Photographic optics and exposure

http://graphics.cs.cmu.edu/courses/15-463
Course announcements

• Homework 1 is out.
  - Due September 14\textsuperscript{th}.
  - Canvas submission website is now open.
  - Make sure to sign up for a camera if you need one.
  - Drop by Yannis’ office to pick up cameras any time.
Overview of today’s lecture

• Paraxial optics.

• Ray transfer matrix analysis.

• Aberrations and compound lenses.

• Lens designations.

• Exposure control.

• Filters.

• Prisms.
Many of these slides were adapted from:

- Kris Kitani (15-463, Fall 2016).
- Fredo Durand (MIT).
- Marc Levoy (Stanford).
- Gordon Wetzstein (Stanford).
Paraxial optics
Thin lens model

Simplification of geometric optics for well-designed lenses.

Two assumptions:
1. Rays passing through lens center are unaffected.
2. Parallel rays converge to a single point located on focal plane.

Where do the thin lens properties come from?
What determines the focal length of a thin lens?

\[
m = \frac{f}{D' - f}
\]

\[
\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}
\]
Real lenses

We will first consider the case of a system with an individual lens element.

The lens’ behavior is determined by three characteristics:
- shape of surfaces
- index of refraction inside and outside
- existence and shape of pupils
Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).
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Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

\[ n_1 = 1 \]
\[ n_2 = 1.33 \]

What happens to the ray when it crosses the interface?
Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

Air \( n_1 = 1 \)

Water \( n_2 = 1.33 \)

\( \theta_1 \) is the angle of incidence in air, and \( \theta_2 \) is the angle of refraction in water. How are the two angles related?
Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

\[
n_1 = 1 \\
\theta_1
\]

\[
n_2 = 1.33 \\
\theta_2
\]

how are the two angles related?

Snell’s law

\[
 n_1 \sin \theta_1 = n_2 \sin \theta_2
\]
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?
Refraction at interfaces of complicated shapes

What shape should an interface have to make parallel rays converge to a point?

Single hyperbolic interface:
point to parallel rays

Double hyperbolic interface:
point to point rays

Therefore, lenses should also have hyperbolic shapes.
Spherical lenses

In practice, lenses are often made to have spherical interfaces for ease of fabrication.

- Two roughly fitting curved surfaces ground together will eventually become spherical.

Spherical lenses don’t bring parallel rays to a point.
- This is called *spherical aberration*.
- Approximately axial (i.e., paraxial) rays behave better.
Paraxial approximation

Assume angles are small. Then:

\[ \sin \theta \approx \theta \quad \cos \theta \approx 1 \quad \tan \theta \approx \theta \]

Where do these approximations come from?
Paraxial approximation (a.k.a. first-order optics)

Assume angles are small. Then:

\[
\sin \theta \simeq \theta \quad \cos \theta \simeq 1 \quad \tan \theta \simeq \theta
\]

Where do these approximations come from?

- First-order expansions of \( \sin \) and \( \cos \) functions.

\[
\sin \theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!} + \cdots
\]

\[
\cos \theta = 1 - \frac{\theta^2}{2!} + \frac{\theta^4}{4!} - \frac{\theta^6}{6!} + \cdots
\]
Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

Snell’s law

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

How is Snell’s law simplified under paraxial approximation?

\( n_1 = 1 \)

\( n_2 = 1.33 \)
Refraction

Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

**Snell’s law**

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

How is Snell’s law simplified under paraxial approximation?

\[ n_1 \theta_1 = n_2 \theta_2 \]
Paraxial focusing

spherical lens surface with radius $r$
Paraxial focusing

Where do these two equations come from?

- assume $e \approx 0$
- assume $\sin u = h/l \approx u$ (for $u$ in radians)
- assume $\cos u \approx z/l \approx 1$
Paraxial focusing

How can we relate angles $i$ and $i'$?
Paraxial focusing

Snell’s law:

\[ n \sin i = n' \sin i' \]

paraxial approximation:

\[ n i \approx n' i' \]
Paraxial focusing

What is this point?
Paraxial focusing

object

(i)

(n)

Center of spherical surface

image
Paraxial focusing

$u \approx \frac{h}{z}$
$u' \approx \frac{h}{z'}$

$n_i \approx n'_i$

What is angle $i$ equal to?
Paraxial focusing

\[ i = u + a \]
\[ u \approx \frac{h}{z} \]
\[ u' \approx \frac{h}{z'} \]

Given object distance \( z \), what is image distance \( z' \)?

\[ n_i \approx n'_i \]
Paraxial focusing

\[ i = u + a \]
\[ u \approx \frac{h}{z} \]
\[ u' \approx \frac{h}{z'} \]

\[ a = u' + i' \]
\[ a \approx \frac{h}{r} \]

\[ n i \approx n' i' \]
Paraxial focusing

What does this last equation imply?

\[ i = u + a \]
\[ a = u' + i' \]

\[ u \approx \frac{h}{z} \]
\[ a \approx \frac{h}{r} \]

\[ u' \approx \frac{h}{z'} \]

\[ n i \approx n' i' \]

\[ n (u + a) \approx n' (a - u') \]

\[ n \left( \frac{h}{z} + \frac{h}{r} \right) \approx n' \left( \frac{h}{r} - \frac{h}{z'} \right) \]

\[ \frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'} \]
Paraxial focusing

\[ i = u + a \]
\[ u \approx \frac{h}{z} \]
\[ u' \approx \frac{h}{z'} \]
\[ a = u' + i' \]
\[ a \approx \frac{h}{r} \]

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\[ n (u + a) \approx n' (a - u') \]
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\[ \frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'} \]

h has cancelled out, so any ray from P will focus at P'.
Paraxial focusing

\[ i = u + a \]
\[ u \approx \frac{h}{z} \]
\[ u' \approx \frac{h}{z'} \]
\[ a = u' + i' \]
\[ a \approx \frac{h}{r} \]

What happens as \( z \) tends to infinity?

\[ n_i \approx n'i' \]
\[ n (u + a) \approx n'(a - u') \]
\[ n \left( \frac{h}{z} + \frac{h}{r} \right) \approx n' \left( \frac{h}{r} - \frac{h}{z'} \right) \]
\[ \frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'} \]
Focal length

What happens if $z$ is $\infty$?

$\bullet \, f \triangleq \text{focal length} = z'$

\[
\frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r - n'/z'}
\]

\[
\frac{n}{r} \approx \frac{n'}{r - n'/z'}
\]

\[
z' \approx \frac{(r \, n')}{(n' - n)}
\]
Thin lens

Using similar derivations, we can extend these results to two spherical interfaces.

• We obtain a spherical lens in air.

• Thin lens approximation: $d$ close to zero.

• Under this approximation, we obtain the lensmaker’s equation.

$$\frac{1}{s_o} + \frac{1}{s_i} = (n_l - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right)$$
Gaussian lens formula

- Starting from the lensmaker’s formula
  \[ \frac{1}{s_o} + \frac{1}{s_i} = (n_t - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right), \]

- and recalling that as object distance \( s_o \) is moved to infinity, image distance \( s_i \) becomes focal length \( f_i \), we get
  \[ \frac{1}{f_i} = (n_t - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right). \]

- Equating these two, we get the Gaussian lens formula
  \[ \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f_i}. \]
Thin lens model

Simplification of geometric optics for well-designed lenses.

Two assumptions:
1. Rays passing through lens center are unaffected.
2. Parallel rays converge to a single point located on focal plane.

Same result as what we obtained last time using ray tracing assumptions.
Ray transfer matrix analysis
Let’s look at thin lenses (yet) again

Assumptions:
• Paraxial → ?
• Thin lens → ?
Let’s look at thin lenses (yet) again

Assumptions:
- Paraxial → angles $\theta$ are small, thus first-order approximations for $\sin\theta$, $\cos\theta$, and $\tan\theta$ apply.
- Thin lens → width of lens is negligible ($d \approx 0$) relative to distances $s$. 
Let’s look at thin lenses (yet) again

\[ s_i \theta_i + s_o \theta_o = 0 \]

\[ x_i = ? \]

\[ x_o = ? \]

\[ \frac{1}{s_o} + \frac{1}{s_i} = ? \]
Let’s look at thin lenses (yet) again

\[ x_i = s_i \theta_i \]

\[ x_o = s_o \theta_o \]

\[ \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \]

\[ d \approx 0 \Rightarrow x_i = x_o \]
Let’s look at thin lenses (yet) again

\[ x_i = s_i \theta_i \]
\[ x_o = s_o \theta_o \]
\[ \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \]
\[ d \approx 0 \Rightarrow x_i = x_o \]

Putting it all together, we can write:

\[
\begin{bmatrix}
  x_o \\
  \theta_o
\end{bmatrix}
= \begin{bmatrix}
  1 & 0 \\
  -\frac{1}{f} & 1
\end{bmatrix}
\begin{bmatrix}
  x_i \\
  \theta_i
\end{bmatrix}
\]
Let’s look at thin lenses (yet) again

\[ x_i = s_i \theta_i \]
\[ x_o = s_o \theta_o \]
\[ \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \]
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    1 & 0 \\
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\end{bmatrix}
\begin{bmatrix}
    x_i \\
    \theta_i
\end{bmatrix}
\]

Ray transfer matrix:
relates each incoming ray to an outgoing ray
Ray transfer matrix analysis

Every optical system implements a (generally non-linear) ray mapping of the form:

\[
\begin{bmatrix}
    x_o \\
    \theta_o
\end{bmatrix} = \begin{bmatrix}
    f(x_i, \theta_i) \\
    g(x_i, \theta_i)
\end{bmatrix}
\]

How do we go from here to a ray transfer matrix?
Ray transfer matrix analysis

Every optical system implements a (generally non-linear) ray mapping of the form:

\[
\begin{bmatrix}
    x_o \\
    \theta_o
\end{bmatrix} =
\begin{bmatrix}
    f(x_i, \theta_i) \\
    g(x_i, \theta_i)
\end{bmatrix}
\]

How do we go from here to a ray transfer matrix?

• Paraxial approximation: Use first-order approximation around axial ray.
Ray transfer matrix analysis

\[
\begin{bmatrix}
  x_o \\
  \theta_o
\end{bmatrix} = \begin{bmatrix}
  f(x_i, \theta_i) \\
  g(x_i, \theta_i)
\end{bmatrix} \approx \begin{bmatrix}
  A & B \\
  C & D
\end{bmatrix} \begin{bmatrix}
  x_i \\
  \theta_i
\end{bmatrix}
\]

where

\[
A = ? \quad B = ? \quad C = ? \quad D = ?
\]
Ray transfer matrix analysis

\[
\begin{bmatrix}
    x_o \\
    \theta_o
\end{bmatrix} = \begin{bmatrix}
    f(x_i, \theta_i) \\
    g(x_i, \theta_i)
\end{bmatrix} \approx \begin{bmatrix}
    A & B \\
    C & D
\end{bmatrix} \begin{bmatrix}
    x_i \\
    \theta_i
\end{bmatrix}
\]

where

\[
A = \left. \frac{\partial f}{\partial x_i} \right|_{x_i=\theta_i=0}
\]

Under paraxial approximation:

\[
A = ? \quad B = ?
\]

\[
C = ? \quad D = ?
\]
Ray transfer matrix analysis

$[x_o] = \begin{bmatrix} f(x_i, \theta_i) \\ g(x_i, \theta_i) \end{bmatrix} \approx \begin{bmatrix} A & B \\ C & D \end{bmatrix} [x_i, \theta_i]$ where

\[ A = \frac{\partial f}{\partial x_i} \bigg|_{x_i=\theta_i=0} \quad B = \frac{\partial f}{\partial \theta_i} \bigg|_{x_i=\theta_i=0} \quad C = ? \quad D = ? \]
Ray transfer matrix analysis

\[ A = \frac{\partial f}{\partial x_i} \bigg|_{x_i=0, \theta_i=0} \]
\[ B = \frac{\partial f}{\partial \theta_i} \bigg|_{x_i=0, \theta_i=0} \]
\[ C = \frac{\partial g}{\partial x_i} \bigg|_{x_i=0, \theta_i=0} \]
\[ D = \frac{\partial g}{\partial \theta_i} \bigg|_{x_i=0, \theta_i=0} \]

where \[ \begin{bmatrix} x_o \\ \theta_o \end{bmatrix} = \begin{bmatrix} f(x_i, \theta_i) \\ g(x_i, \theta_i) \end{bmatrix} \approx \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_i \\ \theta_i \end{bmatrix} \]

Under paraxial approximation:

why at \( x_i = \theta_i = 0 \)?
What is the ABCD matrix of...

• free space propagation?
What is the ABCD matrix of...

- free space propagation?
  \[
  \begin{bmatrix}
  A & B \\
  C & D \\
  \end{bmatrix} = \begin{bmatrix} 1 & d \\
  0 & 1 \end{bmatrix}
  \]

- planar refractive interface?
What is the ABCD matrix of...

• free space propagation?

\[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix} = \begin{bmatrix}
1 & d \\
0 & 1 \\
\end{bmatrix}
\]

• planar refractive interface?

\[
\begin{bmatrix}
A & B \\
C & D \\
\end{bmatrix} = \begin{bmatrix}
1 & 0 \\
0 & \frac{n_1}{n_2} \\
\end{bmatrix}
\]

• planar mirror?
What is the ABCD matrix of...

• free space propagation?

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & d \\
0 & 1
\end{bmatrix}
\]

• planar refractive interface?

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0 & \frac{n_1}{n_2}
\end{bmatrix}
\]

• planar mirror?

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\
0 & 1
\end{bmatrix}
\]
Let’s say we stack together three lenses.
• What is the total ray transfer matrix?
Cascaded optical systems

Let’s say we stack together three lenses.

- What is the total ray transfer matrix?
- Notice the matrix ordering.

\[
\begin{bmatrix}
\theta_o \\
x_o
\end{bmatrix} =
\begin{bmatrix}
1 & 0 \\
-\frac{1}{f_3} & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
-\frac{1}{f_2} & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
-\frac{1}{f_1} & 1
\end{bmatrix}
\begin{bmatrix}
x_i \\
\theta_i
\end{bmatrix}
\]
Ray transfer matrix analysis

- Also known as ABCD matrix analysis (from the form of the ray transfer matrix).

- Any optical system, no matter how complicated, can be described by its ray transfer matrix.

- A cascaded optical system has a ray transfer matrix that is the product of the ray transfer matrices of its components.

- All of the above hold assuming paraxial rays, no aberrations, and no diffraction (geometric optics).
Graphics perspective on ray transfer matrix analysis

- How can I use ray transfer matrix analysis to make ray tracing faster?
- How can I use ray transfer matrix analysis to make Monte Carlo rendering faster?
Why would we ever stack together multiple lenses?
Compound lenses and aberrations
Thin lenses are a fiction

The thin lens model assumes that the lens has no thickness, but this is rarely true...

To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).

Note: Even though we have multiple lenses, the entire optical system can be (paraxially) described using a single focal length and aperture number.
Thin lenses are a fiction

The thin lens model assumes that the lens has no thickness, but this is rarely true...

To make real lenses behave like ideal thin lenses, we have to use combinations of multiple lens elements (compound lenses).
Aberrations

Deviations from ideal thin lens behavior (e.g., imperfect focus).

- Example: chromatic aberration.

- glass has dispersion (refractive index changes with wavelength)

- focal length shifts with wavelength

- one lens cancels out dispersion of other

- glasses of different refractive index

Using a doublet (two-element compound lens), we can reduce chromatic aberration.
Chromatic aberration examples
Aberrations

Deviations from ideal thin lens behavior (i.e., imperfect focus).

• Example: spherical aberration.
Oblique aberrations

These appear only as we move further from the center of the field of view.

- Contrast with chromatic and spherical aberrations, which appear everywhere.
- Many other examples (astigmatism, field curvature, etc.).
Distortion example
Aberrations

Deviations from ideal thin lens behavior (i.e., imperfect focus).

- Example: chromatic aberration.
- Many other types (coma, spherical, astigmatism.)

Why do we wear glasses?
Aberrations

Deviations from ideal thin lens behavior (i.e., imperfect focus).

• Example: chromatic aberration.
• Many other types (coma, spherical, astigmatism.

Why do we wear glasses?
• We turn our eye into a compound lens to correct aberrations!
A costly aberration

Hubble telescope originally suffered from severe spherical aberration.

• COSTAR mission inserted optics to correct the aberration.
Lens designations
Designation based on field of view

<table>
<thead>
<tr>
<th>Category</th>
<th>Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>wide-angle</td>
<td>f = 25 mm</td>
</tr>
<tr>
<td>mid-range</td>
<td>f = 50 mm</td>
</tr>
<tr>
<td>telephoto</td>
<td>f = 135 mm</td>
</tr>
</tbody>
</table>

What focal lengths go to what category depends on sensor size.

- Here we assume full frame sensor (same as 35 mm film).
- Even then, there are no well-defined ranges for each category.
Wide-angle lenses

Lenses with focal length 35 mm or smaller.

They tend to have large and curvy frontal elements.
Wide-angle lenses

Ultra-wide lenses can get impractically wide...

Fish-eye lens: can produce (near) hemispherical field of view.
Telephoto lenses

Lenses with focal length 85 mm or larger.

Technically speaking, “telephoto” refers to a specific lens design, not a focal length range. But that design is mostly useful for long focal lengths, so it has also come to mean any lens with such a focal length.

Telephotos can get very big...
Telephoto lenses

- What is this?
- What is its focal length?

Telephotos can get very big...
Telephoto lenses

- What is this?
- What is its focal length?

About 57 meters.

Telephotos can get very big...
Prime vs zoom lenses

- **Prime lens**: fixed focal length
- **Zoom lens**: variable focal length

**Focus ring**: changes focus distance

**Available focal length range**

**Zoom ring**: changes focal length

**Focus ring**: changes focus distance

Why use prime lenses and not always use the more versatile zoom lenses?
Prime vs zoom lenses

Prime lens: fixed focal length
Zoom lens: variable focal length

Why use prime lenses and not always use the more versatile zoom lenses?

• Zoom lenses have larger aberrations due to the need to cover multiple focal lengths.
Other kinds of lens designations

Macro lens: can achieve very large magnifications (typically at least 1:1).
  • Macro photography: extremely close-up photography.

Achromatic or apochromatic lens: corrected for chromatic aberration.
  • Achromatic: two wavelengths have same focus.
  • Apochromatic (better): three wavelengths have same focus.
  • Often done by inserting elements made from low-dispersion glass.
  • Expensive.

Aspherical lens: manufactured to have special (non-spherical) shape that reduces aberrations.
  • Expensive, often only 1-2 elements in a compound lens are aspherical.
Exposure control
What is exposure?

Roughly speaking, the “brightness” of a captured image given a fixed scene.

Exposure = Gain x Irradiance x Time

- Irradiance is controlled by the aperture.
- Time is controlled by the shutter speed.
- Gain is controlled by the ISO.
Exposure controls brightness of image

Aperture

Exposure

Shutter

ISO
Exposure controls brightness of image
Shutter speed

Controls the **length of time** that shutter remains open.
Shutter speed

Controls the **length of time** that shutter remains open.
Nikon D3s
Shutter speed

Controls the **period of time** that shutter remains open.

What happens to the image as we increase shutter speed?
Side-effects of shutter speed

Moving scene elements appear blurry.

How can we “simulate” decreasing the shutter speed?
Motion deblurring

Shah et al. High-quality Motion Deblurring from a Single Image, SIGGRAPH 2008
Exposure controls brightness of image

- Aperture
- Shutter
- ISO
Aperture controls area of lens that receives light. focal plane
Aperture

controls area of lens that receives light

focal plane
Aperture

- unit: f-number $N = \frac{f}{D}$

focal plane
Aperture size
Circle of Confusion

\[ c = M \cdot D \cdot \frac{|S - S_1|}{S} \]

aperture also determines the size of circle of confusion for out of focus objects

\[ M = \frac{f}{S_1 - f} \]

circle of confusion: c

focal plane: \( S_1 \)
Circle of confusion

Aperture also controls size of circle of confusion for out of focus objects

Take off your glasses and squint.
Depth of field

Range of depths for which the circle of confusion is “acceptable”
$$c = M \cdot D \cdot \frac{|S - S_1|}{S}$$

Canon 5D Mark III: $f=50\text{mm}$, $f/2.8$ ($N=2.8$), focused at $5\text{m}$, pixel size=$7.5\text{um}$
Depth of field
Depth of field

Sharp depth of field ("bokeh") is often desirable
Depth of field

Sharp depth of field ("bokeh") is often desirable ... and not just for campaigning reasons
Depth of field

Sharp depth of field ("bokeh") is often desirable … and not just for campaigning reasons
Depth of field

Form of bokeh is determined by shape of aperture
Lens “speed”

A “fast” lens is one that has a very large max aperture.

- We can use the paraxial approximation to estimate a limit on F-number equal to:

\[ N = \frac{1}{2 \sin \theta'} \]

- Lowest possible N in air is f / 0.5.
Fastest lenses commercially available

In consumer photography, fastest lenses are f/0.9 – f/0.95.

Leica Noctilux 50mm f/0.95 (Price tag: > $10,000)

Fast lenses tend to be bulky and expensive.
Fastest lens made?

Zeiss 50 mm f / 0.7 Planar lens

- Originally developed for NASA’s Apollo missions.
- Stanley Kubrick somehow got to use the lens to shoot movies under only candlelight.
Fastest lens made?

Zeiss 50 mm f / 0.7 Planar lens

- Originally developed for NASA’s Apollo missions.
- Stanley Kubrick somehow got to use the lens to shoot movies under only candlelight.
How can you simulate bokeh?
How can you simulate bokeh?

Infer per-pixel depth, then blur with depth-dependent kernel.
- Example: Google camera “lens blur” feature
Exposure controls brightness of image
The (in-camera) image processing pipeline

The sequence of image processing operations applied by the camera’s image signal processor (ISP) to convert a RAW image into a “conventional” image.

- RAW image (mosaiced, linear, 12-bit)
- analog front-end
- white balance
- tone reproduction
- compression
- final RGB image (non-linear, 8-bit)

- demosaicing
- CFA demosaicing
- color transforms
- denoising
Analog front-end

**Analog amplifier (gain):**
- gets voltage in range needed by A/D converter.
- accommodates ISO settings.
- accounts for vignetting.

**Analog-to-digital converter (ADC):**
- depending on sensor, output has 10-16 bits.
- most often (?) 12 bits.

**Look-up table (LUT):**
- corrects non-linearities in sensor’s response function (within proper exposure).
- corrects defective pixels.
Side-effects of increasing ISO

Image becomes very grainy because noise is amplified.
Note about the name ISO

ISO is not an acronym.
• It refers to the International Organization for Standardization.
• ISO comes from the Greek word ἴσος, which means *equal*.
• It is pronounced (roughly) *eye-zo*, and should not be spelled out.
Camera modes

Aperture priority (“A”): you set aperture, camera sets everything else.
• Pros: Direct depth of field control.
• Cons: Can require impossible shutter speed (e.g. with f/1.4 for a bright scene).

Shutter speed priority (“S”): you set shutter speed, camera sets everything else.
• Pros: Direct motion blur control.
• Cons: Can require impossible aperture (e.g. when requesting a 1/1000 speed for a dark scene).

Automatic (“AUTO”): camera sets everything.
• Pros: Very fast, requires no experience.
• Cons: No control.

• Pros: Full control.
• Cons: Very slow, requires a lot of experience.
Filters
Neutral density (ND) filters

Alternative way to control exposure:
• (Approximately) spectrally flat from 400-700 nm.
• Homogeneous glass that blocks by absorption or by reflection

Often characterized by *optical density* (OD):
• Transmittance = $10^{(-\text{optical density})} \times 100$.
• Optical density is additive as you stack together ND filters.
Graduated neutral-density filters

Variable optical density, from too high to too low/zero.

What are these filters useful for?
Graduated neutral-density filters

Useful in scenes with parts of very different brightness.
• Common scenario: Sky – horizon – ground.
Polarizing filters (or polarizers)

Most commonly circular polarizers.
• Same principle as polarizing sunglasses.

What are these filters useful for?
Polarizing filters (or polarizers)

Reduce sky light

Reduce haze
Polarizing filters (or polarizers)

Reduce direct reflections
Spectral (color) filters

Mostly used for scientific applications or under very special lighting settings.
A note on filter sizes

Each individual filter is often offered in a variety of sizes, ranging from 30 mm to 100 mm.
A note on filter sizes

The filter size you need to use is determined by the lens you are using.

• You can find the filter size marking in the front of the lens.
• You can avoid having to buy dozens of filters by using step-up and step-down rings.
Prisms
Prisms

Many different types of prisms that produce different types of reflections.

right-angle prism

pentaprism

Do you know of any use of pentaprism in photography?
Single Lens Reflex (SLR) cameras

Mechanism to provide direct view through the lens (TTL).

- Any downsides?
Nikon D3s
Mirrorless cameras used to be mostly point-and-shoot, but are quickly becoming viable for high-end photography.

- What are some pros and cons of mirrorless compared to SLR?
Basic reading:
• Szeliski textbook, Section 2.2.3.
  This is a well-known general textbook on optics. Chapters 2 and 3 have the best (in my opinion)
  explanation of paraxial optics and ray transfer matrix analysis among common optics textbooks.

Additional reading:
  Probably the most commonly used optics textbook, also covers paraxial and ray transfer matrix analysis.
  A great book on photography, discussing in detail many of the issues addressed in this lecture.
  Another nice book covering everything about photographic optics.
  Two graphics papers discussing ray transfer matrix analysis from the point of view of rendering.
  Two standard papers on motion deblurring for dealing with long shutter speeds.
  The paper that introduced the lens blur algorithm.