Lecture 15:

Cameras & Lenses

Computer Graphics and Imaging
UC Berkeley CS184/284A
Rendering with Realistic Camera Model

Credit: Bertrand Benoit. “Sweet Feast,” 2009. [Blender /VRay]
Rendering with Realistic Camera Model

Credit: Giuseppe Albergo. “Colibri” [Blender]
Image Capture Overview
What’s Happening Inside the Camera?

Cross-section of Nikon D3, 14-24mm F2.8 lens
Pinholes & Lenses Form Image on Sensor

Photograph made with lens

Photograph made with small pinhole

London and Upton
Shutter Exposes Sensor For Precise Duration

The Slow Mo Guys, https://youtu.be/CmjeCchGRQo
Sensor Accumulates Irradiance During Exposure
Image Processing: From Sensor Values to Image
Optics of Image Formation: Field of View
Effect of Focal Length on FOV

For a fixed sensor size, decreasing the focal length increases the field of view.

\[ \text{FOV} = 2 \arctan \left( \frac{h}{2f} \right) \]
Effect of Sensor Size on FOV

35mm Full Frame

APS-C

Object

Lens

Sensor(s)

Kanazawa & Ng
# Sensor Sizes

<table>
<thead>
<tr>
<th>Sensor Name</th>
<th>Medium Format</th>
<th>Full Frame</th>
<th>APS-H</th>
<th>APS-C</th>
<th>4/3</th>
<th>1&quot;</th>
<th>1/1.63&quot;</th>
<th>1/2.3&quot;</th>
<th>1/3.2&quot;</th>
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<tbody>
<tr>
<td>Sensor Size</td>
<td>53.7 x 40.2mm</td>
<td>36 x 23.9mm</td>
<td>27.9x18.6mm</td>
<td>23.6x15.8mm</td>
<td>17.3x13mm</td>
<td>13.2x8.8mm</td>
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<td>Sensor Area</td>
<td>21.59 cm²</td>
<td>8.6 cm²</td>
<td>5.19 cm²</td>
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<td>2.25 cm²</td>
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<td>2.7</td>
<td>4.3</td>
<td>5.62</td>
<td>7.61</td>
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</tbody>
</table>

**Image**

![Medium Format](image1.jpg) ![Full Frame](image2.jpg) ![APS-H](image3.jpg) ![APS-C](image4.jpg) ![4/3](image5.jpg) ![1"](image6.jpg) ![1/1.63"](image7.jpg) ![1/2.3"](image8.jpg) ![1/3.2"](image9.jpg)

**Example**

![Medium Format Camera](image10.jpg) ![Full Frame Camera](image11.jpg) ![APS-H Camera](image12.jpg) ![APS-C Camera](image13.jpg) ![4/3 Camera](image14.jpg) ![1" Camera](image15.jpg) ![1/1.63" Camera](image16.jpg) ![1/2.3" Camera](image17.jpg) ![1/3.2" Camera](image18.jpg)

Credit: lensvid.com
Maintain FOV on Smaller Sensor?

To maintain FOV, decrease focal length of lens in proportion to width/height of sensor.
Focal Length v. Field of View

• For historical reasons, it is common to refer to angular field of view by focal length of a lens used on a 35mm-format film (36 x 24mm)

• Examples of focal lengths on 35mm format:
  • 17mm is wide angle 104°
  • 50mm is a “normal” lens 47°
  • 200mm is telephoto lens 12°

• Careful! When we say current cell phones have approximately 28mm “equivalent” focal length, this uses the above convention. The physical focal length is often 5-6 times shorter, because the sensor is correspondingly smaller
Focal Length v. Field of View

From London and Upton, and Canon EF Lens Work III
Focal Length v. Field of View

From London and Upton, and Canon EF Lens Work III
Focal Length v. Field of View

From London and Upton, and Canon EF Lens Work III
Focal Length v. Field of View

From London and Upton, and Canon EF Lens Work III
Perspective Composition
(Photographer’s Mindset)
In this sequence, distance from subject increases with focal length to maintain image size of human subject.

Notice the dramatic change in background perspective.

From Canon EF Lens Work III
Perspective Composition

Up close and zoomed wide with short focal length

16 mm (110°)
Perspective Composition

200 mm (12°)

Walk back and zoom in with long focal length
A Photographer’s Mindset

“Choose your perspective before you choose your lens.”

— Ming Thein, mingthein.com
Improve Your Own Photography

Tip 1: Make sure you have a strong subject
• Make it prominent, e.g. 1/3 of your image

Tip 2: choose a good perspective relationship (relative size) between your subject and background (or foreground)
• Complement, don’t compete with the subject

Tip 3: change the zoom and camera distance to your subject
• Implement: actively zoom, and move your camera in/out
• Even works with your smartphone!

Dolly-Zoom Cinema Technique – “Vertigo Effect”

First used by Alfred Hitchcock in “Vertigo” 1958
Dolly-Zoom Cinema Technique – a.k.a. “Vertigo Effect”

By Steven Spielberg in “Jaws” 1975
Exposure
Exposure Duration: Fast and Slow Photography
High-Speed Photography

long exposure
bright strobe illumination
gun synced to camera
High-Speed Photography

Harold Edgerton
High-Speed Photography

Harold Edgerton
Long-Exposure Photography

https://www.demilked.com/best-long-exposure-photos/
Long-Exposure Photography

https://www.demilked.com/best-long-exposure-photos/
Long-Exposure Photography

https://www.demilked.com/best-long-exposure-photos/
Exposure

- $Q = T \times E$
- Exposure = time \times irradiance
- Exposure time ($T$)
  - Controlled by shutter
- Irradiance ($E$)
  - Power of light falling on a unit area of sensor
  - Controlled by lens aperture and focal length
Exposure Levels (1 “Stop” = 2x Exposure)

Exposure bracketing with +/- 1 stop exposure

Exposure Controls: Aperture, Shutter, Gain (ISO)
Definition: F-Number of a Lens

- The F-Number of a lens is defined as the focal length divided by the diameter of the aperture.
- Common F-stops on real lenses: 1.4, 2, 2.8, 4.0, 5.6, 8, 11, 16, 22, 32
- 1 stop doubles exposure
- Notation: an f-stop of, e.g. 2 is sometimes written f/2, or F:2
Exposure Controls: Aperture, Shutter, Gain (ISO)

Aperture size

• Change the f-stop by opening / closing the aperture (if camera has iris control)

Shutter speed

• Change the duration the sensor pixels integrate light

ISO gain

• Change the amplification (analog and/or digital) between sensor values and digital image values
Constant Exposure: F-Stop vs Shutter Speed

Example: these pairs of aperture and shutter speed give equivalent exposure

<table>
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<tr>
<th>F-Stop</th>
<th>1.4</th>
<th>2.0</th>
<th>2.8</th>
<th>4.0</th>
<th>5.6</th>
<th>8.0</th>
<th>11.0</th>
<th>16.0</th>
<th>22.0</th>
<th>32.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shutter</td>
<td>1/500</td>
<td>1/250</td>
<td>1/125</td>
<td>1/60</td>
<td>1/30</td>
<td>1/15</td>
<td>1/8</td>
<td>1/4</td>
<td>1/2</td>
<td>1</td>
</tr>
</tbody>
</table>

If the exposure is too bright/dark, may need to adjust f-stop and/or shutter up/down.
ISO (Gain)

Third variable for exposure

Image sensor: trade sensitivity for noise

- Multiply signal before analog-to-digital conversion
- Linear effect (ISO 200 needs half the light as ISO 100)
ISO Gain vs Noise in Canon T2i

Note: trend is same in current sensors, but much less noise!

Kanazawa & Ng
Physical & Electronic Shutters
Physical Shutter (1/25 Sec Exposure)

The Slow Mo Guys, https://youtu.be/CmjeCchGRQo
Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur
Main Side Effect of Shutter Speed

Motion blur: handshake, subject movement

Doubling shutter time doubles motion blur
Electronic Shutter

• Pixel is electronically reset to start exposure
• Fills with photoelectrons as light falls on sensor
• Reading out pixel electronically “ends” exposure
• Problem: most sensors read out pixels sequentially, takes time (e.g. 1/30 sec) to read entire sensor
  • If reset all pixels at the same time, last pixel read out will have longer exposure
  • So, usually stagger reset of pixels to ensure uniform exposure time
• Problem: rolling shutter artifact
Electronic Rolling Shutter

Credit: Soren Ragsdale
https://flic.kr/p/5S6rKw

Credit: David Adler, B&H Photo Video
Electronic Rolling Shutter

The Slow Mo Guys, https://youtu.be/CmjeCchGRQo
Electronic Rolling Shutter

- Exposure duration (e.g. 1/1000 sec)
- Delay from top to bottom of sensor (e.g. 1/30 sec)
Focal Plane Shutter (Fast Exposures)

The Slow Mo Guys, https://youtu.be/CmjeCchGRQo
Lenses
Real Lens Designs Are Highly Complex
Real Lens Elements Are Not Ideal – Aberrations

Real plano-convex lens (spherical surface shape). Lens does not converge rays to a point anywhere.

More discussion next lecture
First: Thin Lens Approximation
Ideal Thin Lens – Focal Point

Assume all parallel rays entering a lens pass through its focal point.

Credit: Karen Watson
Gauss’ Ray Diagrams
Gauss’ Ray Tracing Construction

Object

Image

Parallel Ray

Chief Ray

Focal Ray
What is the relationship between conjugate depths $z_o, z_i$?
Gauss’ Ray Tracing Construction

\[
\frac{h_o}{z_o - f} = \frac{h_i}{f} \quad \text{and} \quad \frac{h_o}{f} = \frac{h_i}{z_i - f}
\]
Gauss’ Ray Tracing Construction

\[
\frac{h_o}{z_o - f} = \frac{h_i}{f} \\
\frac{h_o}{h_i} = \frac{z_o - f}{f} \\
\frac{h_o}{f} = \frac{h_i}{z_i - f} \\
\frac{h_o}{h_i} = \frac{f}{z_i - f}
\]

Object / image heights factor out - applies to all rays

Newtonian Thin Lens Equation

\[
\frac{z_o - f}{f} = \frac{f}{z_i - f}
\]

\[
(z_o - f)(z_i - f) = f^2
\]

\[
z_o z_i - (z_o + z_i)f + f^2 = f^2
\]

\[
z_o z_i = (z_o + z_i)f
\]

Gaussian Thin Lens Equation

\[
\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}
\]
The Thin Lens Equation

\[
\frac{1}{f} = \frac{1}{z_i} + \frac{1}{z_o}
\]
Changing the Focus Distance

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

- \( z_i \) and \( z_o \) are called conjugate points.
- To focus on objects at different distances, move the sensor relative to the lens.
- For \( z_i < z_o \) the object is larger than the image.
- At \( z_i = z_o \) we have 1:1 macro imaging.
- For \( z_i > z_o \) the image is larger than the object (magnified).
- Can’t focus on objects closer than the lens’ focal length.
Magnification

\[ m = \frac{h_i}{h_o} = \frac{z_i}{z_o} \]
Magnification Example – Focus at Infinity

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

If focused on a distant mountain

• \( z_o \approx \infty \), so \( z_i = f \)
• sensor at focal point
• magnification \( \approx 0 \)
What configuration do we need to achieve a magnification of 1 (i.e. image and object the same size, a.k.a. 1:1 macro)?

- Need $z_i = z_o$, so $z_i = z_o = 2f$ — sensor at twice focal length
- In 1:1 imaging, if the sensor is 36 mm wide, an object 36 mm wide will fill the frame
Thin Lens Demonstration

http://graphics.stanford.edu/courses/cs178-10/applets/gaussian.html
Thin Lens Demonstration Observations

3D image of object is:

- Compressed in depth for low magnification
- 1:1 in 3D for unit magnification
- Stretched in depth for high magnification
Defocus Blur
Circle of Confusion
Circle of Confusion

Further defocused point light

Closer defocused point light
Circle of Confusion

Defocus blur kernel for objects at this depth

Size of blur kernel depends on depth from focal plane. Why?
Circle of Confusion
Computing Circle of Confusion Diameter (C)

Circle of confusion is proportional to the size of the aperture

\[
\frac{C}{A} = \frac{\frac{d'}{z_i}}{z_i} = \frac{|z_s - z_i|}{z_i}
\]
Circle of Confusion – Example

50mm f/2 lens
Full frame sensor (36x24mm)
Focus: 1 meter
Background: 10 meter
Foreground: 0.3 meter

\[ A = \frac{50\text{mm}}{2} = 25\text{mm} \]

\[ z_s = \frac{1}{\frac{1}{50} - \frac{1}{1000}} \approx 52.63\text{mm} \]

Background: \( z_i = \frac{1}{\frac{1}{50} - \frac{1}{10,000}} \approx 50.25\text{mm} \)

\[ C = A\left| \frac{z_s - z_i}{z_i} \right| = 1.18\text{mm} \]

\( \approx 65 \) pixels on HD TV

Foreground: \( z_i = \frac{1}{\frac{1}{50} - \frac{1}{300}} \approx 55.56\text{mm} \)

\[ C = A\left| \frac{z_s - z_i}{z_i} \right| = 3.07\text{mm} \]

\( \approx 169 \) pixels on HD TV
Lens’s F-Number vs F-Number for Photo

A lens’s F-Number is the maximum for that lens

• E.g. 50 mm F/1.4 is a high-quality telephoto lens
  • Maximum aperture is 50/1.4 = 36 mm diameter

But for an individual photo, the lens aperture may be “stopped down” to a smaller size

• E.g. 50 mm F/1.4 lens stopped down to F/4
  • Aperture is closed down with an iris to 50/4 = 12.5 mm

![Diagram showing aperture sizes for different F-numbers](image-url)
Example F-Number Calculations

1. \[ D = 50 \text{ mm} \]
   \[ f = 100 \text{ mm} \]
   \[ N = \frac{f}{D} = 2 \]

2. \[ D = 100 \text{ mm} \]
   \[ f = 200 \text{ mm} \]
   \[ N = \frac{f}{D} = 2 \]

3. \[ D = 100 \text{ mm} \]
   \[ f = 400 \text{ mm} \]
   \[ N = \frac{f}{D} = 4 \]
Size of Circle of Confusion is Inversely Proportional to F-Number for Photo

\[ C = A \frac{|z_s - z_i|}{z_i} = \frac{f}{N} \frac{|z_s - z_i|}{z_i} \]
Exposure Tradeoffs

Depth of Field vs Motion Blur
Constant Exposure: Depth of Field vs Motion Blur

- Photographers must trade off depth of field and motion blur for moving subjects.
Shallow Depth of Field Can Create a Stronger Image

From Peterson, Understanding Exposure
200mm, f/4, 1/1000 (left) and f/11, 1/125 (right)
Motion Blur Can Help Tell The Story

From Peterson, Understanding Exposure
1/60, f/5.6, 180mm
Depth of Field
Depth of Field

- Depth of field is the range of object depths that are rendered with acceptable sharpness in an image.
Circle of Confusion for Depth of Field

Set circle of confusion as the maximum permissible blur spot on the image plane that will appear sharp under final viewing conditions

- For printed photographs from 35mm film, 0.025mm (on negative) is typical
- For digital image sensors, 1 pixel is typical (e.g. 1.4 micron for phones)
- Larger if intended for viewing at web resolution, or if lens is poor

Lens

Ideal focal point

Front depth of field

Rear depth of field

Depth of focus

Permissible circle of confusion

[Canon, EF Lens Work III]

Kanazawa & Ng
Depth of Field

\[ \text{DOF} = D_F - D_N \]

\[ D_F = \frac{D_S f^2}{f^2 - NC(D_S - f)} \]

\[ D_N = \frac{D_S f^2}{f^2 + NC(D_S - f)} \]
DOF Demonstration

http://graphics.stanford.edu/courses/cs178/applets/dof.html
Ray Tracing Ideal Thin Lenses
Example of Rendering with Lens Focus

Credit: Bertrand Benoit. “Sweet Feast,” 2009. [Blender /VRay]
Example of Rendering with Lens Focus

Credit: Giuseppe Albergo. “Colibri” [Blender]
Example of Rendering with Lens Focus

Pharr and Humphreys
Ray Tracing for Defocus Blur (Thin Lens)

Setup:
• Choose sensor size, lens focal length and aperture size
• Choose depth of subject of interest \( z_o \)
  • Calculate corresponding depth of sensor \( z_i \) from thin lens equation (focusing)
Ray Tracing for Defocus Blur (Thin Lens)

To compute value of pixel at position $x'$ by Monte Carlo integration:

- Select random points $x''$ on lens plane
- Rays pass from point $x'$ on image plane $z_i$ through points $x''$ on lens
- Each ray passes through conjugate point $x'''$ on the plane of focus $z_o$
  - Can determine $x'''$ from Gauss’ ray diagram
  - So just trace ray from $x''$ to $x'''$
- Estimate radiance on rays using path-tracing, and sum over all points $x''$
Example of Rendering with Lens Focus

Pharr and Humphreys
Bokeh
Bokeh

Bokeh is the shape and quality of out-of-focus blur

- For small, out-of-focus lights, bokeh takes on the shape of the lens aperture
Bokeh

Heart-shaped bokeh?
Bokeh

Why does the bokeh vary across the image?
Real Compound Lenses
Modern Lens Designs Are Highly Complex

Photographic lens cross section
Modern Lens Designs Are Highly Complex

4 element mobile phone lens (on 24x36mm sensor)
Modern Lens Designs Are Highly Complex
Modern Lens Designs Are Highly Complex

Microscope objective
Recall: Snell’s Law of Refraction

\[ \eta_i \sin \theta_i = \eta_t \sin \theta_t \]
Real Refraction Through A Lens Is Not Ideal – Aberrations

Real plano-convex lens (spherical surface shape). Lens does not converge rays to a point anywhere.
Real Lenses vs Ideal Thin Lenses

- Real optical system
- Multiple physical elements in compound design
- Optical aberrations prevent rays from converging perfectly

- Theoretical abstraction
- Assume all rays refract at a plane & converge to a point
- Quick and intuitive calculation of main imaging effects
**Example Lens Formula: Double Gauss**

Data from W. Smith, Modern Lens Design, p 312

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<th>Radius (mm)</th>
<th>Thick (mm)</th>
<th>n_d</th>
<th>V-no</th>
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</table>
Ray Tracing Through Real Lens Designs

200 mm telephoto

35 mm wide-angle

50 mm double-gauss

16 mm fisheye

From Kolb, Mitchell and Hanrahan (1995)
Ray Tracing Through Real Lens Designs

200 mm telephoto

Notice shallow depth of field (out of focus background)
Ray Tracing Through Real Lens Designs

Notice distortion in the corners (straight lines become curved)
Ray Tracing Real Lens Designs

Monte Carlo approach

- At every sensor pixel, compute integral of rays incident on pixel area arriving from all paths through the lens

Algorithm (for a pixel)

- Choose N random positions in pixel
- For each position $x'$, choose a random position on the back element of the lens $x''$
- Trace a ray through from $x'$ to $x''$, trace refractions through lens elements until it misses the next element (kill ray) or exits the lens (path trace through the scene)
- Weight each ray according to radiometric calculation on next slide to estimate irradiance $E(x')$
Radiometry for Tracing Lens Designs

$$E(x') = \int_{x'' \in D} L(x'' \rightarrow x') \frac{\cos \theta' \cos \theta''}{||x'' - x'||^2} dA''$$

$$= \frac{1}{Z^2} \int_{x'' \in D} L(x'' \rightarrow x') \cos^4 \theta dA''$$
# Things to Remember

<table>
<thead>
<tr>
<th>Effect</th>
<th>Cause</th>
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</thead>
<tbody>
<tr>
<td>Field of view</td>
<td>Sensor size, focal length</td>
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<tr>
<td>Depth of field</td>
<td>Aperture, focal length, object dist.</td>
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<tr>
<td>Exposure</td>
<td>Aperture, shutter, ISO</td>
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<td>Motion blur</td>
<td>Shutter</td>
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<td>Grain/noise</td>
<td>ISO</td>
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Pinholes and lenses form perspective images

Perspective composition, dolly zoom
Acknowledgments

Many thanks to Marc Levoy, who created many of these slides, and Pat Hanrahan.

- Peterson, Understanding Exposure, AMPHOTO 1990.
- The Slow Mo Guys
- bobatkins.com
- Hari Subramanyan
- Canon EF Lens Work III
Extra
Auto Focus
Contrast Detection Autofocus

A target object is imaged through the lens to an image patch on the sensor.

The contrast of this image patch is high if the object is in focus, low otherwise.

The physical focus of the lens is adjusted until the contrast of this image patch is maximized.

Many ways to estimate how in-focus the image patch is: gradient, Sum Modified Laplacian (Nayar), variance...

Demo (Levoy, Willet, Adams)

https://graphics.stanford.edu/courses/cs178-10/applets/autofocusCD.html
Phase Detection Autofocus

Ray bundles from a target object converge to points at different depths in the camera depending on the lens focus.

In a phase detection AF system ray bundles passing through different portions of the lens (red and green shown) are brought to focus on separate lenslets with separate AF sensors.

Depending on depth of focus point, the ray bundles converge to different positions on their respective AF sensors (see interactive demo).

A certain spacing (disparity) between these images is “in focus”

Demo (Levoy, Willet, Adams)

https://graphics.stanford.edu/courses/cs178-10/applets/autofocusPD.html
Phase Detection AF Used in DSLRs

- Distance between phase-detect images correlates to distance in focus to target object (allows “jumping” to the right focus)
- Separate AF units cannot be used with “live view” or video recording
Modern image sensors have small pixels, and may embed phase detection pixels directly into sensor image arrays.