Understanding real cameras
Overview

• Cameras with lenses
  • Depth of field
  • Field of view
  • Lens aberrations

• Digital sensors
Home-made pinhole camera

What is wrong with this image?

Source: P.Debevec via A. Efros
Shrinking the aperture

Why not make the aperture as small as possible?

- Less light gets through
- Diffraction!
Shrinking the aperture
Adding a lens
A lens focuses light onto the film

- Thin lens model:
Adding a lens

A lens focuses light onto the film

- Thin lens model:
  - Rays passing through the center are not deviated
    (pinhole projection model still holds)
Adding a lens

A lens focuses light onto the film

- Thin lens model:
  - Rays passing through the center are not deviated (pinhole projection model still holds)
  - All rays parallel to the optical axis pass through the focal point
  - All parallel rays converge to points on the focal plane
Thin lens formula

- Where does the lens focus the rays coming from a given point in the scene?
Thin lens formula

What is the relation between the focal length \( f \), the distance of the object from the optical center \( D \), and the distance at which the object will be in focus \( D' \)?
Thin lens formula

Similar triangles everywhere!
Thin lens formula

Similar triangles everywhere! \[ \frac{y'}{y} = \frac{D'}{D} \]
Thin lens formula

Similar triangles everywhere!

\[
y'/y = D'/D
\]

\[
y'/y = (D'-f)/f
\]
Thin lens formula

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

Any point satisfying the thin lens equation is in focus.

What happens when \( D \) is very large?
Overview

• Cameras with lenses
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Depth of field

- For a fixed focal length and image plane, there is a specific distance at which objects are “in focus”
  - Other points project to a “circle of confusion” in the image
Depth of field

- Depth of field is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image (Wikipedia)
Controlling depth of field
Controlling depth of field

Changing the *aperture* size affects depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces amount of light – need to increase *exposure*
Varying the aperture

Large aperture = small DOF
Small aperture = large DOF

Slide by A. Efros
Field of view

- The field of view is the angular extent of the world observed by the camera ([Wikipedia](https://en.wikipedia.org/wiki/Field_of_view))
- What determines the FOV?
Field of view

- The field of view is the angular extent of the world observed by the camera (Wikipedia).
- What determines the FOV?
  - Focal length \( (f) \), length of the sensor \( (d) \):
    \[
    \varphi = \tan^{-1} \frac{d}{2f}
    \]
    - Larger focal length = smaller FOV
Field of view

Slide by A. Efros
Field of view

Slide by A. Efros
Field of view / focal length

Large FOV, small $f$
Camera close to car

Small FOV, large $f$
Camera far from the car

Sources: A. Efros, F. Durand
Same effect for faces

wide-angle  standard  telephoto

Source: F. Durand
Approximating an orthographic camera

Source: Hartley & Zisserman
The dolly zoom

- Continuously adjusting the focal length while the camera moves away from (or towards) the subject

The dolly zoom

• Continuously adjusting the focal length while the camera moves away from (or towards) the subject
• “The Vertigo shot”

[Image of dolly zoom from Goodfellas (YouTube)]
[Image of dolly zoom from La Haine (YouTube)]
Choice of lens and viewpoint: A COVID-era illustration
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Real lenses
Lens flaws: Vignetting
Lens flaws: Radial distortion

- Caused by imperfect lenses
- Deviations are most noticeable near the edge of the lens
Lens flaws: Spherical aberration

Spherical lenses don’t focus light perfectly
   Rays farther from the optical axis focus closer
Lens flaws: Chromatic aberration

Lens has different refractive indices for different wavelengths: causes color fringing

Near Lens Center

Near Lens Outer Edge
Overview

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• Digital sensors
Digital camera sensors

- Each cell in a sensor array is a light-sensitive diode that converts photons to electrons
  - Dominant in the past: **Charge Coupled Device (CCD)***
  - Dominant now: **Complementary Metal Oxide Semiconductor (CMOS)***

Color filter arrays

Bayer grid (1976)

Demosaicing:
Estimation of missing components from neighboring values

Why more green?

Human Luminance Sensitivity Function

Source: Steve Seitz
Color filter arrays

**Bayer grid** (1976)

Demosaicing:
Estimation of missing components from neighboring values

Recent cameraphone technology: **pixel binning**
Misc. digital camera artifacts

Noise
- low light is where you most notice noise
- light sensitivity (ISO) / noise tradeoff
- stuck pixels

In-camera processing
- oversharpening can produce halos

Compression
- JPEG artifacts, blocking

Blooming
- CCD charge overflowing into neighboring pixels

Color artifacts
- Color moire
- Purple fringing from microlenses
Historic milestones

• **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
• **Principles of optics (including lenses):** Alhacen (965-1039 CE)
• **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
• **First photo:** Joseph Nicephore Niepce (1822)
• **Daguerréotypes** (1839)
• **Photographic film** (Eastman, 1889)
• **Cinema** (Lumière Brothers, 1895)
• **Color Photography** (Lumière Brothers, 1908)
• **Television** (Baird, Farnsworth, Zworykin, 1920s)
• **First consumer camera with CCD**
  Sony Mavica (1981)
• **First fully digital camera:** Kodak DCS100 (1990)

First digitally scanned photograph

- NIST (1957), 176x176 pixels

Camera sales over time

Source
Camera sales over time

The full chart…

Source