Photographic optics
Course announcements

• Homework 1 is out.
  - Due September 17th.
  - Do not leave second part (pinhole camera) for the very last moment.
  - Any questions about homework 1?

• Homework 2 will be posted on Friday.

• Today’s office hours will be covered by Alice.

• Details about reading groups posted on Piazza.
  - 3 – 5 pm on Fridays when homework is not due, same location as office hours.
  - Suggest topics on Piazza for the first reading group.
Overview of today’s lecture

• Leftover from previous lecture.
• Paraxial optics.
• Ray transfer matrix analysis.
• Aberrations and compound lenses.
• Lens designations.
• Filters.
• Prisms.
• DSLR and mirrorless cameras.
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.

\[ \frac{1}{S'} + \frac{1}{S} = \frac{1}{f} \]

\[ m = \frac{S' - f}{f} \]
Thin lens model

Simplification of geometric optics for well-designed lenses.

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

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

\[
\frac{1}{S'} + \frac{1}{S} = \frac{1}{f} \quad m = \frac{S'}{f} - \frac{1}{f}
\]
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).
Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

\[ n_1 = ? \]

\[ n_2 = ? \]
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* \(n_2 = 1.33\)

What happens to the ray when it crosses the interface?
Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

Refraction diagram:
- Air: $n_1 = 1$
- Water: $n_2 = 1.33$
- Angle $\theta_1$ in air
- Angle $\theta_2$ in water
- Surface normal

How are the two angles related?
Refraction is the bending of rays of light when they cross optical interfaces (i.e., surfaces where the index of refraction changes).

\[ n_1 = 1 \]

\[ n_2 = 1.33 \]

\[ \theta_1 \]

\[ \theta_2 \]

Snell’s law

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

How do we prove Snell’s law?
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.

(Note: conics have different reflective and refractive properties.)
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:

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

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).

\[ n_1 = 1 \]

\[ n_2 = 1.33 \]

Snell’s law

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

How are the two angles related?

How is Snell’s law simplified under paraxial approximation?
Refraction

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

\[ n_1 = 1 \]

\[ n_2 = 1.33 \]

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

object \( P \)

spherical lens surface with radius \( r \)

image \( P' \)
Paraxial focusing

Where do these two equations come from?

- Assume $e \approx 0$
- Assume $\sin u = \frac{h}{l} \approx u$ (for $u$ in radians)
- Assume $\cos u \approx \frac{z}{l} \approx 1$
Paraxial focusing

How can we relate angles $i$ and $i'$?
Snell’s law:
\[ n \sin i = n' \sin i' \]
paraxial approximation:
\[ n i \approx n' i' \]
Paraxial focusing

What is this point?
Paraxial focusing

Center of spherical surface

Object

Image

\( P \)

\((n)\)

\((n')\)

\(P'\)
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

\[ i = u + a \]
\[ u \approx h / z \]
\[ u' \approx h / z' \]

\[ a = u' + i' \]
\[ a \approx h / r \]

\[ n i \approx n' i' \]
\[ n (u + a) \approx n' (a - u') \]
\[ n (h / z + h / r) \approx n' (h / r - h / z') \]

What does this last equation imply?
\[ n / z + n / r \approx n' / r - n' / z' \]
Paraxial focusing

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

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

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?

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

\[ n \, (u + a) \approx n' \, (a - u') \]
\[ n \, \left(\frac{h}{z} + \frac{h}{r}\right) \approx n' \left(\frac{h}{r} - \frac{h}{z'}\right) \]
\[ n / z + n / r \approx n' / r - n' / z' \]
What happens if $z$ is $\infty$? 

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

$$\frac{n}{z} + \frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'}$$

$$\frac{n}{r} \approx \frac{n'}{r} - \frac{n'}{z'}$$

$$z' \approx (r n') / (n' - n)$$
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
\[ \frac{1}{s_o} + \frac{1}{s_i} = (n_l - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right), \]

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

✧ Equating these two, we get the Gaussian lens formula
\[ \frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f_i}. \]
Looks familiar?
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.

\[
\frac{1}{S'} + \frac{1}{S} = \frac{1}{f}
\]

\[
m = \frac{S'}{f} - f
\]
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 θ 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

\[ x_i = ? \]

\[ x_o = ? \]

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

\[ x_i = s_i \theta_i \]

\[ x_o = s_o \theta_o \]

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

\[ d \approx 0 \Rightarrow x_i = x_o \]

Putting it all together, we can write:

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

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

Under paraxial approximation:

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

\[ C = ? \quad D = ? \]
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

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

\[
B = ?
\]

\[
C = ?
\]

\[
D = ?
\]

Under paraxial approximation:
Ray transfer matrix analysis

Input plane \( s_i \) \( x_i \) \( \theta_i \)

Optical black box

Output plane \( s_o \) \( x_o \) \( \theta_o \)

Under paraxial approximation:

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

where

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

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

Under paraxial approximation:

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

where

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

definition of ray transfer matrix, a.k.a. ABCD matrix
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?

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

- planar mirror?

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

Let’s say we stack together three lenses.

- What is the total ray transfer matrix?
Let’s say we stack together three lenses.

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

\[
\begin{bmatrix}
  x_o \\
  \theta_o
\end{bmatrix} =
\begin{bmatrix}
  1 & 0 & 0 & 0 \\
  0 & -\frac{1}{f_3} & 1 & 0 \\
  0 & 0 & -\frac{1}{f_2} & 1 \\
  0 & 0 & -\frac{1}{f_1} & 1
\end{bmatrix}
\begin{bmatrix}
  x_i \\
  \theta_i
\end{bmatrix}
\]
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).

- Even though we have multiple lenses, the entire optical system can be (paraxially) described using a single thin lens of some equivalent focal length and aperture number.
- Where and what exactly this lens is is is difficult to determine.
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).
Aberrations

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

- Example: spherical aberration.
Aberrations

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

- Example: chromatic aberration.

focal length shifts with wavelength

glass has dispersion (refractive index changes 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
Oblique aberrations

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

- Contrast with spherical and chromatic, which appear everywhere.
- Many other examples (astigmatism, field curvature, etc.).
Distortion example
Why do we wear glasses?
Why do we wear glasses?

We turn our eye into a compound lens to:

- Fix incorrect lens-retina placement.
- Correct lens aberrations.

(a) Perfect eye  (b) Myopia  (c) Corrected Myopia  (d) Hyperopia  (e) Corrected Hyperopia

astigmatism
The human eye is already a compound lens

As the human eye is a liquid lens, and water has dispersion, it has chromatic aberration.

- The combined cornea, anterior chamber, and crystalline lens form an achromatic doublet.
- Our brain further reduces *perceived* aberration by “cleverly” processing LMS cone responses.
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

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.

<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>
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

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.
Numerical aperture and f-number

Numerical aperture (NA): sine of half-angle of entering light cone.

- Varies with focus settings, we consider NA at infinity focus.
- A larger NA means a larger aperture.

\[ NA \equiv \sin \theta \]
Numerical aperture and f-number

**Numerical aperture (NA):** sine of half-angle of entering light cone.
- Varies with focus settings, we consider NA at infinity focus.
- A larger NA means a larger aperture.

\[
\text{NA} \equiv \sin \theta
\]

**F-number (f/):** ratio of focal length and aperture diameter.
- Independent of focus setting (at least for ideal lenses).
- A larger f/ means a smaller aperture.

\[
f/ \equiv \frac{f}{D}
\]

How are the two related under paraxial approximation?
Numerical aperture and f-number

**Numerical aperture (NA)**: sine of half-angle of entering light cone.
- Varies with focus settings, we consider NA at infinity focus.
- A larger NA means a larger aperture.

\[ \text{NA} \equiv \sin \theta \]

**F-number (f/)**: ratio of focal length and aperture diameter.
- Independent of focus setting (at least for ideal lenses).
- A larger f/ means a smaller aperture.

\[ f/ \equiv \frac{f}{D} \]

How are the two related under paraxial approximation?

\[ \text{NA} = \sin \theta \approx \tan \theta = \frac{D}{2f} = \frac{1}{2f/} \]
Aperture size

Most lenses have variable aperture size.

- F-number notation: “f/1.4” means $f/ = 1.4$.
- Usually aperture sizes available at steps of one-half or one-third stops.
- Older lenses have separate manual aperture ring.
- Modern lenses control the aperture through a dial on the camera body (“gelded” lenses).

![Lenses with different aperture sizes](image)
Aperture size

Most lenses have variable aperture size.

- F-number notation: “f/1.4” means $f/ = 1.4$.
- Usually aperture sizes available at steps of one-half or one-third stops.
- Older lenses have separate manual aperture ring.
- Modern lenses control the aperture through a dial on the camera body (“gelled” lenses).

Reminder: A “stop” is a change in camera settings that changes amount of light by a factor of 2.
- If the current aperture is at f/4, what is the f-number one stop up and one stop down?
Lens speed

- A *fast* lens is one that has a large *maximum aperture*, or a small *minimum f-number*.
- The “speed” of a lens is its minimum f-number.

Why does this zoom lens have more than one lens speed?
Lens speed

• A *fast* lens is one that has a large *maximum aperture*, or a small *minimum f-number*.
• The “speed” of a lens is its minimum f-number.

Why does this zoom lens have more than one lens speed?
• The max aperture size varies as the focal length (zoom) varies.
Fastest possible lenses

What is the speed of the fastest possible lens?
Fastest possible lenses

What is the speed of the fastest possible lens?
- From paraxial approximation, fastest lens is f/0.5.
- In consumer photography, fastest lenses are f/0.9 – f/0.95.

Fast lenses tend to be bulky and expensive.

Leica Noctilux 50mm f/0.95 (price tag: > $10,000)
Fastest lens ever 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 Barry Lyndon under only candlelight.
Fastest lens ever 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 Barry Lyndon under only candlelight.
Other kinds of lens designations

Macro lens: can achieve very large magnifications (typically at least 1:1).
• Lens body allows effective lens plane to be placed far away from sensor.
• 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.
Other kinds of lens designations

- hyperspectral camera
- depth-of-field target

- standard lens ($500)
- apochromatic lens ($5000)
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

pentaprisim

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

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

• Any downsides?
SLR versus mirrorless

Mirrorless cameras used to be mostly point-and-shoot, but are quickly becoming the dominant choice for high-end photography.

• What are some pros and cons of mirrorless compared to SLR?

1 - Front-mount Lens
2 - Reflex Mirror at 45 degrees
3 - Focal Plane Shutter
4 - Film or Sensor
5 - Focusing Screen
6 - Condenser Lens
7 - Optical Glass Pentaprism
8 - Eyepiece (a.k.a. viewfinder)
References

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.
  A small note on the refractive properties of conics, which seem to be much less known than their reflective ones.
  Two graphics papers discussing ray transfer matrix analysis from the point of view of rendering.
  Two papers discussing the modeling of aberrations and limitations of paraxial optics.
  A discussion on lens design from a graphics-oriented point of view.
- Durand, “The DSLR will probably die. Are mirrorless the future of large standalone cameras?”,
  A great blog post by Fredo Durand, discussing the relative merits of DSLR and mirrorless cameras.