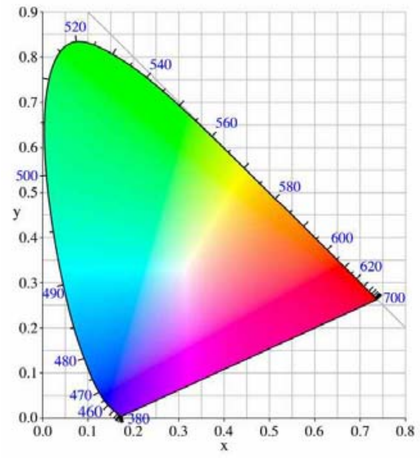
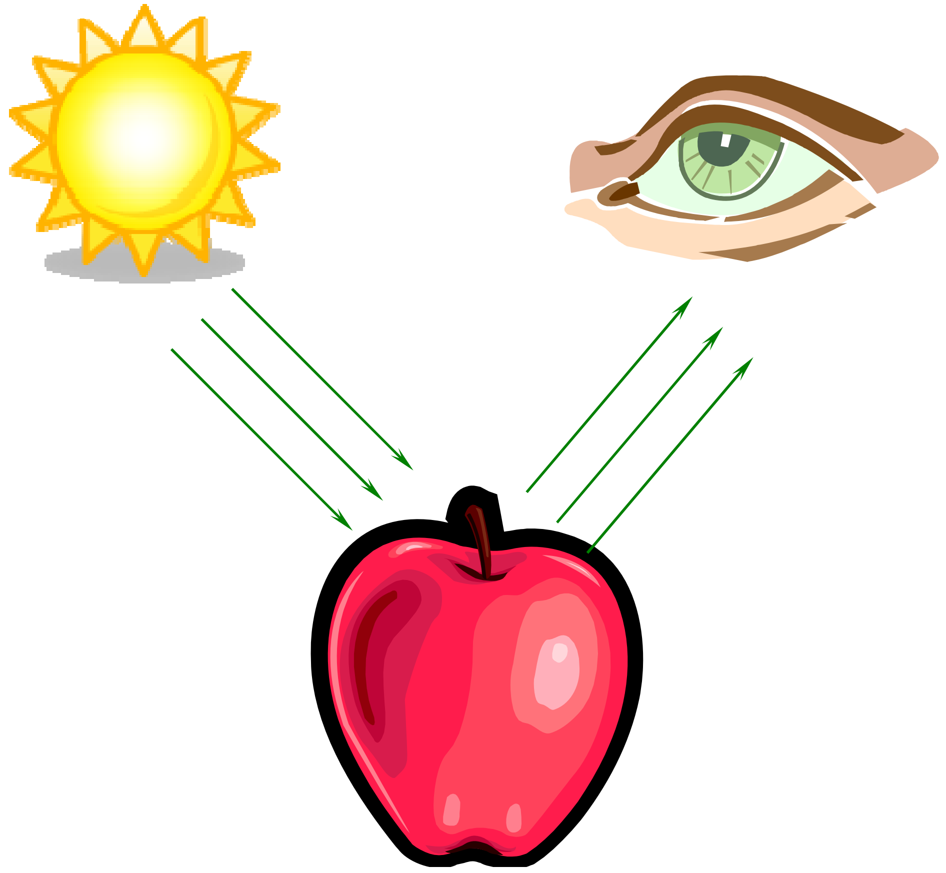
Multimedia Computing

Color Fundamentals



The perception of color

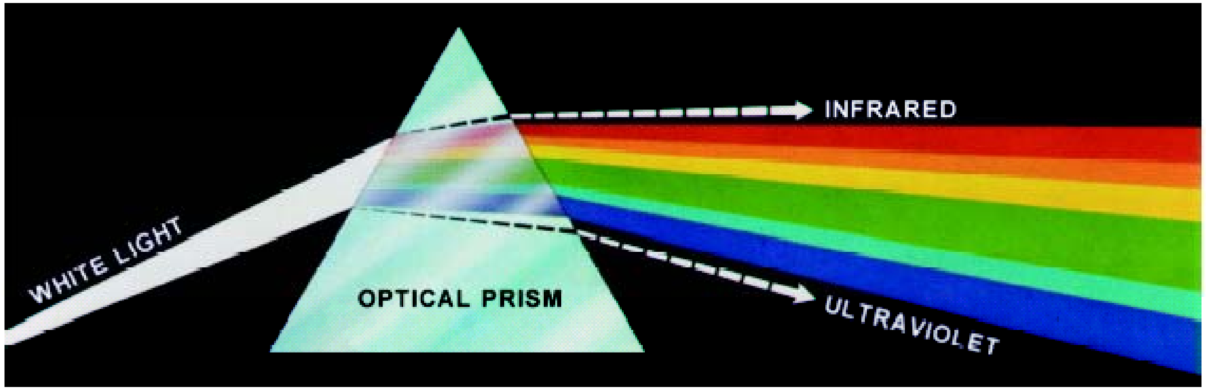
- There are three elements in the perception of color:
  - Light source
  - Object
  - Human visual system



Topics

- Color fundamentals
- Color models
- Case study: color demosaicking in single-chip digital cameras

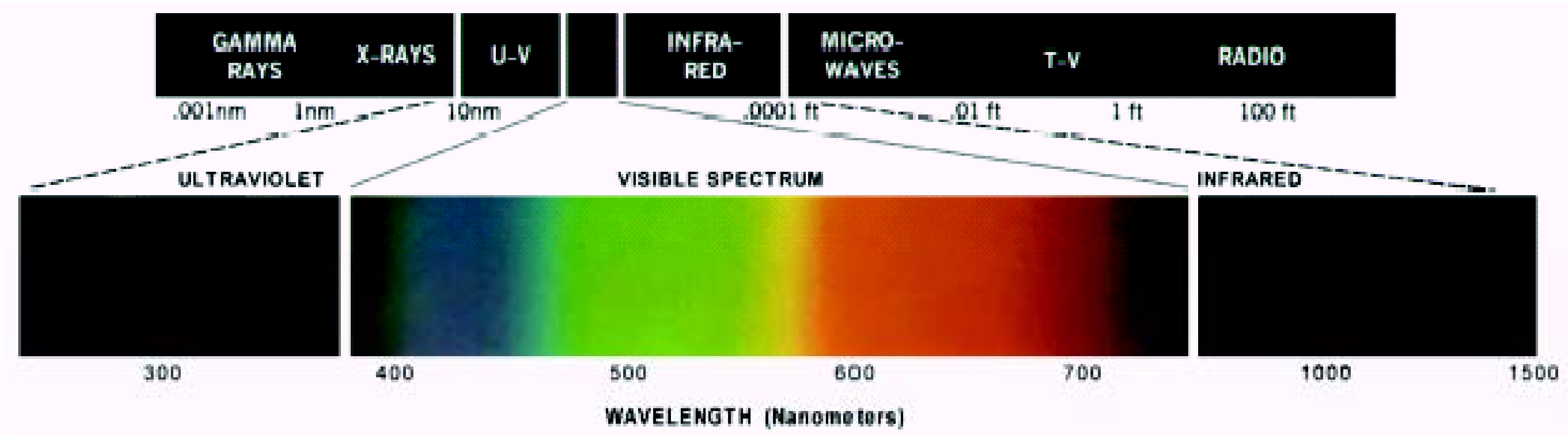
Color fundamentals



- In 1666 Newton discovered that a beam of sunlight passed through a prism will break into a spectrum of colors ranging from violet at one end to red at the other.
- Color spectrum: violet, blue, green yellow, orange, and red.
- No color in the spectrum ends abruptly.

Color fundamentals

- Color perceived from an object is determined by the nature of light reflected from that object.
- A white object reflects light that is balanced in all visible band.
- An objects that favors reflectance in a limited range of the visible spectrum exhibits a specific color.



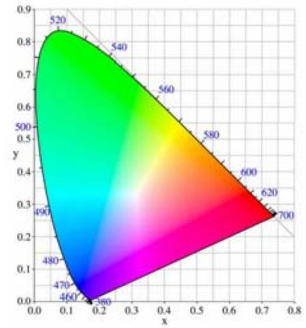
Achromatic and chromatic light

- Achromatic light (without color) is described only by intensity (the amount of gray level).
  - Achromatic light is what you see on a black/white TV.
  - Gray level is a scalar measure of intensity that ranges from black, to grays and to white.
- Chromatic light spans the electromagnetic spectrum from approximately 400nm to 700nm. Chromatic light is described by 3 quantities:
  1. Radiance
  2. Luminance
  3. Brightness

Chromatic light

- Radiance: total amount of energy that flows from the light source.
  - Usually measured in watts (W).
- Luminance: a measure of the amount of energy an observer perceives from a light source.
  - Usually measured by lumens (lm).
  - Infrared source: high energy but zero luminance because observers can hardly perceive it.
- Brightness: a subjective descriptor that is practically impossible to measure.
  - It embodies the achromatic notion of intensity and is one of the key factors in color sensation.

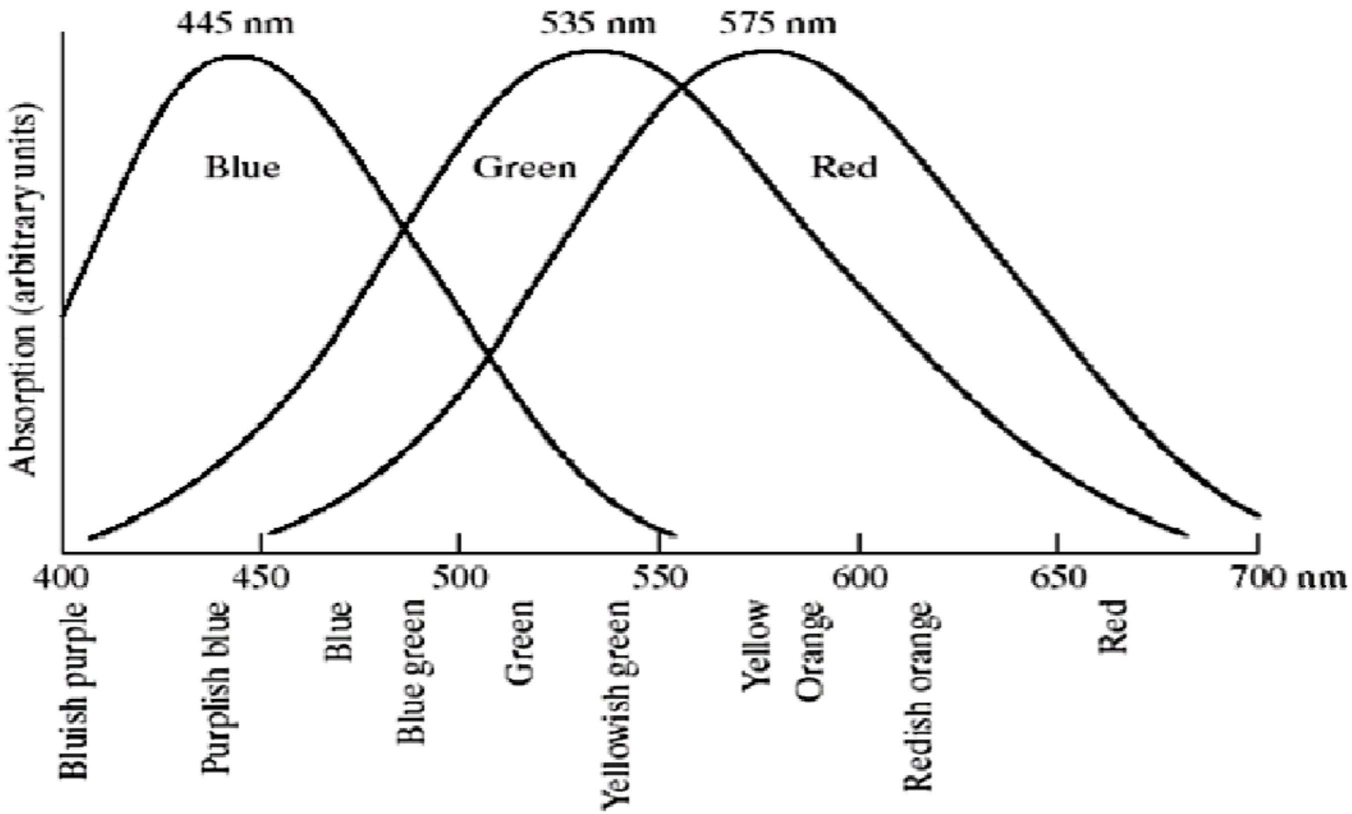
Primary colors



- Detailed experimental evidence has established that the 6~7 million cones in the human eye can be divided into three principal sensing categories: **red**, **green** and **blue**.
  - 65% of all cones are sensitive to red light.
  - 33% are sensitive to green light.
  - 2% are sensitive to blue light but the blue cones are the most sensitive.

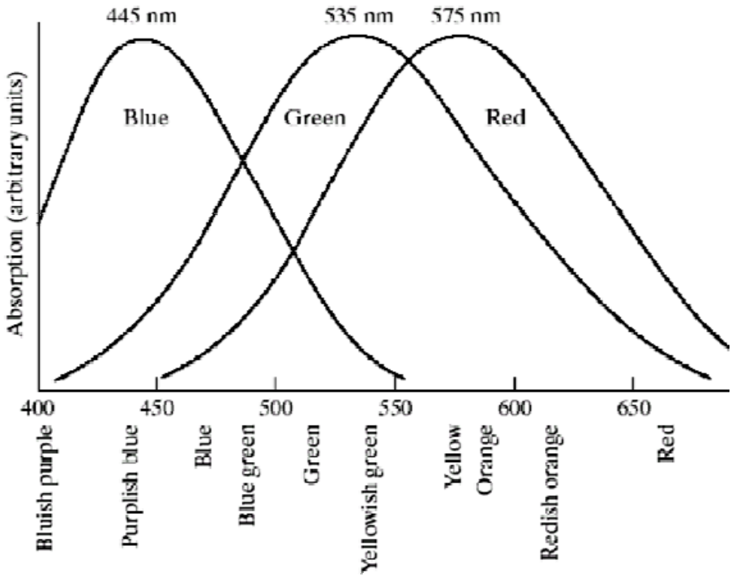
Primary colors

- Due to the absorption characteristics of the human eyes, colors are seen as variable combinations of primary colors R, G and B.



Comments on primary colors

- NO single color may be called red, green or blue.
- Having three specific primary color wavelengths for the purpose of standardization does NOT mean that RGB acting alone can generate all spectrum colors.

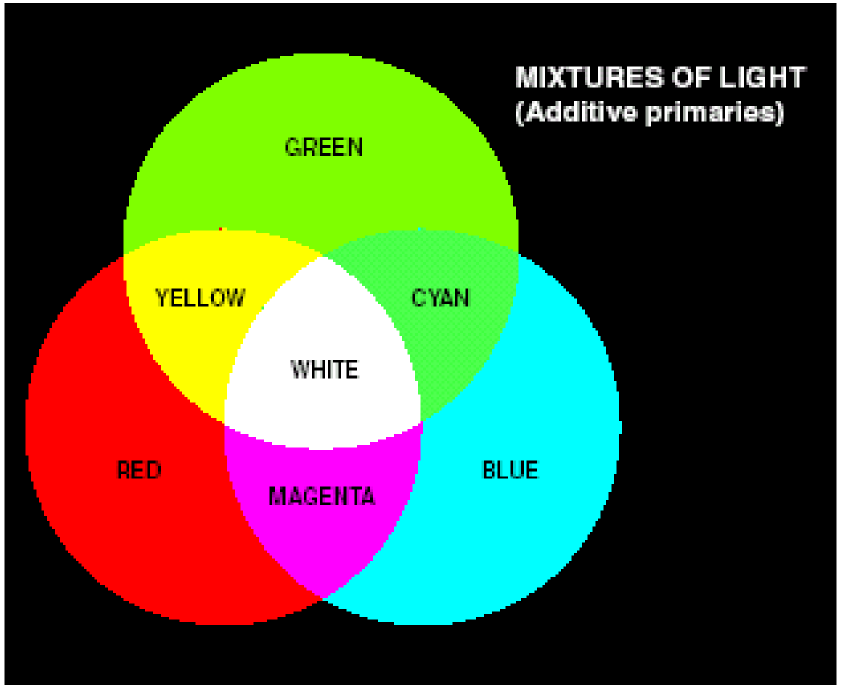


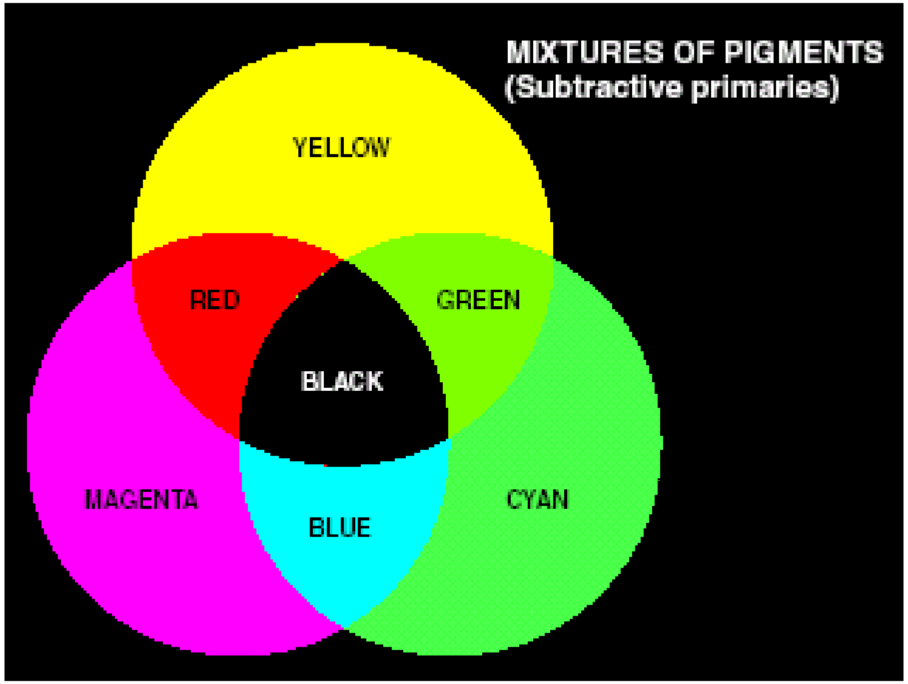
- Use of the word "primary" has been widely misinterpreted to mean that RGB can produce all visible colors.

Secondary colors

- Primary colors can be added to produce secondary colors:
  - Magenta: (red plus blue, opposite to green)
  - Cyan: (green plus blue, opposite to red)
  - Yellow: (red plus green, opposite to blue)
- Mixing three primary colors produce white.
- Mixing a secondary color with its opposite primary color produces white.

Primary and secondary colors

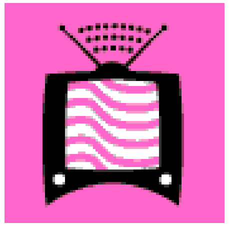




Primary color

Secondary color

Additive nature of light colors



- Color TV: an example of the additive nature of light colors
  - TV tube: a large array of triangular dot patterns of electron sensitive phosphor.
  - Each dot in a triangle produces one of the primary colors.
  - Intensity of red-emitting phosphor is modulated by an electron gun. Similarly for green-emitting and blue-emitting.
  - Three primary colors are added and received by the eye as a full-color image.

Color representation

- One color is distinguished from another by:
  - Brightness embodies the achromatic notion of intensity.
  - Hue is associated with the dominant wavelength (color) in a mixture of light waves. It represents the dominant color perceived by an observer.
    - When we call an object red or yellow, we are specifying its hue.
  - Saturation: relative purity or the amount of white light mixed with a hue.
    - The pure spectrum colors are fully saturated.
    - E.g. pink is less saturated than red.

Tri-chromatic coefficients

- Hue and saturation together are called chromaticity. Therefore, a color can be characterized by its brightness and chromaticity.
- The amounts of red, green and blue needed to form a particular color are called tri-stimulus X, Y, Z.
- A color is specified by its tri-chromatic coefficients:

$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$

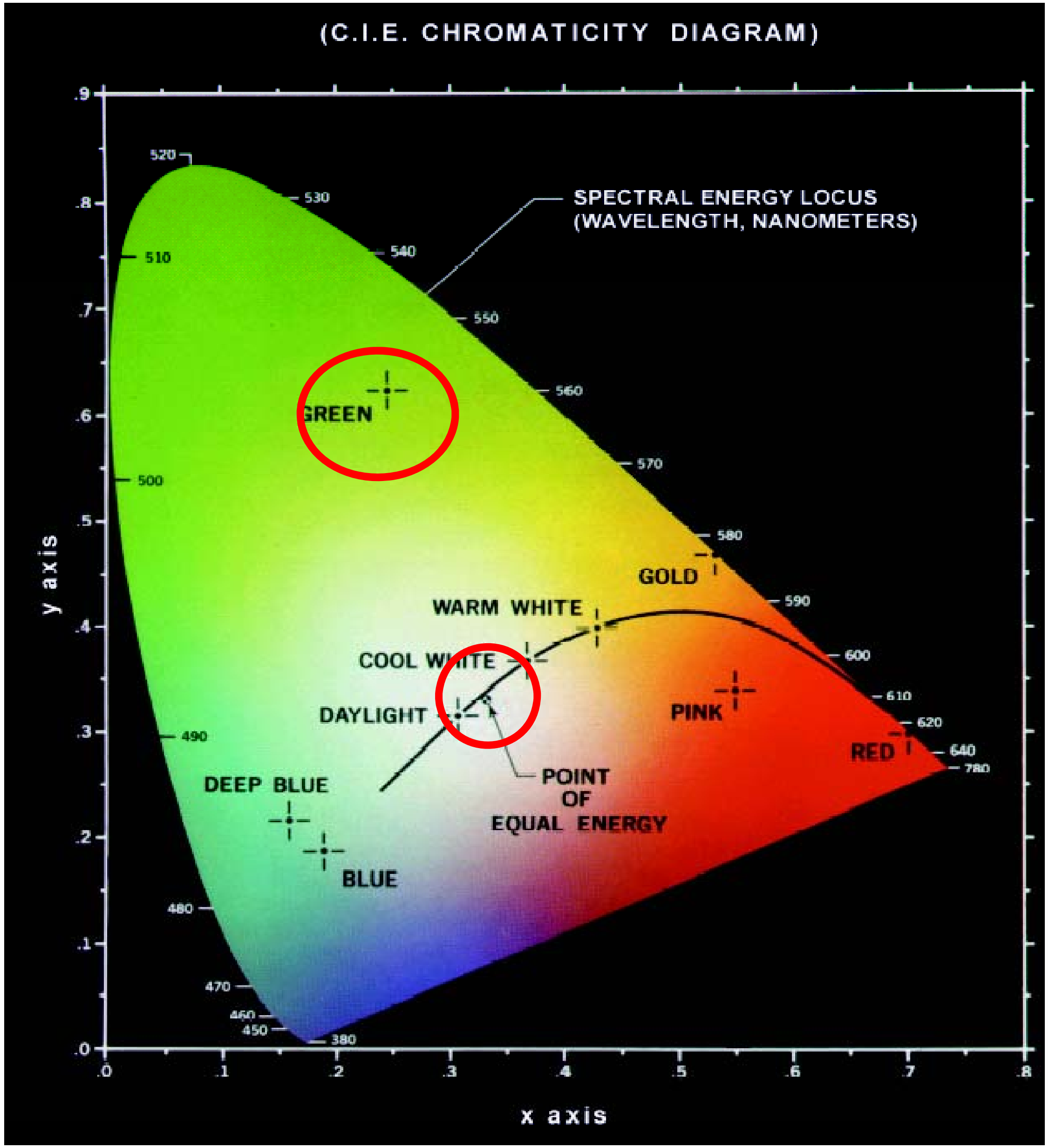
$$z = Z/(X+Y+Z)$$

  - Obviously $x+y+z=1$

Chromaticity diagram

- Another approach for specifying colors is to use CIE chromaticity diagram which shows color composition as a function of x (red) and y (green).
  - CIE: Commission Internationale de l'Eclairage (International Commission on Illumination)
- For any value of x and y, the corresponding value of z (blue) is obtained by $z=1-x-y$.

- For example, the point "GREEN" has 62% green, 25% red and 13% blue.
- Various spectrum colors, i.e. pure colors, from violet (380nm) to red (780nm), are indicated around the boundary of tongue-shaped diagram.
- Points within the diagram represent some mixture of pure colors.

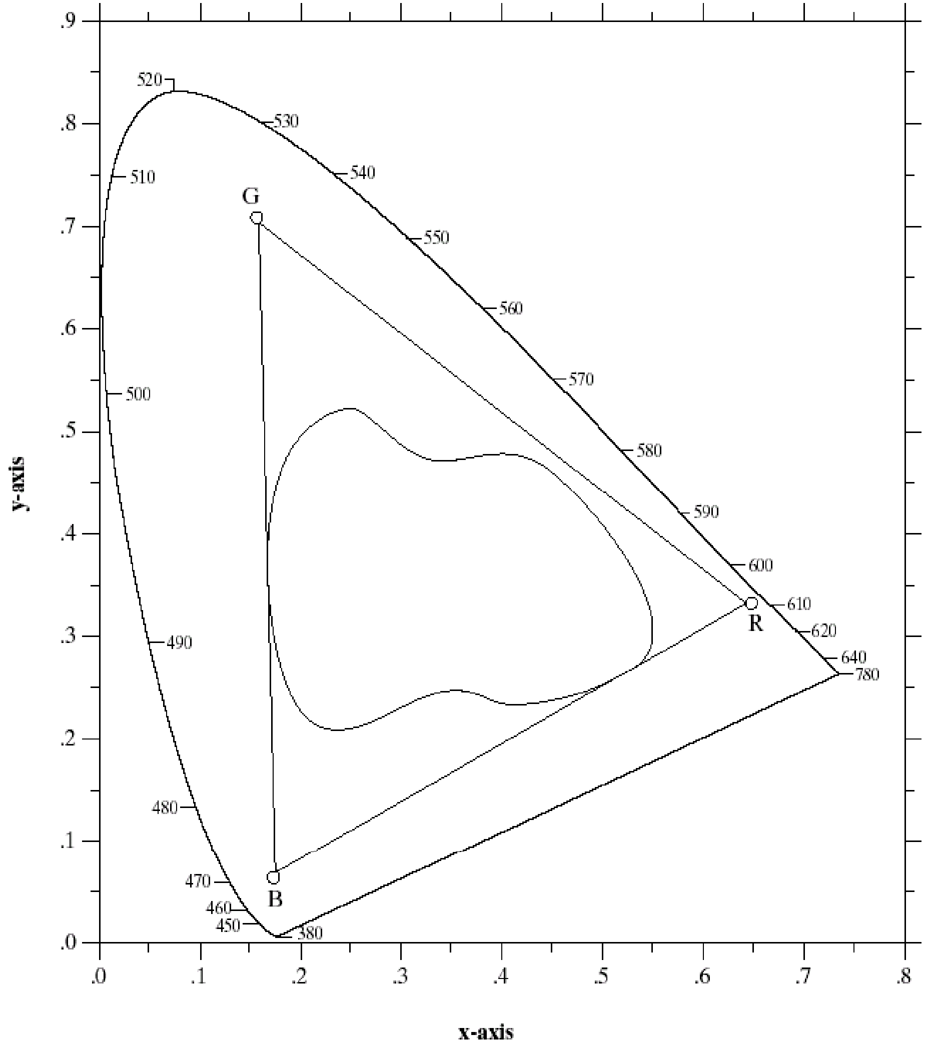


Comments on the chromaticity diagram

- Any point on the boundary is fully saturated (pure).
- The point of equal energy corresponds to equal fractions of RGB. It is the CIE standard of white light.
- A straight line segment linking any two points defines all different colors that can be obtained by combining these two colors additively.
- A line drawn from the white point to any point on the boundary will define all the shades on that color.
- To determine colors that can be obtained from any three given colors, we draw connecting lines to each of the three color points.

Comments on the chromaticity diagram

- To determine colors that can be obtained from any three given colors, we draw connecting lines to each of the three color points. The result is a triangle.
- We see that the triangle determined by R, G and B primary colors can not cover all the colors.



Topics

- Color fundamentals
- Color models
- Case study: color demosaicking in single-chip digital cameras

Color models (color spaces/systems)

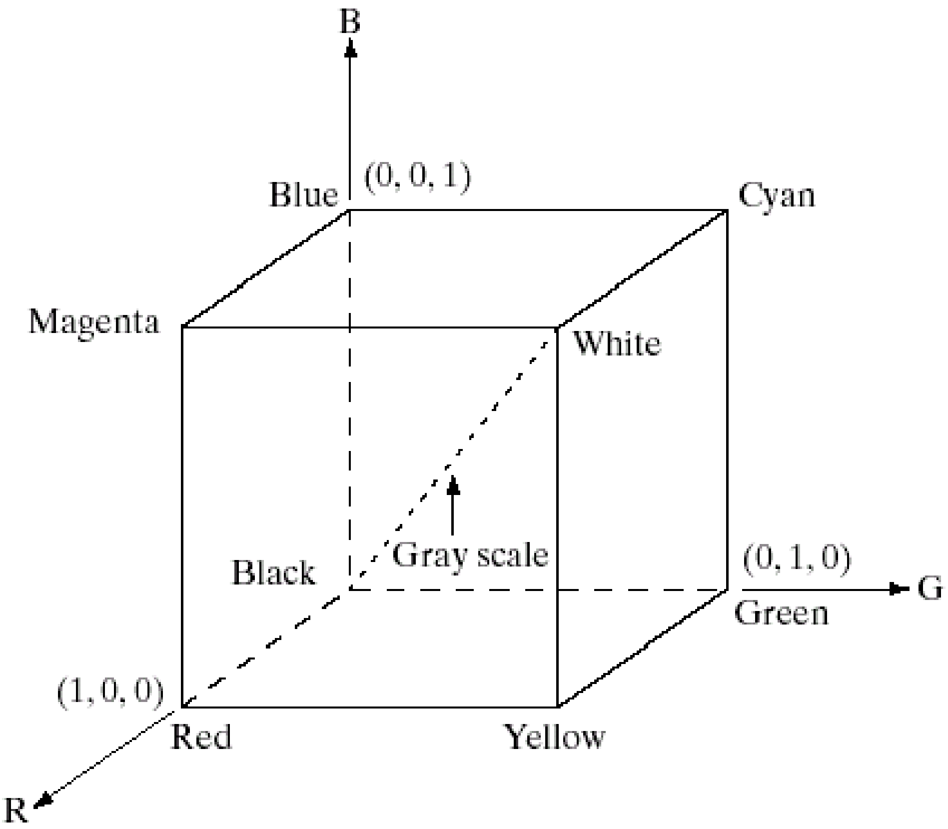
- Color models: used to specify colors in a standard way.
- Color model is a coordinate system where each color is represented by a single point
  - RGB (red, green, blue)
  - CMY (cyan, magenta, yellow)
  - HSI (hue, saturation, intensity)

Color models

- Each model is oriented toward a hardware or application.
  - RGB: color monitors, cameras, color image processing
  - CMY: color monitor
  - HSI: color image processing
    - HSI decouples color and gray level information in an image making it suitable for image interpretation. Many gray scale techniques can also be applied to the "I" (intensity) channel.

RGB

- Each color appears in its primary spectral components of red, green and blue.
- Different colors are points inside the cube.
- Number of bits used to represent each pixel is called the pixel depth.
- If 8 bit is used, then 24-bit RGB color image is obtained.
- Total number of colors: $(2^8)^3 = 2^{24}$



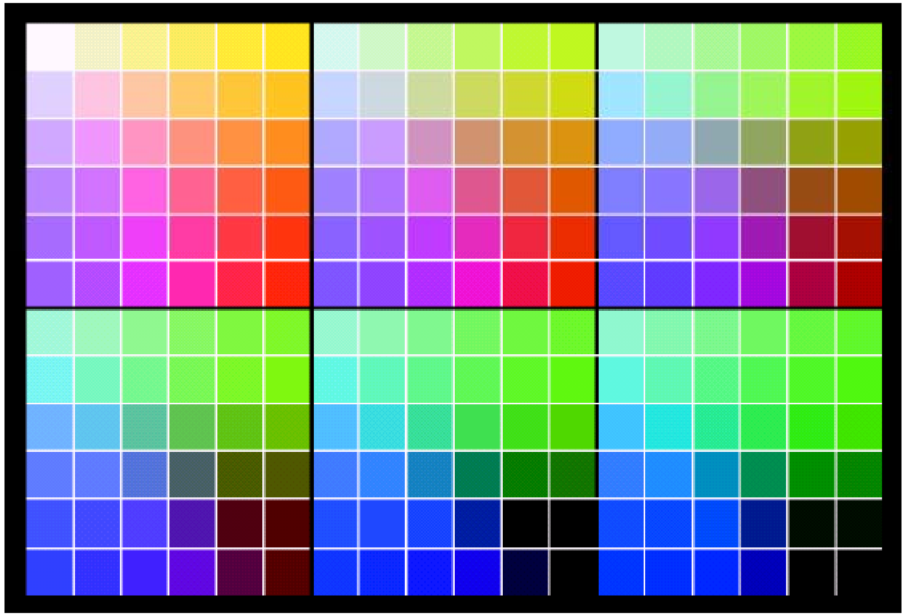
RGB

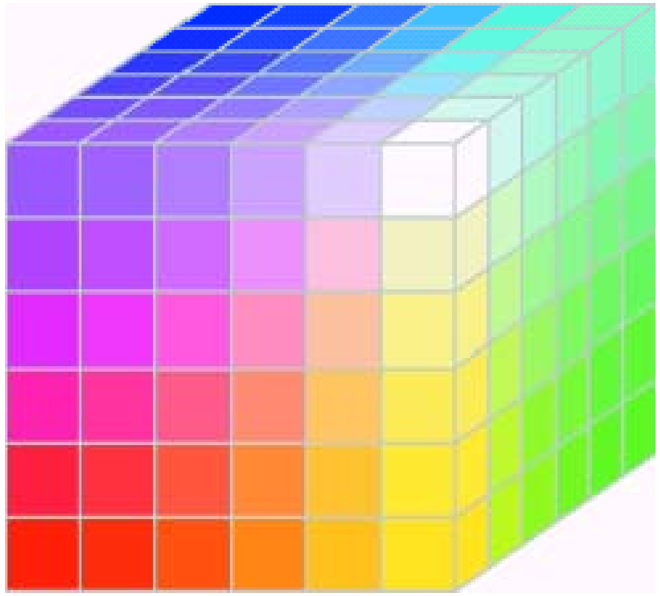
- RGB 24-bit color cube

Safe RGB colors

- In many applications, it makes no sense to use more than a few hundred colors.
- A subset of colors that are likely to be reproduced reasonably and independently of viewer hardware is called safe RGB color.
- 216 colors have become the de facto standard for safe colors.
- Each of 216 safe colors is formed from three RGB values but each value can only be 0, 51, 102, 153, 204 or 255.
- Thus totally 6^3=216 possible values.

Safe RGB colors





CMY

- Cyan, magenta and yellow are the secondary colors of light, or the primary colors of pigments.

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

- Most devices that deposit colored pigments on paper (color printers and copiers) require CMY data input.
- Pure cyan does not reflect red; pure magenta does not reflect green; pure yellow does not reflect blue.

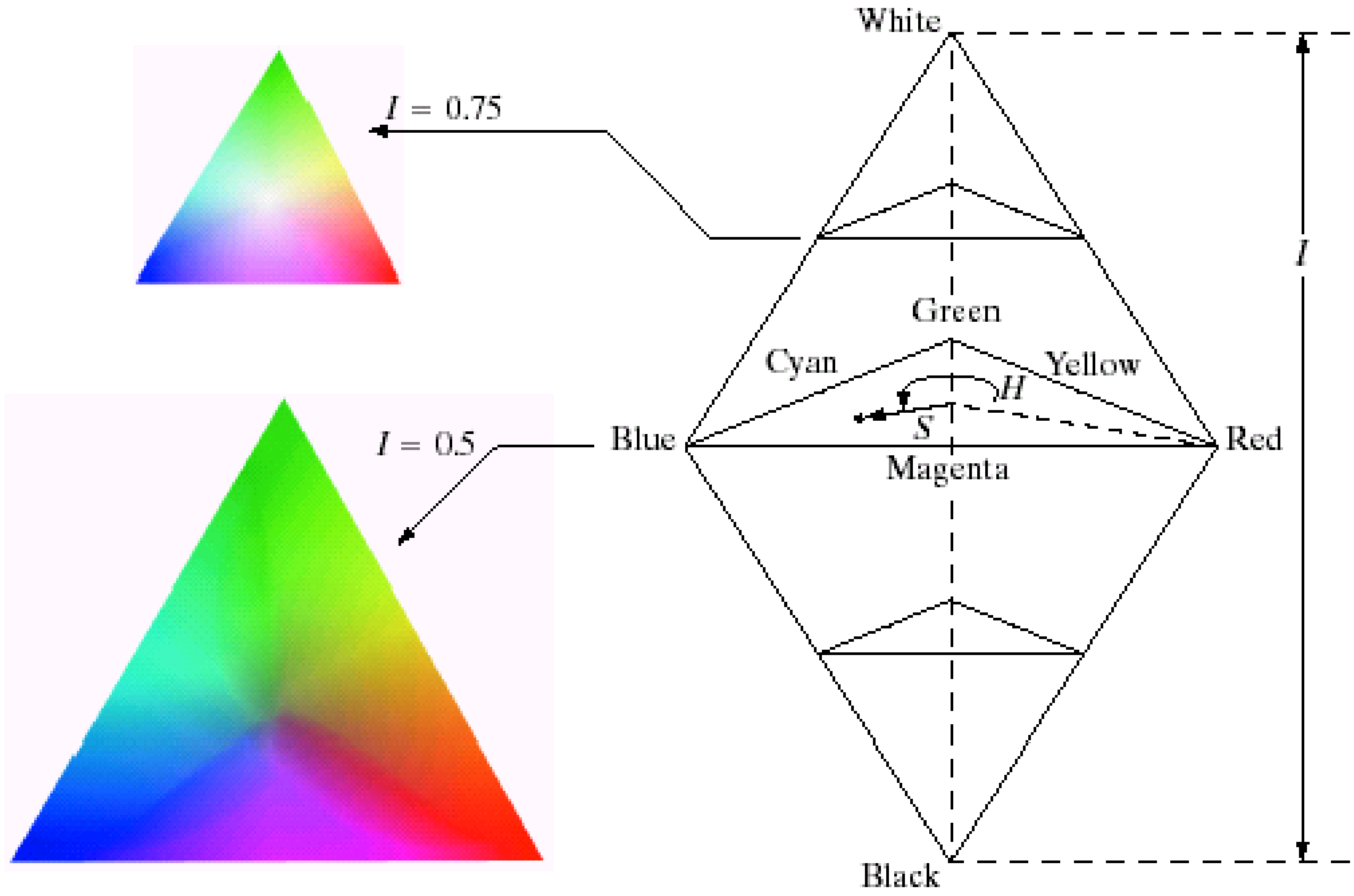
CMY

- Equal amounts of pigments primaries, cyan, magenta and yellow should produce black.
- In practice combing these colors produces a muddy looking black.
- In order to produce true black, a fourth color Black is added, giving rise to CMYK color model.
- When publishers are talking about four color printing they are referring to CMY plus black.

HSI

- RGB (CMY) is ideal for image color generation (image capture by color camera or image display by monitor), but its use for color description is much limited.
- HSI (hue, saturation and intensity) decouples intensity components from the color-carrying information.
    - Hue: dominant color
    - Saturation: relative purity or the amount of white mixed with a hue
    - Intensity: the most useful descriptor of gray images.

The triangular HSI model



RGB to HSI transformation

$$\theta = \cos^{-1}\left\{\frac{[(R-G)+(R-B)]/2}{[(R-G)^2+(R-B)(G-B)]^{1/2}}\right\}$$

$$H = \begin{cases} \theta & \text{if} \quad B \le G \\ 360-\theta & \text{if} \quad B > G \end{cases}$$

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

$$I = (R+G+B)/3$$

HSI to RGB transformation

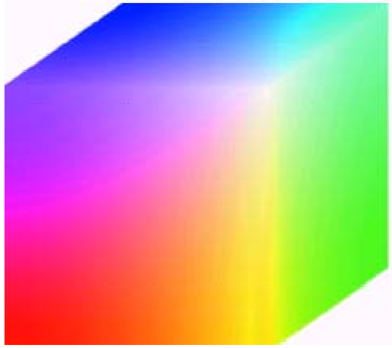
$$0 \le H < 120$$
$$B = I(1-S)$$
$$R = I\left[1+\frac{S\cos H}{\cos(60-H)}\right]$$
$$G = 3I-(R+B)$$

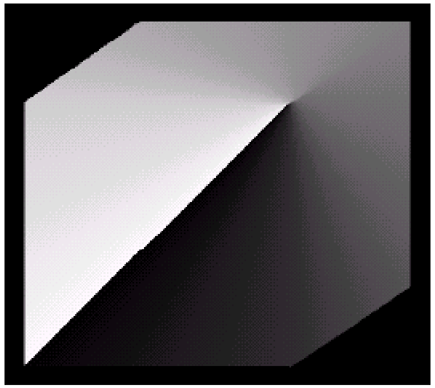
$$120 \le H < 240$$
$$H = H-120$$
$$R = I(1-S)$$
$$G = I\left[1+\frac{S\cos H}{\cos(60-H)}\right]$$
$$B = 3I-(R+G)$$

$$240 \le H < 360$$
$$H = H-240$$
$$G = I(1-S)$$
$$B = I\left[1+\frac{S\cos H}{\cos(60-H)}\right]$$
$$R = 3I-(R+G)$$

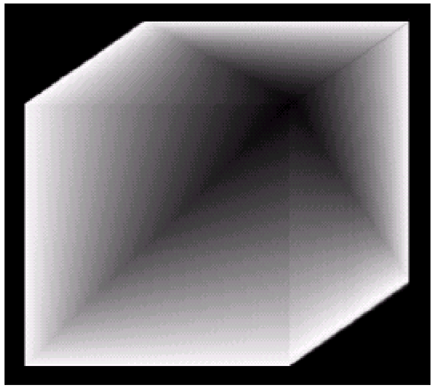
Example

RGB image

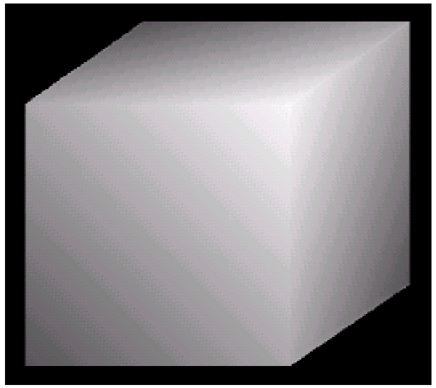




Hue



Saturation

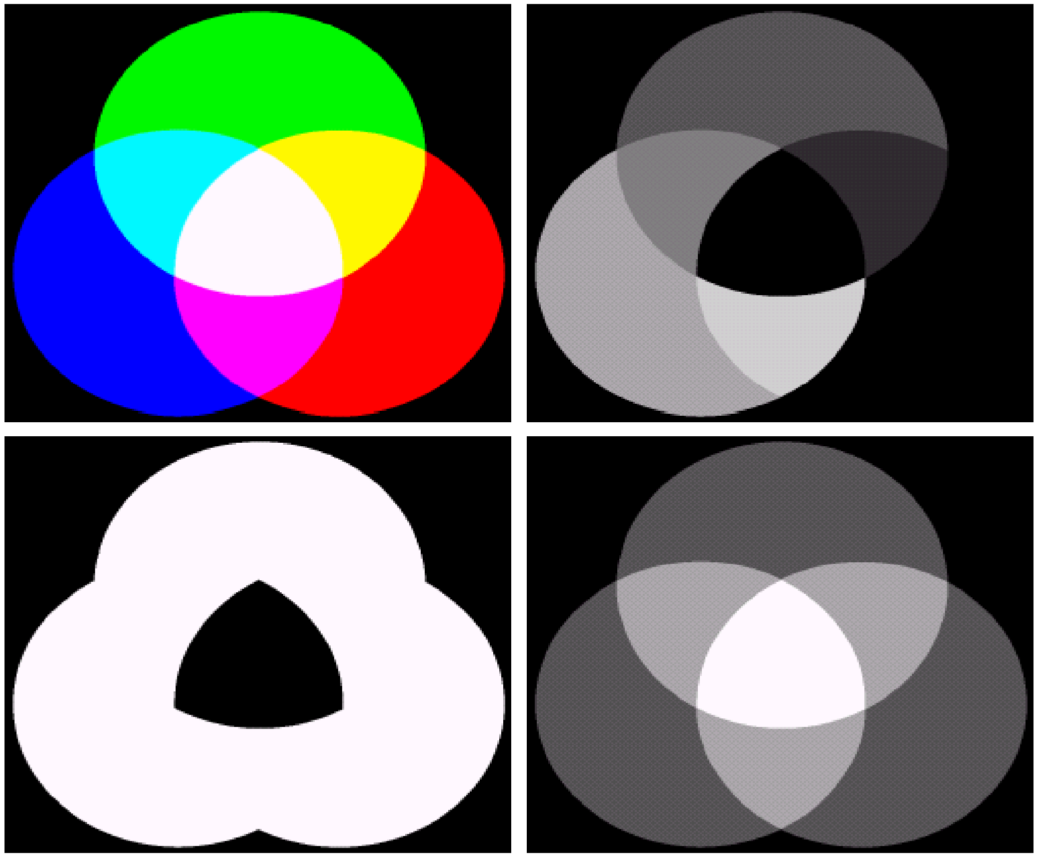


Intensity

Example: manipulating HSI

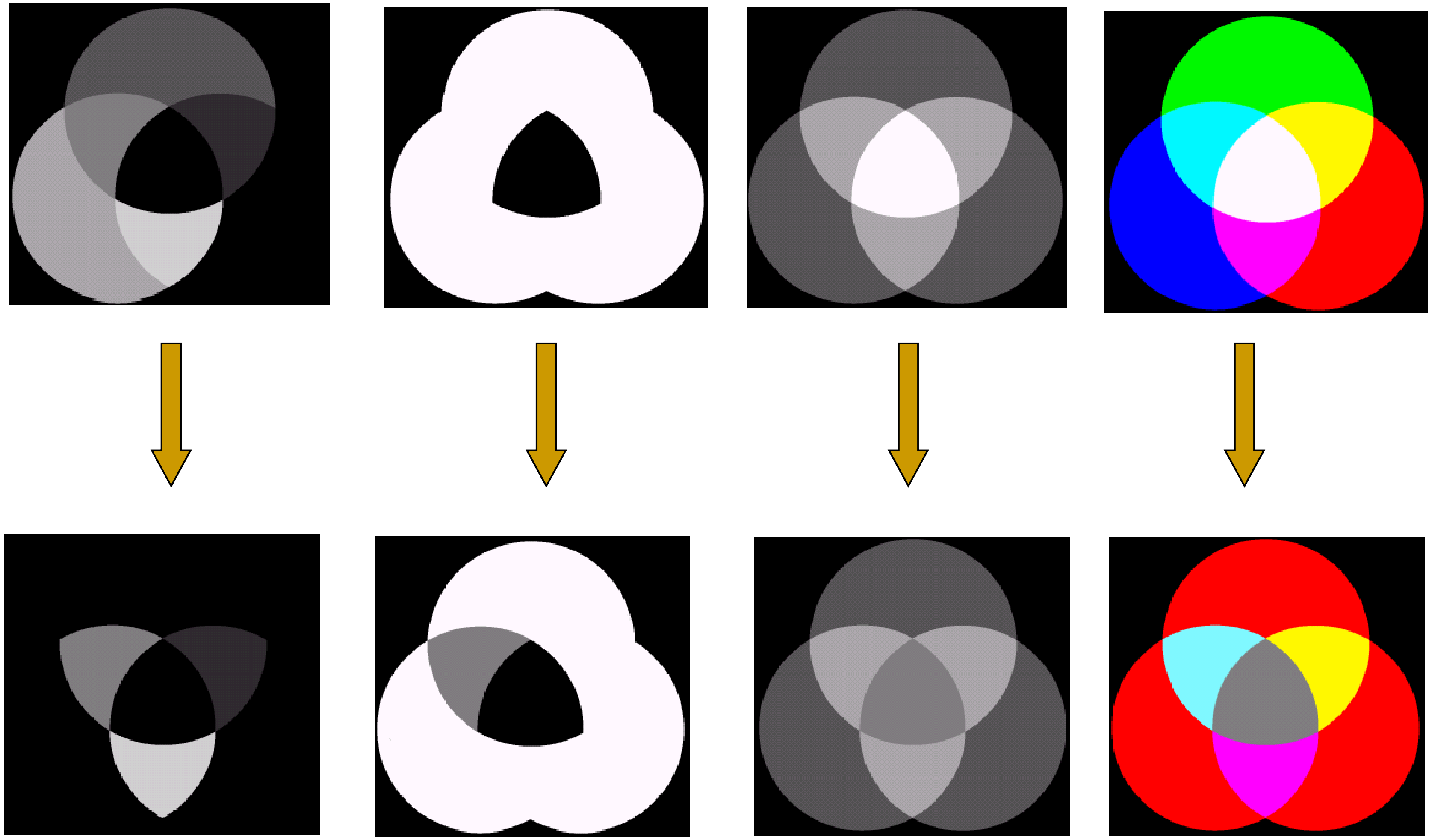
RGB image

Hue



Saturation

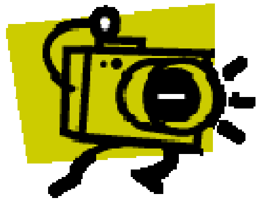
Intensity



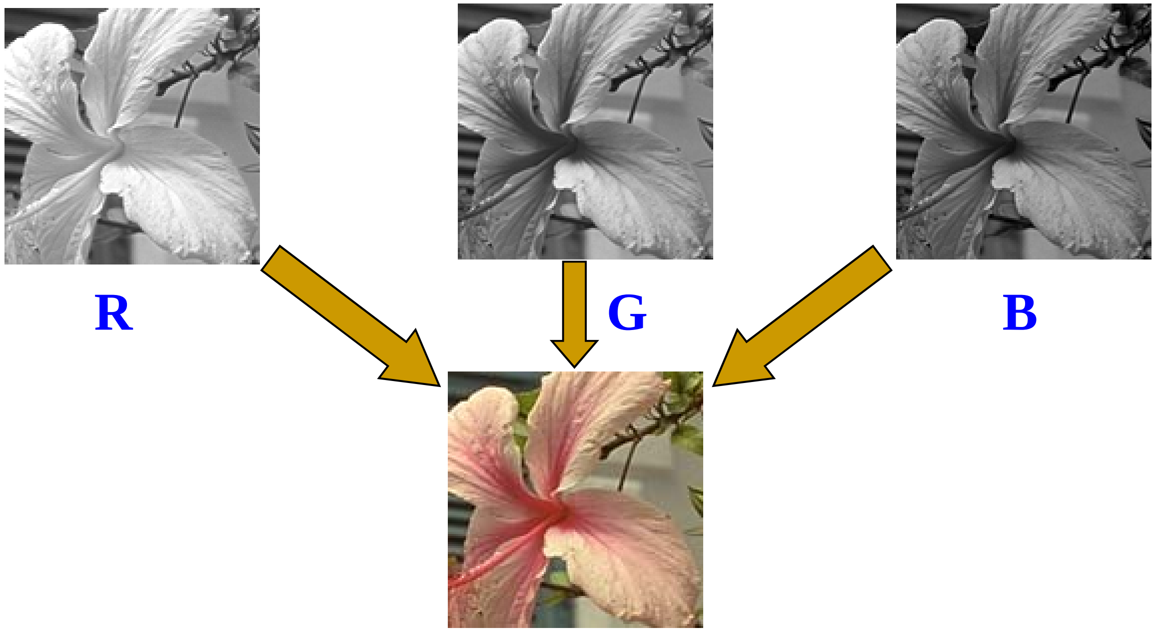
Topics

- Color fundamentals
- Color models
- Case study: color demosaicking in single-chip digital cameras

Digital color camera

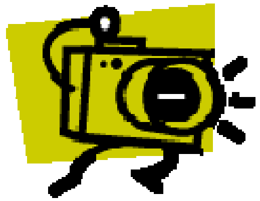


- 3-CCD (charge coupled device) digital color cameras can capture the RGB channels simultaneously, but the price is very high.



Full color image

Digital color camera



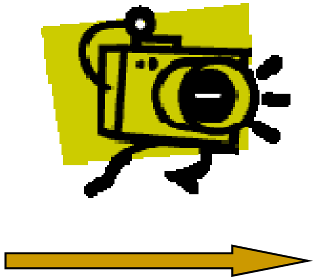
- Most of the commercial digital color cameras are single CCD cameras.
- They capture images using a color filter array (CFA). At each pixel, only one of the three primary colors is sampled.
- Bayer pattern is the most widely used CFA pattern.

G	R	G	R	G	R
B	G	B	G	B	G
G	R	G	R	G	R
B	G	B	G	B	G
G	R	G	R	G	R
B	G	B	G	B	G

Bayer Pattern

Example

Original scene



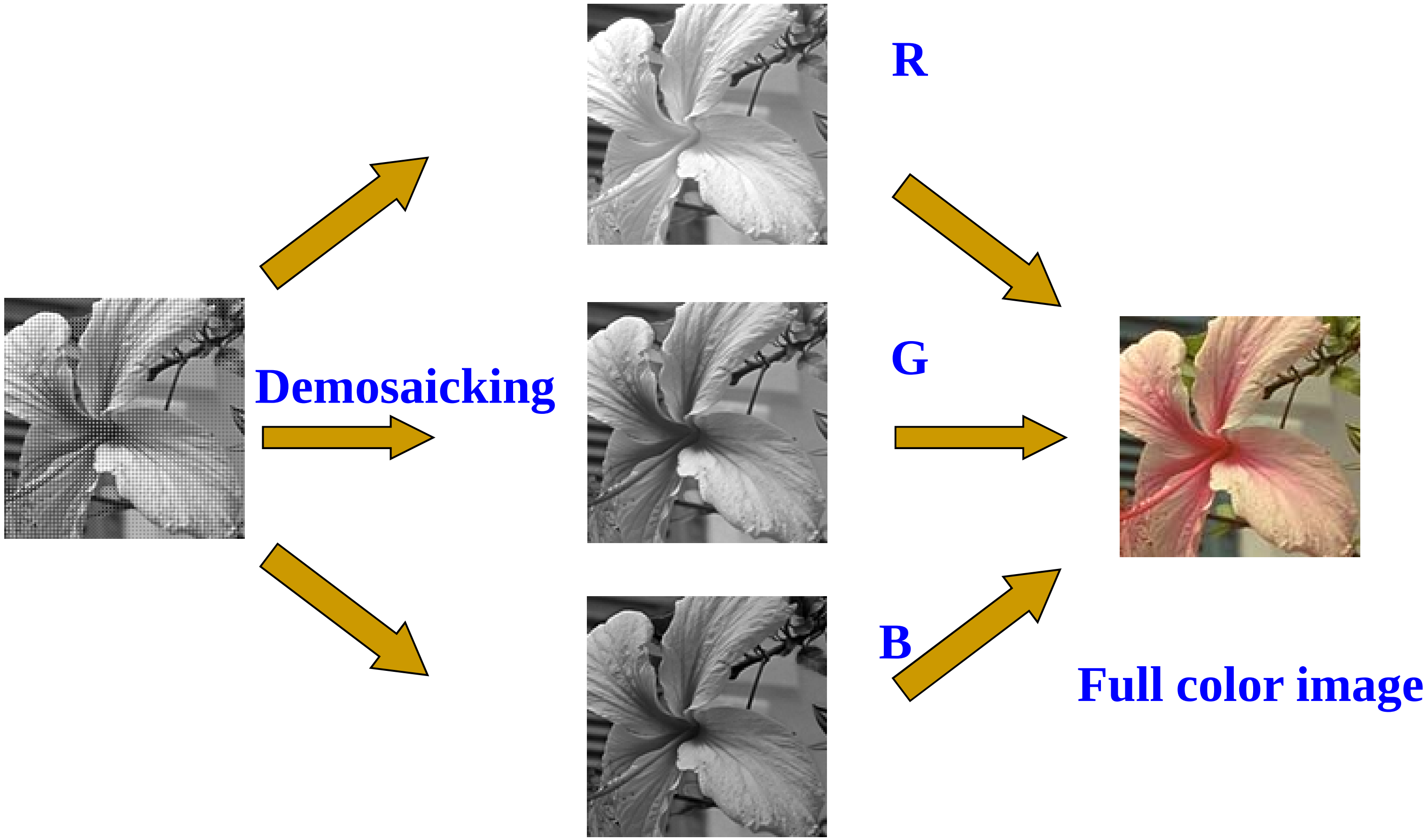
CFA image

- Due to the mosaic effect, we call the CFA image mosaic-CFA image.

Color demosaicking

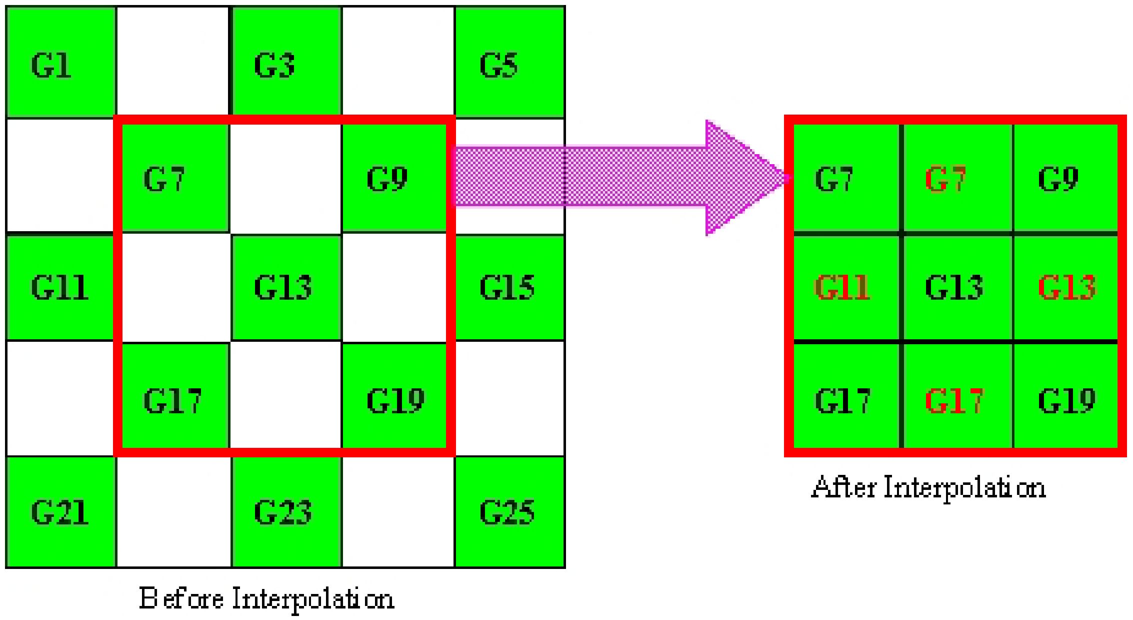
- **Color Demosaicking** is to reconstruct the full color image from the mosaic data.
- The quality of reconstructed image depends on the demosaicking algorithm and the image contents.
- Color Demosaicking is also called color interpolation because the full resolution RGB channels are interpolated from the available CFA image.

Demosaicking process



Demosaicking methods

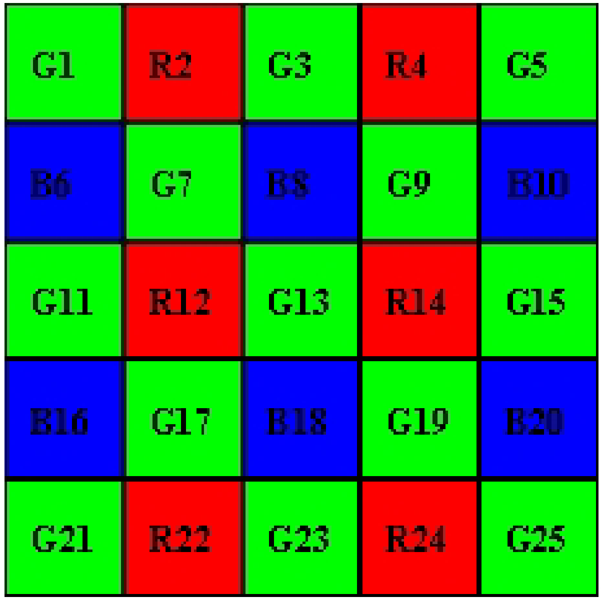
- *Nearest Neighbor Replication*



The red and blue channels are interpolated similarly.

Demosaicking methods

- *Bilinear*



Interpolation of green: the average of the upper, lower, left and right pixel values is assigned as the G value of the interpolated pixel. E.g. G8 = (G3+G7+G9+G13) / 4

Interpolation of a red/blue pixel at a green position : the average of two adjacent pixel values in corresponding color is assigned to the interpolated pixel. E.g. B7 = (B6+B8) / 2 ; R7 = (R2+R12) / 2

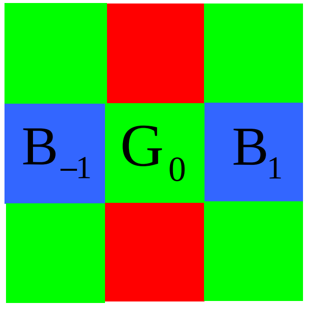
Interpolation of a red/blue pixel at a blue/red position : the average of four adjacent diagonal pixel values is assigned to the interpolated pixel. E.g. R8 = (R2+R4+R12+R14) / 4 ; B12 = (B6+B8+B16+B18) / 4

Demosaicking methods

- The above methods do not exploit the correlation of red, green and blue channels. They are easy to implement but suffer from blocking, blurring and zipper effects.
- *Smooth Hue Transition (SHT):* the images have slowly varying hue, then the ratios B/G and R/G change slowly.

1. Green channel is first interpolated by bilinear or bicubic method.

2. The missing blue samples are interpolated as



$$B_0 = G_0 \bullet (B_{-1} / G_{-1} + B_1 / G_1) / 2$$

3. Red samples are interpolated similarly.

SHT method tends to cause large errors when green values abruptly change.

Demosaicking methods

- *Gradient-based Color Correction:* uses the *second order color gradients* as the correction terms to interpolate the color channels. It is also *edge sensing* and avoids some interpolation error across edges.

$$D_h = \left|G^h_{-1} - G^h_1\right| + \left|2R_0 - R^h_{-2} - R^h_2\right|$$

$$D_v = \left|G^v_{-1} - G^v_1\right| + \left|2R_0 - R^v_{-2} - R^v_2\right|$$

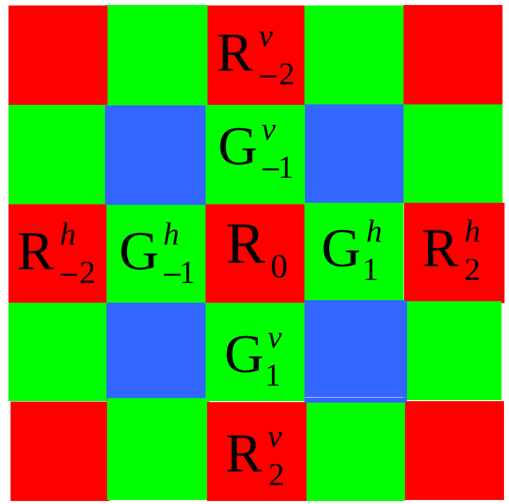
$$If\ \ D_h \le D_v$$

$$G_0 = \frac{1}{2}\left(G^h_{-1} + G^h_1\right) + \frac{1}{4}\left(2 \cdot R_0 - R^h_{-2} - R^h_2\right)$$

$$Else$$

$$G_0 = \frac{1}{2}\left(G^v_{-1} + G^v_1\right) + \frac{1}{4}\left(2 \cdot R_0 - R^v_{-2} - R^v_2\right)$$

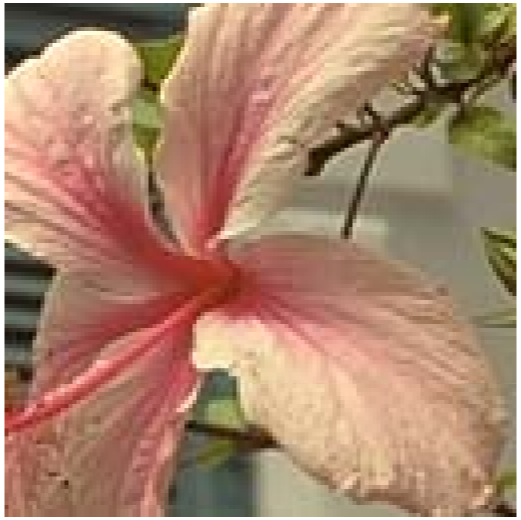
$$End$$



Advanced methods

- Lei Zhang and Xiaolin Wu, “Color demosaicking via directional linear minimum mean square-error estimation,” *IEEE Trans. on Image Processing,* vol. 14, pp. 2167-2178, Dec. 2005.
- X. Wu and L. Zhang, “Color video demosaicking via motion estimation and data fusion,” *IEEE Trans. on Circuits and Systems for Video Technology*, vol. 16, pp. 231-240, Feb. 2006
- J. Mairal, M. Elad and G. Sapiro. Sparse representation for color image restoration. IEEE Transactions on Image Processing. volume 17, issue 1, pp. 53-69, January 2008.
- A. Buades, B. Coll, J.-M. Morel, and C. Sbert, “Self-similarity driven color demosaicking,” *IEEE Trans. Image Processing, vol. 18, no. 6, pp. 1192-1202, June 2009.*
- L. Zhang, X. Wu, A. Buades, and X. Li, "Color Demosaicking by Local Directional Interpolation and Non-local Adaptive Thresholding," *Journal of Electronic Imaging* 20(2), 023016 (Apr-Jun 2011), DOI:10.1117/1.3600632.

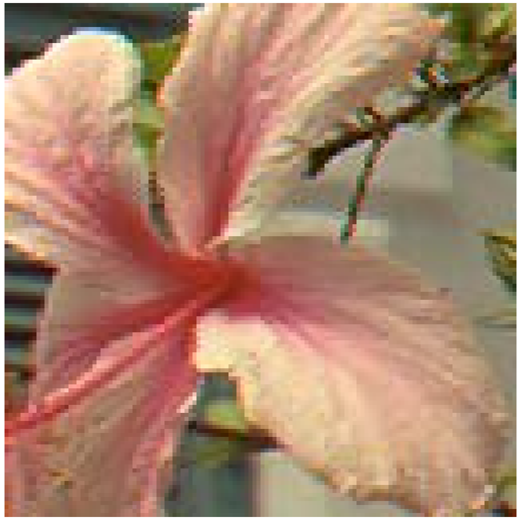
Simulation 1



True full color image

Simulated Bayer pattern CFA image

Simulation 1



Nearest Neighbor Replication

Bilinear Interpolation

Smooth Hue Transition

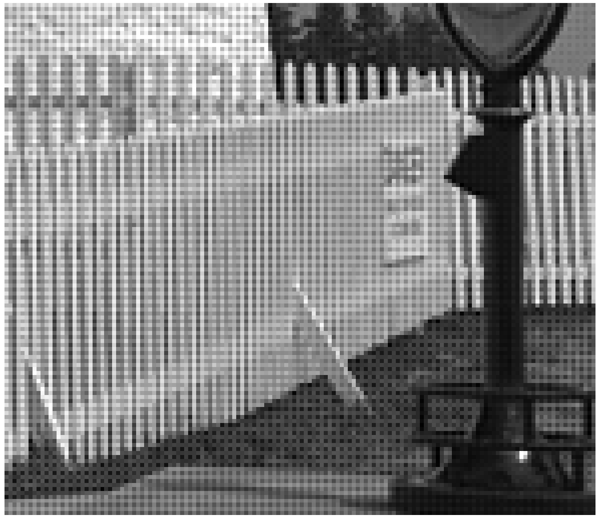
Simulation 1

Gradient-based
Color Correction

Zhang and Wu's
method

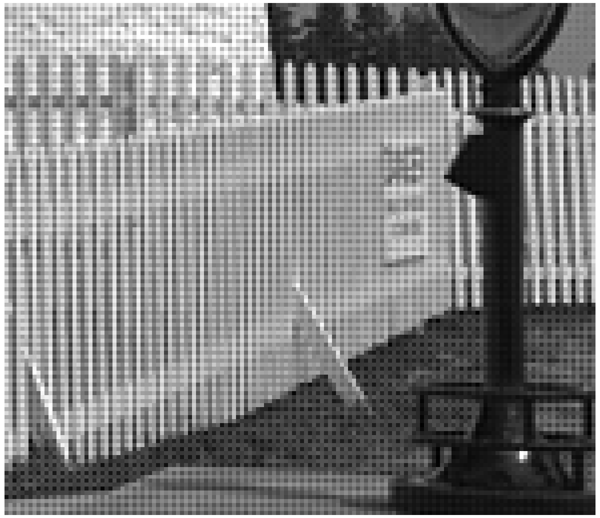
Simulation 2

True full color image



Simulated Bayer pattern CFA image

Simulation 2

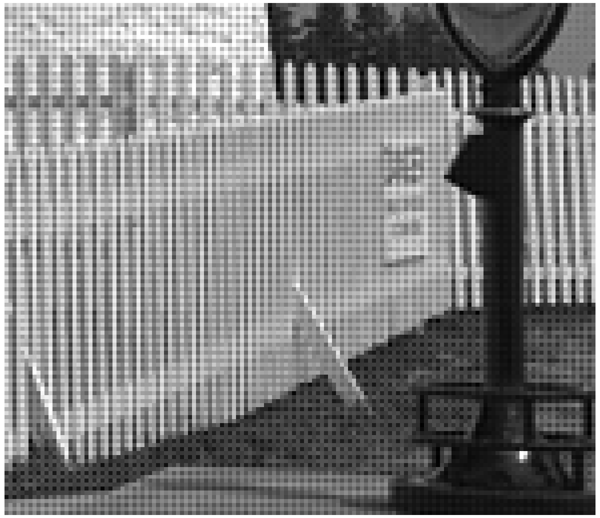


Nearest Neighbor Replication

Bilinear Interpolation

Smooth Hue Transition

Simulation 2



Gradient-based
Color Correction

Zhang and Wu's
method

References

- R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, Prentice Hall Inc., 2008.
- Ze-Nian Li, M. S. Drew, *Fundamentals of Multimedia*, Prentice Hall Inc., 2004.

Happy New Year!