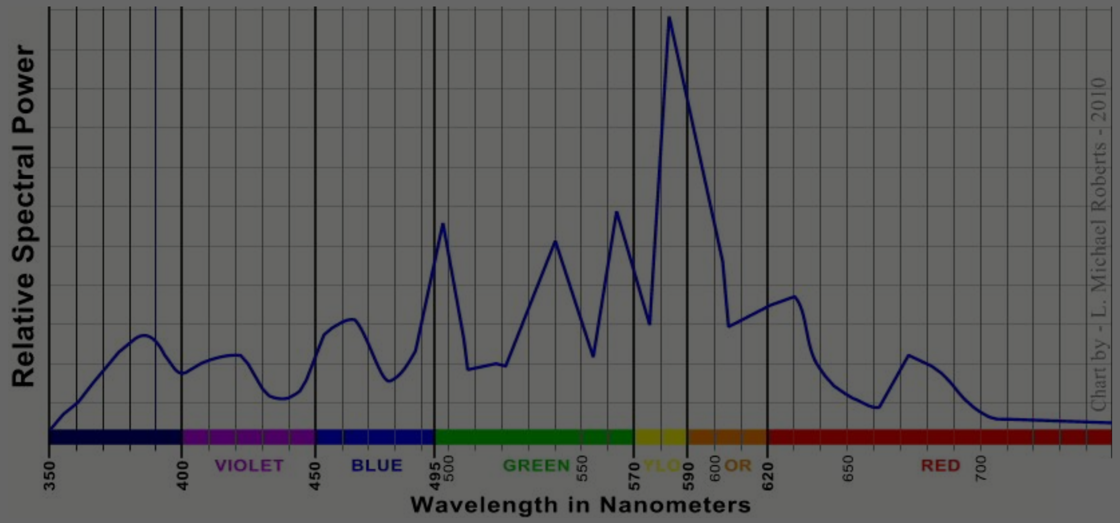
# EE 5098 – Digital Image Processing

## 6. Color Image Processing: Color appearance

Assisted by Dafei Shih

# Color

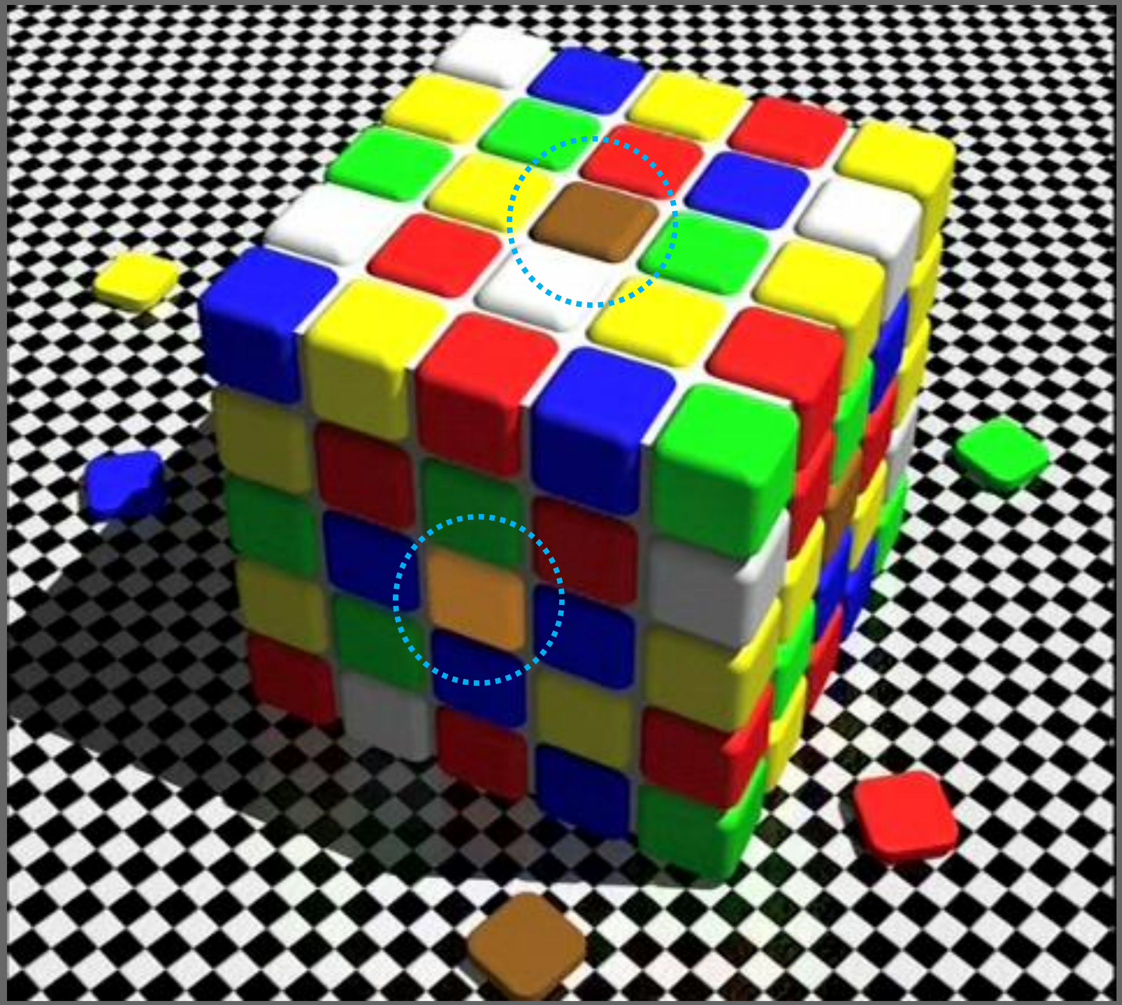
- What is color?
  - An *interpretation* of spectral density distribution of electrical magnetic waves by our brain.
  - *ONLY* in our mind.
- The study of color perception is more psychological and less physical.



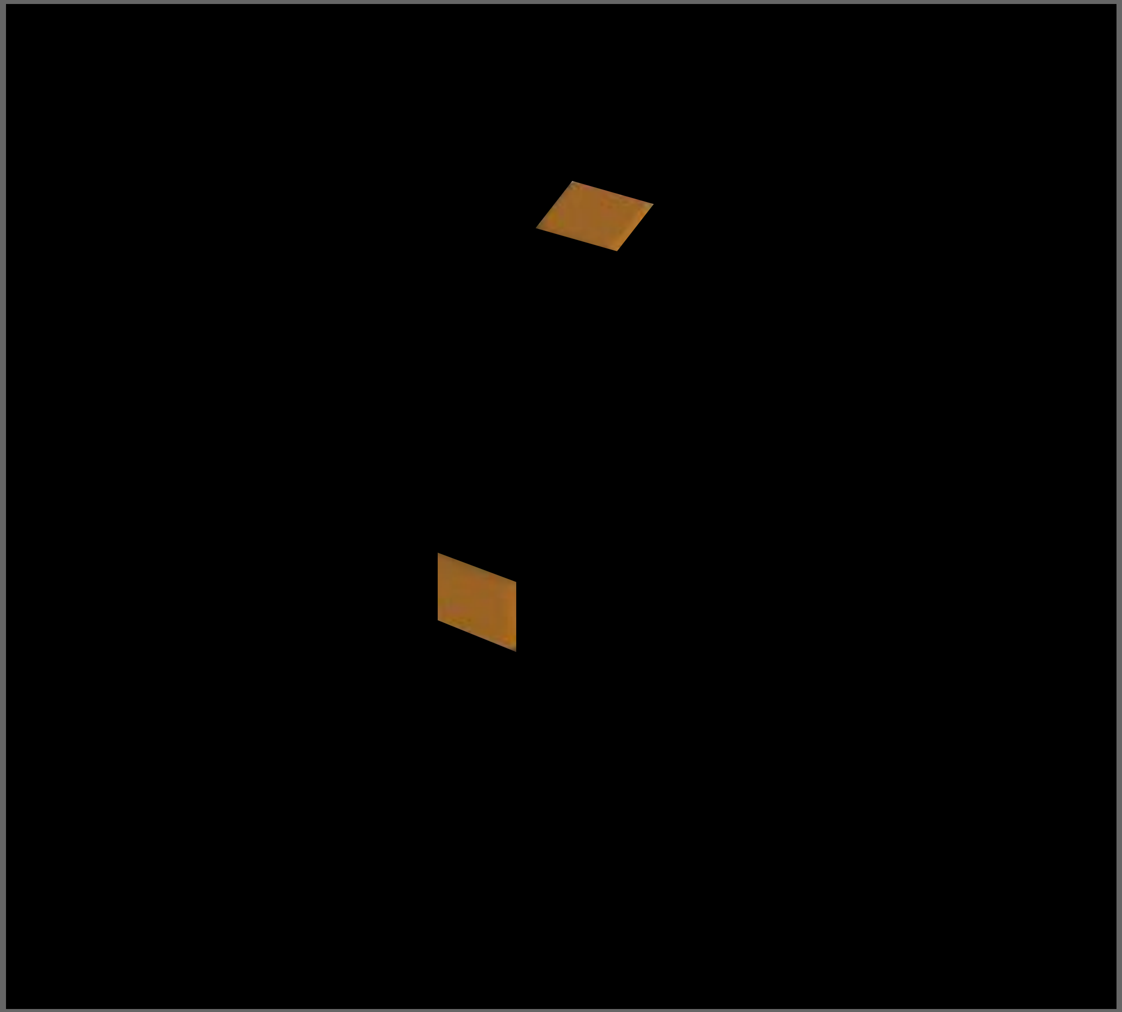

# Why Study Color Appearance Modeling

- Color appearance actually depends on
  - The illumination
  - Our eye's adaptation level
  - The colors and scene interpretation surrounding the observed color
- Spectrum $\Rightarrow$ XYZ $\Rightarrow$ color appearance modeling

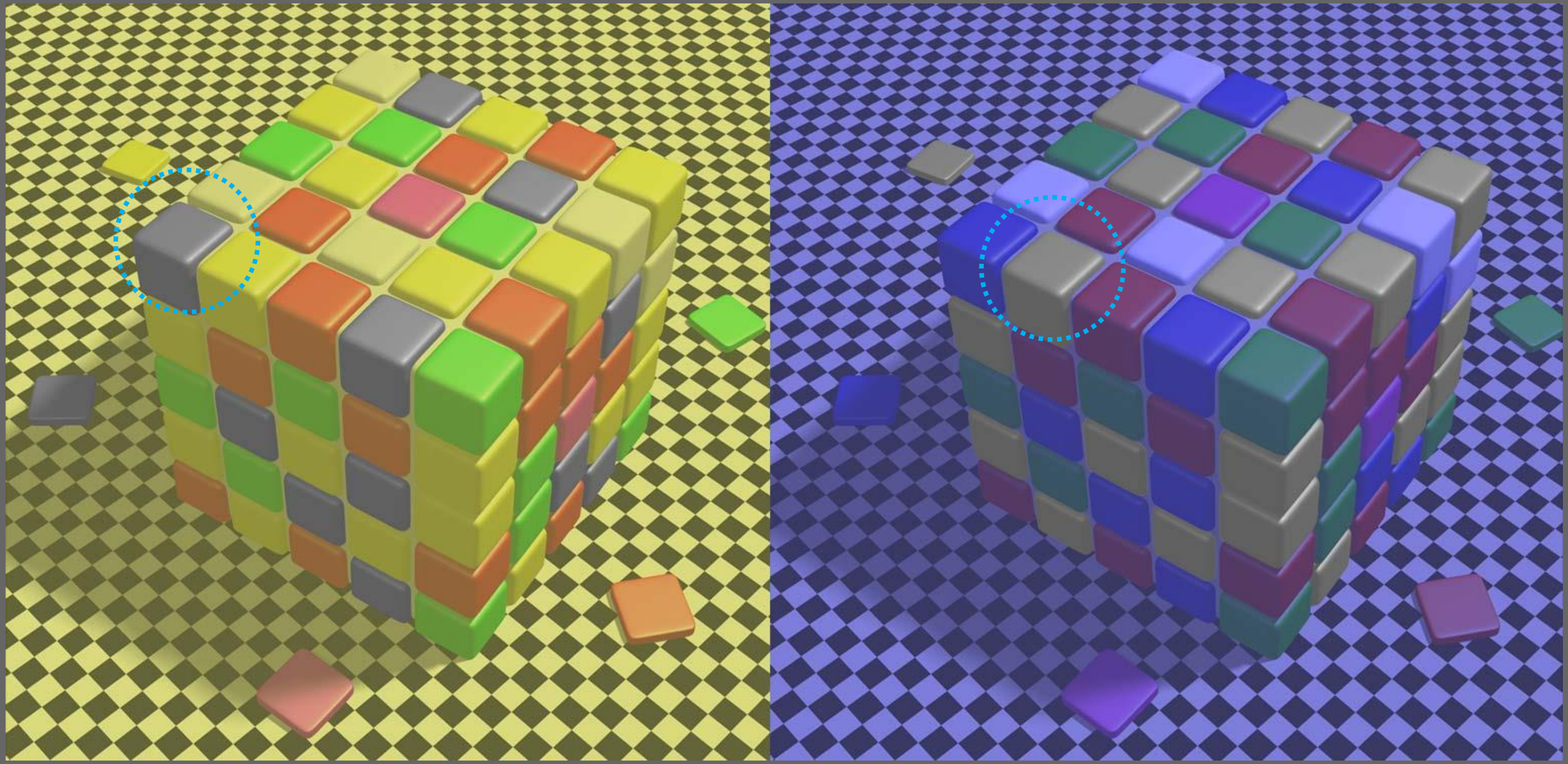
# Color Perception



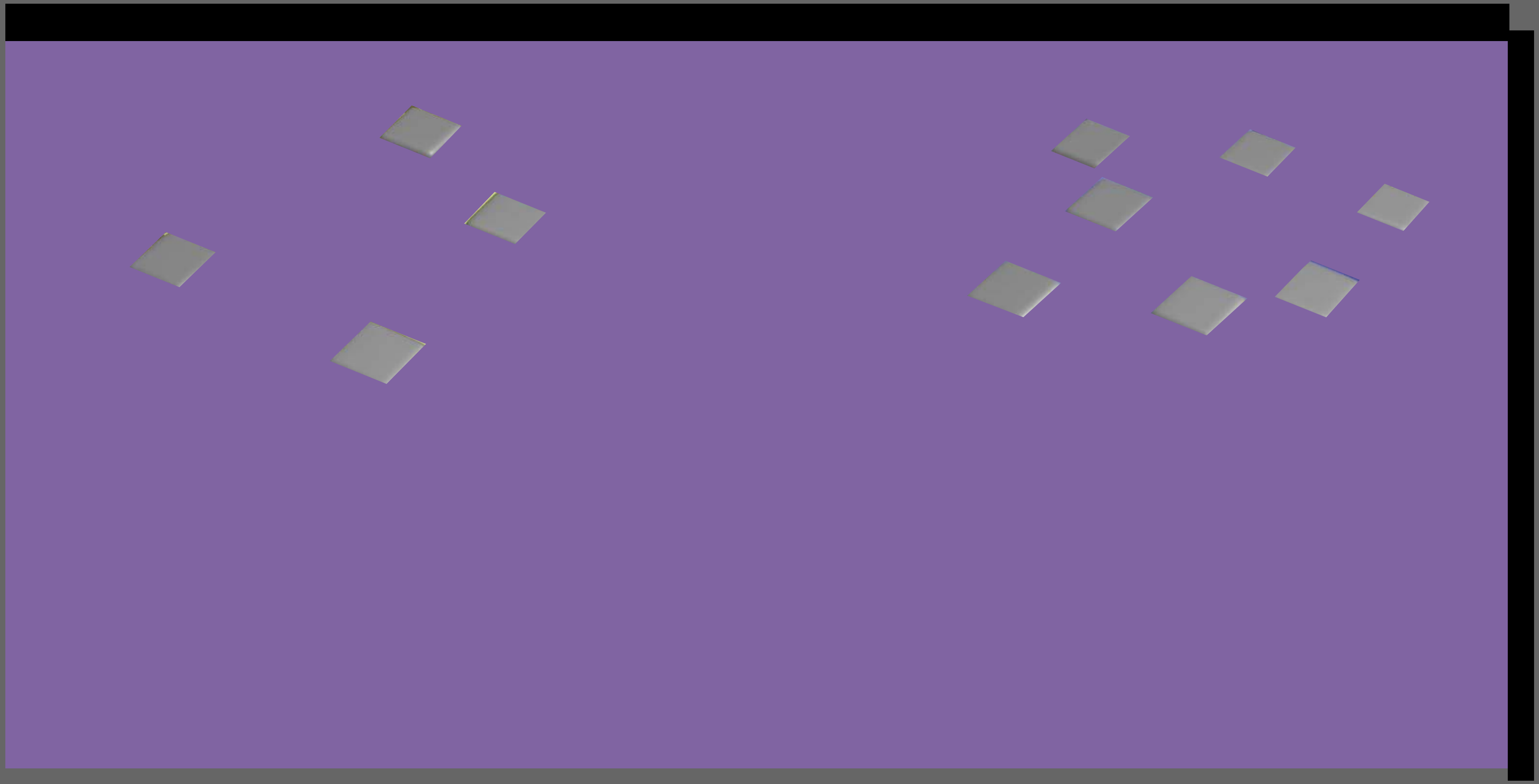
# Color Perception



# Color Perception

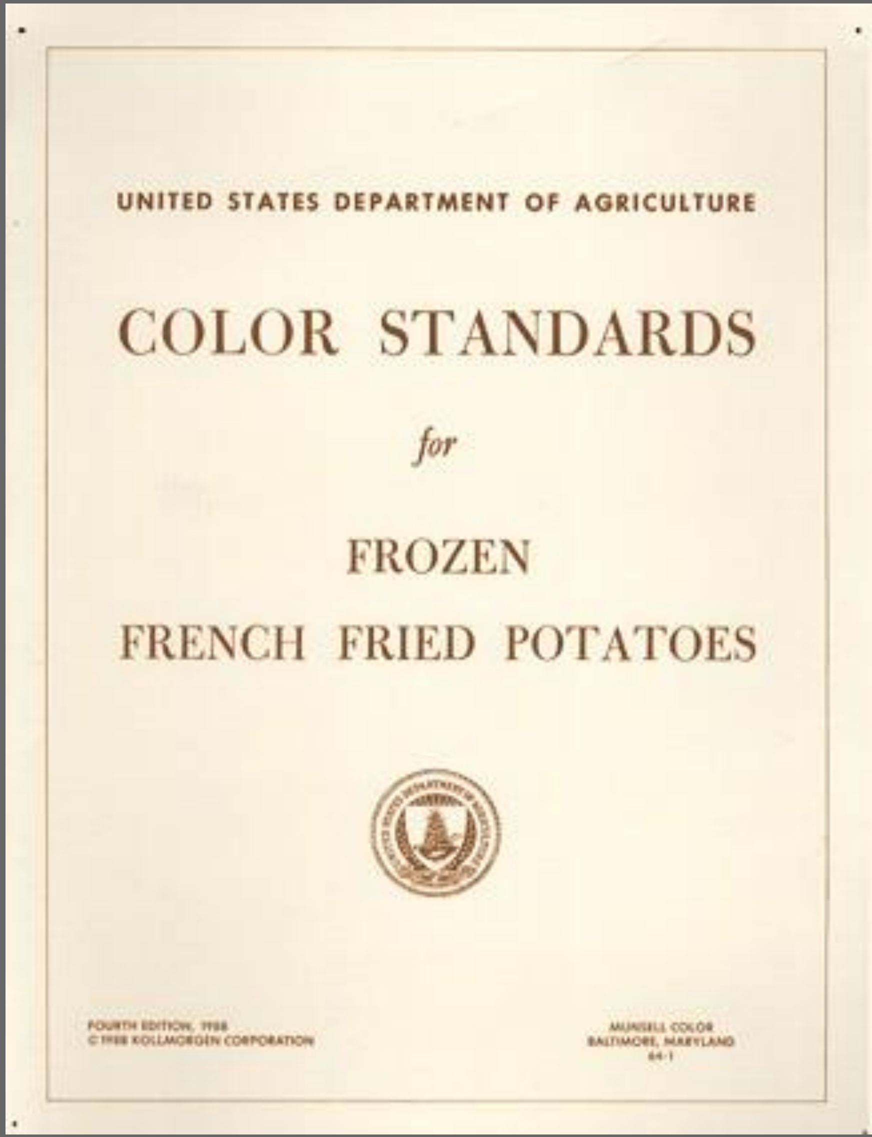


# Color Perception



# Why Specify Color Numerically?

- Accurate color reproduction is commercially valuable
  - Many products are identified by color
- Few color names are widely recognized by English speakers
  - About 10; other languages have fewer/more, but not many more
  - It’s common to disagree on appropriate color names
- Increasing color reproduction problems in the digital imaging era - eg. digital libraries of art
  - How do we ensure that everyone sees the same color?



UNITED STATES DEPARTMENT OF AGRICULTURE

# COLOR STANDARDS

*for*

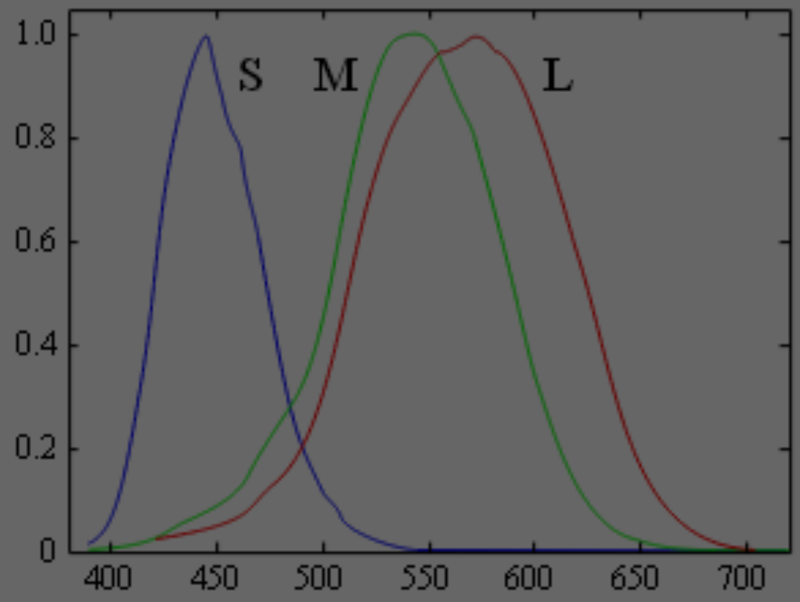
## FROZEN FRENCH FRIED POTATOES

FOURTH EDITION, 1988
© 1988 KOLLMORGEN CORPORATION

MUNSELL COLOR
BALTIMORE, MARYLAND
64-1

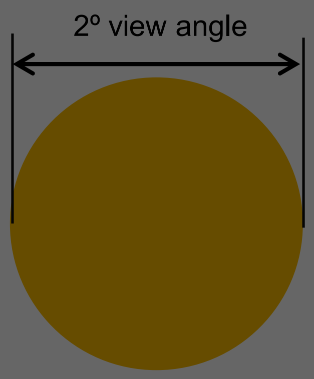
# Colorimetry 比色法、色度學

- The science of quantification of a color
- Psychophysics:
  - Human have 3 types of light spectral sensors called cone cells (long, medium, and short).
  - Therefore, in principle, 3 values are sufficient to describe a color.
- We need a mapping from spectral density to “tristimulus values.”

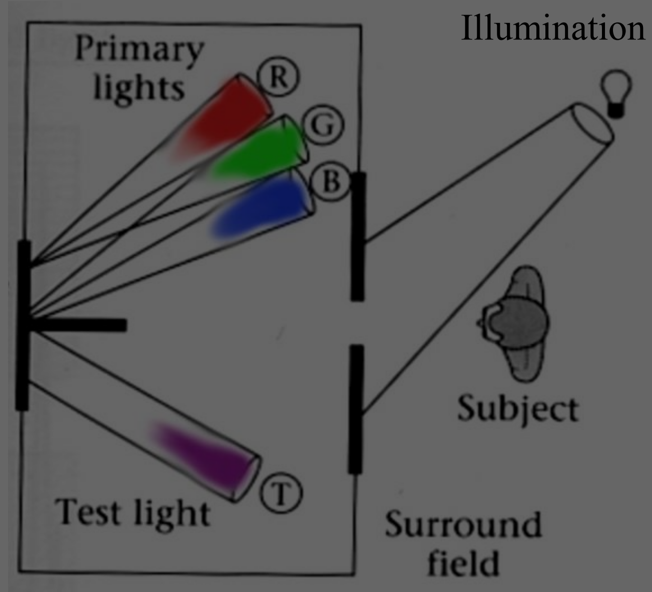


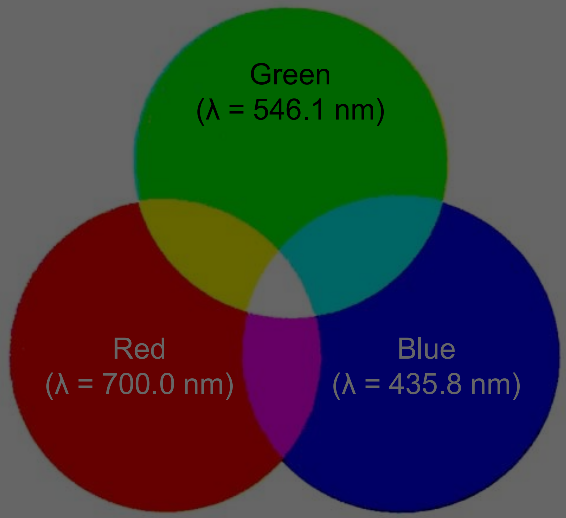
# Color Matching Experiment

- Color matching experiments were done in the 1920s by Wright and Guild independently. Their results were summarized later.
- The experiment:




The Target Stimulus

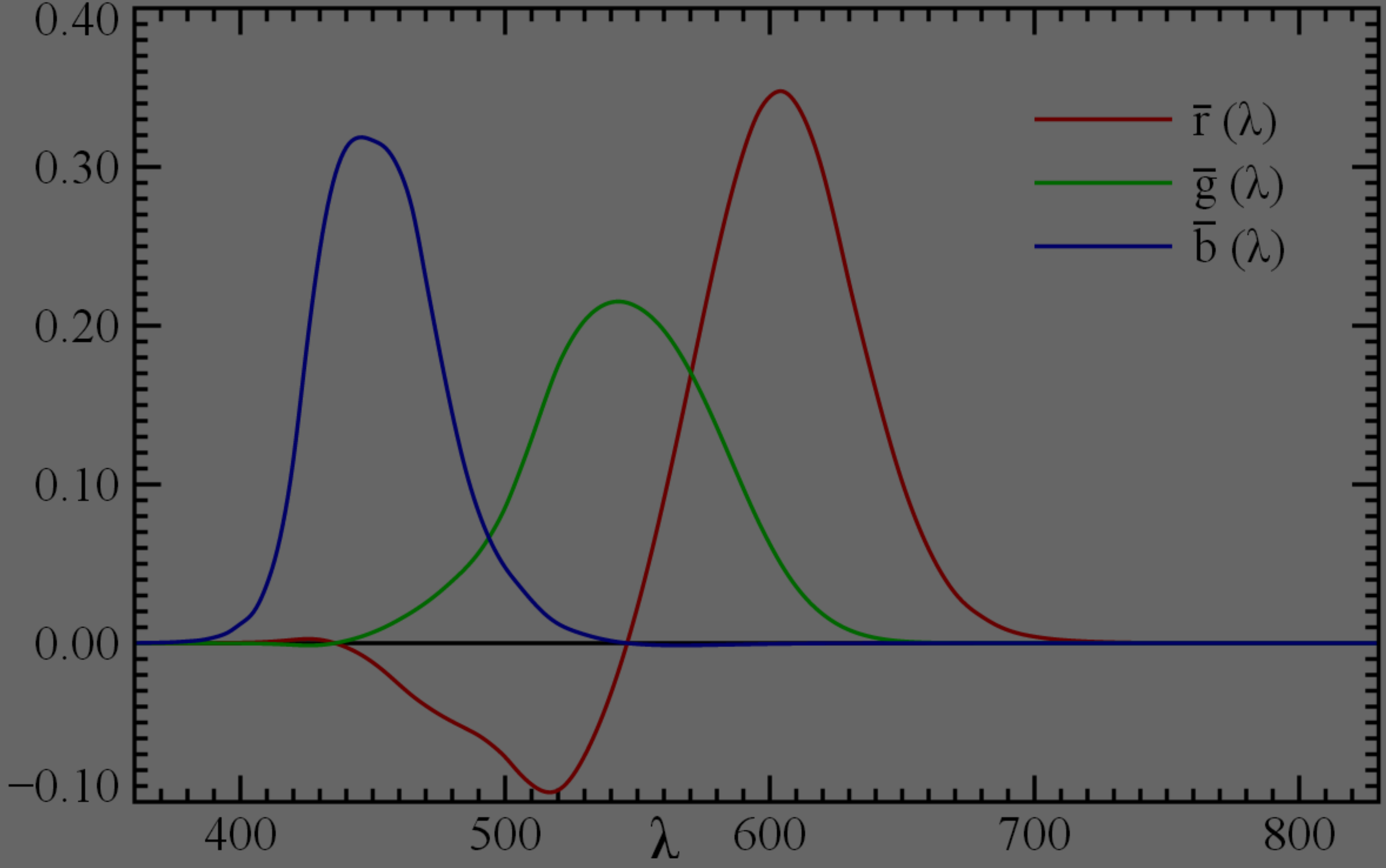



Mixture of Three Primaries
Brightness of each controlled by subjects

# The Color Matching Functions

– for a particular set of primaries



# The CIE RGB Color Space

- Grassman's Law
  - The color matching result of the mixture of two colors is equal to the summation of the result of the two colors.
  - The law is discovered by Hermann Grassman in the $19^{th}$ century as an empirical law.

$$R = \int I(\lambda) \cdot \bar{r}(\lambda) d\lambda$$

$$G = \int I(\lambda) \cdot \bar{g}(\lambda) d\lambda$$

$$B = \int I(\lambda) \cdot \bar{b}(\lambda) d\lambda$$

$I(\lambda)$: Spectral power distribution

# Grassman's Laws

- For color matches
  - symmetry: $U=V \leftrightarrow V=U$
  - transitivity: $U=V$ and $V=W \rightarrow U=W$
  - proportionality: $U=V \leftrightarrow tU=tV$
  - additivity:

    If any two (or more) of the statements

    $U=V$,

    $W=X$,

    $(U+W)=(V+X)$

    are true, then so is the third
- These statements are as true as any biological law, meaning that additive color matching is linear.

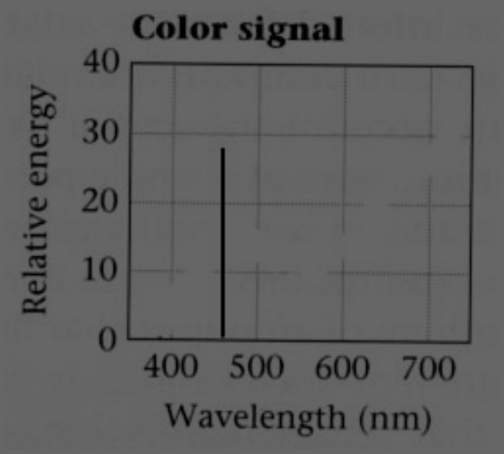
Source: W. Freeman

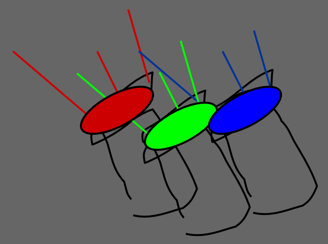
# Color-Matching Paradigm

- To measure the color of a spectral signal t, first pick a set of 3 primary color lights
- Find the amounts ($c_1$, $c_2$, $c_3$) of each primary needed to match t
- Those amounts, $c_1$, $c_2$, and $c_3$, describe the color of t. If you have another spectral signal s, and s matches t perceptually, then $c_1$, $c_2$, $c_3$ will also match s, by Grassman's laws.
- Why this is useful—it lets us:
  - Predict the color of a new spectral signal
  - Translate to representations using other primary lights.

Source: W. Freeman

# Color Matching for Any Color Signal

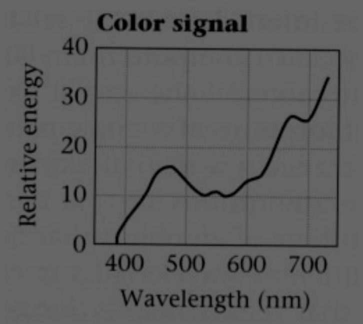


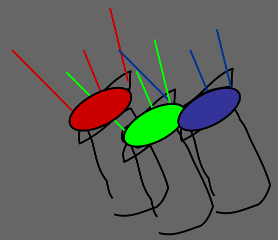



- Pick a set of primaries, $p_1(\lambda), p_2(\lambda), p_3(\lambda)$
- Measure the amount of each primary, $c_1(\lambda), c_2(\lambda), c_3(\lambda)$ needed to match a monochromatic light $t(\lambda)$ at each spectral wavelength $\lambda$ (pick some spectral step size). These are the color matching functions.

Source: W. Freeman

# Color Matching for Any Color Signal



Any spectral signal can be thought of as a linear combination of many monochromatic lights,

$$\vec{t} = \begin{pmatrix} t(\lambda_1) \\ \vdots \\ t(\lambda_N) \end{pmatrix}$$

Source: W. Freeman

# Color Matching for Any Color Signal

Store the color matching functions in the rows of the matrix C,

$$C = \begin{pmatrix} c_1(\lambda_1) & \cdots & c_1(\lambda_N) \\ c_2(\lambda_1) & \cdots & c_2(\lambda_N) \\ c_3(\lambda_1) & \cdots & c_3(\lambda_N) \end{pmatrix}$$

Then the amounts of each primary needed to match ***t*** can be described by

$$C\vec{t}$$

The result is a 3x1 vector.

# Color Transform: Translating Colors between Different Systems of Primaries

$p_1 = (0\ 0\ 0\ 0\ 0 \ldots\ 0\ 1\ 0)^T$

$p_2 = (0\ 0\ \ldots\ 0\ 1\ 0\ \ldots 0\ 0)^T$

$p_3 = (0\ 1\ 0\ 0\ \ldots\ 0\ 0\ 0\ 0)^T$

Primary spectra, P

Color matching functions, C

$p'_1 = (0\ 0.2\ 0.3\ 4.5\ 7\ \ldots.\ 2.1)^T$

$p'_2 = (0.1\ 0.44\ 2.1\ \ldots\ 0.3\ 0)^T$

$p'_3 = (1.2\ 1.7\ 1.6\ \ldots.\ 0\ 0)^T$

Primary spectra, P′

Color matching functions, C′

Any color with spectrum $\vec{t}$

The amount of each primary in P needed to match the color with spectrum $\vec{t}$

$$C\vec{t} = CP'C'\vec{t}$$

The amount of each P′ primary needed to match $\vec{t}$

The spectrum of a perceptual match to $\vec{t}$, made using the primaries P′

The color of that matched to $\vec{t}$, described by the primaries P



Source: W. Freeman

# Color Transform: Translating Colors between Different Systems of Primaries

The values of the 3 primaries in the unprimed system

The values of the 3 primaries in the primed system

$$e = \underbrace{CP'}_{\text{a 3x3 matrix}} e'$$

P′ are the old primaries
C are the new primaries' color matching functions



Source: W.  Freeman

# Translate Color Matching Functions

From an earlier slide

$$C\vec{t} = CP'C'\vec{t}$$

But this holds for any input spectrum $\vec{t}$, *so*

$$C = \underbrace{CP'}_{\text{A 3x3 matrix that transforms the color representation from one set of primaries to another.}}C'$$



Source: W. Freeman

# Recap

- What are colors?
  - Arise from power spectrum of light.
- How to represent colors:
  - Pick primaries
  - Measure color matching functions (CMF’s)
  - Multiply power spectrum by CMF’s to represent color by the 3 primary color values.
- How to share color descriptions between people?
  - Translate colors between systems of primaries
  - Standardize on a few sets of primaries.

Source: W. Freeman

# The CIE XYZ Color Space

- Based on the RGB color space, scientists wish to design a new color space XYZ such that
  - The XYZ values are linear combinations of RGB
  - Non-negative tristimulus values for all colors
  - One of the matching function being the photopic luminous efficiency function $V(\lambda)$.
  - For constant energy white, the tristimulus values are the same, that is, $X=Y=Z$.
- These properties are desirable mainly due to computational considerations. (Computers were not invented yet at that time.)

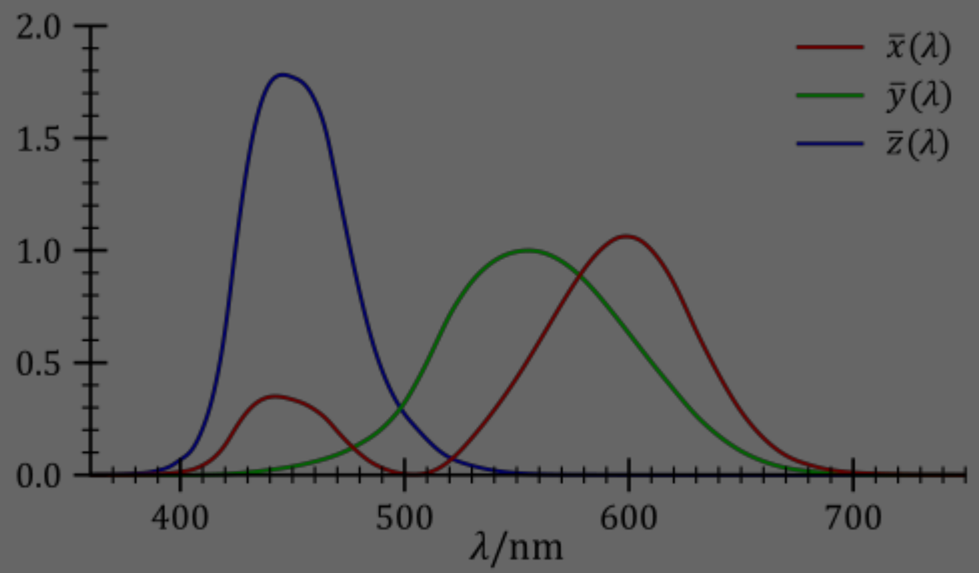
# The CIE 1931 XYZ Color Space

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

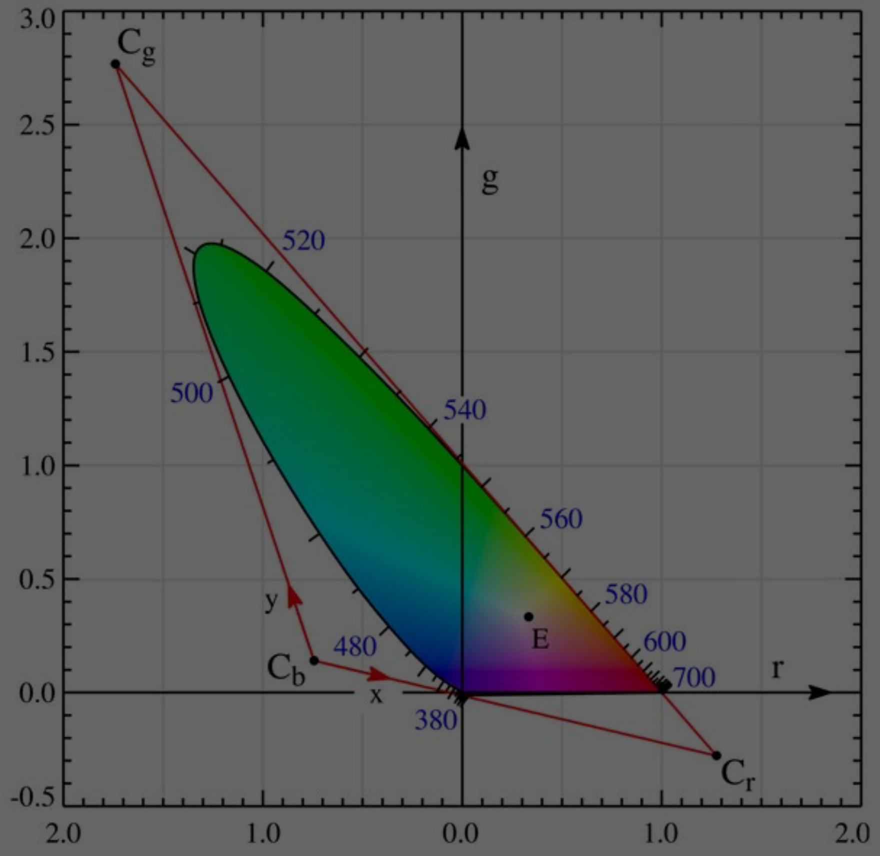
$$X = \int I(\lambda) \cdot \bar{x}(\lambda) d\lambda$$

$$Y = \int I(\lambda) \cdot \bar{y}(\lambda) d\lambda$$

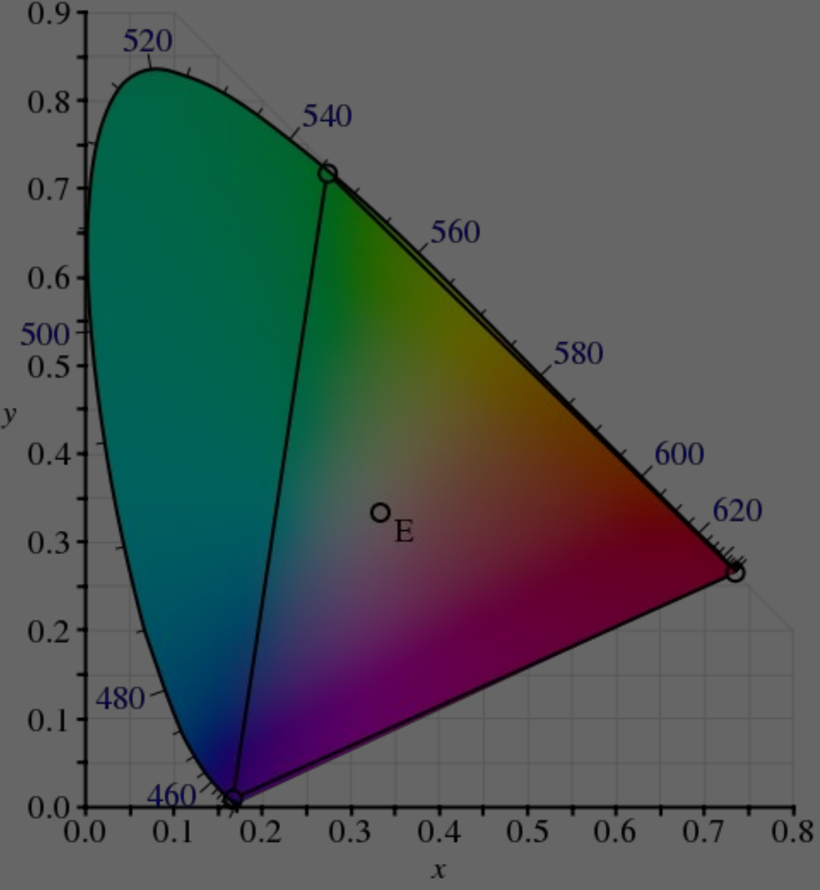
$$Z = \int I(\lambda) \cdot \bar{z}(\lambda) d\lambda$$



# Basis Transformation

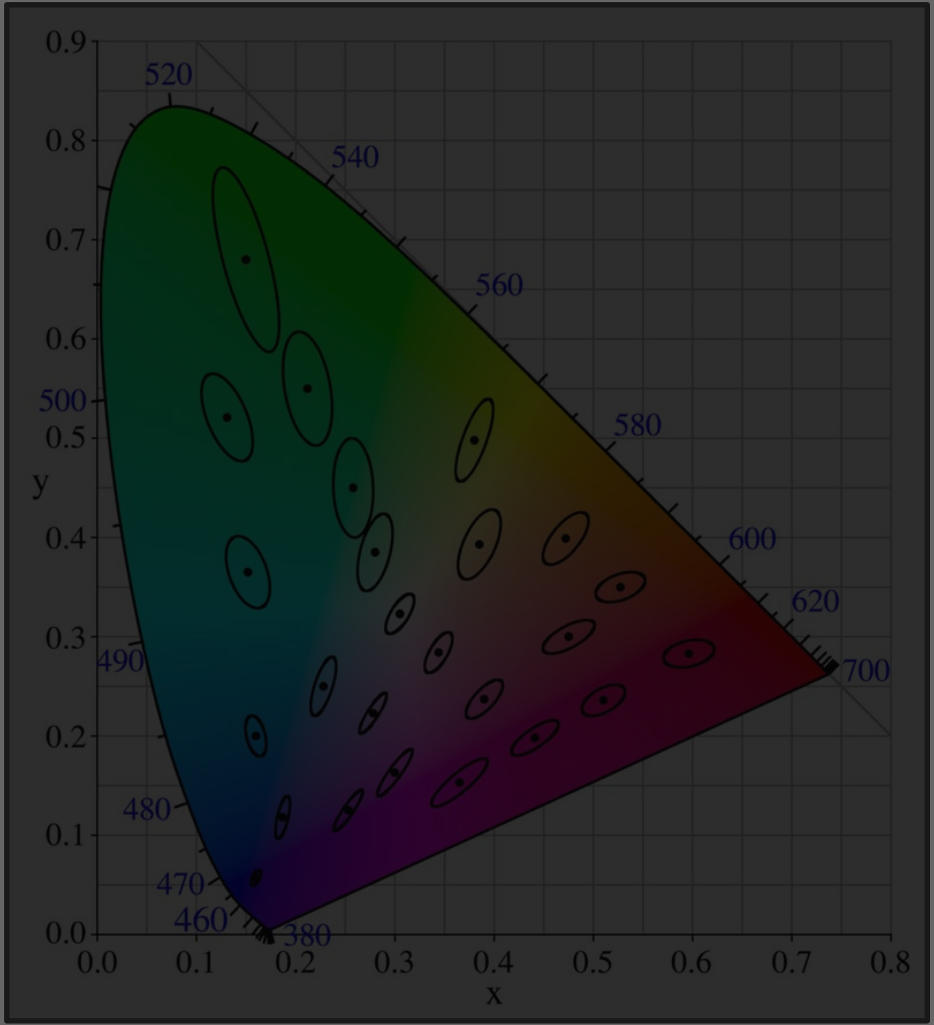



$$r = R/(R+G+B)$$
$$g = G/(R+G+B)$$




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

# CIE XYZ




MacAdam ellipses (x10): colors indistinguishable to human eyes

Distance is nonlinear

*CIE XYZ* 雖然改進了*CIE RGB* 的負成份問題，但仍然存在另一個問題: 色度圖上的距離與視覺差異不一致

# Limitations of XYZ Specification

- Theoretically, XYZ is valid only for the specific viewing condition that is strictly controlled
  - Clean background
  - The stimulus extends 3 degrees in field-of-view
- XYZ does not account for personal difference
  - The CIE1931 color matching functions are obtained by averaging over a number of subjects

# From Colorimetry to Color Appearance

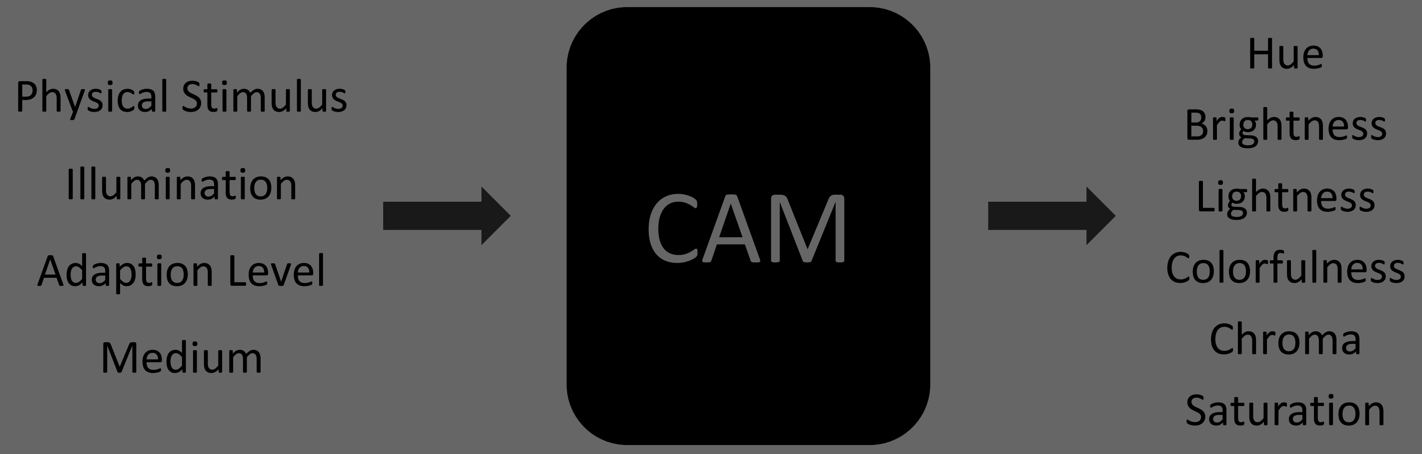
- There are factors that affect our perception of colors
  - Luminance adaptation and chromatic adaptation
  - Other color appearance phenomena (e.g. simultaneous contrast, crispening…etc.)

# Color Appearance Model

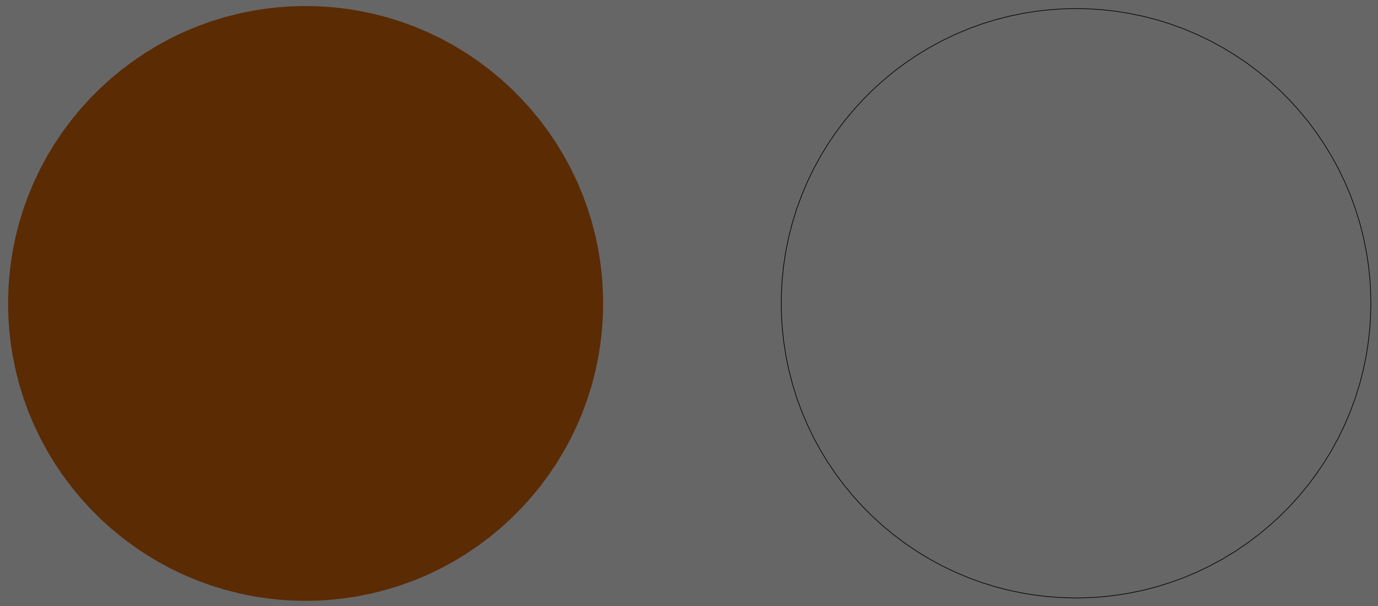
- A numerical model predicting human color perception in various contexts
- From physical description of color (colorimetry) to psychological description of color (perceptual attributes)
- Objectives of an appearance model:
  - Predict perceptual attributes
  - Account for the effects of different viewing conditions
  - Account for psychological phenomena (e.g. Hunt effect, Steven's effect…etc.)

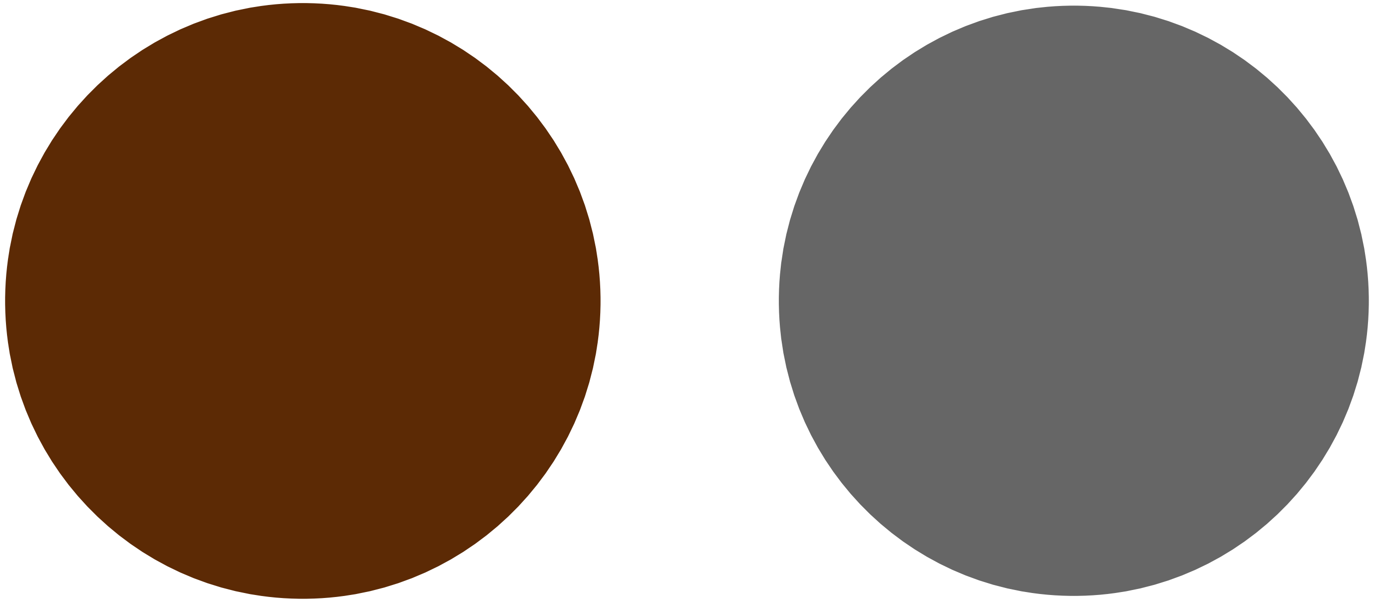
**Hunt effect:** Colorfulness increases with luminance.
**Stevens effect:** Contrast increases with luminance.

# Color Appearance Model




- Q: How do you *define* these perceptual attributes?
- An equivalent question: How do you “describe” a color to visually impaired people?
- The “definitions” we are to introduce is *literal* rather than *mathematical*



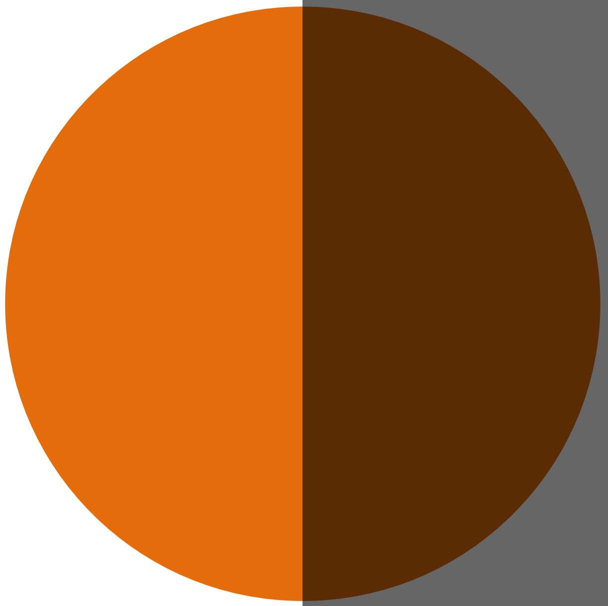


# Color Appearance Attributes

- **Hue (色調)**
  - *The degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow.*
  - Whether hue is absolute or relative attribute is of less concern
- **Brightness**
  - *The subjective appearance of how bright an object appears given its surroundings and how it is illuminated.*
  - Absolute attribute
- **Lightness**
  - *The subjective appearance of how light a color appears to be*
  - Relative attribute

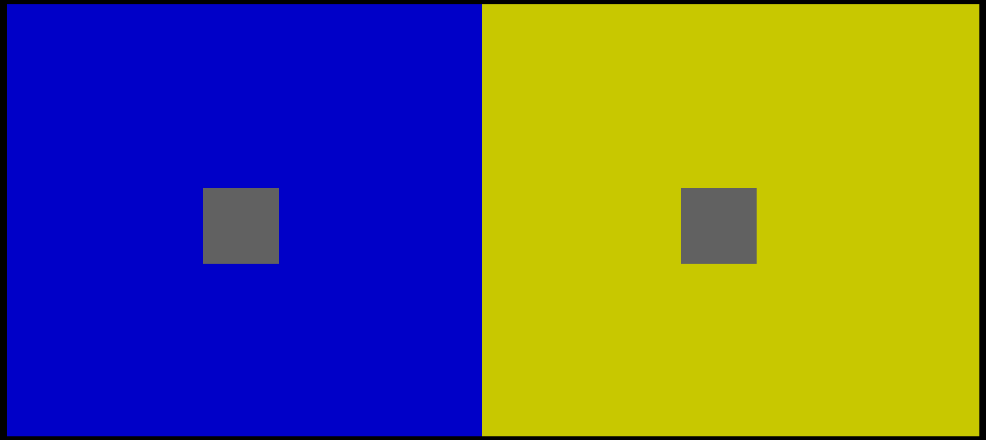
# Attributes of Color Appearance

- **Colorfulness**
  - *The degree of difference between a color and gray*
  - Absolute attribute
- **Chroma**
  - *The colorfulness relative to the brightness of another color that appears white under similar viewing conditions*
  - Allows to present the fact that a surface of a given chroma displays increasing colorfulness as the level of illumination increases
  - Relative attribute
- **Saturation**
  - *Colorfulness of a color relative to its own brightness*
  - Absolute attribute



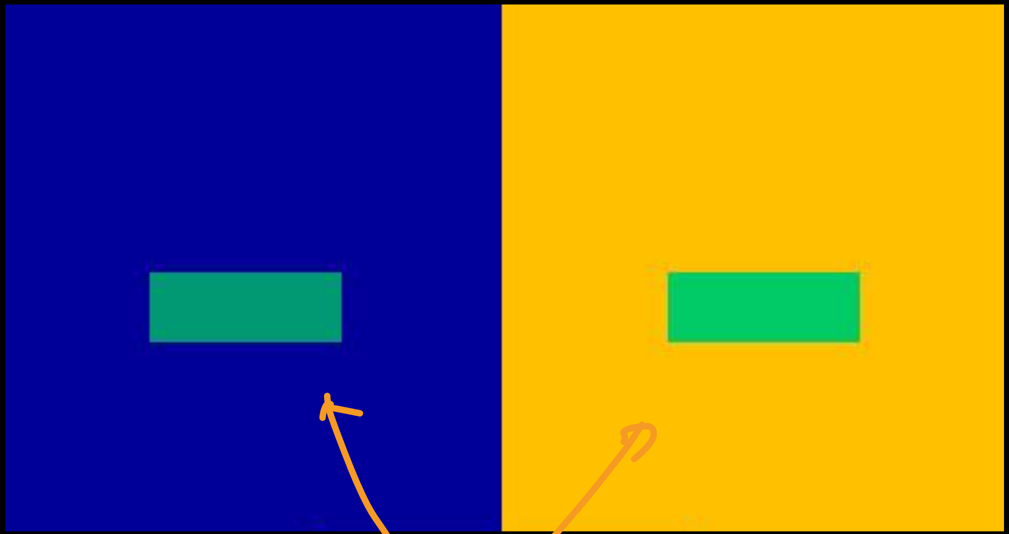
Hue = Hue
Brightness > Brightness
Lightness = Lightness
Colorfulness > Colorfulness
Chroma = Chroma
Saturation ≈ Saturation

# Simultaneous Contrast



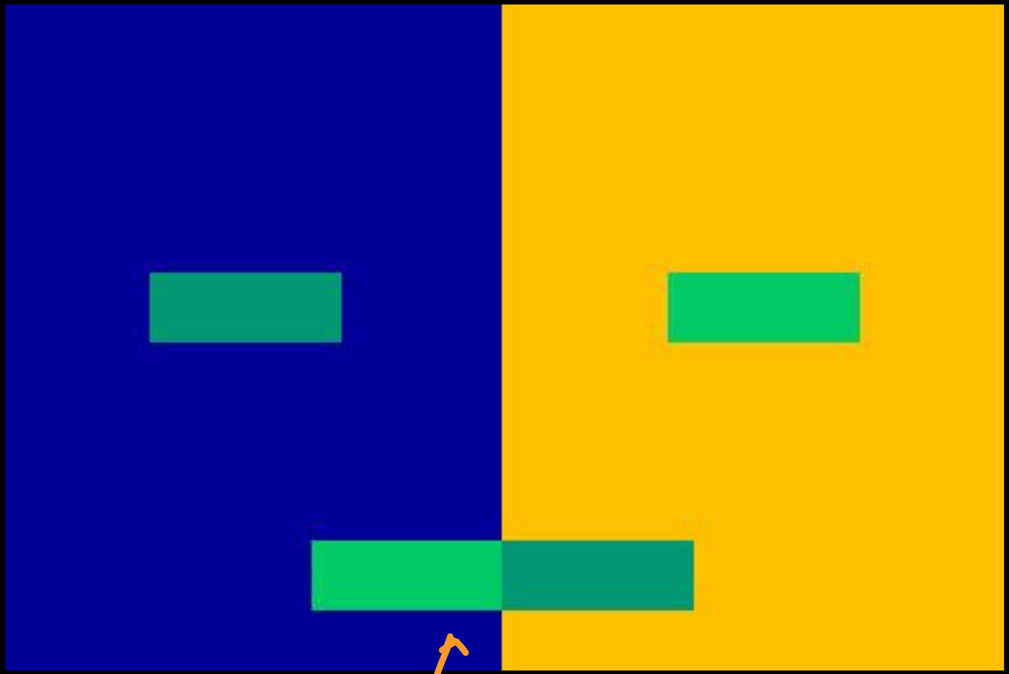
Two colors, side by side, interact with one another and change our perception accordingly. The effect of this interaction is called simultaneous contrast.

# Simultaneous Contrast



看起来同色

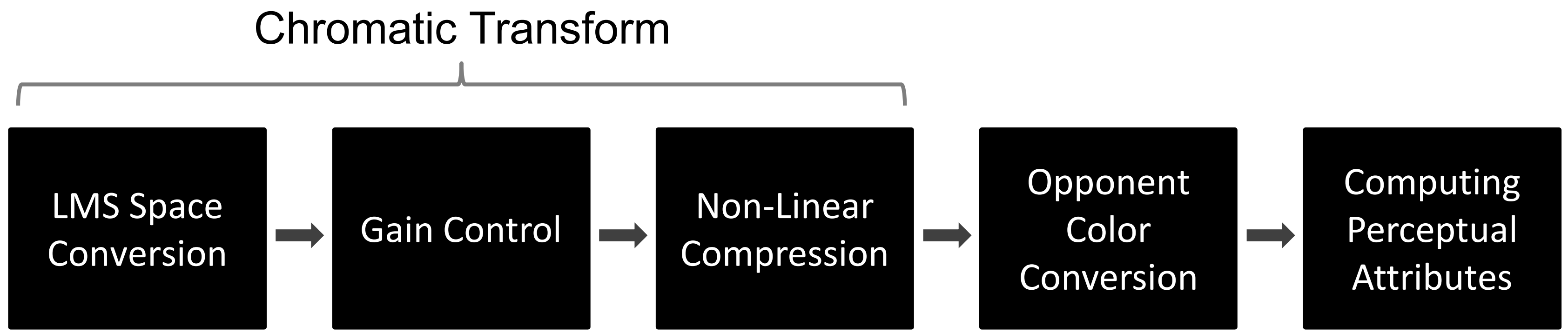
# Simultaneous Contrast

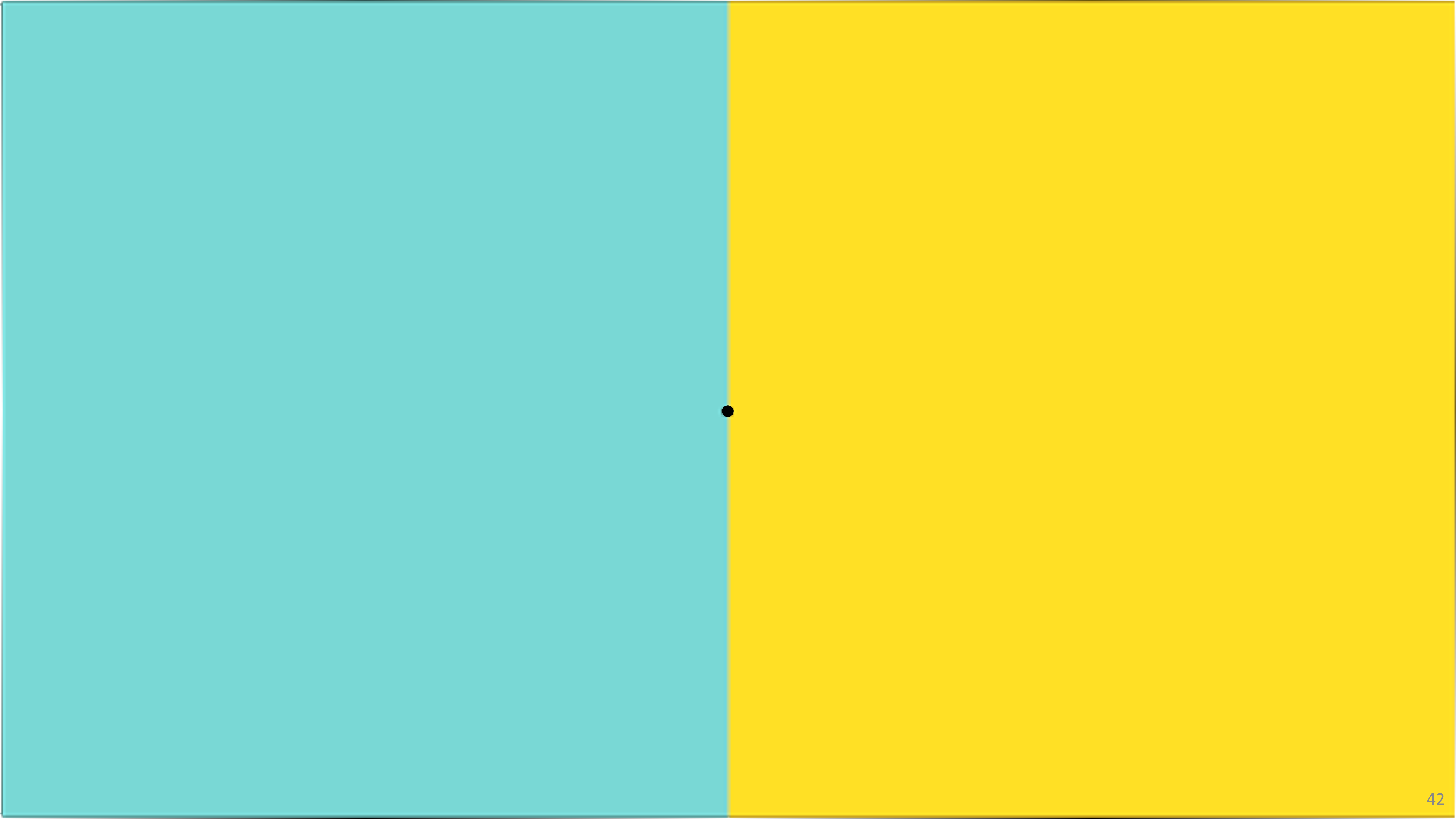


實際不同

# Prediction of Appearance

- Most of the color appearance models follow the flow below, although the details may not be the same.





# Chromatic Adaptation

眼睛對色彩的分辨能力會被剛剛所看到的色彩影響。
色彩飽和度的增減也會影響色彩判定的能力。

- A fundamental mechanism of human visual system so important that must be addressed in all color appearance models
- Physiologically speaking, this adaptation is caused by the depletion of visual pigment in eyes
  - Incoming light breaks down the molecules of visual pigment, and hence at higher intensity levels, there are fewer molecules capable of producing visual response
- The key: **The gain control is independent in each of the three types of cones cells**

# Chromatic Transform in CIECAM02

Published in 2002 by CIE

- Color space transformation

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \mathbf{M}_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \mathbf{M}_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

- Von Kries Model

$$S_{\mathrm{a}} = k_S S$$
$$M_{\mathrm{a}} = k_M M$$
$$L_{\mathrm{a}} = k_L L$$

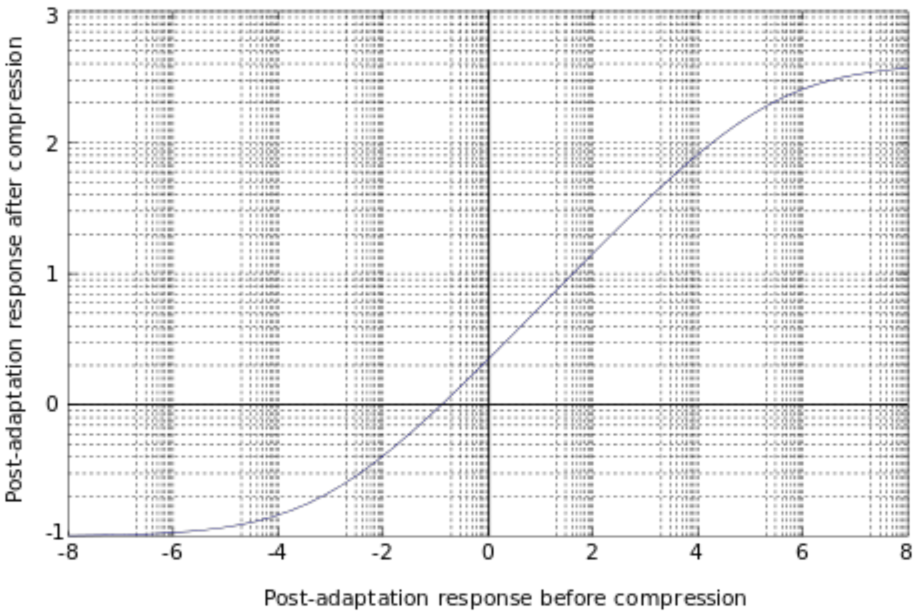
# Non-Linear Compression

- Human are able to see 9 orders of luminance, but only 3 orders can be seen simultaneously.
- In addition to adjusting pupil size, cones adapt to the luminance of scenes as well
- The process usually follows the Naka-Rushton eq.

$$\frac{V}{V_m} = \frac{I^n}{I^n + \sigma^n}$$

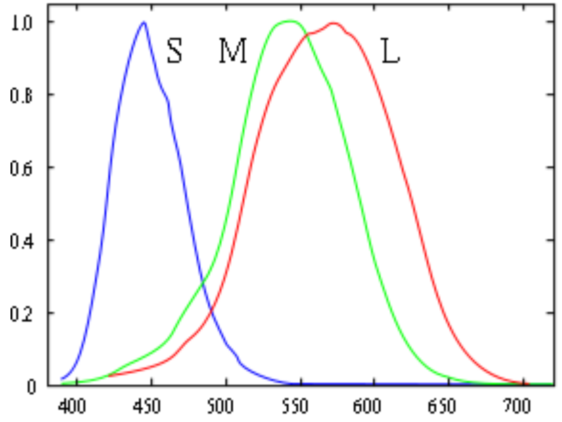
Michaelis-Menten eq. when n=1.

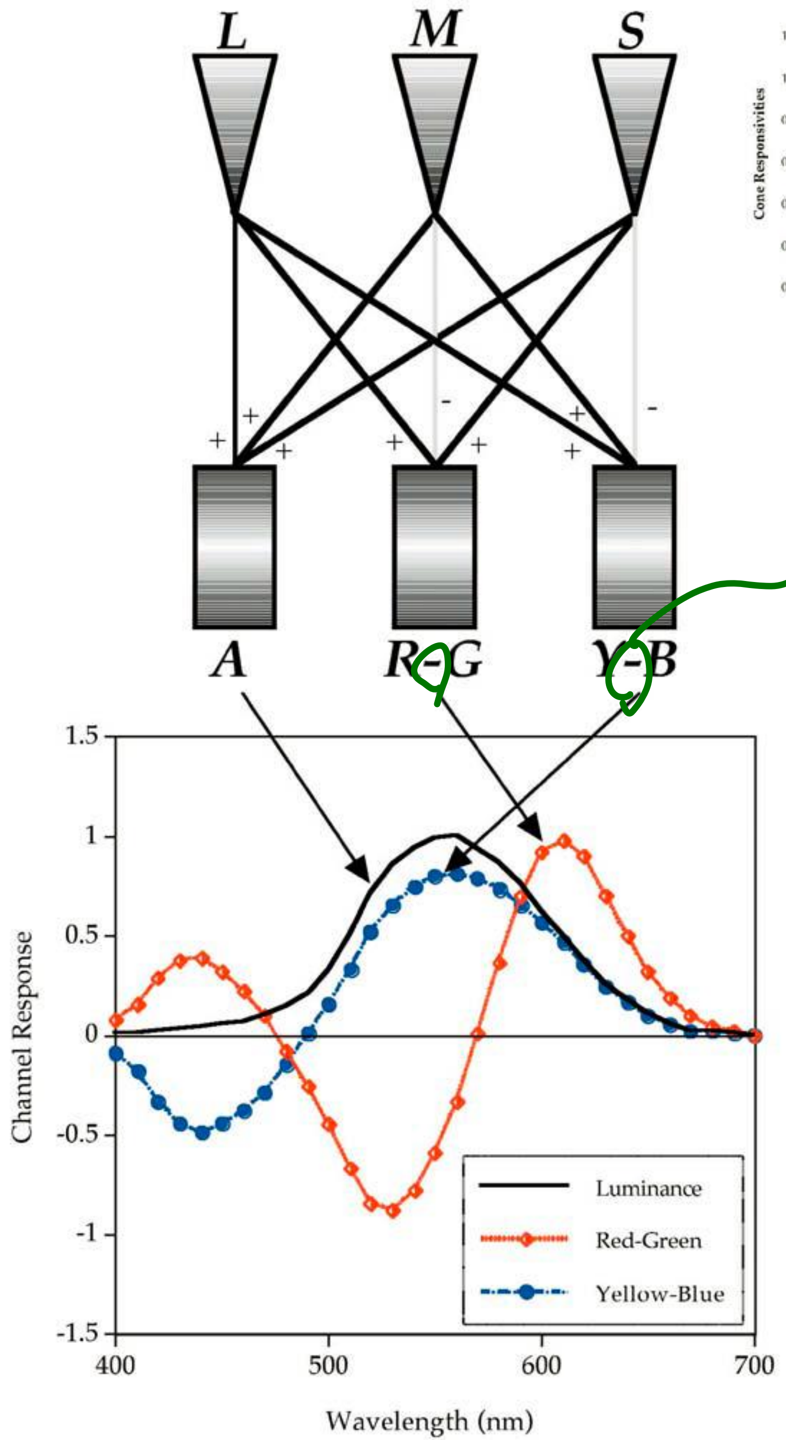
$V$ : Photoreceptor response
$V_m$ : Maximum response
$I$: Light intensity
$\sigma$: semisaturation constant
$n$: normally in the range [0.7, 1.0]

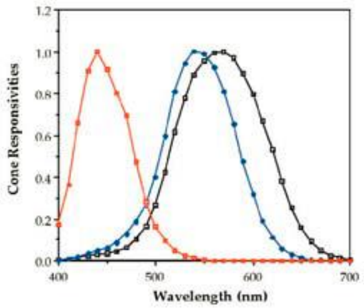


# Opponent Color Theory

– Origin of the theory traces back to a century ago. Now widely accepted.
– Since the frequency responses of the 3 types of cone overlap, it is more efficient to record the differences of the cone signals (decoupling)
– 3 Difference signals:
  - A (from white to black, achromatic)
  - $C_1$ (from red to green)
  - $C_2$ (from yellow to blue)






dash是指中間這條線

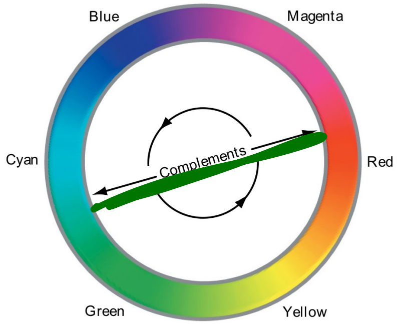
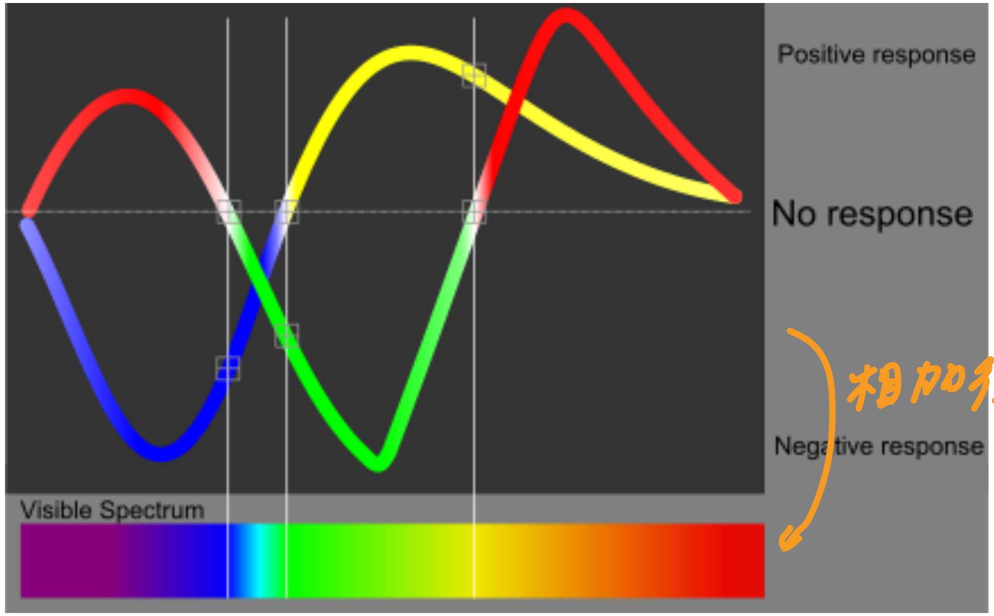



FIGURE 6.30 Color complements on the color circle.



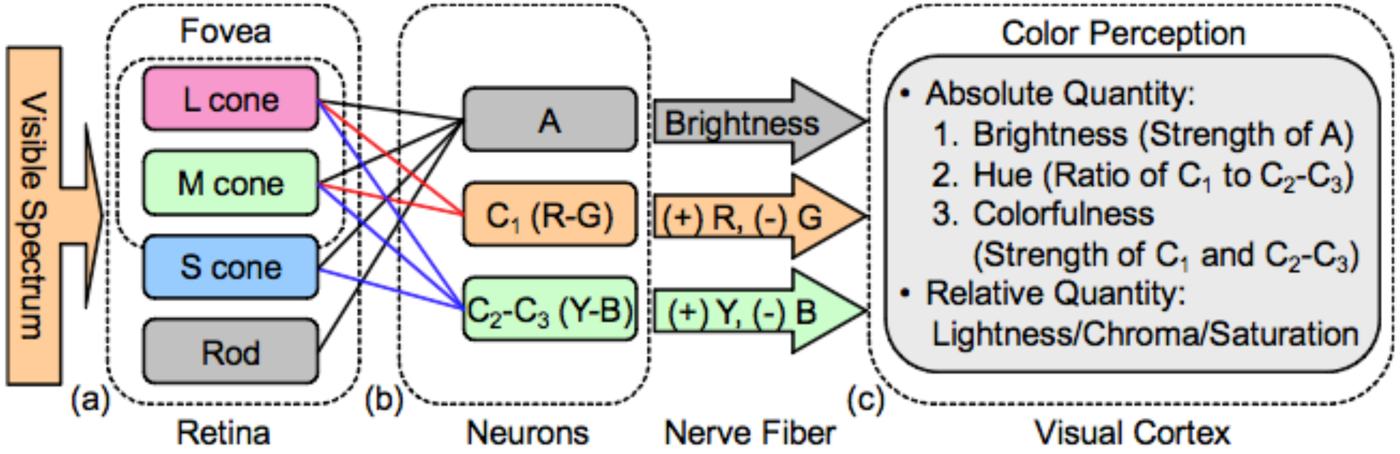

相加後

# Opponent Color Processing in CIECAM02

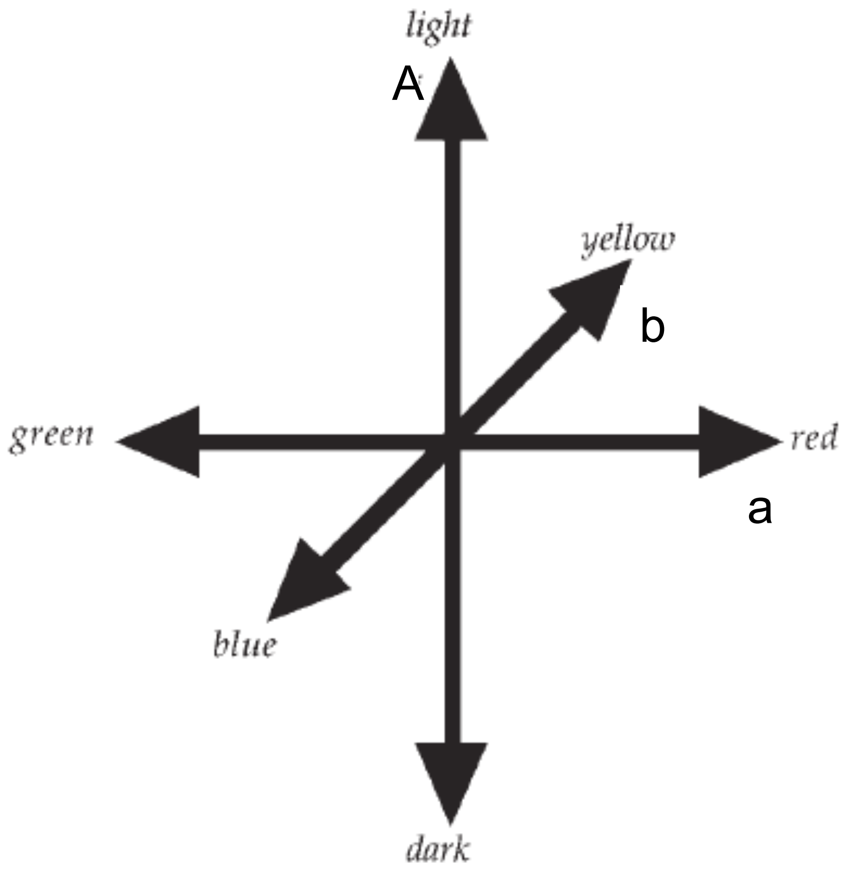
$$C_1 = L'_a - M'_a$$
$$C_2 = M'_a - S'_a$$
$$C_3 = S'_a - L'_a$$

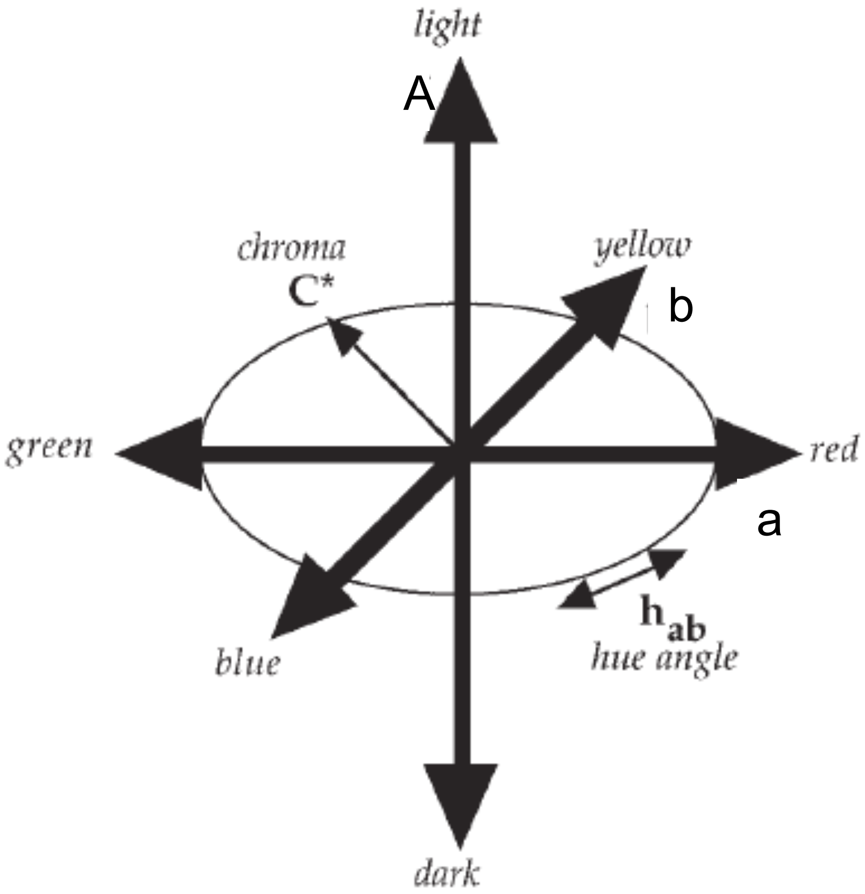
$$N_{bb} = N_{cb} = 0.725 n^{-0.2}$$
$$n = Y_b / Y_w$$

$$A = (2L'_a + M'_a + \tfrac{1}{20} S'_a - 0.305) N_{bb}$$
$$a = C_1 - \tfrac{1}{11} C_2 \qquad = L'_a - \tfrac{12}{11} M'_a + \tfrac{1}{11} S'_a$$
$$b = \tfrac{1}{2} (C_2 - C_1 + C_1 - C_3) / 4.5 \quad = \tfrac{1}{9} (L'_a + M'_a - 2S'_a)$$



# Perceptual Attributes




- The last stage of a color appearance model.
- A, a, and b are obtained from the previous slide.
- Hue angle refers to the angle of C*.

# Perceptual Attributes in CIECAM02

Hue $h = \angle(a, b),\ (0 < h < 360°)$

Lightness $J = 100\,(A/A_w)^{cz}$

Brightness $Q = (4/c)\,\sqrt{\frac{1}{100}J}\,(A_w + 4)\,F_L^{1/4}$

Chroma $C = t^{0.9}\sqrt{\frac{1}{100}J}(1.64 - 0.29^n)^{0.73}$

Colorfulness $M = C \cdot F_L^{1/4}$

Saturation $s = 100\sqrt{M/Q}$

# Summary

- Color is a psychological phenomenon
- Color matching and tristimulus colorimetry: the CIE 1931 2° Standard Observer
- Color appearance
  - Attributes definition
  - Chromatic adaptation
  - Opponent color theory
- Color appearance model example: CIECAM02

http://www.youtube.com/watch?v=VeDOpGRMZ7Y