Demosaicking

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MIT EECS 6.815/6.865
Color 101
4.1 **NEWTON’S SUMMARY DRAWING** of his experiments with light. Using a point source of light and a prism, Newton separated sunlight into its fundamental components. By reconverging the rays, he also showed that the decomposition is reversible.

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Light is a wave  
Visible: between 450 and 700nm
Light is characterized by its spectrum:
amount of energy at each wavelength
This is a full distribution:
one value per wavelength (infinite number of values)
CD spectrograph

Light-matter interaction

Where spectra come from:
- light source spectrum
- object reflectance (aka spectral albedo)
get multiplied wavelength by wavelength

There are different physical processes that explain this multiplication
  e.g. absorption, interferences

Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995
Spectrum demo

• Diffraction grating:
  – shifts light as a function of wavelength
  – Allows you to see spectra
  – In particular, using a slit light source, we get a nice band showing the spectrum

• See the effect of filters
• See different light source spectra

Source: Canon red book

Tuesday, September 24, 13
Questions?

• So far, physical side of colors: spectra
  – an infinite number of values
    (one per wavelength)
Plan

- Spectra
- **Cones and spectral response**
- Color blindness and metamers
- Color matching
- Color spaces
What is Color?

Reflectance Spectrum

Electromagnetic Wave

Illuminant D65

Spectral Power Distribution

Slide from Victor Ostromoukhov
What is Color?

- Reflectance Spectrum

- Neon Lamp

- Spectral Power Distribution

- Illuminant F1

- Spectral Power Distribution Under D65

- Spectral Power Distribution Under F1

Slide from Victor Ostromoukhov
What is Color?

Stimulus

Observer

Slide from Victor Ostromoukhov
What is Color?

Spectral Sensibility of the L, M and S Cones

Slide from Victor Ostromoukhov

Tuesday, September 24, 13
Cones

- We focus on low-level aspects of color
  - Cones and early processing in the retina
- We won’t talk about rods (night vision)
Summary (and time for questions)

• Spectrum: infinite number of values
  – can be multiplied
  – can be added

• Light spectrum multiplied by reflectance spectrum
  – spectrum depends on illuminant

• Human visual system is complicated
Plan

• What is color
• Cones and spectral response
• Color blindness and metamers
• Fundamental difficulty with colors
Cone spectral sensitivity

- Short, Medium and Long wavelength
- Response for a cone

\[ \int_{\lambda} \text{stimulus}(\lambda) \times \text{response}(\lambda) \, d\lambda \]
Cone response

Start from infinite number of values (one per wavelength)

End up with 3 values (one per cone type)

Stimulus

Multiply wavelength by wavelength

Integrate

1 number 1 number 1 number
For matrix lovers

- Spectrum: big long vector size $N$ where $N=\infty$
- Cone response: $3 \times N$ matrix of individual responses

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**Cone spectral response**

<table>
<thead>
<tr>
<th>S</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
</table>

**Kind of RGB**

**Observed spectrum**
Big picture

- It’s all linear!

Light reflectance multiply

Stimulus

Cone responses

Multiply wavelength by wavelength

Integrate
**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
Questions?

Light reflectance

Multiply

Stimulus

Cone responses

Multiply wavelength by wavelength

Integrate
A cone does not “see” colors

- Different wavelength, different intensity
- Same response
Response comparison

- Different wavelength, different intensity
- But different response for different cones

![Graph showing response comparison for different wavelengths and intensities for different cones.](image-url)
von Helmholtz 1859: Trichromatic theory

- Colors as relative responses (ratios)

Violet
Blue
Green
Yellow
Orange
Red

- Short wavelength receptors
- Medium wavelength receptors
- Long wavelength receptors

Wavelengths (nm)

400 500 600 700
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
• http://en.wikipedia.org/wiki/Prokudin-Gorskii
• 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
Brewster’s version

- Swiss cheese mirror

Diagram of the Camera.
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 provided resolution increase
  - usually selectable (not shifted for lower-res, shifted to get HD)
  - Often horizontal only
• http://www.petapixel.com/2011/05/26/hasselblad-h4d-200ms-shoots-200mp-photos-with-a-50mp-sensor/
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?
  – 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
• 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

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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:
  \[ \text{newgreen} = 0.25(\text{up} + \text{left} + \text{right} + \text{down}) \]
Better

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

```
0 0 1
0 0 1
0 0 1
0 0 1
1 1 1
```
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
- Notion of edge-based unclear for pixels in empty rows or columns
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

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Denoising & Demosaicking

Demosaicking inversion

Links

More

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