Building a Real Camera
Overview

• Cameras with lenses
  • Depth of field
  • Field of view
  • Lens aberrations
• Digital sensors
Home-made pinhole camera

http://www.debevec.org/Pinhole/
Shrinking the aperture

Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…
Shrinking the aperture
Adding a lens
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

Slide by Steve Seitz
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!

\[ \frac{y'}{y} = \frac{D'}{D} \]

\[ \frac{y'}{y} = \frac{(D' - f)}{f} \]
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?
Depth of Field

For a fixed focal length, 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

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm

Slide by A. Efros
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
Field of View

- 1000 mm: 2.5°
- 500 mm: 5°
- 300 mm: 8°
- 135 mm: 18°
- 85 mm: 28°
- 50 mm: 47°
- 28 mm: 75°
- 17 mm: 104°
Field of View
Field of View

FOV depends on focal length and size of the camera retina

\[ \varphi = \tan^{-1}\left(\frac{d}{2f}\right) \]

Larger focal length = smaller FOV
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”

Example of dolly zoom from *Goodfellas* (YouTube)
Example of dolly zoom from *La Haine* (YouTube)
Real lenses
Lens flaws: Vignetting
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
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)**

[Link to article on CCD vs CMOS technology](http://electronics360.globalspec.com/article/9464/ccd-vs-cmos-the-shift-in-image-sensor-technology)
Color filter arrays

Demosaicing:
Estimation of missing components from neighboring values

Why more green?

Human Luminance Sensitivity Function

Source: Steve Seitz
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

- 1957, 176x176 pixels

Camera sales over time

Source
Camera sales over time

The full chart…