## Visual Imaging and the Electronic Age

## Color Science

Color Spaces for User Interaction

Lecture \#8
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## 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

$$
\begin{aligned}
& R(P)=\int P(\lambda) \bar{r}(\lambda) d \lambda \\
& G(P)=\int P(\lambda) \bar{g}(\lambda) d \lambda \\
& B(P)=\int P(\lambda) \bar{b}(\lambda) d \lambda
\end{aligned}
$$

## Response Matching Functions



## Response Matching Functions

$$
\begin{aligned}
& \mathrm{R}=650 \mathrm{~nm} \\
& \mathrm{G}=530 \mathrm{~nm} \\
& \mathrm{~B}=460 \mathrm{~nm}
\end{aligned}
$$



## Transformations Between RGB and XYZ

$$
\begin{aligned}
& \left\{\begin{array}{l}
X \\
Y \\
Z
\end{array}\right\}=\left[\begin{array}{lll}
+0.607 & +0.174 & +0.200 \\
+0.299 & +0.587 & +0.114 \\
+0.000 & +0.066 & +1.111
\end{array}\right]\left\{\begin{array}{l}
R \\
G \\
B
\end{array}\right\} \\
& \left\{\begin{array}{l}
R \\
G
\end{array}\right\}=\left[\begin{array}{ccc}
1.909 & -0.532 & -0.288 \\
-0.985 & +1.997 & -0.028 \\
0.058 & -0.119 & +0.902
\end{array}\right]\left\{\begin{array}{l}
X \\
Y \\
Z
\end{array}\right\} \\
& \mathrm{R}=700 \mathrm{~nm}, \mathrm{G}=546.1 \mathrm{~nm}, \mathrm{~B}=435.8 \mathrm{~nm}
\end{aligned}
$$

## Three Identical Disks

## Receptive Fields



## Color Constancy



The most deeply shadowed regions of the church's white siding project luminances to the eye almost equal to the luminances projected by the black shingles in the direct sunlight. Yet they look very different.

## Color Constancy

- "The eye has evolved to see the world in unchanging colors,... regardless of shifting and uneven illumination."
- "The fact remains that objects retain their color identity under a great variety of lighting conditions."


## Color Constancy



## Color Constancy



## Claude Monet (1840-1926)




## Claude Monet



The basin with the Nymphea, 1899 (without cataract)


The basin with the Nymphea, 1923 (with cataract)


Claude Monet (1925) La maison vue du jardin aux roses. [House Seen from the Rose Garden]. Oil on canvas, $89 \times 100 \mathrm{~cm}$. Musée Marmottan, Paris.


Claude Monet (1925) La maison vue du jardin aux roses. [House Seen from the Rose Garden]. Oil on canvas, $81 \times 92 \mathrm{~cm}$. Musée Marmottan, Paris.


Monet in his studio at Giverny in front of one of the Nymphéas panels for the Orangerie (Room 1, South Wall)

Musée de l'Orangerie. "The Nymphéas of Claude Monet," Paris 2006


## Musée de l'Orangerie. "The Nymphéas of Claude Monet," 1920-26



A cycle of Monet's water-lily paintings, known as the Nympheas, was arranged on the ground floor of the Orangerie in 1927. The Orangerie was renovated (19992006) and the paintings are now available under direct diffused light.

## Interaction of Color <br> - Josef Albers

Yale University Press - 1971

## Albers drawing Structural Constellations




Josef Albers, Interaction of Color, 1963 Yale University, Plate XIII-1.



## Color Spaces for User Interaction

- RGB Cube
- Hexacone Model
- HSL Biconical Solid (Hue, Saturation, Lightness)
- Munsell Color System
- Others


## RGB Cube



## Hexacone Model



## Hexacone Model



## Hexacone Model

## HSV Hexagon



## HSL Double Hexagon



## Biconical Color Solid



## Biconical Color Solid



## Biconical Color Solid



## Biconical Color Solid



## Munsell Color System



## Munsell Color System



Billmeyer

## Munsell Color System



## Munsell Color System




## Munsell Color System




## Munsell Color System



## Munsell Color System



## Perceptually Uniform Color Spaces

- Chromaticity specifies the basic color (hue) of an object.
- Comparing chromaticities gives the best indicator of the color differences between two objects.
- A chromaticity diagram where equal physical distances (on the diagram) indicate equal perceptual differences would be useful.
- Why?


## MacAdam Experiments

- Subjects were shown colors of known chromaticity (luminance was held constant) and were asked to match the sample using an adjustable color source.
- Each chromaticity point studied is surrounded by an ellipse proportional in size to the standard deviation of the difference between the actual and match chromaticities.
- The ellipse indicate how rapidly the color change is perceived.


## Just Noticeable Differences (JND's) MacAdam Ellipses



Note the varying size and orientation of the ellipses.

## MacAdam Ellipses - Nonlinear Color Spaces (uvw)

$$
\begin{aligned}
& u=\frac{2 x}{(6 y-x+1.5)} \\
& v=\frac{3 y}{(6 y-x+1.5)}
\end{aligned}
$$



Basis for the CIELUV and CIELab systems


## Opponent Color Theory

## Hering 1892

- Four particular colors appear to be "unique".
- Red, Green, Blue, and Yellow
- He considered these to be the "cardinal directions" of chromaticity
- All other colors seem to be intermediate between these four


## Biconical Color Solid



## Opponent Color Theory

There are three types of color receptive fields called opponent channels.

Black - White (luminance) channel
$M+L$

Green - Red channel
M - L
Yellow - Blue channel

$$
M+L-S
$$

Red-Green


Blue-Yellow


Light-Dark



Cones interconnect in the retina, eventually leading to opponenttype signals.


## Full Color Image



## Luminance Image (Y)



## Color Addition (Red/Green Axis)(I)

## Color Addition (Yellow/Blue Axis)(Q)

## Full Color Image





End

