Fundamentals of Rendering - Image Pipeline

Introduction to Computer Graphics
Torsten Möller

© Machiraju/Möller
Reading


• Chapter 8 of “Physically Based Rendering” by Pharr&Humphreys (1st edition)

• Chapter 26+28 in Hughes, van Dam et al.

• “Illumination and Color in Computer Generated Imagery,” by Roy Hall.
Image Pipeline

 SPD → XYZ → Tone Reproduction → RGB

 Display ← Dither ← γ
Image Pipeline

SPD
Visible Light
SPD

• Light not a single wavelength
• Combination of wavelengths
• A spectrum, or spectral power distribution (SPD).
Image Pipeline

SPD → XYZ
3-Component Color

• The de facto representation of color on screen display is RGB. (additive color)
• Most printers use CMY(K), (subtractive color)
• Why?
  – Color spectrum can be represented by 3 basis functions?
Human eye and vision

• Eye is an amazing device!
  – Vision is even more so
• Yet, can trick it rather easily
• Need to understand what is important
• CG has to be tuned to perception
  – Already used three receptor fact – got RGB
The eye and the retina
Retina detectors

- 3 types of color sensors - S, M, L (cones)
  - Works for bright light
  - Peak sensitivities located at approx. 430nm, 560nm, and 610nm for "average" observer.
  - Roughly equivalent to blue, green, and red sensors
Retina detectors

• 1 type of monochrome sensor (rods)
  − Important at low light
• Next level: lots of specialized cells
  − Detect edges, corners, etc.
• Sensitive to contrast
  − Weber’s law: $DL \sim L$
Just Noticeable Differences

- Contrast: $\frac{\Delta I}{I}$
- For most intensities, contrast of 0.02 is just noticeable
- We’re sensitive to contrasts, not intensity!
Contrast

• Inner gray boxes are the same intensity
Contrast sensitivity

• In reality, different sensitivity for different frequencies
  – Max at ~8 cycles/degree
  – Look at the pictures in your book or web pictures
• Loose sensitivity in darkness
• More sensitive to achromatic changes
  – Try the same but red on green pattern
  – Practical consequence: color needs fewer bits
  • Used in video coding

© Machiraju/Möller
Constancies

• Ability to extract the same information under different conditions – approximately the same info, in fact
• Size constancy: object at 10m vs. 100m
• Lightness constancy: dusk vs. noon
• Color constancy: tungsten vs. sunlight
• Not completely clear how this happens
Adaptation

• Partially discard “average” signal
  – If everything is yellowish – ignore this
• Receptors “getting tired” of the same input
• Need some time to adapt when conditions change
  – Stepping into sunlit outside from inside
• Model “adaptation” to look more realistic
  – Viewing conditions for monitors might be very different
Image Pipeline

SPD → XYZ → Tone Reproduction
Tone Reproduction

$\sim 10^{-5} \text{ cd/m}^2$ Real world $\sim 10^5 \text{ cd/m}^2$

$\sim 1 \text{ cd/m}^2$ Monitors $\sim 100 \text{ cd/m}^2$

Same Visual Response?
Tone mapping

• Real world range (physical light energy units)
• Monitors cover very small part of it
• Sensible conversion is needed
  – Tone mapping procedure
  – Book describes a few methods
• Often ignored in many applications
  – Might calibrate Light = (1,1,1), surface = (0.5, 0.5, 0.5)
  – No “right” basis for light
  – Works because of real-world adaptation process
## Ranges

<table>
<thead>
<tr>
<th>Luminance (cd/m², or nits)</th>
<th>Sun at horizon</th>
<th>Clear sky</th>
</tr>
</thead>
<tbody>
<tr>
<td>600,000</td>
<td>60 Watt light bulb</td>
<td>Typical office</td>
</tr>
<tr>
<td>120,000</td>
<td></td>
<td>Typical computer display</td>
</tr>
<tr>
<td>8,000</td>
<td></td>
<td>Street lighting</td>
</tr>
<tr>
<td>100–1000</td>
<td></td>
<td>Cloudy moonlight</td>
</tr>
<tr>
<td>1–100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
High Dynamic Range (HDR)

• The range of light in the real world spans 10 orders of magnitude!
• A single scene’s luminance values may have as much as 4 orders of magnitude difference
• A typical CRT can only display 2 orders of magnitude
• Tone-mapping is the process of producing a good image of HDR data

2002 Reinhard et al
Automatic Dodging-and-Burning

- Details recovered by using dodging-and-burning

2002 Reinhard et al
HDR processing

• Smartphone photography: combine photos with varying exposure time
• Map HDR non-linearly into LDR 8bit JPG color channels

Contrast reduction:  Local tone mapping:
Image Pipeline

SPD → XYZ → Tone Reproduction → RGB
Colour Systems

• Response: \( R = \int w(\lambda)L(\lambda)d\lambda \)

• Detector response is linear
  – Scaled input -> scaled response
  – response(\(L_1+L_2\)) = response(L_1)+response(L_2)

• Choose three basis lights \(L_1, L_2, L_3\)
  – Record responses to them
  – Can compute response to any linear combination
  – Tristimulus theory of light

• Most color systems are just a different choice of basis lights
  – Could have “RGB” lights as a basis
Colour Systems

• Our perception registers:
  − Hue
  − Saturation
  − Lightness or brightness

• Artists often specify colours in terms of
  − Tint
  − Shade
  − Tone
Tristimulus Response

• Given spectral power distribution \( S(\lambda) \)

\[
X = \int x(\lambda)S(\lambda)d\lambda
\]

\[
Y = \int y(\lambda)S(\lambda)d\lambda
\]

\[
Z = \int z(\lambda)S(\lambda)d\lambda
\]

• Given \( S_1(\lambda) , S_2(\lambda) \), if the X, Y, and Z responses are same then they are metamers wrt to the sensor
CIE Standard

• Human perception based standard (1931), established with color matching experiment
• Standard observer: a composite of a group of 15 to 20 people
CIE Color Matching Experiment

• Basis for industrial color standards and “pointwise” color models

4.10 THE COLOR-MATCHING EXPERIMENT. The observer views a bipartite field and adjusts the intensities of the three primary lights to match the appearance of the test light. (A) A top view of the experimental apparatus. (B) The appearance of the stimuli to the observer. After Judd and Wyszecki, 1975.
CIE Experiment
CIE Experiment Result

• Three pure light sources:
  \( R = 700 \text{ nm}, \ G = 546 \text{ nm}, \ B = 438 \text{ nm} \).
  \[
  S(\lambda) = rR(\lambda) + gG(\lambda) + bB(\lambda)
  \]
  \[
  X_S = \int x(\lambda)S(\lambda)d\lambda = rX_R + gX_G + bX_B
  \]
  
  • \( r, g, b \) can be negative
CIE Experiment

We say a “negative” amount of $p_2$ was needed to make the match, because we added it to the test color’s side.

The primary color amounts needed for a match:

- $p_1$
- $p_2$
- $p_3$
CIE Color Space

• 3 hypothetical light sources, X, Y, and Z, which yield positive matching curves
• Use linear combinations of real lights, (eg –R,G-2R,B+R)
  – One of the lights is grey and has no hue
  – Two of the lights have zero luminance and provide hue
• Y: roughly corresponds to luminous efficiency characteristic of human eye

\[
X_S = 683 \int_{380}^{800} x(\lambda)S(\lambda) \, d\lambda \\
Y_S = 683 \int_{380}^{800} y(\lambda)S(\lambda) \, d\lambda \\
Z_S = 683 \int_{380}^{800} z(\lambda)S(\lambda) \, d\lambda
\]
CIE tristimulus values

• Particular way of choosing basis lights
  – Gives rise to a standard !!!
• Gives X, Y, Z colour values
  – Y corresponds to achromatic (no colour) channel
• Chromaticity values:
  – $x = X/(X+Y+Z)$; $y = Y/(X+Y+Z)$
  – Typically use $x, y, Y$
Chromaticity

- Normalize XYZ by dividing by luminance
- Project onto \( X+Y+Z=1 \)
- Doesn’t represent all visible colors, since luminous energy is not represented
Chromaticity
Chromaticity

• When 2 colors are added together, the new color lies along the straight line between the original colors
  - E.g. A is mixture of B (spectrally pure) and C (white light)
  - B - dominant wavelength
  - AC/BC (as a percentage) is excitation purity of A
  - The closer A is to C, the whiter and less pure it is.
Chromaticity

- D and E are complementary colors
- can be mixed to produce white light
- color F is a mix of G and C
- F is non-spectral, its dominant wavelength is the complement of B
Color Gamut

• area of colors that a physical device can represent
• hence - some colors can't be represented on an RGB screen
Color Gamut
Color Gamut

- no triangle can lie within the horseshoe and cover the whole area
RGB <-> XYZ

• Just a change of basis
• Need detailed monitor information to do this right
  – Used in high quality settings (movie industry, lighting design, publishing)
• Normalized (lazy) way:
  – \((1,1,1)\) in RGB <-> \((1,1,1)\) in XYZ
  – matrices exist

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
0.5149 & 0.3244 & 0.1607 \\
0.2654 & 0.6704 & 0.0642 \\
0.0248 & 0.1248 & 0.8504
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
The RGB Cube

• RGB color space is perceptually non-linear
• Dealing with $> 1.0$ and $< 0$!
• RGB space is a subset of the colors human can perceive
• Con: what is ‘bloody red’ in RGB?
Other colour spaces

• CMY(K) – used in printing
• LMS – sensor response
• HSV – popular for artists
• Lab, UVW, YUV, YCrCb, Luv,
• Opponent color space – relates to brain input:
  − R+G+B(achromatic); R+G-B(yellow-blue); R-G(red-green)
• All can be converted to/from each other
  − There are whole reference books on the subject
Differences in Color Spaces

• What is the use? For display, editing, computation, compression, …?
• Several key (very often conflicting) features may be sought after:
  – Additive (RGB) or subtractive (CMYK)
  – Separation of luminance and chromaticity
  – Equal distance between colors are equally perceivable (Lab)
CMY(K): printing

- Cyan, Magenta, Yellow (Black) – CMY(K)
- A subtractive color model

<table>
<thead>
<tr>
<th>dye color</th>
<th>absorbs</th>
<th>reflects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyan</td>
<td>red</td>
<td>blue and green</td>
</tr>
<tr>
<td>Magenta</td>
<td>green</td>
<td>blue and red</td>
</tr>
<tr>
<td>yellow</td>
<td>blue</td>
<td>red and green</td>
</tr>
<tr>
<td>Black</td>
<td>all</td>
<td>none</td>
</tr>
</tbody>
</table>
RGB and CMY

• Converting between RGB and CMY

The RGB Cube

The CMY Cube

\[
\begin{bmatrix}
C \\
M \\
Y \\
K
\end{bmatrix} = \begin{bmatrix}
\max(R, G, B) \\
\max(R, G, B) \\
\max(R, G, B) \\
1
\end{bmatrix} - \begin{bmatrix}
R \\
G \\
B \\
\max(R, G, B)
\end{bmatrix}
\]
RGB and CMY
Primary Colors

Green

Red

Blue
Secondary Colors

Green

Yellow

Cyan

Red

Blue

Magenta

© Machiraju/Möller
Tertiary Colors

- Green
- Yellow
- Cyan
- Red
- Blue
- Magenta
HSV

• This colour model is based on polar coordinates, not Cartesian coordinates.
• HSV is a non-linearly transformed (skewed) version of RGB cube
  − Hue: quantity that distinguishes colour family, say red from yellow, green from blue
  − Saturation (Chroma): colour intensity (strong to weak). Intensity of distinctive hue, or degree of colour sensation from that of white or grey
  − Value (luminance): light colour or dark colour
HSV Hexcone

• Intuitive interface to color
Munsell Atlas

Courtesy Gretag-Macbeth
Interactive Munsell Tool

• From www.munsell.com

Courtesy of Maureen Stone

© Machiraju/Möller
Luv and UVW

• A color model for which a unit change in luminance and chrominance are uniformly perceptible
• Chrominance is defined as the difference between a color and a reference white at the same luminance.
• Luv is derived from UVW and Lab, with all components guaranteed to be positive
Yuv and YCrCb: digital video

• Initially, for PAL analog video, it is now also used in CCIR 601 standard for digital video.

• Y (luminance) is the CIE Y primary.
  \[ Y = 0.299R + 0.587G + 0.114B \]

• It can be represented by U and V -- the color differences.
  \[ U = B - Y; \ V = R - Y \]

• YCrCb is a scaled and shifted version of YUV and used in JPEG and MPEG (all components are positive).

• \[ Cb = (B - Y)/1.772 + 0.5; \ Cr = (R - Y) / 1.402 + 0.5 \]
Examples (RGB, HSV, Luv)
Image Pipeline

SPD → XYZ → Tone Reproduction → RGB

γ
Colour Matching on Monitors

• Use CIE XYZ space as the standard

\[
\begin{bmatrix}
  x \\
  y \\
  z \\
\end{bmatrix} =
\begin{bmatrix}
  X_R & X_G & X_B \\
  Y_R & Y_G & Y_B \\
  Z_R & Z_G & Z_B \\
\end{bmatrix}
\begin{bmatrix}
  R \\
  G \\
  B \\
\end{bmatrix} = MC
\]

• Use a simple linear conversion

\[C_2 = M_2^{-1} M_1 C_1\]

• Color matching on printer is more difficult, approximation is needed (CMYK)
Gamma correction

http://en.wikipedia.org/wiki/Gamma_correction

© Machiraju/Möller
Gamma Correction

• displayed intensity = $a^\gamma$
• $\gamma$ is dependent on the monitor
• clever way to compute $\gamma$:
• $0.5 = a^\gamma \rightarrow \gamma = \ln 0.5 / \ln a$
Image Pipeline

SPD → XYZ → Tone Reproduction → RGB

Dither → γ
Half-toning

• If we cannot display enough intensities? reduce spatial resolution and increase intensity resolution by allowing our eyes to perform spatial integration

• example is halftoning
  – approximate 5 intensity levels with the following 2x2 patterns.
Dithering

• maintain the same spatial resolution
• diffuse the error between the ideal intensity and the closest available intensity to neighbouring pixels below and to the right
• try different scan orders to "better" diffuse the errors
• e.g. Floyd-Steinberg:

<table>
<thead>
<tr>
<th></th>
<th>7/16</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/16</td>
<td>5/16</td>
</tr>
</tbody>
</table>
Image Pipeline

SPD → XYZ → Tone Reproduction → RGB

Display → Dither → γ