Light

Computer Vision

James Hays
If \( X = 2, \ Y = 3, \) 
\( Z = 5, \) and \( f = 2 \)

What are \( U \) and \( V? \)

\[
\begin{align*}
\frac{v'}{-f} &= \frac{y}{z} \\
v' &= -y \times \frac{f}{z} \\
u' &= -x \times \frac{f}{z} \\
u' &= -2 \times \frac{2}{5} \\
v' &= -3 \times \frac{2}{5}
\end{align*}
\]
Interlude: why does this matter?
Relating multiple views
Projection matrix

Intrinsic Assumptions
- Unit aspect ratio
- Optical center at (0,0)
- No skew

Extrinsic Assumptions
- No rotation
- Camera at (0,0,0)

\[
\begin{bmatrix}
u \\
v \\
1
\end{bmatrix} = \begin{bmatrix}
f & 0 & 0 & 0 \\
0 & f & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
\]
Remove assumption: optical center at origin

Intrinsic Assumptions
• Unit aspect ratio
• No skew

Extrinsic Assumptions
• No rotation
• Camera at (0,0,0)

\[ x = K[I \ 0]X \]

\[
\begin{bmatrix}
    u \\
    v \\
    1
\end{bmatrix} =
\begin{bmatrix}
    f & 0 & u_0 & 0 \\
    0 & f & v_0 & 0 \\
    0 & 0 & 1 & 0 \\
    0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    x \\
    y \\
    z \\
    1
\end{bmatrix}
\]
Remove assumption: square pixels

Intrinsic Assumptions
• No skew

Extrinsic Assumptions
• No rotation
• Camera at (0,0,0)

\[ x = K[I \ 0] X \]

\[ w \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & 0 & u_0 & 0 \\ 0 & \beta & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \]
Remove assumption: non-skewed pixels

**Intrinsic Assumptions**

**Extrinsic Assumptions**
- No rotation
- Camera at (0,0,0)

\[
x = K[I \ 0]X
\]

Note: different books use different notation for parameters
Oriented and Translated Camera
Allow camera translation

Intrinsic Assumptions  Extrinsic Assumptions
• No rotation

\[ x = K[I \quad t]X \]  \[ w = \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \alpha & 0 & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \]
3D Rotation of Points

Rotation around the coordinate axes, **counter-clockwise**:

- Rotation around the x-axis:
  \[
  R_x(\alpha) = \begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \alpha & -\sin \alpha \\
  0 & \sin \alpha & \cos \alpha
  \end{bmatrix}
  \]

- Rotation around the y-axis:
  \[
  R_y(\beta) = \begin{bmatrix}
  \cos \beta & 0 & \sin \beta \\
  0 & 1 & 0 \\
  -\sin \beta & 0 & \cos \beta
  \end{bmatrix}
  \]

- Rotation around the z-axis:
  \[
  R_z(\gamma) = \begin{bmatrix}
  \cos \gamma & -\sin \gamma & 0 \\
  \sin \gamma & \cos \gamma & 0 \\
  0 & 0 & 1
  \end{bmatrix}
  \]
Allow camera rotation

\[
x = K [ R \ t ] X
\]
Degrees of freedom

\[ x = K[R \ t]X \]
Reminder: read your book

• Lectures have assigned readings
• Szeliski 2.1 and especially 2.1.5 cover the geometry of image formation
Field of View (Zoom, focal length)

From London and Upton
Things to remember

• Vanishing points and vanishing lines

• Pinhole camera model and camera projection matrix

• Homogeneous coordinates
Image Formation

Digital Camera

The Eye
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

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\[ \lambda \]
A photon’s life choices

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• **Interreflection**
Lambertian Reflectance

• In computer vision, surfaces are often assumed to be ideal diffuse reflectors with no dependence on viewing direction.
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
FIGURE 2.17 (a) Continuous image projected onto a sensor array. (b) Result of image sampling and quantization.
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.
Interlace vs. progressive scan

Progressive scan

Interlace


Slide by Steve Seitz
Rolling Shutter
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 “film”?  
    - photoreceptor cells (rods and cones) in the retina
Aside: why do we care about human vision in this class?

• We don’t, necessarily.
Ornithopters
Why do we care about human vision?

• We don’t, necessarily.
• But cameras necessarily imitate the frequency response of the human eye, so we should know that much.
• Also, computer vision probably wouldn’t get as much scrutiny if biological vision (especially human vision) hadn’t proved that it was possible to make important judgements from 2d images.
Does computer vision “understand” images?

"Can machines fly?" The answer is yes, because airplanes fly.

"Can machines swim?" The answer is no, because submarines don't swim.

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

Source: Norvig
The Retina

Cross-section of eye

Cross section of retina

Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
Pigmented epithelium

What humans don’t have: tapetum lucidum

Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.
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
Rod / Cone sensitivity

Intensity of light reflected from objects (lamberts)

- 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

Night Sky: why are there more stars off-center?
Averted vision: http://en.wikipedia.org/wiki/Averted_vision
Wait, the blood vessels are in front of the photoreceptors??

https://www.youtube.com/watch?v=L_W-IXqoxHA
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
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.
### Some examples of the spectra of light sources

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Wavelength (nm.)</th>
<th># Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Ruby Laser</strong></td>
<td>400 - 700</td>
<td><img src="image1.png" alt="Graph" /></td>
</tr>
<tr>
<td><strong>B. Gallium Phosphide Crystal</strong></td>
<td>400 - 700</td>
<td><img src="image2.png" alt="Graph" /></td>
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<tr>
<td><strong>C. Tungsten Lightbulb</strong></td>
<td>400 - 700</td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td><strong>D. Normal Daylight</strong></td>
<td>400 - 700</td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>
Some examples of the **reflectance** spectra of **surfaces**

- **Red**
  - Wavelength: 400 nm to 700 nm
  - % Photons Reflected:
    - 400 nm: 70%
    - 700 nm: 0%

- **Yellow**
  - Wavelength: 400 nm to 700 nm
  - % Photons Reflected:
    - 400 nm: 70%
    - 700 nm: 0%

- **Blue**
  - Wavelength: 400 nm to 700 nm
  - % Photons Reflected:
    - 400 nm: 70%
    - 700 nm: 0%

- **Purple**
  - Wavelength: 400 nm to 700 nm
  - % Photons Reflected:
    - 400 nm: 70%
    - 700 nm: 0%

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The Psychophysical Correspondence

There is no simple functional description for the perceived color of all lights under all viewing conditions, but ……

A helpful constraint:
Consider only physical spectra with normal distributions

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Mean ↔ Hue

# Photons

Wavelength

blue  green  yellow

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Variance ↔ Saturation

# Photons

Wavelength
The Psychophysical Correspondence

Area ↔ Brightness

Wavelength

# Photons

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Physiology of Color Vision

Three kinds of cones:

- Why are M and L cones so close?
- Why are there 3?
Most birds, and many other animals, have cones for ultraviolet light.

Some humans, mostly female, seem to have slight tetrachromatism.
More Spectra

metamers
Practical Color Sensing: Bayer Grid

- Estimate RGB at ‘G’ cells from neighboring values
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<sup>th</sup> channel
  - im(N, M, 3) = bottom-right pixel value in B-channel
- imread(filename) returns a uint8 image (values 0 to 255)
  - Convert to double format (values 0 to 1) with im2double
Color spaces

• How can we represent color?

Color spaces: RGB

Default color space

Some drawbacks
• Strongly correlated channels
• Non-perceptual

Color spaces: HSV

Intuitive color space

Hue

Value

Saturation

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

Y=0

Y=0.5

Y=1

Cb

Cr

Y (Cb=0.5,Cr=0.5)

Cb (Y=0.5,Cr=0.5)

Cr (Y=0.5,Cb=0.5)
Color spaces: $L^*a^*b^*$

“Perceptually uniform”* color space

$L^*(a=0,b=0)$

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

$b$  
$(L=65,a=0)$
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
Back to grayscale intensity

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Next week

• Convolution, Filtering, Image Pyramids, Frequencies, Project 1