

Intro & Cameras

EECS 442 – David Fouhey

Winter 2023, University of Michigan

https://web.eecs.umich.edu/~fouhey/teaching/EECS442_W23/

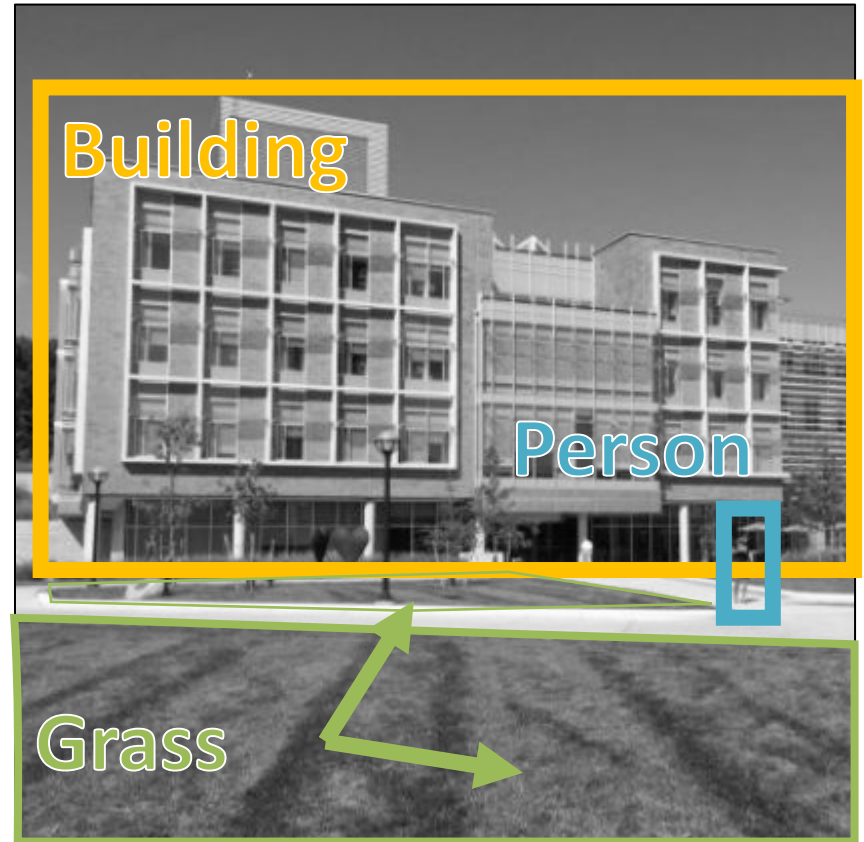
Welcome!

Goals of Computer Vision

Get a computer to understand



Goal: Naming

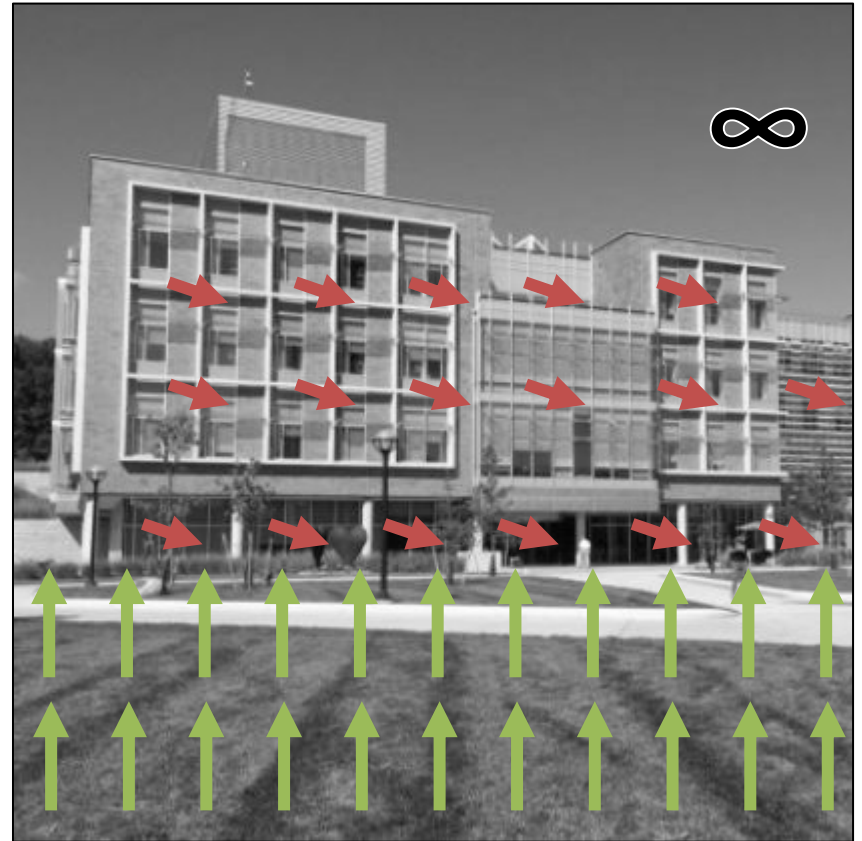


Goal: Naming



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

Goal: 3D



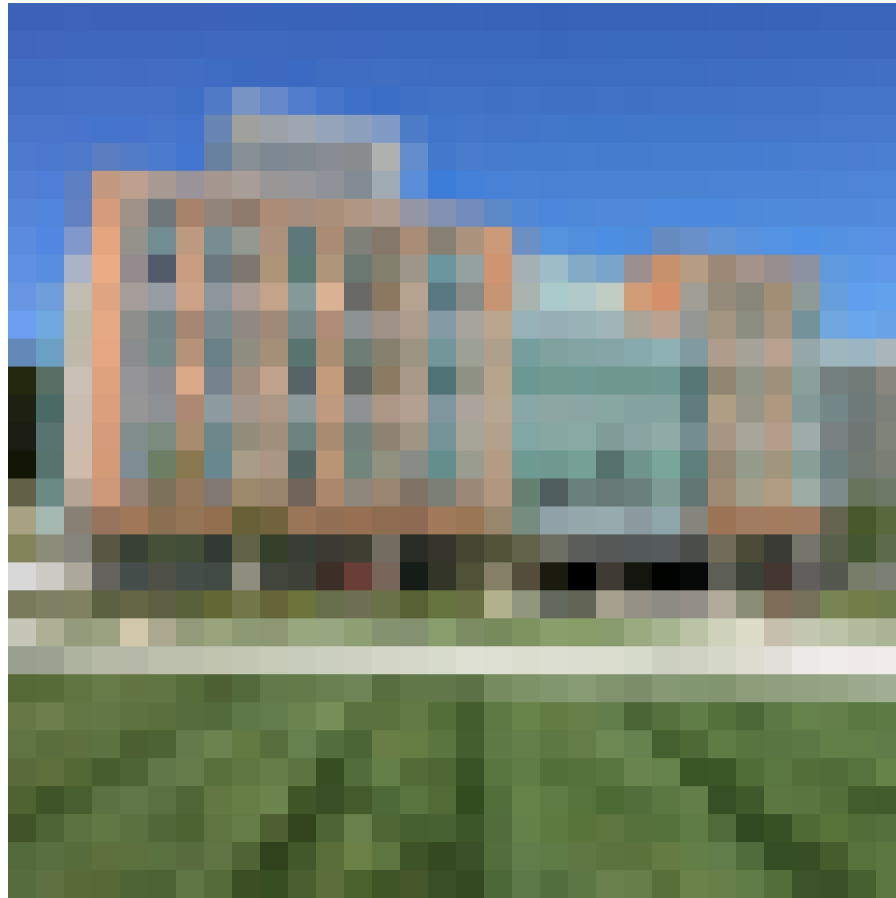
Goal: Actions



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?



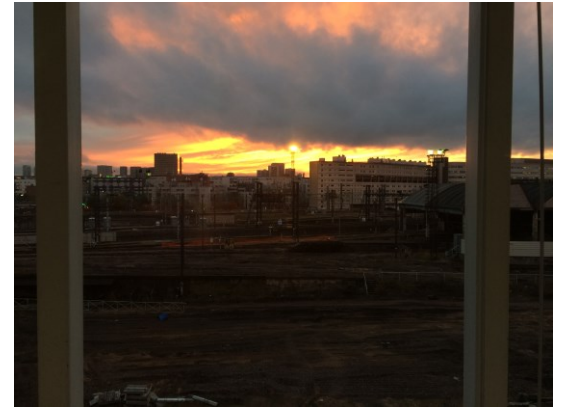
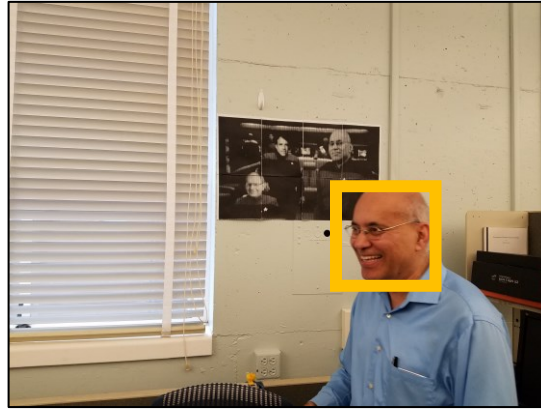
Why is it Hard?

097	097	097	097	097	097	097	097	096	097	097	096	096	096
100	100	100	100	100	100	101	101	102	101	100	100	100	099
105	105	105	105	105	105	105	103	102	102	101	103	104	105
109	109	109	109	109	110	107	118	145	132	120	112	106	103
113	113	113	112	112	113	110	129	160	160	164	162	157	151
118	117	118	123	119	118	112	125	142	134	135	139	139	175
123	121	125	162	166	157	149	153	160	151	150	146	137	168
127	127	125	168	147	117	139	135	126	147	147	149	156	160
133	130	150	179	145	132	160	134	150	150	111	145	126	121
138	134	179	185	141	090	166	117	120	153	111	153	114	126
144	151	188	178	159	154	172	147	159	170	147	185	105	122
152	157	184	183	142	127	141	133	137	141	131	147	144	147
130	147	185	180	139	131	154	121	140	147	107	147	120	128
035	102	194	175	149	140	179	128	146	168	096	163	101	125

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)

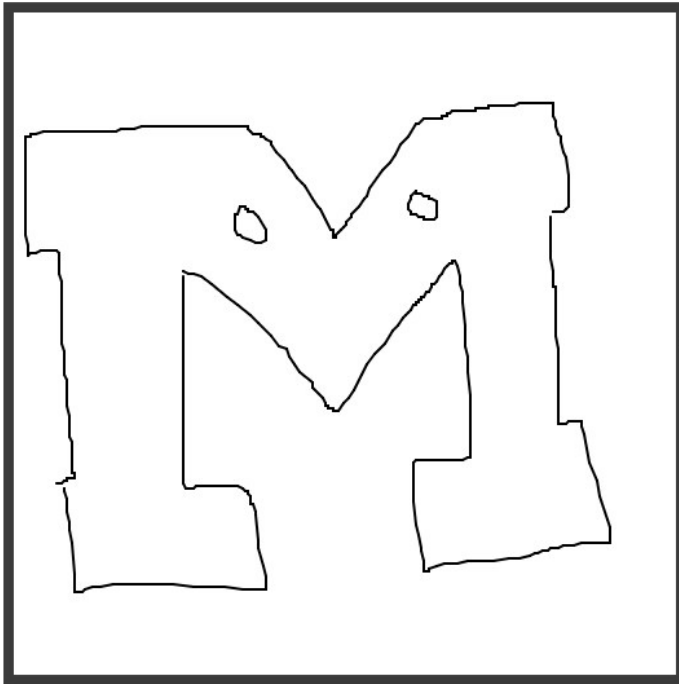
Look at Your Phone



Graphics

<https://affinelayer.com/pixsrv/>

INPUT



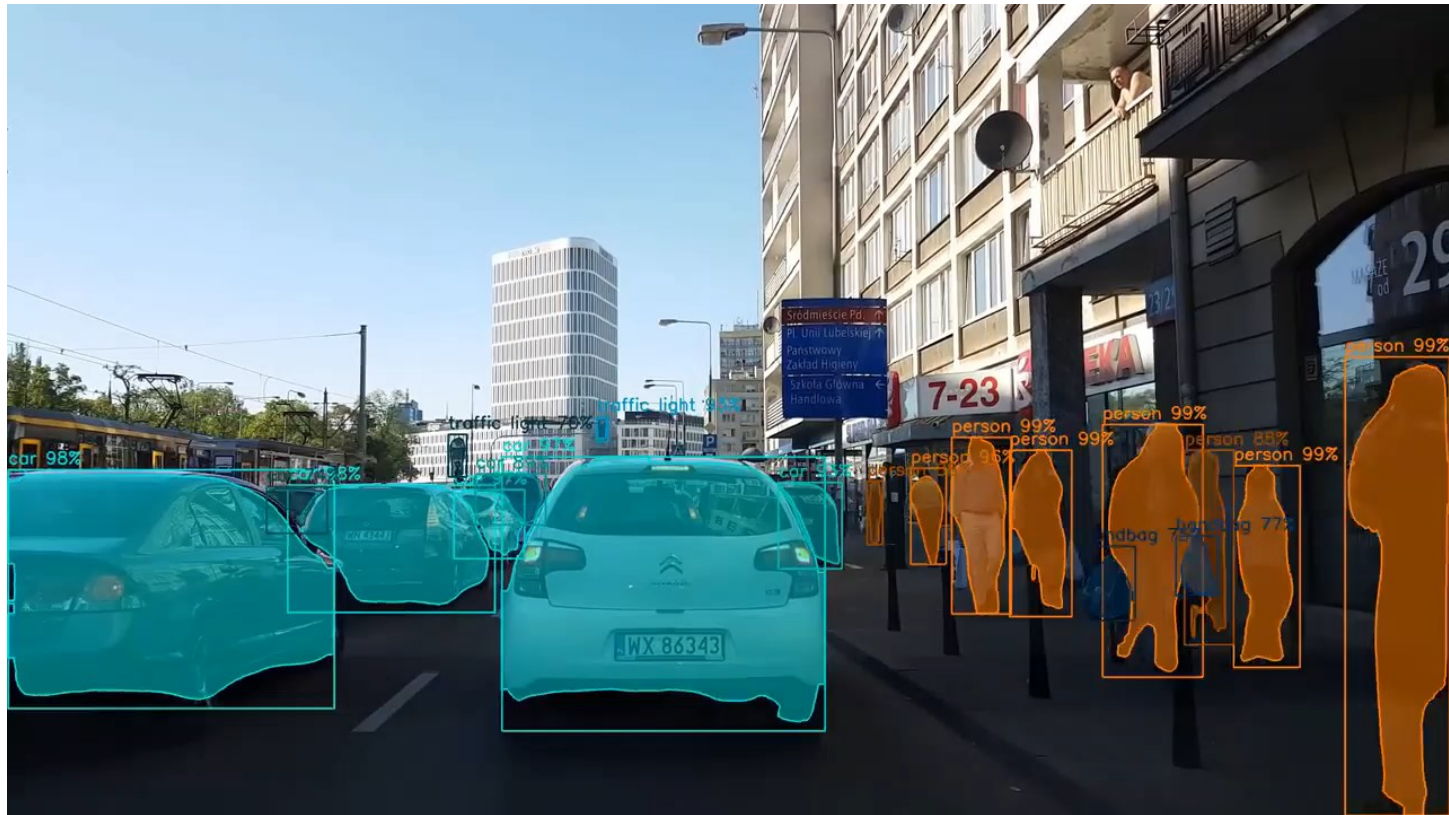
OUTPUT



Stable Diffusion



Recognition



He et al. *Mask RCNN*. ICCV 2017.

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

3D



Administrivia

Meeting and Communication

- Class: Mon/Wed 10:30AM-Noon, STAMPS and Zoom + Recordings (but **please** give it a minute!)
- Discussions (6), attend **any**, starting Monday January 9. One will be recorded.
- Office Hours (a bunch, mainly in-person): Poll out this afternoon – 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

- *Thing to keep in mind:* there are 280 students, 1 professor, 6 GSIs and 1 IA
- *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*

Office Hours + Piazza



Photo credit: Business Insider

Office Hours + Piazza

- 140 hours of work available for the course across me, GSIs, IAs. Needs to cover:
 - Lectures + Discussion: ~10 hours of standing-there time
 - Writing, testing, debugging, and setting up grading for HW; preparing for lectures + discussions; conceptual Qs; course administration
 - Helping students learn the material + do HW
- Lining up for a personal zoom room with a GSI for debugging / debugging via piazza is inefficient and makes everyone want to tear their hair out. **Why?**

Let's Work Together

- Please watch the lectures + discussions and then do the HWs; please don't do the reverse.
- We'll try to teach you how to debug better. Debugging well is a hard skill, but it will be important for your career.
- Work together from the beginning.
- I really want to do and encourage modalities for OH that are more efficient

Zoom, Recordings, etc.

- I'll attempt to monitor zoom and in-person at the same time. It's trickier than it looks!
- Recordings may take a little bit of time to get up.
- Anticipate at least one tech screw-up during the semester

Websites

- Canvas: Links to other stuff and turning in big files
- Course website: slides, assignments, syllabus
https://web.eecs.umich.edu/~fouhey/teaching/EECS442_W23/ .
- Piazza: ask questions, answer questions
<https://piazza.com/umich/winter2023/eecs442>
- Gradescope: details later with release of HW1

Evaluation

- Homework (5x12%) – five mini-project homeworks with a writeup and code
- Midterm (20%) – One in-class midterm
- Project (2% [proposal] +18% [report+presentation])
– a semester-long project done in a team

Homework Philosophy

- **Tons** of fantastic resources for many things so teaching you to setup stable diffusion is a waste
- Few components remain the same in the long run. I want to teach these.
- Some work may be frustrating or hard to wrap your head around; please expect some of that
- This may be your first ULCS. Be patient and build in some transition time
- Homework \neq spec. We'll often ask you to interpolate details, figure things out, etc.

Evaluation: Homework Late Policy

- Penalty: 1% per hour, rounded to nearest
- Example:
 - Due: 5pm Tuesday.
 - Submitted 5:15pm Tue: No penalty!
 - Submitted 12:15am Wed: 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 for exceptional situations. 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

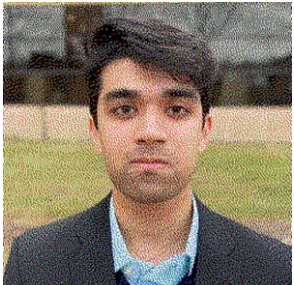
Evaluation: Term Project

- Work in a team of 3-4 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 1 homeworks worth of work per person


Doing Well in 442 – Work Together



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

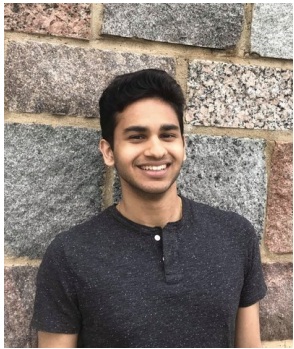


+1 on finding people to work with. It made the class much more enjoyable. – Jacob Skwirsk

Don't have friends in the class?

We'll introduce you to people (stay tuned)

Doing Well in 442 – Start Early



Start early. – Nikhil Devraj



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

We're trying to figure out how to optimally handle the GPU situation.

How To Have a Bad Time in 442

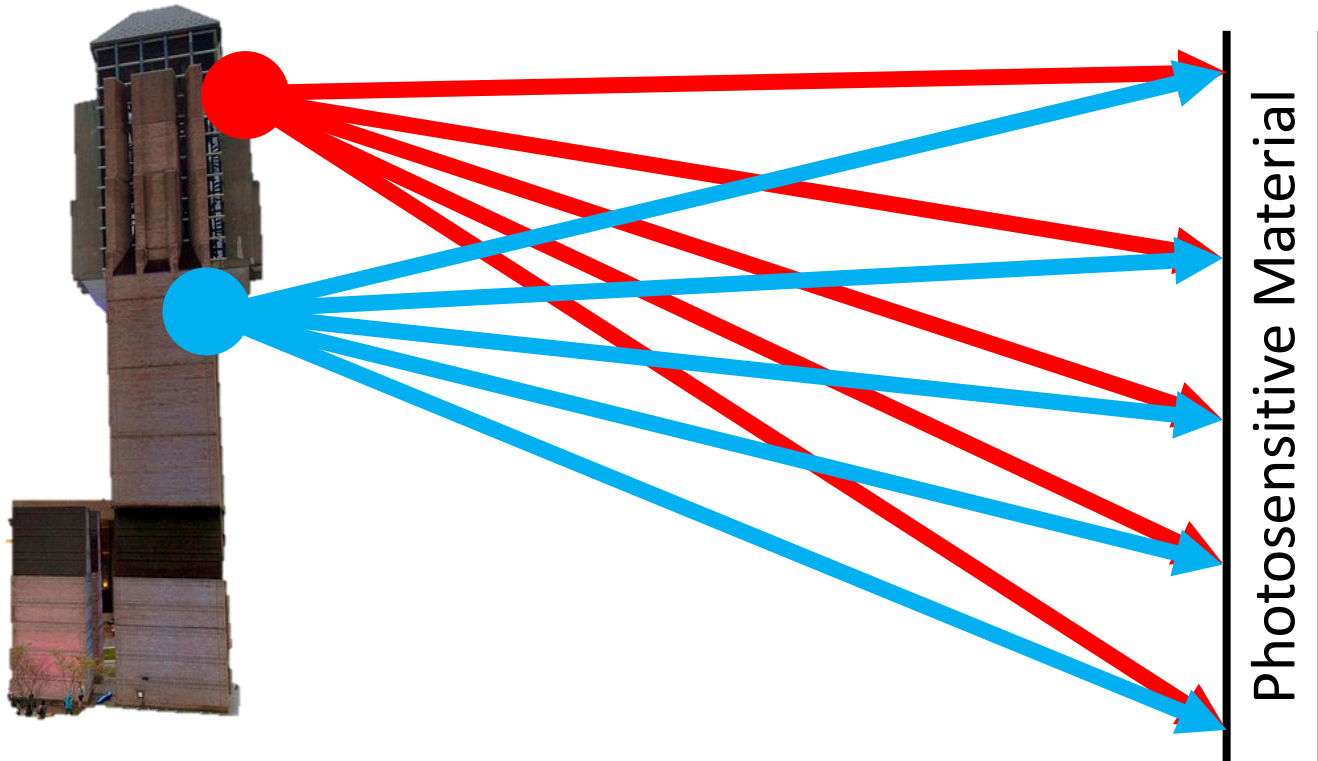
- Bad time: start homeworks with three days to go; have conceptual issues **and** debugging fun
- Bad time: ignore lectures; just-in-time lecture-watching by scrubbing through lectures while doing homeworks
- Bad time: debug by piazza + OH queue

Your Todos

- Office hours poll if you have preferences
- Study buddy matching poll if you'd like us to help you match
- Background poll if you'd like to help me tailor the course (and future offerings)
- Get to know you poll if you'd like
- First homework out next week. No need to do anything. Just relax

Cameras

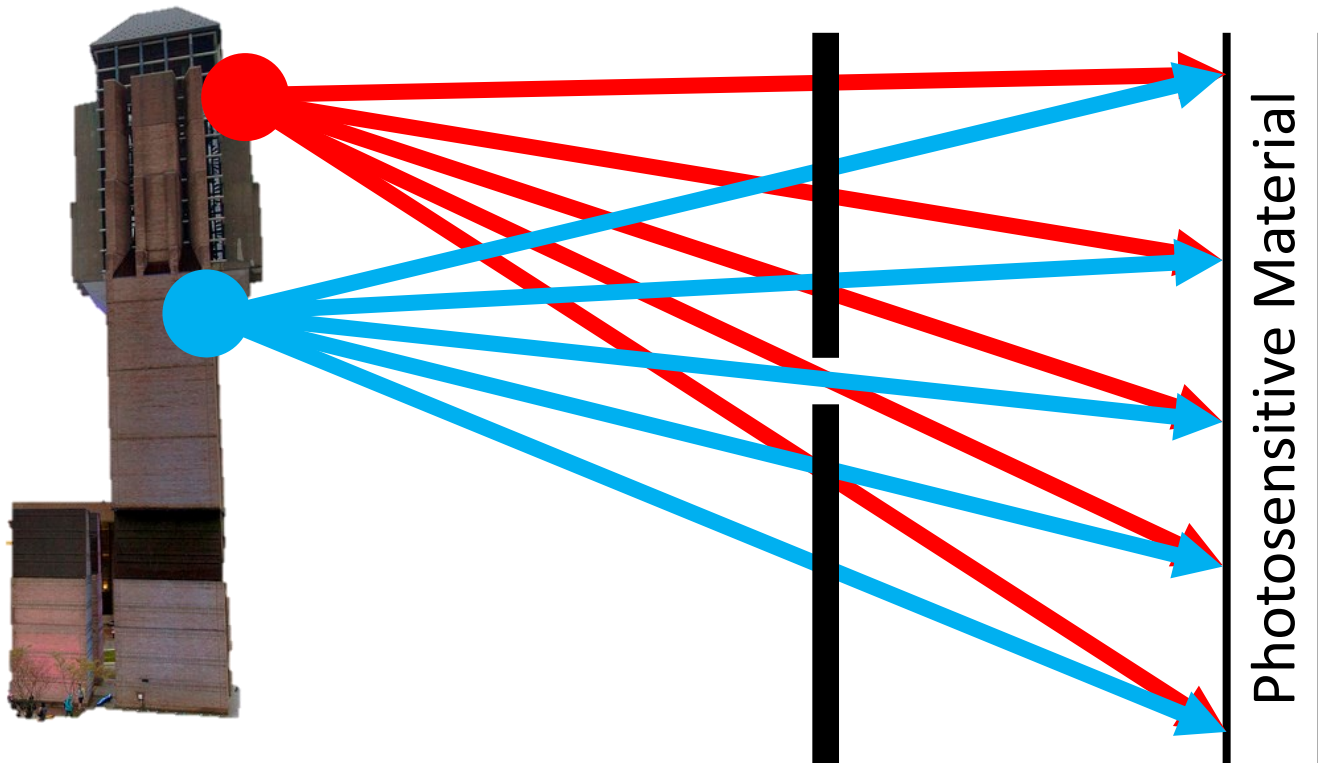
Let's Take a Picture!



Idea 1: Just use film

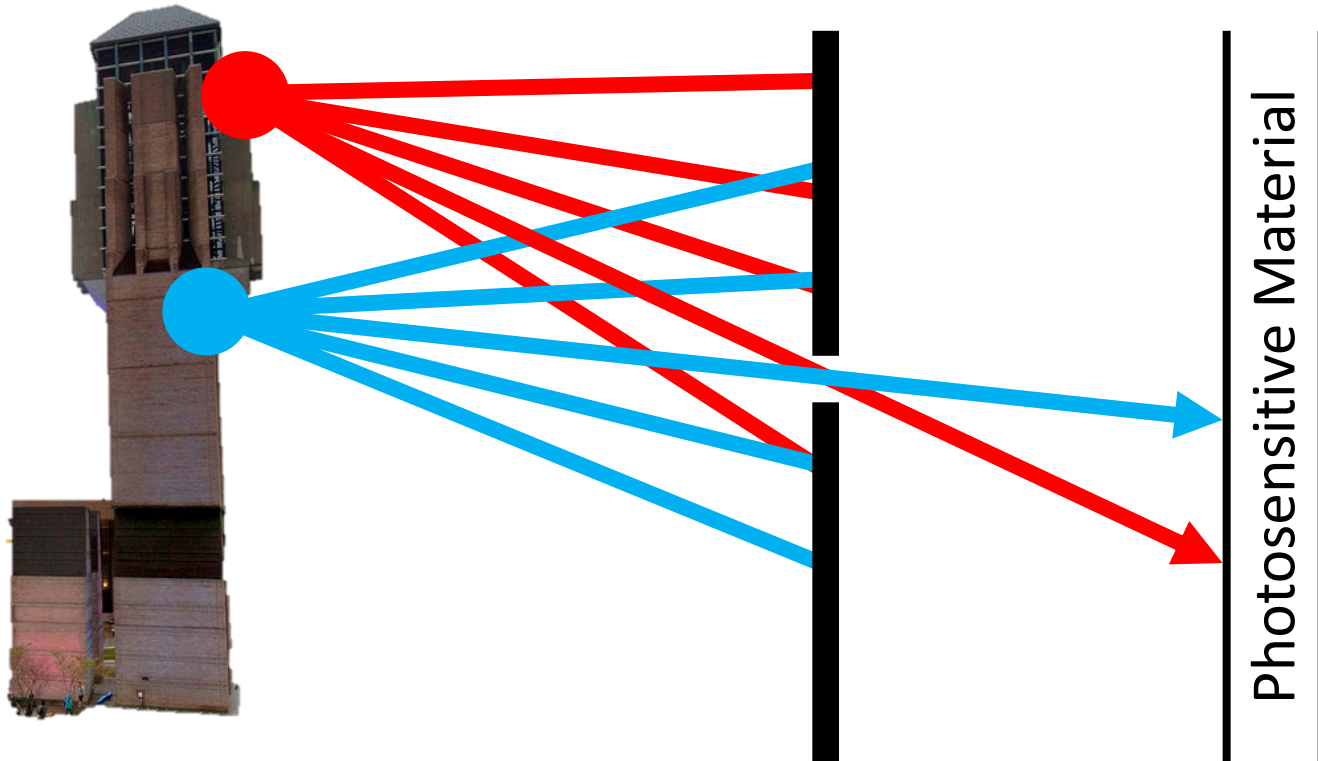
Result: **Junk**

Let's Take a Picture!



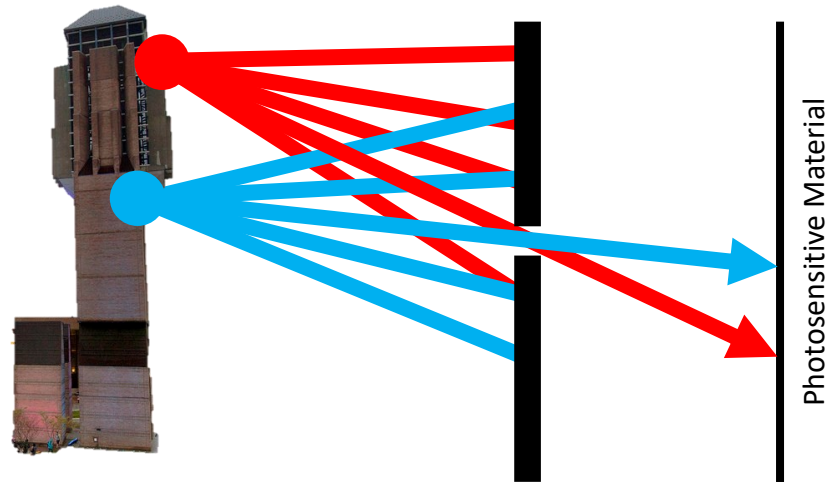
Idea 2: add a barrier

Let's Take a Picture!



Idea 2: add a barrier

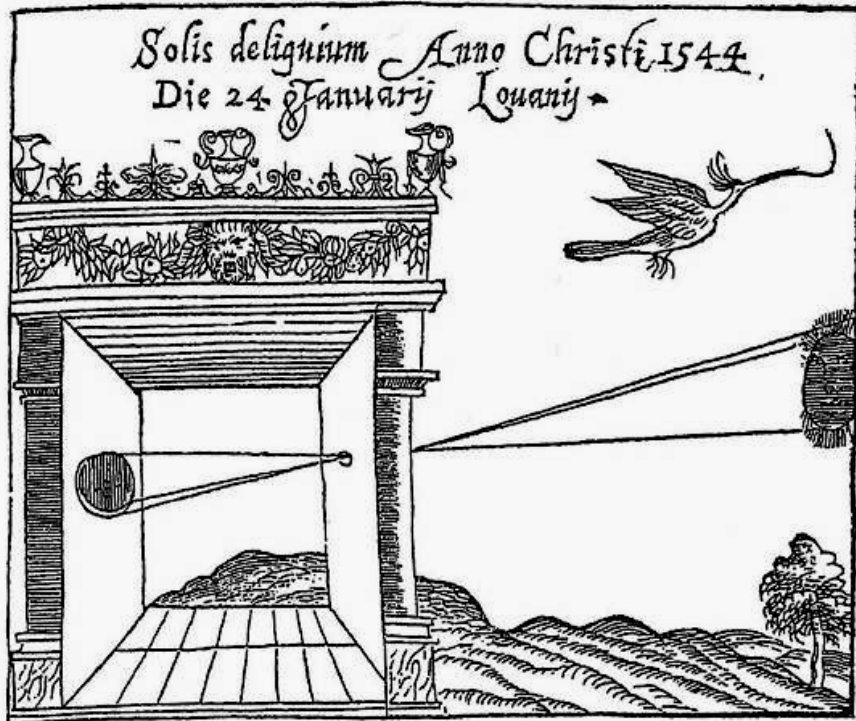
Let's Take a Picture!



Film captures all the rays going through a point (a *pencil of rays*).

Result: good in theory!

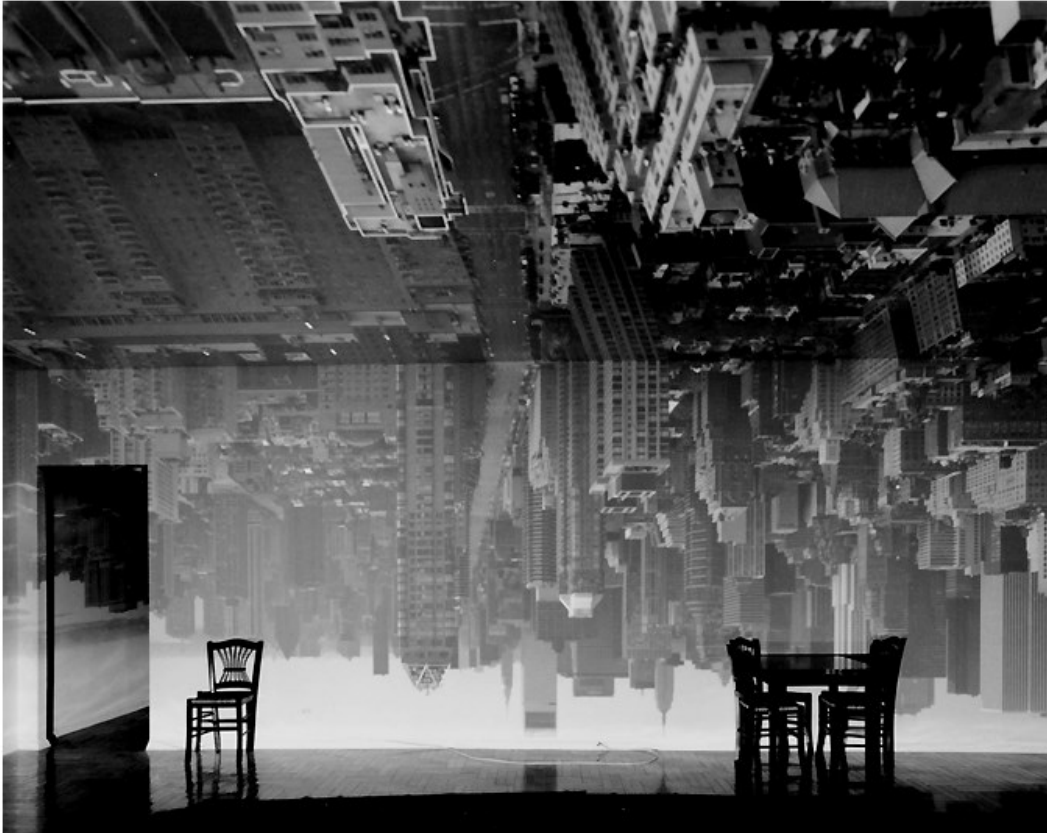
Camera Obscura



Gemma Frisius, 1558

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

Camera Obscura



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

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.

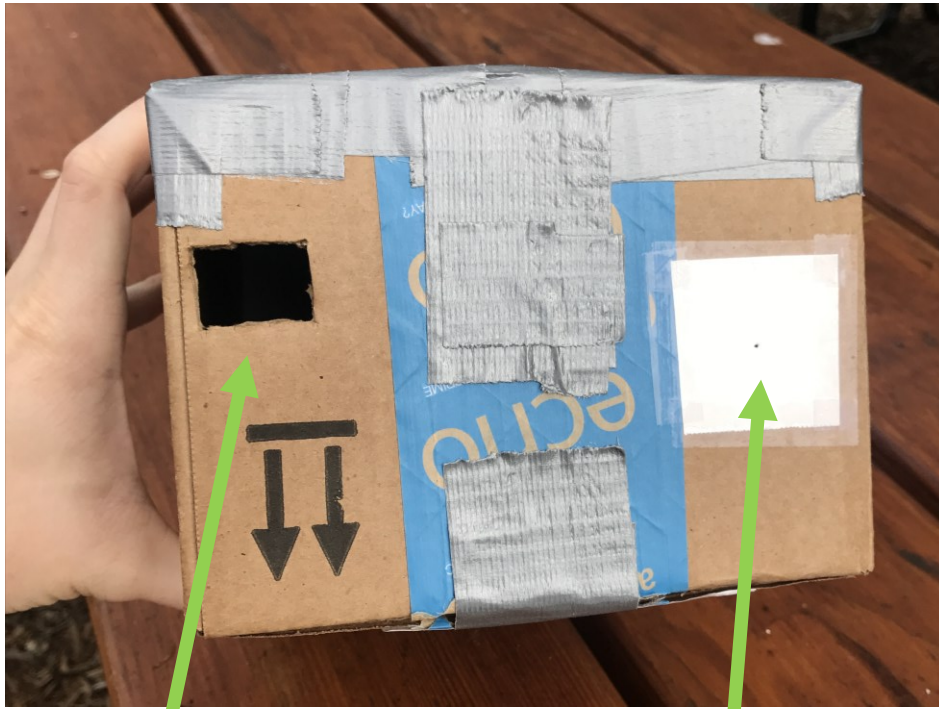
After he's done inside, it gets harder. "I leave the room and I am constantly checking the weather, I'm hoping the maid reads my note not to come in, I'm worrying that the sun will hit the plastic masking and it will fall down, or that I didn't trigger the lens."

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



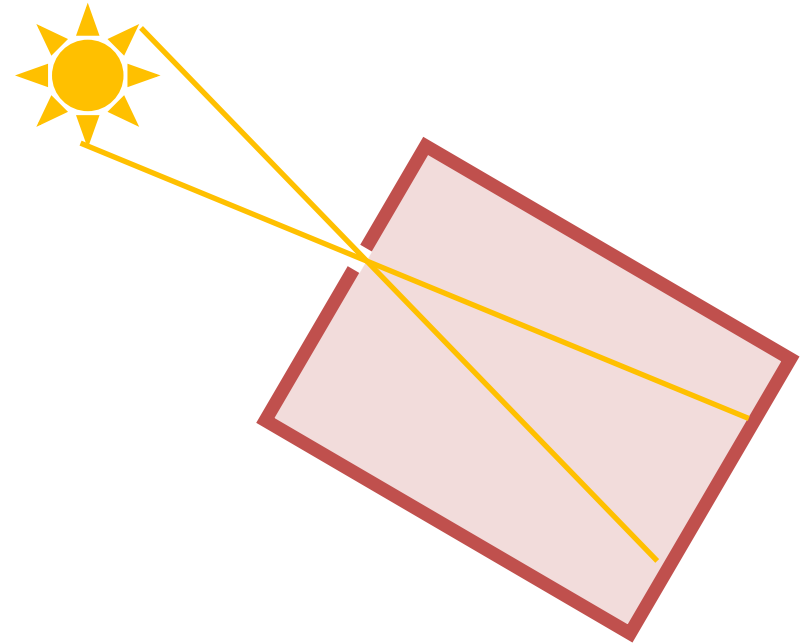
Camera Obscura

Useful for viewing solar eclipses!



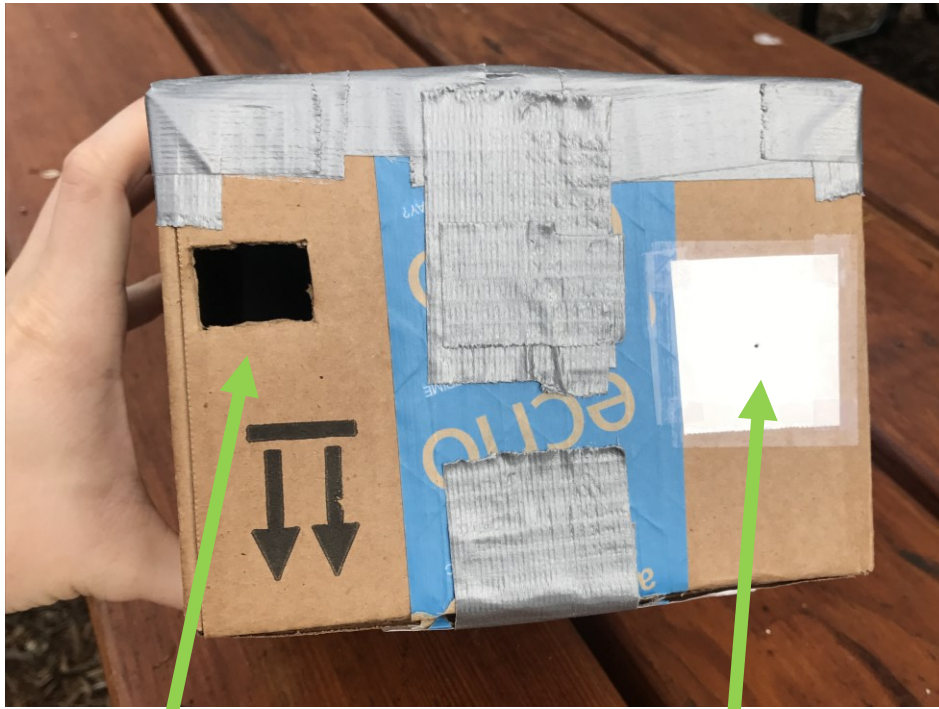
Put your
eye here

Pinhole: aluminum
foil with a tiny hole



Camera Obscura

Useful for viewing solar eclipses!



Put your
eye here

Pinhole: aluminum
foil with a tiny hole



Justin on 8/21/2017

Camera Obscura

Useful for viewing solar eclipses!



Photo of
the sun

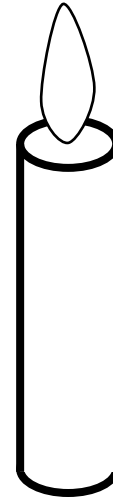
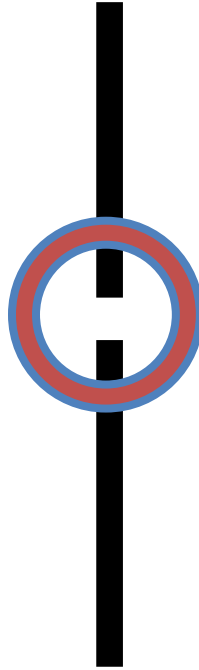
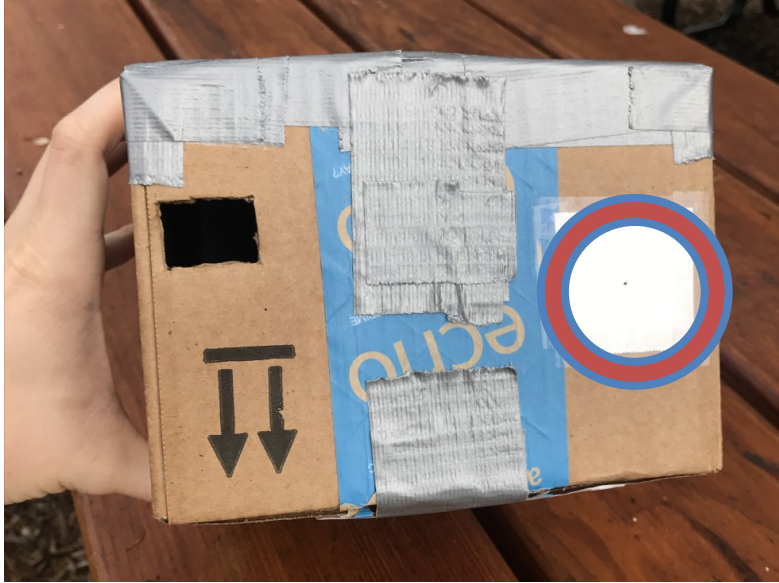


View in
the box

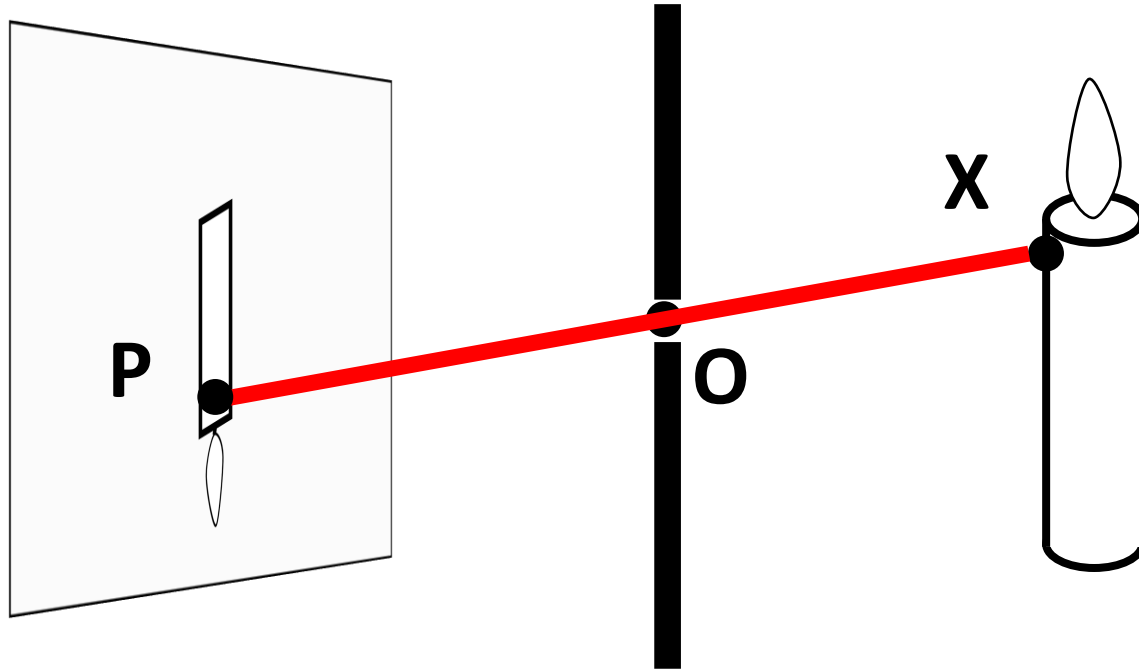


Justin on 8/21/2017

Projection



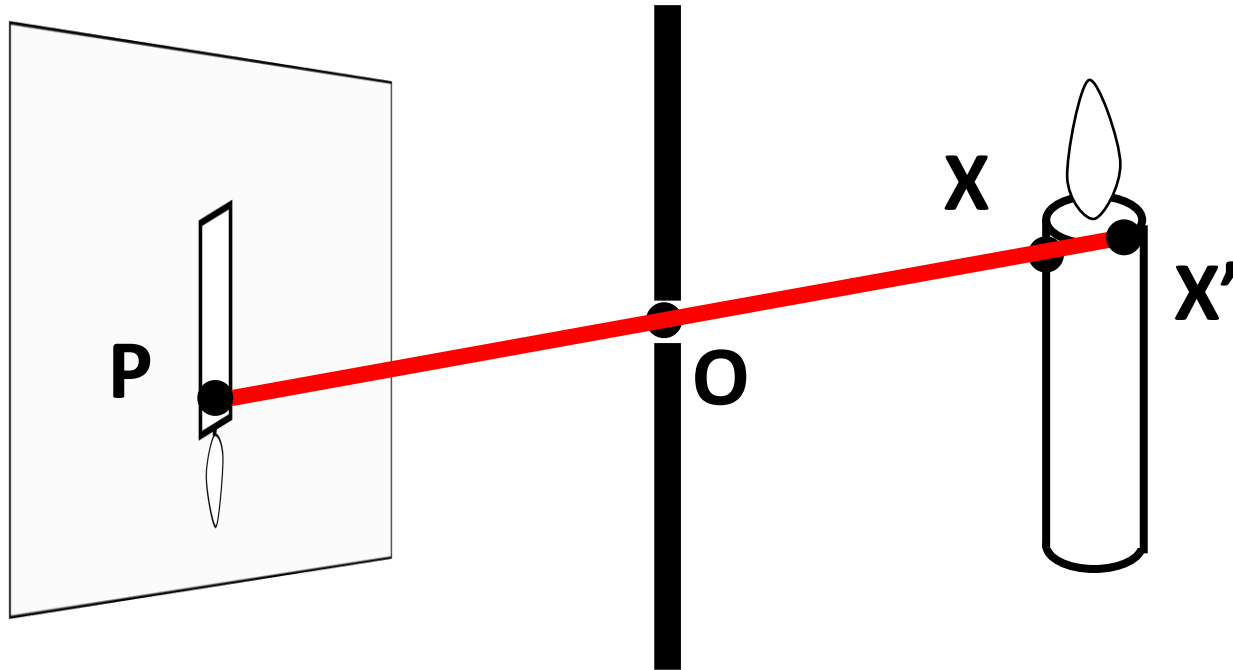
Projection



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

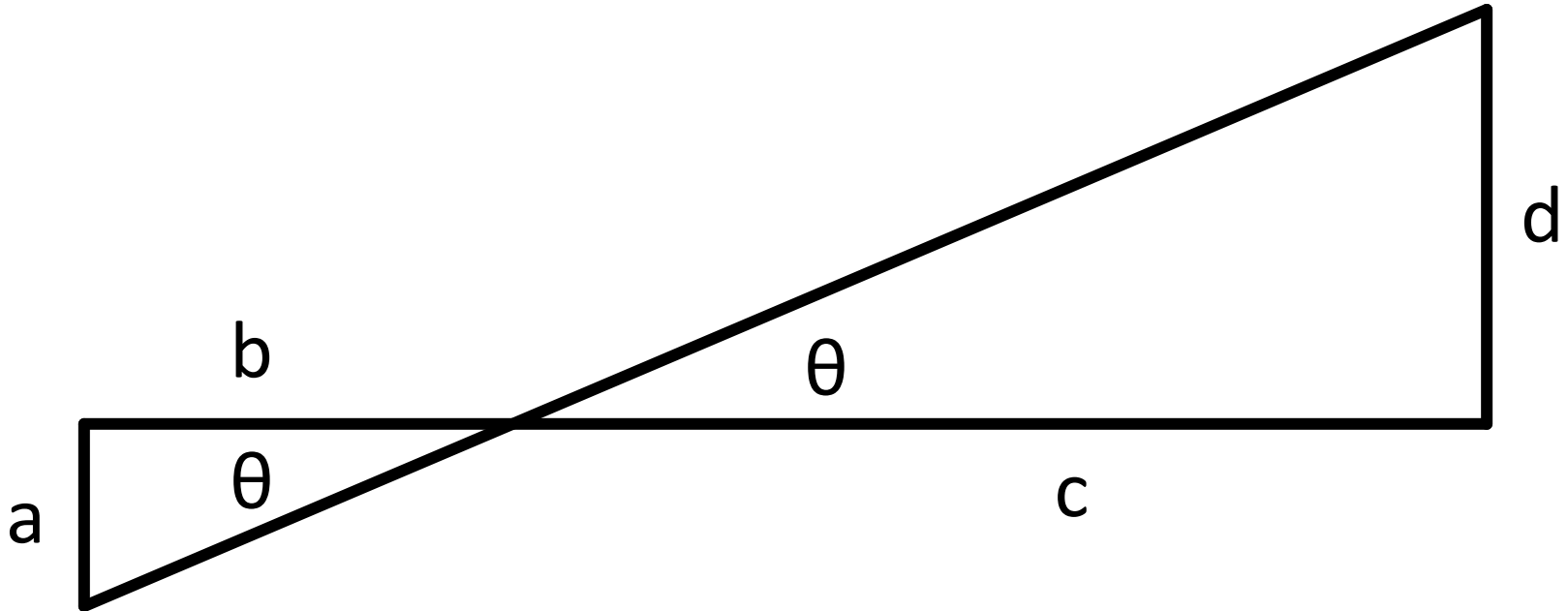
Projection



Both X and X' project to P. Which appears in the image?

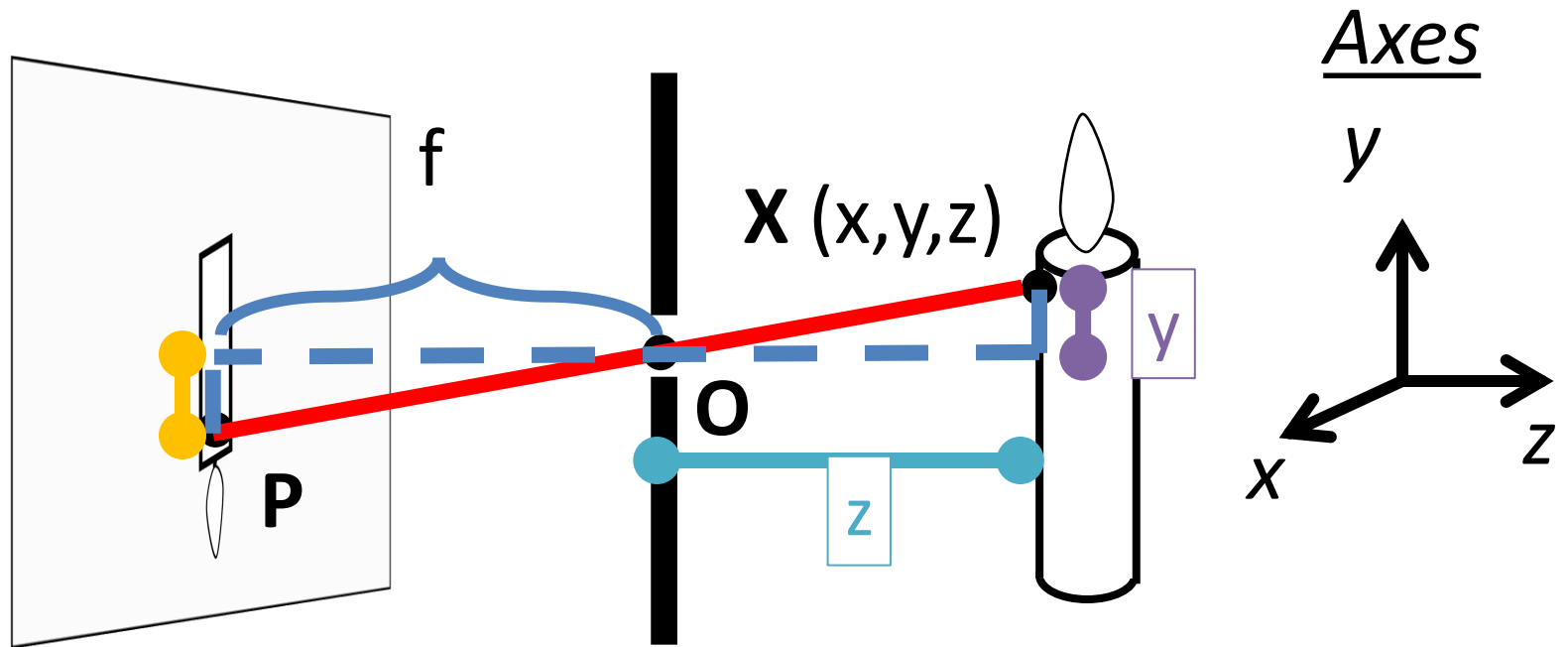
Are there points for which projection is undefined?

Quick Aside: Remember This?



$$\frac{a}{b} = \frac{d}{c} \longrightarrow a = \frac{bd}{c}$$

Projection Equations



Coordinate system: 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

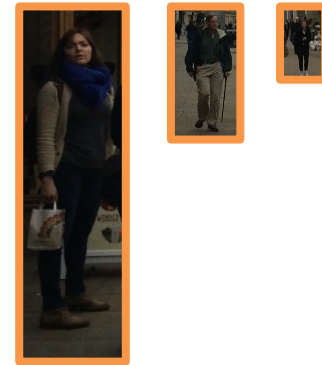
Some Facts About Projection



3D lines project to 2D lines

The projection of any 3D parallel lines converge at a vanishing point

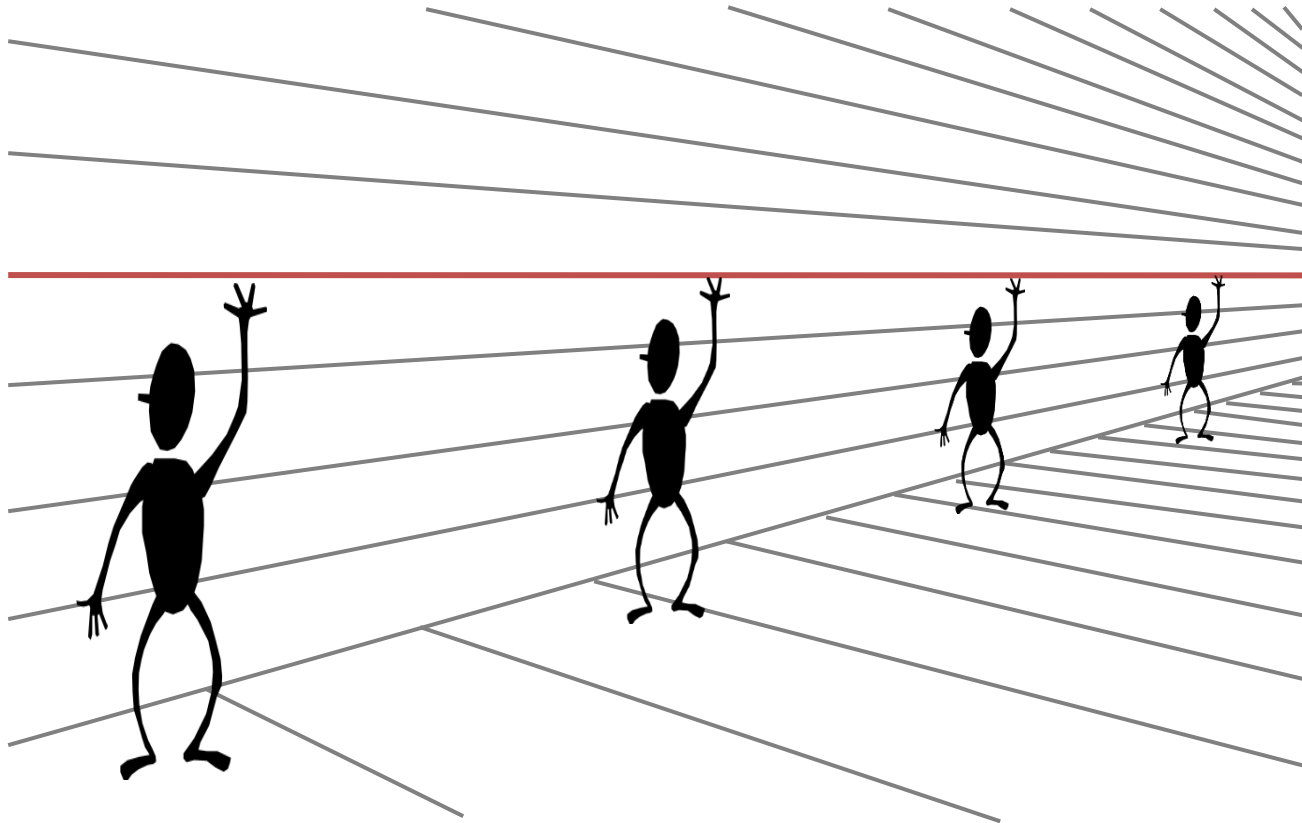
Distant objects are smaller



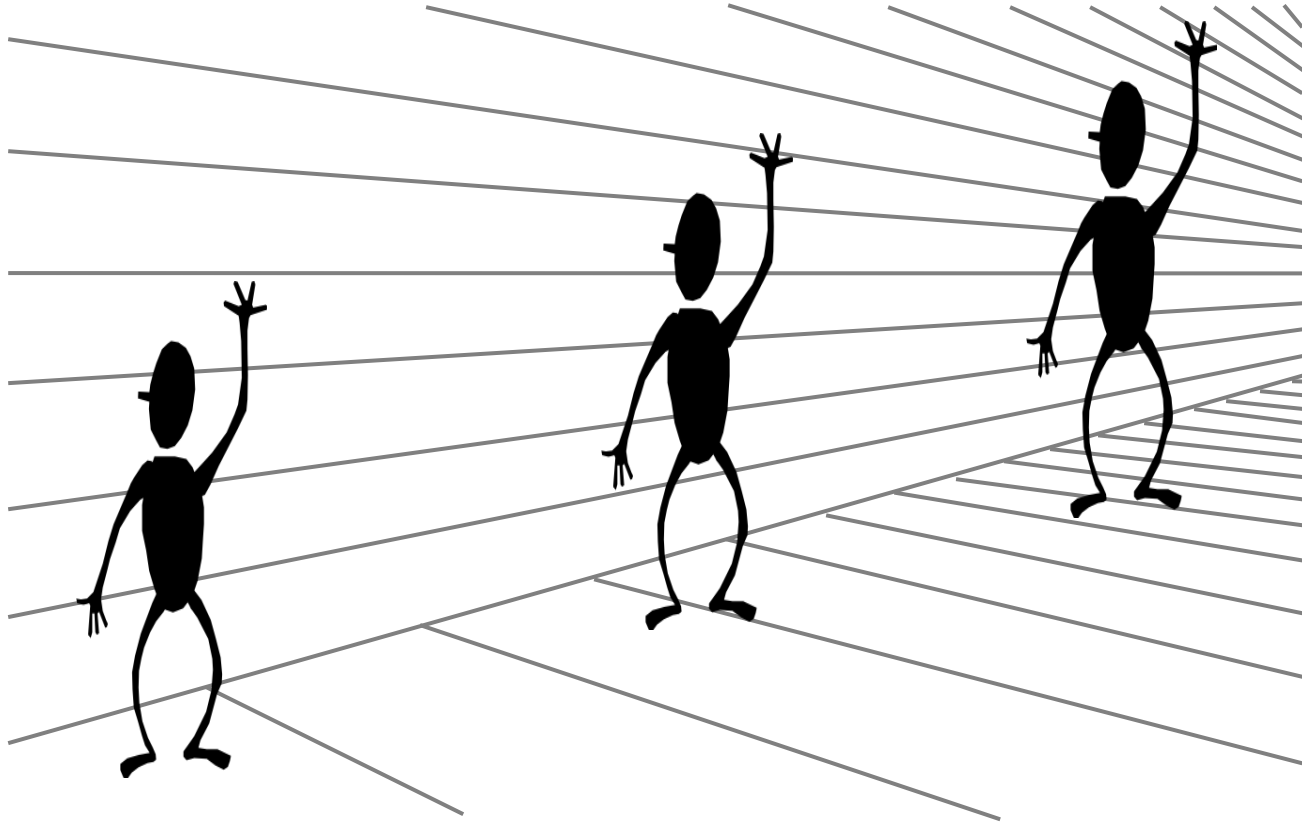
Some Facts About Projection

Let's try some fake images

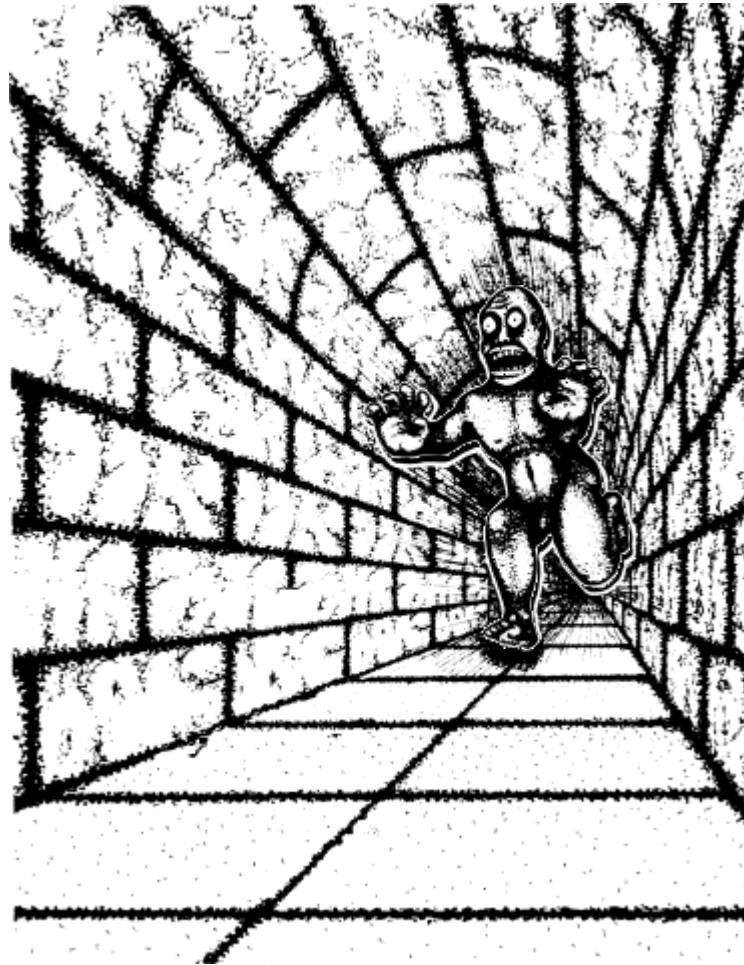
Some Facts About Projection



Some Facts About Projection



Some Facts About Projection



What's Lost?



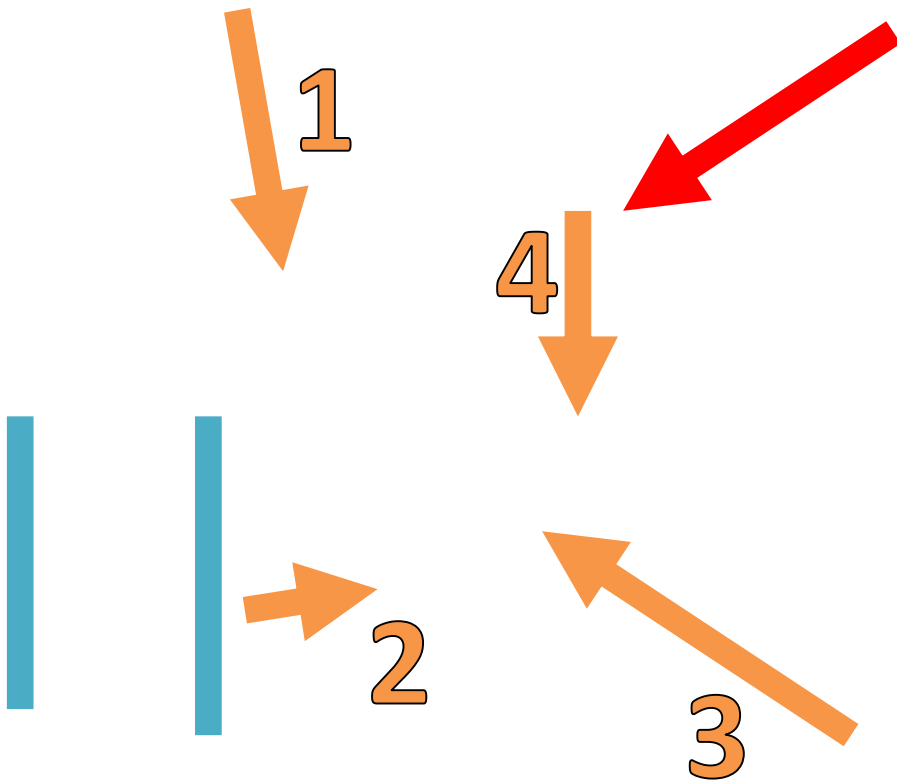
Is she shorter or further away?

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**?



What's Lost?

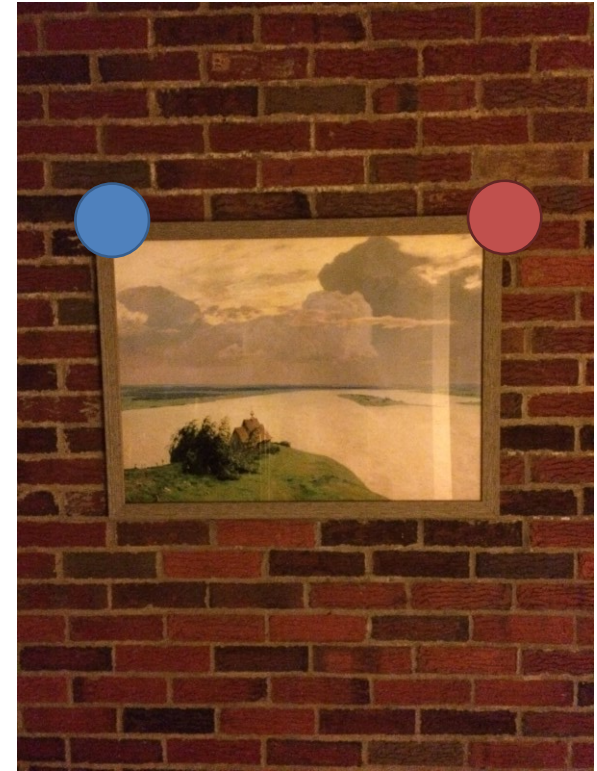
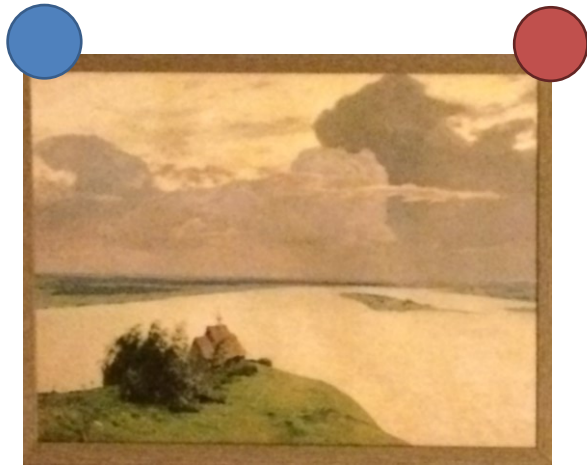
Be careful of drawing conclusions:

- 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:

$$\frac{fy}{z_2}$$

$$\frac{fy}{z_1}$$

$$\frac{fy}{z}$$

$$\frac{fy}{z}$$

Do You Always Get Perspective?



When plane is fronto-parallel
(parallel to camera plane),
everything is:

- scaled by f/z
- otherwise is preserved.

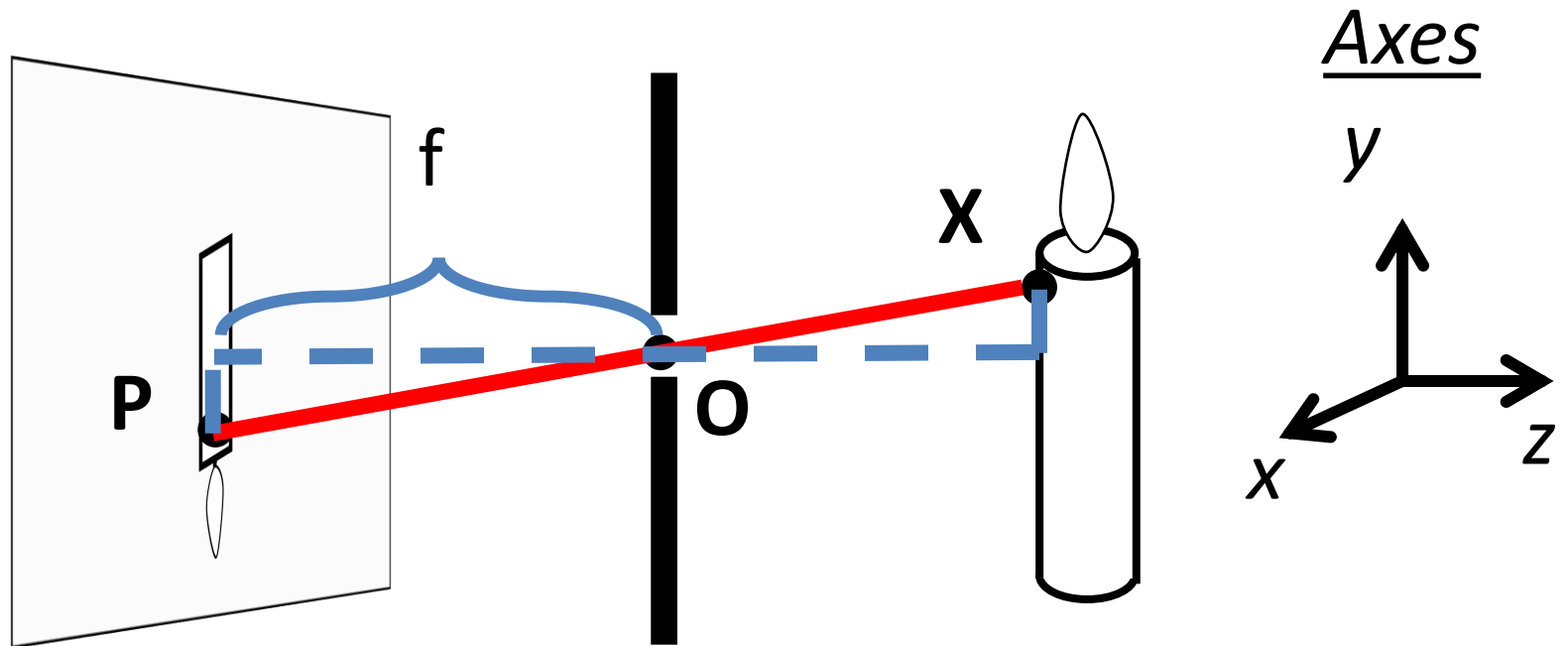


What's This Useful For?



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)

Homogeneous Coordinates (2D)

Trick: add a dimension!

This also clears up lots of nasty special cases

Physical
Point

$$\begin{bmatrix} x \\ y \end{bmatrix}$$



Concat
 $w=1$

Homogeneous
Point

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix}$$



Divide
by w

Physical
Point

$$\begin{bmatrix} u/w \\ v/w \end{bmatrix}$$

What if $w = 0$?

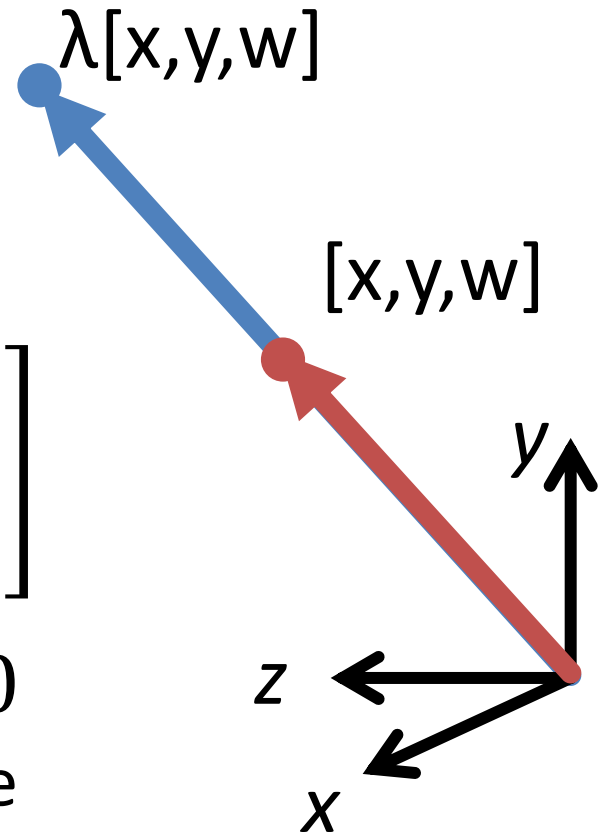
Homogeneous Coordinates

Triple /
Equivalent

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} \equiv \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} \iff \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \lambda \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix}$$

Double /
Equals

$\lambda \neq 0$



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

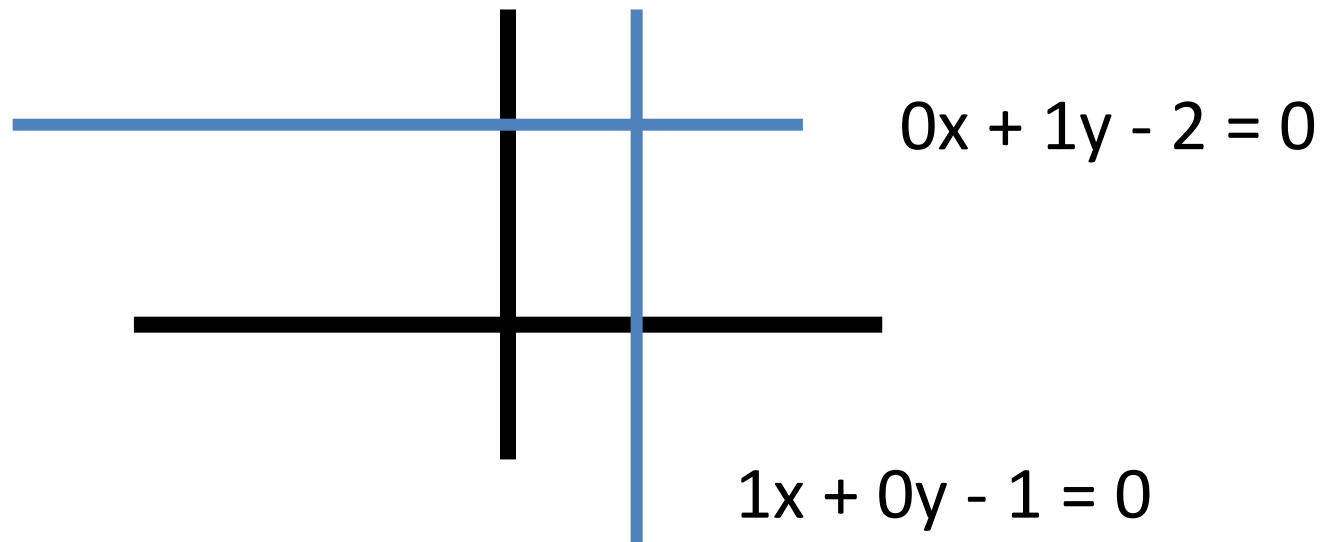
$$l^T \mathbf{p} = 0, \quad l = \begin{bmatrix} a \\ b \\ c \end{bmatrix}, \quad \mathbf{p} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Benefits of Homogeneous Coords

- Lines (3D) and points (2D \rightarrow 3D) are now the same dimension.
- Use the *cross* (\times) and *dot product* for:
 - Intersection of lines \mathbf{l} and \mathbf{m} : $\mathbf{l} \times \mathbf{m}$
 - Line through two points \mathbf{p} and \mathbf{q} : $\mathbf{p} \times \mathbf{q}$
 - Point \mathbf{p} on line \mathbf{l} : $\mathbf{l}^T \mathbf{p}$
- Parallel lines, vertical lines become easy (compared to $y=mx+b$)

Benefits of Homogeneous Coords

What's the intersection?

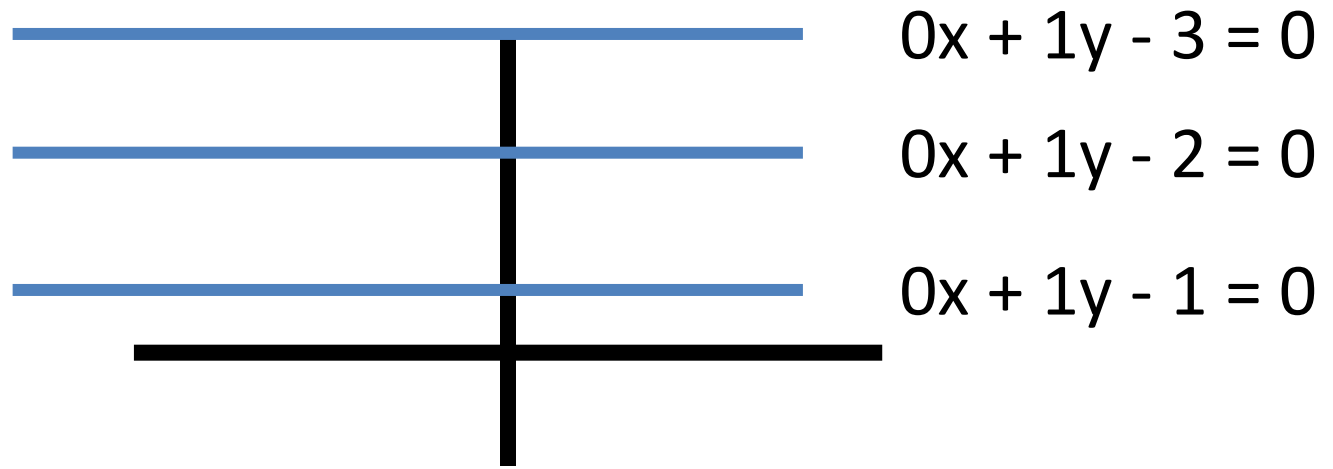


$$[0, 1, -2] \times [1, 0, -1] = [-1, -2, -1]$$

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

$$\text{If } w = 1 \quad \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} u + t_x \\ v + t_y \\ 1 \end{bmatrix}$$

$$\text{Generically} \quad \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} u + wt_x \\ v + wt_y \\ w \end{bmatrix}$$

Rigid body transforms (rot + trans) now linear

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & t_x \\ r_{21} & r_{22} & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

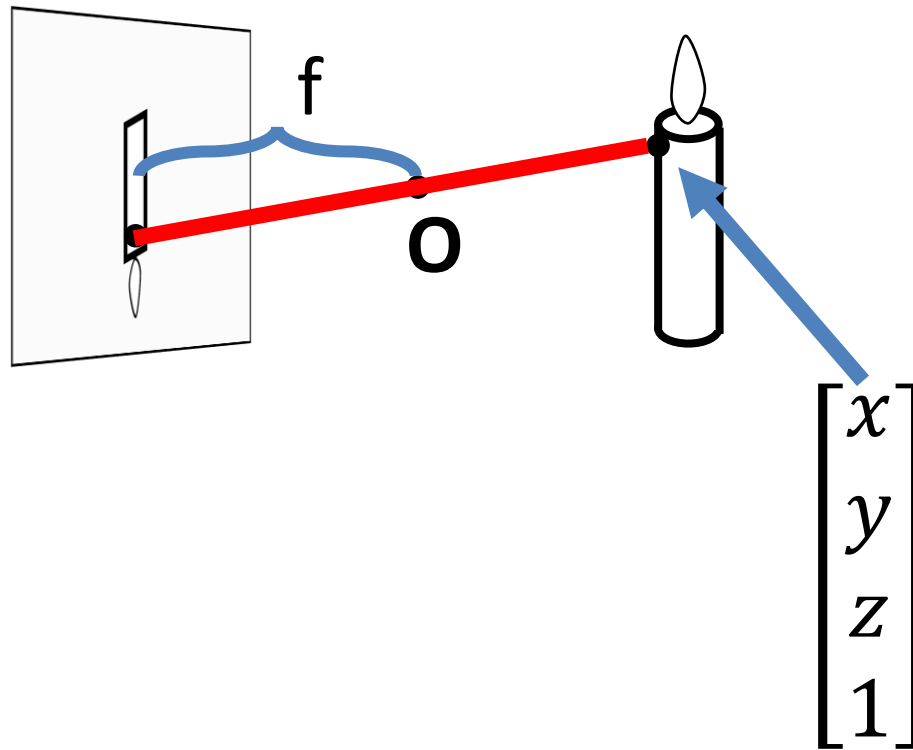
3D Homogeneous Coordinates

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

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} \longrightarrow \begin{bmatrix} u \\ v \\ w \\ t \end{bmatrix} \longrightarrow \begin{bmatrix} u/t \\ v/t \\ w/t \end{bmatrix}$$

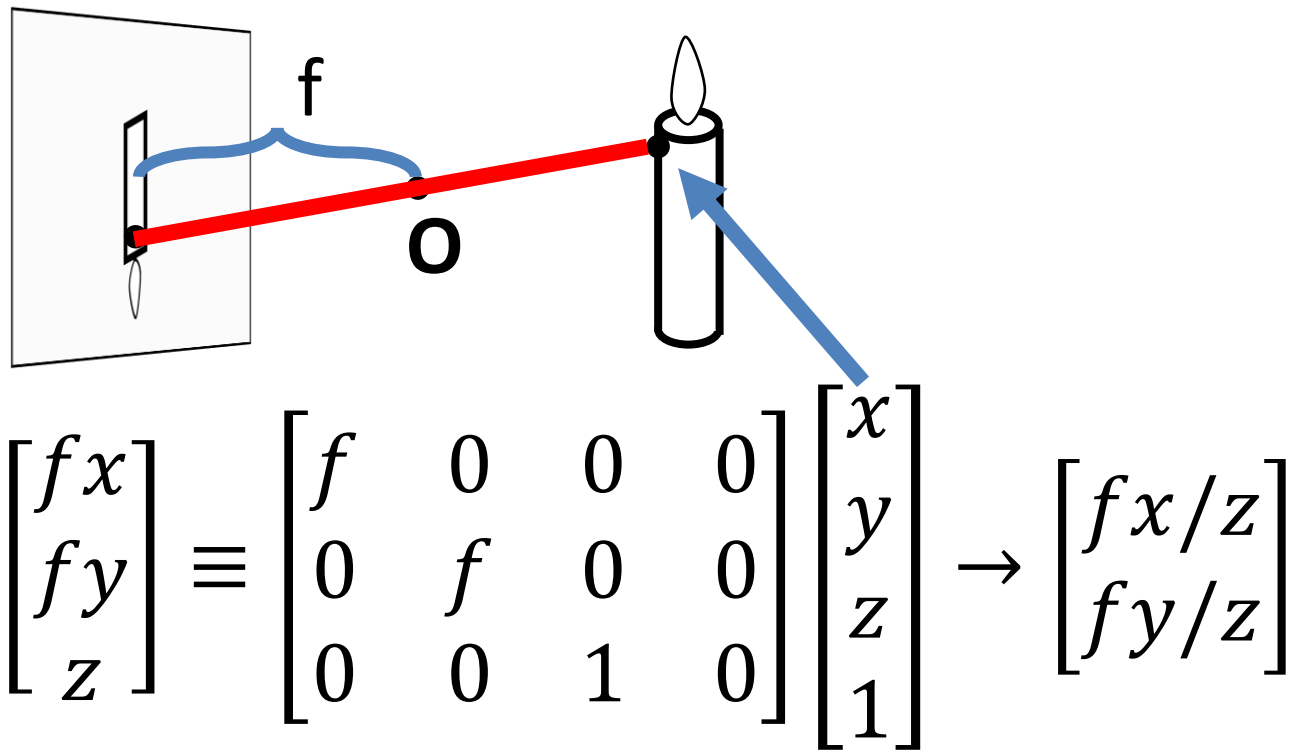
Projection Matrix

Projection $(f_x/z, f_y/z)$ is matrix multiplication

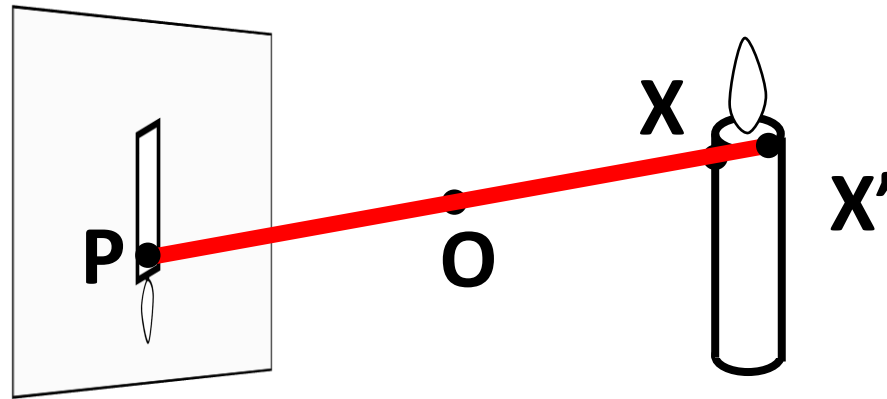


Projection Matrix

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



Why $\equiv \neq =$



Project X and X' to the image and compare them

YES $\begin{bmatrix} fx \\ fy \\ z \end{bmatrix} \equiv \begin{bmatrix} fx' \\ fy' \\ z' \end{bmatrix}$

NO $\begin{bmatrix} fx \\ fy \\ z \end{bmatrix} = \begin{bmatrix} fx' \\ fy' \\ z' \end{bmatrix}$

Typical Perspective Model


P: 2D homogeneous
point (3D)

$P \equiv$



X: 3d homogeneous
point (4D)

$X_{4 \times 1}$

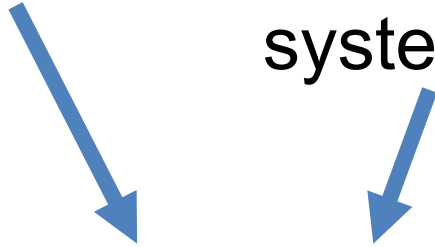


Typical Perspective Model

R: rotation between
world system and
camera

t: translation
between world
system and camera

$P \equiv$

$$\begin{bmatrix} \mathbf{R}_{3 \times 3} & \mathbf{t}_{3 \times 1} \end{bmatrix} \mathbf{X}_{4 \times 1}$$


Typical Perspective Model

f focal length

u_0, v_0 : principal point (image coords of camera origin on retina)

$$\mathbf{P} \equiv \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[\mathbf{R}_{3 \times 3} \quad \mathbf{t}_{3 \times 1}] \quad \mathbf{X}_{4 \times 1}$$

Typical Perspective Model

**Intrinsic
Matrix K**

**Extrinsic
Matrix [R,t]**

$$P \equiv \begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R}_{3 \times 3} & \mathbf{t}_{3 \times 1} \end{bmatrix} \mathbf{X}_{4 \times 1}$$

$$P \equiv K[R, t]X \equiv M_{3 \times 4}X_{4 \times 1}$$

Other Cameras – Orthographic

Orthographic Camera (z infinite)

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \mathbf{X}_{3 \times 1}$$

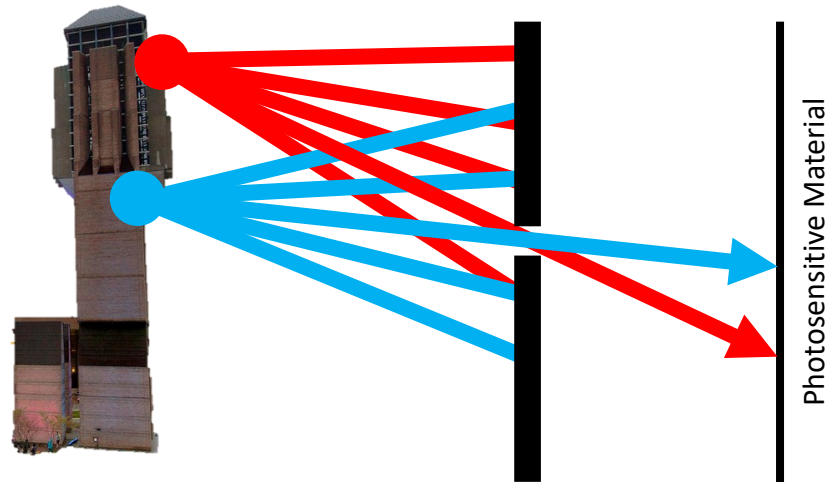


Other Cameras – Orthographic

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

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

The Big Issue



Film captures all the rays going through a **point** (a *pencil of rays*).

How big is a point?

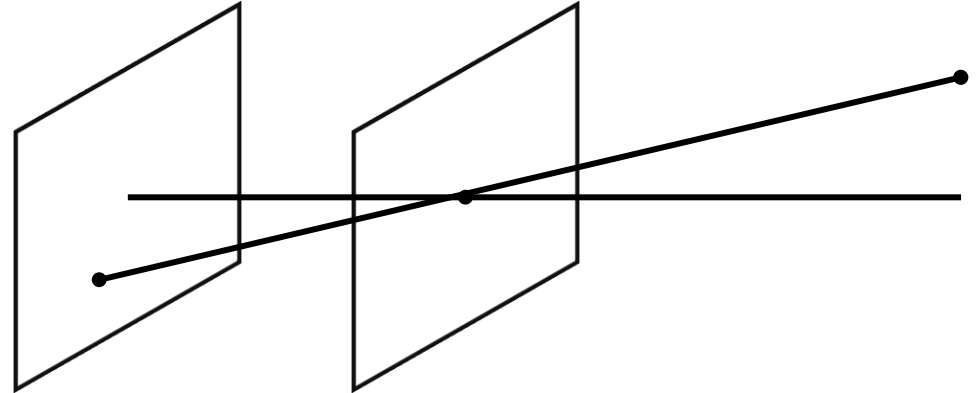
Math vs. Reality

- 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

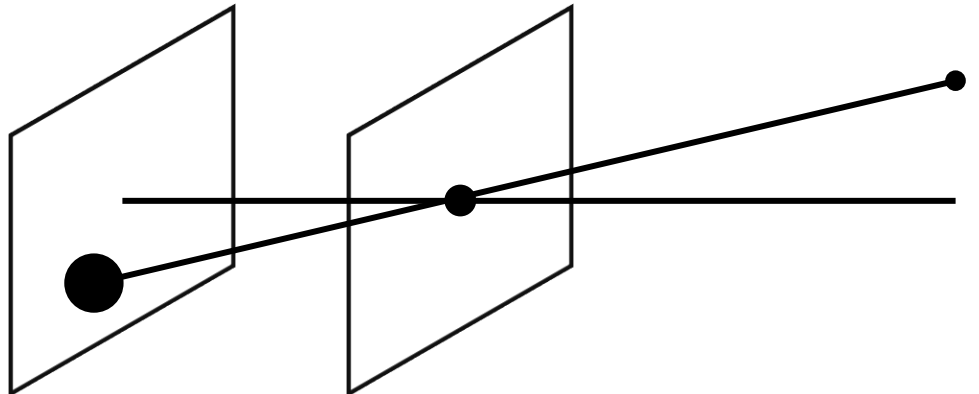
Ideal Pinhole

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

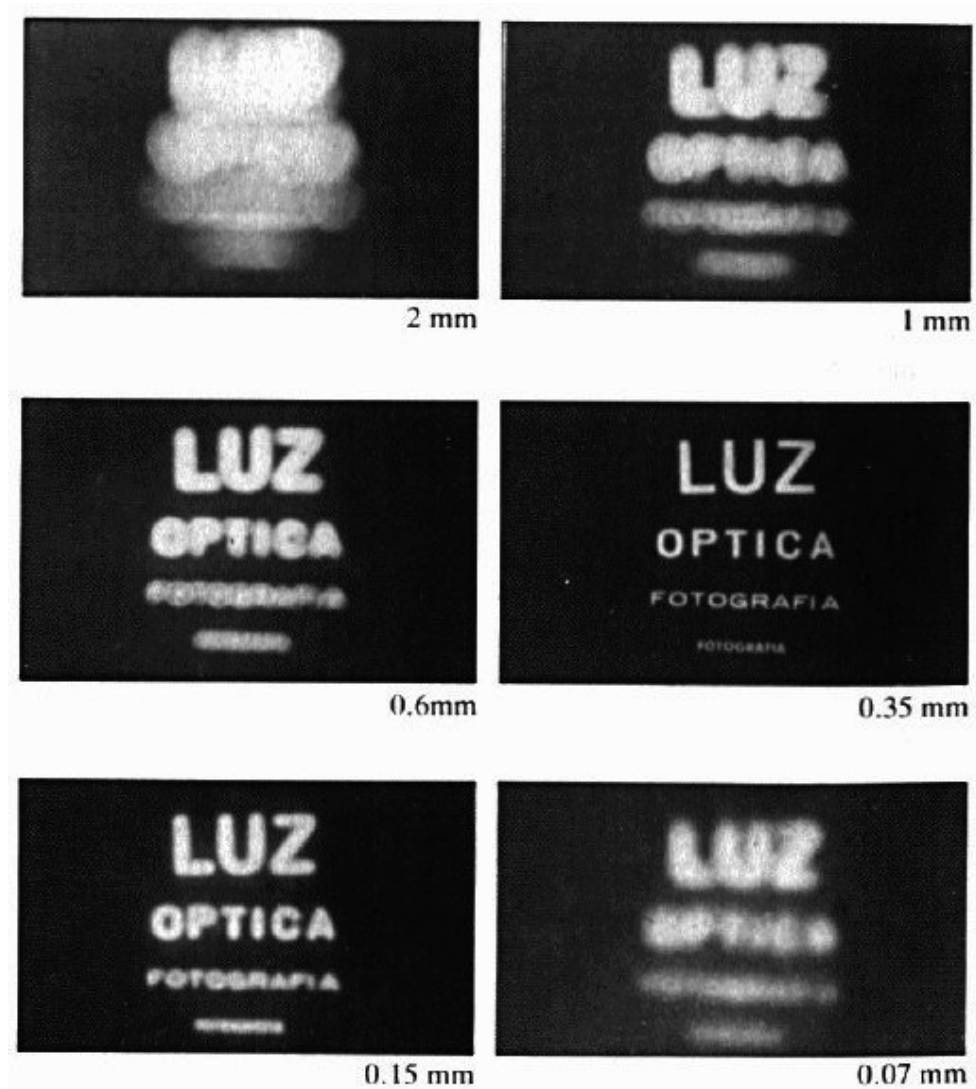


Finite Pinhole

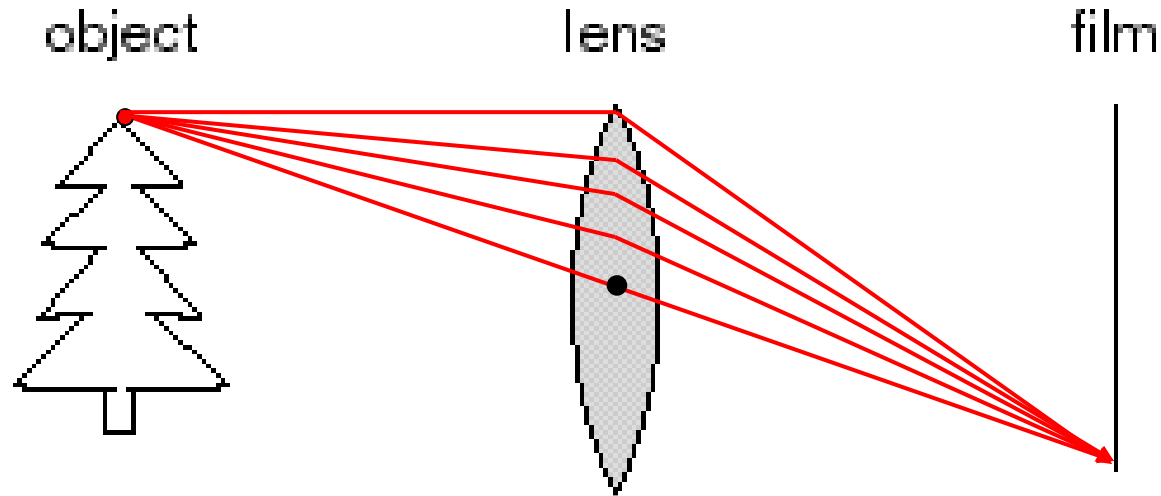
- 1 point generates region
- Blurry.**
- Why is it blurry?**



Limitations of Pinhole Model

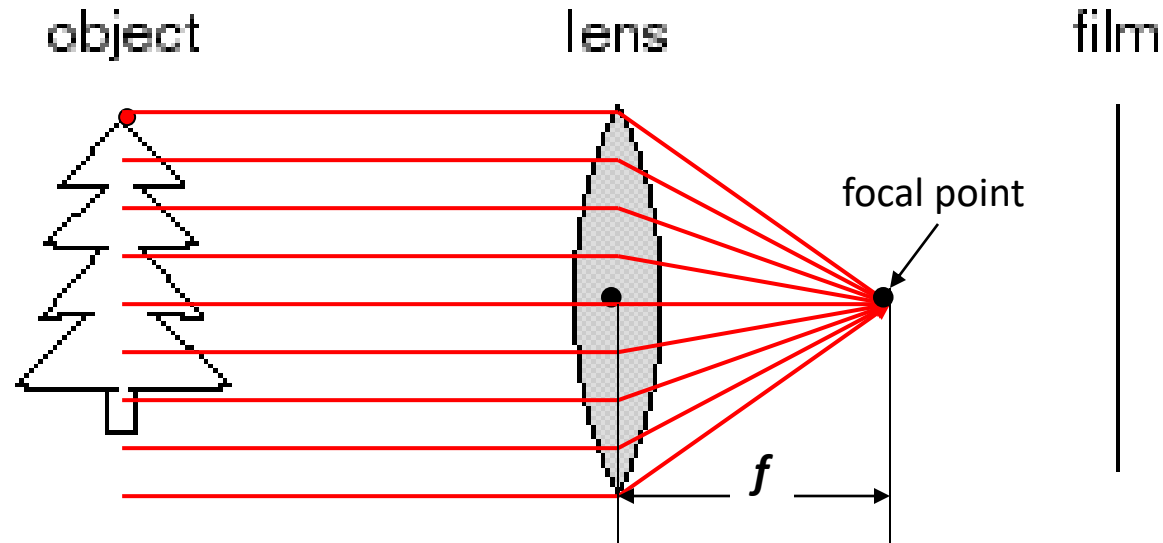


Adding a Lens



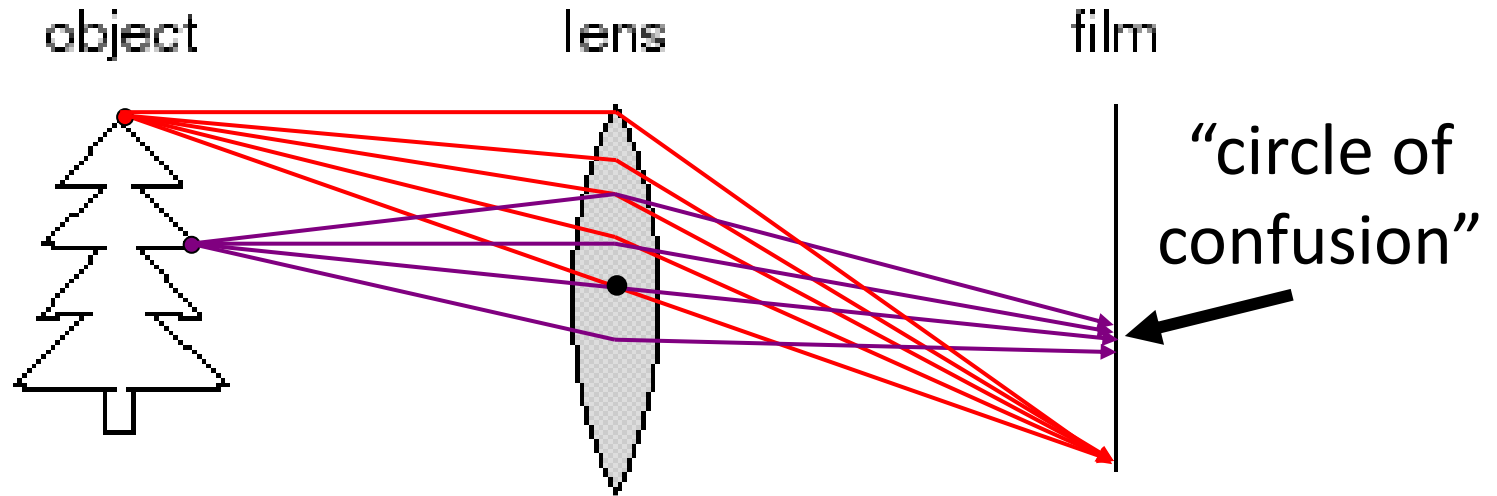
- A lens focuses light onto the film
- Thin lens model: rays passing through the center are not deviated (pinhole projection model still holds)

Adding a Lens



- All rays parallel to the optical axis pass through the *focal point*

What's The Catch?



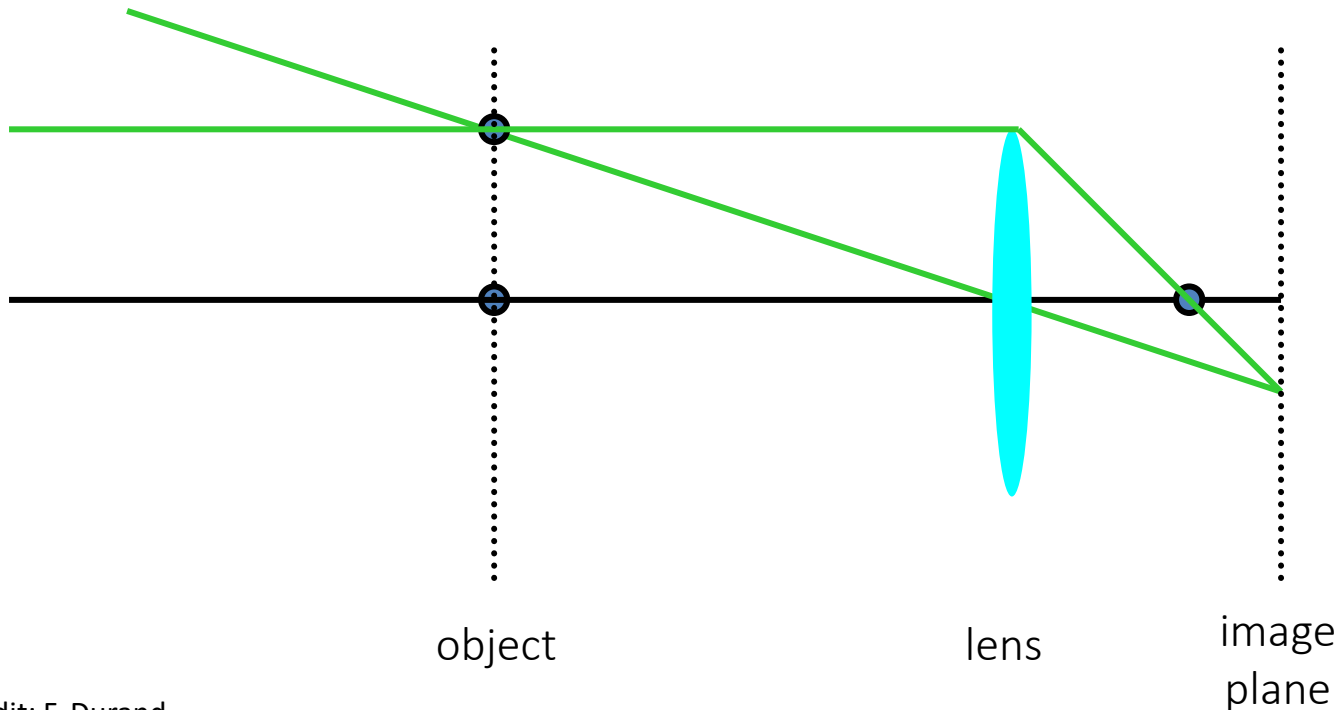
- There's a distance where objects are "in focus"
- Other points project to a "circle of confusion"

Thin Lens Formula

We care about images that are in focus.

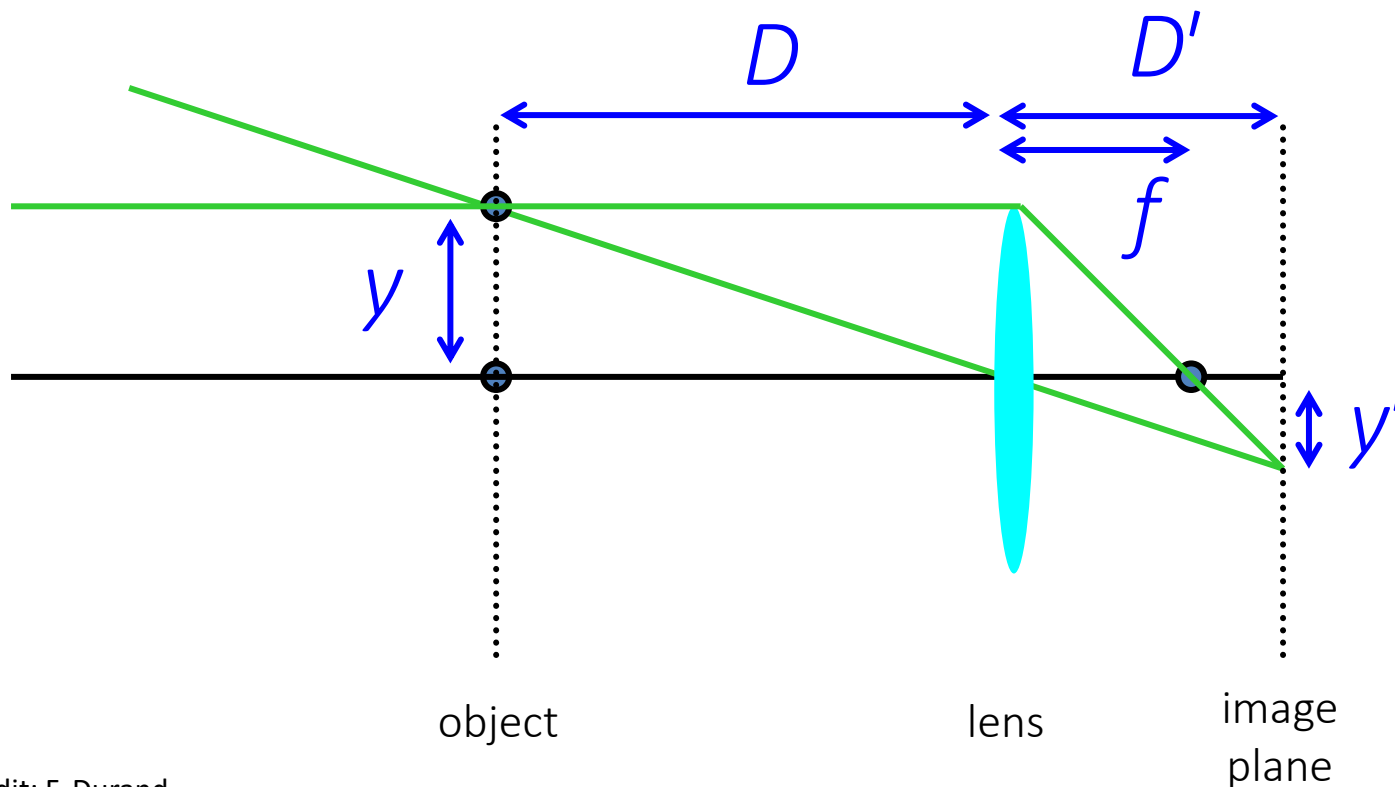
When is this true?

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



Thin Lens Formula

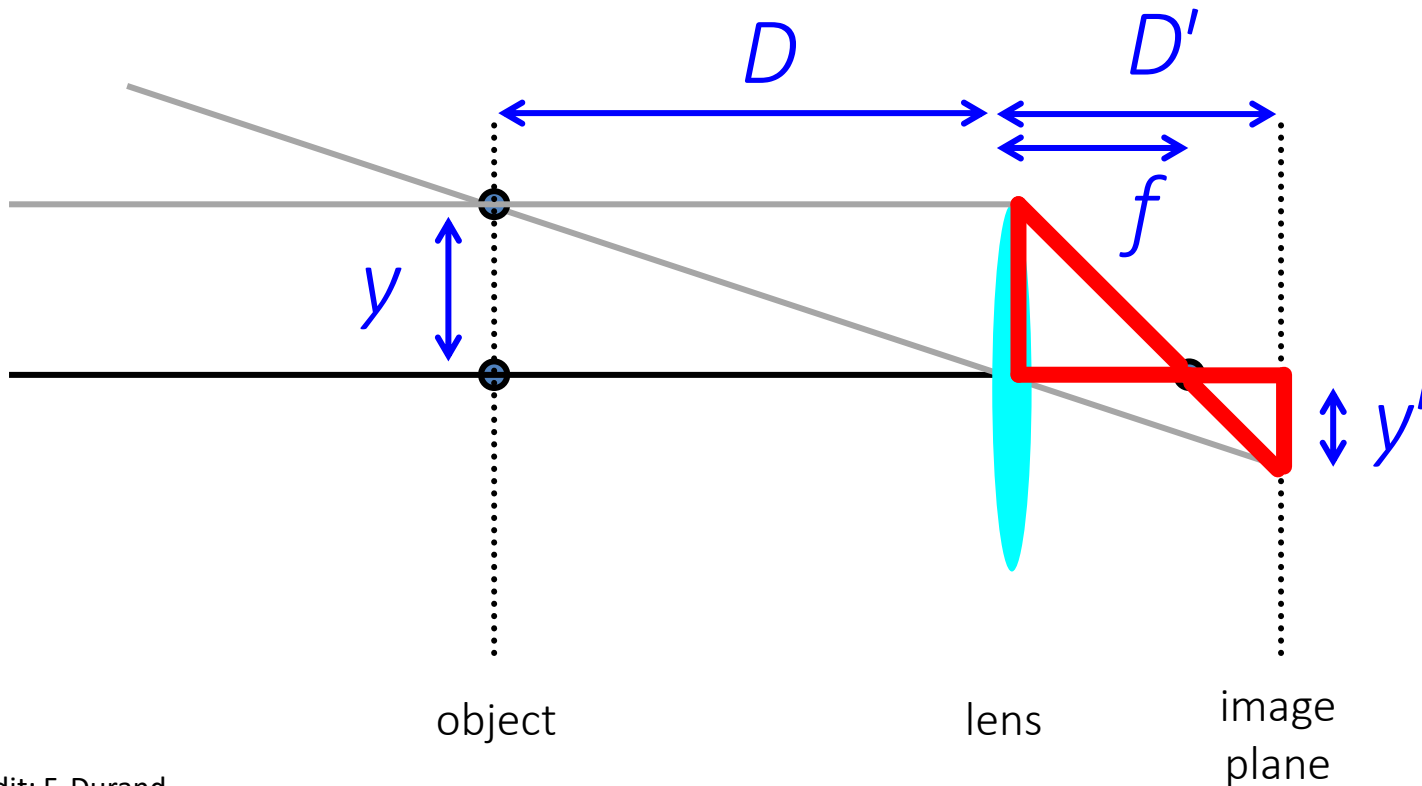
Let's derive the relationship between object distance D , image plane distance D' , and focal length f .



Thin Lens Formula

One set of similar triangles:

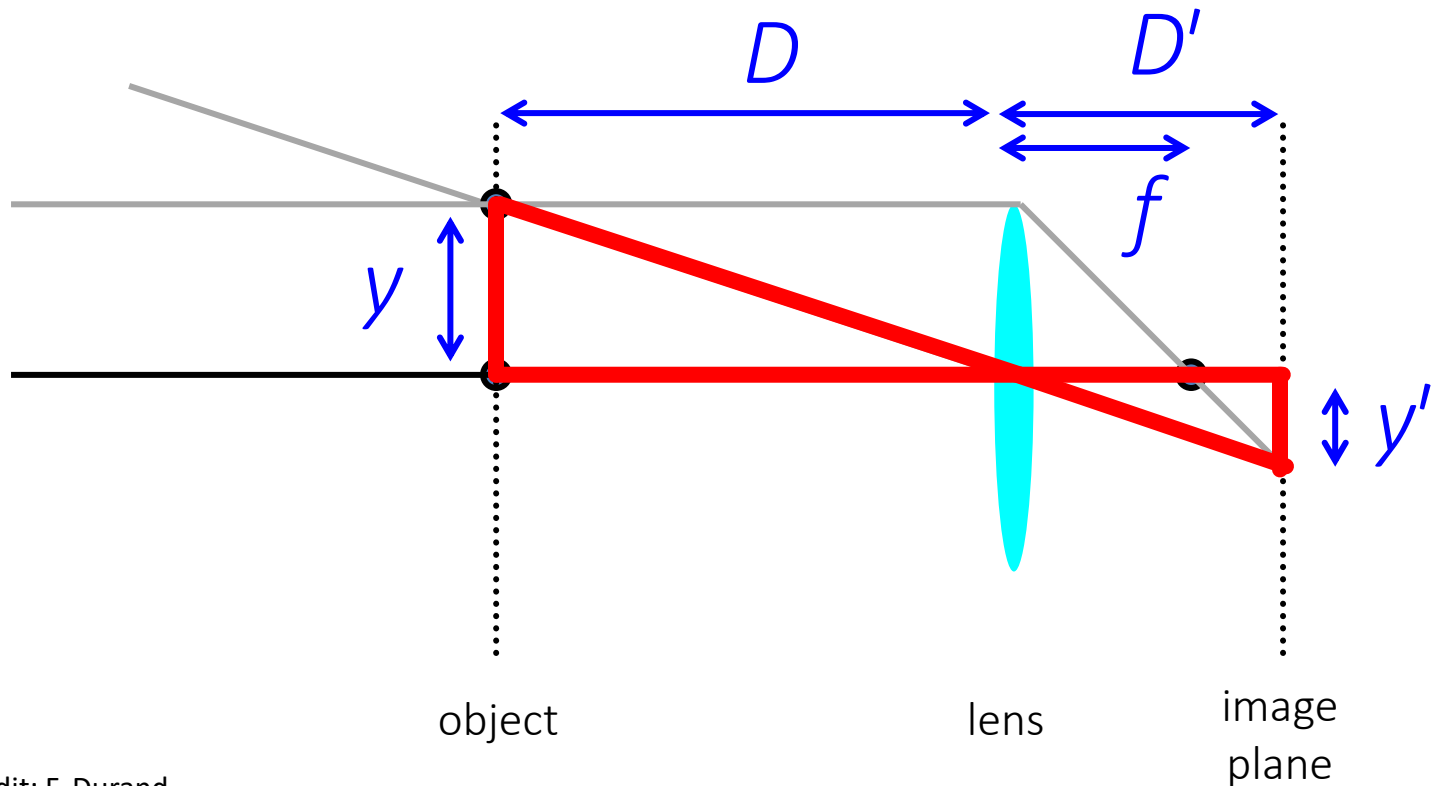
$$\frac{y'}{D' - f} = \frac{y}{f} \longrightarrow \frac{y'}{y} = \frac{D' - f}{f}$$



Thin Lens Formula

Another set of similar triangles:

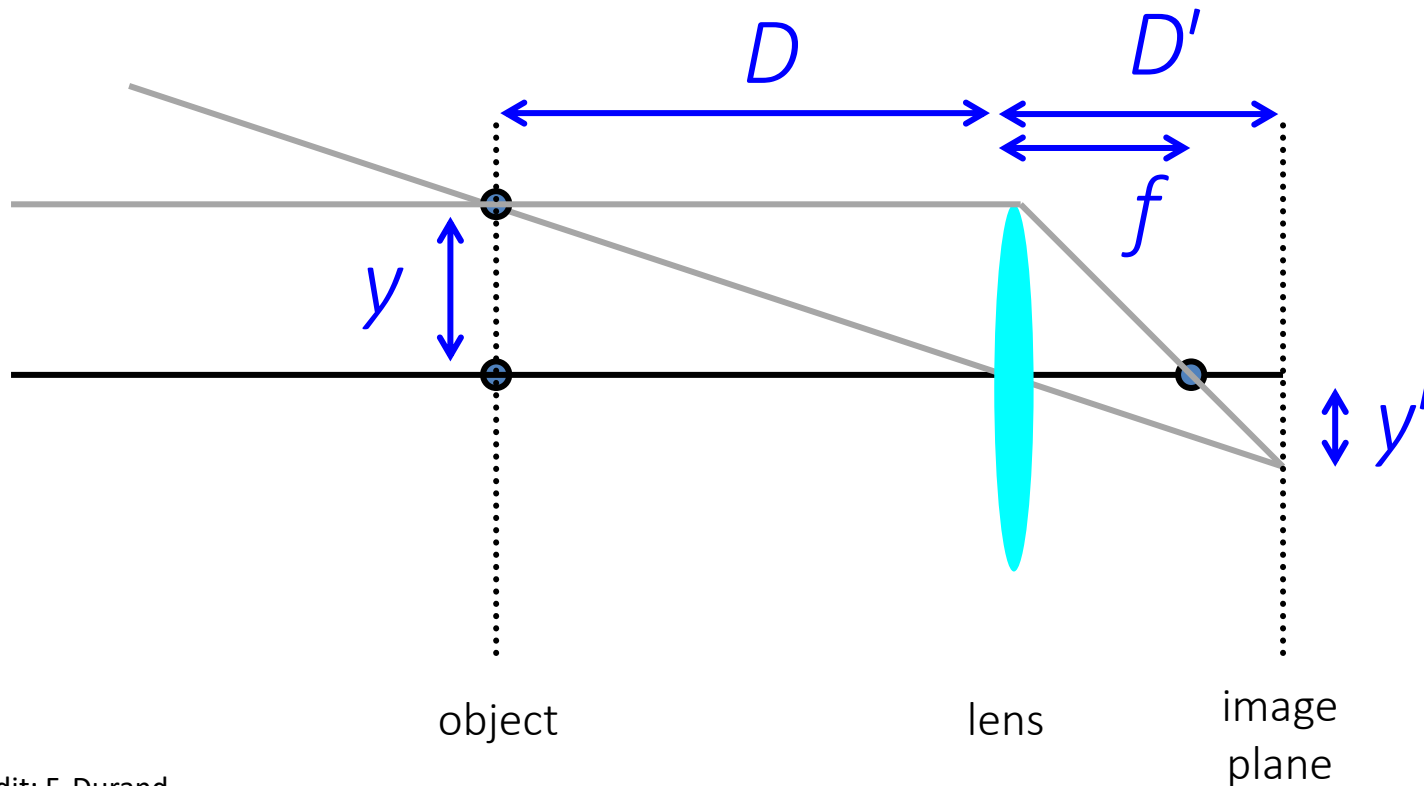
$$\frac{y'}{D'} = \frac{y}{D} \longrightarrow \frac{y'}{y} = \frac{D'}{D}$$



Thin Lens Formula

Set them
equal:

$$\frac{D'}{D} = \frac{D - f}{f} \longrightarrow \frac{1}{D} + \frac{1}{D'} = \frac{1}{f}$$

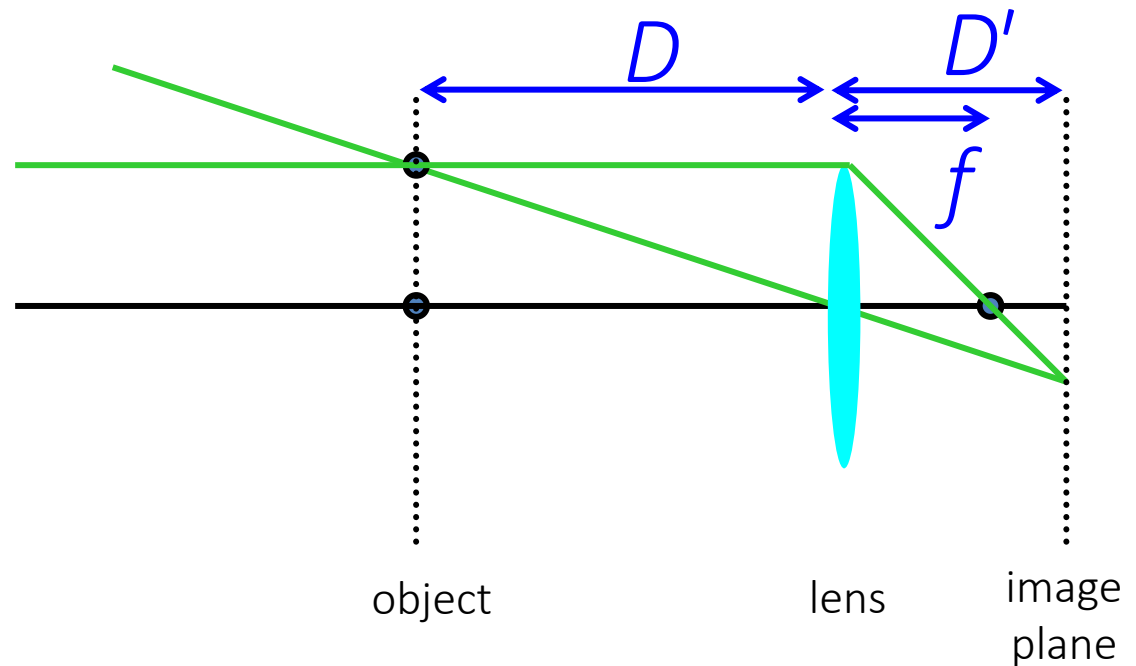


Thin Lens Formula

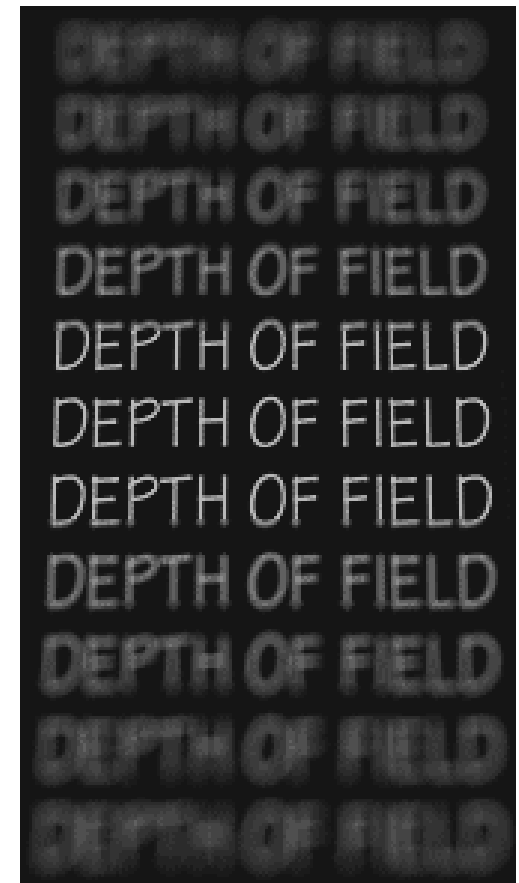
Suppose I want to take a picture of a lion with D big?
Which of D , D' , f are fixed?

How do we take pictures of things at different distances?

$$\frac{1}{D} + \frac{1}{D'} = \frac{1}{f}$$

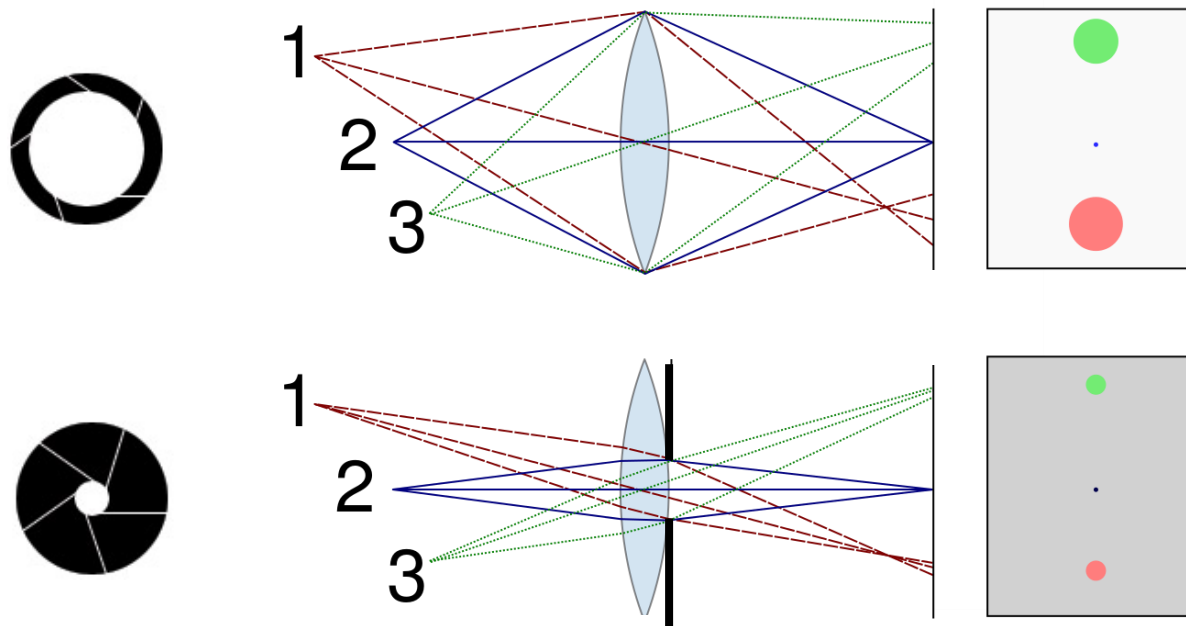


Depth of Field



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

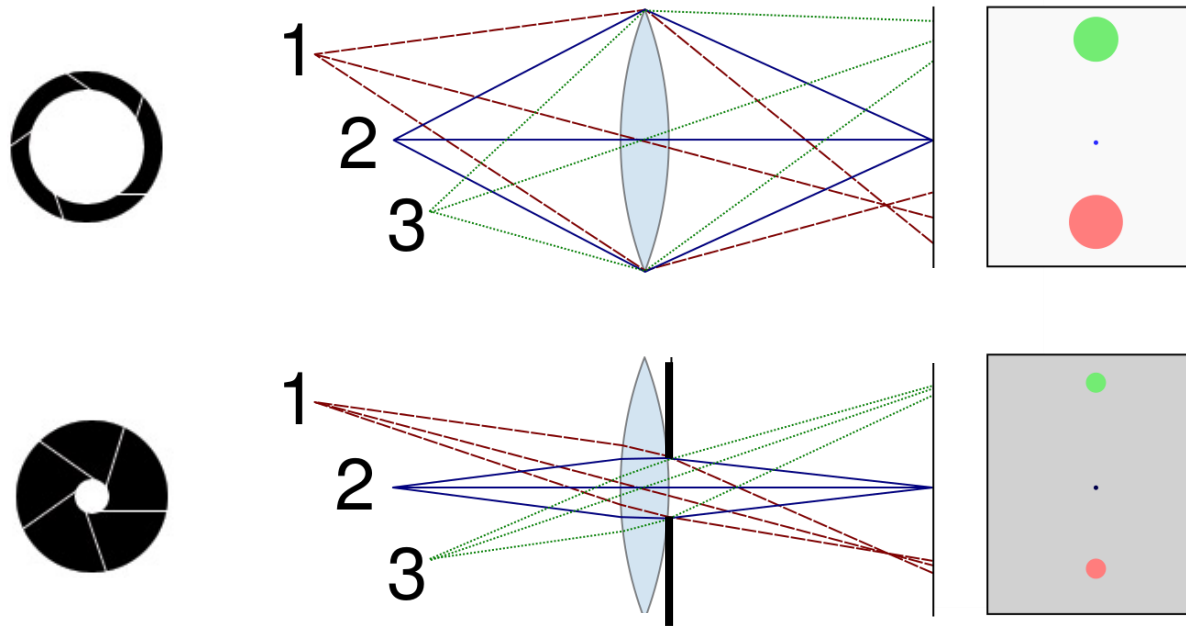
Controlling Depth of Field



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

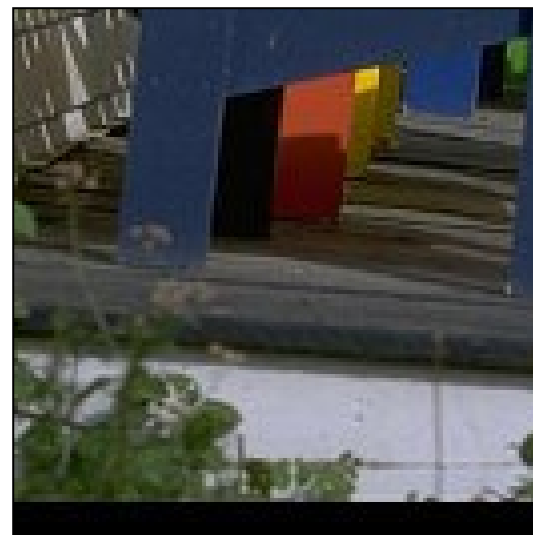
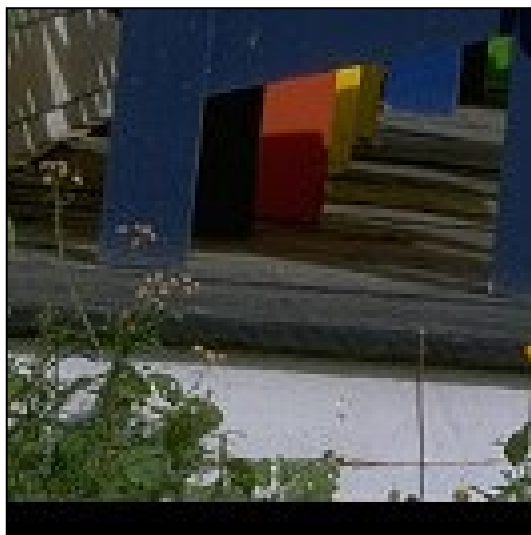


Small aperture = large DOF

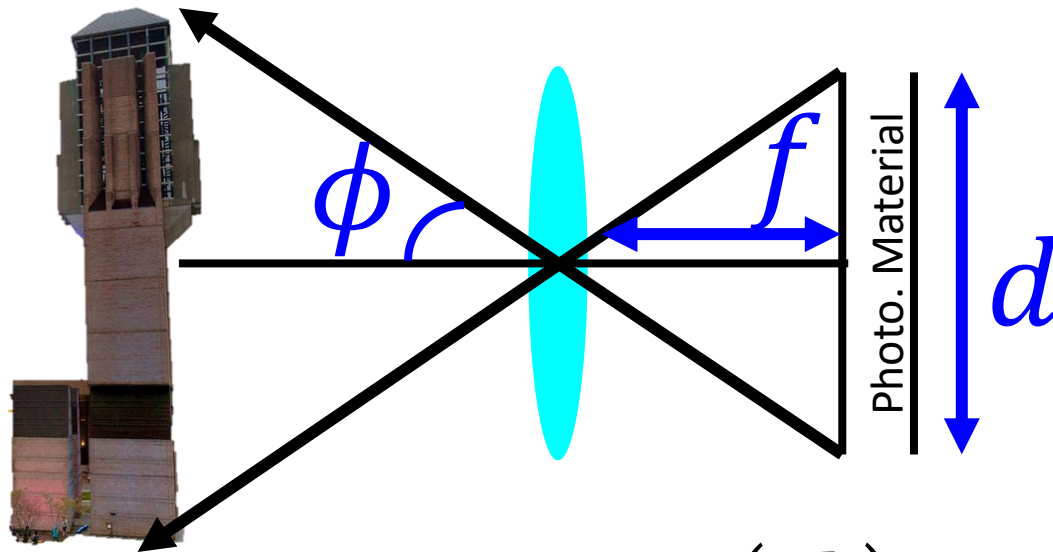


Large aperture = small DOF

Varying the Aperture



Field of View (FOV)

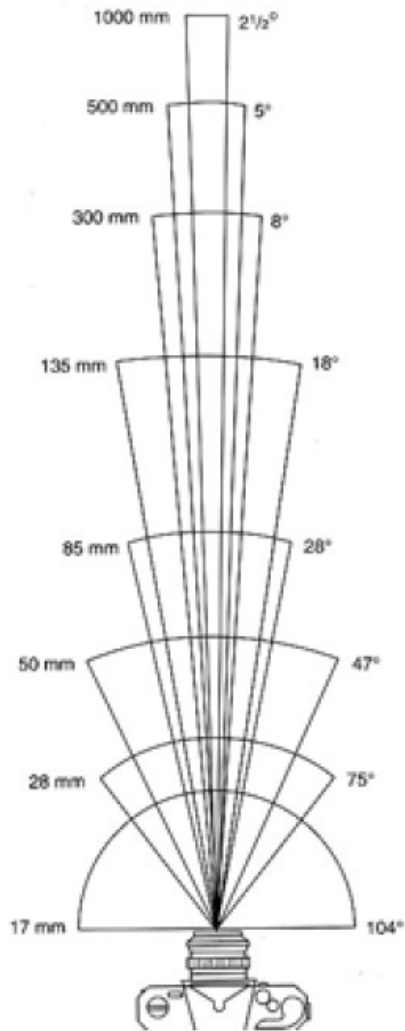


$$\phi = \tan^{-1} \left(\frac{d}{2f} \right)$$

\tan^{-1} is monotonic increasing.

How can I get the FOV bigger?

Field of View



17mm



28mm

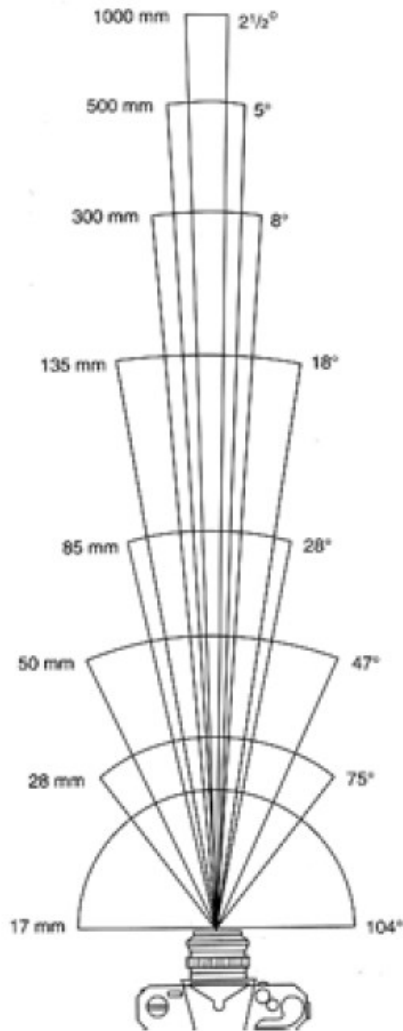


50mm

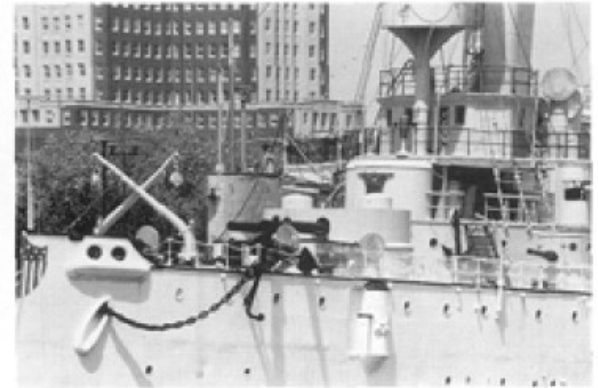


85mm

Field of View



135mm



300mm

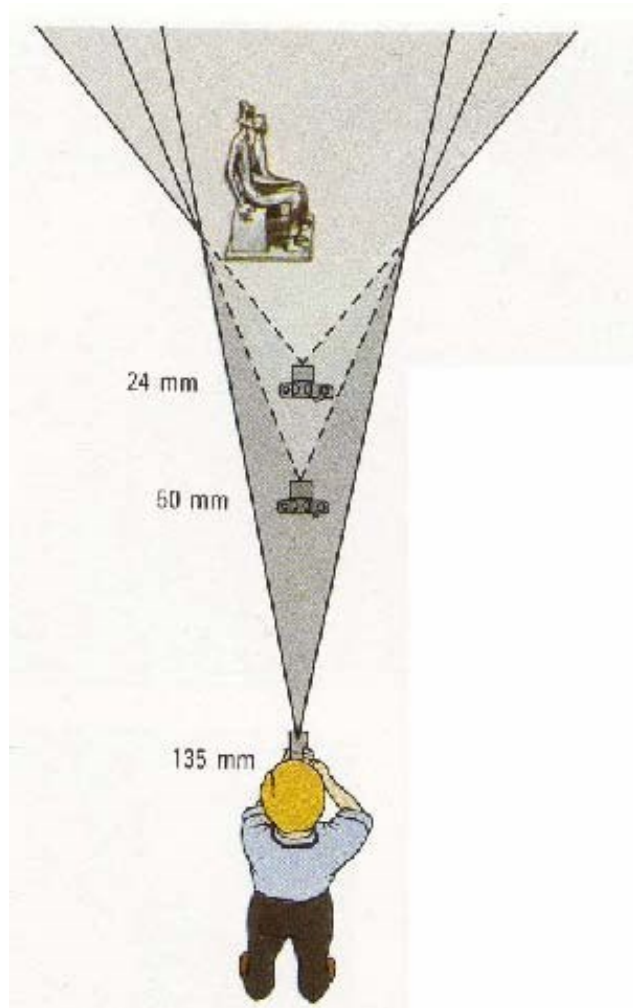


500mm



1000mm

Field of View and Focal Length



Large FOV, small f
Camera close to car



Small FOV, large f
Camera far from the car

Field of View and Focal Length



wide-angle



standard



telephoto

Dolly Zoom

Change f and distance at the same time



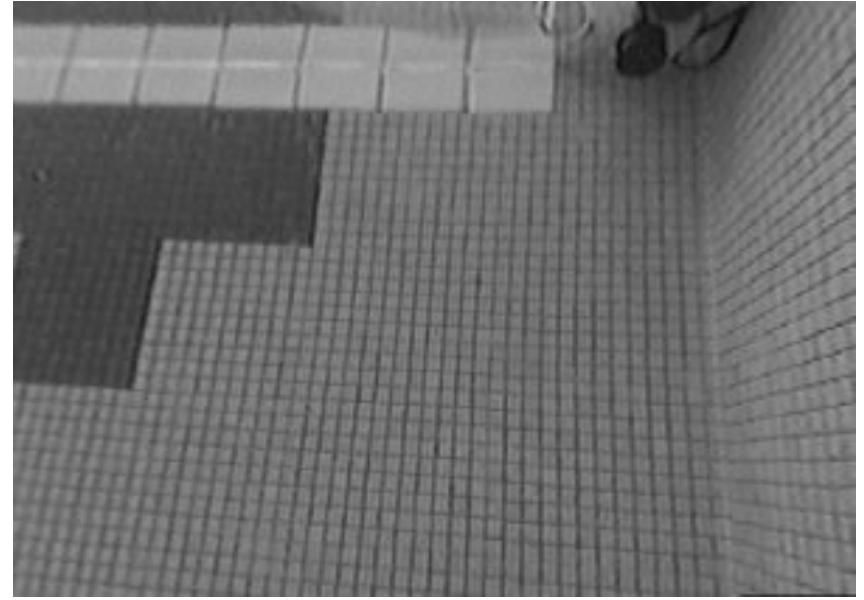
More Bad News!

- First a pinhole...
- Then a thin lens model....



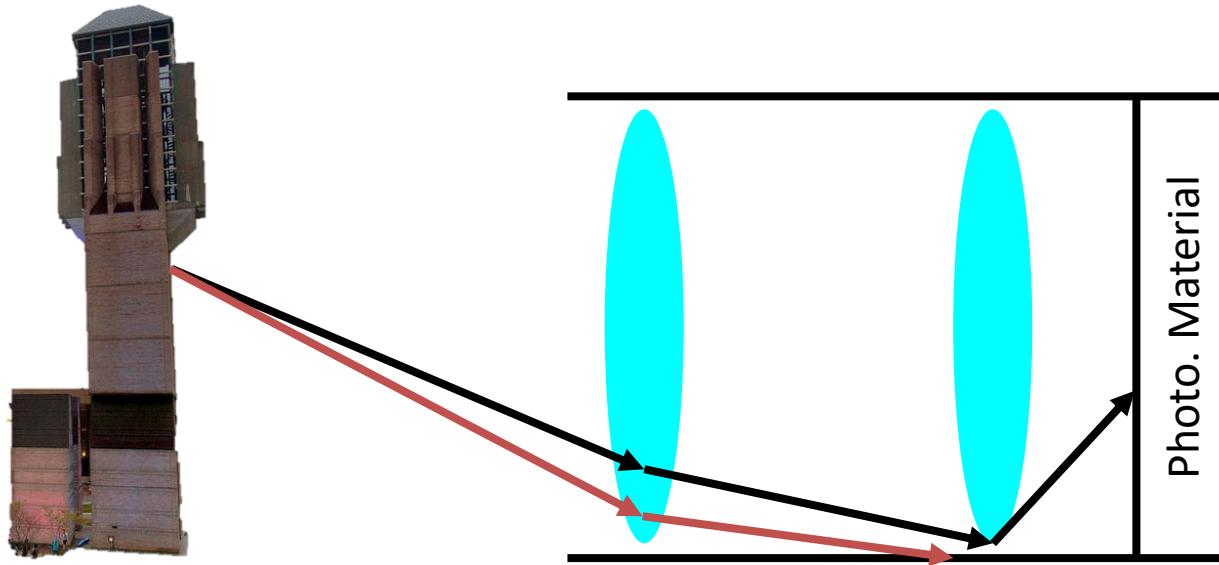
Lens Flaws: Radial Distortion

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



Less common these days in consumer devices

Vignetting



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

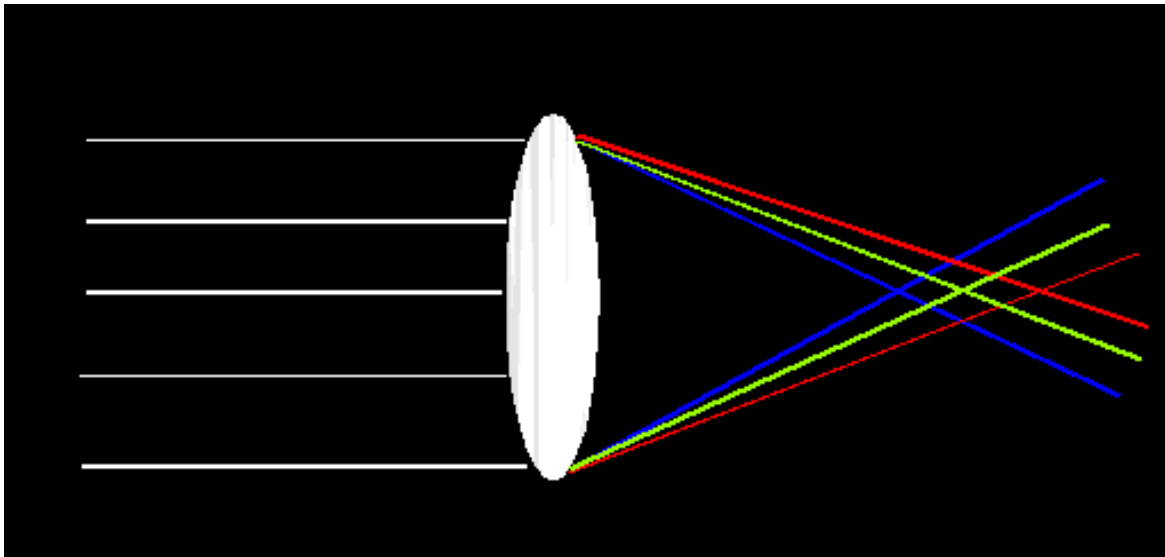
Vignetting



Photo credit: Wikipedia (<https://en.wikipedia.org/wiki/Vignetting>)

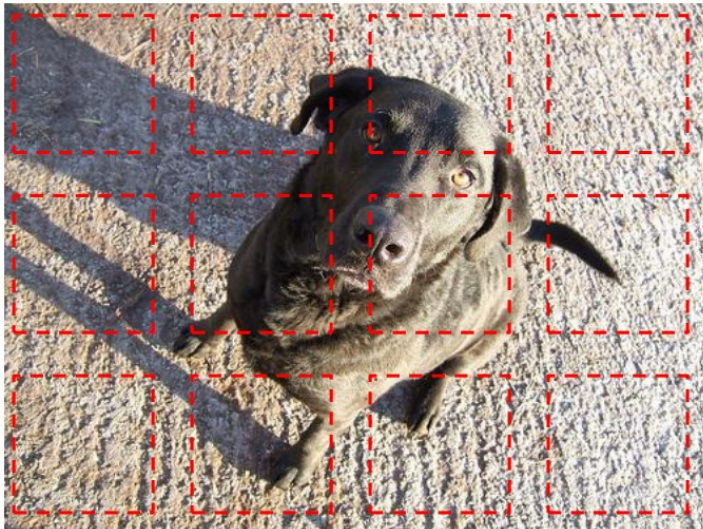
Lens Flaws: Chromatic Abberation

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



Lens Flaws: Chromatic Abberation

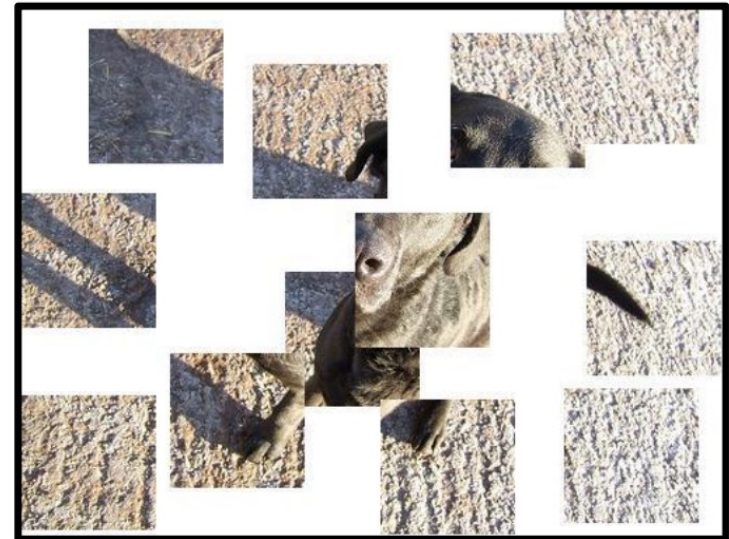
Researchers tried teaching a network about objects by forcing it to assemble jigsaws.



Initial layout, with sampled patches in red

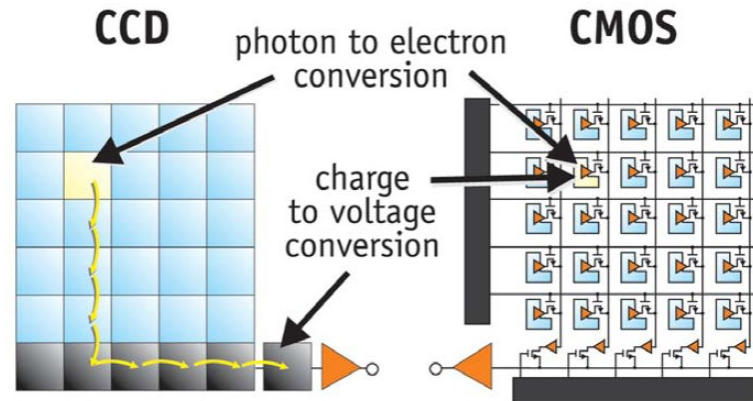


Image layout is discarded



We can recover image layout automatically

From Photon to Photo

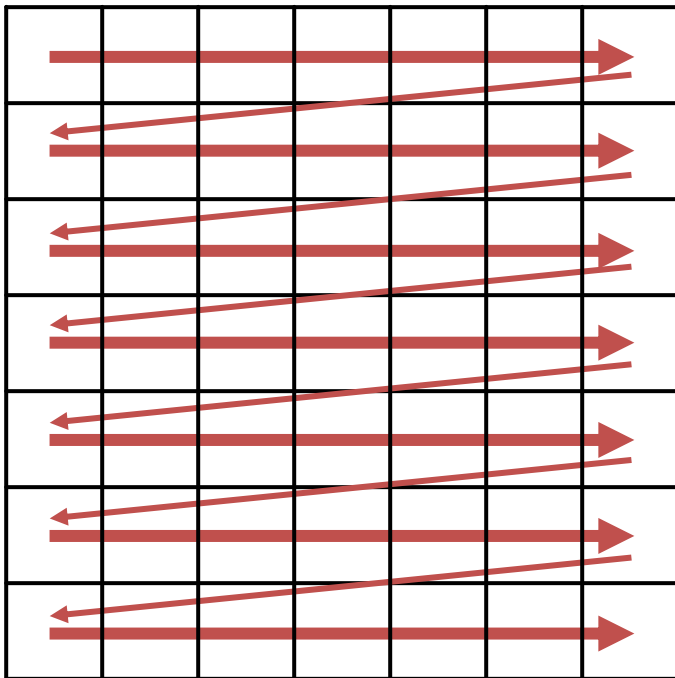


CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

- 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)**

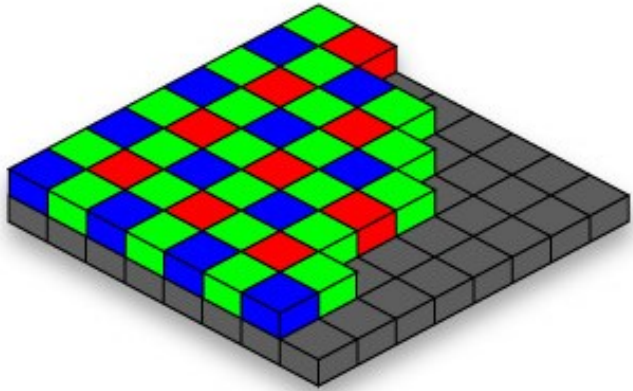
From Photon to Photo

Rolling Shutter: pixels read in sequence
Can get global reading, but \$\$\$



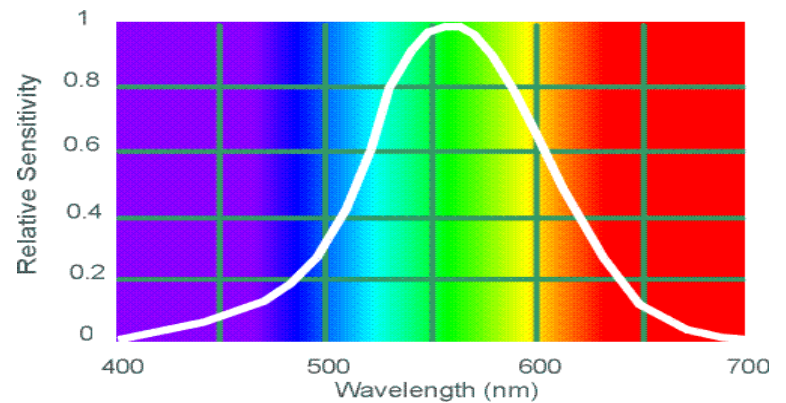
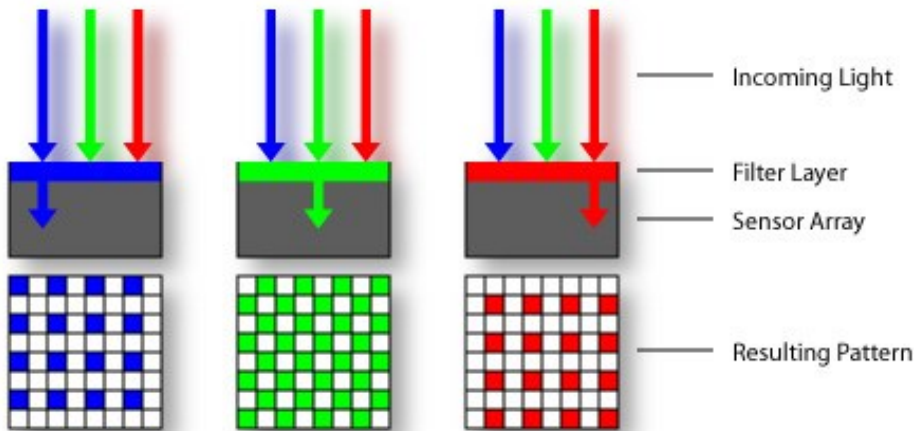
Preview of What's Next

Bayer grid



Demosaicing:

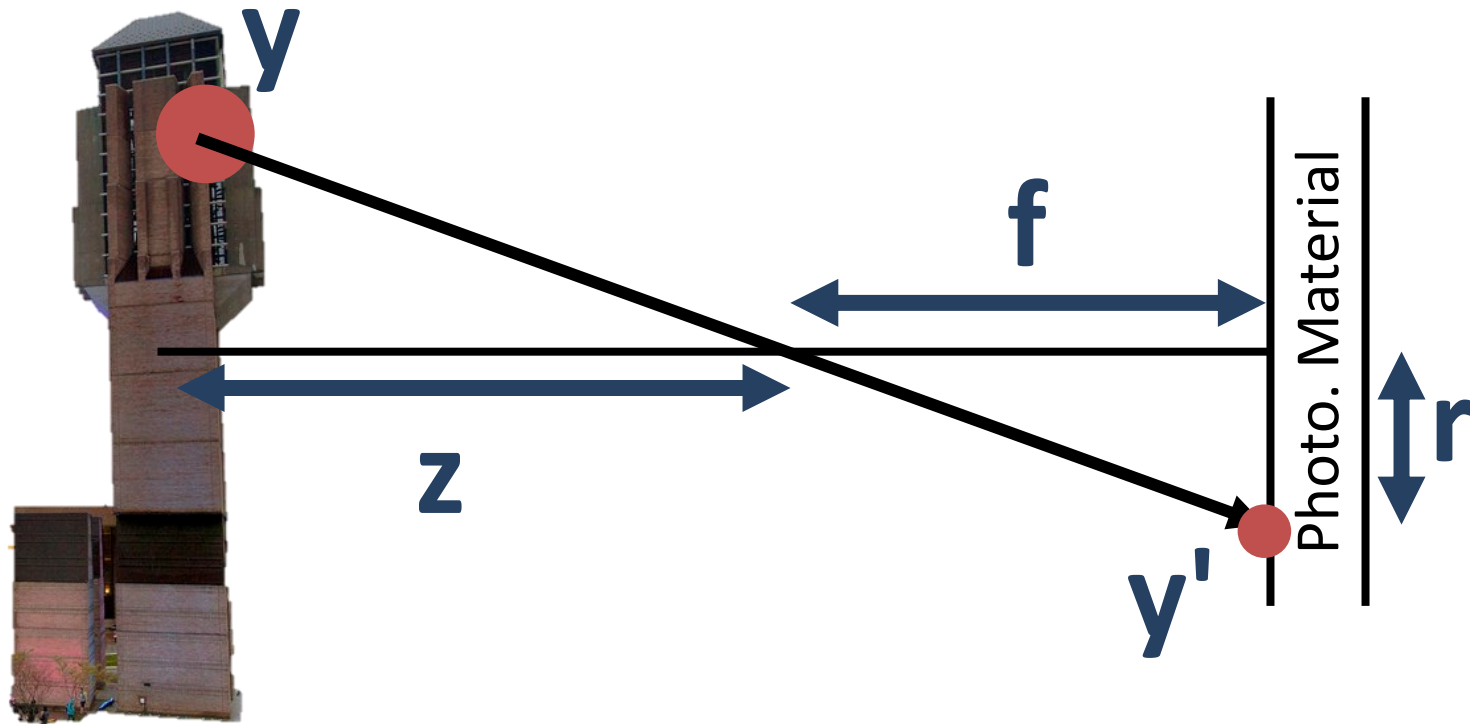
Estimation of missing components from neighboring values



For the Curious

- Cut in the interest of time

Radial Distortion Correction



Ideal

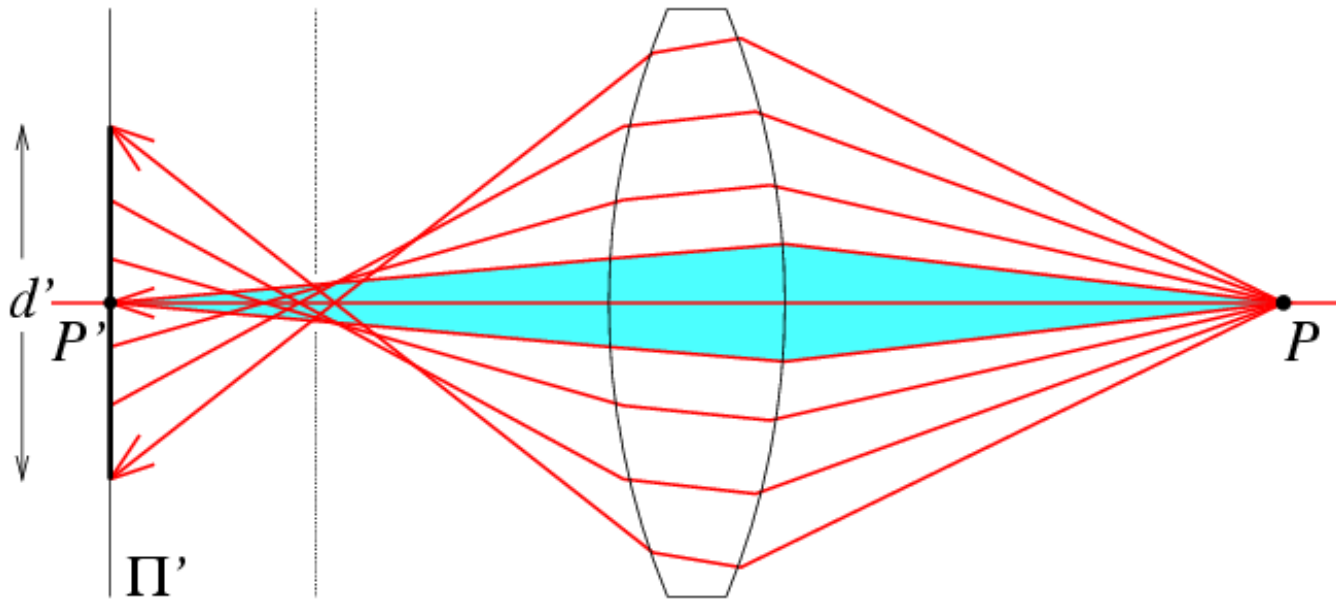
$$y' = f \frac{y}{z}$$

Distorted

$$y' = (1 + k_1 r^2 + \dots) \frac{y}{z}$$

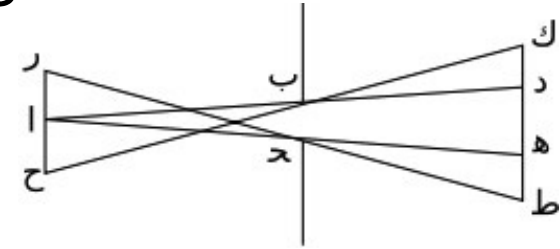
Lens Flaws: Spherical Abberation

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

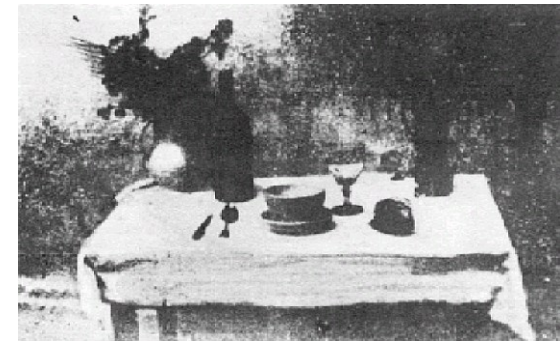


Historic milestones

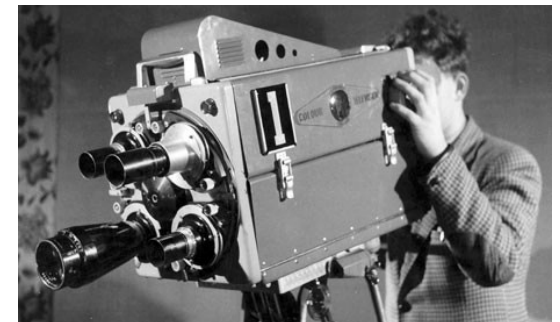
- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):** Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic 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)



Alhacen's notes



Niepce, "La Table Servie," 1822



Old television camera

First digitally scanned photograph

- 1957, 176x176 pixels



Historic Milestone

Sergey Prokudin-Gorskii (1863-1944)

Photographs of the Russian empire (1909-1916)

**Blue
Filter
(B)**



**Green
Filter
(G)**



**Red
Filter
(R)**



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

