Introduction to cameras
Overview

• Pinhole projection model
• Cameras with lenses
  • Depth of field
  • Field of view
  • Lens aberrations
• Digital sensors
Let’s design a camera

Idea 1: put a piece of film in front of an object
Do we get a reasonable image?

Slide by Steve Seitz
Pinhole camera

Add a barrier to block off most of the rays
Pinhole camera

- Captures pencil of rays – all rays through a single point: aperture, center of projection, optical center, focal point, camera center
- The image is formed on the image plane
Pinhole cameras are everywhere
Pinhole cameras are everywhere

Tree shadow during a solar eclipse

photo credit: Nils van der Burg
http://www.physicstogo.org/index.cfm
Camera obscura

• Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
• Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

Source: A. Efros
Turning a room into a camera obscura

After scouting rooms and reserving one for at least a day, Morell masks the windows except for the aperture. He controls three elements: the size of the hole, with a smaller one yielding a sharper but dimmer image; the length of the exposure, usually eight hours; and the distance from the hole to the surface on which the outside image falls and which he will photograph. He used 4 x 5 and 8 x 10 view cameras and lenses ranging from 75 to 150 mm.

After he’s done inside, it gets harder. “I leave the room and I am constantly checking the weather. I’m hoping the maid reads my note not to come in, I’m worrying that the sun will hit the plastic masking and it will fall down, or that I didn’t trigger the lens.”

From Grand Images Through a Tiny Opening, Photo District News, February 2005

Abelardo Morell, Camera Obscura Image of Manhattan View Looking South in Large Room, 1996

https://www.abelardomorell.net/camera-obscura
Turning a room into a camera obscura

My hotel room, contrast enhanced. The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

A. Torralba and W. Freeman, Accidental Pinhole and Pinspeck Cameras, CVPR 2012
Modeling projection

- How do we find the projection $P'$ of a scene point $P$?
  - Form the visual ray connecting $P$ to the camera center $O$ and find where it intersects the image plane.
- All scene points that lie on this visual ray have the same projection in the image.
- Are there scene points for which this projection is undefined?
Modeling projection

Canonical coordinate system

- The optical center \(O\) is at the origin
- The \(z\) axis is the \textit{optical axis} perpendicular to the image plane
- The \(xy\) plane is parallel to the image plane, \(x\) and \(y\) axes are horizontal and vertical directions of the image plane
Deriving projected coordinates

\[(x, y, z) \rightarrow \left( f \frac{x}{z}, f \frac{y}{z} \right)\]
Properties of projection

• Real-world sizes (lengths) are *not* preserved in projection
  • What other properties are/are not preserved?

Piero della Francesca, *Flagellation of Christ*, 1455-1460
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
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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

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!

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

\[
y'/y = (D'-f)/f
\]
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?

Slide by Frédéric Durand
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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)
- What determines the FOV?
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?
  - Focal length \(f\), length of the sensor \(d\):

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

- Larger focal length = smaller FOV
Field of view
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
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)
My “dolly zoom”
My “dolly zoom”
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
- Distortion is stronger towards the edges of the photo
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
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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
Camera sales over time

The full chart…