Intro & Cameras

EECS 442 – David Fouhey
Winter 2022, University of Michigan
https://web.eecs.umich.edu/~fouhey/teaching/EECS442_W22/
Goals of Computer Vision

Get a computer to understand
Goal: Naming
Goal: Naming

The picture shows a building with many windows and grass in front of it. There is a person walking on the right...
Goal: 3D
Goal: Actions

What can I do here?
Seems Obvious, Right?

- **Key concept to keep in mind throughout the course**: you see with both your eyes **and** your brain.
Why is it Hard?
Why is it Hard?
## Why is it Hard?

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Despite This, We’ve Made Progress

• Few of these problems are **solved** *(and there are lots of dangers to pretending things are solved when they aren’t)*

• But we do have systems with performance ranging from non-embarrassing to super-human (with the right caveats)
Look at Your Phone

Iphone Image Credit: arstechnica.net
Recognition


Video Credit: Karol Majek (https://www.youtube.com/watch?v=OOT3UIXZztE)
3D

Administrivia
Meeting and Communication

• Class:
  • Tue/Thu noon-1:30pm, 1571 GGBL and Zoom
  • Recordings (but give it a minute!)

• Discussions: 5 of them, attend any, starting Jan 13

• Office Hours: Poll out – please fill in.

• Piazza: Sign up (link on canvas). We monitor but don’t guarantee instant responses.

• Direct Email: Avoid. Why?
Class Size, Waitlist, Modalities

• Course was supposed to be 120 students
• I saw the waitlist and was sad → now 300 students
• Remote section was least disruptive means
• Remote Section: Give it a week, we’ll sort it out.
• Waitlist: I’m limited by staff. I don’t reorder the waitlist – each person has a good reason and it’s a zero-sum game. Contact the advising office
• Thing to keep in mind: there are 300 students, 1 professor, 2 GSIs and 9 IAs.
Websites

• Canvas: Links to other stuff and turning in big files
• Course website: slides, assignments, syllabus
  https://web.eecs.umich.edu/~fouhey/teaching/EECS442_W22/schedule.html
• Piazza: ask questions, answer questions
  https://piazza.com/umich/winter2022/eecs442
• Gradescope: details later with release of HW0
Evaluation

• HW0 assignment (6%) – make all your linear algebra mistakes in a low-stakes setting with an autograder. Learn how to do 442 right.

• Homework (6x12%) – six mini-project homeworks with a writeup

• Project (2% [proposal] +14% [report] +6% [presentation]) – a semester-long project done in a team
Evaluation: Homework Late Policy

- Penalty: 1% per hour, rounded to nearest
- Example:
  - Due: Midnight Mon. (1s after 11:59:59pm Mon)
  - Submitted at 12:15am Tue: No penalty!
  - Submitted at 6:50am Tue: 7% penalty (i.e., 90% -> 83%)
- Everyone gets 120 free late hours, applied automatically and optimally. These waive late penalties. Assume you will need these
- Exceptions only for exceptional circumstances. Contact us.
Copying

• Read the syllabus – don’t look at peoples’ code, no pair programming
• We will run MOSS
• Submit it late (*that’s why we have late days*), half-working (*that’s why we have partial credit*), or take the zero on the homework – I guarantee you won’t care about one bad homework in a year
• If you’re overwhelmed, talk to us
Evaluation: Term Project

• Work in a team of 3-5 to do *something cool*
• There will be a piazza thread for pairing up
• Could be:
  • Applying vision to a problem you care about
  • Independent re-implementation of a paper
  • Trying to build and extend an approach
  • An idea that we give you
• Should be 2 homeworks worth of work per person
Enjoy each topic like a story. Discuss with friends about homework. Check piazza for similar questions, ask for help or get inspiring ideas on piazza as well. Go to discussions – Siyi Chen

Exchanging advice and discussing concepts with your peers is a valuable learning opportunity and something that we want you to do (as long as it's within the limits of the Honor Code) – Ahmed Khan

+1 on finding people to work with. It made the class much more enjoyable. – Jacob Skwirsk

Don’t have friends in the class? We’ll introduce you to people (stay tuned)
Doing Well in 442 – Ask for Help

OH are a great resource in this class, especially since there are more times where you need to rehash a concept rather than have code looked at compared to other EECS courses. The IAs / GSIs / profs were and are always super patient and happy to help with these concepts, because some are really abstract! – Jacob Skwirsk

Ask questions on Piazza or Google them when you get stuck with HWs because things like numpy, pytorch could be hard to get started with. – Victor Li

Ask for help *effectively* (Piazza, OH)

We’ve got more office hours than in past years
Doing Well in 442 – Start Early

Start early. – Nikhil Devraj

Start early, especially for any projects using colab and gpus. – Rahul Gupta

We’re spending a bunch of time investigating how to optimally handle the GPU situation.
Doing Well in 442 – Projects

I would say setting up regular meetings with project teammates will be very useful. Constantly sharing ideas and progress is beneficial for final project. – Yinwei Dai

Go to OH to discuss the scope and feasibility of the final project. Pay attention to shapes of arrays when writing code. – Changyuan Qiu

There’s a group project instead of an exam. We’ll give you ideas and have more info
Doing Well in 442 – My Additions

• Invest in learning to debug effectively early. It will take you a few hours, but will pay off later on.

• Some fraction of the assignments may be frustrating or hard to wrap your head around, so expect some of that.
Cameras
Let’s Take a Picture!

Idea 1: Just use film

Result: Junk

Slide inspired by S. Seitz; image from Michigan Engineering
Let’s Take a Picture!

Idea 2: add a barrier

Slide inspired by S. Seitz; image from Michigan Engineering
Let’s Take a Picture!

Idea 2: add a barrier

Slide inspired by S. Seitz; image from Michigan Engineering
Let’s Take a Picture!

Film captures all the rays going through a point (a pencil of rays).
Result: good in theory!
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
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
Camera Obscura
Useful for viewing solar eclipses!

Put your eye here

Pinhole: aluminum foil with a tiny hole

Photo Credit: Justin Johnson
Camera Obscura
Useful for viewing solar eclipses!

Put your eye here

Pinhole: aluminum foil with a tiny hole

Justin on 8/21/2017

Photo Credit: Justin Johnson
Camera Obscura
Useful for viewing solar eclipses!

Photo of the sun
View in the box
Justin on 8/21/2017

Photo Credit: Justin Johnson
Projection

Source: L Lazebnik
How do we find the projection $P$ of a point $X$?
Form visual ray from $X$ to camera center and intersect it with camera plane.

Source: L Lazebnik
Both X and X' project to P. Which appears in the image?

Are there points for which projection is undefined?
Quick Aside: Remember This?

\[
\begin{align*}
\frac{a}{b} &= \frac{d}{c} \\
\Rightarrow \quad a &= \frac{bd}{c}
\end{align*}
\]
Projection Equations

Coordinate system: \( \mathbf{O} \) is origin, \( XY \) in image, \( Z \) sticks out. \( XY \) is image plane, \( Z \) is optical axis.

\( (x,y,z) \) projects to \( (fx/z, fy/z) \) via similar triangles

Source: L Lazebnik
Some Facts About Projection

- 3D lines project to 2D lines
- The projection of any 3D parallel lines converge at a vanishing point
- Distant objects are smaller

List of properties from M. Hebert
Some Facts About Projection

Let’s try some fake images
Some Facts About Projection
Some Facts About Projection
Some Facts About Projection

Illusion Credit: RN Shepard, Mind Sights: Original Visual Illusions, Ambiguities, and other Anomalies
What’s Lost?

Is she shorter or further away?

Are the orange lines we see parallel / perpendicular / neither to the red line?
What's Lost?

Is she shorter or further away?

Are the orange lines we see parallel / perpendicular / neither to the red line?

Adapted from D. Hoiem slide
What’s Lost?

Be careful of drawing conclusions:

• Projection of 3D line is 2D line; NOT 2D line is 3D line.

• Can you think of a counter-example (a 2D line that is not a 3D line)?

• Projections of parallel 3D lines converge at VP; NOT any pair of lines that converge are parallel in 3D.

• Can you think of a counter-example?
Do You Always Get Perspective?
Do You Always Get Perspective?

Y location of blue and red dots in image:

\[
\begin{align*}
\frac{f_y}{z_2} & \quad \frac{f_y}{z_1} & \quad \frac{f_y}{z} & \quad \frac{f_y}{z}
\end{align*}
\]
Do You Always Get Perspective?

When plane is fronto-parallel (parallel to camera plane), everything is:
- scaled by $f/z$
- otherwise is preserved.
What’s This Useful For?

Things looking different when viewed from different angles seems like a nuisance. It’s also a cue. Why?
Projection Equation

\[(x, y, z) \rightarrow (fx/z, fy/z)\]

I promised you linear algebra: is this linear?

**Nope:** division by \(z\) is non-linear (and risks division by 0)

Adapted from S. Seitz slide
Homogeneous Coordinates (2D)

Trick: add a dimension!

*This also clears up lots of nasty special cases*

What if $w = 0$?

Adapted from M. Hebert slide
Homogeneous Coordinates

Two homogeneous coordinates are **equivalent** if they are proportional to each other. **Not = !**
Benefits of Homogeneous Coords

General equation of 2D line:

\[ ax + by + c = 0 \]

Homogeneous Coordinates

\[ l^T p = 0, \quad l = \begin{bmatrix} a \\ b \\ c \end{bmatrix}, \quad p = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \]
Benefits of Homogeneous Coords

• Lines (3D) and points (2D → 3D) are now the same dimension.

• Use the cross (x) and dot product for:
  • Intersection of lines \( l \) and \( m \): \( l \times m \)
  • Line through two points \( p \) and \( q \): \( p \times q \)
  • Point \( p \) on line \( l \): \( l^T p \)

• Parallel lines, vertical lines become easy (compared to \( y=mx+b \))
Benefits of Homogeneous Coords

What’s the intersection?

\[ [0, 1, -2] \times [1, 0, -1] = [-1, -2, -1] \]

Converting back (divide by -1)

(1,2)
Benefits of Homogeneous Coords

Intersection of $y=2$, $y=1$

$[0,1,-2] \times [0,1,-1] = [1,0,0]$  

Does it lie on $y=3$? Intuitively?

$[0,1,-3]^T[1,0,0] = 0$
Benefits of Homogeneous Coords

Translation is now linear / matrix-multiply

\[
\begin{bmatrix}
    u' \\
    v' \\
    w'
\end{bmatrix} = \begin{bmatrix}
    1 & 0 & t_x \\
    0 & 1 & t_y \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    u \\
    v \\
    1
\end{bmatrix} = \begin{bmatrix}
    u + t_x \\
    v + t_y \\
    1
\end{bmatrix}
\]

If \( w = 1 \)

Generically

\[
\begin{bmatrix}
    u' \\
    v' \\
    w'
\end{bmatrix} = \begin{bmatrix}
    1 & 0 & t_x \\
    0 & 1 & t_y \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix} = \begin{bmatrix}
    u + wt_x \\
    v + wt_y \\
    w
\end{bmatrix}
\]

Rigid body transforms (rot + trans) now linear

\[
\begin{bmatrix}
    u' \\
    v' \\
    w'
\end{bmatrix} = \begin{bmatrix}
    r_{11} & r_{12} & t_x \\
    r_{21} & r_{22} & t_y \\
    0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
    u \\
    v \\
    w
\end{bmatrix}
\]
3D Homogeneous Coordinates

Same story: add a coordinate, things are equivalent if they’re proportional

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix}
\rightarrow
\begin{bmatrix}
  u \\
  v \\
  w \\
  t
\end{bmatrix}
\rightarrow
\begin{bmatrix}
  u/t \\
  v/t \\
  w/t
\end{bmatrix}
\]
Projection Matrix

Projection \((fx/z, fy/z)\) is matrix multiplication

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z \\
1
\end{bmatrix}
\rightarrow
\begin{bmatrix}
\frac{x}{z} \\
\frac{y}{z}
\end{bmatrix}
\]
Projection (fx/z, fy/z) is matrix multiplication

\[
\begin{bmatrix}
  fx \\
  fy \\
  z
\end{bmatrix}
\equiv
\begin{bmatrix}
  f & 0 & 0 & 0 & 0 \\
  0 & f & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  x \\
  y \\
  z \\
  1
\end{bmatrix}
\rightarrow
\begin{bmatrix}
  fx/z \\
  fy/z
\end{bmatrix}
\]
Project $X$ and $X'$ to the image and compare them.

YES

\[
\begin{bmatrix}
fx \\
fy \\
z
\end{bmatrix} =
\begin{bmatrix}
fx' \\
fy' \\
z'
\end{bmatrix}
\]

NO

\[
\begin{bmatrix}
fx \\
fy \\
z
\end{bmatrix} =
\begin{bmatrix}
fx' \\
fy' \\
z'
\end{bmatrix}
\]
Typical Perspective Model

\[ P \equiv f_0 u_0 f_v 0 0 0 1 \]
\[ R_{3 \times 3} t_{3 \times 1} X_{4 \times 1} \]

**P**: 2D homogeneous point (3D)

**X**: 3D homogeneous point (4D)
Typical Perspective Model

\[ P \equiv \begin{bmatrix} R_{3x3} & t_{3x1} \end{bmatrix} X_{4x1} \]

**R**: rotation between world system and camera

**t**: translation between world system and camera
Typical Perspective Model

\[ P \equiv \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix} \]

- \( f \): focal length
- \( u_0, v_0 \): principal point (image coords of camera origin on retina)

\[[R_{3x3} \quad t_{3x1}] \quad X_{4x1}\]
Typical Perspective Model

\[
P \equiv K[R, t]X \equiv M_{3 \times 4}X_{4 \times 1}
\]
Other Cameras – Orthographic

Orthographic Camera (z infinite)

\[
P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad X_{3 \times 1}
\]
Other Cameras – Orthographic

Why does this make things easy and why is this popular in old games?

\[ P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \]
Film captures all the rays going through a point (a pencil of rays).

How big is a point?
Math vs. Reality

- **Math:** Any point projects to one point

- **Reality:**
  - Don’t image points behind the camera / objects
  - Don’t have an infinite amount of sensor material

- **Other issues**
  - Light is limited
  - Spooky stuff happens with infinitely small holes
Limitations of Pinhole Model

**Ideal Pinhole**
- 1 point generates 1 image
- Low-light levels

**Finite Pinhole**
- 1 point generates region
- Blurry.

Why is it blurry?

Slide inspired by M. Hebert
Limitations of Pinhole Model

Slide Credit: S. Seitz
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)

Slide Credit: S. Seitz
Adding a Lens

• All rays parallel to the optical axis pass through the focal point
What’s The Catch?

- There’s a distance where objects are “in focus”
- Other points project to a “circle of confusion”
Thin Lens Formula

We care about images that are in focus.

**When is this true?**

When two paths from a point hit the same image location.
Thin Lens Formula

Let’s derive the relationship between object distance $D$, image plane distance $D'$, and focal length $f$. 

Diagram credit: F. Durand
Thin Lens Formula

One set of similar triangles:

\[
\frac{y'}{D' - f} = \frac{y}{f} \quad \rightarrow \quad \frac{y'}{y} = \frac{D' - f}{f}
\]
Thin Lens Formula

Another set of similar triangles:

\[
\frac{y'}{D'} = \frac{y}{D} \quad \rightarrow \quad \frac{y'}{y} = \frac{D'}{D}
\]
Thin Lens Formula

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

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

Set them equal:

Diagram credit: F. Durand
Thin Lens Formula

Suppose I want to take a picture of a lion with D big? Which of D, D’, f are fixed?

How do we take pictures of things at different distances?

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

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

Slide Credit: 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

Controlling Depth of Field

If a smaller aperture makes everything focused, why don’t we just always use it?
Varying the Aperture

Small aperture = large DOF

Large aperture = small DOF

Slide Credit: A. Efros, Photo: Philip Greenspun
Varying the Aperture
Field of View (FOV)

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

\( \tan^{-1} \) is monotonic increasing.

How can I get the FOV bigger?
Field of View
Field of View

Slide Credit: A. Efros
Field of View and Focal Length

Large FOV, small $f$
Camera close to car

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

Slide Credit: A. Efros, F. Durand
Field of View and Focal Length

wide-angle

standard

telephoto

Slide Credit: F. Durand
Dolly Zoom

Change f and distance at the same time

Video Credit: Goodfellas 1990
More Bad News!

• First a pinhole...
• Then a thin lens model....
Lens Flaws: Radial Distortion

Lens imperfections cause distortions as a function of distance from optical axis

Less common these days in consumer devices

Photo: Mark Fiala, U. Alberta
Vignetting

What happens to the light between the black and red lines?
Vignetting

Lens Flaws: Chromatic Abberation

Lens refraction index is a function of the wavelength. Colors “fringe” or bleed.

Image credits: L. Lazebnik, Wikipedia
Lens Flaws: Chromatic Abberation

Researchers tried teaching a network about objects by forcing it to assemble jigsaws.

Initial layout, with sampled patches in red

Image layout is discarded

We can recover image layout automatically

Slide Credit: C. Doersch
From Photon to Photo

• 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)**

Slide Credit: L. Lazebnik, Photo Credit: Wikipedia, Stefano Meroli
From Photon to Photo

Rolling Shutter: pixels read in sequence
Can get global reading, but $$$
Preview of What’s Next

Demosaicing:
Estimation of missing components from neighboring values

Bayer grid

Slide Credit: S. Seitz
For the Curious

• Cut in the interest of time
Radial Distortion Correction

Ideal

\[ y' = f \frac{y}{z} \]

Distorted

\[ y' = (1 + k_1 r^2 + \cdots) \frac{y}{z} \]
Lens Flaws: Spherical Abbeation

Lenses don’t focus light perfectly!
Rays farther from the optical axis focus closer
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)

Slide Credit: S. Lazebnik
First digitally scanned photograph

- 1957, 176x176 pixels

Slide Credit: http://listverse.com/history/top-10-incredible-early-firsts-in-photography/
Historic Milestone

Sergey Prokudin-Gorskii (1863-1944)
Photographs of the Russian empire (1909-1916)
Historic Milestone
Future Milestone

Your job in homework 1:
Make the left look like the right.

Note: it won’t quite look like this – this was done by a professional human. But it should look similar