Describing Color

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Describing Color: Contents

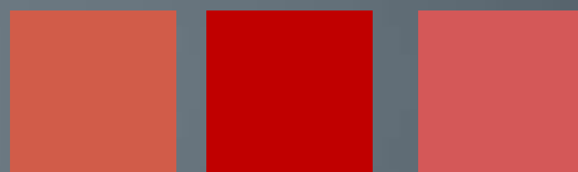
- Describing Relative Color
- Describing Absolute Color
- Comparing Colors
- Metamerism

Describing Relative Color

Why? How?

- Need of a vocabulary to describe a color (e.g., red, gray, blue, green).

- Two (or more) samples may be all red, but different.



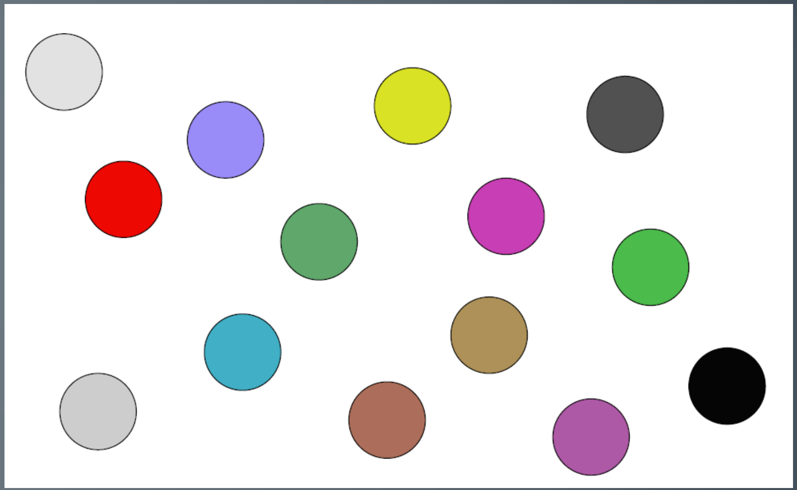
→ Need additional descriptions within colors.

- How do we organize colors?

  Need of arranging colors systematically to form transitions between them.

Experiment: Desert Island

- A person with normal color vision is on a desert island, with nothing but a set of colored pebbles.



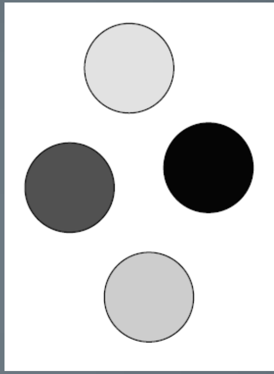
- Suppose this person wanted to arrange the pebbles according to their color,

  How can we describe color based on the way the pebbles will be arranged by the person?

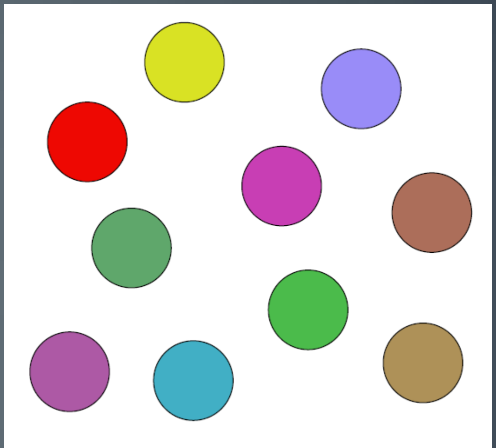
Judd (1979), *"Contributions to Color Science"*

Experiment: Desert Island

1. Think about color in terms of common color names (red, blue, green, etc.).

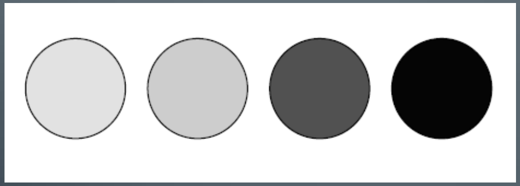


achromatic



chromatic

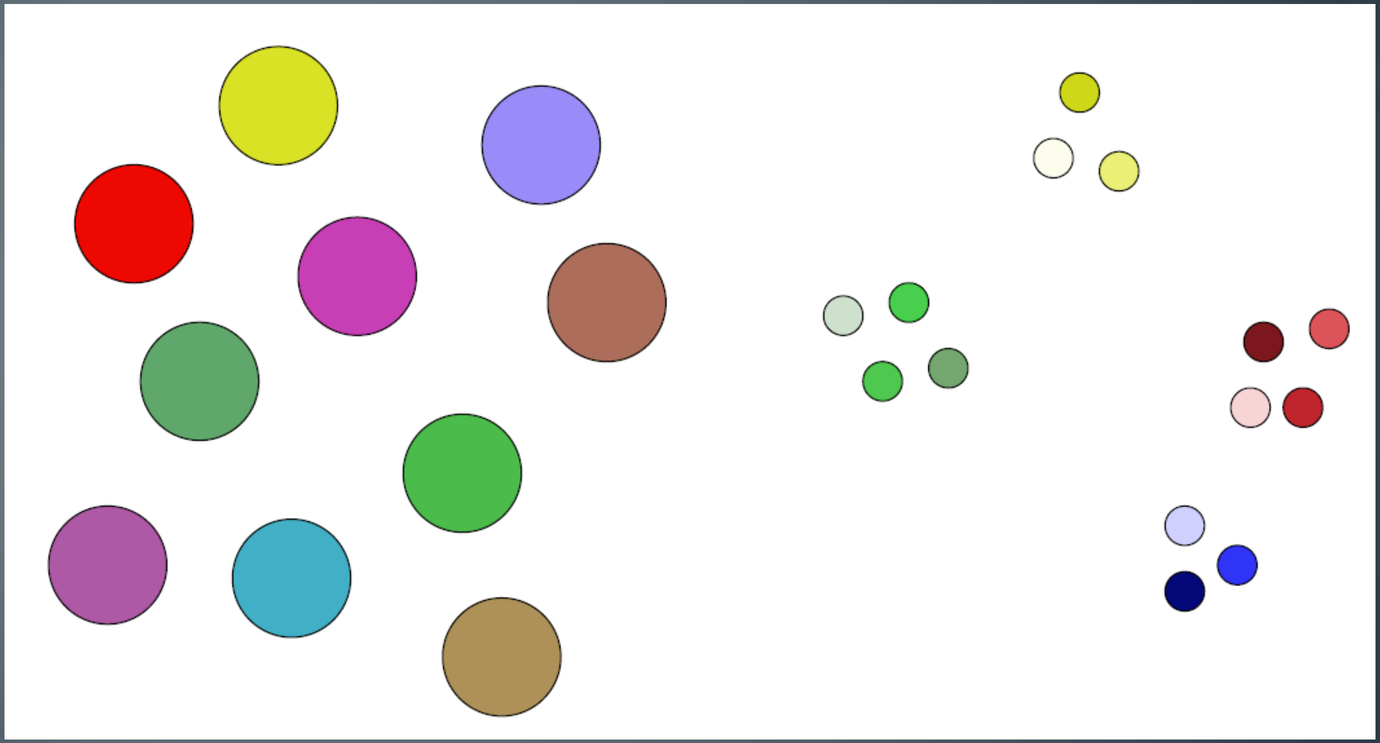
2. How to arrange achromatic samples?



order by whiteness or blackness (*lightness*)

Experiment: Desert Island

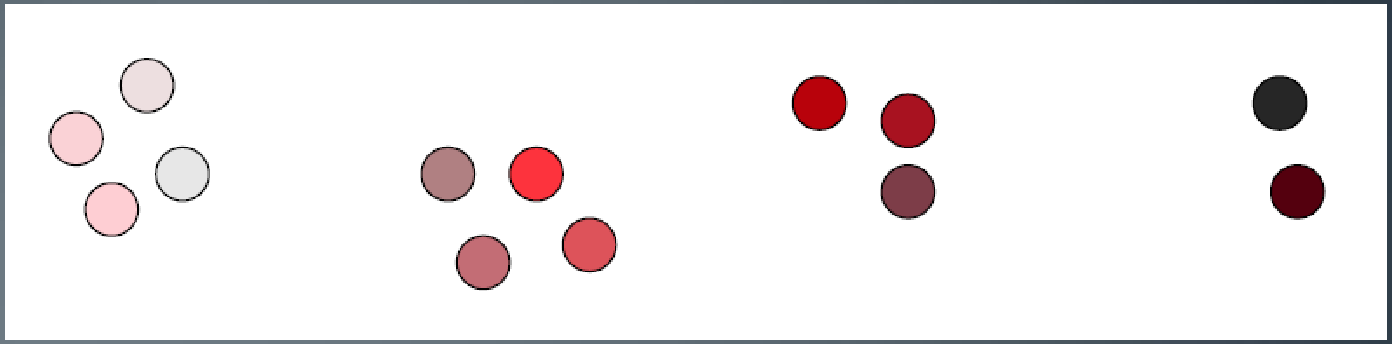
3. How to arrange chromatic samples?



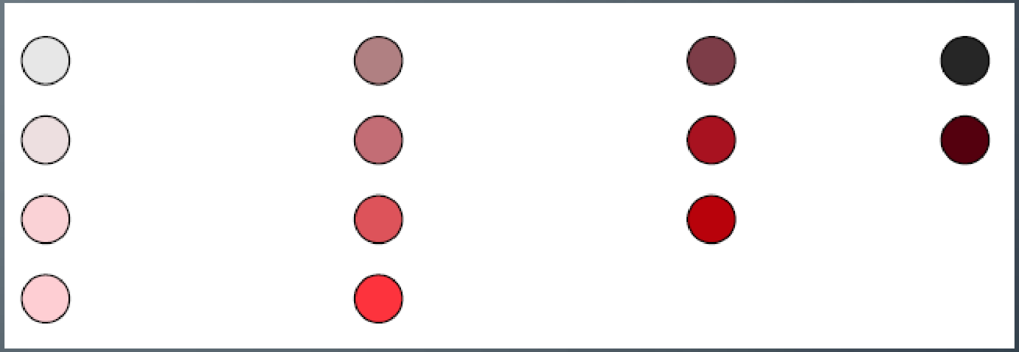
Group them according to their “color” (*hue*)
For instance, group all “red” pebbles together

Experiment: Desert Island

4. How to arrange chromatic samples of the same *hue*?



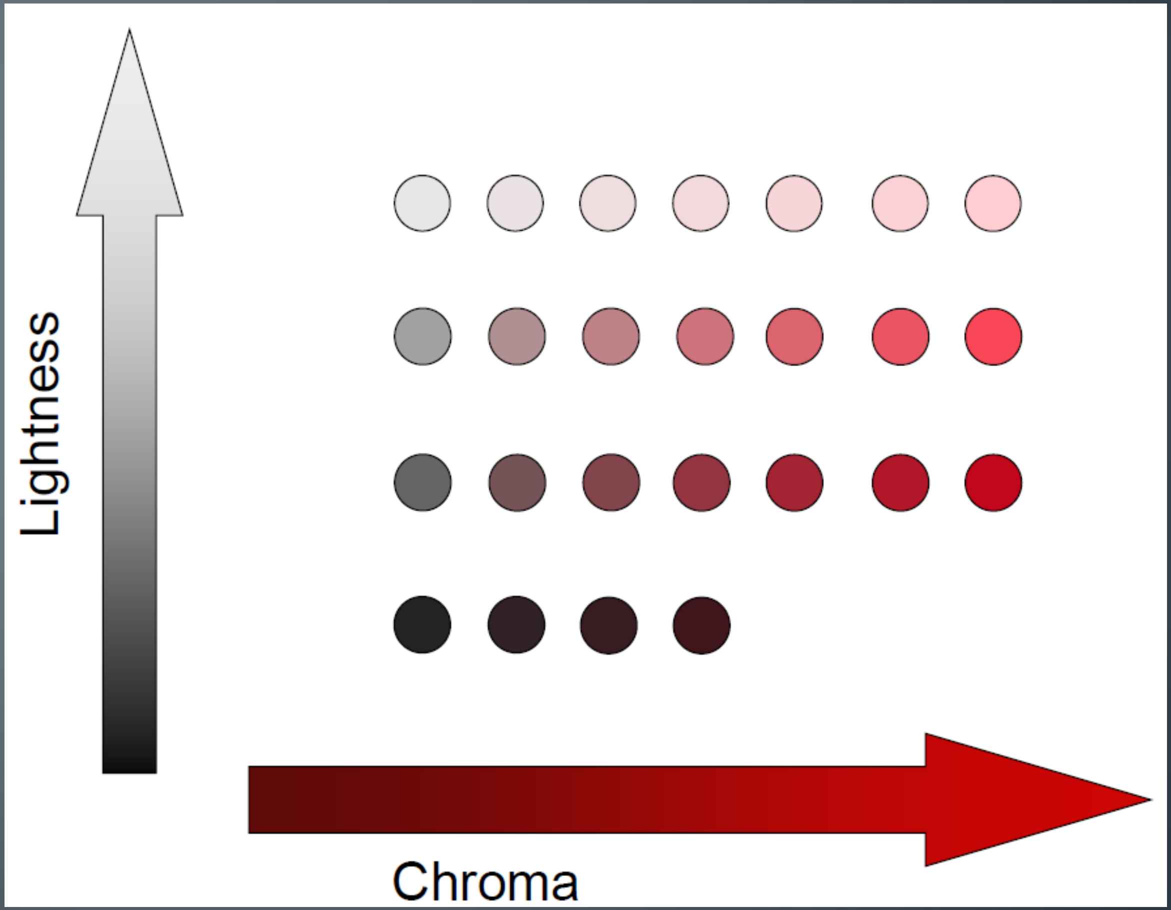
order by *lightness*



order by how much color they contain (*chroma*)

Experiment: Desert Island

- We know how to arrange chromatic samples of the same *hue*.



Color Attributes

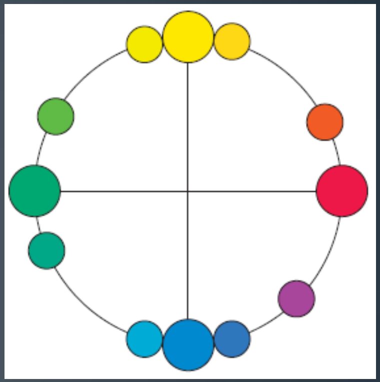
- Psychological Attributes that describe colors:
  - Hue
  - Lightness
  - Chroma

Kuehni and Schwarz (2008), “Color Ordered: A Survey of Color Order Systems from Antiquity to the Present”

Color Attributes: Hue Definition

Attribute of a visual sensation according to which an area appears to be similar to one of the perceived colors: red, yellow, green, and blue, or to a combination of two of them.

impossible to define it without using examples



achromatic color — perceived color lacking hue

chromatic color — perceived color with hue

→ 11 primitive colors have been identified*:

white, gray, black

red, green, yellow, blue, orange, purple

pink, brown

elementary colors

unique hues according to opponent color theory → no reddish-green, no yellowish-blue

* Berlin and Kay (1969), "*Basic Color Terms: Their Universality and Evolution*"

Color Attributes: Lightness Definition

- *Brightness*

Attribute of a visual sensation according to which an area appears to emit, or reflect, more or less light.

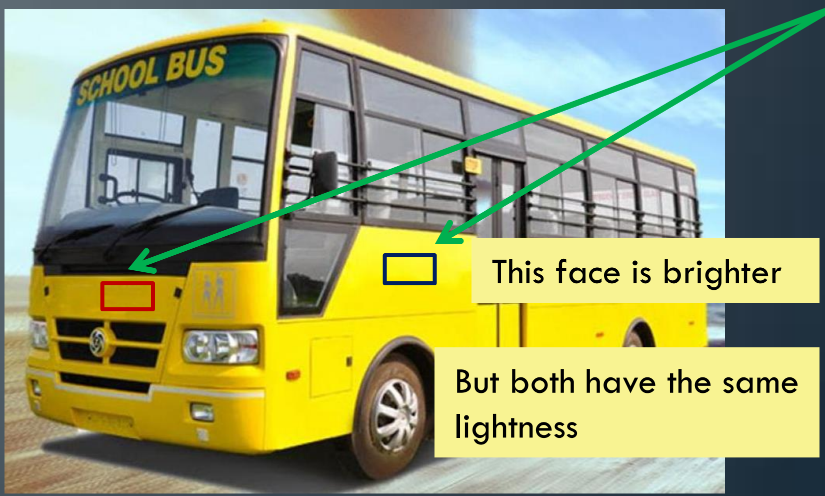
- *Lightness*

The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

$$Lightness = \frac{Brightness}{Brightness\ (white)}$$

White

Brightness	Brightness (white)	Lightness
96	120	0.8
48	60	0.8



Color Attributes: Chroma Definition

- *Colorfulness*

Attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.

 Sunny day → everything looks very colorful

 Cloudy day → everything appears less colorful

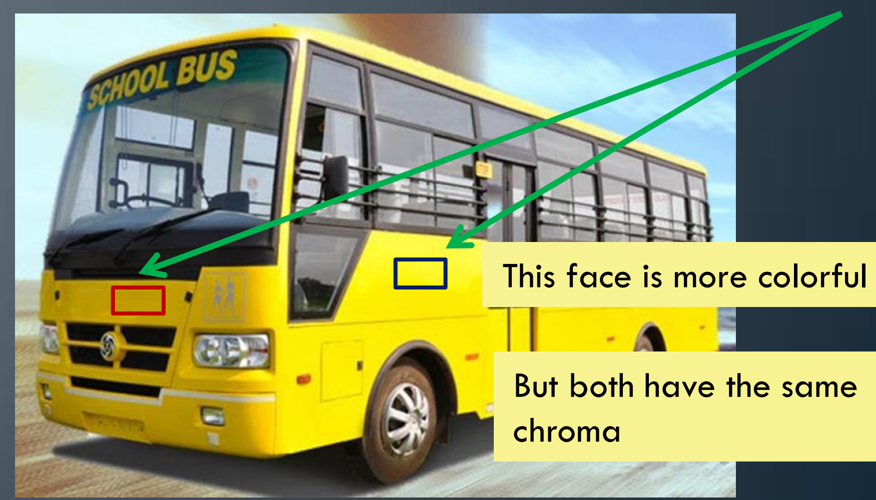
- *Chroma*

Colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

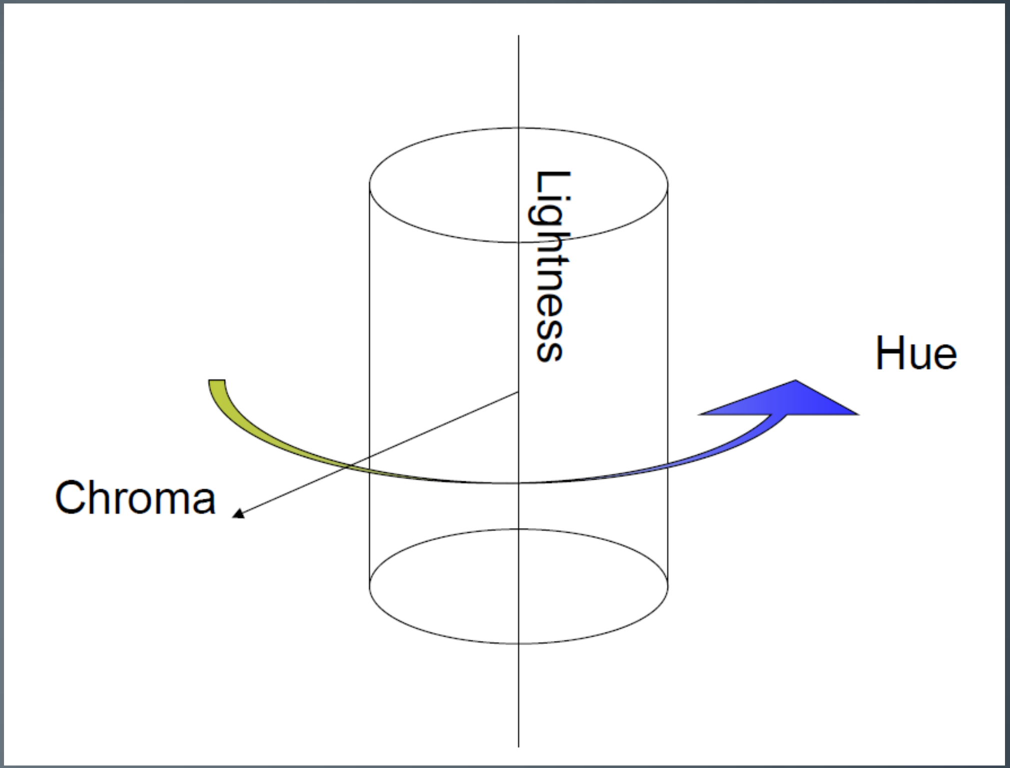
$$Chroma = \frac{Colorfulness}{Brightness\ (white)}$$

White

Colorfulness	Brightness (white)	Chroma
150	120	1.25
75	60	1.25

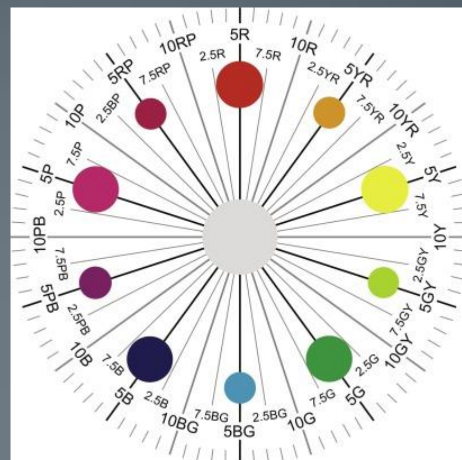


Color Order Systems

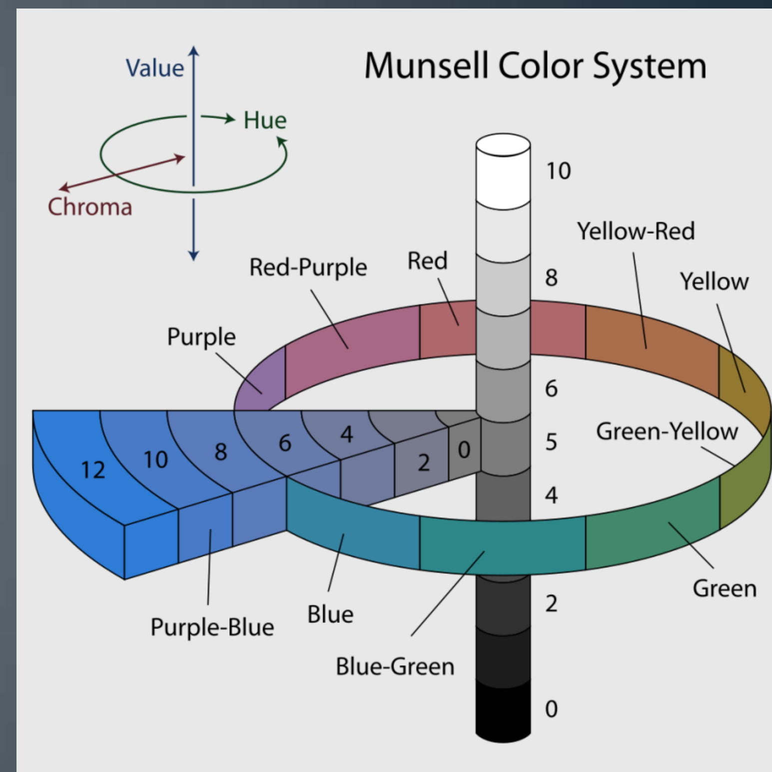


- Natural Color System
- Munsell Color System
- Optical Society of America Uniform Color Scales System

Munsell Color System



https://en.wikipedia.org/wiki/Munsell_color_system



<u>Composition</u>

- **Hue**

  10 hues (each divided into 10 subhues)

- **Lightness** (called Value)

  11 steps (0: ideal black, 10: ideal white)

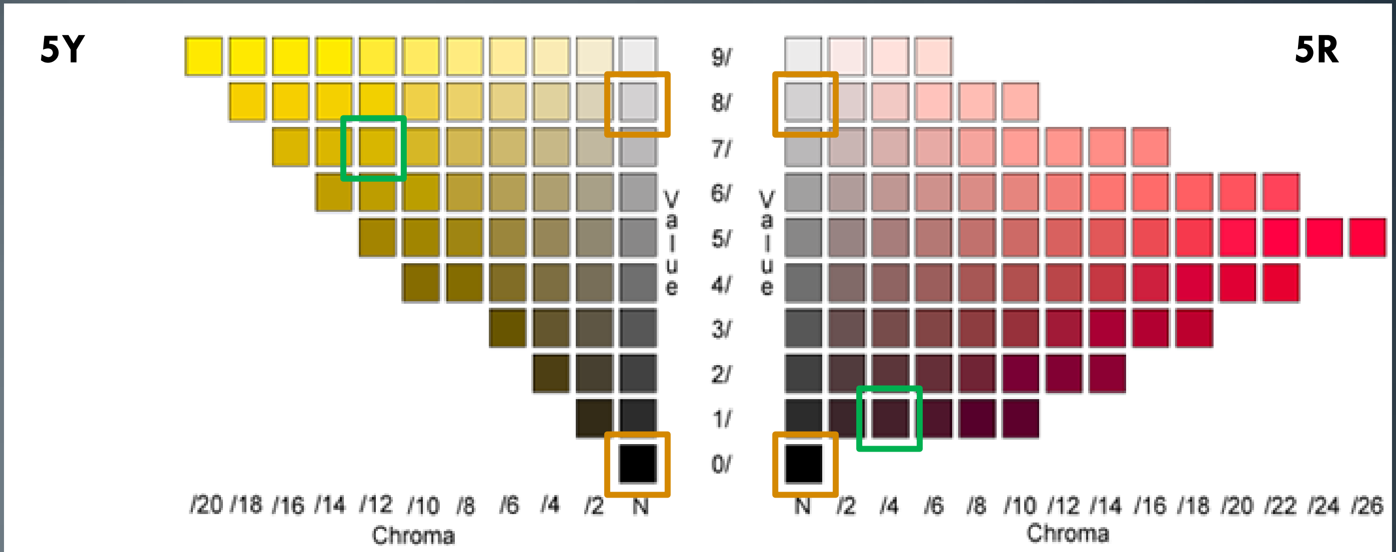
- **Chroma**

  Range depending on the hue

  (e.g., at lightness 5, Purple-Blue has 7 steps, but Red has 14 steps)

ASTM D1535, "*Standard Practice for Specifying Color by the Munsell System*"

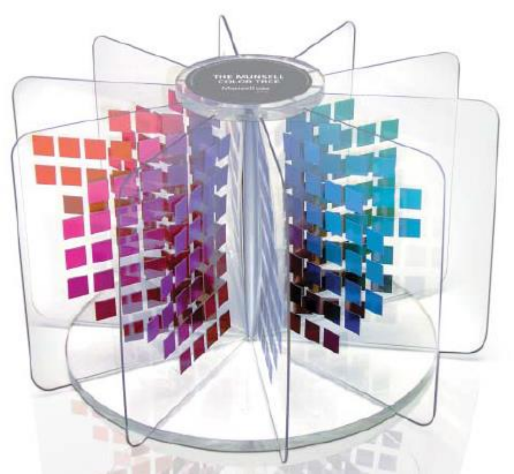
Munsell Color System



Notation

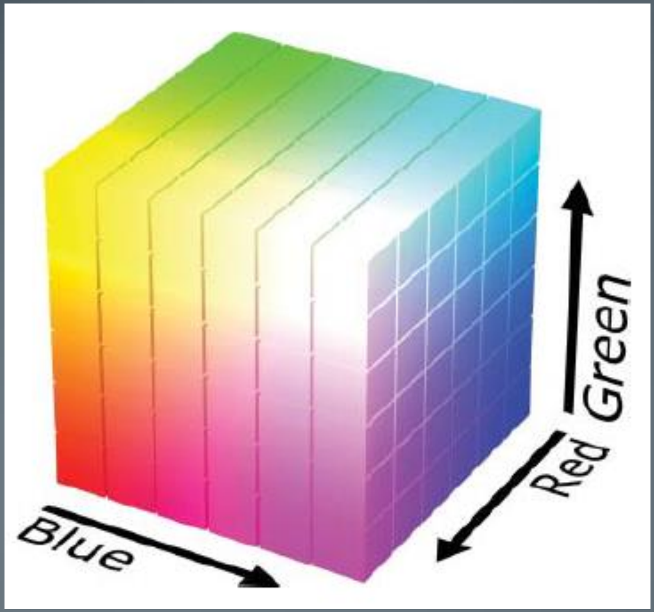
- H V/C for chromatic colors
  H=Hue, V=Value, C=Chroma
  e.g., 5Y 7/12 or 5R 1/4

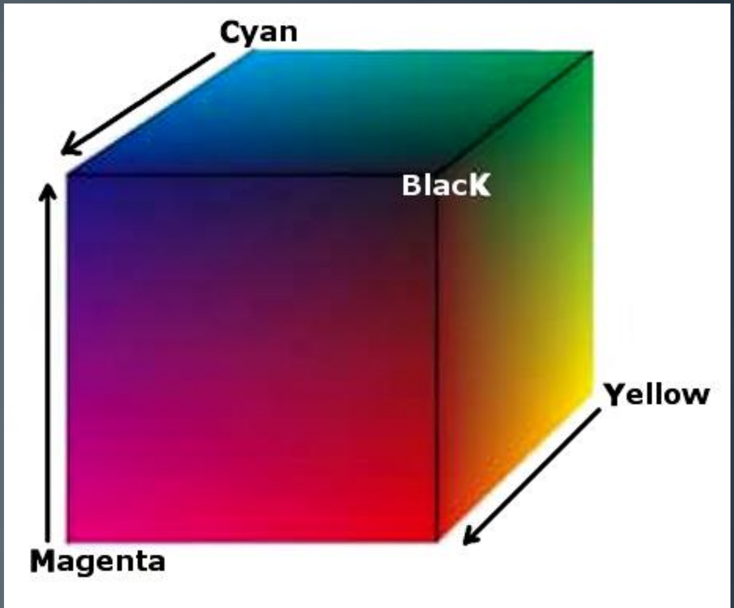
- N/V for achromatic colors
  V = value
  e.g., N0, N8



Munsell Color Tree from Pantone®

Describing Color: Color-Mixing Systems

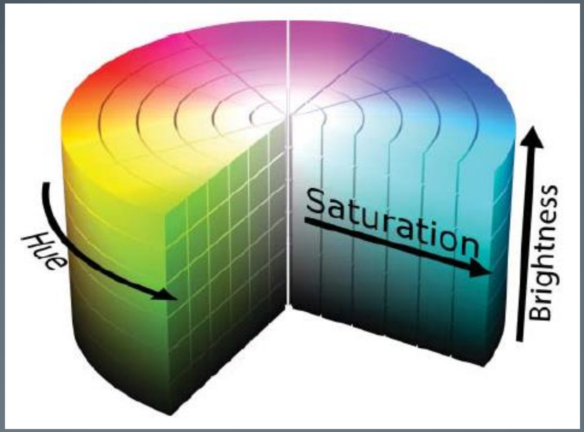




Amounts give an specification, not the resulting color.

- RGB value {70,80,90} in your screen ≠ RGB {70,80,90} value in my screen.
- CMY value {50,70,90} in your printer ≠ {50,70,90} CMY value in my printer.

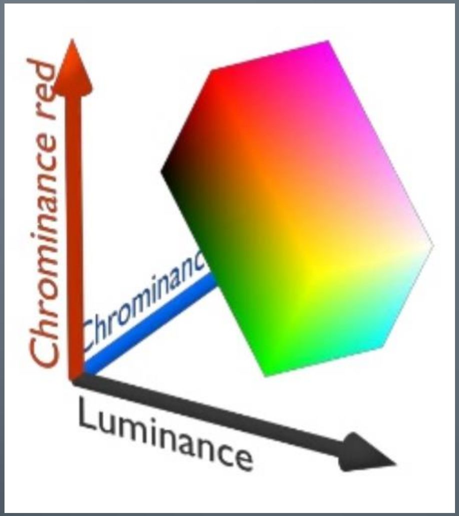
Describing Color: Other Color Spaces



<u>HSB Space</u>

"Saturation" is related to Chroma

"Brightness" is related to Lightness



<u>YCbCr Space</u>

"Y" is related to Luminance

"Cb" is related to blue Chrominance

"Cr" is related to red Chrominance

Used frequently in Image and Video Processing (e.g., skin detection).
However, as RGB and CMYK, resulting color is only relative to capture conditions.

Describing Relative Color: Recap

- Three attributes are enough to describe related colors:

  Hue **Lightness** **Chroma**

- Brightness and Colorfulness can be used when we need an absolute way to describe color.

- Color Spaces (RGB, CMYK, HSB, YCbCr) can be used to describe or process color; but only relative to a certain viewing and illumination condition (e.g., relative to a "white").

Describing Standard Color

Why? How?

- Use an universal way (i.e., numbers) to communicate color instead of using names.

- Need to standardize the color forming conditions:
  - Illuminant (viewing lighting)
  - Observer (the human visual response to a given stimulus)
  - Object Reflectance (λ-dependent spectral measurement)

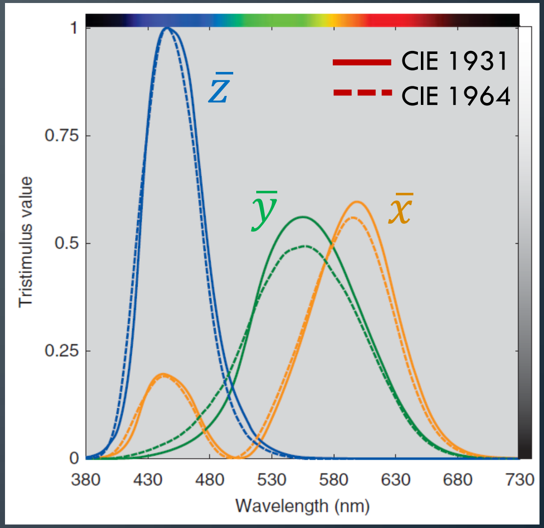
- Colorimetry* (i.e., the science of color measurement) is built upon these standards.

*CIE Technical Report 15:2018, "*Colorimetry*"

CIE Standard Observers

- Light sources (primaries): 435.8nm, 546.1nm, 700nm
- CIE 1931 Standard Colorimetric Observer
  - 2° visual angle (2° Observer)
  - 17 color normal observers
- CIE 1964 Standard Colorimetric Observer
  - 10° visual angle (10° Observer)
  - 76 color normal observers

$\bar{x}, \bar{y}, \bar{z}$ are linear transformations of the eye's spectral sensitivities



CIE Standard Iluminants

D different types of daylight

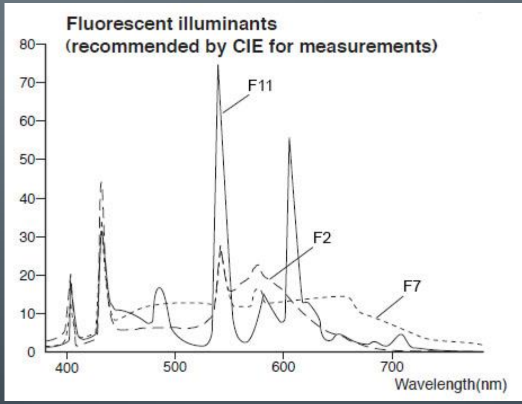
D50 (5003K) [*warm daylight*] printing/graphic arts

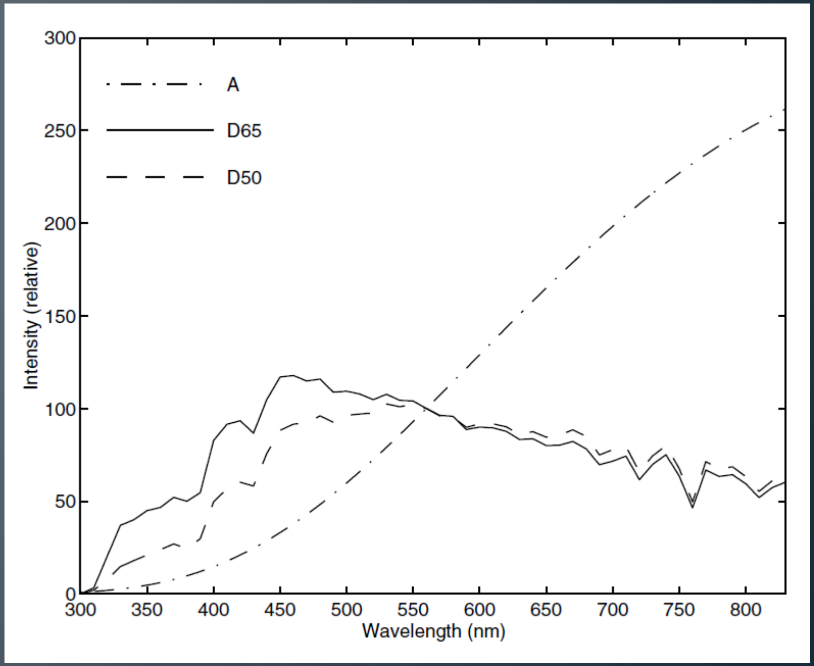
D65 (6504K) [*natural daylight*] art/film/photography

A incandescent lamp (2856K)

F fluorescent lights

F2 (4230K), F11 (4000K)





---K → Illuminant Temperature

Low→warmer, High→colder

CIE Standard Iluminants

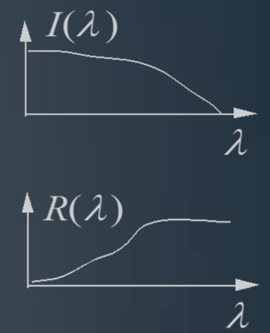
“warmest”

“coldest”

Gallery of late Neoclassicism in European art and design at the Getty Museum, L.A.

Computing XYZ Tristimulus Values

- *Tristimulus value* amounts of three specified stimuli required to match a color.

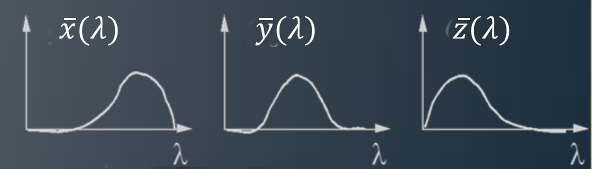


$$X = k\int_{\lambda} I(\lambda)R(\lambda)\,\bar{x}_{\lambda}d\lambda$$

Luminance Factor
(lightness of material)

$$Y = k\int_{\lambda} I(\lambda)R(\lambda)\bar{y}_{\lambda}d\lambda \qquad k = \frac{100}{\int_{\lambda} S_{\lambda}\bar{y}_{\lambda}d\lambda}$$

$$Z = k\int_{\lambda} I(\lambda)R(\lambda)\bar{z}_{\lambda}d\lambda$$

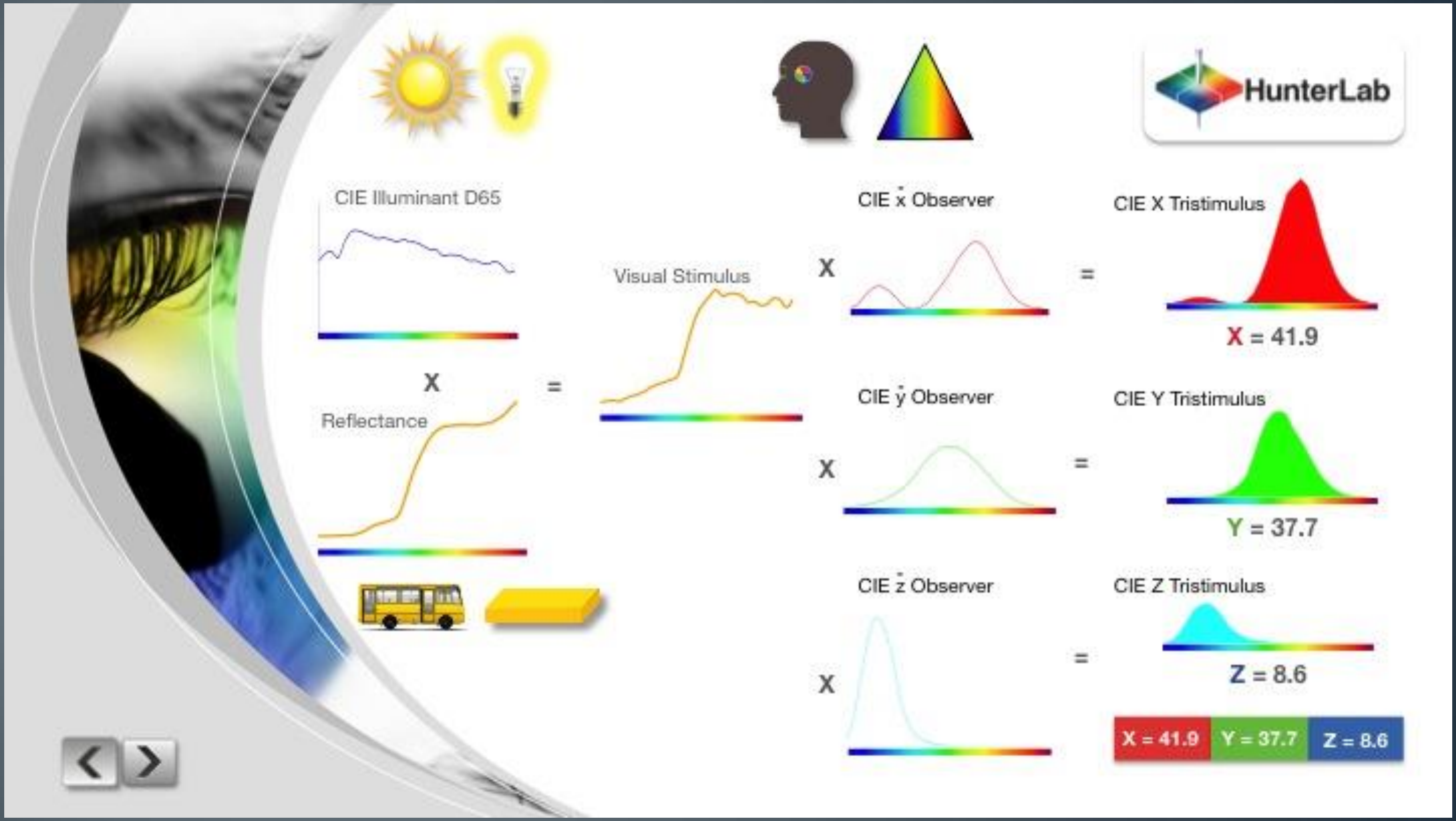


If the XYZ measured *tristimulus values* of two samples are equal → samples match visually

(provided the same viewing conditions)

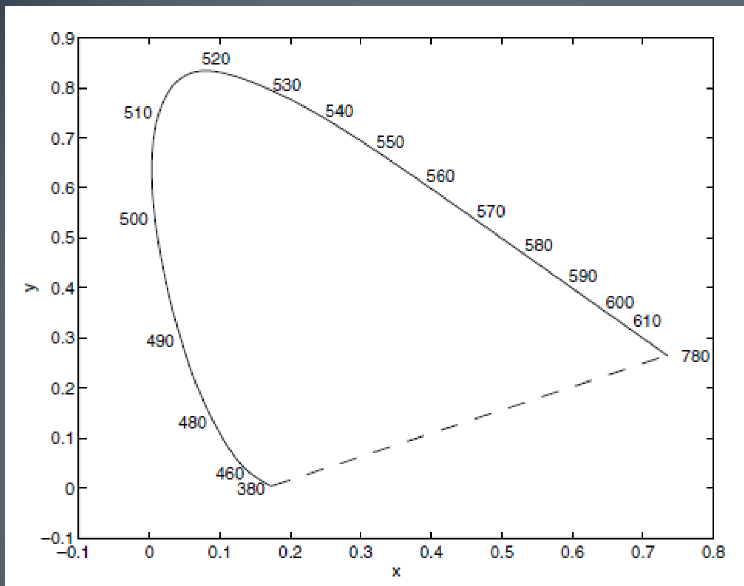
ASTM E308–15 *Standard practice for computing the colors of objects by using the CIE system.*
ISO 11664-1:2007 *(CIE S 014-1/E:2006) Colorimetry -- Part 2: CIE colorimetric observers.*

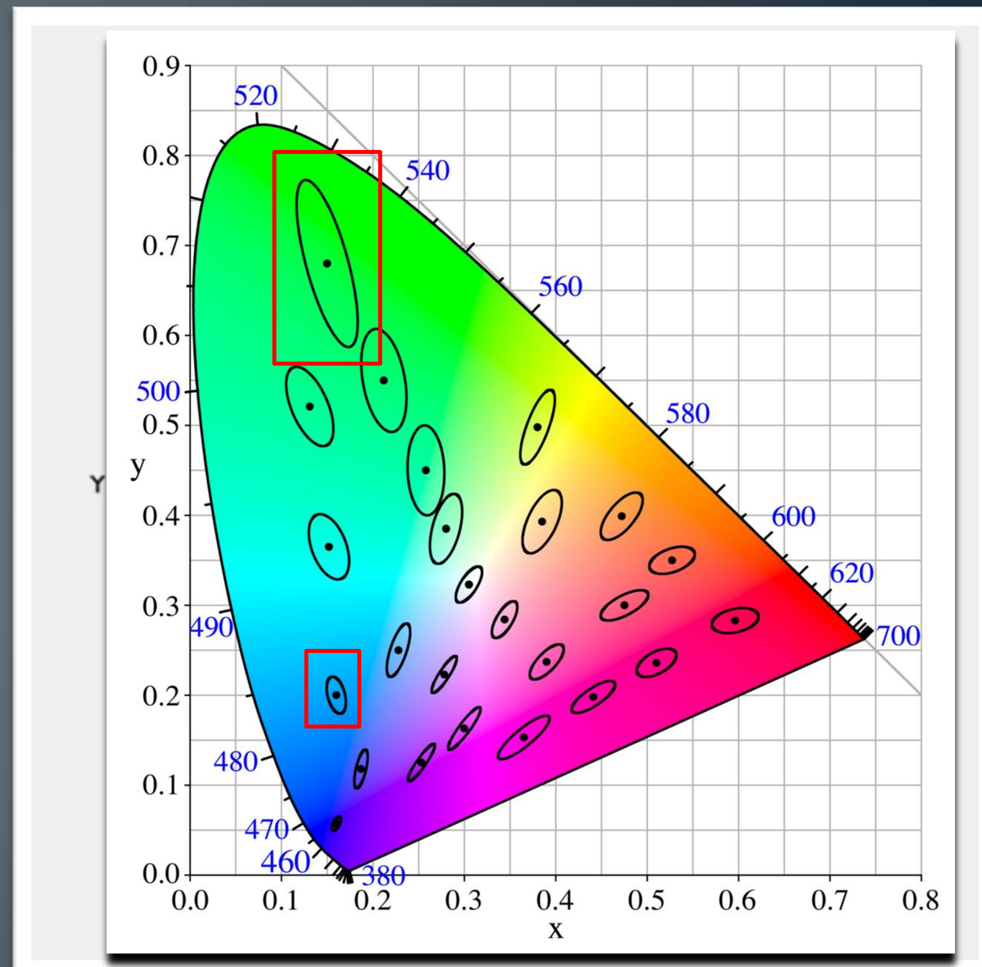
Computing XYZ: Recap



https://www.hunterlab.com/blog/color-measurement-2/understanding-tristimulus-values-taking-guesswork-color-measurement-instrumentation/

Chromaticity Diagrams: CIE 1931





<u>Where is gray? brown? black?</u>

No lightness

Use it with care!

MacAdam Ellipses

Uniform Color Spaces

- CIE XYZ Space is not perceptually uniform

  equal perceptual differences between colors

  $\neq$

  equal distances in the XYZ space

- Recommended uniform color spaces
  - CIE 1976 L*u*v* (CIELUV)
  - CIE 1976 L*a*b* (CIELAB)

  where the difference in color coordinates for the sample pair correlated with their perceived difference in color.

(*) *Lab* refers to Hunter's Color Space, which CIE used as a base to create *L*a*b**

CIE L*a*b* Space (CIELAB)

$$L^* = 116 f\left({}^{Y}\!/_{Y_n} \right) - 16$$

$$a^* = 500 \left[f\left({}^{X}\!/_{X_n} \right) - f\left({}^{Y}\!/_{Y_n} \right) \right]$$

$$b^* = 200 \left[f\left({}^{Y}\!/_{Y_n} \right) - f\left({}^{Z}\!/_{Z_n} \right) \right]$$

$$f(x) = \begin{cases} x^{1/3} & x > \left({}^{24}\!/_{116} \right)^3 \\ \left({}^{841}\!/_{108} \right) x + {}^{16}\!/_{116} & x \le \left({}^{24}\!/_{116} \right)^3 \end{cases}$$

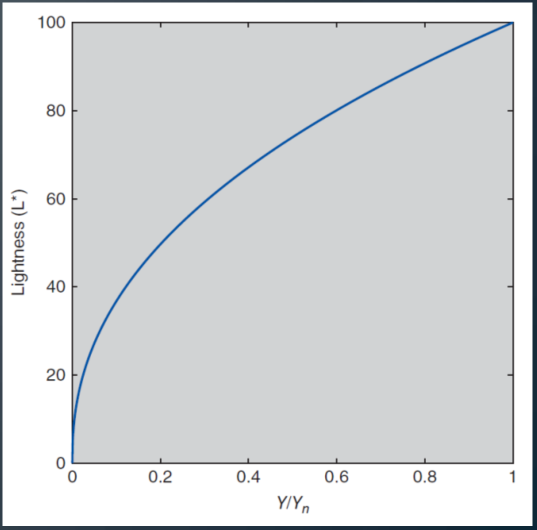
Xn, Yn, Zn : tristimuli of the white stimulus (white point)

$$X_n = k \int_\lambda I(\lambda) \bar{x}_\lambda d\lambda \quad Y_n = 1 \quad Z_n = k \int_\lambda I(\lambda) \bar{z}_\lambda d\lambda$$

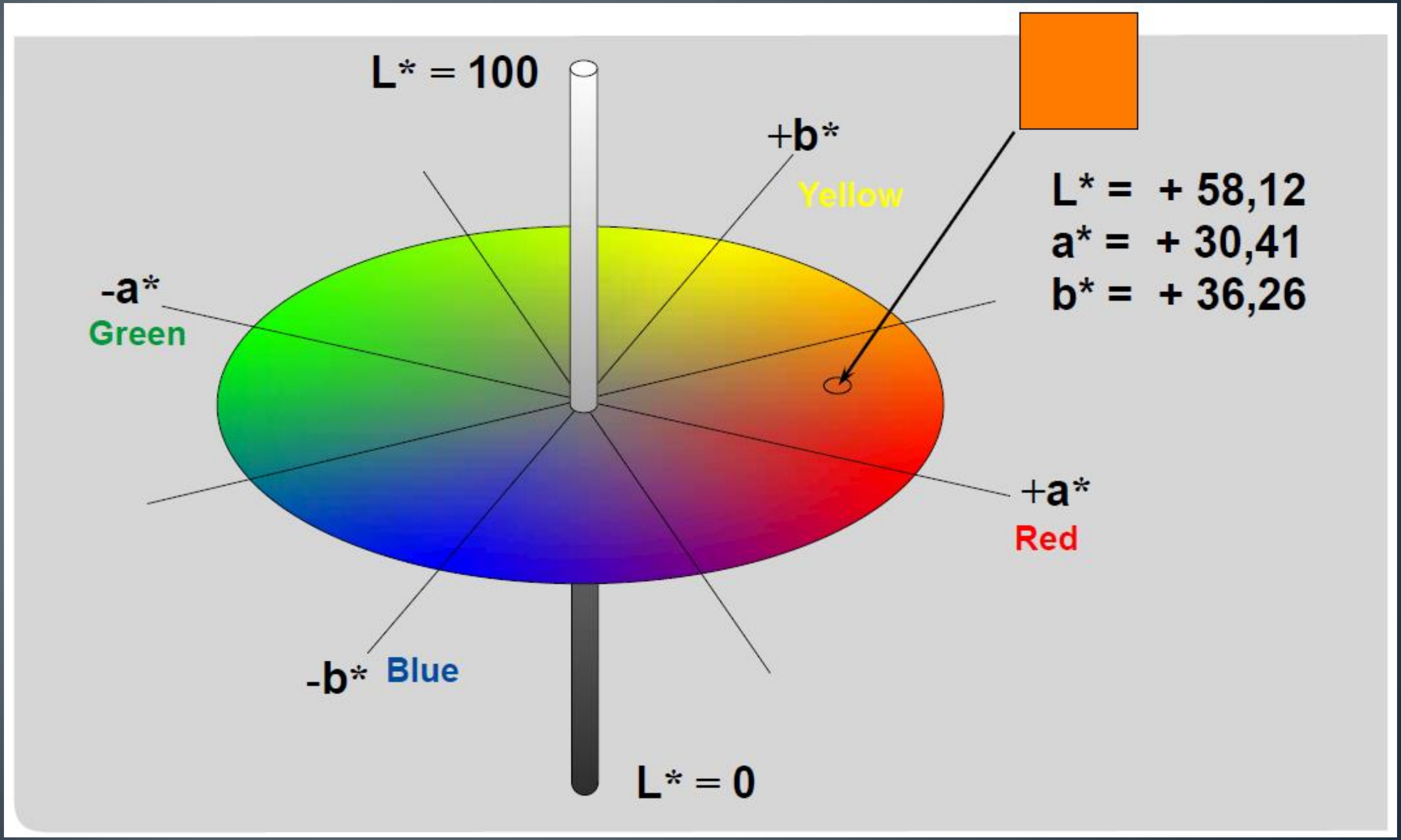
a*	red-green	[+a*→reddish, −a*→greenish]
b*	yellow-blue	[+b*→yellowish, −b*→blueish]

Achromatic stimuli (white, grays, black) means a*=b*=0

Non-linear relationship between relative Luminance Factor (Y/Yn) and L*

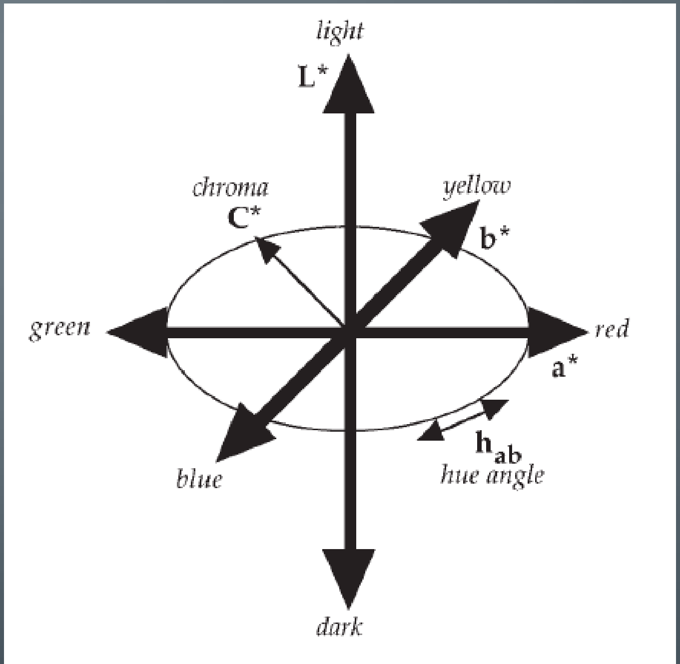


CIE L*a*b* Space (CIELAB)



CIE L*a*b* Space: L*C*h

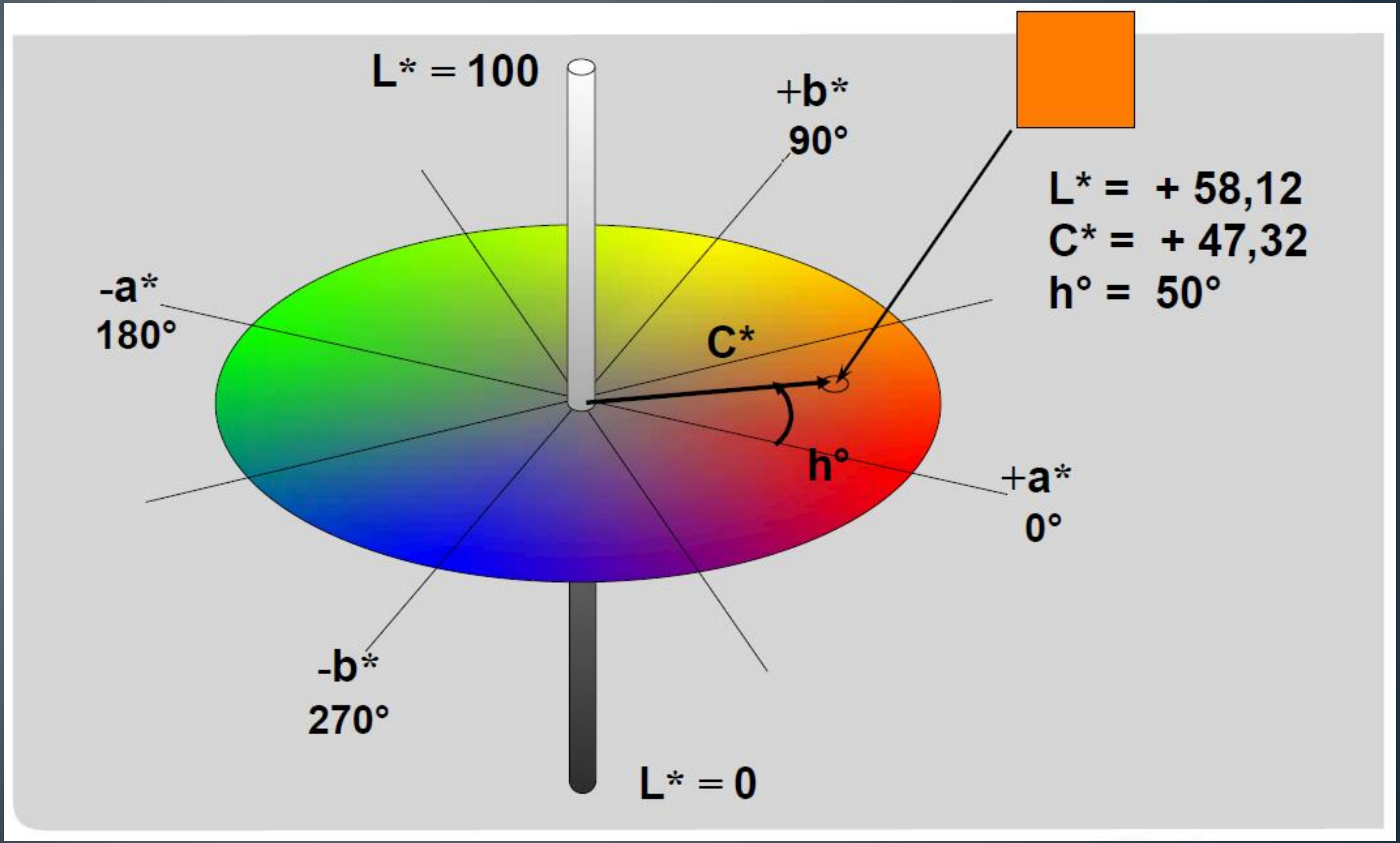
- L*a*b* is given in cartesian coordinates.
- It can be represented in cylindrical coordinates, for easier understanding.
- C^*_{ab} for chroma, h_{ab} for hue angle



Mark Fairchild, "*Color Appearance Models*", 2ed, 2005

$$C^*_{ab} = \sqrt{(a^{*2} + b^{*2})} \qquad h_{ab} = \tan^{-1}(b^*/a^*)$$

CIE L*a*b* Space: L*C*h



Describing Standard Color: Recap

- Using standards allows a back and forth understanding of the same color.

- Our eyes are not equally sensitive to all color differences.

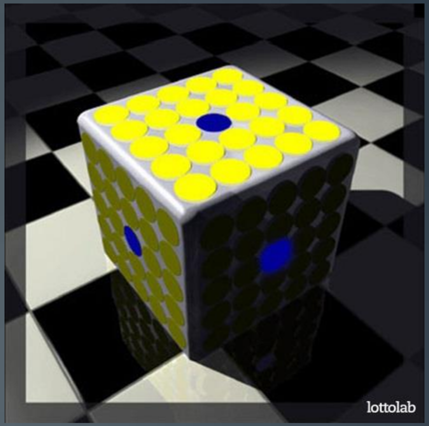
- XYZ Space can be used to communicate color; but CIELAB is the *de-facto* color space in colorimetry, because it allows a evaluating color differences uniformly.
  - In any case, conversion XYZ ↔ L*a*b* is straightforward if we know the White Point (X_n, Y_n, Z_n).

D65 Illuminant → {0.9504, 1.0, 1.0888}

A Illuminant → {1.0985, 1.0, 0.3558}

Describing Color: What's left?

- Modeling cognitive effects or phenomena.



Describing Color: What's left?

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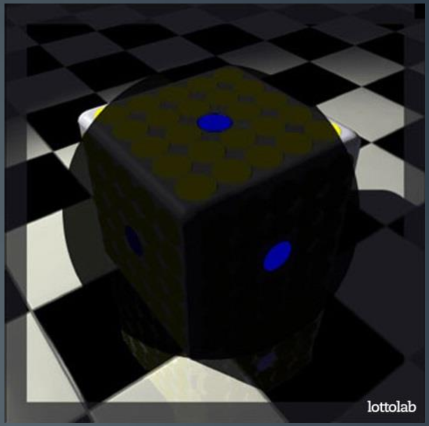
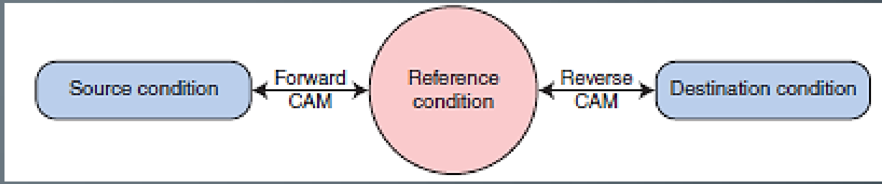


- How to obtain absolute color attributes (brightness and colorfulness)?



Need for Color Appearance Models (CAM) working across different viewing conditions.

- Debate about accuracy of $\bar{x}, \bar{y}, \bar{z}$ Color Matching Functions
  - Representativeness of the population used for the experiments
  - Limitations of equipment used for the experiments
  - How to understand color perception of "color anomalous" observers?

Comparing Color

Why we need to compare?

- Does the color of the product matches the standard color?
- If I make a copy, is the copy a close reproduction?
- If I print something many times, do I get the same color always?
- What is the tolerance for accepting the difference?

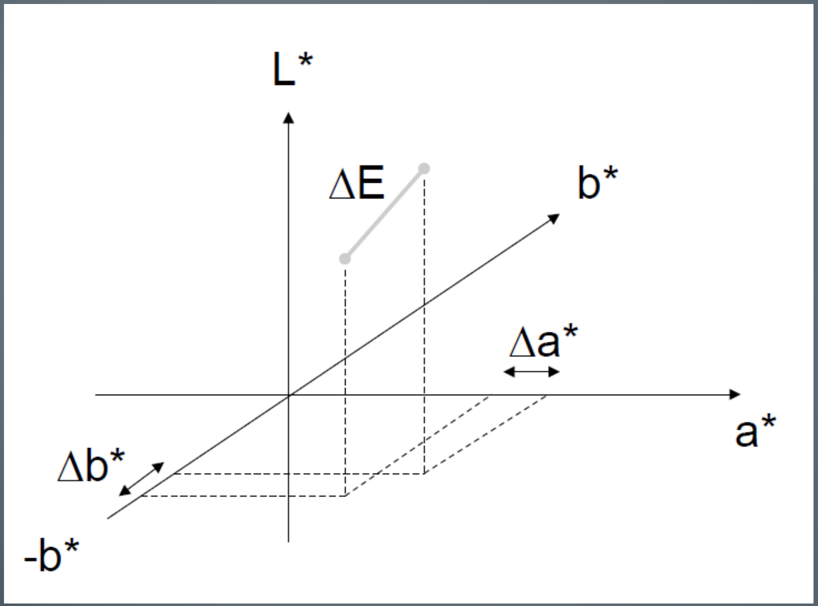
Need for Color Difference metrics!

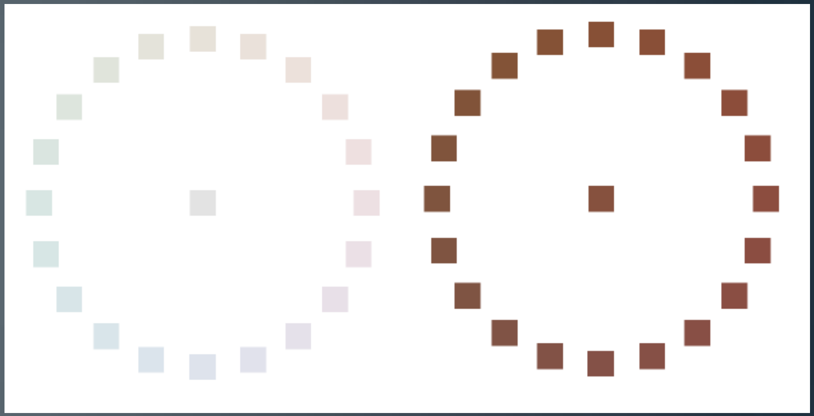
Also known as delta E (ΔE)

ΔE^*_{ab} (or ΔE 1976): The Obvious One

- Euclidean distance between two L*a*b* colors.

$$\Delta E^*_{ab} = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$





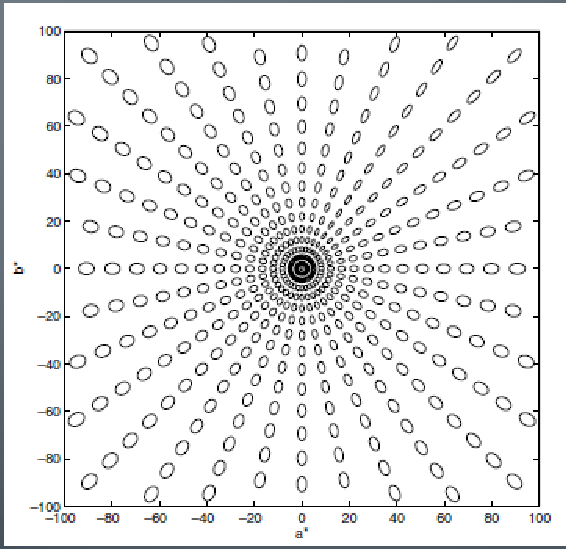
In both cases the ΔE^*_{ab} is 5

- Differences not perceptually uniform throughout the entire color space.

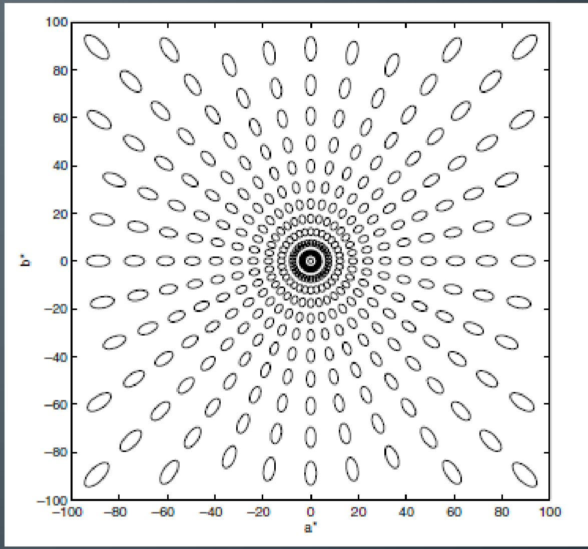
ΔE_{CMC} (or $\Delta E\ CMC_{l:c}$) and ΔE^*_{94} (or CIE94)

- $\Delta E\ CMC_{l:c}$ was developed by the Color Measurement Committee of the Society of Dyers and Colourists (UK) in 1988.
  - l:c controls the size of the ellipsoid (2:1 is the most used).

- In 1994, the CIE recommended an improved color difference metric, for industrial use, based on the CMC formula.



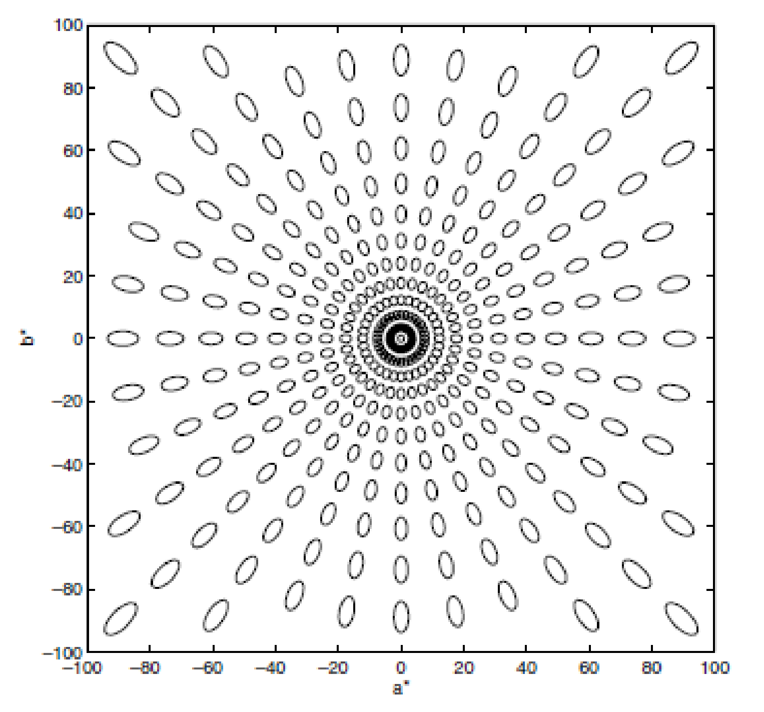
CMC



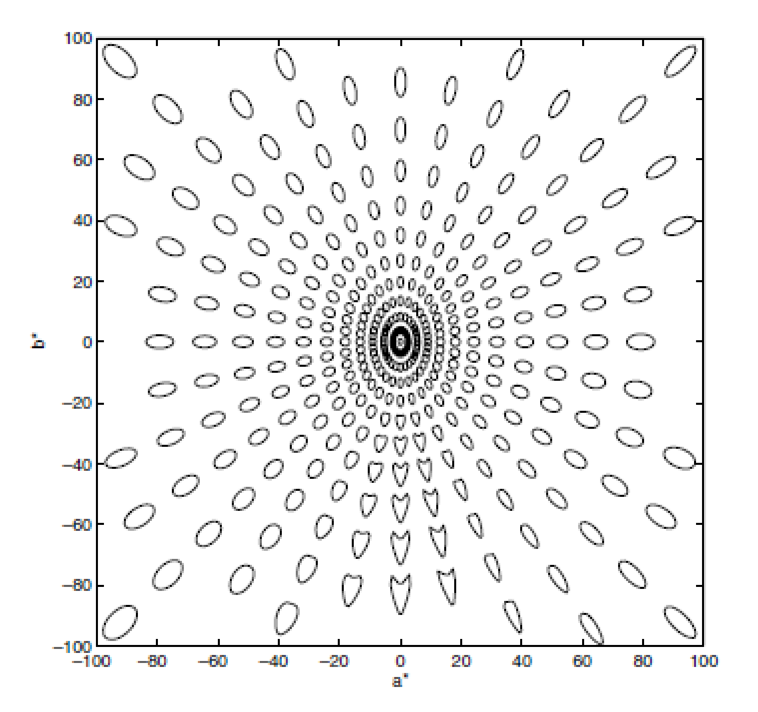
CIE94

ΔE^*_{00} (or CIEDE2000): The Latest Metric

- In 2000, the CIE proposed several improvements to the CIE94:
  - Improvements in Hue Scaling (Poor correlation for blues)
  - Improvements in Lightness weighting
  - Improvement near neutral tolerances



CIE94



CIEDE2000

ΔE^*_{00} (or CIEDE2000): The Equations

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

k_L, k_C, k_H: constant value chosen according to application

S_L, S_C, S_H: lightness-, chroma- and hue-dependent scaling functions

1. Calculate C'_i, h'_i:

$$C^*_{i,ab} = \sqrt{(a^*_i)^2 + (b^*_i)^2} \qquad i = 1, 2$$

$$\bar{C}^*_{ab} = \frac{C^*_{1,ab} + C^*_{2,ab}}{2}$$

$$G = 0.5\left(1 - \sqrt{\frac{\bar{C}^{*\,7}_{ab}}{\bar{C}^{*\,7}_{ab} + 25^7}}\right)$$

$$a'_i = (1+G)a^*_i \qquad i = 1, 2$$

$$C'_i = \sqrt{(a'_i)^2 + (b^*_i)^2} \qquad i = 1, 2$$

$$h'_i = \begin{cases} 0 & b^*_i = a'_i = 0 \\ \tan^{-1}(b^*_i, a'_i) & \text{otherwise} \end{cases} \qquad i = 1, 2$$

2. Calculate $\Delta L'$, $\Delta C'$, $\Delta H'$:

$$\Delta L' = L^*_2 - L^*_1$$

$$\Delta C' = C'_2 - C'_1$$

$$\Delta h' = \begin{cases} 0 & C'_1 C'_2 = 0 \\ h'_2 - h'_1 & C'_1 C'_2 \neq 0;\ |h'_2 - h'_1| \leq 180^\circ \\ (h'_2 - h'_1) - 360 & C'_1 C'_2 \neq 0;\ (h'_2 - h'_1) > 180^\circ \\ (h'_2 - h'_1) + 360 & C'_1 C'_2 \neq 0;\ (h'_2 - h'_1) < -180^\circ \end{cases}$$

$$\Delta H' = 2\sqrt{C'_1 C'_2}\,\sin\left(\frac{\Delta h'}{2}\right)$$

Standard color: L^*_1, a^*_1, b^*_1 (reference)
Sample color: L^*_2, a^*_2, b^*_2

k_L = {1 (default), 2 (textiles)}
$k_C = k_H = 1$

ΔE^*_{00} (or CIEDE2000): The Equations

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T\left(\frac{\Delta C'}{k_C S_C}\right)\left(\frac{\Delta H'}{k_H S_H}\right)}$$

k_L, k_C, k_H: constant value chosen according to application

S_L, S_C, S_H: lightness-, chroma- and hue-dependent scaling functions

3. Calculate CIEDE2000 Color-Difference ΔE_{00}:

$$\bar{L}' = (L_1^* + L_2^*)/2$$

$$\bar{C}' = (C_1' + C_2')/2$$

$$\bar{h}' = \begin{cases} \dfrac{h_1'+h_2'}{2} & |h_1'-h_2'| \le 180°;\ C_1'C_2' \ne 0 \\ \dfrac{h_1'+h_2'+360°}{2} & |h_1'-h_2'| > 180°;\ (h_1'+h_2') < 360°;\ C_1'C_2' \ne 0 \\ \dfrac{h_1'+h_2'-360°}{2} & |h_1'-h_2'| > 180°;\ (h_1'+h_2') \ge 360°;\ C_1'C_2' \ne 0 \\ (h_1'+h_2') & C_1'C_2' = 0 \end{cases}$$

$$T = 1 - 0.17\cos(\bar{h}' - 30°) + 0.24\cos(2\bar{h}') + 0.32\cos(3\bar{h}' + 6°) - 0.20\cos(4\bar{h}' - 63°)$$

$$\Delta\theta = 30\exp\left\{-\left[\frac{\bar{h}' - 275°}{25}\right]^2\right\}$$

$$R_C = 2\sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}}$$

$$S_L = 1 + \frac{0.015(\bar{L}' - 50)^2}{\sqrt{20 + (\bar{L}' - 50)^2}}$$

$$S_C = 1 + 0.045\bar{C}'$$

$$S_H = 1 + 0.015\bar{C}'T$$

$$R_T = -\sin(2\Delta\theta)R_C$$

Comparing Color: Recap

- CIEDE2000 is the most used metric nowadays
  - Generally speaking, if the difference between colors is:
    - $0 > \Delta E \leq 1$ → The difference is not noticeable
    - $1 > \Delta E \leq 5$ → Small differences are noticeable
    - $\Delta E > 5$ → Noticeable differences, but acceptable

- CMC formula still used in the textile industry, mostly for historical reasons.

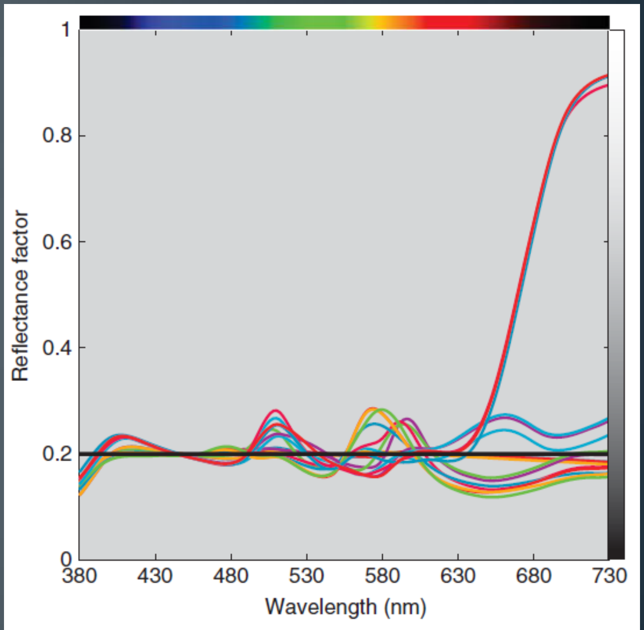
- Current formulas can still be improved
  - Formulas developed under specific conditions (no "universal" formula)
  - New applications and material constantly being developed (e.g., relief and 3D printing)

Metamerism

Metamerism: What's that?

- Spectrally dissimilar stimuli can produce the same visual response for an observer.
  - Tristimulus values of two spectrally different colors match.

$$X_1Y_1Z_1 = X_2Y_2Z_2$$



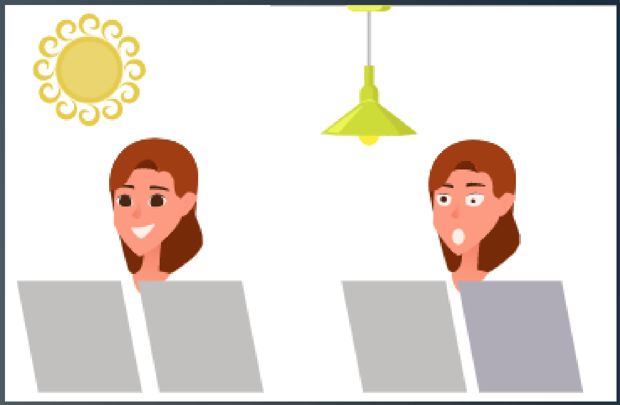
Because we can produce the same color with different materials (video displays using 3 lights, printing using 3 or more inks)

A change in illumination produces a change in color (color inconstancy)

Most important Types

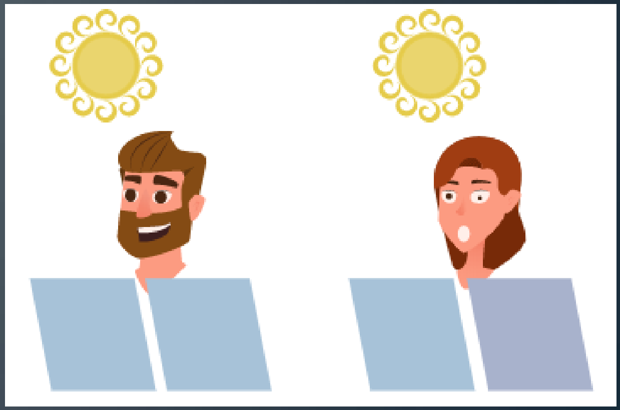
- *Illuminant Metamerism*

  Different spectral characteristics but same color when viewed under a given illuminant and different color when viewed under another illuminant (same observer and same viewing conditions).

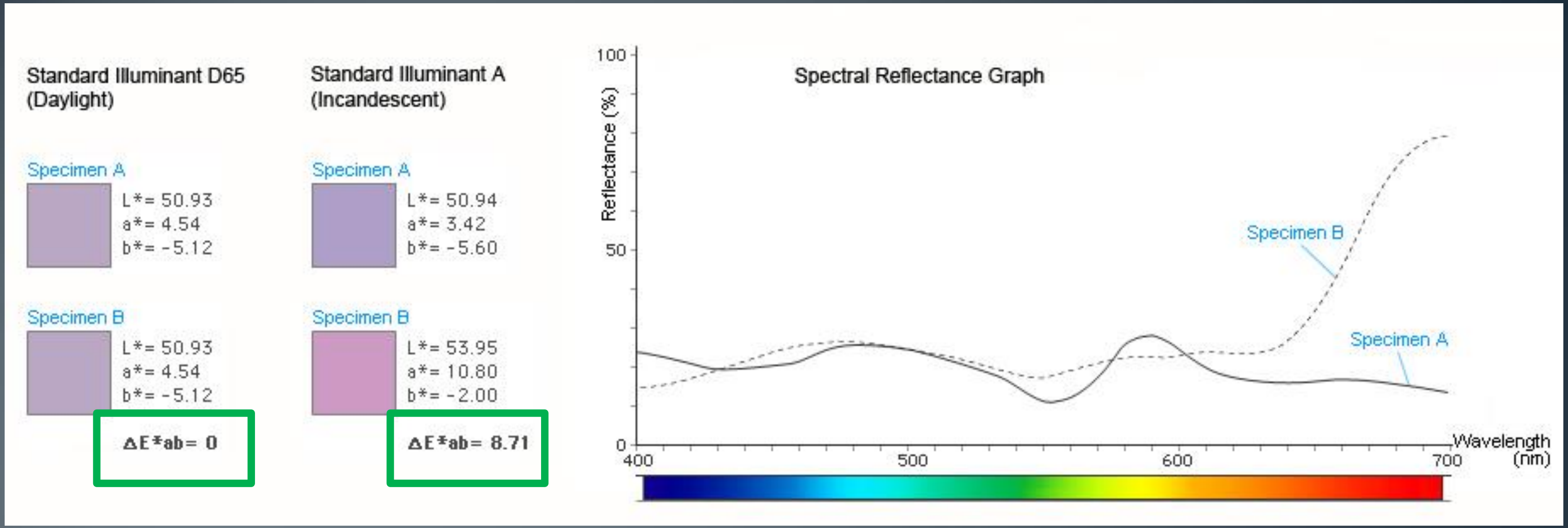


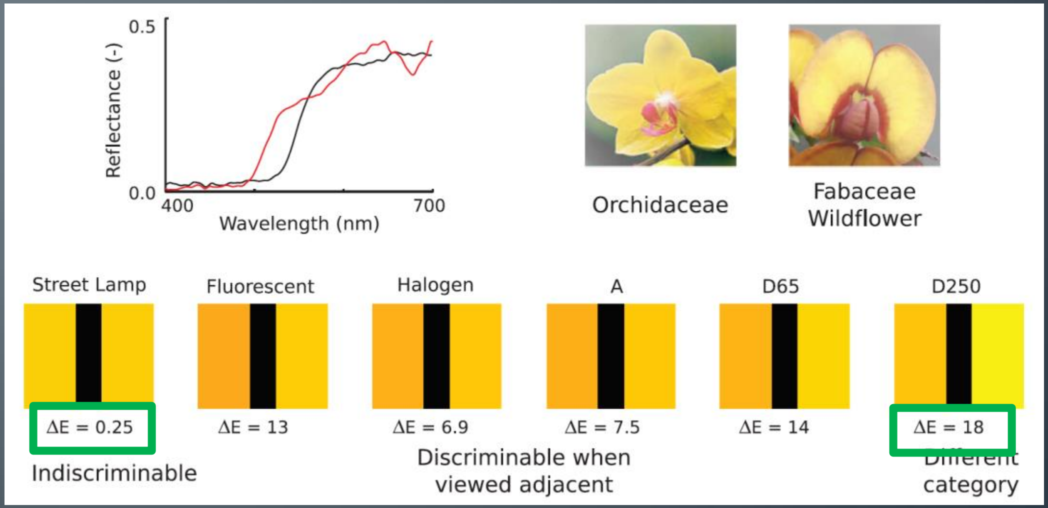
- *Observer Metamerism*

  Different spectral characteristics and same color when viewed by one observer, but different color when viewed by another observer (same illumination and viewing conditions)



In Practice



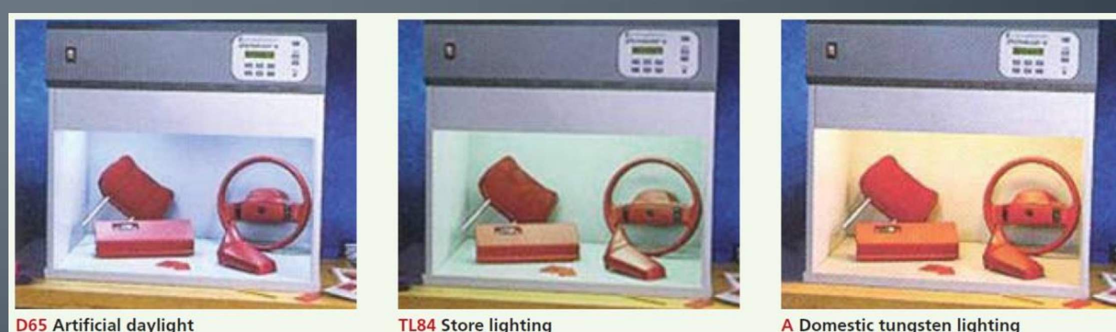


Konica Minolta, "Metamerism meets its Match" (https://sensing.konicaminolta.us/blog/metamerism-meets-its-match/)
Arash Akbarinia and Karl R. Gegenfurtner, "Color metamerism and the structure of illuminant space," J. Opt. Soc. Am. A **35**, B231-B238 (2018)

Examples: Car Industry

Sunlight

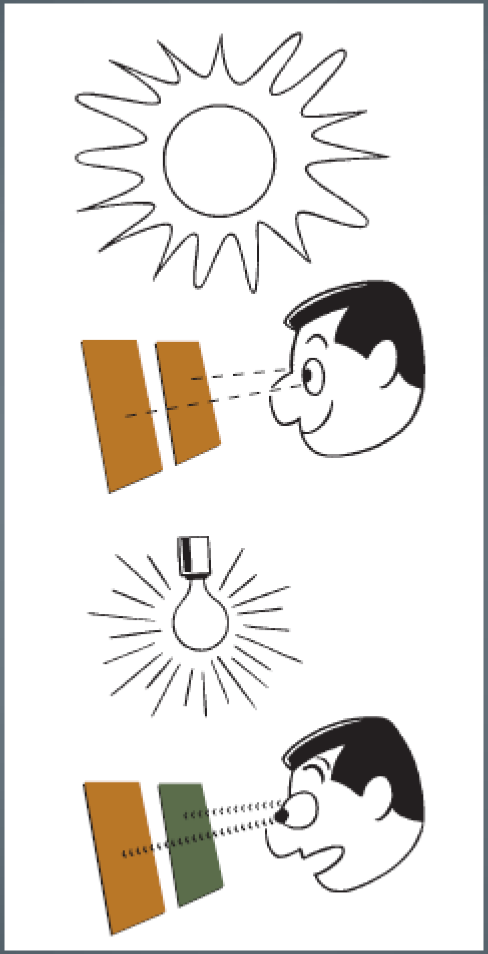
Fluorescent (Light Booth)

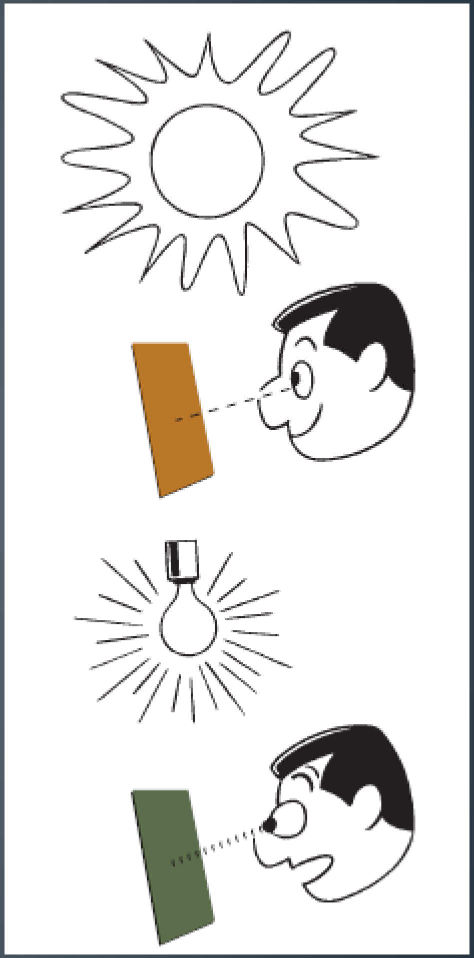


Ben's Paint Supply – Auto and Collision FAQ (http://www.benspaintsupply.com) Coats Industrial, "Metamerism and Illuminants", Bulletin Post September 2014

Examples: Other

Metamerism vs. Color Inconstancy





Metameric pair:	Two objects having dissimilar color inconstancy.
Color inconstancy:	A single object changing color with changes in the color of the illumination.

Metamerism: Recap

- Metamerism is an effect we need to consider if a pair of objects will be viewed under more than one type of illuminant.
- In the printing industry, neutral (grayscale) colors are more susceptible to illuminant metamerism as a mix of inks is used.
- In the case of displays, illuminant metamerism is not a problem as they create their own light.
- Very important in the paints and textile industry, to ensure that what you saw in the store matches outside or in your home.

The End