BBM 413
Fundamentals of Image Processing

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Image Formation and Color

Acknowledgement: The course slides are mostly adapted from the slides prepared by Steve Marschner, James Hays, Ali Farhadi and Anat Levin
Today

- Image formation
- Digital images
- Perception of color and light
- Color spaces
Today

- Image formation
- Digital images
- Perception of color and light
- Color spaces
An image is:

- A 2D distribution of intensity or color
- A function defined on a two-dimensional plane

\[ I : \mathbb{R}^2 \rightarrow \ldots \]

- Note: no mention of pixels yet
- To process images, must:
  - obtain images—capture the scenes via hardware
  - represent images—encode them numerically
Image Formation

Three Dimensional World → Two Dimensional Image Space

• What is measured in an image location?
  – brightness
  – color

viewpoint
<< illumination conditions
  local geometry
  local material properties

Figures: Francis Crick, The Astonishing Hypothesis,
Image Formation

Three Dimensional World \rightarrow Two Dimensional Image Space

• What is measured in an image location?
  – brightness
  – color
  \(<<\) viewpoint
  \(<<\) illumination conditions
  \(<<\) surface properties
  \(<<\) (local geometry and local material properties)

Figures: Francis Crick, The Astonishing Hypothesis,
A photon’s life choices

• Absorption
• Diffusion
• Reflection
• Transparency
• Refraction
• Fluorescence
• Subsurface scattering
• Phosphorescence
• Interreflection
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

- Absorption
- Diffusion
- Specular Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- **Transparency**
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection
A photon’s life choices

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• Diffusion
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• **Refraction**
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- **Phosphorescence**
- Interreflection
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- **Interreflection**
Image Formation

Images cannot exist without light!

Why is there no image on a white piece of paper?

It receives light from all directions

From Photography, London et al.
Image Formation

- Let’s design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?
Pinhole camera

A pinhole projects all rays through a common center of projection.

From Photography, London et al.
Pinhole camera

- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening is known as the aperture
  - How does this transform the image?
Camera Obscura

- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
Camera Obscura
Abelardo Morell: Through the Looking Glass

https://www.youtube.com/watch?v=DTa9wLkaizQ
Camera Obscura

• The first camera
  – How does the aperture size affect the image?
Pinhole Size?

Photograph made with small pinhole

Small pinhole - sharp but hard to collect enough light

Photograph made with larger pinhole

Larger pinhole - Blur

From Photography, London et al.
small hole => sharp, but doesn’t collect enough light (noise)
larger hole => easy to collect enough light, but blur occurs
Pinhole Size

- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects...
Solution: light refraction!
Lenses

- gather more light!
- But need to be focused

To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.

This time, using a simple convex lens with an f/16 aperture, the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.

The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.

From Photography, London et al.
Adding a lens

- A lens focuses light onto the film
  - There is a specific distance at which objects are “in focus”
    - other points project to a “circle of confusion” in the image
  - Changing the shape of the lens changes this distance
**Lenses**

- A lens focuses parallel rays onto a single focal point
  - focal point at a distance $f$ beyond the plane of the lens
    - $f$ is a function of the shape and index of refraction of the lens
  - Aperture of diameter $D$ restricts the range of rays
    - aperture may be on either side of the lens
  - Lenses are typically spherical (easier to produce)
  - Real cameras use many lenses together (to correct for aberrations)
Thin lenses

- Thin lens equation: \( \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \)
  - Any object point satisfying this equation is in focus
  - What is the shape of the focus region?
  - How can we change the focus region?
A lens is focused at a single depth

\[ \frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f} \]

- \( z_o \): distance to the (focused) object
- \( z_i \): distance behind the lens at which the image is formed
- \( f \): focal length

Object at focus depth

All rays emerge from a single object point => The captured image is sharp
A lens is focused at a single depth

Object away from focus depth

Rays emerge from multiple object points (circle of confusion) => the captured image is blurred
A lens is focused at a single depth

\[ \frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f} \]
The thin lens assumption assumes the lens has no thickness, but this isn’t true…

By adding more elements to the lens, the distance at which a scene is in focus can be made roughly planar.
Projection

• Mapping from the world (3d) to an image (2d)
• Can we have a 1-to-1 mapping?
• How many possible mappings are there?

• An optical system defines a particular projection.
• Two examples:
  1. Perspective projection (how we see “normally”)
  2. Orthographic projection (e.g., telephoto lenses)
Modeling projection

- **The coordinate system**
  - We will use the pin-hole model as an approximation
  - Put the optical center (Center Of Projection) at the origin
  - Put the image plane (Projection Plane) in front of the COP
  - The camera looks down the negative z axis
    - we need this if we want right-handed-coordinates
Modeling projection

- Projection equations
  - Compute intersection with PP of ray from \((x,y,z)\) to COP
  - Derived using similar triangles

\[(x, y, z) \rightarrow \left(-d\frac{x}{z}, -d\frac{y}{z}, -d\right)\]

- We get the projection by throwing out the last coordinate:

\[(x, y, z) \rightarrow \left(-d\frac{x}{z}, -d\frac{y}{z}\right)\]
Homogeneous coordinates

- Is this a linear transformation?
  - no—division by z is nonlinear

Trick: add one more coordinate:

\[
(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \quad \text{homogeneous image coordinates}
\]

\[
(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \quad \text{homogeneous scene coordinates}
\]

Converting from homogeneous coordinates

\[
\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)
\]

\[
\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow (x/w, y/w, z/w)
\]
Perspective Projection

- Projection is a matrix multiply using homogeneous coordinates:

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/d & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix} = \begin{bmatrix}
x \\
y \\
-z/d \\
1
\end{bmatrix} \Rightarrow (-\frac{x}{z}, -\frac{y}{z})
\]

divide by third coordinate

This is known as perspective projection

- The matrix is the projection matrix
Perspective Projection Example

1. Object point at (10, 6, 4), d=2

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/d & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/2 & 0 \\
0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
10 \\
6 \\
4 \\
1
\end{bmatrix} = \begin{bmatrix}
10 \\
6 \\
-2
\end{bmatrix}
\]

⇒ \(x' = -5, \ y' = -3\)

2. Object point at (25, 15, 10)

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/d & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1/2 & 0 \\
0 & 0 & 1 & 1
\end{bmatrix}
\begin{bmatrix}
25 \\
15 \\
10 \\
1
\end{bmatrix} = \begin{bmatrix}
25 \\
15 \\
-5
\end{bmatrix}
\]

⇒ \(x' = -5, \ y' = -3\)

Perspective projection is not 1-to-1!
Perspective Projection

- preserves lines (collinearity), cross ratio
- does not always preserve parallel lines.
- Lines parallel to projection plane remain parallel.
- Lines not parallel to projection plane converge to a single point on the horizon called the vanishing point.
Perspective Projection

- What happens when $d \to \infty$?

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/d & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ -z/d \end{bmatrix} \Rightarrow (-d\frac{x}{z}, -d\frac{y}{z})$$
Orthographic projection

• Special case of perspective projection
  – Distance from the COP to the PP is infinite

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
= \begin{bmatrix}
x \\
y \\
1
\end{bmatrix} \Rightarrow (x, y)
\]

– Good approximation for telephoto optics
– Also called “parallel projection”:
  \((x, y, z) \Rightarrow (x, y)\)
Orthographic projection

- preserves ratios, but not angles.
- parallel lines remain parallel.
- loses depth information.
Orthographic ("telecentric") lenses

Navitar telecentric zoom lens

http://www.lhup.edu/~dsimanek/3d/telecent.htm
• Changing the aperture size affects depth of field
  
  – A smaller aperture increases the range in which the object is approximately in focus

Aperture

• Diameter of the lens opening (controlled by diaphragm)
• Controls depth of field
• Expressed as a fraction of focal length, in f-number
  – f/2.0 on a 50mm means that the aperture is 25mm
  – f/2.0 on a 100mm means that the aperture is 50mm
• Disconcerting: small f number = big aperture
• What happens to the area of the aperture when going from f/2.0 to f/4.0?
• Typical f numbers are f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32
Main effect of aperture

- **Depth of field**: Allowable depth variation in the scene that limits the circle of confusion to a tolerable number

From Photography, London et al.
Depth of field

Image of object in focus - sharp (all rays hitting a single sensor point emerge from a single point on the object)
Depth of field

- Image of object in focus - sharp (all rays hitting a single sensor point emerge from a single point on the object)
- Image of an object away from focus depth - blurred (rays hitting a single sensor point emerge from multiple points on the object)
Depth of field

- We allow for some tolerance
Depth of Field
**Depth of Field**

- **Shallow Depth of Field**
  - Portrait: Small Aperture (f/5.6)
  - Landscape: Large Aperture (f/2.8)

- **Large Depth of Field**
  - Portrait: Large Aperture (f/2.8)
  - Landscape: Small Aperture (f/5.6)

[http://photographertips.net](http://photographertips.net)
Exposure

- Exposure: How much light falls on sensor
- Get the right amount of light to sensor/film
- Main parameters:
  - Shutter speed: How long sensor is exposed to light
  - Aperture (area of lens): How much light can pass through from the lens
  - Sensitivity: How much light is needed by the sensor
  - Lighting conditions
Field of View (Zoom, focal length)

From London and Upton
Shutter speed

• Controls how long the film/sensor is exposed, i.e. the amount of light reaching the sensor

• Pretty much linear effect on exposure

• Usually in fraction of a second:
  – 1/30, 1/60, 1/125, 1/250, 1/500
  – Get the pattern?

• Faster shutter (e.g. 1/500th sec) = less light

• Slower shutter (e.g. 1/30th sec) = more light

• On a normal lens, normal humans can hand-hold down to 1/60
  – In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500 for a 500mm
Shutter speed

Short exposure - dark  medium exposure  long exposure - saturation
Shutter speed

Short exposure after contrast adjustment - noise

medium exposure

long exposure - saturation
Main effect of slower shutter speed

- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.

- Camera shake

  Image taken with a tripod

  Image taken with a hand held camera
Main effect of slower shutter speed

- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.
- Scene motion

From Photography, London et al.
Effect of Shutter Speed

- Freezing motion

Walking people  Running people  Car  Fast train

1/125  1/250  1/500  1/1000
Today

• Image formation
• Digital images
• Perception of color and light
• Color spaces
Digital camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - CMOS
Digital camera

- Color typically captured using color mosaic
- Demosaicing
Digital camera

How do digital cameras work?  https://www.youtube.com/watch?v=lc0czeUjrGE
**Sensor Array**

**FIGURE 2.17** (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
Issues with digital cameras

• Noise
  – big difference between consumer vs. SLR-style cameras
  – low light is where you most notice noise

• Compression
  – creates artifacts except in uncompressed formats (tiff, raw)

• Color
  – color fringing artifacts from Bayer patterns

• Blooming
  – charge overflowing into neighboring pixels

• In-camera processing
  – oversharpening can produce halos

• Interlaced vs. progressive scan video
  – even/odd rows from different exposures

• Are more megapixels better?
  – requires higher quality lens
  – noise issues

• Stabilization
  – compensate for camera shake (mechanical vs. electronic)

More info online, e.g.,
http://www.dpreview.com/
Sampling and Quantization

Figure 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.
Image Representation

- Discretization
  - in image space - sampling
  - In image brightness - quantization
Image Representation

- **Digital image**: 2D discrete function $f$
- **Pixel**: Smallest element of an image $f(x,y)$
Image Representation

- **Digital image**: 2D discrete function $f$
- **Pixel**: Smallest element of an image $f(x,y)$
Datatypes for raster images

- **Bitmaps:** boolean per pixel (1 bpp): \( I : \mathbb{R}^2 \rightarrow \{0, 1\} \)
  - interp. = black and white; e.g. fax

- **Grayscale:** integer per pixel: \( I : \mathbb{R}^2 \rightarrow [0, 1] \)
  - interp. = shades of gray; e.g. black-and-white print
  - precision: usually byte (8 bpp); sometimes 10, 12, or 16 bpp

- **Color:** 3 integers per pixel: \( I : \mathbb{R}^2 \rightarrow [0, 1]^3 \)
  - interp. = full range of displayable color; e.g. color print
  - precision: usually byte [3] (24 bpp)
  - sometimes 16 (5+6+5) or 30 or 36 or 48 bpp
  - indexed color: a fading idea
Datatypes for raster images

- **Floating point:** \( I : \mathbb{R}^2 \rightarrow \mathbb{R}_+ \) or \( I : \mathbb{R}^2 \rightarrow \mathbb{R}^3_+ \)
  - more abstract, because no output device has infinite range
  - provides *high dynamic range* (HDR)
  - represent real scenes independent of display
  - becoming the standard intermediate format in graphics processors

- **Clipping and white point**
  - common to compute FP, then convert to integer
  - full range of values may not “fit” in display’s output range
  - simplest solution: choose a maximum value, scale so that value becomes full intensity (\(2^n-1\) in an \(n\)-bit integer image)
Intensity encoding in images

- What do the numbers in images (pixel values) mean?
  - they determine how bright that pixel is
  - bigger numbers are (usually) brighter
Datatypes for raster images

- For color or grayscale, sometimes add *alpha* channel
  - describes transparency of images
Storage requirements for images

- 1024x1024 image (1 megapixel)
  - bitmap: 128KB
  - grayscale 8bpp: 1MB
  - grayscale 16bpp: 2MB
  - color 24bpp: 3MB
  - floating-point HDR color: 12MB
Converting pixel formats

- Color to gray
  - could take one channel (blue, say)
    • leads to odd choices of gray value
  - combination of channels is better
    • but different colors contribute differently to lightness
    • which is lighter, full blue or full green?
    • good choice: gray = 0.2 R + 0.7 G + 0.1 B
    • more on this in color, later on

Same pixel values.

Same luminance?
Converting pixel precision

• Up is easy; down loses information—be careful

1 bpp (2 grays)
Today

• Image formation
• Digital images
• Perception of color and light
• Color spaces
Why does a visual system need color?

http://www.hobbyinc.com/gr/pll/pll5019.jpg

Slide credit: W. Freeman
Why does a visual system need color? (an incomplete list...)

• To tell what food is edible.
• To distinguish material changes from shading changes.
• To group parts of one object together in a scene.
• To find people’s skin.
• Check whether a person’s appearance looks normal/healthy.

Slide credit: W. Freeman
What is color?

• Color is the result of interaction between physical light in the environment and our visual system.

• Color is a psychological property of our visual experiences when we look at objects and lights, *not* a physical property of those objects or lights (S. Palmer, Vision Science: Photons to Phenomenology).
#thedress

• What is the color of the dress?
  
  • blue and black
  • white and gold
  • blue and brown

• What #thedress tell about our color perception?

http://nyti.ms/186m3wE
#thedress

- Let’s take averages

two pieces of the dress

averages

basic pattern

http://nyti.ms/186m3wE
#thedress

• The dress in the photograph

http://nyti.ms/186m3wE
#thedishess

• Consider the dress is in shadow.

• Your brain remove the blue cast, and perceive it as white and gold.

http://nyti.ms/186m3wE
#thedress

- The dress in the photograph

http://nyti.ms/186m3wE
#thedress

- Consider the dress is in bright light.

- Your brain perceive the dress as a darker blue and black

http://nyti.ms/186m3wE
#thedress

• Answer:

• The dress is actually blue and black.

http://nyti.ms/186m3wE
Brightness perception

http://web.mit.edu/persci/people/adelson/illusions_demos.html

Edward Adelson
Brightness perception

http://web.mit.edu/persci/people/adelson/illusions_demos.html
Brightness perception

http://web.mit.edu/persci/people/adelson/illusions_demos.html
Brightness perception
Land’s Experiment (1959)

• Cover all patches except a blue rectangle
• Make it look gray by changing illumination
• Uncover the other patches

Color Constancy

We filter out illumination variations

Slide credit: S. Narasimhan
Land’s Experiment (1959)

- Cover all patches except a blue rectangle
- Make it look gray by changing illumination
- Uncover the other patches

Color Constancy

We filter out illumination variations

Slide credit: S. Narasimhan
In David Ingle's experiment, a goldfish has been trained to swim to a patch of a given color for a reward—a piece of liver. It swims to the green patch regardless of the exact setting of the three projectors' intensities. The behavior is strikingly similar to the perceptual result in humans.

http://neuro.med.harvard.edu/site/dh/b45.htm

Slide credit: S. Narasimhan
Image Brightness (Intensity)

- Monochromatic Light: \( \lambda = \lambda_i \)

\[
b'(x, y) = r'(x, y) \cdot e'(x, y) \quad q(\lambda_i) = 1
\]

NOTE: The analysis can be applied to COLORED LIGHT using FILTERS

Slide credit: S. Narasimhan
Recovering Lightness

- Image Intensity: $b'(x, y) = r'(x, y) e'(x, y)$

Can we recover $e'$ and $r'$ from $b'$?

- Retinex theory, Land and McCann, 1971

- use constraints (or priors) on shading and reflectance
- employ additional information (multiple images, depth maps, etc.)

Slide credit: S. Narasimhan
Color and light

- **Color of light** arriving at camera depends on
  - Spectral reflectance of the surface light is leaving
  - Spectral radiance of light falling on that patch

- **Color perceived** depends on
  - Physics of light
  - Visual system receptors
  - Brain processing, environment

- Color is a phenomenon of human perception; it is **not** a universal property of light

Slide credit: K. Grauman, S. Marschner
Color

White light: composed of about equal energy in all wavelengths of the visible spectrum

Newton 1665

From Foundations of Vision, by Brian Wandell, Sinauer Assoc., 1995

Slide credit: B. Freeman, A. Torralba, K. Grauman
Electromagnetic spectrum

- Light is electromagnetic radiation
  - exists as oscillations of different frequency (or, wavelength)

![Electromagnetic Spectrum Diagram](image)

Solar Radiation Spectrum

Human Luminance Sensitivity Function

Slide credit: A. Efros
Any source of light can be completely described physically by its spectrum: the amount of energy emitted (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

Slide credit: A. Efros
The Physics of light

Some examples of the reflectance spectra of surfaces

<table>
<thead>
<tr>
<th></th>
<th>Wavelength (nm)</th>
<th>% Light Reflected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>400</td>
<td>700</td>
</tr>
<tr>
<td>Yellow</td>
<td>400</td>
<td>700</td>
</tr>
<tr>
<td>Blue</td>
<td>400</td>
<td>700</td>
</tr>
<tr>
<td>Purple</td>
<td>400</td>
<td>700</td>
</tr>
</tbody>
</table>

© Stephen E. Palmer, 2002

Slide credit: A. Efros
Image formation

- What determines the brightness of an image pixel?

- Light source properties
- Optics
- Surface shape and orientation
- Surface reflectance properties
- Sensor characteristics
- Exposure

Slide credit: L. Fei-Fei
Color mixing

Cartoon spectra for color names:

- Red
- Green
- Blue
- Cyan
- Magenta
- Yellow

Credit: W. Freeman
Additive color mixing

Colors combine by adding color spectra

Light adds to black.
Examples of additive color systems

CRT phosphors

multiple projectors

Slide credit: K. Grauman

http://www.jegsworks.com
http://www.crtprojectors.co.uk/
Subtractive color mixing

Colors combine by multiplying color spectra.

Pigments remove color from incident light (white).

Credit: W. Freeman
Examples of subtractive color systems

• Printing on paper
• Crayons
• Photographic film
Interaction of light and surfaces

- Reflected color is the result of interaction of light source spectrum with surface reflectance

Slide credit: A. Efros
Reflection from colored surface

Slide credit: S. Marschner
The Eye

- **Iris** - colored annulus with radial muscles
- **Pupil** - the hole (aperture) whose size is controlled by the iris
- **Lens** - changes shape by using ciliary muscles (to focus on objects at different distances)
- **Retina** - photoreceptor cells

Slide credit: S. Seitz
The eye as a measurement device

- We can model the low-level behavior of the eye by thinking of it as a light-measuring machine
  - its optics are much like a camera
  - its detection mechanism is also much like a camera

- Light is measured by the photoreceptors in the retina
  - they respond to visible light
  - different types respond to different wavelengths

- **The human eye is a camera!**
Layers of the retina

Slide credit: S. Ullman
Layers of the retina

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

Slide credit: J. Hays
Wait, the blood vessels are in front of the photoreceptors??

Why we have blind spots - and how to see the blood vessels inside your own eye!  

https://www.youtube.com/watch?v=L_W-IXqoxHA  

Slide credit: J. Hays
Eye Movements

• Saccades
  – Can be consciously controlled. Related to perceptual attention.
  – 200ms to initiation, 20 to 200ms to carry out. Large amplitude.

• Microsaccades

• Ocular microtremor (OMT)
  – involuntary. high frequency (up to 80Hz), small amplitude.

• Smooth pursuit – tracking an object
Receptors Density - Fovea

Slide credit: S. Ullman
# Receptors Density - Fovea

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**Human Photoreceptors**


Slide Credit: B. Freeman and A. Torralba
3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

Two types of light-sensitive receptors

Cones
cone-shaped
less sensitive
operate in high light
color vision

Rods
rod-shaped
highly sensitive
operate at night
gray-scale vision

Images by Shimon Ullman

Slide credit: A. Efros
Rods and cones

Rods are responsible for intensity, cones for color perception.

Rods and cones are non-uniformly distributed on the retina.
- Fovea - Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods)

Slide credit: S. Seitz
Three kinds of cones:

- Ratio of L to M to S cones: approx. 10:5:1
- Almost no S cones in the center of the fovea
Color perception

Rods and cones act as filters on the spectrum
- To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
  - Each cone yields one number

Q: How can we represent an entire spectrum with 3 numbers?
A: We can’t! Most of the information is lost.
  - As a result, two different spectra may appear indistinguishable

Slide credit: S. Seitz
Today

• Image formation
• Digital images
• Perception of color and light
• Color spaces
Recall: Digital images

- **Sample** the 2D space on a regular grid
- **Quantize** each sample (round to nearest integer)

- Image thus represented as a matrix of integer values.

Slide credit: K. Grauman, S. Seitz
Color Images: Bayer Grid

- Estimate RGB at ‘G’ cells from neighboring values

http://www.cooldictionary.com/words/Bayer-filter.wikipedia

Slide credit: S. Seitz
Digital color images

Color images, RGB color space

Slide credit: K. Grauman
Images in Matlab

- Images represented as a matrix
- Suppose we have a N×M RGB image called “im”
  - \(\text{im}(1,1,1)\) = top-left pixel value in R-channel
  - \(\text{im}(y,x,b)\) = \(y\) pixels down, \(x\) pixels to right in the \(b\)th channel
  - \(\text{im}(N,M,3)\) = bottom-right pixel in B-channel
- \(\text{imread(filename)}\) returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with \(\text{im2double}\)
Color spaces

- How can we represent color?
Color spaces: RGB

- Single wavelength primaries
- makes a particular monitor RGB standard
- Good for devices (e.g., phosphors for monitor), but not for perception

Slide credit: K. Grauman, S. Marschner
Color spaces: RGB

Some drawbacks
- Strongly correlated channels
- Non-perceptual


Slide credit: D. Hoiem
Color spaces: CIE XYZ

- Standardized by CIE (*Commission Internationale de l’Eclairage*, the standards organization for color science)
- Based on three “imaginary” primaries $X$, $Y$, and $Z$
  - imaginary = only realizable by spectra that are negative at some wavelengths
  - separates out luminance: $X$, $Z$ have zero luminance, so $Y$ tells you the luminance by itself

Slide credit: K. Grauman, S. Marschner
Color spaces: CIE XYZ

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\[
\begin{bmatrix}
X \\
Y \\
Z \\
\end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix}
0.49 & 0.31 & 0.20 \\
0.17697 & 0.81240 & 0.01063 \\
0.00 & 0.01 & 0.99 \\
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B \\
\end{bmatrix}
\]
Perceptually organized color spaces

• Artists often refer to colors as *tints*, *shades*, and *tones* of pure pigments
  – tint: mixture with white
  – shade: mixture with black
  – tones: mixture with black and white
  – gray: no color at all (aka. neutral)

• This seems intuitive
  – tints and shades are inherently related to the pure color
    • “same” color but lighter, darker, paler, etc.
Perceptual dimensions of color

• Hue
  – the “kind” of color, regardless of attributes
  – colorimetric correlate: dominant wavelength
  – artist’s correlate: the chosen pigment color

• Saturation
  – the “colorfulness”
  – colorimetric correlate: purity
  – artist’s correlate: fraction of paint from the colored tube

• Lightness (or value)
  – the overall amount of light
  – colorimetric correlate: luminance
  – artist’s correlate: tints are lighter, shades are darker

Slide credit: S. Marschner
Color spaces: HSV

- **Hue, Saturation, Value**
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- **Matlab**: hsv2rgb, rgb2hsv.
Color spaces: HSV

- **Hue, Saturation, Value**
- Nonlinear – reflects topology of colors by coding **hue** as an angle
- **Matlab**: hsv2rgb, rgb2hsv.
Color spaces: HSV

Intuitive color space

Slide credit: D. Hoiem
**Color spaces: YCbCr**

Fast to compute, good for compression, used by TV

Slide credit: D. Hoiem
Color spaces: YCbCr

Fast to compute, good for compression, used by TV

\[
\begin{bmatrix}
Y' \\
C_b \\
C_r
\end{bmatrix} =
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
-0.168736 & -0.331264 & 0.5 \\
0.5 & -0.418688 & -0.081312
\end{bmatrix}
\begin{bmatrix}
R' \\
G' \\
B'
\end{bmatrix} +
\begin{bmatrix}
0 \\
128 \\
128
\end{bmatrix}
\]

Slide credit: D. Hoiem
Distances in color space

- Are distances between points in a color space perceptually meaningful?
Distances in color space

- Not necessarily: CIE XYZ is not a uniform color space, so magnitude of differences in coordinates are poor indicator of color “distance”.

McAdam ellipses:
Just noticeable differences in color

Slide credit: K. Grauman
Uniform color spaces

- Attempt to correct this limitation by remapping color space so that just-noticeable differences are contained by circles distances more perceptually meaningful.

- Examples:
  - CIE $u'v'$
  - CIE Lab

Slide credit: K. Grauman
Perceptually uniform spaces

- Two major spaces standardized by CIE
  - designed so that equal differences in coordinates produce equally visible differences in color
  - by remapping color space so that just-noticeable differences are contained by circles → distances more perceptually meaningful.
  - LUV: earlier, simpler space; \( L^*, u^*, v^* \)
  - LAB: more complex but more uniform: \( L^*, a^*, b^* \)
  - both separate luminance from chromaticity
  - including a gamma-like nonlinear component is important
Color spaces: L*a*b*

“Perceptually uniform”* color space

Slide credit: D. Hoiem
Color spaces: L*a*b*

“Perceptually uniform”* color space

\[
L^* = 116f \left( \frac{Y}{Y_n} \right)
\]

\[
f(t) = \begin{cases} 
  t^{1/3} & \text{if } t > \delta^3 \\
  t/(3\delta^2) + 2\delta/3 & \text{else,}
\end{cases}
\]

\[
a^* = 500 \left[ f \left( \frac{X}{X_n} \right) - f \left( \frac{Y}{Y_n} \right) \right]
\]

\[
b^* = 200 \left[ f \left( \frac{Y}{Y_n} \right) - f \left( \frac{Z}{Z_n} \right) \right]
\]

\((X_n, Y_n, Z_n)\): measured white point

\(L\) (a=0,b=0)

\(a\) (L=65,b=0)

\(b\) (L=65,a=0)

Slide credit: D. Hoiem
Most information in intensity

Only intensity shown – constant color

Slide credit: D. Hoiem
Most information in intensity

Original image

Slide credit: D. Hoiem
Back to grayscale intensity

Slide credit: D. Hoiem
Today

• Image formation
• Digital images
• Perception of color and light
• Color spaces
Next week

• Point operations
• Histogram processing