Human Vision, Color and Basic Image Processing

Connelly Barnes
CS4810
University of Virginia

Acknowledgement: slides by Jason Lawrence, Misha Kazhdan, Allison Klein, Tom Funkhouser, Adam Finkelstein and David Dobkin
Outline

‣ Human Vision and Color
‣ Image Representation
‣ Reducing Color Quantization Artifacts
‣ Basic Image Processing
Human Vision

Sun

Objects in world

Human eye
Human Vision

Vision Components:
- Incoming Light
- The Human Eye

Objects in world

Sun
Typical Human Eye

- Iris
- Pupil
- Cornea
- Anterior chamber (aqueous humour)
- Posterior chamber
- Zonular fibres
- Ciliary muscle
- Suspensory ligament
- Lens
- Vitreous humour
- Choroid
- Sclera
- Retina
- Hyaloid canal
- Optic disc
- Optic nerve
- Fovea
- Retinal blood vessels
Color

- Two types of photo-sensitive cells ("photo receptors")

Rods and cones

Cones in fovea
Rods and Cones

- Rods
  - More sensitive in low light: “scotopic” vision
  - More dense near periphery
- Cones
  - Only function with higher light levels: “photopic” vision
  - Densely packed at center of eye: fovea
  - Different types of cones → color vision
Electromagnetic Spectrum

- Visible light frequencies range between ...
  - Red = $4.3 \times 10^{14}$ hertz (700nm)
  - Violet = $7.5 \times 10^{14}$ hertz (400nm)

Figures 15.1 from H&B
Visible Light

- The human eye can “see” light in the frequency range 400nm – 700nm

“White” Light

Figure 15.3 from H&B
Visible Light

- The human eye can “see” light in the frequency range 400nm – 700nm

This does not mean that we can see the difference between the different spectral distributions.

“White” Light

Figure 15.3 from H&B
Visible Light

• Color may be characterized by …
  • Hue = dominant frequency (highest peak)
  • Saturation = excitation purity (ratio of highest to rest)
  • Lightness = luminance (area under curve)
Tristimulus Theory of Color

Spectral-response functions of each of the three types of cones.

This motivates encoding color as a combination of red, green, and blue (RGB).

Figure 13.18 from FvDFH
Tristimulus Color

‣ Any distribution of light can be summarized by its effect on 3 types of cones
‣ Therefore, human perception of color is a 3-dimensional space
‣ Metamerism: different spectra, same response
‣ Color blindness: fewer than 3 types of cones
  ‣ Most commonly L cone = M cone
Color Models

- RGB
- XYZ
- CMYK
- HSV
- etc...

Different ways of parameterizing 3D space.

RGB most common and used in this class:
R=645.16nm, G=526.32nm, B=444.44nm
RGB Color Model

Plate II.3 from FvDFH
RGB Color Cube

Figures 15.11 & 15.12 from H&B
### CMY(K) Color Model

Colors are subtractive

<table>
<thead>
<tr>
<th>C</th>
<th>M</th>
<th>Y</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>White</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Cyan</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>Magenta</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>Yellow</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>Blue</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>Green</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>Red</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>Black</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td>?</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>?</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.0</td>
<td>?</td>
</tr>
</tbody>
</table>

Plate II.7 from FvDFH

Colors are subtractive
HSV Color Model

<table>
<thead>
<tr>
<th>H</th>
<th>S</th>
<th>V</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>Red</td>
</tr>
<tr>
<td>120</td>
<td>1.0</td>
<td>1.0</td>
<td>Green</td>
</tr>
<tr>
<td>240</td>
<td>1.0</td>
<td>1.0</td>
<td>Blue</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>1.0</td>
<td>White</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>0.5</td>
<td>Gray</td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>0.0</td>
<td>Black</td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
<td>1.0</td>
<td>?</td>
</tr>
<tr>
<td>270</td>
<td>0.5</td>
<td>1.0</td>
<td>?</td>
</tr>
<tr>
<td>270</td>
<td>0.0</td>
<td>0.7</td>
<td>?</td>
</tr>
</tbody>
</table>

Figure 15.16&15.17 from H&B
Outline

- Human Vision and Color
- **Image Representation**
- Reducing Color Quantization Artifacts
- Basic Image Processing
Image Representation

- What is an image?
Image Representation

- An image is a 2D rectilinear array of pixels:
  - A width x height array where each entry of the array stores a single pixel.

Continuous image

Digital image
Image Representation

- What is a pixel?

**Continuous image**

**Digital image**
Image Representation

‣ A pixel is something that captures the notion of “intensity” and possibly “color”
‣ Luminance pixels
  ‣ Grey-scale images (aka “Intensity images”)
  ‣ 0 – 1.0 or 0 – 255
‣ Red, Green, Blue pixels (RGB)
  ‣ Color images
  ‣ 0 – 1.0 or 0 – 255
# Image Resolution

- Spatial resolution: width x height pixels
- Intensity/Color resolution: n bits per pixel
- Temporal resolution: n Hz (fps)

<table>
<thead>
<tr>
<th></th>
<th>Width x Height</th>
<th>Bit Depth</th>
<th>Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTSC</td>
<td>640 x 480</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>iPhone5</td>
<td>640 x 1136</td>
<td>24</td>
<td>60</td>
</tr>
<tr>
<td>Monitor</td>
<td>1920 x 1200</td>
<td>24</td>
<td>75</td>
</tr>
<tr>
<td>CCDs</td>
<td>3000 x 2000</td>
<td>36</td>
<td>-</td>
</tr>
<tr>
<td>Laser Printer</td>
<td>6600 x 5100</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>
Image Quantization Artifacts

- With only a small number of bits associated to each color channel of a pixel there is a limit to intensity resolutions of an image
  - A black and white image allocates a single bit to the luminance channel of a pixel.
    - The number of different colors that can be represented by a pixel is 2.
  - A 24 bit bitmap image allocates 8 bits to the red, green, and blue channels of a pixel.
    - The number of different colors that can be represented by a pixel is $2^{24} = 16.8$ million.
Outline

- Human Vision
- Image Representation
- **Reducing Color Quantization Artifacts**
  - Halftoning and Dithering
- Basic Image Processing
Quantization

- Image with decreasing bits per pixel
  - Note contouring!

8 bits  4 bits  2 bits  1 bit
Quantization

- When you have a small number of bits per pixel, you can coarsely represent an image by quantizing the color values:

\[ P(x, y) = Q(I(x, y)) = \text{floor} \left( \frac{I(x, y)}{256} 2^b \right) \]

\( b \) is the number of bits per pixel
Reducing Effects of Quantization

- Trade spatial resolution for intensity resolution
- Halftoning
- Dithering
  - Random dither
  - Ordered dither
  - Error diffusion dither
Classical Halftoning

- Varying-size dots represent intensities
- Area of dots inversely proportional to intensity
Classical Halftoning

Newspaper Image

From New York Times, 9/21/99
Digital Halftoning

- Use cluster of pixels to represent intensity
- Trades spatial resolution for intensity resolution
- Note that halftoning pattern matters
  - Want to avoid vertical, horizontal lines

\[
\begin{align*}
0 \leq I & \leq 0.2 \\
0.2 < I & \leq 0.4 \\
0.4 < I & \leq 0.6 \\
0.6 < I & \leq 0.8 \\
0.8 < I & \leq 1.0
\end{align*}
\]
Digital Halftoning

- Use cluster of pixels to represent intensity
- Trades spatial resolution for intensity resolution
- Note that halftoning pattern matters

Original (8 bits)  |  Quantized (1 bit)  |  Halftoned (1 bit)
Dithering

• Distribute errors among pixels
  • Exploit spatial integration in our eye
  • Display greater range of perceptible intensities
Random Dither

- Randomize quantization errors
- Errors appear as noise

\[ P(x, y) = Q(I(x, y) + \text{noise}(x, y)) \]
Random Dither

- Randomize quantization errors
- Errors appear as noise

If a pixel is black, then adding random noise to it, you are less likely to turn it into a white pixel then if the pixel were dark gray.

\[ P(x, y) = Q(I(x, y) + \text{noise}(x, y)) \]
Random Dither

- Randomize quantization errors
- Errors appear as noise

If a pixel is black, then adding random noise to it, you are less likely to turn it into a white pixel then if the pixel were dark gray.

How much noise should we add?

\[ P(x, y) = Q(I(x, y) + \text{noise}(x, y)) \]
Random Dither

- Randomize quantization errors
- Errors appear as noise

I(x,y) → P(x, y) = Q(I(x, y) + noise(x, y))

How much noise should we add?

Enough so that we can effect rounding but not so much that we overshoot: [-0.5, 0.5]
Random Dither

Original (8 bits)  
Uniform Quantization (1 bit)  
Random Dither (1 bit)
Ordered Dither

- Pseudo-random quantization errors
- Matrix stores pattern of thresholds

For Binary Displays

\[ D_2 = \begin{bmatrix} 1 & 3 \\ 4 & 2 \end{bmatrix} \]

\[
i = x \mod n \\
j = y \mod n \\
\text{if } (I(x,y)/255 > D(i,j) / (n^2+1)) \\
P(x,y) = 1 \\
\text{else} \\
P(x,y) = 0
\]
Ordered Dither

- Pseudo-random quantization errors
- Matrix stores pattern of thresholds

For b-Bit Displays

\[
i = x \mod n \\
j = y \mod n \\
c = \left(\frac{I(x,y)}{255}\right)\times(2^b-1) \\
e = c - \text{floor}(c) \\
\text{if } (e > D(i,j) / (n^2+1) ) \\
P(x,y) = \text{ceil}(c) \\
\text{else} \\
P(x,y) = \text{floor}(c)
\]

\[
D_2 = \begin{bmatrix}
1 & 3 \\
4 & 2
\end{bmatrix}
\]
Ordered Dither

Original (8 bits)  
Random Dither (1 bit)  
Ordered Dither (1 bit)
Error Diffusion Dither

- Spread quantization error over neighbor pixels
  - Error dispersed to pixels right and below
- Floyd-Steinberg Dither Method:

\[ \alpha + \beta + \gamma + \delta = 1.0 \]

Figure 14.42 from H&B
Floyd-Steinberg Dither

\[
\begin{align*}
\text{for } (i = 0; & \ i < \text{width}; \ i++) \\
& \text{for } (j = 0; \ j < \text{height}; \ j++) \\
& \quad \text{Dest}[i,j] = \text{quantize(Source}[i,j]) \\
& \quad \text{error} = \text{Source}[i,j] - \text{Dest}[i,j] \\
& \quad \text{Source}[i,j+1] = \text{Source}[i,j+1] + \alpha \cdot \text{error} \\
& \quad \text{Source}[i+1,j-1] = \text{Source}[i+1,j-1] + \beta \cdot \text{error} \\
& \quad \text{Source}[i+1,j] = \text{Source}[i+1,j] + \gamma \cdot \text{error} \\
& \quad \text{Source}[i+1,j+1] = \text{Source}[i+1,j+1] + \delta \cdot \text{error}
\end{align*}
\]

\[\alpha = \frac{7}{16} \quad \beta = \frac{3}{16} \quad \gamma = \frac{5}{16} \quad \delta = \frac{1}{16}\]
Floyd-Steinberg Dither

Original (8 bits)

Random Dither (1 bit)

Ordered Dither (1 bit)

Floyd-Steinberg Dither (1 bit)
Outline

- Human Vision
- Image Representation
- Reducing Color Quantization Artifacts
- **Basic Image Processing**
  - Single Pixel Operations
  - Multi-Pixel Operations
Computing Grayscale

- The human retina perceives red, green, and blue as having different levels of brightness.
- To compute the luminance (perceived brightness) of a pixel, we need to take the weighted average of the RGBs: \( L = 0.30 \times r + 0.59 \times g + 0.11 \times b \)
Adjusting Brightness

- Simply scale pixel components
  - Must clamp to range (e.g., 0 to 255)

![Original](image1.png)  ![Brighter](image2.png)
Adjusting Contrast

- Compute mean luminance $L$ for all pixels
  - $L = 0.30*r + 0.59*g + 0.11*b$
- Scale deviation from $L$ for each pixel component
  - Must clamp to range (e.g., 0 to 255)
Adjusting Saturation

- Compute luminance $L(p)$ for each pixel $p$
  - $L(p) = 0.30*r(p) + 0.59*g(p) + 0.11*b(p)$
- Scale deviation from $L(p)$ for each pixel component (RGB)
  - Must clamp to range (e.g., 0 to 255)
Image Processing by Interpolation

- Nice discussion of these operations:
  http://www.graficaobscura.com/interp/index.html
Image Processing by Interpolation

- Nice discussion of these operations:
  http://www.graficaobscura.com/interp/index.html

\[ \text{out} = (1-\alpha) \ast \text{in0} + \alpha \ast \text{in1} \]
Image Processing by Interpolation

- Nice discussion of these operations:
  http://www.graficaobscura.com/interp/index.html

\[
\text{out} = (1 - \alpha)\text{in0} + \alpha\text{in1}
\]
Image Processing by Interpolation

- Nice discussion of these operations: http://www.graficaobscura.com/interp/index.html

\[ \text{out} = (1-\alpha)\times \text{in0} + \alpha \times \text{in1} \]