Recap so far

• What is an image?
  – Sampling and aliasing
  – Thinking in frequency

• Image filtering
  – Kernels and their responses
  – Kernel orientation
  – Kernel sizes and scale spaces

• Local features
  – Detection by finding corners via peaks
  – Description by hand-coding local ‘texture’
  – Matching robustly
Elephant in room: COLOR
Grayscale intensity
Color
Images in Python Numpy

N x M RGB image “im”
- \( \text{im}[0,0,0] \) = top-left pixel value in R-channel
- \( \text{Im}[x, y, b] \) = \( x \) pixels to right, \( y \) pixels down in the \( b \)th channel
- \( \text{Im}[N-1, M-1, 3] \) = bottom-right pixel in B-channel

<table>
<thead>
<tr>
<th>Row</th>
<th>Column</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.93</td>
<td>0.94</td>
<td>0.97</td>
<td>0.62</td>
</tr>
<tr>
<td>0.95</td>
<td>0.89</td>
<td>0.82</td>
<td>0.89</td>
<td>0.56</td>
</tr>
<tr>
<td>0.89</td>
<td>0.72</td>
<td>0.51</td>
<td>0.55</td>
<td>0.51</td>
</tr>
<tr>
<td>0.96</td>
<td>0.95</td>
<td>0.88</td>
<td>0.94</td>
<td>0.56</td>
</tr>
<tr>
<td>0.71</td>
<td>0.81</td>
<td>0.81</td>
<td>0.87</td>
<td>0.57</td>
</tr>
<tr>
<td>0.49</td>
<td>0.62</td>
<td>0.60</td>
<td>0.58</td>
<td>0.50</td>
</tr>
<tr>
<td>0.86</td>
<td>0.84</td>
<td>0.74</td>
<td>0.58</td>
<td>0.51</td>
</tr>
<tr>
<td>0.96</td>
<td>0.67</td>
<td>0.54</td>
<td>0.85</td>
<td>0.48</td>
</tr>
<tr>
<td>0.69</td>
<td>0.73</td>
<td>0.90</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>0.91</td>
<td>0.94</td>
<td>0.89</td>
<td>0.49</td>
<td>0.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Row</th>
<th>Column</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.92</td>
<td>0.99</td>
<td>0.92</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>0.95</td>
<td>0.91</td>
<td>0.95</td>
<td>0.91</td>
<td>0.95</td>
</tr>
<tr>
<td>0.91</td>
<td>0.92</td>
<td>0.91</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>0.97</td>
<td>0.95</td>
<td>0.97</td>
<td>0.95</td>
<td>0.97</td>
</tr>
<tr>
<td>0.79</td>
<td>0.85</td>
<td>0.79</td>
<td>0.85</td>
<td>0.79</td>
</tr>
<tr>
<td>0.45</td>
<td>0.33</td>
<td>0.45</td>
<td>0.33</td>
<td>0.45</td>
</tr>
<tr>
<td>0.49</td>
<td>0.74</td>
<td>0.49</td>
<td>0.74</td>
<td>0.49</td>
</tr>
<tr>
<td>0.82</td>
<td>0.93</td>
<td>0.82</td>
<td>0.93</td>
<td>0.82</td>
</tr>
<tr>
<td>0.90</td>
<td>0.99</td>
<td>0.90</td>
<td>0.99</td>
<td>0.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Row</th>
<th>Column</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>0.73</td>
<td>0.90</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>0.91</td>
<td>0.94</td>
<td>0.89</td>
<td>0.49</td>
<td>0.41</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Row</th>
<th>Column</th>
<th>R</th>
<th>G</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.79</td>
<td>0.73</td>
<td>0.90</td>
<td>0.67</td>
<td>0.33</td>
</tr>
<tr>
<td>0.91</td>
<td>0.94</td>
<td>0.89</td>
<td>0.49</td>
<td>0.41</td>
</tr>
</tbody>
</table>

James Hays
But what is color?

ANATOMY
• The human eye is a camera
  – **Iris** - colored annulus with radial muscles
  – **Pupil** - the hole (aperture) whose size is controlled by the iris
  – What’s the sensor?
    – photoreceptor cells (rods and cones) in the **retina**
The Retina

Axon = nerve fibre
Ganglion cell = a neuron (nerve cell)
Bipolar cell = pass ‘graded signal changes’
Wait, the blood vessels are in front of the photoreceptors??

https://www.youtube.com/watch?v=L_W-IXqoxHA
What humans don’t have: tapetum lucidum

Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.
Tapetum lucidum exposed (cow eye)
Two types of light-sensitive receptors

**Cone**
- cone-shaped
- less sensitive
- operate in high light
- color vision

**Rods**
- rod-shaped
- highly sensitive
- operate at night
- gray-scale vision
Night Sky: why are there more stars off-center?
Does the eye alias?

Spatially, apparently not. The retina (sensor) has high resolution, but the optics (lens) of the eye cannot meet that resolution. The image is blurred optically before being sampled (removes high-frequency content!)

[Thanks to Leslie Bresnahan]
Electromagnetic Spectrum

Wavelength of light and its perceived color

http://www.yorku.ca/eye/photopik.htm
Physiology of Color Vision

Three kinds of cones:

- S: Short (440 nm)
- M: Medium (530 nm)
- L: Long (560 nm)

Cone mosaic
Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.
Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight
Some examples of the reflectance spectra of surfaces

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>% Photons Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
</tr>
<tr>
<td>Purple</td>
<td></td>
</tr>
</tbody>
</table>
Physiology of Color Vision

Three kinds of cones:

- Why are M and L cones so close?
- Why are there 3?
Electromagnetic Spectrum

Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm
• Most birds, and many other animals, have cones for ultraviolet light.
• Some humans seem to have four cones (12% of females).
• True tetrachromatism is _rare_; requires learning.
Bee vision
Mantis Shrimp

• 16 photoreceptor types
Impossible Colors

Can you make the cones respond in ways that typical light spectra never would?

http://en.wikipedia.org/wiki/Impossible_colors
CHIMERICIAL COLOR DEMO TEMPLATES

Fatigue template (stare at "x")  Target field (glance at "x")  Approximate Rendering

STYGIAN BLUE (simultaneously deep blue and black)

SELF-LUMINOUS RED (simultaneously red and brighter than white)

HYPERBOLIC ORANGE (more than 100% color saturation)
What is color?

Why do we even care about human vision in this class?
Why do we care about human vision?

• We don’t, necessarily.

• But biological vision shows that it is possible to make important judgements from images.
Why do we care about human vision?

• We don’t, necessarily.

• But biological vision shows that it is possible to make important judgements from images.

• It’s a human world -> cameras imitate the frequency response of the human eye to try to see as we see.
Ornithopters
"Can machines fly like a bird?"
No, because airplanes don’t flap.

"Can machines fly?"
Yes, but airplanes use a different mechanism.

"Can machines perceive?"
Is this question like the first, or like the second?

Adapted from Peter Norvig
Cameras with Three Sensors

[Edmund Optics; Adam Wilt]
Color Sensing in Camera (RGB)

- 3-chip vs. 1-chip: quality vs. cost
- Why more green?

Why 3 colors?

http://www.cooldictionary.com/words/Bayer-filter.wikipedia
Cheaper/More Compact Color Sensing: Bayer Grid

Estimate RGB at ‘G’ cells from neighboring values
Why more green?

Approximate human spectral sensitivity

Less than ~400nm to 10nm = ultraviolet (UV)

Human visible portion of electromagnetic (EM) spectrum

Greater than ~700nm to 1mm = infrared (IR)
RGB Camera Color Response

Canon 450D Quantum Efficiency

What’s going on over here?
Display Color Response

PA248Q LCD Monitor
Color Calibration Testing Report

Every ASUS PA248Q is equipped with pre-tuned sRGB and has undergone rigorous tests and calibration processes to ensure that color difference, ΔE, is less than 5, thus preventing color inaccuracy and inconsistency on screen. ASUS advanced gray-scale tracking technology ensures smoother color gradation delivered by every ASUS PA248Q.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>EJLMQ5158406</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Equipment</td>
<td>Minolta Color Analyzer CA210</td>
</tr>
</tbody>
</table>

Gray-Scale Tracking

Gamma Value

Note: The sRGB calibrations of every ASUS PA248Q are pre-tuned and tested under ASUS standardized procedures using calibrated facilities at the factory manufacturing line. This report is a certificate only for the newly manufactured ASUS PA248Q monitor unit. Test results may vary under different test procedures, equipment and patterns.
Display Color Response

PA248Q LCD Monitor
Color Calibration Testing Report

Every ASUS PA248Q is equipped with pre-tuned sRGB and has undergone rigorous tests and calibration processes to ensure that color difference, ΔE, is less than 5, thus preventing color inaccuracy and inconsistency on screen. ASUS advanced gray-scale tracking technology ensures smoother color gradation delivered by every ASUS PA248Q.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>J4LMQ5157085</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Equipment</td>
<td>Minolta Color Analyzer CA210</td>
</tr>
</tbody>
</table>

Gray-Scale Tracking

- Color Temp (K): 7000 - 5000
- Gray Level: 0 - 250

Gamma Value

- Brightness (cd/m²): 0 - 400
- Gray Level: 0 - 250

Note: The sRGB calibrations of every ASUS PA248Q are pre-tuned and tested under ASUS standardized procedures using calibrated facilities at the factory manufacturing line. This report is a certificate only for the newly manufactured ASUS PA248Q monitor unit. Test results may vary under different test procedures, equipment and patterns.
Color spaces

How can we represent color?

Color spaces: RGB

Default color space

Any color = r*R + g*G + b*B
- Strongly correlated channels
- Non-perceptual

Got it.  \[ C = r*R + g*G + b*B \]

**IS COLOR A VECTOR SPACE?**

**THINK-PAIR-SHARE**
Color spaces: HSV

Intuitive color space
If you had to choose, would you rather go without:
- intensity (‘value’), or
- hue + saturation (‘chroma’)?

Think-Pair-Share
Most information in intensity

Only color shown – constant intensity
Most information in intensity

Only intensity shown – constant color
Most information in intensity

Original image
Color spaces: HSV

Intuitive color space

- **H** (S=1, V=1)
- **S** (H=1, V=1)
- **V** (H=1, S=0)

James Hays
Color spaces: YCbCr

Fast to compute, good for compression, used by TV

Y=0

Y=0.5

Y=1

Cr

Cb

James Hays
Most JPEG images & videos subsample chroma
IS COLOR PERCEPTION A VECTOR SPACE?
Color spaces: L*a*b*

“Perceptually uniform”* color space

James Hays
EVOlUTION OF MY UNDERSTANDING OF COLOR OVER TIME:

"COLOR" IS...

...THREE PRIMARY
COLORS MIXED TOGETHER

...A RAINBOW, AND EACH
COLOR IS A WAVELENGTH

...UNKNOWABLE ("MAYBE WHAT
I SEE AS BLUE, YOU SEE AS..."

...THREE-Ish PRIMARY
COLORS MIXED TOGETHER
(RGB/RYB/CMYK)

...A MIX OF INFINITE
WAVELENGTHS FILTERED
THROUGH THREE EYE PIGMENTS

[SOMETHING ABOUT THE
OPPONENT COLOR MODEL]

...AN ABSTRACT MULTIDIMENSIONAL
GAMUT (CIE 1931, L*A*B*, ETC)

...AN ABSTRACT MULTIDIMENSIONAL GAMUT
FILTERED THROUGH INCONSISTENTLY-
IMPLEMENTED DEVICE COLOR PROFILES

...A HYPERDIMENSIONAL FOUR-
SIDED QUANTUM KLEIN MANIFOLD?
IS THAT A THING?

...HOPEFULLY SOMEBODY
ELSE'S PROBLEM.
More references

• https://www.colors system.com/

• A description of many different color systems developed through history.

• Navigate from the right-hand links.

• Thanks to Alex Nibley!
Rainbow color map considered harmful

Borland and Taylor
WHY DOES COLOR LOOK LIKE IT MAPS SMOOTHLY TO A CIRCLE?

Wait a minute…
‘Color’ != position on EM spectrum

Our cells induce color perception by interpreting spectra.

Most mammals are dichromats:
• Lack ‘L’ cone; cannot distinguish green-red
• 1% of men (protanopia color blindness)

Trichromaticity evolved. No implicit reason for effect of extra cone to be linear.

Thanks to Cam Allen-Lloyd
‘Color’ != position on EM spectrum

Many different ways to parameterize color. Ask Prof. Thomas Serre for a qualified answer.

Or...

“When some primates started growing a third cone in their retinas, the old bipolar system remained, with the third cone adding a 2nd dimension of color encoding: red versus green. since color is now encoded in a 2d space, you find that you can draw a circle of colors in that space, which when you think about the fact that wavelength is 1d is really weird.”

- aggasalk, Reddit.

Thanks to Alexander Nibley
Fig. 1. Apparatus for equating motion and consequent visual feedback for an actively moving (A) and a passively moved (P) S.
A Bird’s-Eye View of Nature’s Hidden Order

HYPERUNIFORMITY IN CHICKEN EYES

Apparent disorder
The colored dots below correspond to the arrangement of green, blue, red, violet and double-type (black) cone photoreceptors in a chicken’s retina. Each cone is a different size. At first glance, the distribution appears to be disordered.

Order revealed
By considering the cone types separately, we can see that each cone is surrounded by an “exclusion region” that cones of other types can enter but cones of the same type avoid. Each set of cones, although not perfectly uniform, is as uniform as it can be given the packing constraints of five different cone sizes.