Achromatic Light

Attributes:
Luminance: Physical intensity
Brightness: Perceived intensity

Intensity Display:

- ☆ b: # bits to encode 2^b levels of intensity.
- ☆ How should levels be distributed?
  Black: 0 White: 1
- ☆ Linear scale: Uniformly distributed
  $I_k = k/2^b \quad 0 \le k < 2^b$

Intensity Perception:

- ☆ Eyes perceive ratio of intensities.
- ☆ Intensity 0.11 is to 0.1, perceptually the same as 0.55 is to 0.5.

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Logarithmic Display

Ideally: Each level should increase the intensity by a constant factor.
$n = 2^b - 1$, I_0: minimum intensity, $I_n = 1$.

$$I_1 = rI_0, \quad I_2 = rI_1 = r^2 I_0, \quad I_3 = rI_2 = r^3 I_0.$$

$$I_n = r^n I_0 = 1.0 \Rightarrow r = \left(\frac{1}{I_0}\right)^{1/n}$$

$$I_j = I_0^{1-j/n}.$$

Example: $I_0 = 1/128$, $b = 3$, $n = 7$.

$$I = \frac{1}{128}, \frac{1}{64}, \frac{1}{32}, \frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1.$$

- ☆ *Dynamic range:* $1/I_0$.
- ☆ *# Intensities:* $n = \log_r(1/I_0)$.
- ☆ Typical value of r: 1.01.

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Typical values

Display Media	Dynamic range	# Intensity
CRT	50 – 200	400 – 350
Photographic prints	100	465
Photographic slides	1000	700
Coated B/W paper	100	465
Coated colored paper	50	400
Newspaper print	10	234

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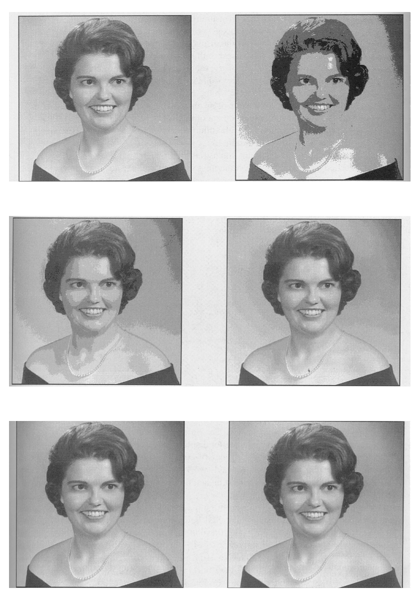
Examples



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Gamma Correction

- V: Input voltage.
- N: # electrons in the beam.
  $N \propto V$

$$I = k'N^\gamma = kV^\gamma \qquad 1.8 \le \gamma \le 2.5.$$

$$V = \left(\frac{I}{k}\right)^{1/\gamma}.$$

How do we determine the voltage for a perceived intensity?

- Compute the I_j closest to I.
  $j = \text{Round}(\log_r \frac{I}{I_0}); \qquad I_j = I_0^{1-j/n}.$
- $V_j = \text{Round}((\frac{I_j}{k})^{1/\gamma})$.

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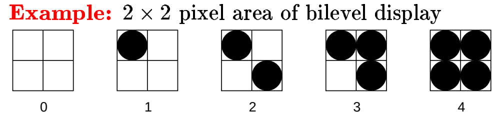
Halftone Approximation

- More intensity levels than allowed by the device.
- Integration of intensity over small areas.
- A small area is printed with black disks.
- Black area is proportional to $1 - I$.
- Newspaper: 60–80 halftones per inch.
  Magazine: 110–200 halftones per inch.

Example: 2×2 pixel area of bilevel display



$n \times n$ pixel matrix generates $n^2 + 1$ levels.

3 × 3 pixel matrix values: $\begin{bmatrix} 6 & 8 & 4 \\ 1 & 0 & 3 \\ 5 & 2 & 7 \end{bmatrix}$

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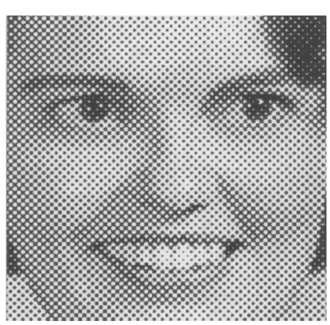
Halftone Approximation



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Chromatic Light

Color depends on:

- *Physical conditions*
  - Material properties.
  - Spectral distribution of incident light.
  - Medium in which light travels.
- *Psychophysical conditions*
  - Background/surrounding color.
  - Adaption of visual system.

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Color Specification

Hue: Distinguishes among colors.
Example: red, green, blue, purple.

Saturation: Distance from equal-intensity gray.
Example: red vs pink, royal blue vs sky blue.

Lightness: Perceived intensity of reflected light.

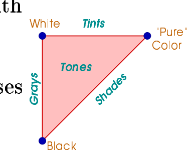
Brightness: Perceived intensity of self-luminous light.

Artist's view:

Tint: Saturation; decreases with white pigments.

Shade: Lightness; decreases with black pigments.

Tone: Combination of above.



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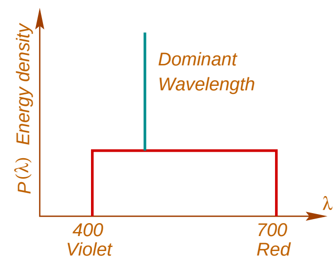
Colorimetry

Dominant wavelength: Hue.
Wavelength of the color we see.

Excitation purity: Saturation.
Ratio of pure light of the dominant wavelength and the white light present in the color.

Luminance: Lightness, brightness.
Amount of light energy.



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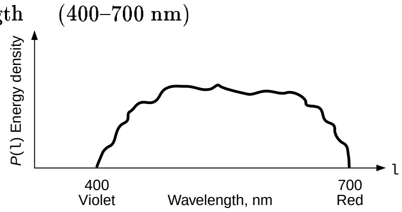
Colored Light

Colored light is distribution of energy over wavelength (400–700 nm)



Color can be specified by

- ☆ dominant wavelength,
- ☆ excitation purity,
- ☆ luminance.

Many spectral distributions produce the same color.

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Human Visual System

Retina has four main layers:

- ☆ Epithelium
- ☆ Rods and cones
- ☆ Bipolar cells
- ☆ Ganglion cells

- ☆ Many more rods (≈ 120M) than cones (≈ 6M).
- ☆ Rods are more sensitive.
- ☆ Rods are responsible for achromatic light.
- ☆ Cones detect colors.
- ☆ Cones are concentrated near *fovea*: ≈ 147K cones/mm.

Trichromatic Theory:

- ☆ First proposed by Thoms Young, 1801.
- ☆ Refined by Herman von Helmhotz, 1861.
- ☆ Three types of cones: blue, green, red.
- ☆ Explains color blindness.
  - Protanope (red blindness)
  - Deuteranope (green blindness)
  - Tritanope (blue blindness); very rare.

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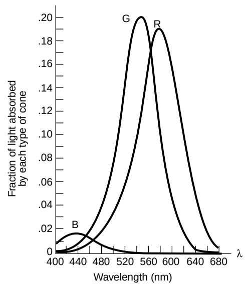
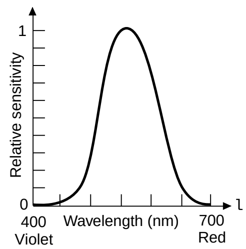
Trichromatic Theory

Spectral Response of three types of cones.



Luminous efficiency. Conjecture: Sum of the response of three cones.



Conjecture: Colors can be specified by the positive weighted sum of red, blue, and green!

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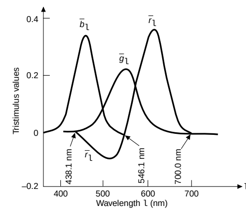
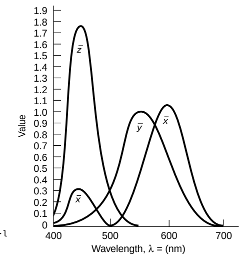
Trichromatic Theory





R, G, B values needed to match the color luminance for each dominant wavelength.

Some values are negative!

Commission Internationale de l'Éclairage (CIE), 1931!

Defined three primary colors: **X**, **Y**, **Z**.

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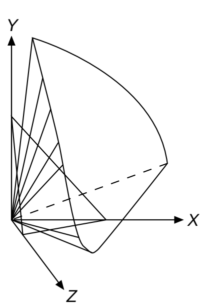
Trichromatic Theory

- ☆ **Y**: Same as luminance-efficiency curve.
- ☆ Each color C is specified as a positive weighted sum of **X**, **Y**, **Z**.

$$C = X\mathbf{X} + Y\mathbf{Y} + Z\mathbf{Z}.$$

- ☆ $P(\lambda)$: Spectral distribution of C.
  $X = k\int P(\lambda)x_\lambda d\lambda,\ Y = k\int P(\lambda)y_\lambda d\lambda,$
  $Z = k\int P(\lambda)z_\lambda d\lambda.$
- ☆ (X, Y, Z) specify a color; called XYZ-space.



Cone specifies all visible colors.

Clipped at the plane $X + Y + Z = 1.$

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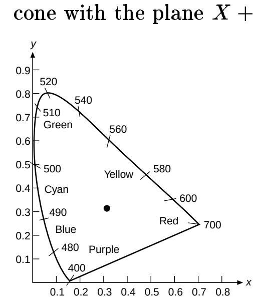
Chromaticity

Chromaticity:

- ☆ depends on dominant wavelength & saturation.
- ☆ Independent of luminance.

$$x = \frac{X}{X+Y+Z},\ y = \frac{Y}{X+Y+Z},\ z = \frac{Z}{X+Y+Z}.$$

Chromaticity is encoded in the cross-section of the cone with the plane $X + Y + Z = 1$.



- ☆ Interior and boundary contain all visible chromaticities.
- ☆ Spectral pure colors lie along the boundary.

White light: Center dot C, near $x = y = z = 1/3$

Power distribution that is close to daylight at a correlated temp. 6774K.

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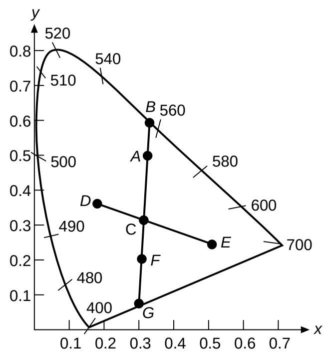
CIE Diagram



Color adding:

- ☆ Combination of two colors C_1, C_2 lies on the segment C_1C_2.
  A is mix of white C and B.
- ☆ *Dominant wavelength* of A is B.
- ☆ *Excitation purity* of $A = |AC|/|BC|$.

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CIE Diagram

Complementary colors:

- ☆ Mixing complementary colors C_1, C_2 produces white C.
  C is the midpoint of the segment C_1C_2.
- ☆ D and E are complementary colors.

Non spectral colors:

- ☆ Cannot be defined by a dominant wavelength (e.g. F).
- ☆ Define dominant wavelength as:
  Dominant wavelength of its complementary color.
- ☆ Excitation purity remains the same.
  Excitation purity of F: $|CF|/|CG|$.

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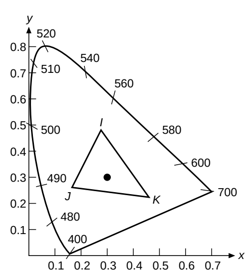
Color Gamut



- ☆ Mixture of I, J, K produces colors in $\triangle IJK$.
- ☆ $\triangle IJK$: *color gamut* of I, J, K.

	Short persistence			Long persistence		
	R	G	B	R	G	B
x	0.61	0.29	0.15	0.62	0.21	0.15
y	0.35	0.59	0.063	0.33	0.685	0.063

- ☆ Smaller gamut $\Longrightarrow$ fewer colors.
- ☆ Can compare gamuts.

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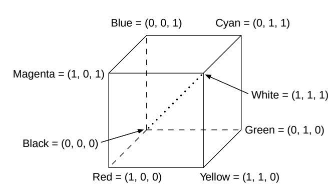
RGB Model

- ☆ Additive color model.
- ☆ Uses Cartesian coordinate system.
- ☆ Origin is black.
- ☆ Grays: principal diagonal.



Linear relationship between RGB and XYZ colors.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

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CMY Model

- ☆ Subtractive primitives.
- ☆ Cartesian coordinate system.
- ☆ Start with white; color is specified by what is removed.

Example: RGB color printer.

- ☆ Cyan ink absorbs red light.
- ☆ Magenta ink absorbs green light.
- ☆ Yellow ink absorbs blue light.

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

$C + M + Y =$ Black

CMYK Model: Use black ink (K: Carbon)

$K = \min(C, M, Y)$.

$C = C - K$, $M = M - K$, $Y = Y - K$.

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YIQ Model

- ☆ Used for TV broadcasting.
- ☆ Compatibility with black and white TV.
- ☆ Y: Primary color **Y**; luminance efficiency.
- ☆ Y component is used by black and white TV.
- ☆ Chromaticity is encoded by I and Q.

$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.523 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

	R	G	B
x	0.67	0.21	0.14
y	0.33	0.71	0.09

White: $x_w = 0.31$, $y_w = 0.316$, and $Y_w = 100.00$

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YIQ Model

- ☆ Human eyes are more sensitive to luminance than to chromaticity.
- ☆ Assigns more bandwidth to Y
  - 4MHz to Y
  - 1.5 MHz to I
  - 0.6 MHz to Q
- ☆ Use Y values to disambiguate colors when converting to black and white TV.
- ☆ Objects lying in a narrow field of view:
  - Color is not so important.
  - Use only one color(I).

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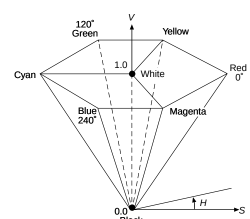
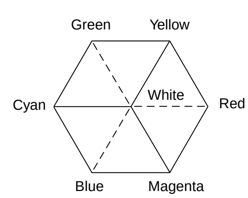
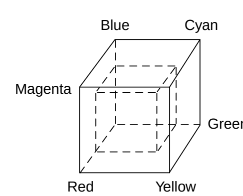
HSV Model



- ☆ Top of hexcone: $V = 1$; bright colors.
- ☆ H: Angle around the vertical axis: $R = 0°$, $G = 120°$, $B = 240°$.
- ☆ Complementary colors are 180° apart.
- ☆ $S \in [0, 1]$: Fractional distance from the vertical axis.
- ☆ Apex: Black ($V = 0$), white: $S = 0, V = 1$, gray $V < 1, S = 0$.





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