Color & Demosaicking

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MIT EECS 6.815/6.865
Color

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**Big picture**

- It’s all linear!
  - multiply
  - add
- But
  - non-orthogonal basis
  - infinite dimension
  - light must be positive
- Depends on light source

Light reflectance multiply

Stimulus

Cone responses

Multiply wavelength by wavelength

Integrate
Good news: color reproduction

- 3 primaries are (to a first order) enough to reproduce all colors
Recap

• Spectrum: infinite number of values
• projected according to cone spectral response
  => 3 values
• metamers: spectra that induce the same response
  (physically different but look the same)

• Questions?
Questions?

Meryon (a colorblind painter), *Le Vaisseau Fantôme*
Analysis & Synthesis

- Now let’s talk about technology
- We want to measure & reproduce color as seen by humans
- No need for full spectrum
- Only need to match up to metamerism
3 primary colors
adjust amount of red, green, blue
-> recreate any physical color

http://www.iriscam.info/PIXELS.html
Analysis & Synthesis

- Focus on additive color synthesis
- We’ll use 3 primaries (e.g. red green and blue) to match all colors

What should those primaries be?
How do we tell the amount of each primary needed to reproduce a given target color?

http://www.iriscam.info/PIXELS.html
Additive Synthesis - wrong way
Additive Synthesis - wrong way

\[ \mathbf{V} = (\mathbf{v}_1, \mathbf{v}_2) \]

\[ \text{orthogonal} \]

\[ \mathbf{V} = (\mathbf{v}_1, \mathbf{v}_2) + (\mathbf{w}_1, \mathbf{w}_2) \]
Additive Synthesis - wrong way
Additive Synthesis - wrong way

Not orthogonal!
Additive Synthesis - wrong way

- Take a given stimulus and the corresponding responses s, m, l (here 0.5, 0, 0)
Additive Synthesis - wrong way

- Use it to scale the cone spectra (here 0.5 * S)
- You don’t get the same cone response! (here 0.5, 0.1, 0.1)
What’s going on?

- The three cone responses are not orthogonal
- i.e. they overlap and “pollute” each other
Geometry
Warning: Tricky thing with color

- Spectrum for the stimulus / synthesis
  - Light, monitor, reflectance

- Response curve for receptor / analysis
  - Cones, camera, scanner

often different
can't directly use same spectrum for analysis & synthesis
Warning: Tricky thing with color

- Spectrum for the stimulus / synthesis
  - Light, monitor, reflectance
- Response curve for receptor / analysis
  - Cones, camera, scanner

Usually not the same

Because cone responses are not orthogonal
Questions?
CIE color matching
Standard color spaces

• We need a well-agreed color space
• Many possible definition
  – Including cone response (LMS)
  – Unfortunately not really used, (because not known when colorimetry was invented)

• The good news is that color vision is linear and 3-dimensional, so any new color space based on color matching can be obtained using 3x3 matrix
  – But there are also non-linear color spaces (e.g. Hue Saturation Value, Lab)
Overview

- Most standard color space: CIE XYZ
- LMS and the various flavors of RGB are just linear transformations of the XYZ basis
  - 3x3 matrices
Why not measure cone sensitivity?
Why not measure cone sensitivity?

- Less directly measurable
  - electrode in photoreceptor?
  - not available when color spaces were defined
Why not measure cone sensitivity?

- Less directly measurable
  - electrode in photoreceptor?
  - not available when color spaces were defined

- Most directly available measurement:
  - notion of metamers & color matching
  - directly in terms of color reproduction: given an input color, how to reproduce it with 3 primary colors?

- Commission Internationale de l’Eclairage (International Lighting Commission)
- Circa 1920
CIE color matching

• Given an input color, how to reproduce it with 3 primary colors?
  – (Idea by Maxwell)
CIE color matching

- Primaries (synthesis) at 435.8, 546.1 and 700nm
  - Chosen for robust reproduction, good separation in red-green
  - Don’t worry, we’ll be able to convert it to any other set of primaries (Linear algebra to the rescue!)

- Resulting 3 numbers for each input wavelength are called tristimulus values
Applet

- [http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html](http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html)
Color Matching Problem
Color Matching Problem

• Some colors cannot be produced using only positively weighted primaries
Color Matching Problem

- Some colors cannot be produced using only positively weighted primaries
- Solution: add light on the other side!
CIE color matching

• Meaning of these curves: a monochromatic wavelength $\lambda$ can be reproduced with $b(\lambda)$ amount of the 435.8 nm primary, $+g(\lambda)$ amount of the 546.1 primary, $+r(\lambda)$ amount of the 700 nm primary

• This fully specifies the color perceived by a human

• Careful: this is not your usual rgb
CIE color matching: what does it mean?

These curves are the color-matching functions for the 1931 standard observer. The average results of 17 color-normal observers having matched each wavelength of the equal-energy spectrum with primaries of 435.8 nm, 546.1 nm, and 700 nm.
CIE color matching: what does it mean?

- If I have a given spectrum X
- I compute its response to the 3 matching curves (multiply and integrate)
- I use these 3 responses to scale my 3 primaries (435.8, 546.1 and 700nm)
- I get a metamer of X (perfect color reproduction)
Relation to cone curves

• Project to the same subspace
  – b, g, and r are linear combinations of S, M and L

• Related by 3x3 matrix.

• Unfortunately unknown at that time. This would have made life a lot easier!
Recap

- Spectra: infinite dimensional
- Cones: 3 spectral responses
- Metamers: spectra that look the same (same projection onto cone responses)
- CIE measured color response:
  - chose 3 primaries
  - tristimulus curves to reproduce any wavelength

Questions?
How to build a measurement device?

• Idea:
  – Start with light sensor sensitive to all wavelength
  – Use three filters with spectra b, r, g
  – measure 3 numbers

• This is pretty much what the eyes do!
CIE’s problem

Idea:
- Start with light sensor sensitive to all wavelength
- Use three filters with spectra b, r, g
- Measure 3 numbers

But for those primaries, we need negative spectra
CIE’s problem

• Obvious solution: use cone response!
  – but unknown at the time

• => new set of tristimulus curves
  – linear combinations of b, g, r
  – pretty much add enough b and g until r is positive
CIE XYZ space

• The most standard color space
• Based on tristimulus curves
• Y corresponds to luminance/brightness
• Linear transform compared to RGB or LMS

\[
\begin{bmatrix}
L \\
M \\
S
\end{bmatrix}
= \begin{bmatrix}
0.8951 & 0.2664 & -0.1614 \\
-0.7502 & 1.7135 & 0.0367 \\
0.0389 & -0.0685 & 1.0296
\end{bmatrix}
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]
CIE’s problem

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### XYZ to RGB & back


<table>
<thead>
<tr>
<th>sRGB to XYZ</th>
<th>XYZ to sRGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.412424 0.212656 0.0193324</td>
<td>3.24071 -0.969258 0.0556352</td>
</tr>
<tr>
<td>0.357579 0.715158 0.119193</td>
<td>-1.53726 1.87599 -0.203996</td>
</tr>
<tr>
<td>0.180464 0.0721856 0.950444</td>
<td>-0.498571 0.0415557 1.05707</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Adobe RGB to XYZ</th>
<th>XYZ to Adobe RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.576700 0.297361 0.0270328</td>
<td>2.04148 -0.969258 0.0134455</td>
</tr>
<tr>
<td>0.185556 0.627355 0.0706879</td>
<td>-0.564977 1.87599 -0.118373</td>
</tr>
<tr>
<td>0.188212 0.0752847 0.991248</td>
<td>-0.344713 0.0415557 1.01527</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NTSC RGB to XYZ</th>
<th>XYZ to NTSC RGB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.606734 0.298839 0.000000</td>
<td>1.91049 -0.984310 0.0583744</td>
</tr>
<tr>
<td>0.173564 0.586811 0.0661196</td>
<td>-0.532592 1.99845 -0.118518</td>
</tr>
<tr>
<td>0.200112 0.114350 1.11491</td>
<td>-0.288284 -0.0282980 0.898611</td>
</tr>
</tbody>
</table>
CIE XYZ space: QUESTIONS?

- The most standard color space
- Based on tristimulus curves
- Y corresponds to luminance/brightness
- Linear transform compared to RGB or LMS

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\]

The 1931 standard observer, as it is usually shown.
Chromaticity diagram
Chromaticity diagrams: motivation

• 3D space are tough to visualize

• Chrominance is our notion of color, as opposed to brightness/luminance

• Recall that our eyes correct for multiplicative scale factors
  ➖ discount light intensity
Chromaticity diagrams

• Project XYZ to 2D
• normalize against by $X + Y + Z$:

$$x = \frac{X}{X+Y+Z}; \quad y = \frac{Y}{X+Y+Z};$$

—equivalent to perspective projection to plane $X+Y+Z=1$
Applet

- [http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html](http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html)
Color gamut
Color gamut

• Given 3 primaries
• The realisable chromaticities lay in the triangle in xy chromaticity diagram
• Because we can only add light, no negative light
RGB limitations

- [http://dba.med.sc.edu/price/irf/Adobe_tg/manage/images/gamuts.jpg](http://dba.med.sc.edu/price/irf/Adobe_tg/manage/images/gamuts.jpg)
- [http://www.petrvodnakphotography.com/Articles/ColorSpace.htm](http://www.petrvodnakphotography.com/Articles/ColorSpace.htm)
Recap

• Metamers enable color reproduction
• CIE defined XYZ using color matching experiments
• Linear transform to/from RGB or LMS
• Chromaticity diagram: 2D version, remove luminance
• Lack of negative numbers makes life hard
Questions?

- Chromaticity of crayons
Take home message

• Cone spectra are non-orthogonal
• Analysis spectrum (camera, eyes) cannot be the same as synthesis one (display)
• Impossible to encode all possible colors without something negative
  - CIE XYZ only needs positive coordinates, but would need primaries with negative light
  - RGB can use physical (non-negative) primaries, but needs negative coordinates for some colors
Selected Bibliography

Vision Science
by Stephen E. Palmer
760 pages (May 7, 1999)

Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition
by Roy S. Berns, Fred W. Billmeyer, Max Saltzman
304 pages 3 edition (March 31, 2000)

Vision and Art: The Biology of Seeing
by Margaret Livingstone, David H. Hubel
208 pages (May 2002)
Selected Bibliography

The Reproduction of Color
by R. W. G. Hunt
Fountain Press, 1995

Color Appearance Models
by Mark Fairchild
Addison Wesley, 1998
Questions?

VIII. Philipp Otto Runge, Colour Sphere, 1809, Hamburg Kunsthalle.
Check out the demo applets

- [http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html](http://graphics.stanford.edu/courses/cs178-10/applets/colormatching.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html](http://graphics.stanford.edu/courses/cs178-10/applets/threedgamut.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/gamutmapping.html](http://graphics.stanford.edu/courses/cs178-10/applets/gamutmapping.html)
- [http://graphics.stanford.edu/courses/cs178-10/applets/gamma.html](http://graphics.stanford.edu/courses/cs178-10/applets/gamma.html)
Color acquisition
Color sampling

• Problem: a photosite can record only one number
• We need 3 numbers for color
• What can we do?
What are some approaches to sensing color images?

- Scan 3 times (temporal multiplexing)
- Use 3 detectors (3-ccd camera)
- Use offset color sample (spatial multiplexing)
- Multiplex in depth (Tripack film, Foveon)
- Interferences (Lipmann)
Temporal multiplexing

- Examples:
  - Drum scanners
  - Flat-bed scanners
  - Maxwell, Russian photographs from 1900’s

- Pros:
  - 3 real values per pixel
  - Can use a single sensor

- Cons
  - Only for static scenes, slow
Prokudin-Gorskii

- Early 1900s
- Pset 4 for 6.865
3-chip

• High-end 3-ccd video cameras
• Use separation prisms
  – prisms that split wavelengths
• Pros
  – 3 real values per pixel
  – Little photon loss
• Cons
  – costly (needs 3 sensors)
  – space
Prokudin-Gorskii

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- High-end 3-ccd video cameras
- Use separation prisms
  - prisms that split wavelengths
- Pros
  - 3 real values per pixel
  - Little photon loss
- Cons
  - costly (needs 3 sensors)
  - space
Brewster’s version

• Swiss cheese mirror

Diagram of the Camera.
A—Lens.  B—Shutter.
C—Rubber tubing in bulb.
Spatial multiplexing

• Human eye (cone mosaic)
• Older color film (Autochrome)
• Bayer mosaic or CFA (color filter array)
• Most still cameras, most cheap camcorder, some high-end video cameras (e.g. RED)

• Pros
  – single sensor
  – well mastered technology, high resolution

• Cons
  – needs interpolation, color jaggies
  – requires antialiasing filter (reduces sharpness)
  – loss of light
Combination: pixel shift

- 3-ccd with prisms + spatial multiplexing
- The 3 ccds are shifted by 1/2 pixel to provide resolution increase
  - usually selectable (not shifted for lower-res, shifted to get HD)
  - Often horizontal only

From Panasonic
Depth multiplexing (Foveon X3 sensor)

- Leverage difference in absorption per wavelength
- Pros
  - 3 real numbers per pixel
  - Less light loss
- Cons
  - Requires more color processing (3 numbers must be multiplied by matrix to get RGB)
  - Tends to be noisier (because color processing and because shallow blue layer)
Depth multiplexing

- Good old color film (tripack)
Interferences (Lippmann process)

- Metal mirror to create interferences
  - ancestor of holography
  - similar to colors in thin oil film

http://nobelprize.org/nobel_prizes/physics/articles/biedermann/index.html
Interferences (Lippmann process)

- Metal mirror to create interferences
  - ancestor of holography
  - similar to colors in thin oil film

- Pros
  - Full spectrum!!!!!!
  - Gets you the Nobel if you invent it ;-)

- Cons
  - Needs high-resolution sensor/film
  - limited field of view for display

'Saint-Maxime', 1891-1899
Photographer: Gabriel Lippmann (1845-1929)
Recap & Questions?

• Scan 3 times  
  (temporal multiplexing)

• Use 3 detectors 
  (3-ccd camera)

• Use offset color sample 
  (spatial multiplexing)

• Multiplex in depth 
  (Tripack film, Foveon)

• Interferences (Lipmann)
Bayer mosaic
Sensor

Microscope view of a CCD

• By kevincollins123

http://www.flickr.com/photos/kevincollins123/4584180753/
Bayer RGB mosaic

• Each photosite has a different color filter

Note that which one is the upper left color is arbitrary and depends on the camera
Bayer RGB mosaic

• Why more green?
Bayer RGB mosaic

• Why more green?
  – We have 3 channels and square lattices don’t like odd numbers
  – It’s the spectrum “in the middle”
  – More important to human perception of luminance
RAW files

- Straight measurement from sensor
  - right after A/D conversion
  - (well, kind of)
- Each photosite has only one value
  - Filtered by R, G or B
- Usually 12-14 bits per pixel
- Linear encoding
  - No gamma!
- Can be read and converted using dcraw
  - ./dcrawx86 -v -d pics/DSC_8274.nef
How to get linear files

- http://www.mit.edu/~kimo/blog/linear.html
A RAW file

- From a Nikon D70
Demosaicking
Demosaicing

- Interpolate missing values
Demosaicing

- Simplest solution: downsample!
  - Nearest-neighbor reconstruction
- Problem: resolution loss (and megapixels are so important for marketing!)
**Linear interpolation**

- Average of the 4 or 2 nearest neighbors
  - Linear (tent) kernel

- For example:

  \[
  \text{newgreen} = \frac{1}{4} \left( \text{up} + \text{left} + \text{right} + \text{down} \right)
  \]
Linear interpolation

• Average of the 4 or 2 nearest neighbors
  – Linear (tent) kernel

• For example:
  newgreen = 0.25(up + left + right + down)
Better

• Smoother kernels can also be used (e.g. bicubic) but need wider support
Results of simple linear
Results - not perfect
Questions?

NO

PER ORDER MIT CAMPUS POLICE

NO

NO

NO
The problem

• Imagine a black-on-white corner
• Let’s focus on the green channel for now
The problem

- Imagine a black-on-white corner
The problem

- Imagine a black-on-white corner
The problem

- Imagine a black-on-white corner
Yep, that’s what we saw
Green channel
Edge-based Demosaicking
Idea

- Take into account structure in image
  - Here, 1D edges
- Interpolate along preferred direction
  - In our case, only use 2 neighbors
Idea

• Take into account structure in image
  - Here, 1D edges
• Interpolate along preferred direction
  - In our case, only use 2 neighbors
How do we decide

- Look at the similarity of recorded neighbors
  - Compare up-down and right-left
  - Be smart
  - See pset 4

- Called edge-based demosaicking
Green channel -- naive
Green channel -- edge-based
Challenge with other channels
Problem

• What do we do with red and blue?
• We could apply the edge-based principle
• But we’re missing more information
• But color transitions might be shifted
Example

- Black on white corner
- Even if we imagine we can do some decent job for each channel
Example

- Black on white corner
- Even if we imagine we can do some decent job for each channel
- The channels don’t line up
  - Because they are not recorded at the same
Example

- Bad color fringes!
Recall color artifacts
Green-based Demosaicking
Green-based demosaicking

• Green is a better color channel
  - Twice as many pixels
  - Often better SNR
  - We know how to do edge-based green interpolation

• Do the best job you can and get high resolution from green

• Then use green to guide red & blue interpolation
Interpolate difference to green

- Interpolate green
  - using e.g. edge-based
- For recorded red pixels
  - compute R-G
- At empty pixels
  - Interpolate R-G naively
  - Add G
- Same for blue
Black on white corner
Measurements
Edge-based green
Red-Green difference

- Zero everywhere!
Red-Green interpolation

• Easy!
Add back green
Same for blue
Fully naive
Edge-based green, naive red blue
Green-based blue and red
Still not 100% perfect

- But will be good enough for pset 4
Questions?
Alternative

- Interpolate ratio
Edge cases

Denoising & Demosaicking

Demosaick+denoise+…

Demosaicking inversion

Links

• http://www.csee.wvu.edu/~xinl/papers/demosaicing_survey.pdf
• http://www.unc.edu/~rjean/demosaicing/demosaicing.pdf
• http://www.pages.drexel.edu/~par24/rawhistogram/40D_Demosaicing/40D_DemosaicingArtifacts.html
• http://www.guillermoluijk.com/tutorial/dcraw/index_en.htm
• http://www.cambridgeincolour.com/tutorials/RAW-file-format.htm
• http://www.cambridgeincolour.com/tutorials/camera-sensors.htm
More

• http://www.ists.dartmouth.edu/library/edf0205.pdf