Recap: Frequency Domain
Fourier Bases

Teases away fast vs. slow changes in the image.

This change of basis is the Fourier Transform
Fourier Bases

in Matlab, check out: `imagesc(log(abs(fftshift(fft2(im)))));`
1. Match the spatial domain image to the Fourier magnitude image

A  B  C  D  E
Sampling

Why does a lower resolution image still make sense to us? What do we lose?

Image: http://www.flickr.com/photos/igorms/136916757/
Subsampling by a factor of 2

Throw away every other row and column to create a 1/2 size image
Aliasing problem

- 1D example (sinewave):

Source: S. Marschner
Aliasing problem

- 1D example (sinewave):
Aliasing problem

• Sub-sampling may be dangerous....
• Characteristic errors may appear:
  – “car wheels rolling the wrong way in movies”
  – “Checkerboards disintegrate in ray tracing”
  – “Striped shirts look funny on color television”
A form of spatial aliasing: Moire Pattern

https://en.wikipedia.org/wiki/Moir%C3%A9_pattern
Aliasing in video

Imagine a spoked wheel moving to the right (rotating clockwise). Mark wheel with dot so we can see what’s happening.

If camera shutter is only open for a fraction of a frame time (frame time = 1/30 sec. for video, 1/24 sec. for film):

Without dot, wheel appears to be rotating slowly backwards! (counterclockwise)
Aliasing in graphics

Disintegrating textures
Sampling and aliasing

256x256  128x128  64x64  32x32  16x16
Nyquist-Shannon Sampling Theorem

- When sampling a signal at discrete intervals, the sampling frequency must be $\geq 2 \times f_{\text{max}}$
- $f_{\text{max}} = \text{max frequency of the input signal}$
- This will allow to reconstruct the original perfectly from the sampled version
Anti-aliasing

Solutions:
• Sample more often

• Get rid of all frequencies that are greater than half the new sampling frequency
  – Will lose information
  – But it’s better than aliasing
  – Apply a smoothing filter
Algorithm for downsampling by factor of 2

1. Start with image(h, w)
2. Apply low-pass filter
   \[ \text{im\_blur} = \text{imfilter(image, fspecial('gaussian', 7, 1))} \]
3. Sample every other pixel
   \[ \text{im\_small} = \text{im\_blur(1:2:end, 1:2:end);} \]
Anti-aliasing

Forsyth and Ponce 2002
Subsampling without pre-filtering

1/2  1/4 (2x zoom)  1/8 (4x zoom)

Slide by Steve Seitz
Subsampling with Gaussian pre-filtering

Gaussian 1/2

G 1/4

G 1/8

Slide by Steve Seitz
Recap – Light, Cameras, Eyes

- Light source
- Fovea
- Blind Spot
- Receptors/mm²

Cross-section of eye
- Ganglion axons
- Ganglion cell layer
- Bipolar cell layer
- Receptor layer
- Pigmented epithelium

Cross section of retina

Dazzling light: bright sun on snow
Outdoors in full sunlight
Outdoors under a tree on a sunny day
Comfortable indoor illumination; night sports events
Threshold for perception of color; bright moonlight
Threshold when dark-adapted

Fovea
Blind Spot

Visual Angle (degrees from fovea)

# Receptors/mm²

Electromagnetic Spectrum

Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm
Visible Light

Why do we see light of these wavelengths?

...because that’s where the Sun radiates EM energy
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.
The Physics of Light

Some examples of the spectra of light sources

A. Ruby Laser

B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

© Stephen E. Palmer, 2002
Some examples of the reflectance spectra of surfaces.
Physiology of Color Vision

Three kinds of cones:

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

- Most birds, and many other animals, have cones for ultraviolet light.
- Some humans, mostly female, seem to have slight tetrachromatism.
### Table 1.

Cone pigment complements in some eutherian mammals.

<table>
<thead>
<tr>
<th>Order</th>
<th>Exemplar</th>
<th>SWS1 pigment</th>
<th>LWS pigment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rodentia</td>
<td>Mus (mouse)</td>
<td>UV</td>
<td>M</td>
<td>Jacobs et al. (1991)</td>
</tr>
<tr>
<td></td>
<td>Rattus (rat)</td>
<td>UV</td>
<td>M</td>
<td>Jacobs et al. (1991)</td>
</tr>
<tr>
<td></td>
<td>Geomys (gerbil)</td>
<td>UV</td>
<td>M</td>
<td>Williams et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Cavia (guinea pig)</td>
<td>S</td>
<td>M</td>
<td>Parry &amp; Bowmaker (2002)</td>
</tr>
<tr>
<td></td>
<td>Spermophilus (squirrel)</td>
<td>S</td>
<td>M</td>
<td>Jacobs et al. (1981)</td>
</tr>
<tr>
<td>Lagomorpha</td>
<td>Oryctolagus (rabbit)</td>
<td>S</td>
<td>M</td>
<td>Nishio et al. (1991)</td>
</tr>
<tr>
<td></td>
<td>Macaca (macaque monkey)</td>
<td>S</td>
<td>M+L</td>
<td>Scharpf et al. (1988)</td>
</tr>
<tr>
<td></td>
<td>Saimiri (squirrel monkey)</td>
<td>S</td>
<td>poly (3)</td>
<td>Molina et al. (1983)</td>
</tr>
<tr>
<td></td>
<td>Aotus (owl monkey)</td>
<td>absent</td>
<td>L</td>
<td>Jacobs et al. (1993)</td>
</tr>
<tr>
<td></td>
<td>Alouatta (howler monkey)</td>
<td>S</td>
<td>M+L</td>
<td>Jacobs et al. (1996)</td>
</tr>
<tr>
<td></td>
<td>Galago (bushbaby)</td>
<td>absent</td>
<td>L</td>
<td>Degnan &amp; Jacobs (1999)</td>
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<tr>
<td></td>
<td>Lemur (ring-tailed)</td>
<td>L</td>
<td></td>
<td>Jacobs &amp; Degnan (1993)</td>
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<td>Propithecus (sifaka)</td>
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<td>poly (2)</td>
<td>Tan &amp; Li (1999)</td>
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<tr>
<td>Scandentia</td>
<td>Dasyus (tree shrew)</td>
<td>S</td>
<td>L</td>
<td>Jacobs &amp; Nitz (1988)</td>
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<tr>
<td>Cetacea</td>
<td>Enaliornis (whale)</td>
<td>absent</td>
<td>L</td>
<td>Levenson &amp; Denon (2003)</td>
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<tr>
<td></td>
<td>Tursiops (dolphin)</td>
<td>absent</td>
<td>L</td>
<td>Fisch et al. (1999)</td>
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<tr>
<td>Artiodactyla</td>
<td>Bos (cows)</td>
<td>S</td>
<td>L</td>
<td>Jacobs et al. (1994)</td>
</tr>
<tr>
<td></td>
<td>Odobenus (deer)</td>
<td>S</td>
<td>M</td>
<td>Jacobs et al. (1994)</td>
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<tr>
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<td>Sus (pig)</td>
<td>S</td>
<td>L</td>
<td>Nitz &amp; Jacobs (1989)</td>
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<tr>
<td>Perissodactyla</td>
<td>Equus (horse)</td>
<td>S</td>
<td>L</td>
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<td>Carnivora</td>
<td>Felis (cat)</td>
<td>S</td>
<td>L</td>
<td>Loop et al. (1987)</td>
</tr>
<tr>
<td></td>
<td>Canis (dog)</td>
<td>S</td>
<td>L</td>
<td>Jacobs et al. (1992a)</td>
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<td></td>
<td>Ursus (bear)</td>
<td>S</td>
<td>L</td>
<td>Levenson et al. (2006)</td>
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<td></td>
<td>Crocuta (hyena)</td>
<td>UV/S</td>
<td>M+L</td>
<td>Calderone et al. (2003)</td>
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<td>Phoca (seal)</td>
<td>absent</td>
<td>L</td>
<td>Levenson et al. (2006)</td>
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<tr>
<td></td>
<td>Erignathus (sealer)</td>
<td>S</td>
<td>L</td>
<td>Levenson et al. (2006)</td>
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</tbody>
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(b) Eutherians

Representatives from two cone opsin gene families appear in contemporary eutherian mammals and, with the exception of some primates, none of these animals derive more than a single photopigment type from each of their two gene families (SWIS and LWS; figure 1). Given that commonality, what cone pigments may have been present in the retinas of the early eutherians? Sequence comparisons of cone opsin genes have suggested that the ancestral mammalian pigments drawn from these two gene families peaked in the UV, at about 360 nm (Hunt et al., 2001), and in the long wavelengths at 560 nm (Yokoyama et al., 2008). Assuming the visual pigment chromophore of early mammals was 11-cis-retinal, the same as that of contemporary mammals, the cone pigments of early eutherian mammals would have had absorption properties similar to those sketched at the bottom of figure 1.

If these deductions are correct, the retinas of the early eutherians were similar to those of the majority of contemporary mammals in containing two types of cone pigment. Such an arrangement could support dichromatic colour vision. Whether it did would additionally depend on there having been at least some degree of selective expression of the two pigment types in separate receptor classes, on these early mammals having a nervous system organized to allow a contrast of signals from the two types of cone, and on them at least occasionally encountering photic environments sufficiently intense to activate neural comparison circuits. The fact that this basic two cone pigment arrangement is largely conserved among contemporary mammals strongly attests to its adaptive utility in our eutherian ancestors and to its probable role in supporting dichromatic colour vision in these early mammals.

More Spectra

metamers
Color can be ambiguous
Color can be ambiguous
The dress

From Wikipedia, the free encyclopedia

For other uses, see The Dress.

The dress is a photograph that became a viral internet sensation on 26 February 2015, when viewers disagreed over whether the dress pictured was coloured black and blue, or white and gold. The phenomenon revealed differences in human colour perception, which have been the subject of ongoing scientific investigations into neuroscience and vision science, producing a number of papers published in peer-reviewed science journals.

The photo originated from a washed-out colour photograph of a dress posted on the social networking service Facebook. Within the first week after the surfacing of the image, more than 10 million tweets mentioned the dress, using hashtags such as #thedress, #whiteandgold, and #blackandblue. Although the colour of the dress was eventually confirmed as black and blue,[3][4] the image prompted many discussions, with users discussing their different perceptions of the dress's colour. Members of the scientific community began to investigate the photo for fresh insights into human colour vision.

The dress itself, which was identified as a product of the retailer Roman Originals, experienced a major surge in sales as a result of the incident. The retailer also produced a one-off version of the dress in white and gold as a charity campaign.

https://en.wikipedia.org/wiki/The_dress
Practical Color Sensing: Bayer Grid

- Estimate RGB at ‘G’ cells from neighboring values

Slide by Steve Seitz
Color Image
Images in Matlab

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - \(im(1,1,1)\) = top-left pixel value in R-channel
  - \(im(y, x, b)\) = \(y\) pixels down, \(x\) pixels to right in the \(b^{th}\) channel
  - \(im(N, M, 3)\) = bottom-right pixel in B-channel
Images in Matlab Python

- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - \( \text{im}(0,0,0) = \) top-left pixel value in R-channel
  - \( \text{im}(y, x, b) = \) y pixels down, x pixels to right in the b\(^{th}\) channel
  - \( \text{im}(N-1, M-1, 2) = \) bottom-right pixel in B-channel
Color spaces

• How can we represent color?

Color spaces: RGB

Some drawbacks
• Strongly correlated channels
• Non-perceptual
Color spaces: HSV

Intuitive color space

H (S=1,V=1)

S (H=1,V=1)

V (H=1,S=0)
Color spaces: YCbCr

Fast to compute, good for compression, used by TV
Color spaces: L*a*b*

“Perceptually uniform”* color space

[Diagram showing L*a*b* color space with images representing L, a, and b values]
If you had to choose, would you rather go without luminance or chrominance?
If you had to choose, would you rather go without **luminance** or chrominance?
Most information in intensity

Only color shown – constant intensity
Most information in intensity

Only intensity shown – constant color
Most information in intensity

Original image
Back to grayscale intensity

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Wrap up: Why do we care about cameras and eyes?
Inside Tesla as Elon Musk Pushed an Unflinching Vision for Self-Driving Cars

The automaker may have undermined safety in designing its Autopilot driver-assistance system to fit its chief executive’s vision, former employees say.
Hardware choices have also raised safety questions. Within Tesla, some argued for pairing cameras with radar and other sensors that worked better in heavy rain and snow, bright sunshine and other difficult conditions. For several years, Autopilot incorporated radar, and for a time Tesla worked on developing its own radar technology. But three people who worked on the project said Mr. Musk had repeatedly told members of the Autopilot team that humans could drive with only two eyes and that this meant cars should be able to drive with cameras alone.
Schuyler Cullen, who oversaw a team that explored autonomous-driving possibilities at the South Korean tech giant Samsung, said in an interview that Mr. Musk’s cameras-only approach was fundamentally flawed. “Cameras are not eyes! Pixels are not retinal ganglia! The F.S.D. computer is nothing like the visual cortex!” said Mr. Cullen, a computer vision specialist who now runs a start-up that is building a new kind of camera-based sensor.

Amnon Shashua, chief executive of Mobileye, a former Tesla supplier that has been testing technology that is similar to the electric-car maker’s, said Mr. Musk’s idea of using only cameras in a self-driving system could ultimately work, though other sensors may be needed in the short term. He added that Mr. Musk might exaggerate the capabilities of the company’s technology, but that those statements shouldn’t be taken too seriously.
Another driving system with human level eyesight
On the whole, cameras are a reasonable analogy for eyes. They do capture sufficient information for safe driving 99.9% of the time.
gets G's halfway over and then tries to go back to
• On the whole, cameras are a reasonable analogy for eyes. They do capture sufficient information for safe driving 99.9% of the time.
  – Imagine remote controlling a vehicle based on a camera feed.
• But the computer vision and machine learning methods that interpret the camera images are not yet a reasonable analogy for the human brain.
Next class: Interest points and corners