What is Color Science?

- Quantifying the physical energy which reaches the eye (physical)
- Determining the perceptual responses of the human visual system (perceptual)
- How does the brain interpret what is seen? (cognitive)
Rainbow over London.
Visible Light Spectrum
Frequency Spectrum
Comparison of a rod cell (right) and cone cell (left). This shows how each cell acquired its name from its shape.
Visible Light Spectrum

Dominant wavelengths of human receptor system

S, M, L
How can we map a *Physical light description* to a *Perceptual color sensation*?
Question?

• Why can a TV display reproduce (almost) every color sensation that we can experience using only 3 color phosphors?

R,G,B ?
Question?

- Why can a printer reproduce (almost) every color sensation that we can experience using only 3 color inks?
Question?

How can we reproduce such a vast range of color using two completely different sets of three primary colors?
Additive Color
Subtractive Color
Printer Inks

Black  Cyan  Magenta  Yellow
Subtractive Reflection Processes
Additive & Subtractive Color Spaces

RGB

CMY
What is Color Science?

• Quantifying the physical energy which reaches the eye (physical)
• Determining the perceptual responses of the human visual system (perceptual)
• How does the brain interpret what is seen? (cognitive)
Spectral Distributions of Emissive Light Sources

Test lamp

CIE standard

- $D_{55}$: typical sunlight
- $D_{65}$: typical average daylight
- $D_{75}$: typical ‘north-sky’ light
Spectral Distributions of Emissive Light Sources

Test lamp

\[ P = \sum_{\lambda} E_{\lambda} \]

\[ = E_{400} + E_{410} + E_{420} + E_{430} + + + \]
Emitted Light

\[ P = \sum_\lambda E_\lambda \]

\[ P = \int_{390}^{700} E_\lambda \, d\lambda \]

\( P \) = energy reaching the eye at all wavelengths

\( E_\lambda \) = emitted light energy at each wavelength
Spectral Distributions of Reflective Colors
Reflected Light

\[ P = \sum_{\lambda} E_{\lambda} \] (Emitted Light)

\[ P = \sum_{\lambda} E_{\lambda} \cdot \rho_{\lambda} \]

\[ P = \text{energy reaching the eye at all wavelengths} \]

\[ E_{\lambda} = \text{emitted light energy at each wavelength} \]

\[ \rho_{\lambda} = \text{reflected light energy at each wavelength} \]

\[ P = \int_{390}^{700} E_{\lambda} \cdot \rho_{\lambda} \, d\lambda \]
Reflected Light

\[ E_\lambda \cdot \rho_\lambda \]
Transmitted Light

\[
P = \sum_{\lambda} E_{\lambda} \quad \text{(Emitted Light)}
\]

\[
P = \sum_{\lambda} E_{\lambda} \cdot \rho_{\lambda} \quad \text{(Reflected Light)}
\]

\[
P = \sum_{\lambda} E_{\lambda} \cdot T_{\lambda} \quad \text{(Transmitted Light)}
\]

\[
T_{\lambda} = \text{transmitted light energy at each wavelength}
\]
Transparency
Transparency
What is Color Science?

- Quantifying the physical energy which reaches the eye (physical)
- Determining the perceptual responses of the human visual system (perceptual)
- How does the brain interpret what is seen? (cognitive)
Cross Section of Eye & Retina
Rods and Cones
Receptor Distribution

Receptor Distribution

[Diagram showing receptor density distribution with peaks for cones and rods, and labels for temporal, fovea, and nasal areas.]
Receptor Distribution

Cone Responses

- S, M, L cones have broadband spectral sensitivity
- S, M, L neural response is integrated with respect to $\lambda$
- results in a trichromatic visual system
The relative spectral sensitivity of the L, M, and S cones (Stockman 1993). These spectral sensitivities are based on measurements in front of the eye rather than of isolated photoreceptors. Strictly speaking, these are called cone fundamentals.

Grassmann’s Color Matching Experiments (1853)

Matching a Test Lamp with 3 Primary Lights

• We can match a color sensation from *any* spectrum using only 3 primary colors (R,G,B)
Matching a Test Lamp with 3 Primary Colors

Dull Blue Green = $B_50 + G_{40} + R_{10}$
Matching a Test Lamp with 3 Primary Lights

- Need to allow “negative light”
  - Can’t match a bright yellow (Y) light with R,G,B.
  - But can match Y + B with R + G.
Matching a Test Color (Lamp) with 3 Primary Colors

\[
\begin{align*}
\text{Vivid Yellow} & \neq \text{Red} + \text{Green} \\
\text{Vivid Yellow} + 3 & = \text{Red}^{100} + \text{Green}^{100} \\
\text{Vivid Yellow} & = \text{Red}^{100} + \text{Green}^{100} - 3
\end{align*}
\]
Trichromatic Generalization

• Many colors can be matched by additive mixtures of suitable amounts of three fixed primary colors.

• Others have to be mixed with a suitable amount of one before it can be matched by the other two.

• All the colors can be matched in one of these two ways:
  – The restriction is that none of the primary colors can be matched by an additive mixture of the other two.
Proportionality and additivity are valid over a large range of observing conditions.

Proportionality -

If $A=B$, then $kA=kB$

Additivity -

If $A=B$, and $C=D$, the $A+C=B+D$
Experiment to Determine the Response Matching Functions of the Average Human Observer

Individually match the RGB primary lights to the unit values of each of the spectral lamps.
Response Matching Functions of the Average Human Observer

These are the response matching functions of the average human observer for these three primary lights.
Observer Response

Response Matching Functions

Stimulus (source x object)

Observer response

Computing Tristimulus Values with the Response Matching Functions

• For each test lamp we can compute the equivalent RGB tristimulus values using the color matching functions

\[
R = \int P(\lambda) \bar{r}(\lambda) d\lambda \\
G = \int P(\lambda) \bar{g}(\lambda) d\lambda \\
B = \int P(\lambda) \bar{b}(\lambda) d\lambda
\]
The integrated L, M, and S responses that result from the light entering the eye from an illuminated object. This can be calculated as the product of the spectral properties of the light source, the object, and the observer’s sensitivities, followed by integration over wavelength, essentially, calculating the areas under the last row of curves.
Observer Response

Stimulus (source x object) = Observer spectral sensitivity

Trichromacy

\[
S = \int P(\lambda)s(\lambda)d\lambda
\]

\[
M = \int P(\lambda)m(\lambda)d\lambda
\]

\[
L = \int P(\lambda)l(\lambda)d\lambda
\]
End...