\ \beta_I \end{bmatrix}$ and

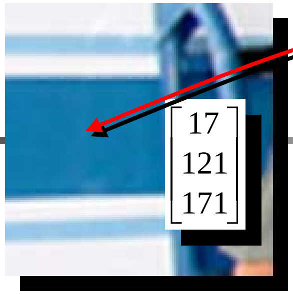
image $J(r,c) = \begin{bmatrix} \rho_J \\ \gamma_J \\ \beta_J \end{bmatrix}$,

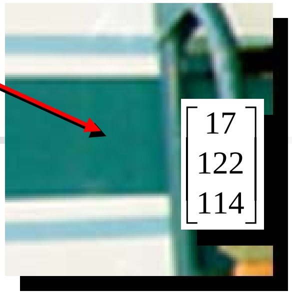
then $J(r,c) = AI(r,c)$, or

$$\begin{bmatrix} \rho_J \\ \gamma_J \\ \beta_J \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \begin{bmatrix} \rho_I \\ \gamma_I \\ \beta_I \end{bmatrix}$$

$$= \begin{bmatrix} a_{11}\rho_I & + & a_{12}\gamma_I & + & a_{13}\beta_I \\ a_{21}\rho_I & + & a_{22}\gamma_I & + & a_{23}\beta_I \\ a_{31}\rho_I & + & a_{32}\gamma_I & + & a_{33}\beta_I \end{bmatrix}.$$

Color Mapping 1

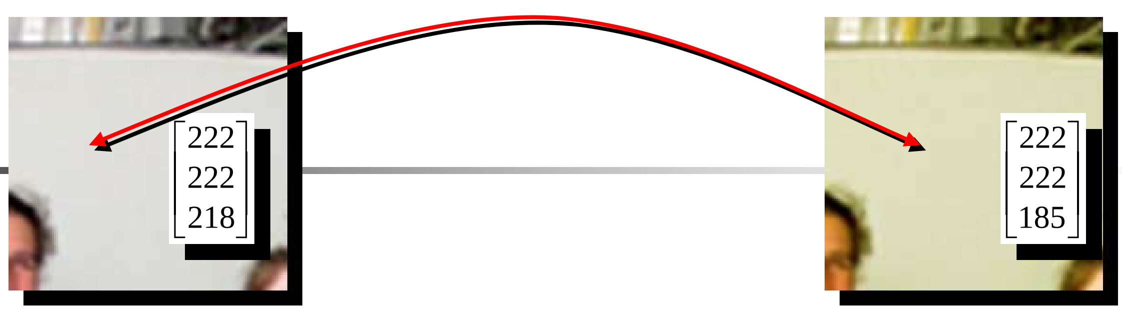




Original Image

“Aged” Image

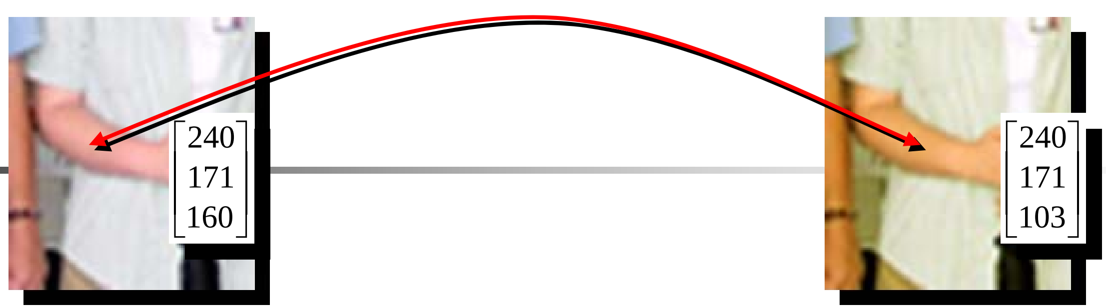
Color Mapping 2



Original Image

“Aged” Image

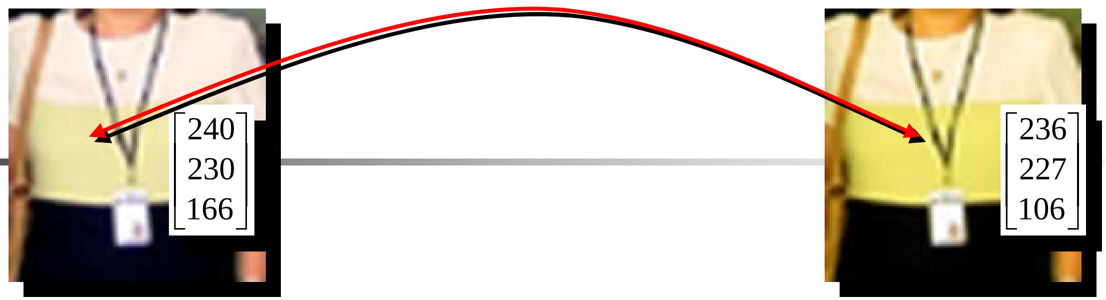
Color Mapping 3



Original Image

“Aged” Image

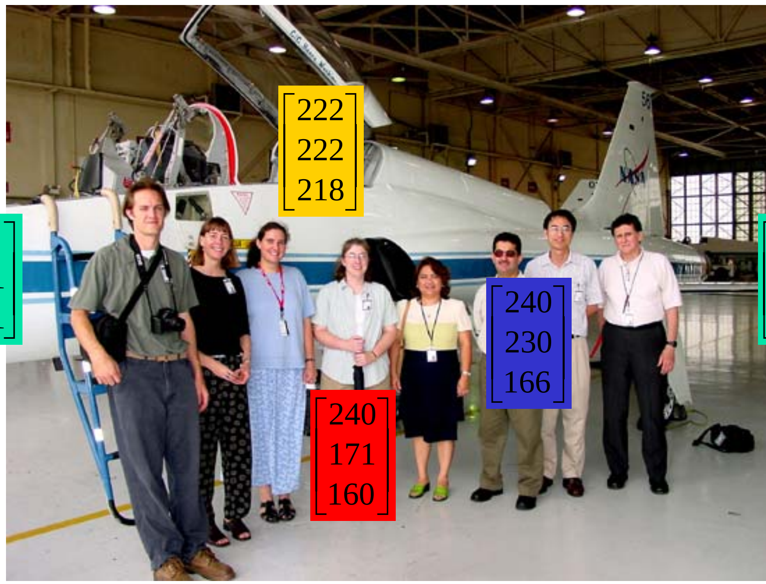
Color Mapping 4

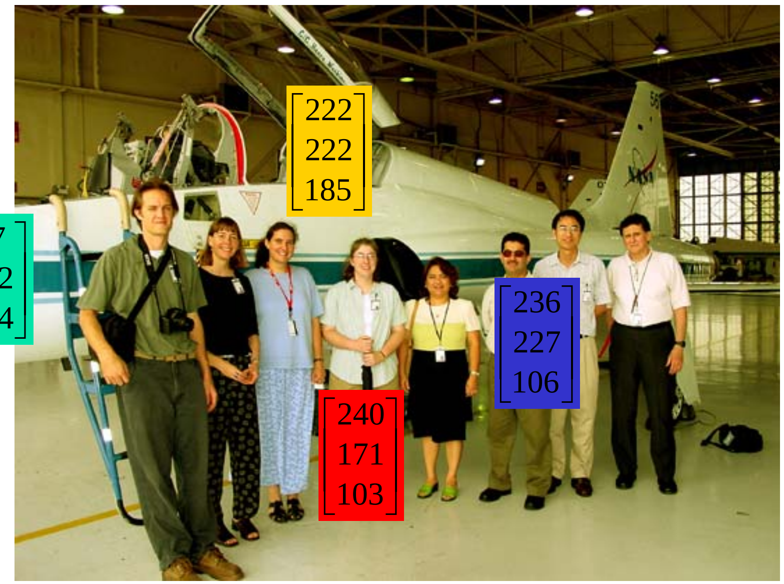


Original Image

“Aged” Image

Forward Color Transformation
正向映射/变换





The aging process was a transformation, Φ, that mapped:

$$\begin{bmatrix}240\\171\\103\end{bmatrix} = \Phi\left\{\begin{bmatrix}240\\171\\160\end{bmatrix}\right\}$$

$$\begin{bmatrix}222\\222\\185\end{bmatrix} = \Phi\left\{\begin{bmatrix}222\\222\\218\end{bmatrix}\right\} \quad \begin{bmatrix}17\\122\\114\end{bmatrix} = \Phi\left\{\begin{bmatrix}17\\121\\171\end{bmatrix}\right\} \quad \begin{bmatrix}236\\227\\106\end{bmatrix} = \Phi\left\{\begin{bmatrix}240\\230\\166\end{bmatrix}\right\}$$

Correction Using 3 Mappings

$$Y = AX, A = YX^{-1}$$

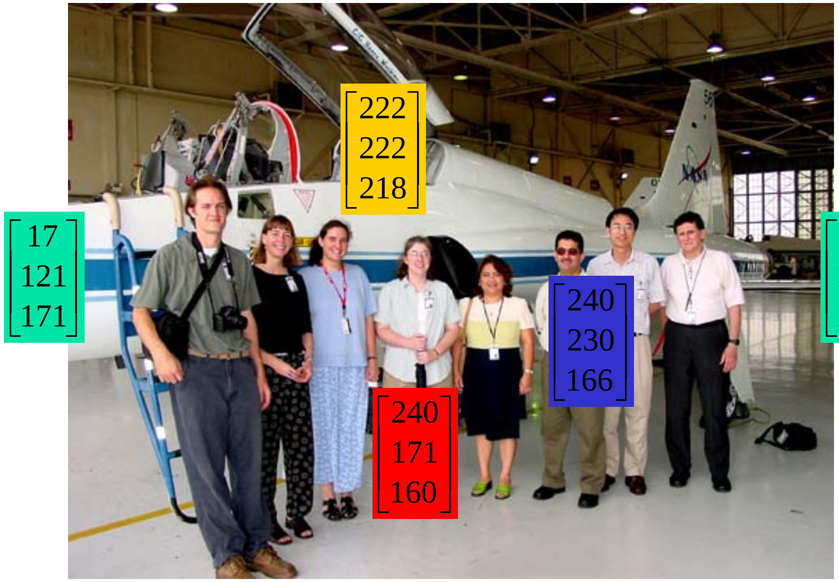
original

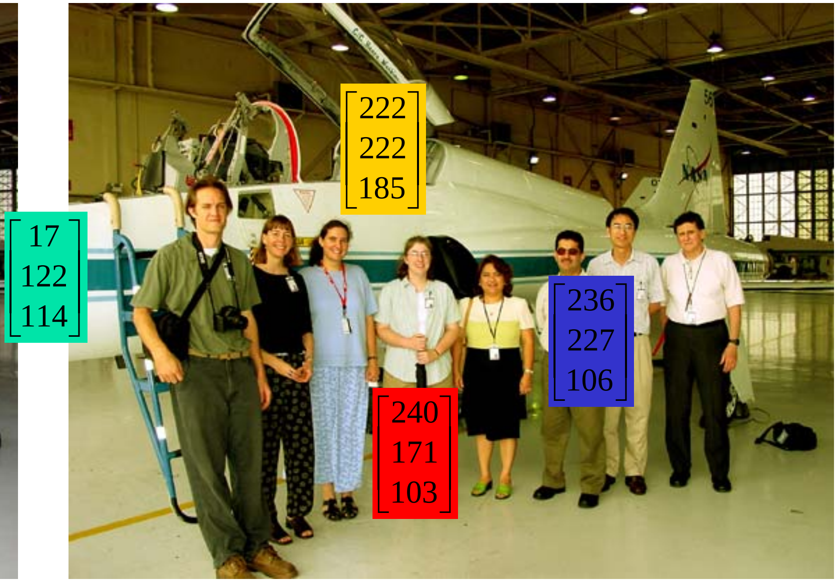
$$X = \begin{bmatrix} 222 & 17 & 240 \\ 222 & 121 & 230 \\ 218 & 171 & 166 \end{bmatrix}$$

corrected

$$Y = \begin{bmatrix} 222 & 17 & 236 \\ 222 & 122 & 227 \\ 185 & 114 & 106 \end{bmatrix}$$

Inverse Color Transformation 反向映射/变换





To undo the process we need to find, Φ^{-1}, that maps:

$$\begin{bmatrix}240\\171\\160\end{bmatrix}=\Phi^{-1}\left\{\begin{bmatrix}240\\171\\103\end{bmatrix}\right\}$$

$$\begin{bmatrix}222\\222\\218\end{bmatrix}=\Phi^{-1}\left\{\begin{bmatrix}222\\222\\185\end{bmatrix}\right\}\quad\begin{bmatrix}17\\121\\171\end{bmatrix}=\Phi^{-1}\left\{\begin{bmatrix}17\\122\\114\end{bmatrix}\right\}\quad\begin{bmatrix}240\\230\\166\end{bmatrix}=\Phi^{-1}\left\{\begin{bmatrix}236\\227\\106\end{bmatrix}\right\}$$

Inverse mapping

$$X = A^{-1}Y$$

$$Y = \begin{bmatrix} 222 & 17 & 236 \\ 222 & 122 & 227 \\ 185 & 114 & 106 \end{bmatrix}$$

$$X = \begin{bmatrix} 222 & 17 & 240 \\ 222 & 121 & 230 \\ 218 & 171 & 166 \end{bmatrix}$$

Correction Using More Mappings

$$Y = AX$$

$$A = YX^{-1}$$

$$Y = \begin{bmatrix} 111 & & 235 \\ 103 & \cdots & 233 \\ 22 & & 210 \end{bmatrix}$$

....

$$X = \begin{bmatrix} 111 & & 234 \\ 102 & \cdots & 233 \\ 71 & & 229 \end{bmatrix}$$

....

Over-determined Systems: One practical solution

The linearly optimal solution is the least mean squared solution that is given by

$$Y = AX$$

$$A = YX^T\left(XX^T\right)^{-1}$$

where X^T represents the transpose of matrix X.

Notes:

1. n, the number of color pairs, must be ≥ 3,
2. XX^T must be invertible, *i.e.*, rank$(XX^T) = 3$,
3. If n=3, then $X^T(XX^T)^{-1} = X^{-1}$.

Correction Using 4 Mappings

$$Y = AX, A = YX^T \left(XX^T \right)^{-1}$$

$$X = \begin{bmatrix} 222 & 17 & 240 & 240 \\ 222 & 121 & 230 & 171 \\ 218 & 171 & 166 & 160 \end{bmatrix}$$

$$Y = \begin{bmatrix} 222 & 17 & 236 & 240 \\ 222 & 122 & 227 & 171 \\ 185 & 114 & 106 & 103 \end{bmatrix}$$

Correction Using More Mappings

$$Y = AX\,,\; A = YX^{T}\left(XX^{T}\right)^{-1}$$

$$X = \begin{bmatrix} 111 & & 234 \\ 102 & \cdots & 233 \\ 71 & & 229 \end{bmatrix}$$

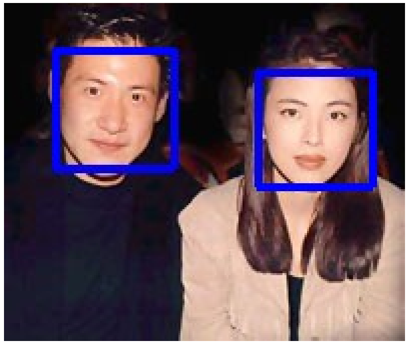
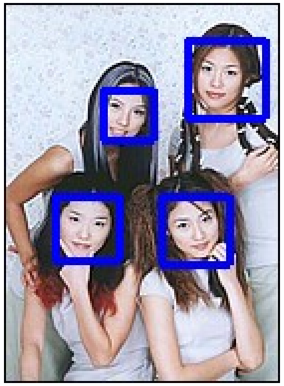
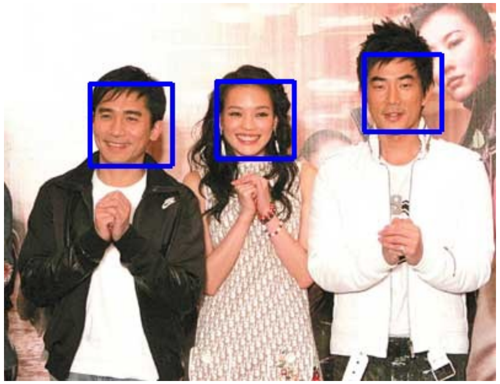
$$Y = \begin{bmatrix} 111 & & 235 \\ 103 & \cdots & 233 \\ 22 & & 210 \end{bmatrix}$$

....

....

Lab project

- Face detection in color image
- First step: image segmentation based on skin color statistics
  - Select one color space
  - Obtain skin color statistics by using a set of face samples
  - Threshold the image using the skin color statistics

Lab project (cont')

- Color modelling
  - Simple models
    - Model 1: (R,G,B) is classified as skin if R>95 and G>40 and B>20 and max{R,G,B}-min{R,G,B}>15 and |R-G|>15 and R>G and R>B.
    - Model 2: Let r=R/(R+G+B), g=G/(R+G+B), Y=0.3R+0.59G+0.11B, (R,G,B) is classified as skin if 0.333<r<0.664 and 0.246<g<0.398 and r>g and g>=0.5-0.5r. When Y<40, (R,G,B) may be hair color.
  - Parametric and non-parametric models

Lab project (cont')

- Skin color model 1: (R,G,B) is classified as skin if R>95 and G>40 and B>20 and max{R,G,B}-min{R,G,B}>15 and |R-G|>15 and R>G and R>B.

Lab project (cont')

- Skin color model 2: Let r=R/(R+G+B), g=G/(R+G+B), Y=0.3R+0.59G+0.11B, (R,G,B) is classified as skin if 0.333<r<0.664 and 0.246<g<0.398 and r>g and g>=0.5-0.5r. When Y<40, (R,G,B) may be hair color.

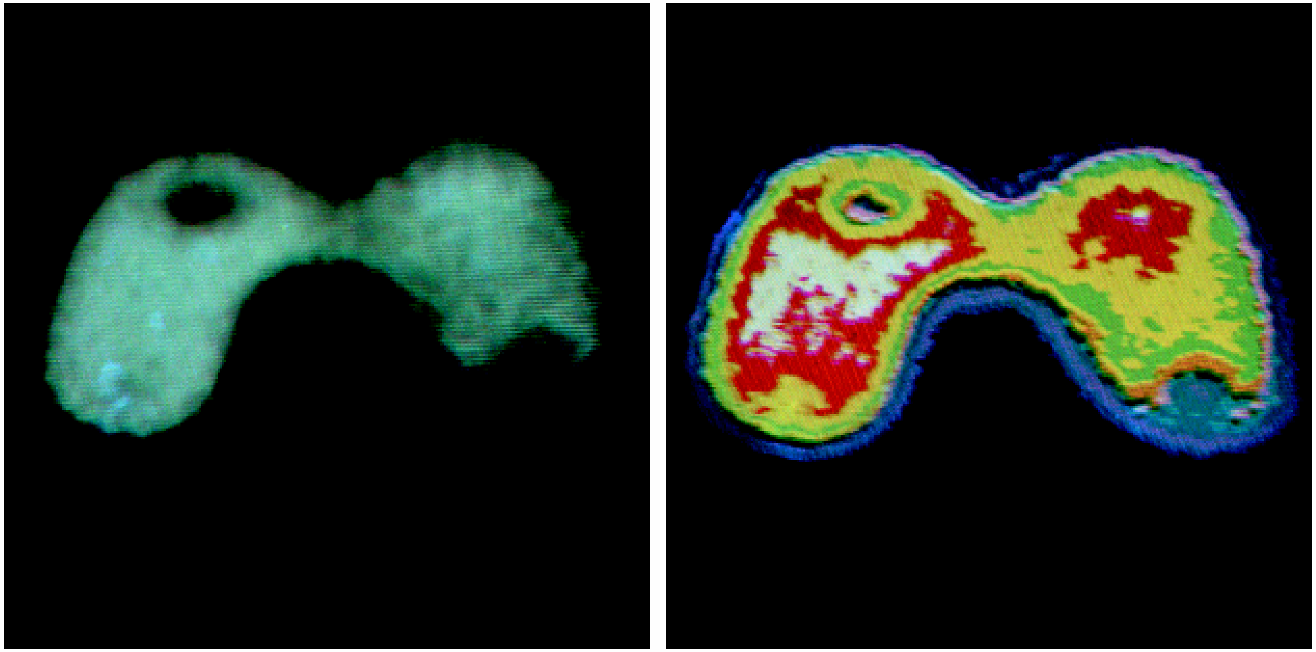
Homework IV

- Try build a skin color model and detect skin regions in the following picture. Submit your code and the result as a binary image.
- A perfect output may be very very difficult. Just try your best.

Pseudo color image processing

- Assign color to monochrome images
- Perform three independent transformations on the gray level of any input pixel
- The three result can then serve as the red, green, and blue component of a color image
- The motivations for using color is that humans can discern thousands of color shades and intensities, compared to only dozen or so shades of gray.

Intensity slicing (cont')



a b

FIGURE 6.20 (a) Monochrome image of the Picker Thyroid Phantom. (b) Result of density slicing into eight colors. (Courtesy of Dr. J. L. Blankenship, Instrumentation and Controls Division, Oak Ridge National Laboratory.)

Gray level to color transformations

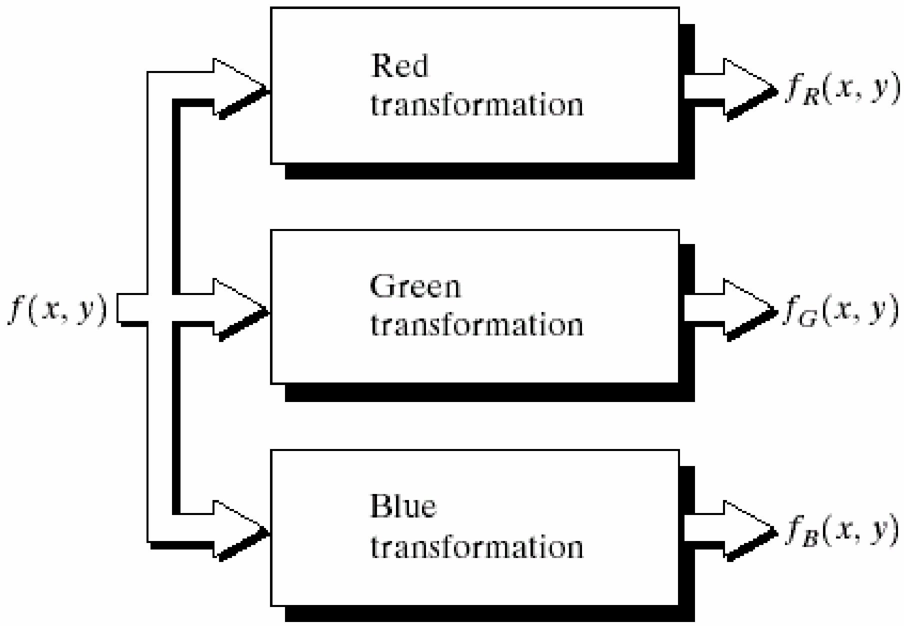
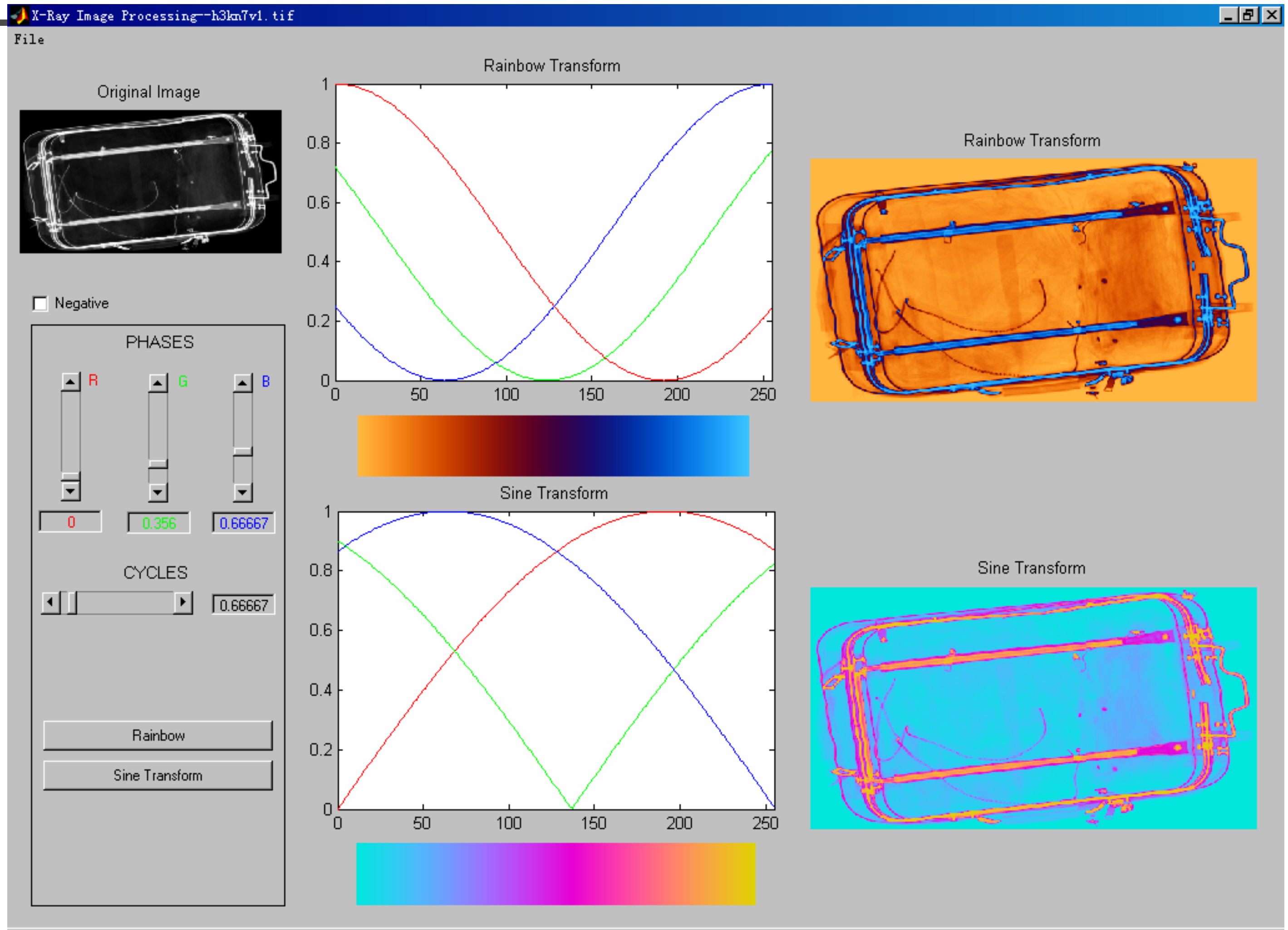


FIGURE 6.23 Functional block diagram for pseudocolor image processing. f_R, f_G, and f_B are fed into the corresponding red, green, and blue inputs of an RGB color monitor.

Gray level to color transformations (cont')



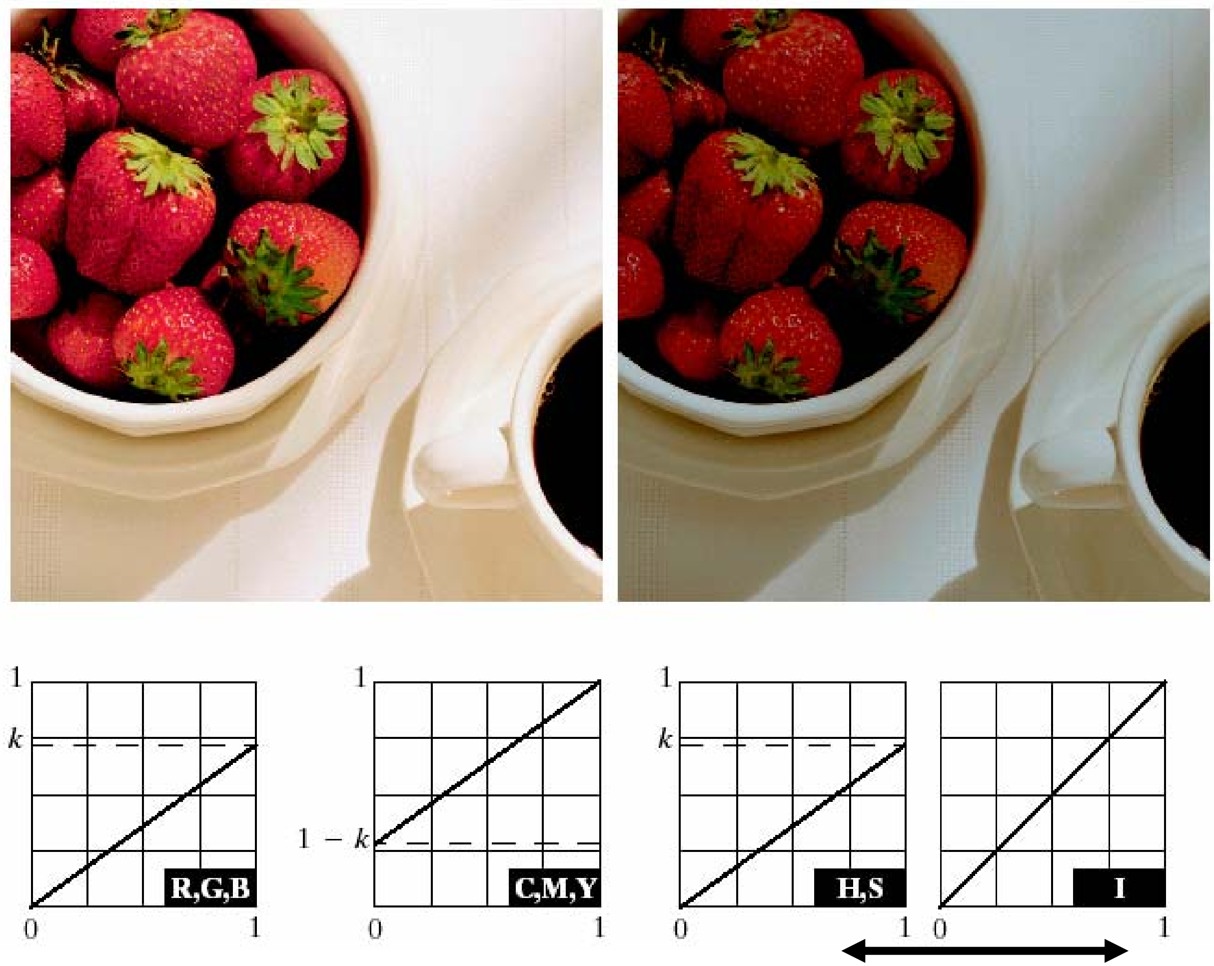
Full-color image processing

- Approach 1: process each component image individually and then form a composite processed color image
- Approach 2: work with color pixels directly
- They are not always equivalent

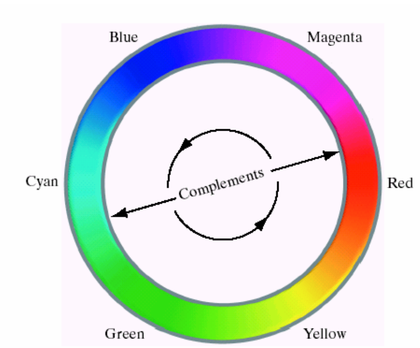
Color transform

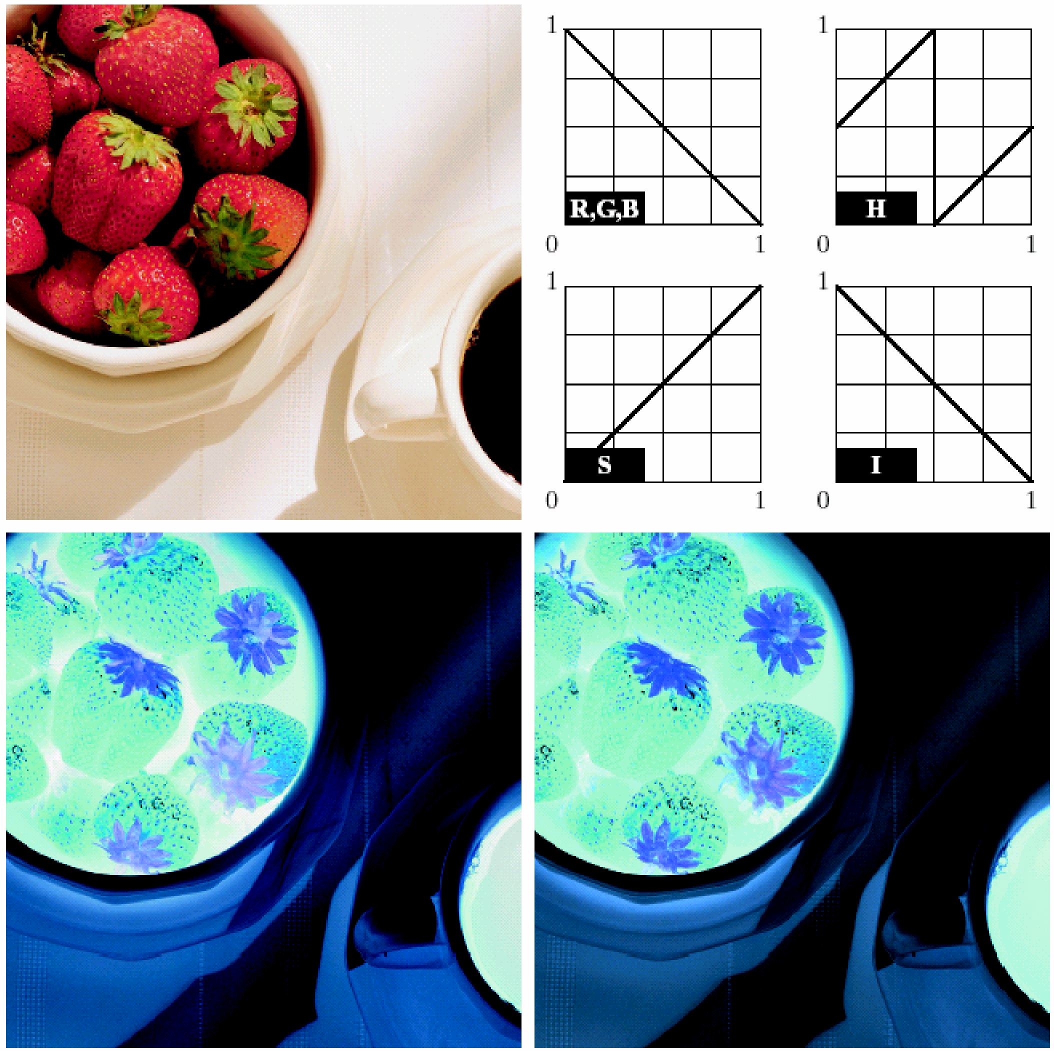
a b
c d e

FIGURE 6.31 Adjusting the intensity of an image using color transformations. (a) Original image. (b) Result of decreasing its intensity by 30% (i.e., letting $k = 0.7$). (c)–(e) The required RGB, CMY, and HSI transformation functions. (Original image courtesy of MedData Interactive.)



Color complements





a b
c d

FIGURE 6.33 Color complement transformations. (a) Original image. (b) Complement transformation functions. (c) Complement of (a) based on the RGB mapping functions. (d) An approximation of the RGB complement using HSI transformations.

Histogram processing

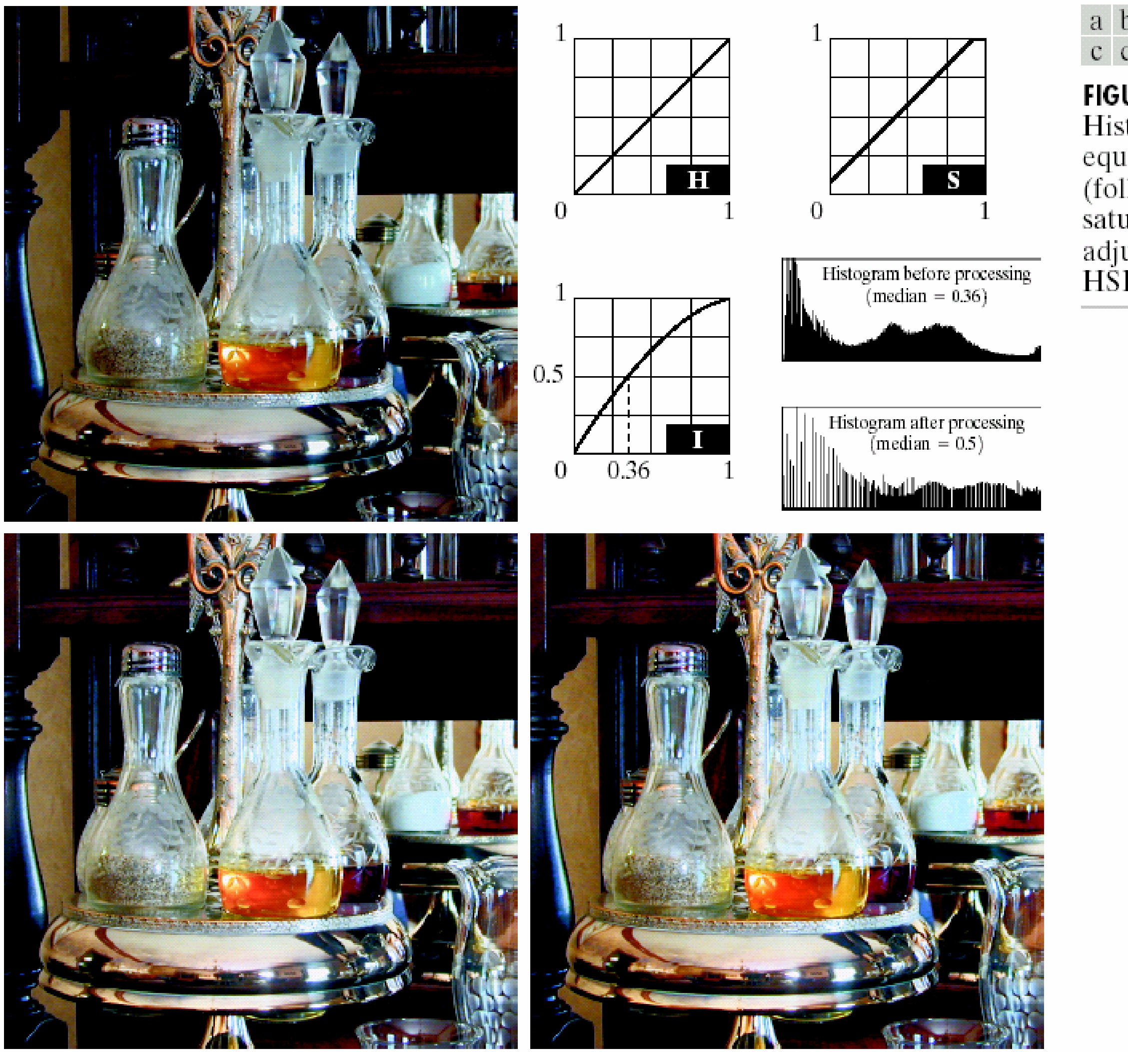
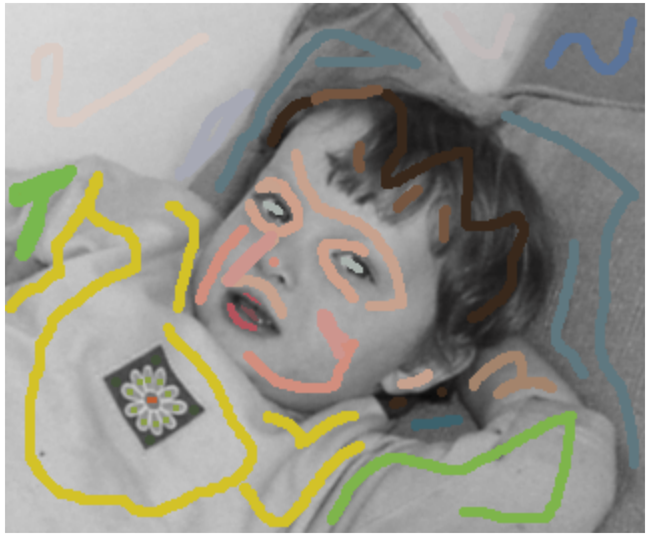


FIGURE 6.37 Histogram equalization (followed by saturation adjustment) in the HSI color space.

Image Colorization

---Gray image to Color image



Anat Levin, Dani Lischinski, and Yair Weiss. 2004. Colorization using optimization. In ACM SIGGRAPH 2004 Papers (SIGGRAPH '04), Joe Marks (Ed.). ACM, New York, NY, USA, 689-694.

Image Colorization

---Gray image to Color image

$$J(U) = \sum_{\mathbf{r}} \left(U(\mathbf{r}) - \sum_{\mathbf{s} \in N(\mathbf{r})} w_{\mathbf{rs}} U(\mathbf{s}) \right)^2$$

Image Colorization

---Gray image to Color image

$$J(U) = \sum_{\mathbf{r}} \left(U(\mathbf{r}) - \sum_{\mathbf{s} \in N(\mathbf{r})} w_{\mathbf{rs}} U(\mathbf{s}) \right)^2$$

Image Colorization

---Gray image to Color image

Input image

Marked image

Result

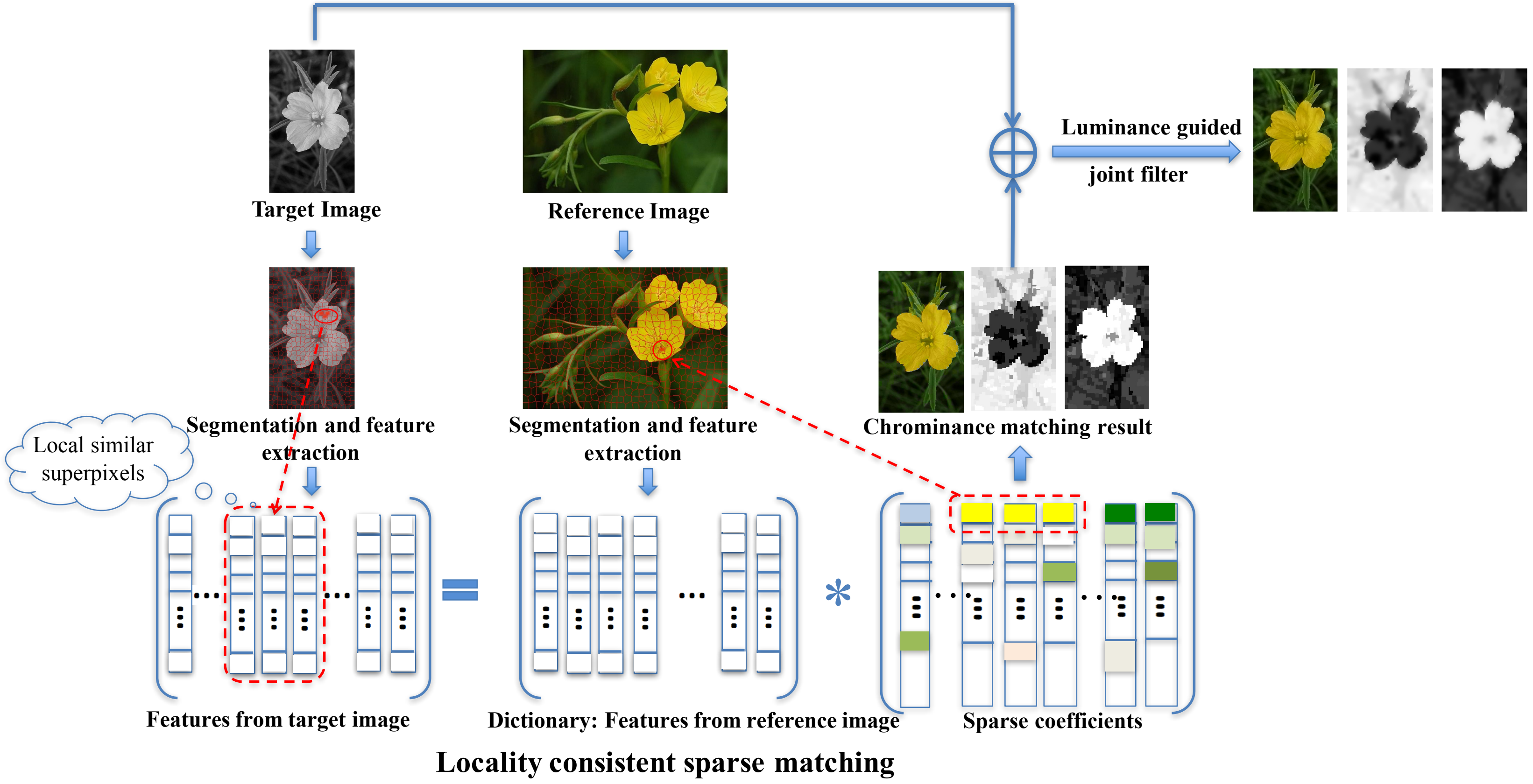
Input image

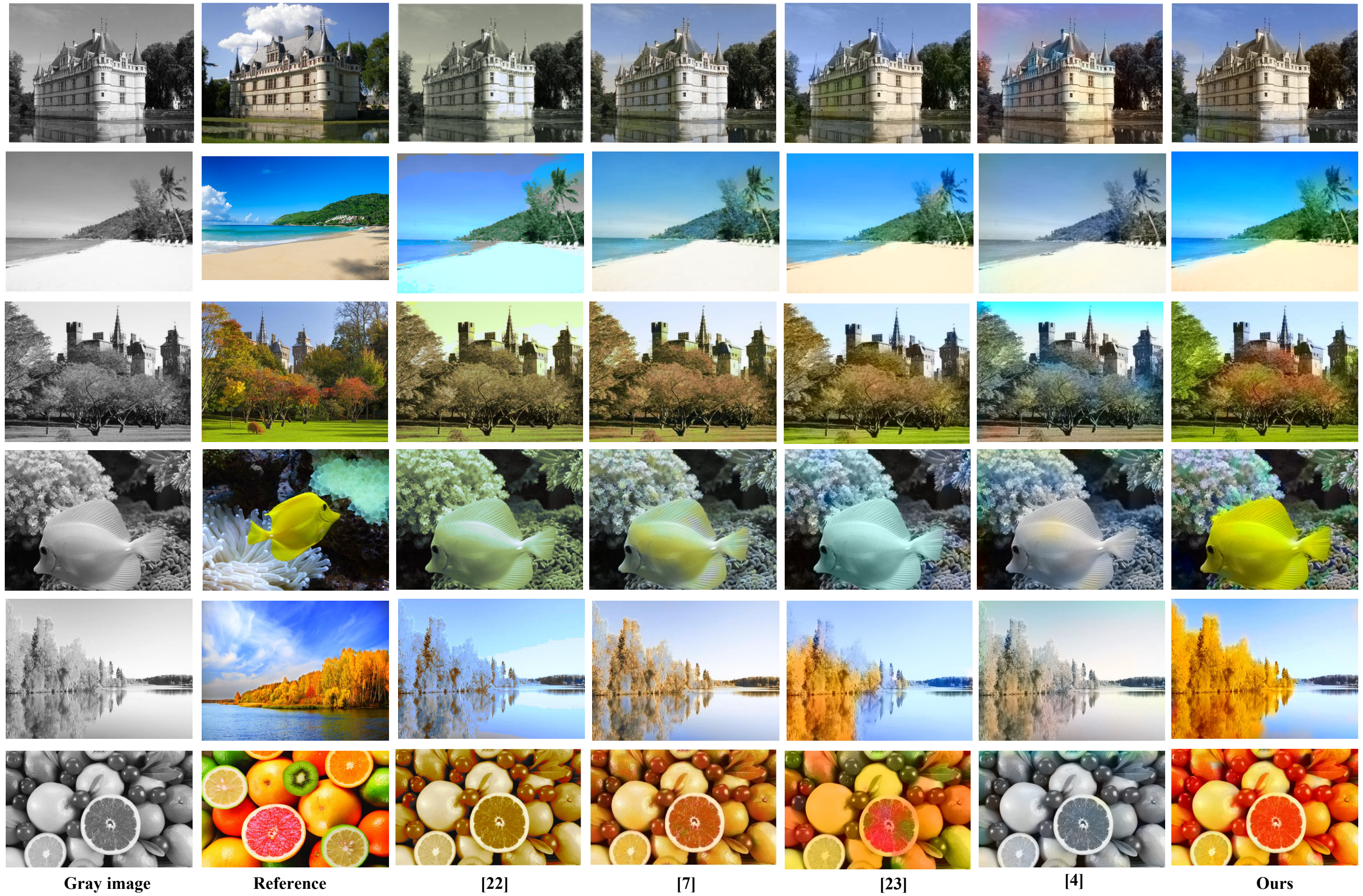
Marked image

Result

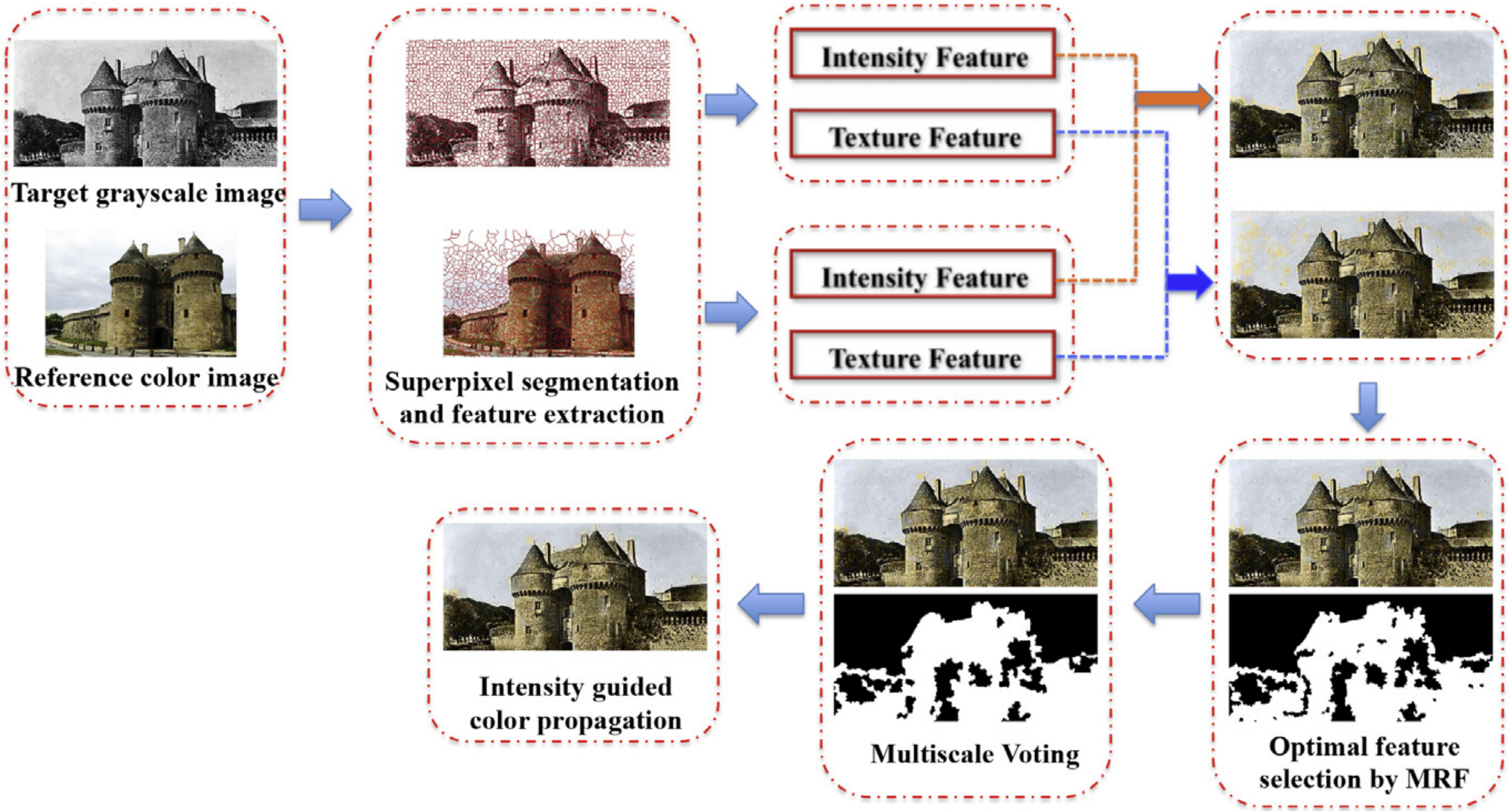
$$J(U) = \sum_{\mathbf{r}} \left(U(\mathbf{r}) - \sum_{\mathbf{s} \in N(\mathbf{r})} w_{\mathbf{rs}} U(\mathbf{s}) \right)^2$$

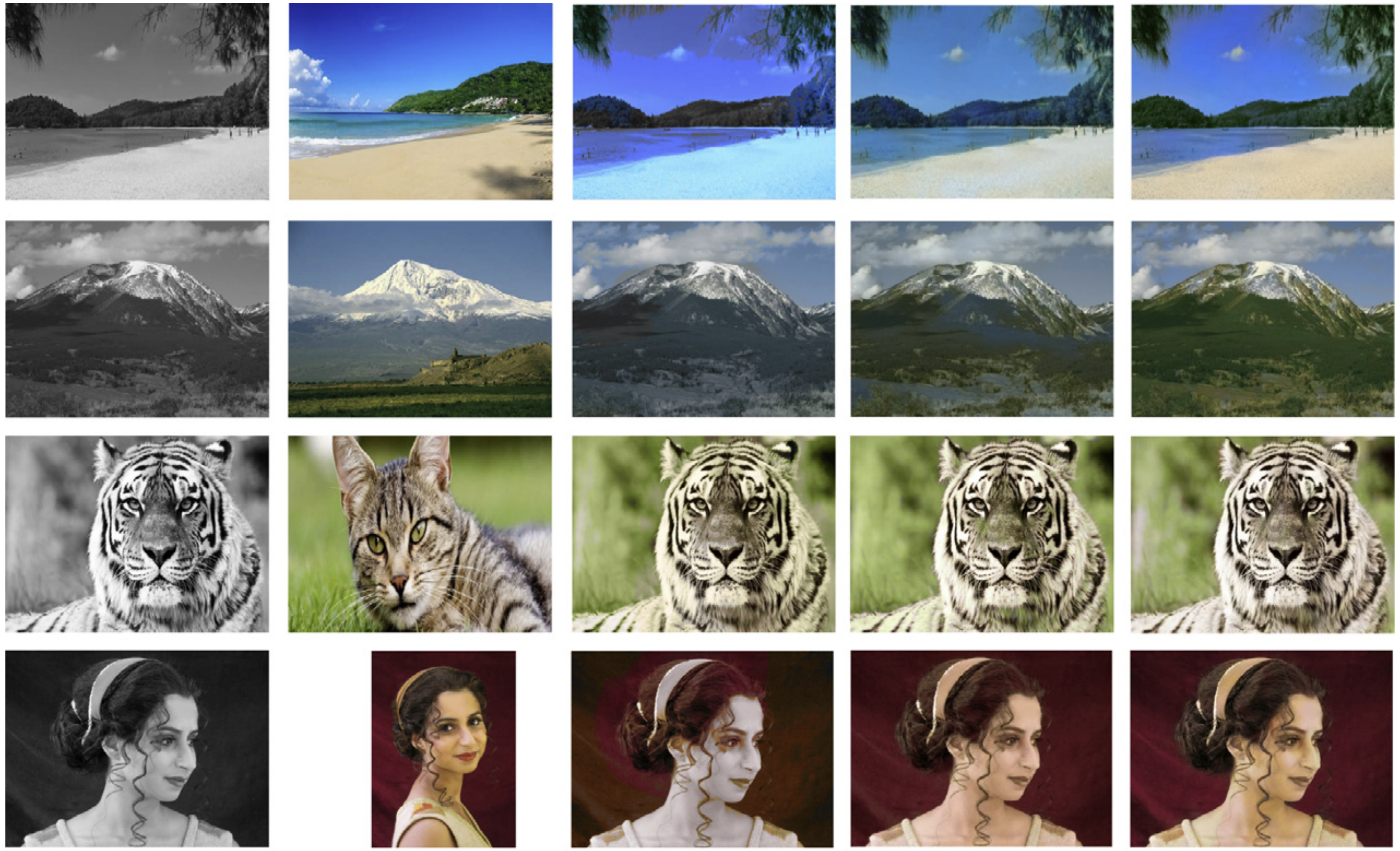
B. Li, F.C. Zhao, Z. Su, X.G. Liang, Y.-K. Lai and P. L. Rosin, “Example-based Image Colorization using Locality Consistent Sparse Representation”, *IEEE Transactions on Image Processing*, 26(11), 5188-5202. 2017. SCI二区, CCF A类



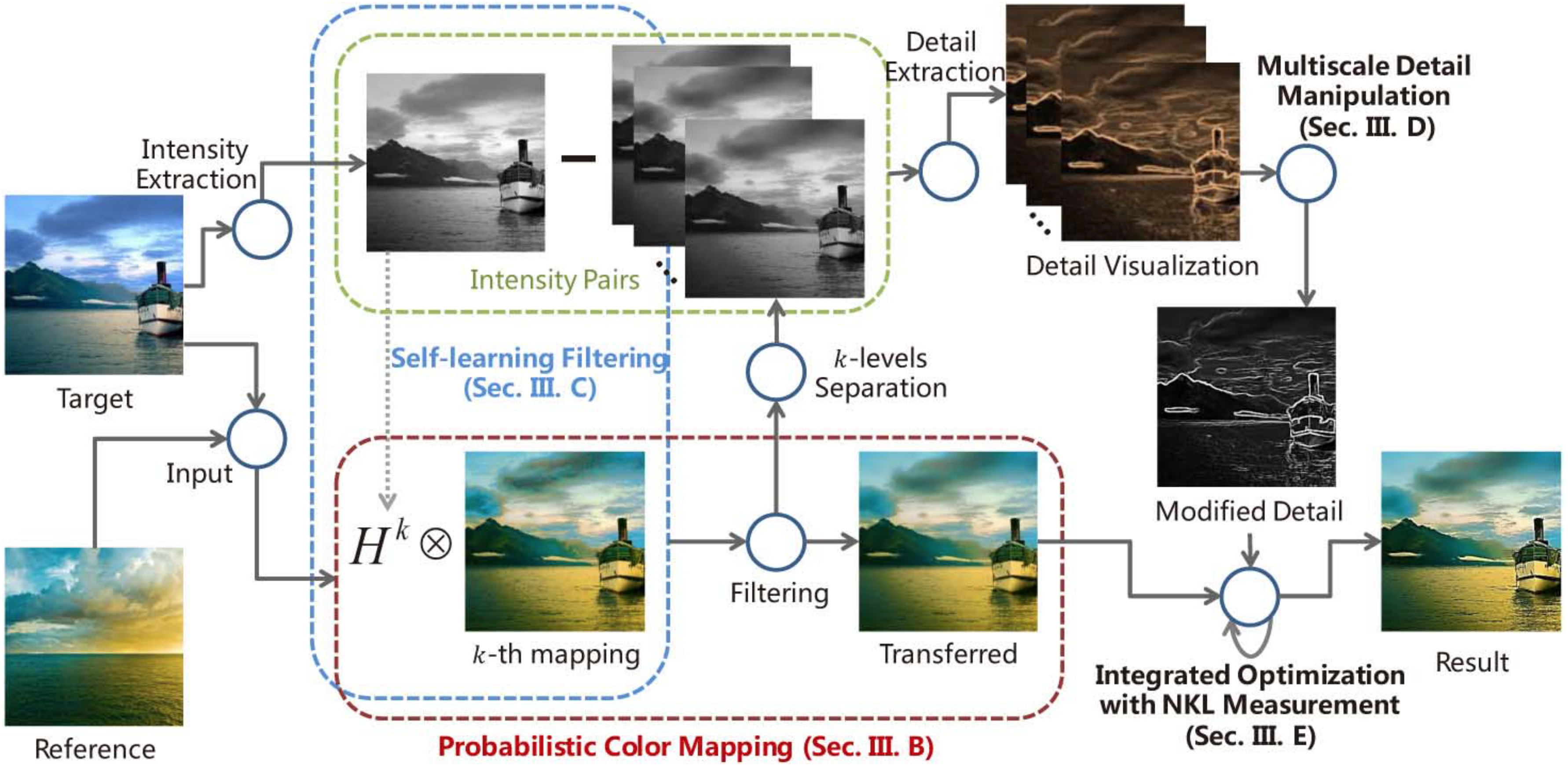

Gray image
Reference
[22]
[7]
[23]
[4]
Ours

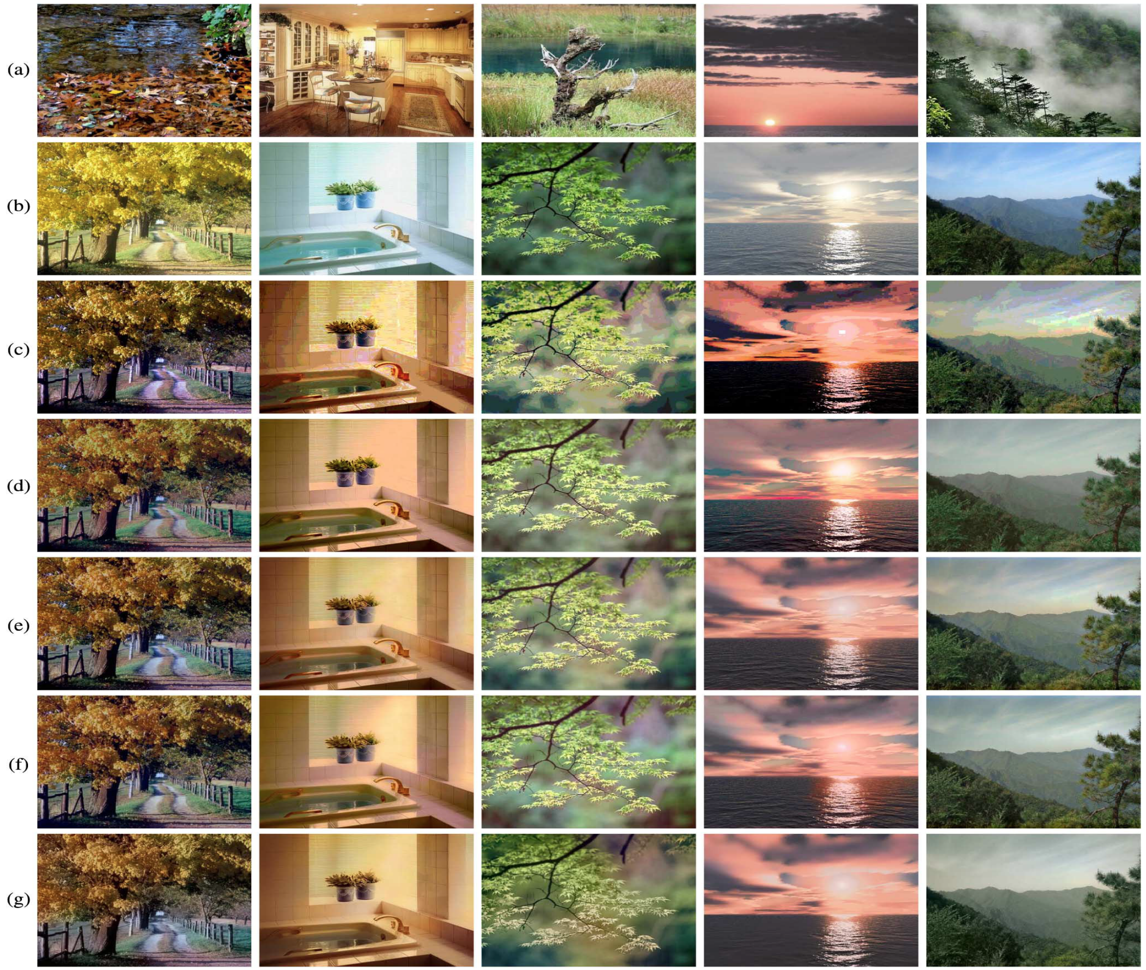
B. Li, Y.-K. Lai, and P. L. Rosin, “Example-based image colorization via automatic feature selection and fusion,” Neurocomputing, 2017.11.29, 266: 687 – 698. SCI二区




Target image
Reference image
[17]
[16]
Ours

Z. Su, K. Zeng, L. Liu, **B. Li**, X. N. Luo, “Corruptive Artifacts Suppression for Example-Based Color Transfer”, IEEE Transactions on Multimedia, 2014.6.01, 16(4): 988 – 999. SCI二区





(a)
(b)
(c)
(d)
(e)
(f)
(g)


(a)
(b)


(a)
(b)
(c)