Intro & Cameras

EECS 442 – David Fouhey

Winter 2022, University of Michigan

https://web.eecs.umich.edu/~fouhey/teaching/EECS442_W22/

Goals of Computer Vision

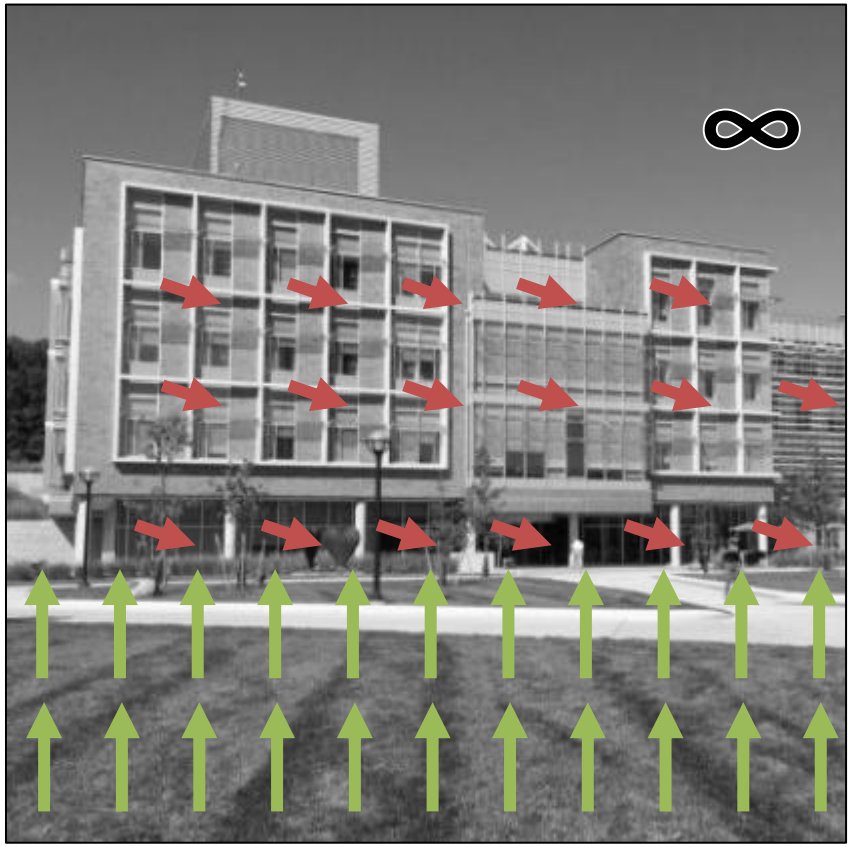
Get a computer to understand

Goal: Naming

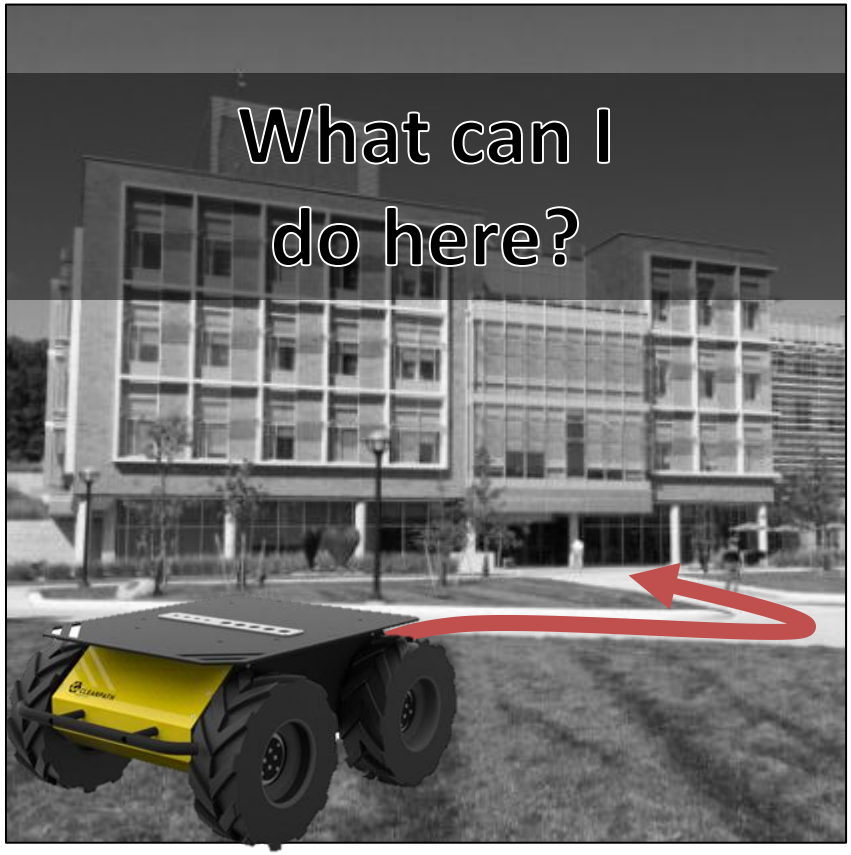
Goal: Naming

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



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?

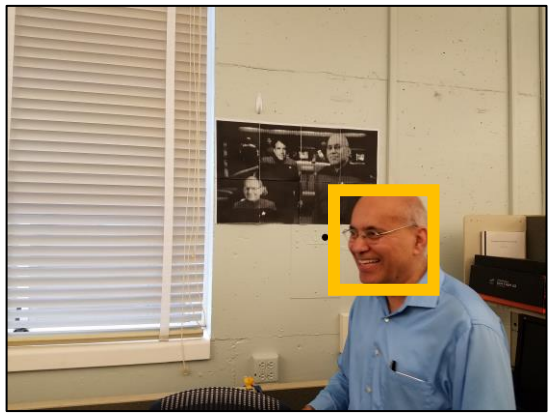
Why is it Hard?

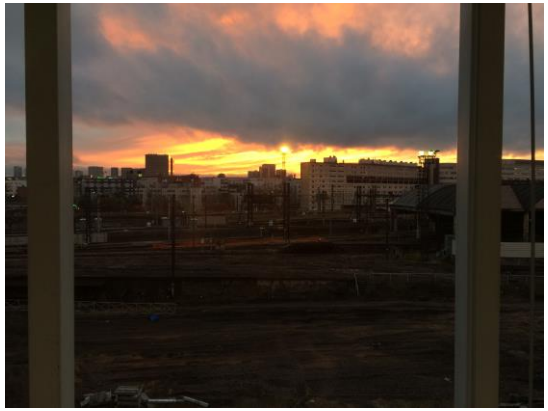
097	097	097	097	097	097	097	097	096	097	097	096	096	096
100	100	100	100	100	100	101	101	102	101	100	100	100	099
105	105	105	105	105	105	105	103	102	102	101	103	104	105
109	109	109	109	109	110	107	118	145	132	120	112	106	103
113	113	113	112	112	113	110	129	160	160	164	162	157	151
118	117	118	123	119	118	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

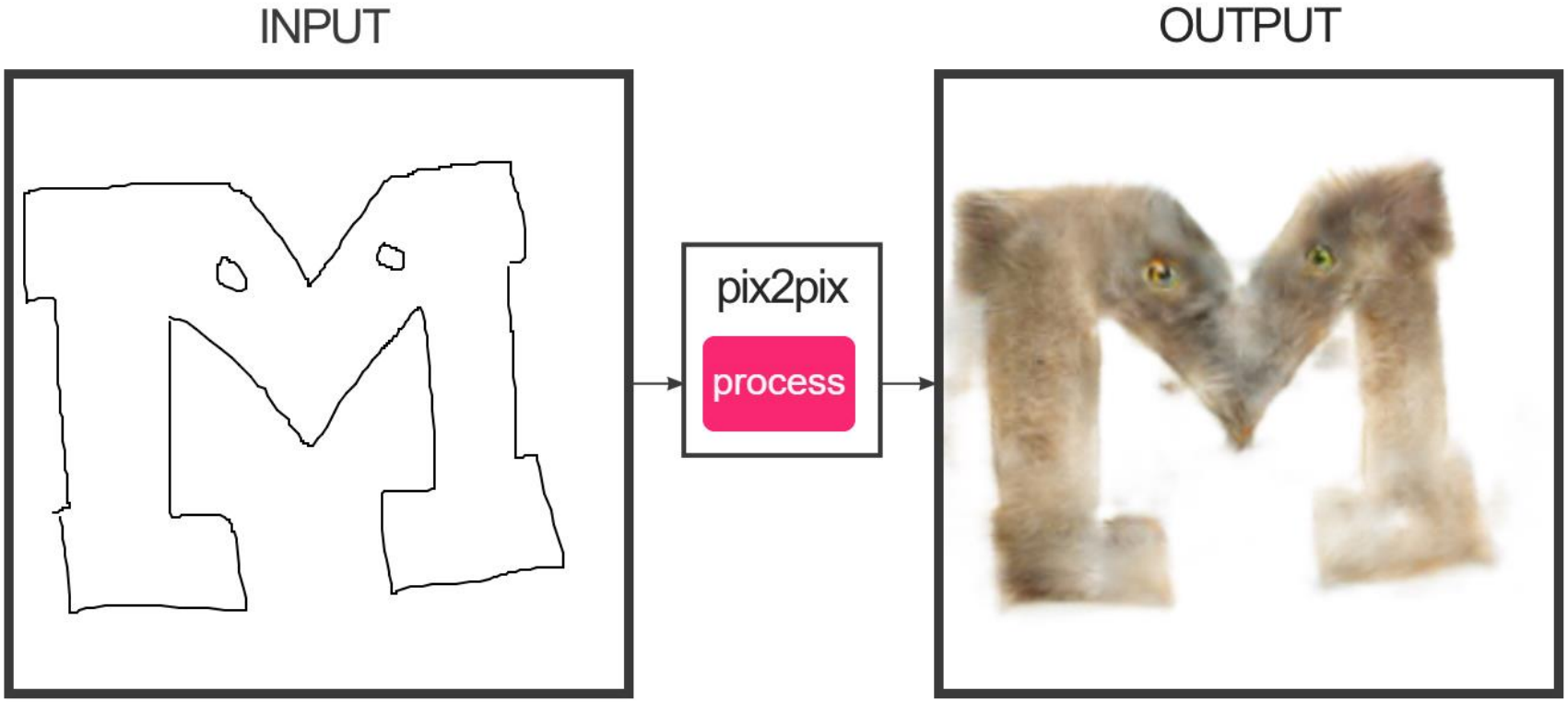




Iphone Image Credit: arstechnica.net

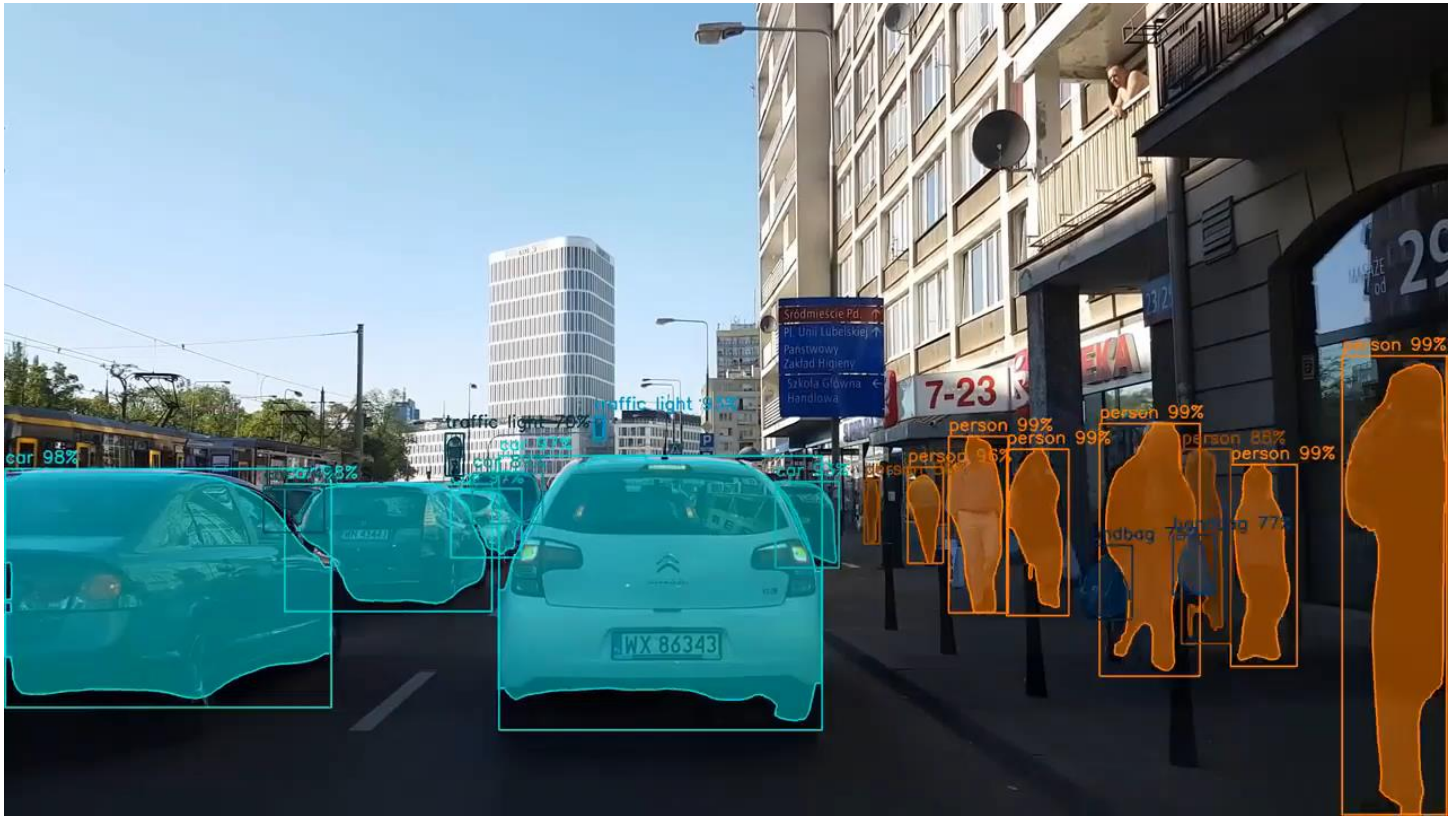
Graphics

https://affinelayer.com/pixsrv/



Isola et al. *Image-to-Image Translation with Conditional Adversarial Networks*. CVPR 2017

Recognition



He et al. *Mask RCNN*. ICCV 2017.
Video Credit: Karol Majek (https://www.youtube.com/watch?v=OOT3UIXZztE)

3D

Agarwal et al. *Building Rome In A Day*. ICCV 2009.

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://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. <u>Assume you will need these</u>
- Exceptions only for exceptional circumstances. Contact us.

Copying

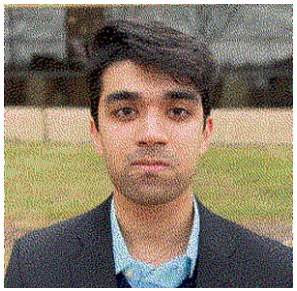
- Read the syllabus – don't look at peoples' code, no pair programming
- We will run MOSS
- Submit it late (*that's why we have late days*), half-working (*that's why we have partial credit*), or take the zero on the homework – I guarantee you won't care about one bad homework in a year
- If you're overwhelmed,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

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

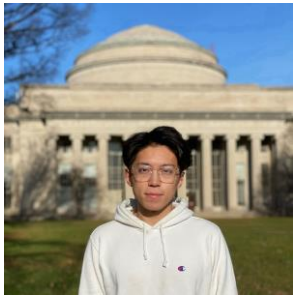
+1 on finding people to work with. It made the class much more enjoyable. – Jacob Skwirsk

Don’t have friends in the class?

We’ll introduce you to people (stay tuned)

Doing Well in 442 – 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

R

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.

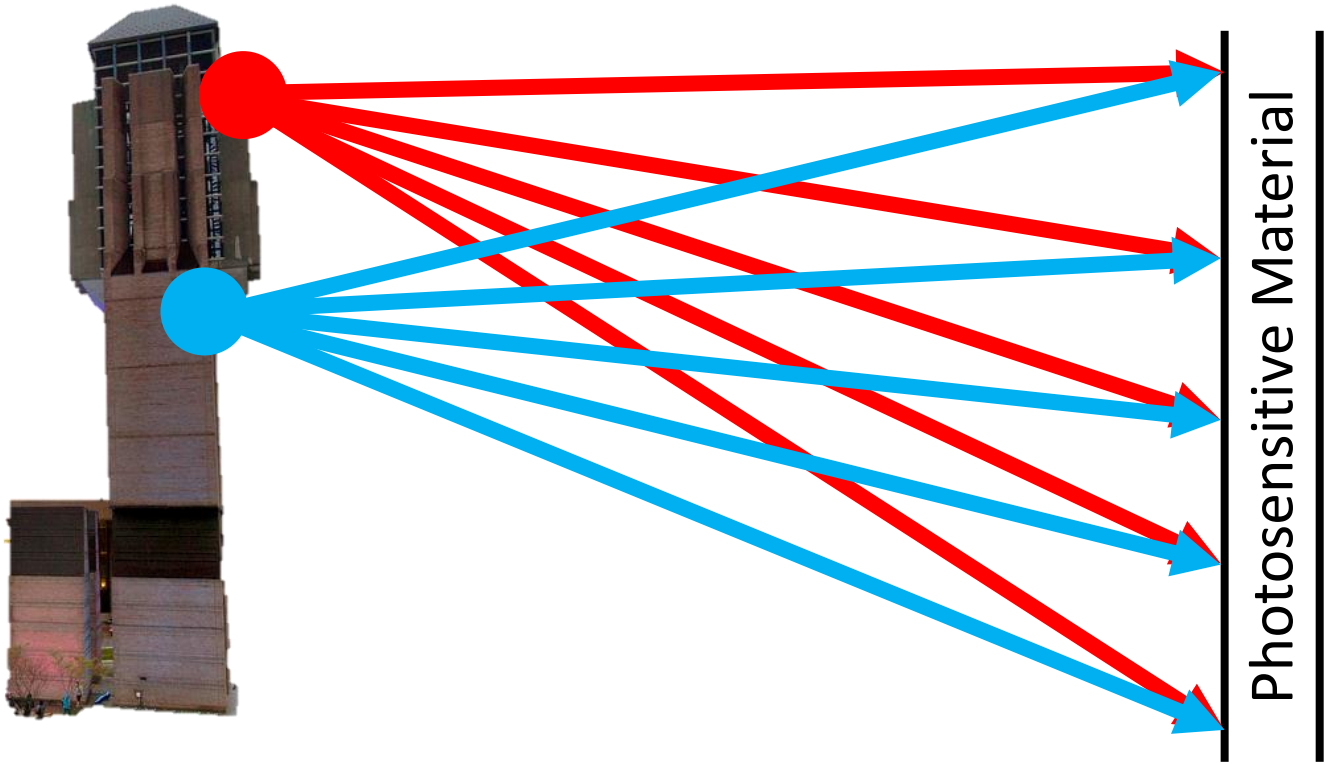
We'll give you ideas and have more info

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!

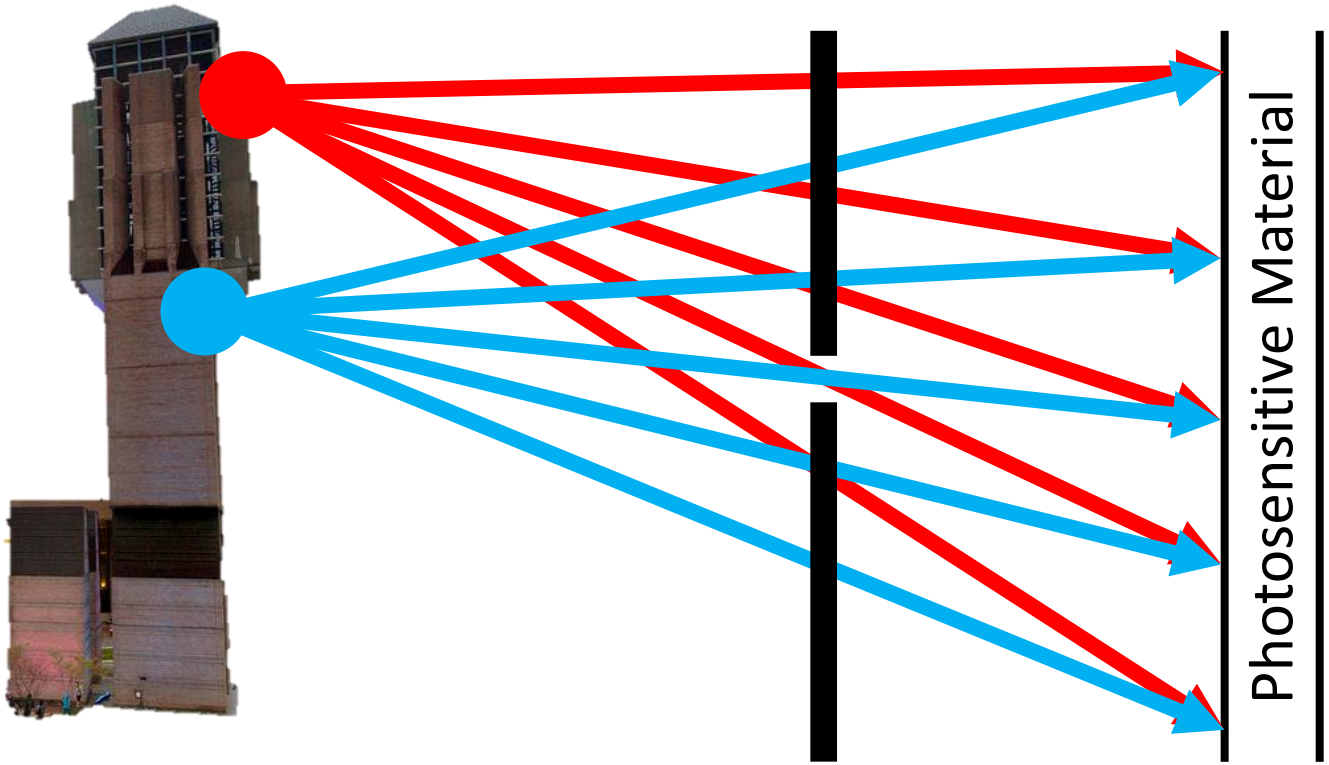


Idea 1: Just use film

Result: **Junk**

Slide inspired by S. Seitz; image from Michigan Engineering

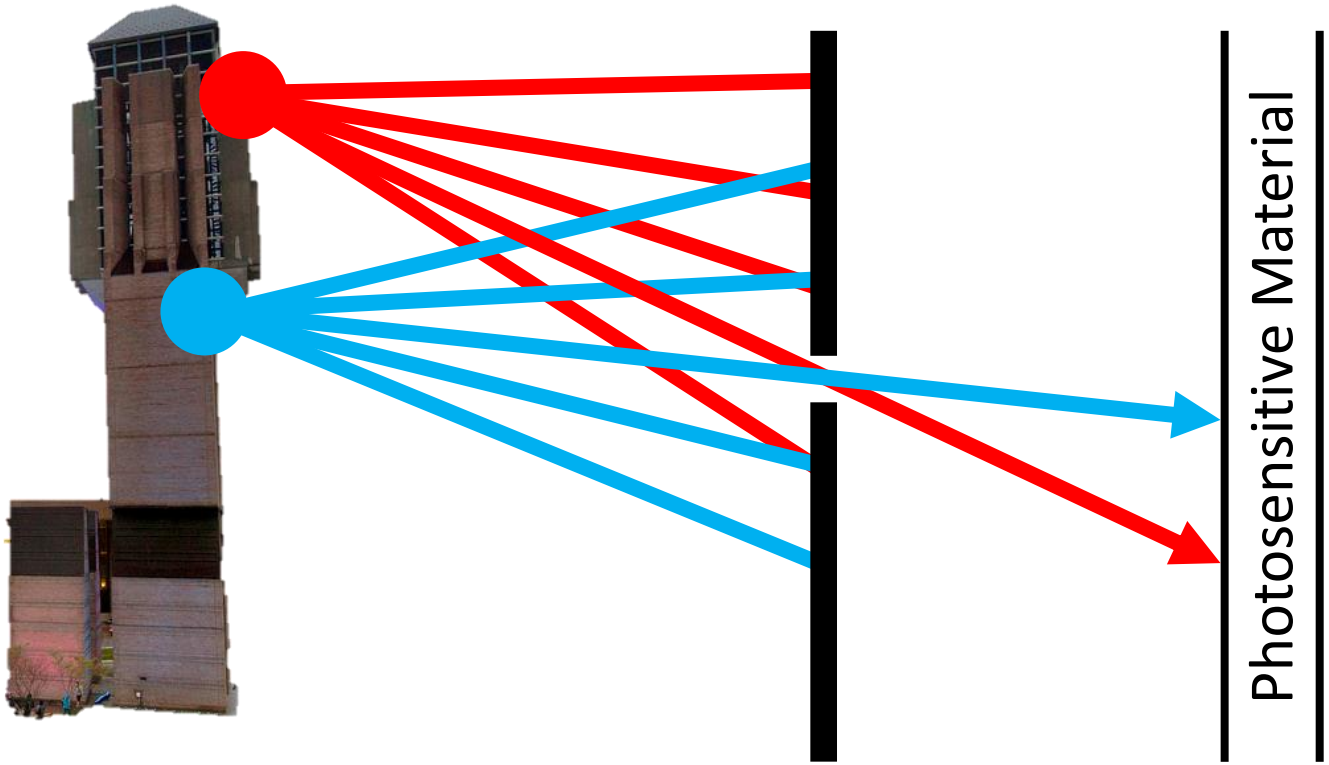
Let’s Take a Picture!



Idea 2: add a barrier

Slide inspired by S. Seitz; image from Michigan Engineering

Let’s Take a Picture!



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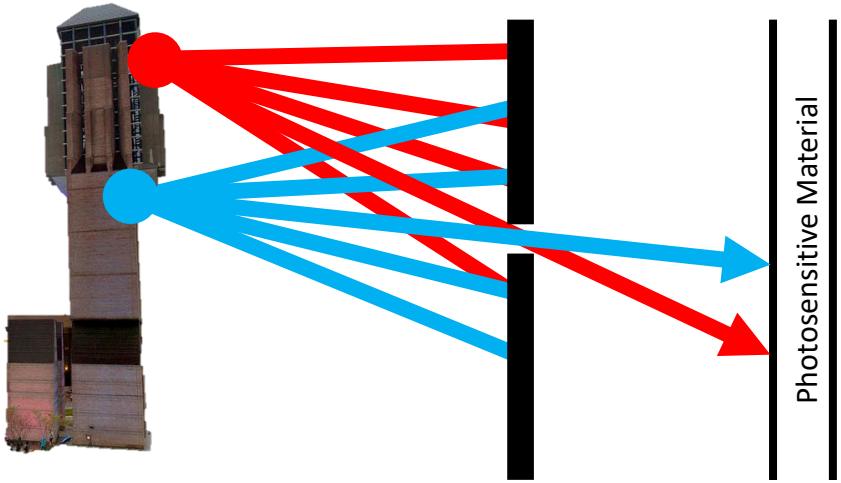
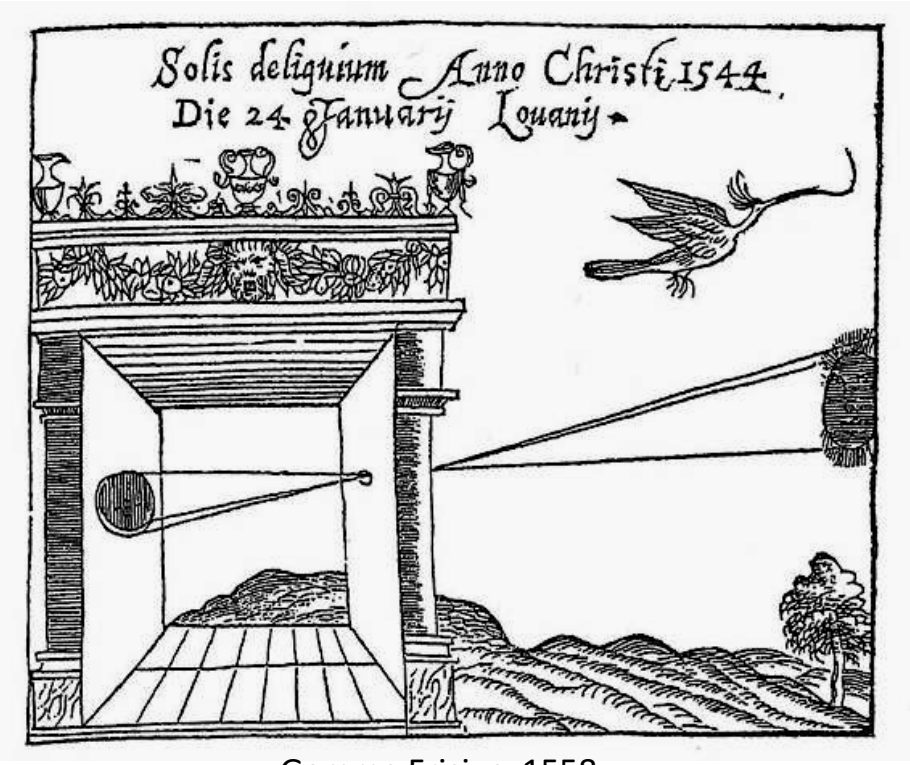


Film captures all the rays going through a point (a p*encil of rays).*

Result: good in theory!

Slide inspired by S. Seitz; image from Michigan Engineering

Camera Obscura

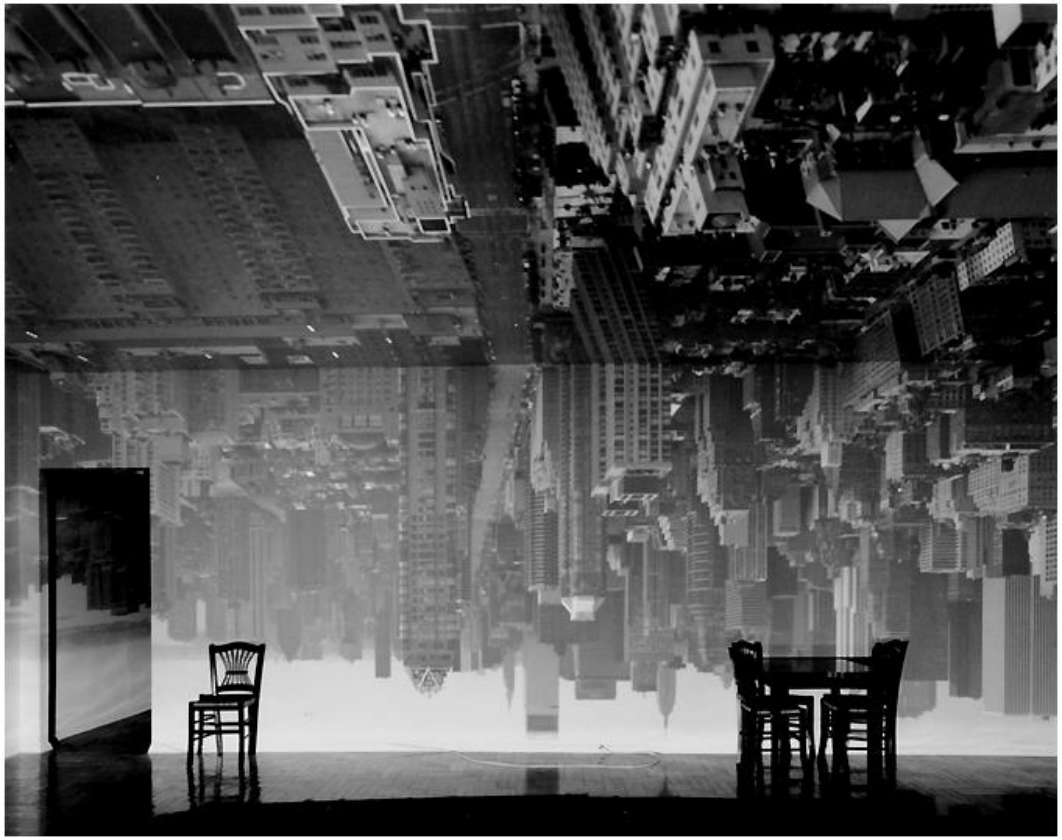


Gemma Frisius, 1558

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

Source: A. Efros

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.

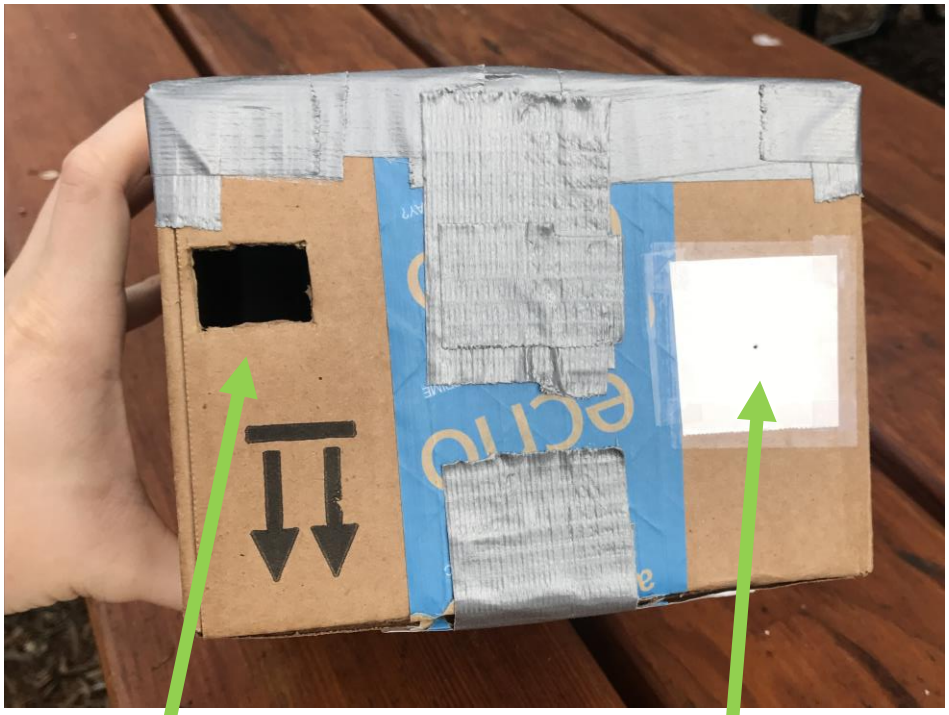
After he's done inside, it gets harder. "I leave the room and I am constantly checking the weather, I'm hoping the maid reads my note not to come in, I'm worrying that the sun will hit the plastic masking and it will fall down, or that I didn't trigger the lens."

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

Abelardomorell.com (now gone ☹)

Camera Obscura

Useful for viewing solar eclipses!



Put your eye here

Pinhole: aluminum foil with a tiny hole

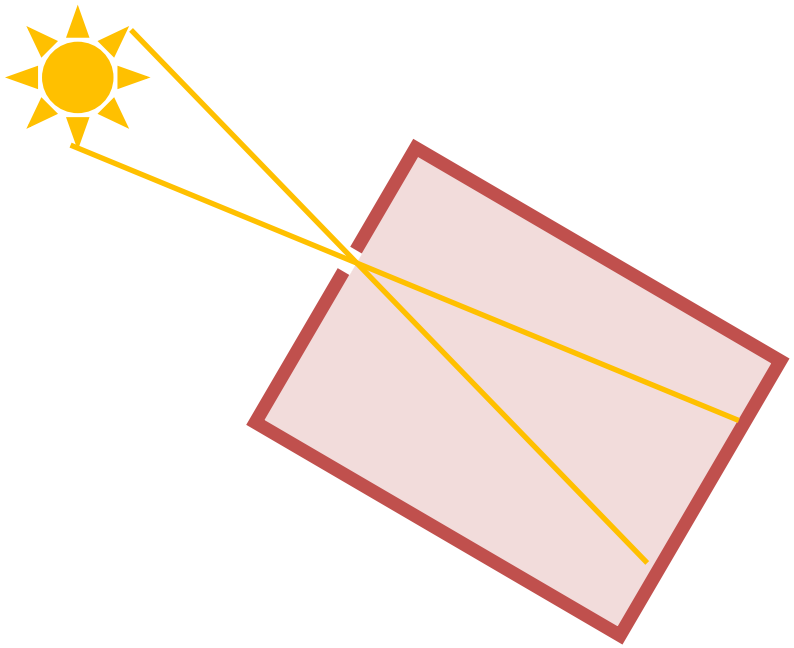


Photo Credit: Justin Johnson

Camera Obscura

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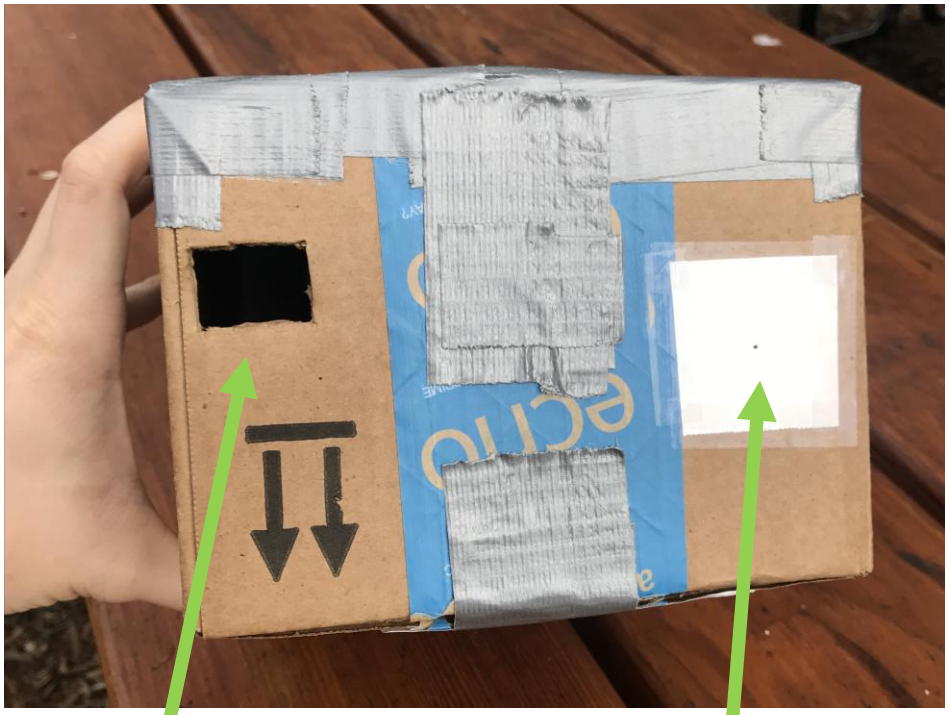

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Justin on 8/21/2017

Photo Credit: Justin Johnson

Camera Obscura

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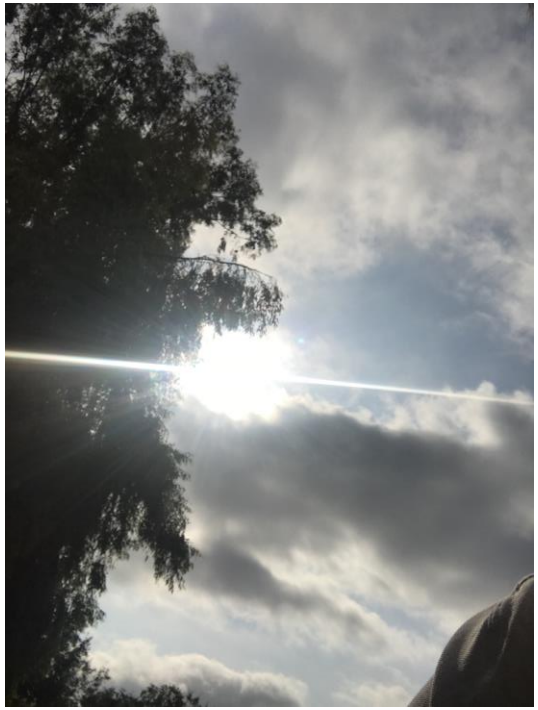


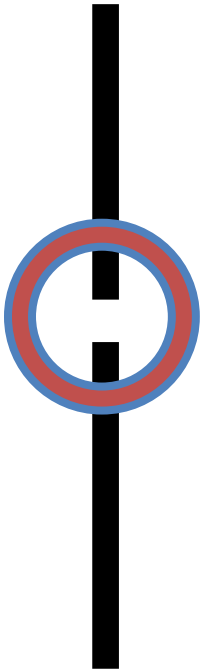
Photo of the sun

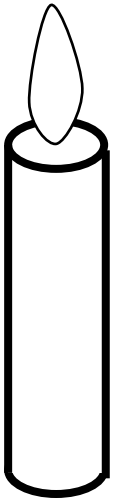
View in the box

Justin on 8/21/2017

Photo Credit: Justin Johnson

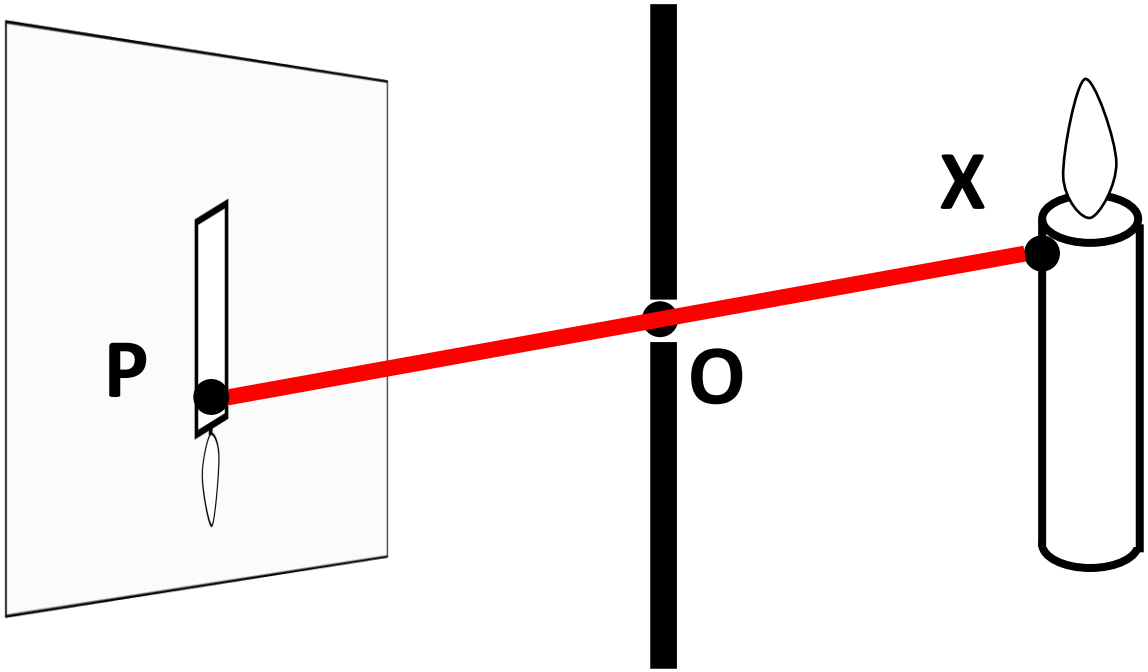
Projection





Source: L Lazebnik

Projection

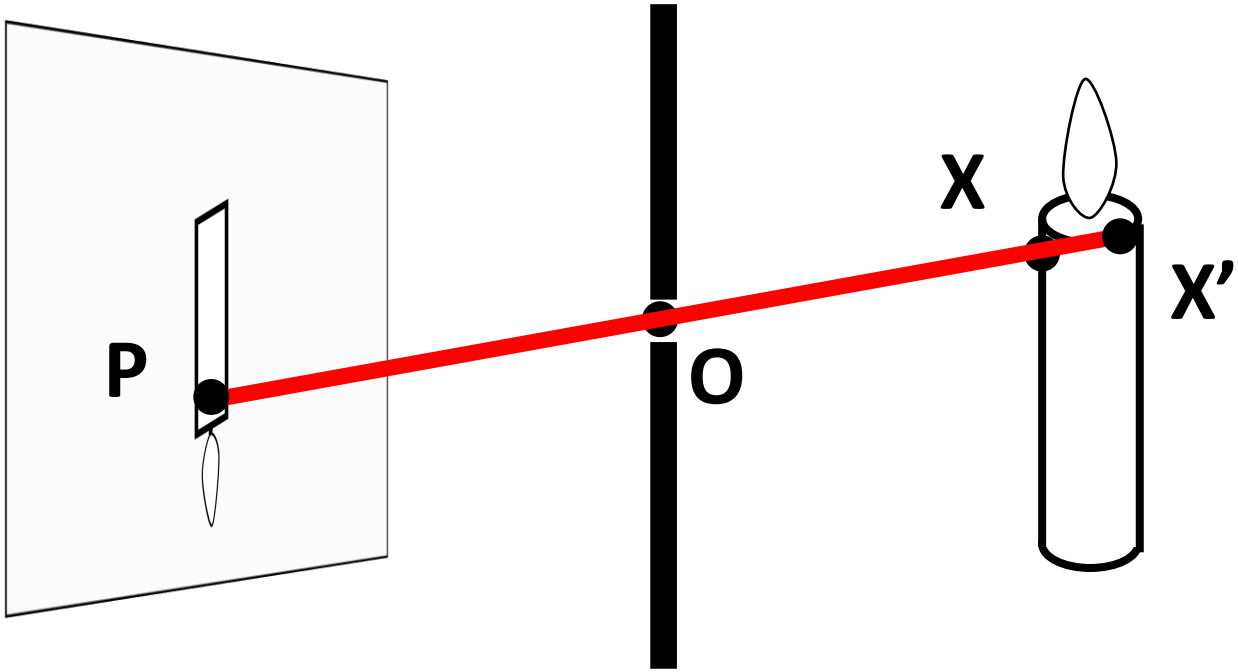


How do we find the projection P of a point X?

Form visual ray from X to camera center and intersect it with camera plane

Source: L Lazebnik

Projection

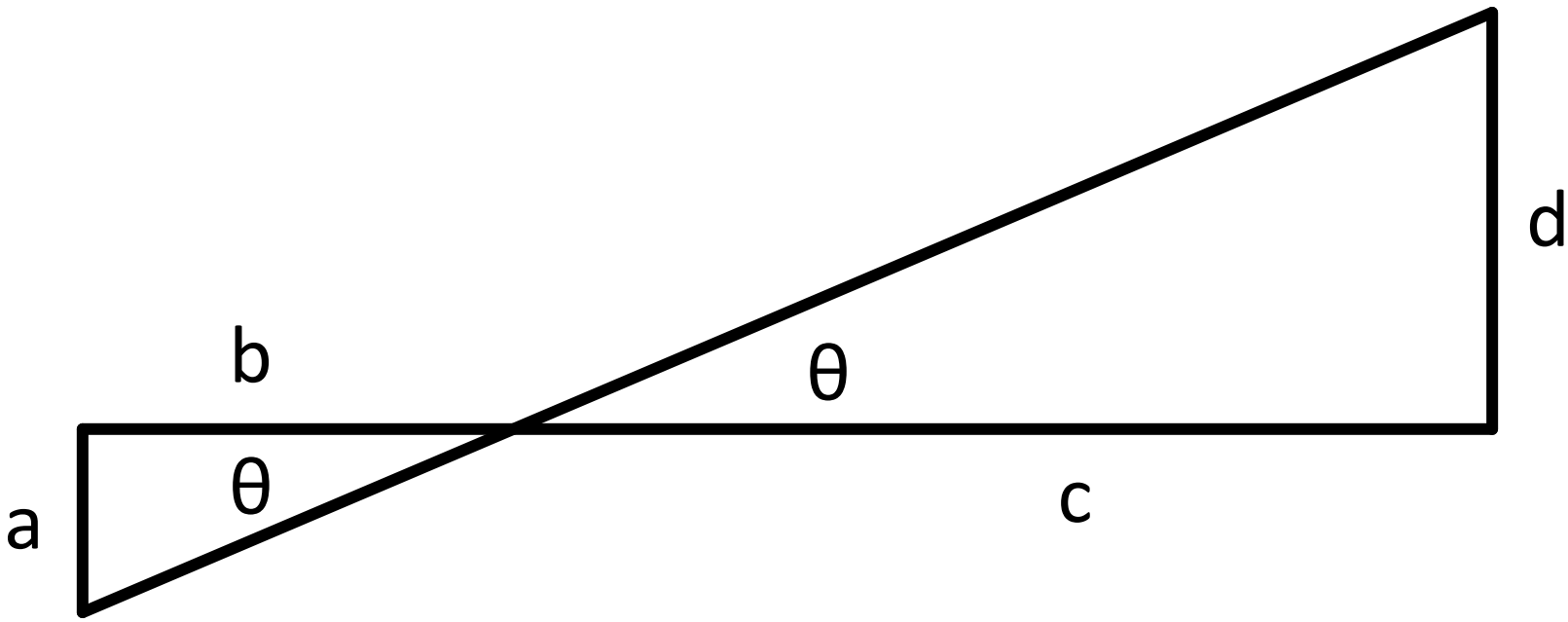


Both X and X' project to P. Which appears in the image?

Are there points for which projection is undefined?

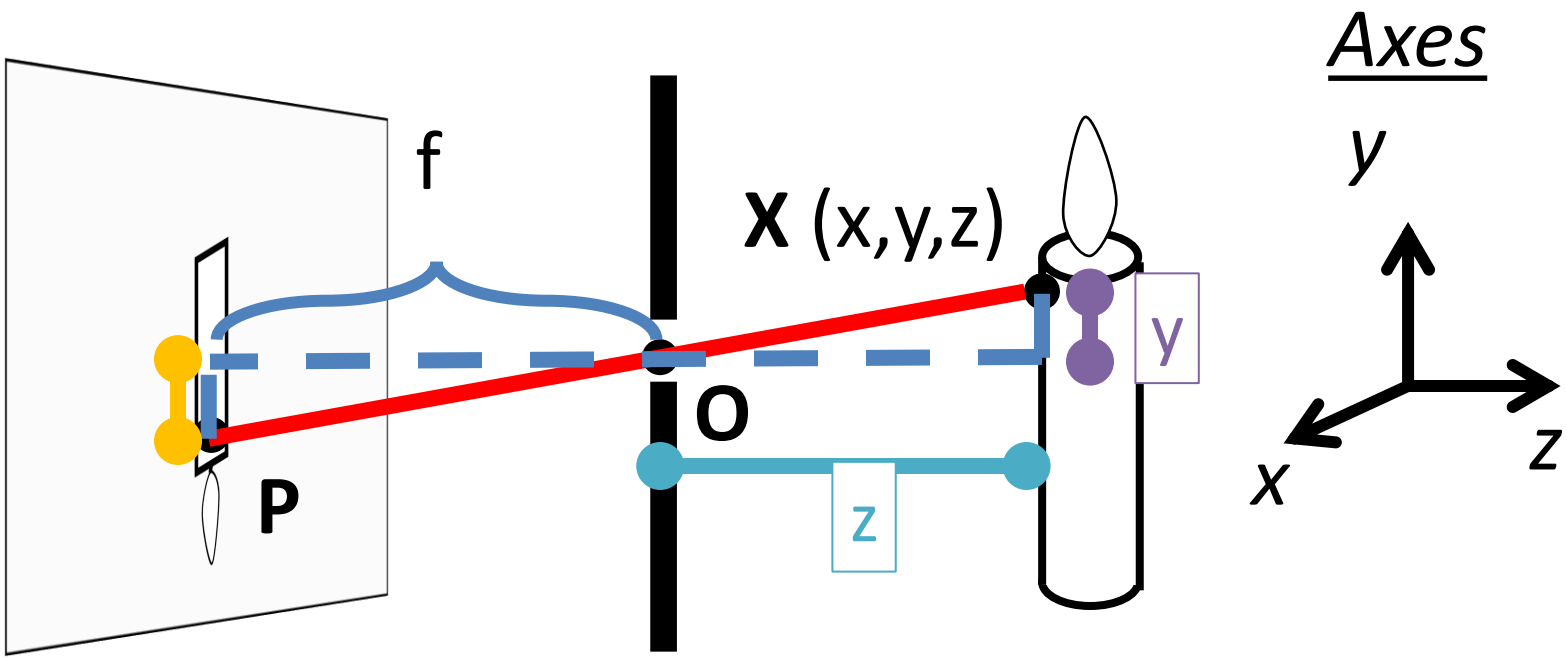
Source: L Lazebnik

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

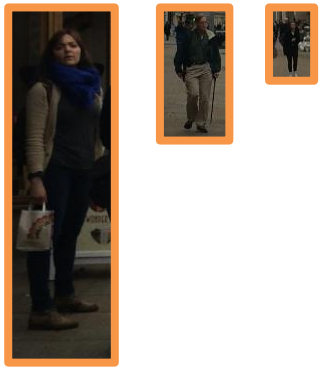
Source: L Lazebnik

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

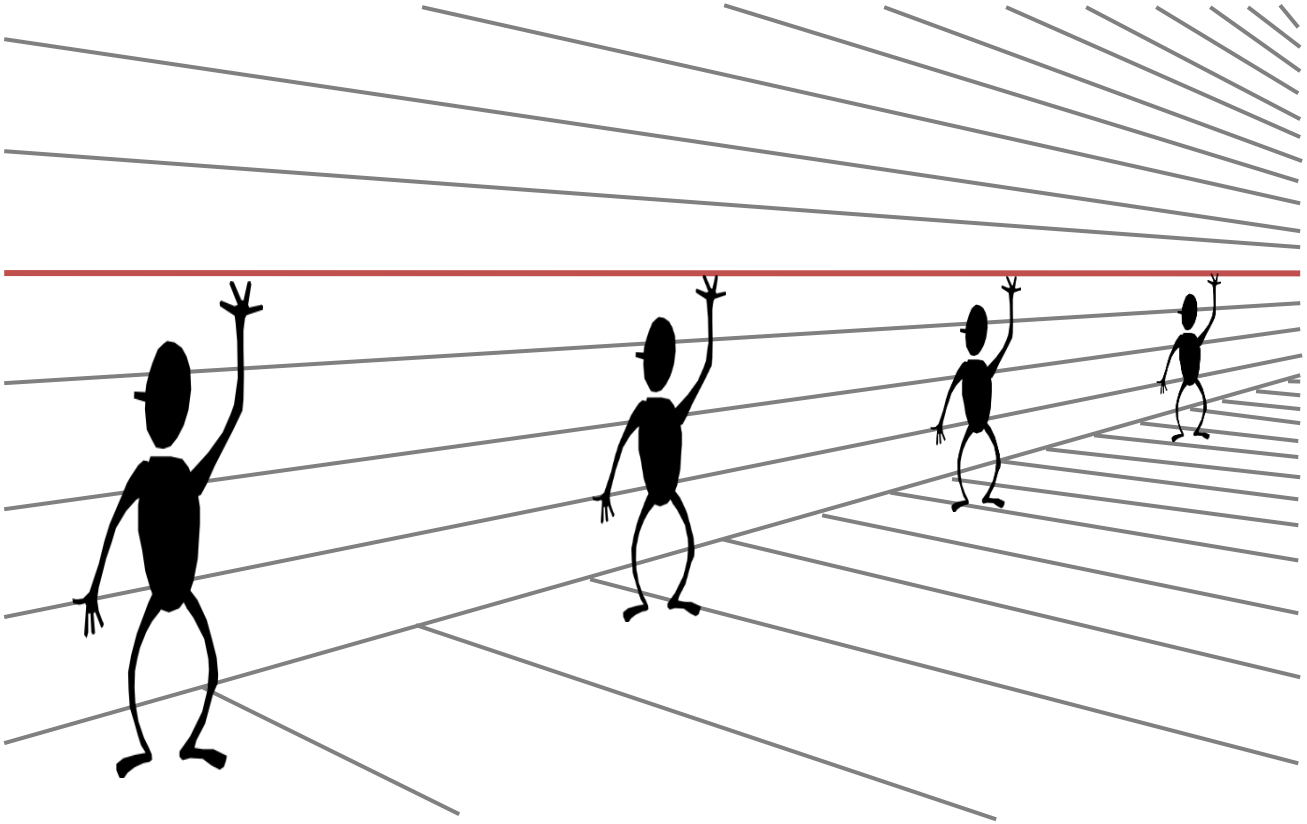


List of properties from M. Hebert

Some Facts About Projection

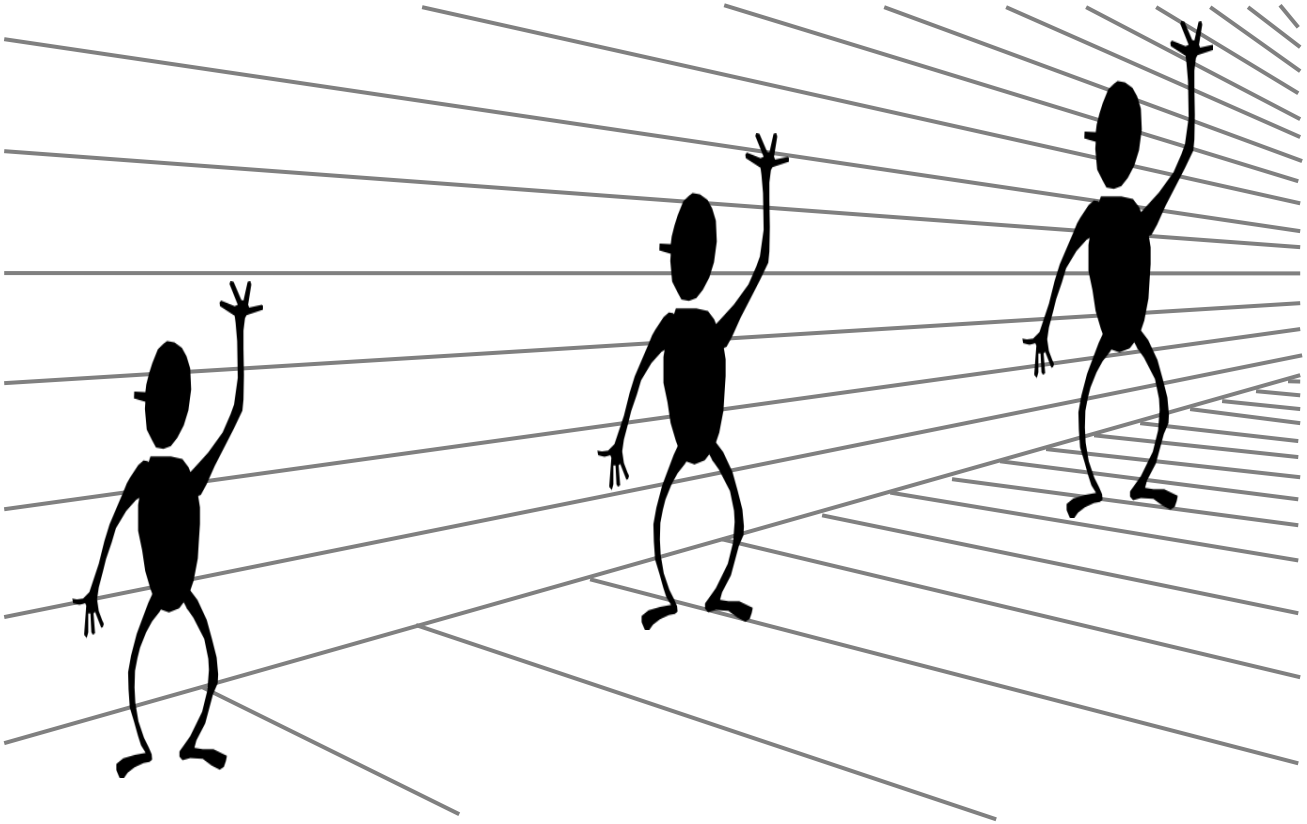
Let’s try some fake images

Some Facts About Projection



Slide by Steve Seitz

Some Facts About Projection



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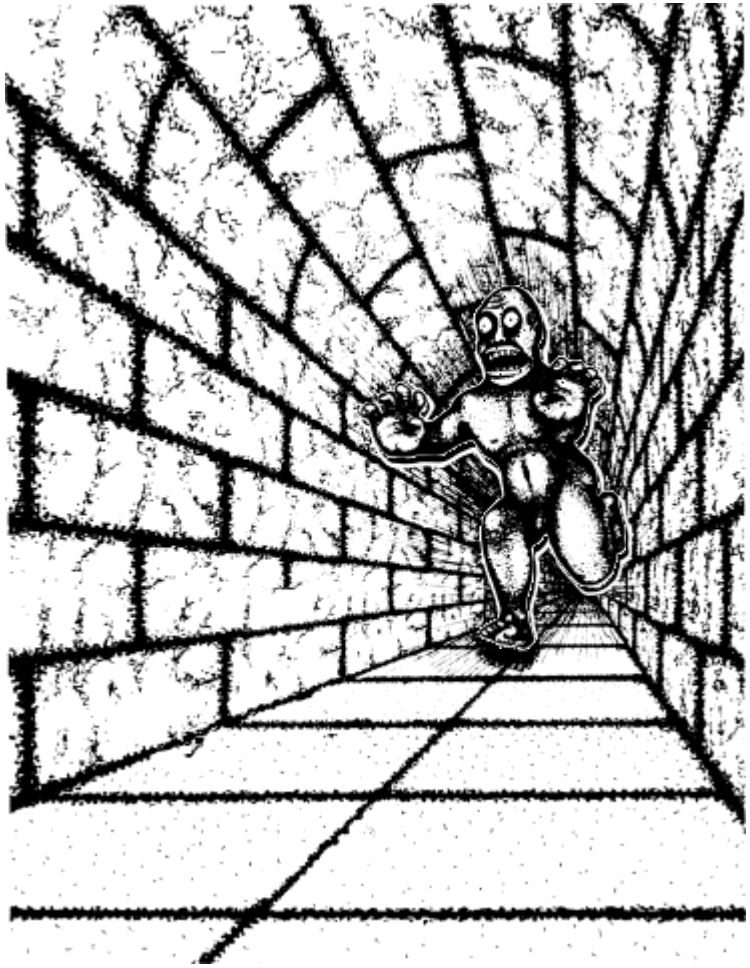
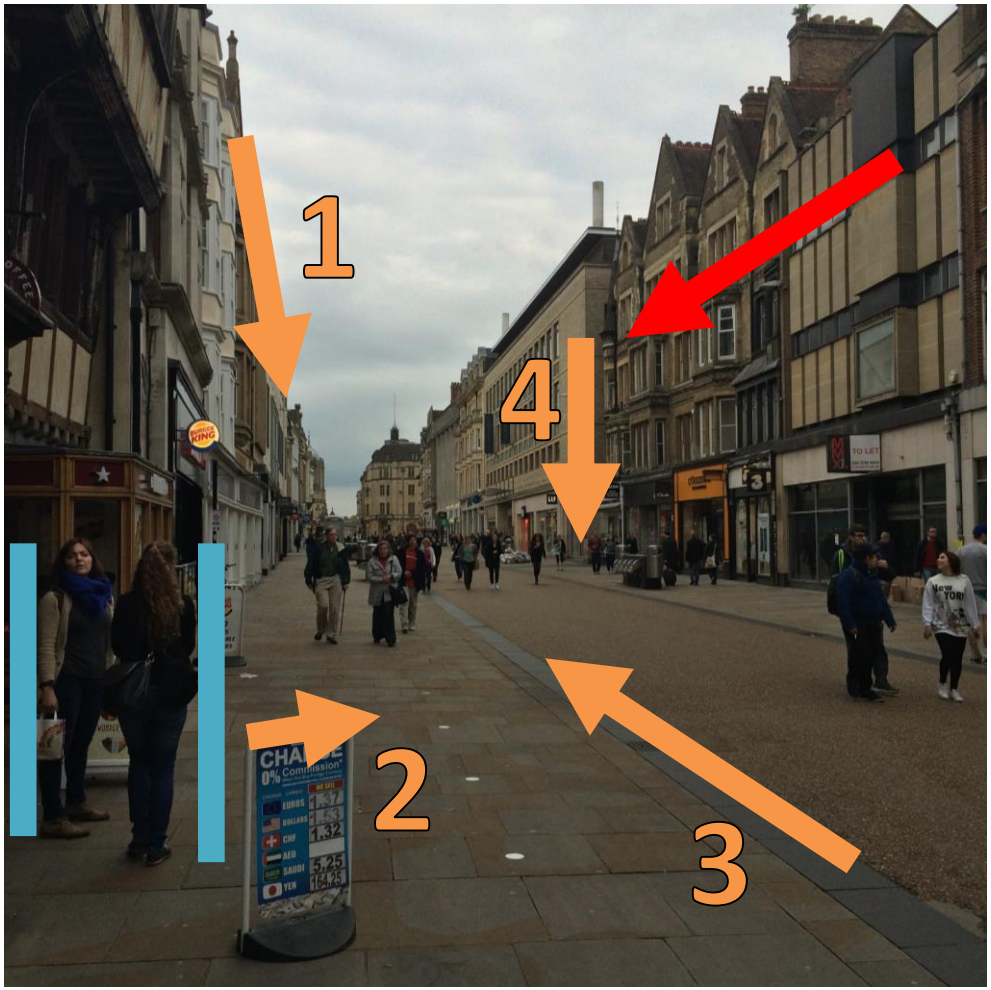


Illusion Credit: RN Shepard, Mind Sights: Original Visual Illusions, Ambiguities, and other Anomalies

What's Lost?

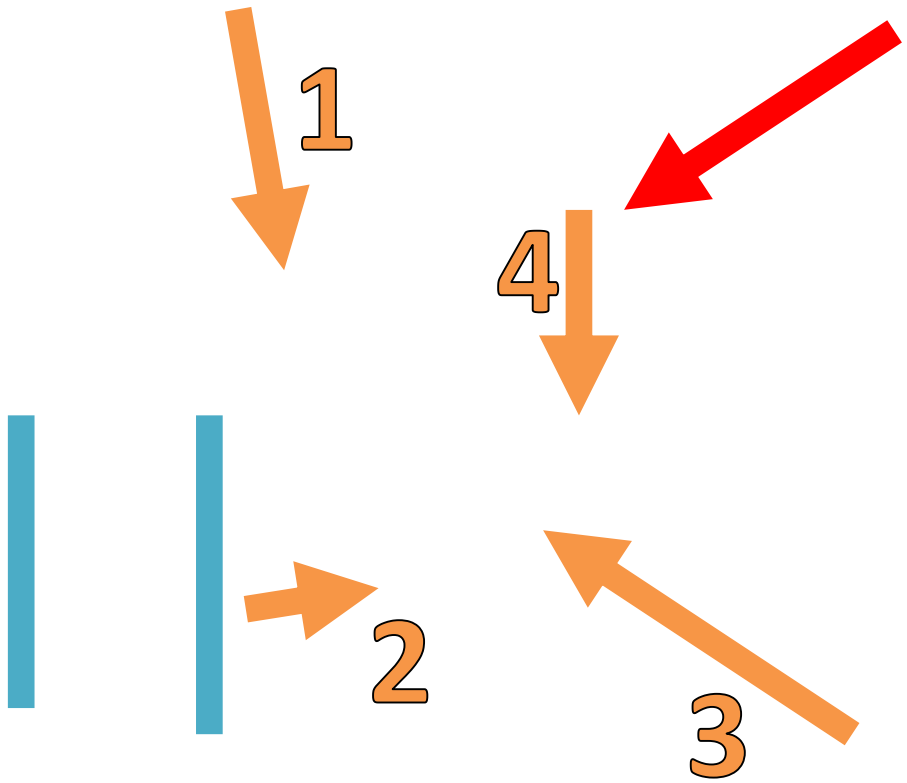


Is she shorter or further away?

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

Inspired by D. Hoiem slide

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

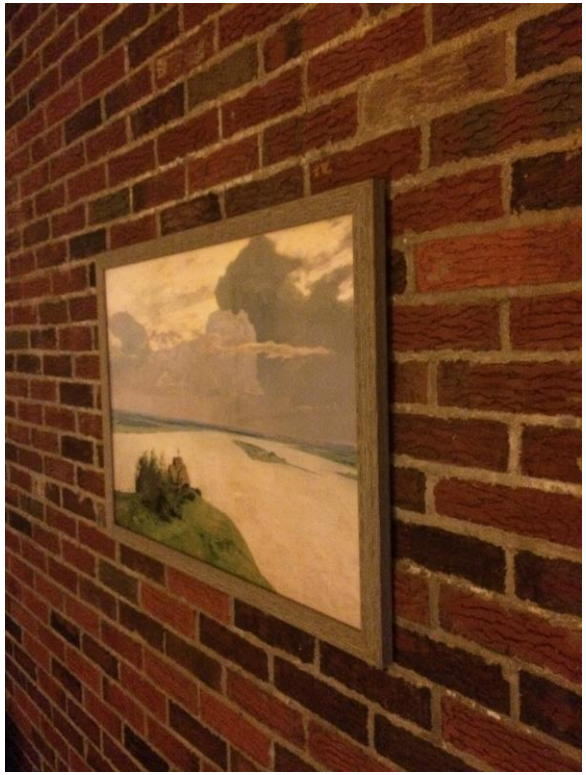
What's Lost?

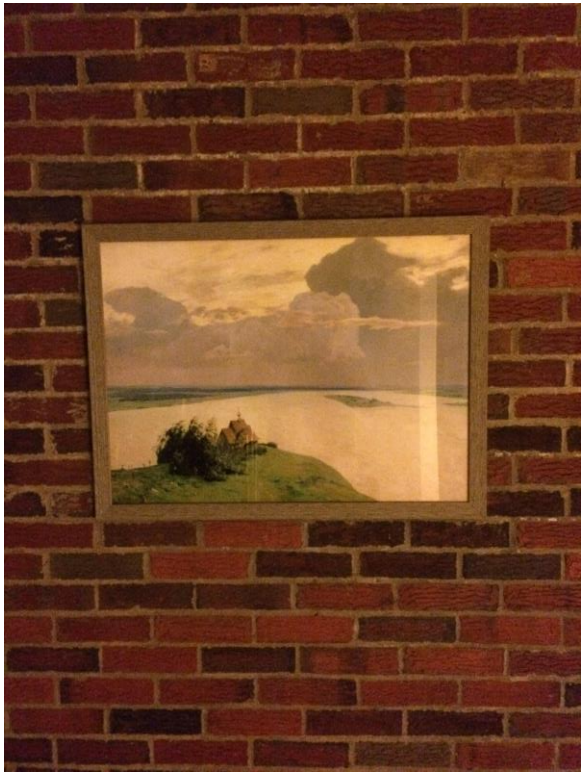
Be careful of drawing conclusions:

- 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)?**

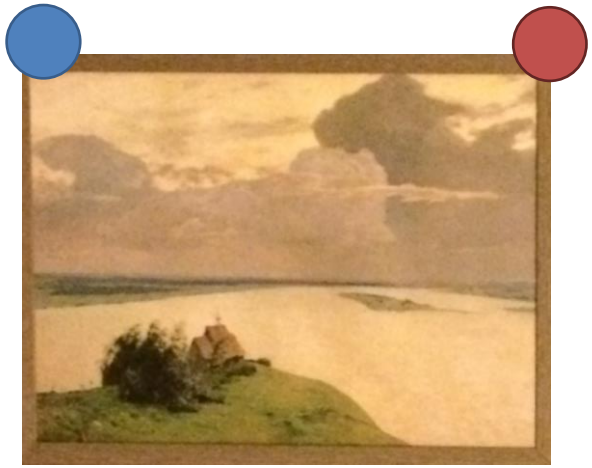
- Projections of parallel 3D lines converge at VP; NOT any pair of lines that converge are parallel in 3D.
- **Can you think of a counter-example?**

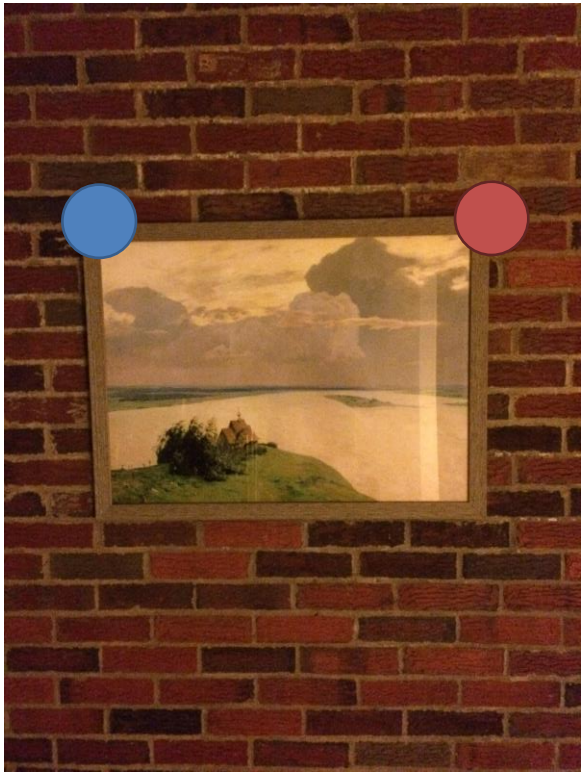
Do You Always Get Perspective?





Do You Always Get Perspective?



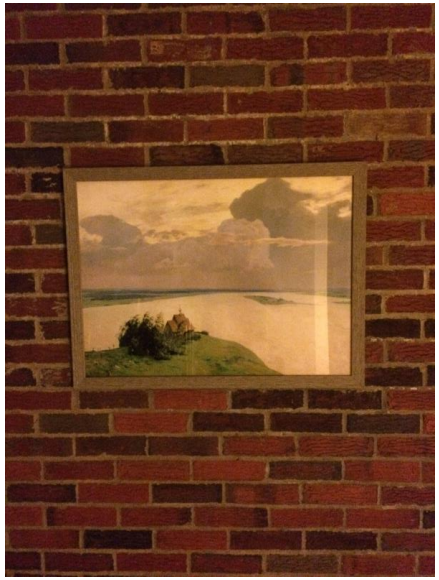


Y location of blue and red dots in image:

$$\frac{fy}{z_2} \qquad \frac{fy}{z_1}$$

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

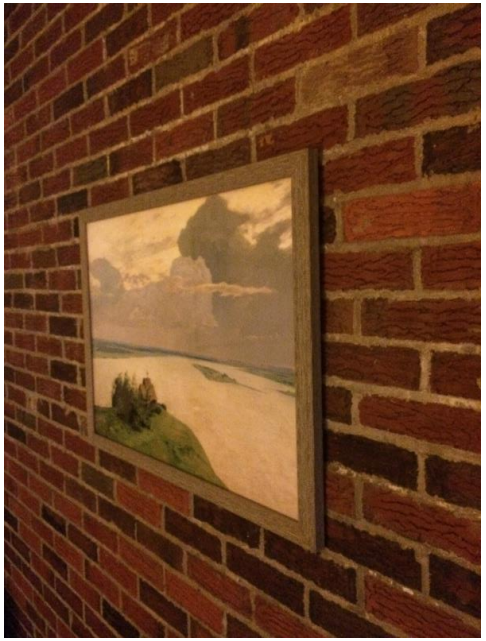
Do You Always Get Perspective?

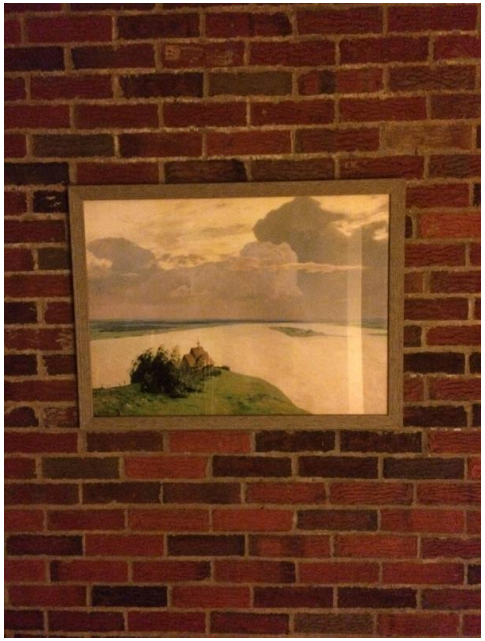


When plane is fronto-parallel (parallel to camera plane), everything is:

- scaled by f/z
- otherwise is preserved.

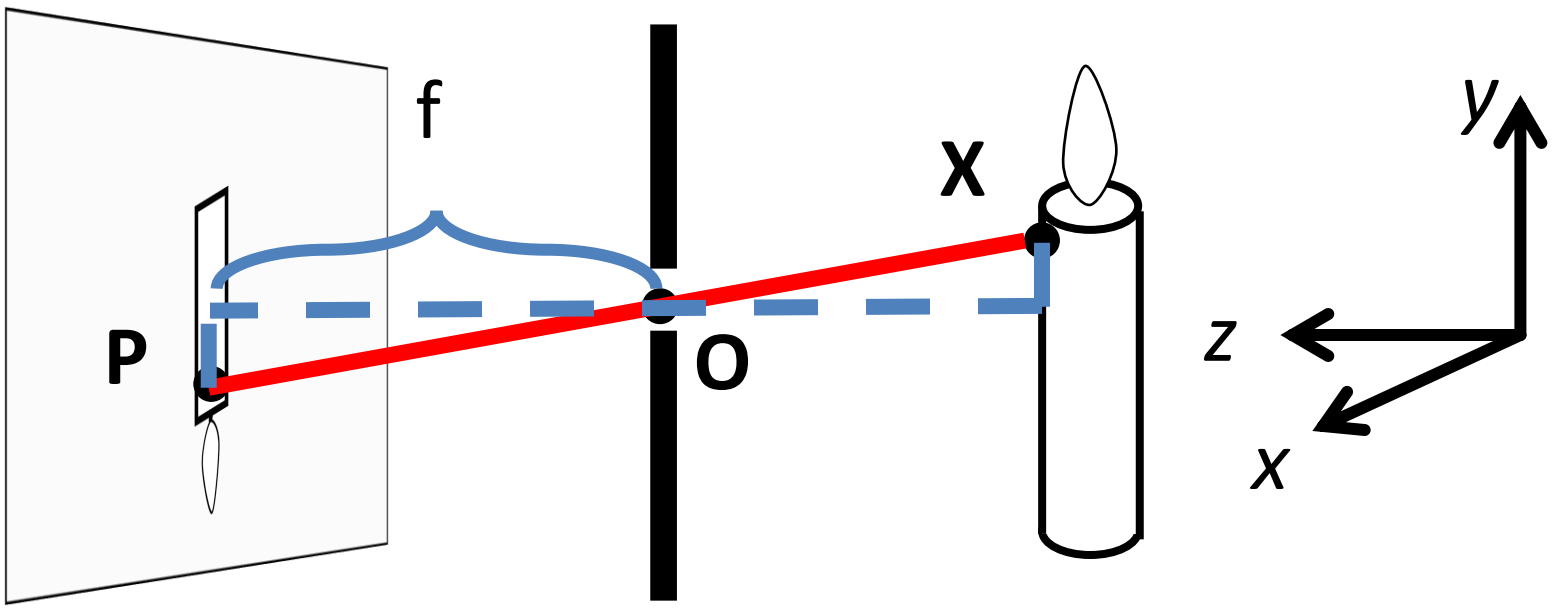
What’s This Useful For?





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)

Adapted from S. Seitz slide

Homogeneous Coordinates (2D)

Trick: add a dimension!

This also clears up lots of nasty special cases

Physical Point		Homogeneous Point		Physical Point
$\begin{bmatrix} x \\ y \end{bmatrix}$	$\xrightarrow[\text{w=1}]{\text{Concat}}$	$\begin{bmatrix} u \\ v \\ w \end{bmatrix}$	$\xrightarrow[\text{by w}]{\text{Divide}}$	$\begin{bmatrix} u/w \\ v/w \end{bmatrix}$

What if w = 0?

Adapted from M. Hebert slide

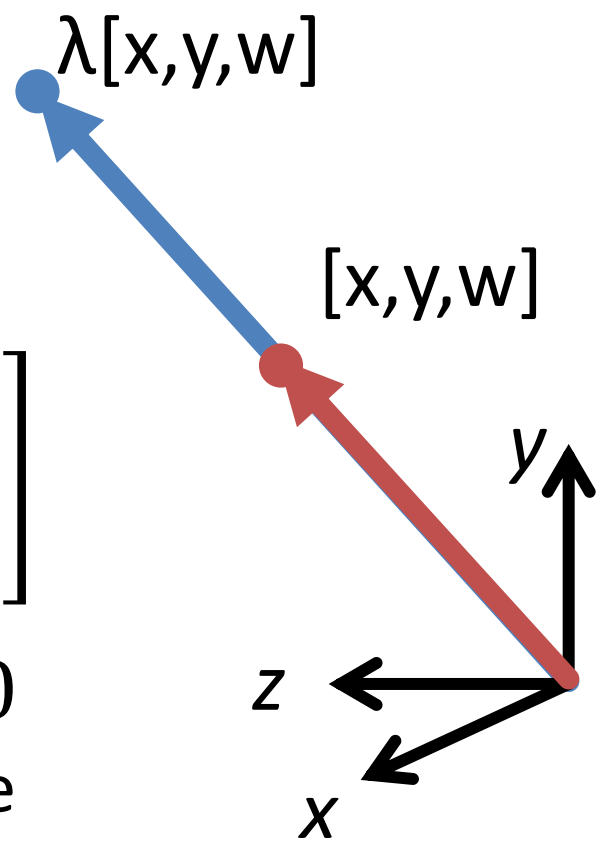
Homogeneous Coordinates

Triple / Equivalent

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} \boxed{\equiv} \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} \quad \leftrightarrow \quad \begin{bmatrix} u \\ v \\ w \end{bmatrix} \boxed{=} \lambda \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix}$$

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

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

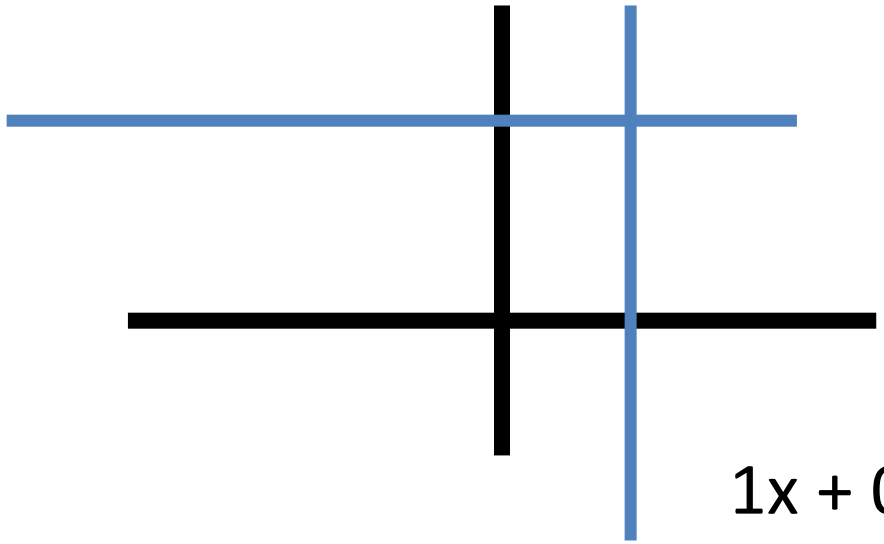
Slide from M. Hebert

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** x **m**
  - Line through two points **p** and **q**: **p** x **q**
  - Point **p** on line **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?



$0x + 1y - 2 = 0$

$1x + 0y - 1 = 0$

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

Converting back (divide by -1)

$(1,2)$

Benefits of Homogeneous Coords

$0x + 1y - 3 = 0$

$0x + 1y - 2 = 0$

$0x + 1y - 1 = 0$

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

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

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

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

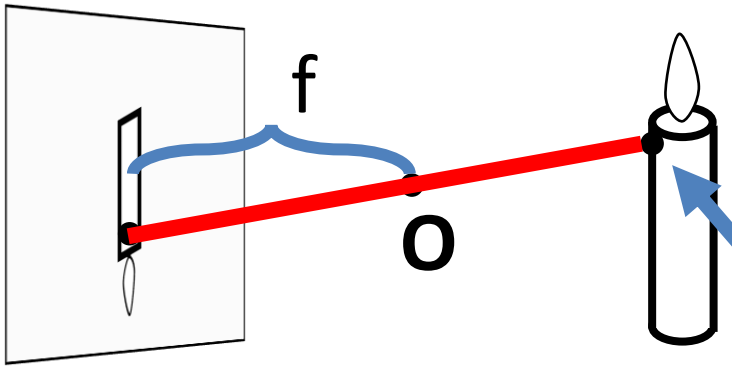
3D Homogeneous Coordinates

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

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

Projection Matrix

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

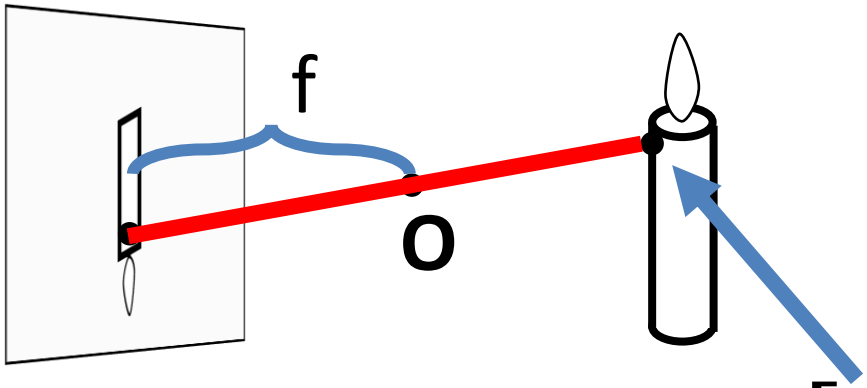


$$\begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Slide inspired from L. Lazebnik

Projection Matrix

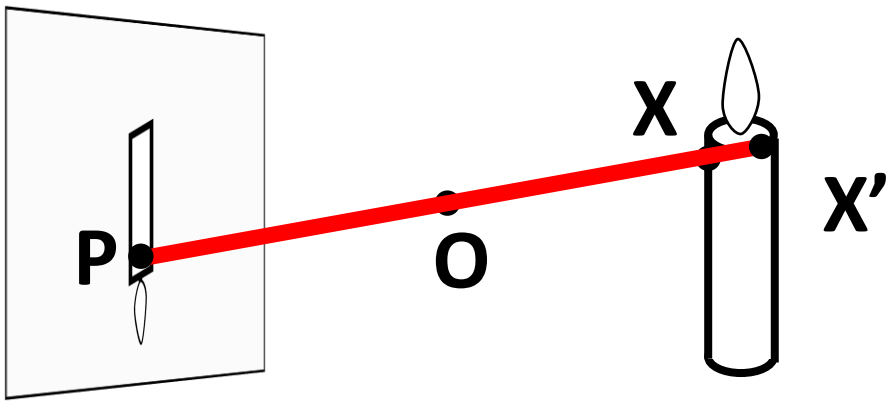
Projection (fx/z, fy/z) is matrix multiplication



$$\begin{bmatrix} fx \\ fy \\ z \end{bmatrix} \equiv \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \rightarrow \begin{bmatrix} fx/z \\ fy/z \end{bmatrix}$$

Slide inspired from L. Lazebnik

Why ≡ ≠ =



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)

X: 3d homogeneous point (4D)

$\boldsymbol{P} \equiv$

$\boldsymbol{X}_{4x1}$

Typical Perspective Model

R: rotation between world system and camera

t: translation between world system and camera

$$\boldsymbol{P} \equiv \quad [\boldsymbol{R}_{3x3} \quad \boldsymbol{t}_{3x1}] \quad \boldsymbol{X}_{4x1}$$

Typical Perspective Model

f focal length

u0,v0: principal point (image coords of camera origin on retina)

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

$$[\boldsymbol{R}_{3x3} \quad \boldsymbol{t}_{3x1}] \quad \boldsymbol{X}_{4x1}$$

Typical Perspective Model

Intrinsic Matrix K **Extrinsic Matrix [R,t]**

$$\boldsymbol{P} \equiv \boxed{\begin{bmatrix} f & 0 & u_0 \\ 0 & f & v_0 \\ 0 & 0 & 1 \end{bmatrix}} \boxed{\begin{bmatrix} \boldsymbol{R}_{3x3} & \boldsymbol{t}_{3x1} \end{bmatrix}} \boldsymbol{X}_{4x1}$$

$$\boldsymbol{P} \equiv \boldsymbol{K}[\boldsymbol{R}, \boldsymbol{t}]\boldsymbol{X} \equiv \boldsymbol{M}_{3x4}\boldsymbol{X}_{4x1}$$

Other Cameras – Orthographic

Orthographic Camera (z infinite)

$$\boldsymbol{P} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \boldsymbol{X}_{3x1}$$

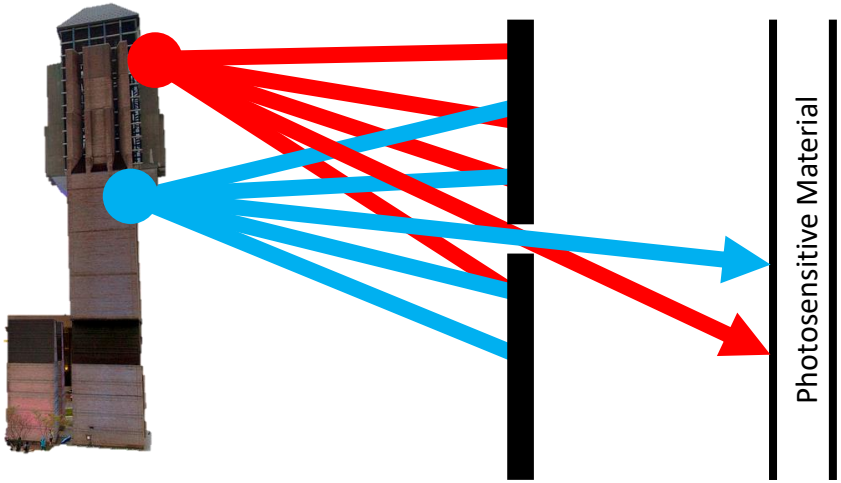
Image Credit: Wikipedia

Other Cameras – Orthographic

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

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

The Big Issue



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

How big is a point?

Slide inspired by S. Seitz; image from Michigan Engineering

Math vs. Reality

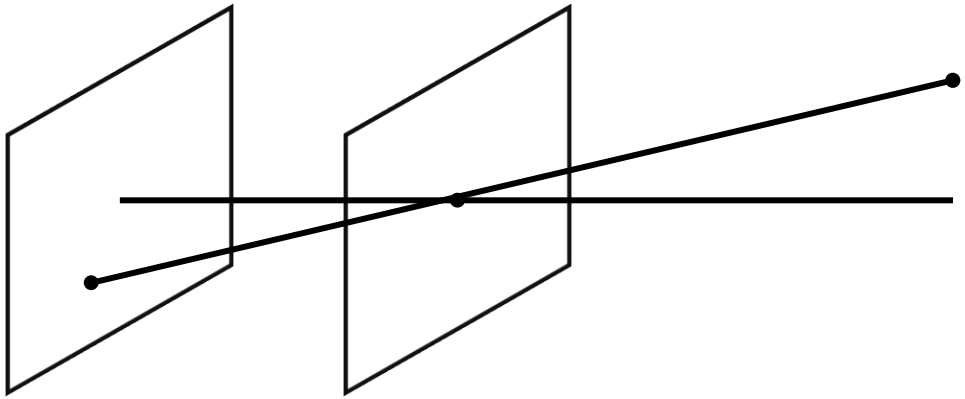
- Math: Any point projects to one point
- Reality:
  - Don’t image points behind the camera / objects
  - Don’t have an infinite amount of sensor material
- Other issues
  - Light is limited
  - Spooky stuff happens with infinitely small holes

Limitations of Pinhole Model

<u>Ideal Pinhole</u>

-1 point generates 1 image

-Low-light levels

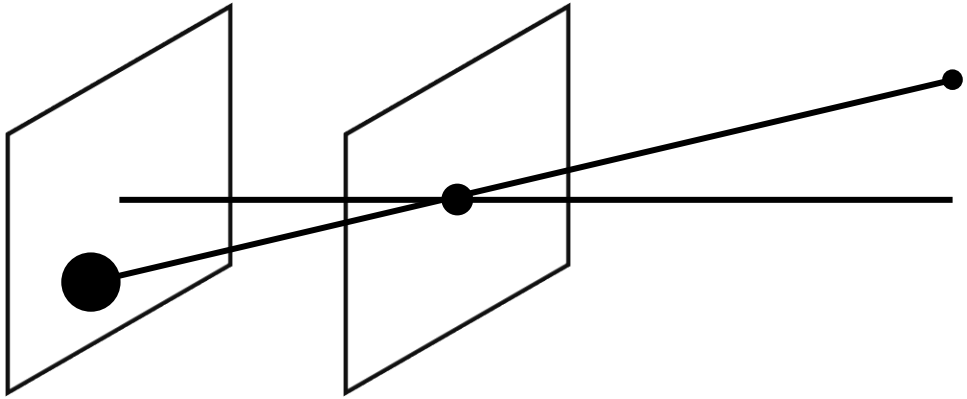


<u>Finite Pinhole</u>

-1 point generates region

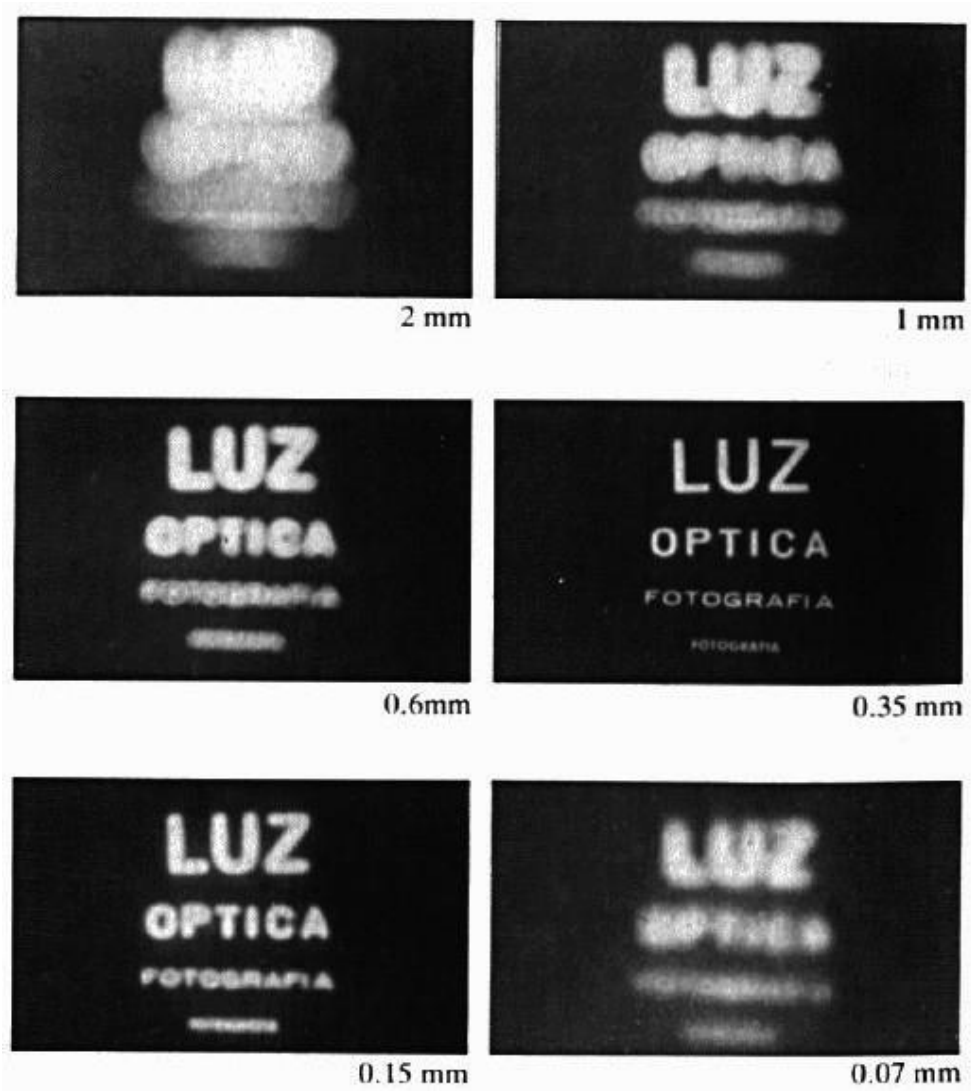
-Blurry.

Why is it blurry?



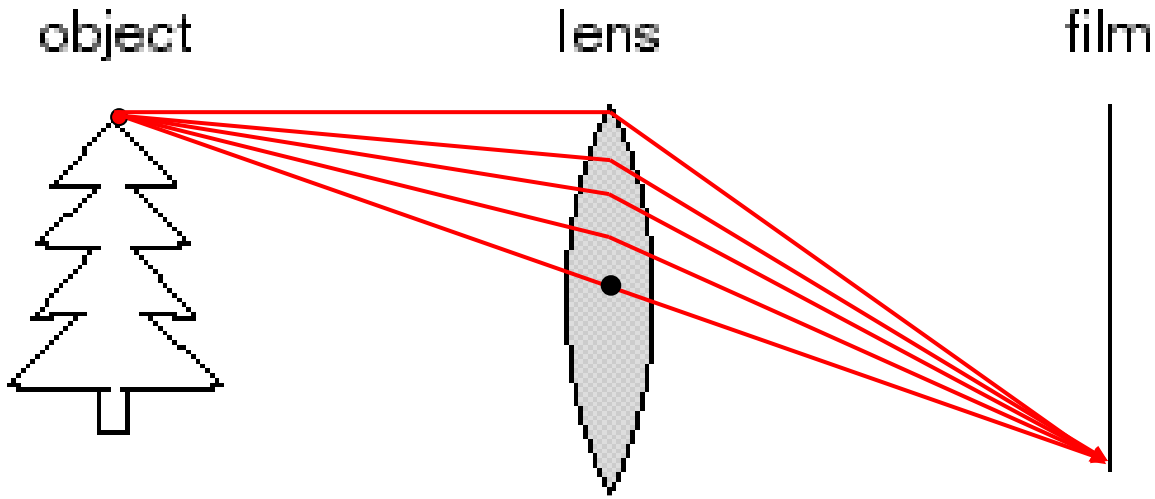
Slide inspired by M. Hebert

Limitations of Pinhole Model



Slide Credit: S. Seitz

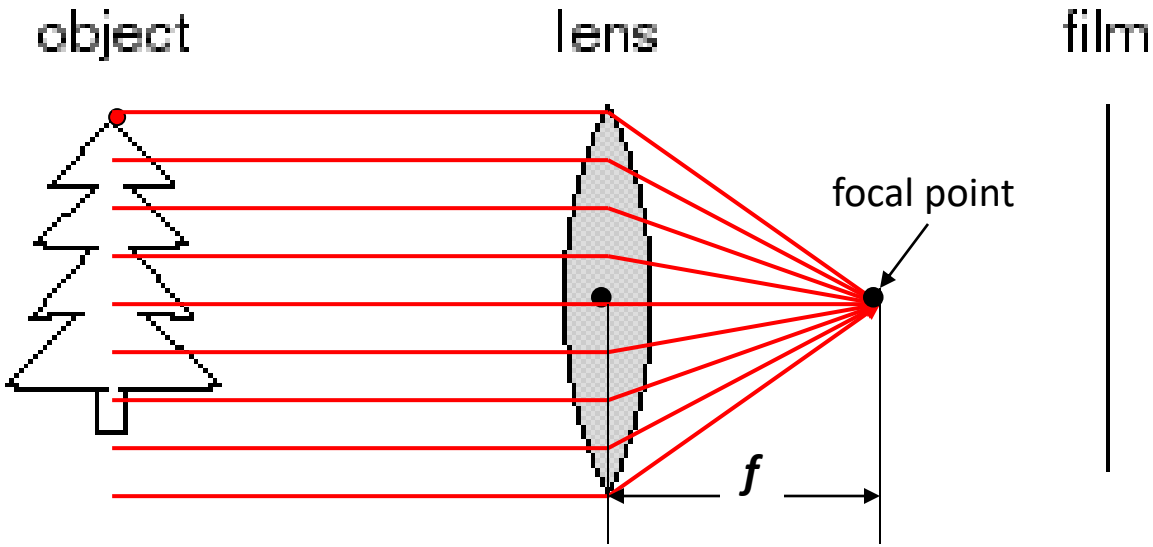
Adding a Lens



- 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

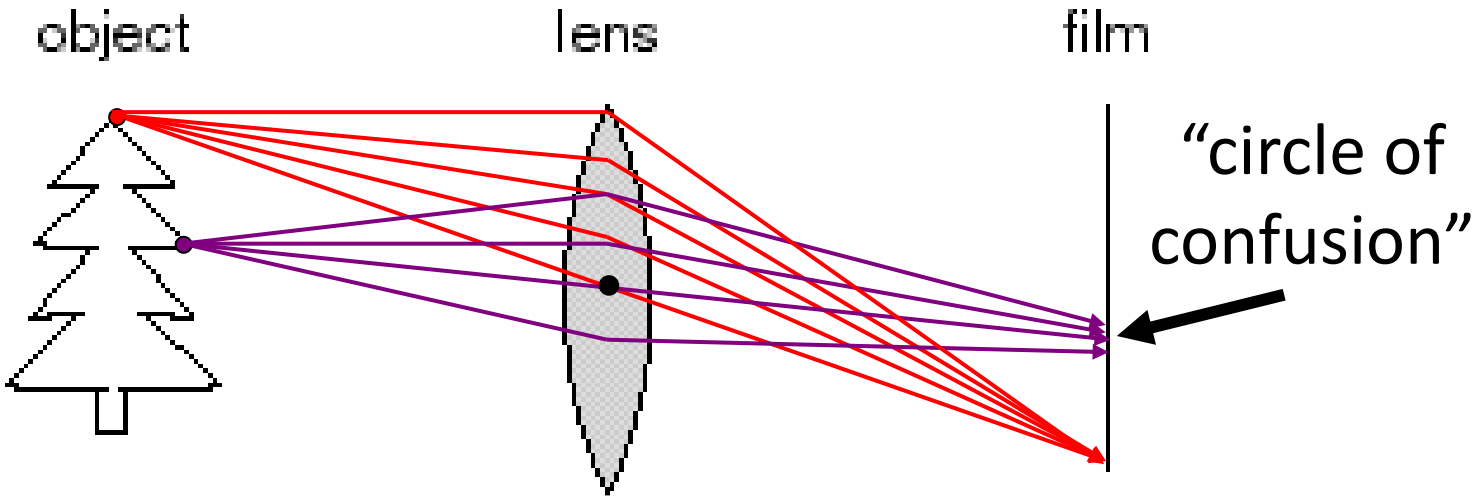
Adding a Lens



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

Slide Credit: S. Seitz

What's The Catch?



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

Slide Credit: S. Seitz

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.

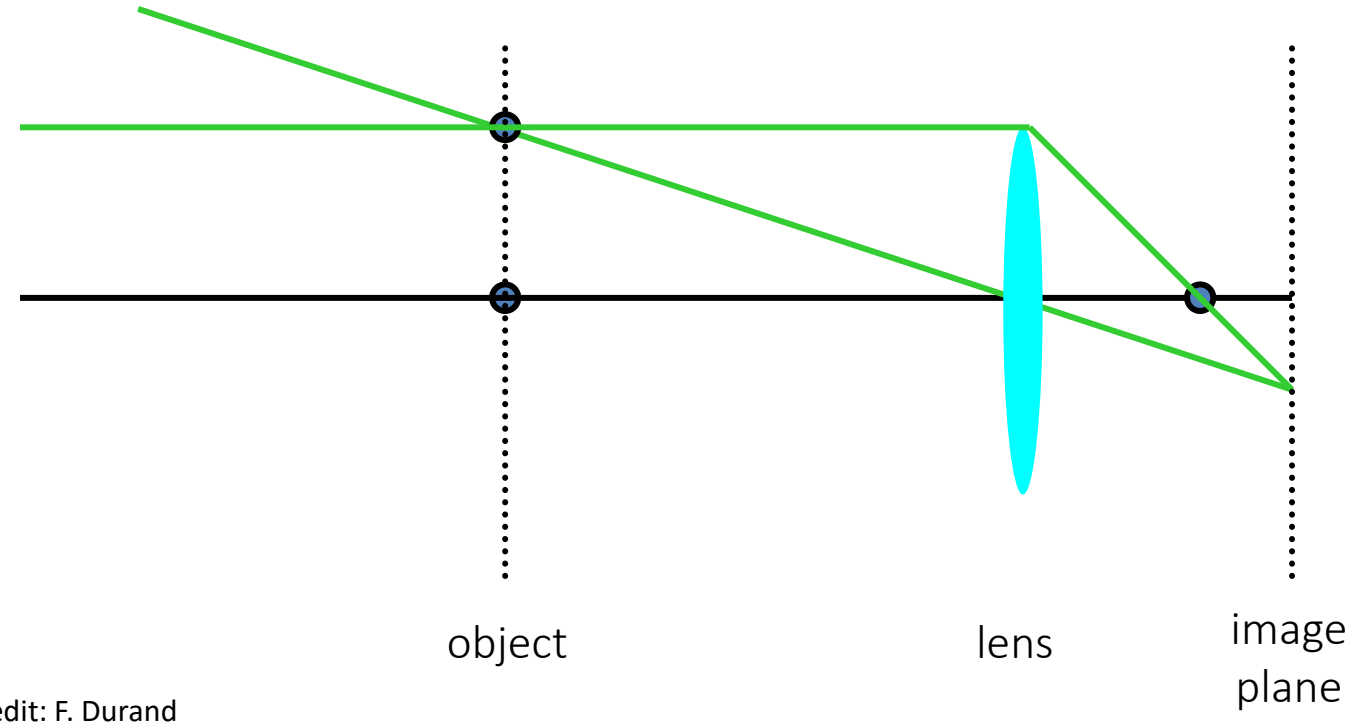


Diagram credit: F. Durand

Thin Lens Formula

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

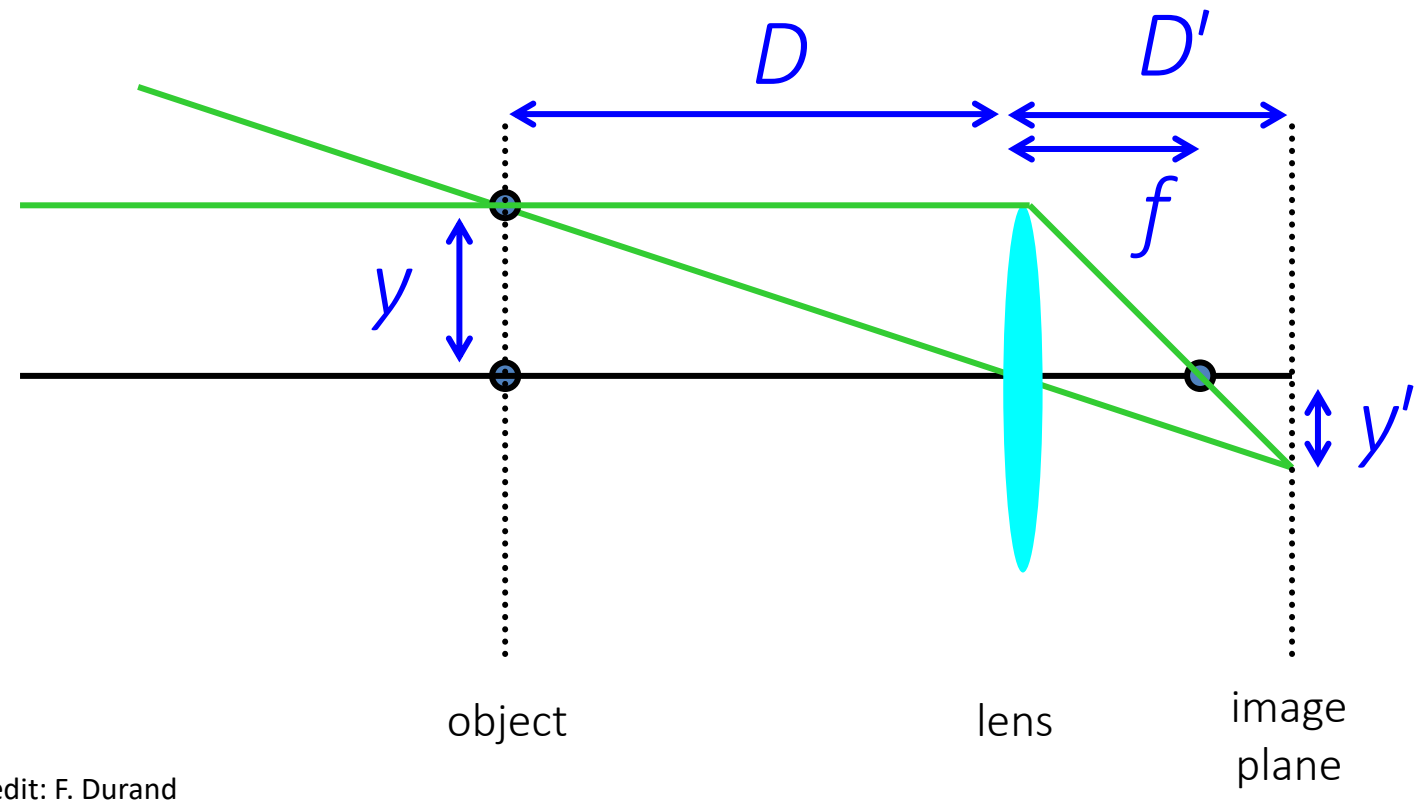


Diagram credit: F. Durand

Thin Lens Formula

One set of similar triangles:

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

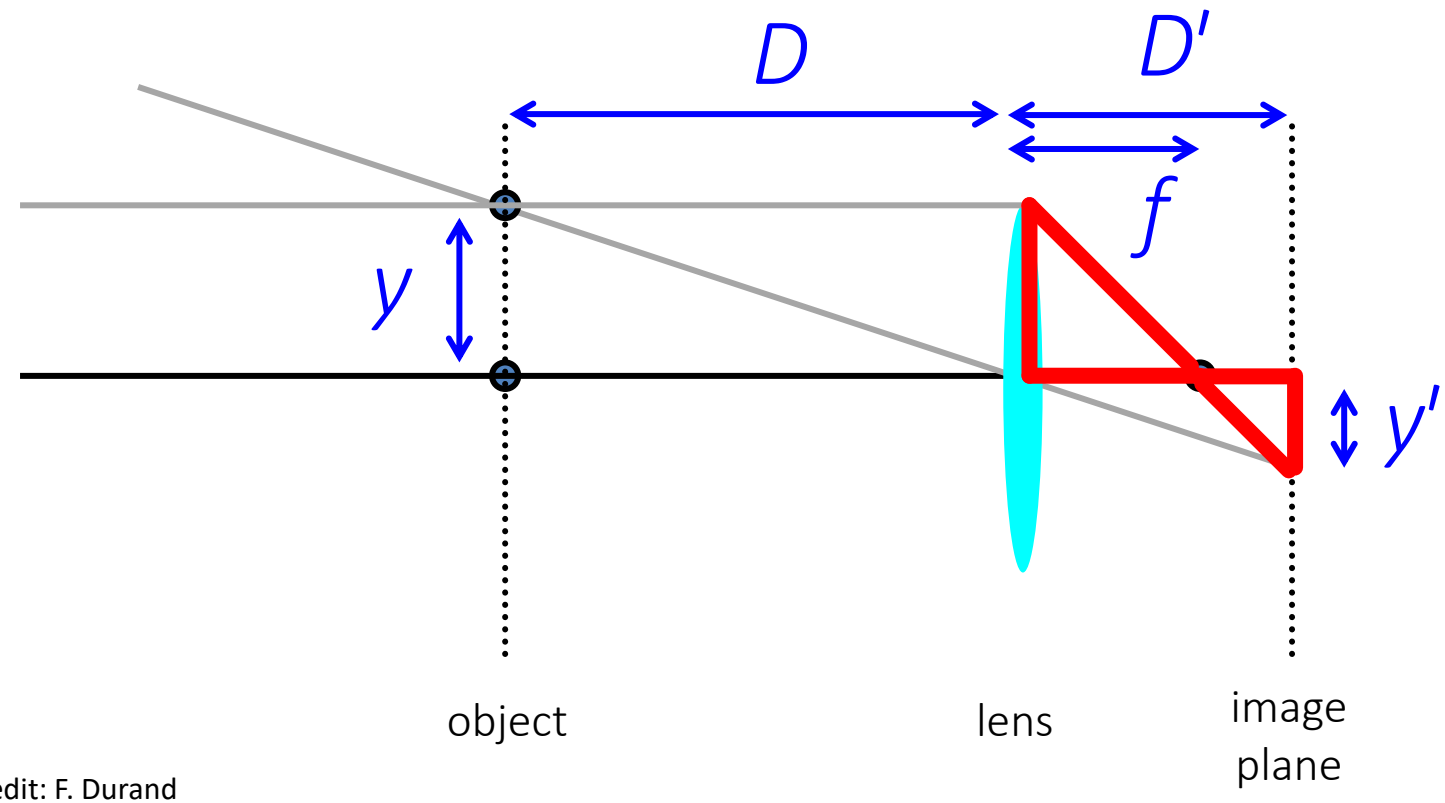


Diagram credit: F. Durand

Thin Lens Formula

Another set of similar triangles:

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

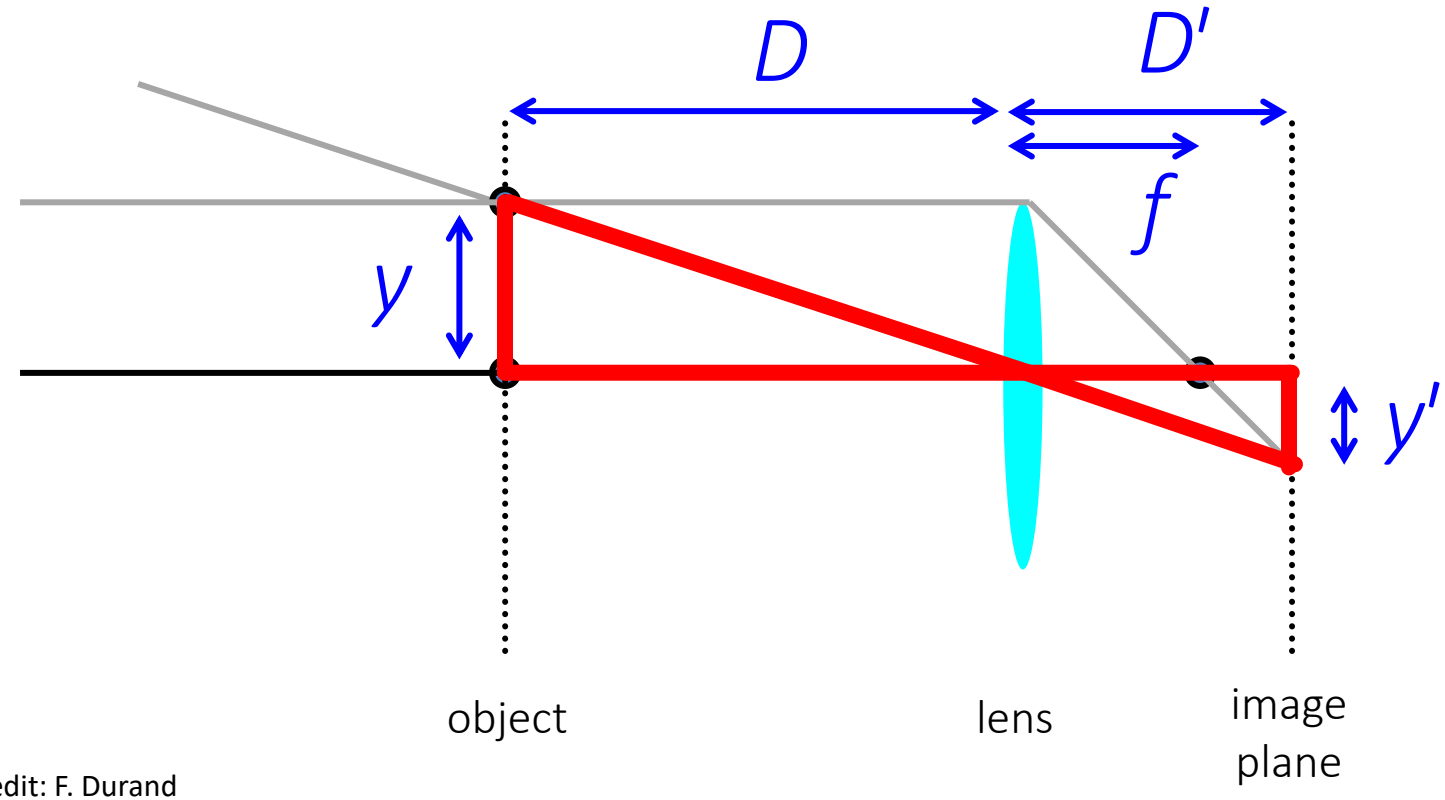


Diagram credit: F. Durand

Thin Lens Formula

Set them equal:

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

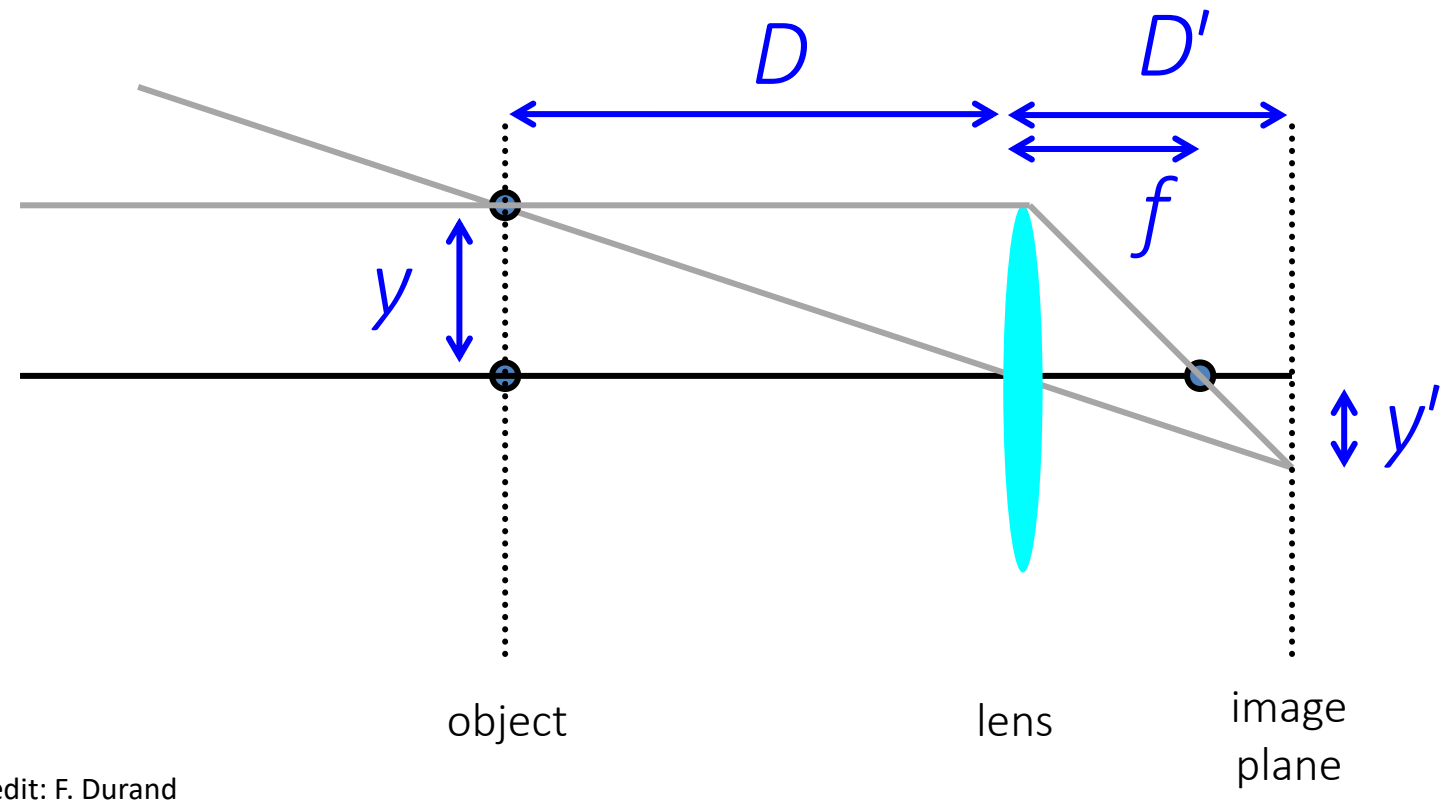


Diagram credit: F. Durand

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?

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

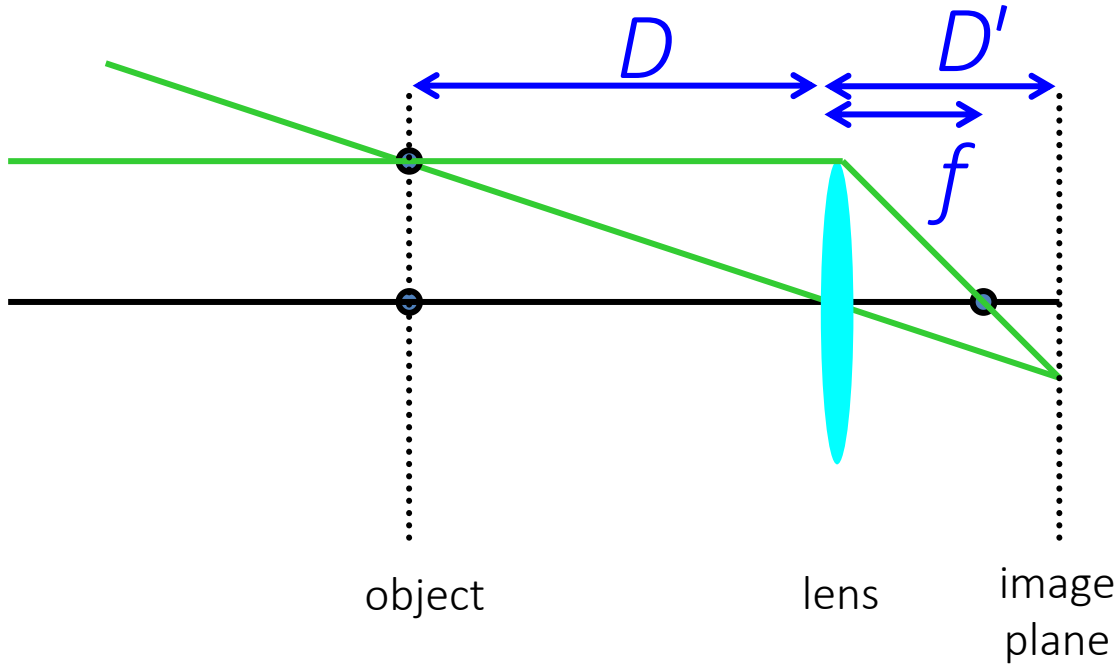
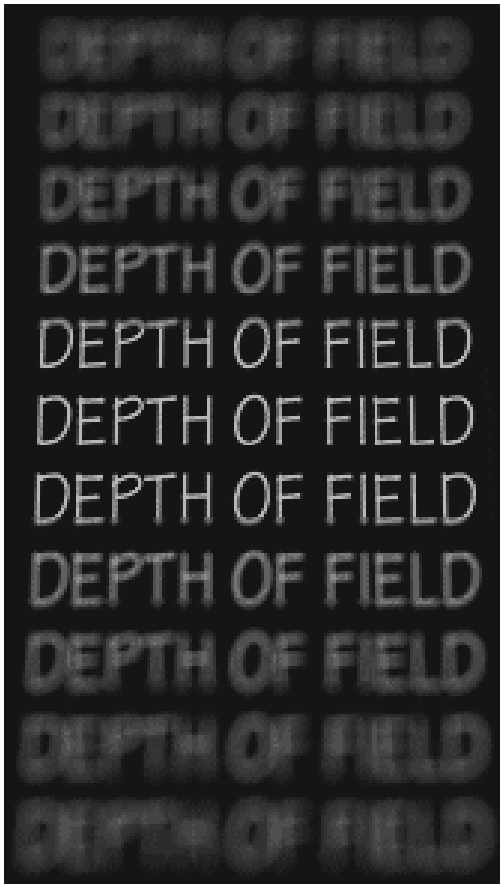


Diagram credit: F. Durand

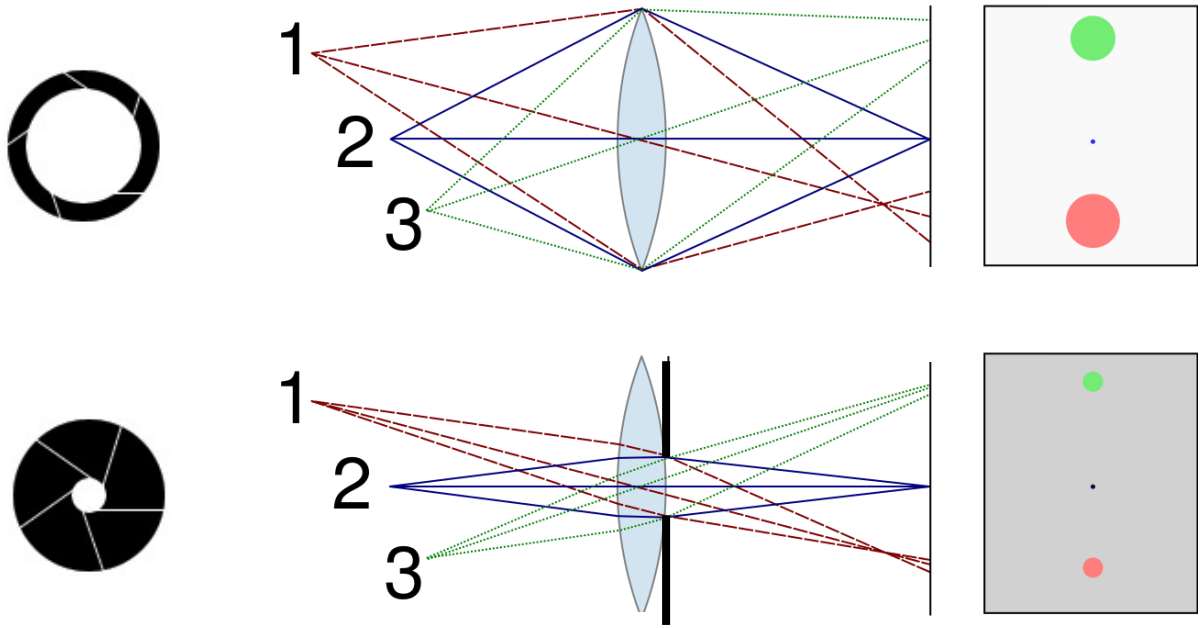
Depth of Field



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

Slide Credit: A. Efros

Controlling Depth of Field

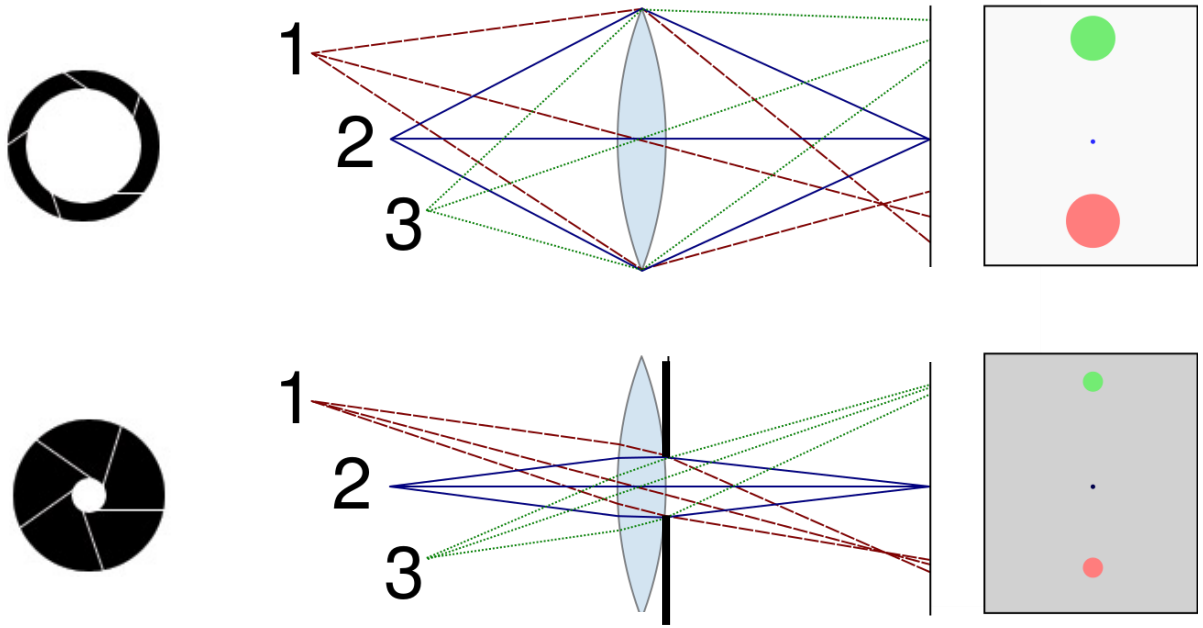


Changing the aperture size affects depth of field

A smaller aperture increases the range in which the object is approximately in focus

Diagram: Wikipedia

Controlling Depth of Field



If a smaller aperture makes everything focused, why don't we just always use it?

Diagram: Wikipedia

Varying the Aperture

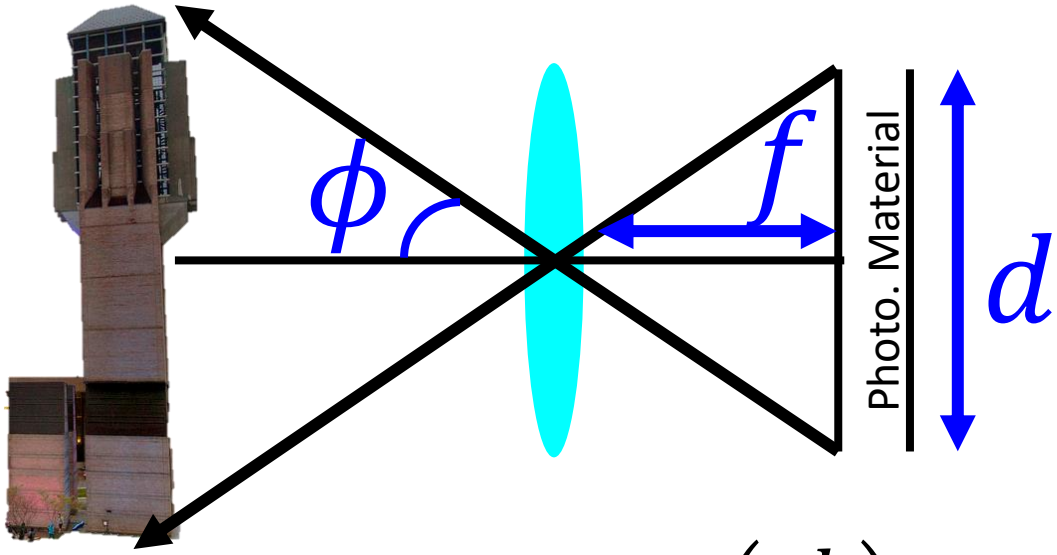
Small aperture = large DOF

Large aperture = small DOF

Slide Credit: A. Efros, Photo: Philip Greenspun

Varying the Aperture

Field of View (FOV)

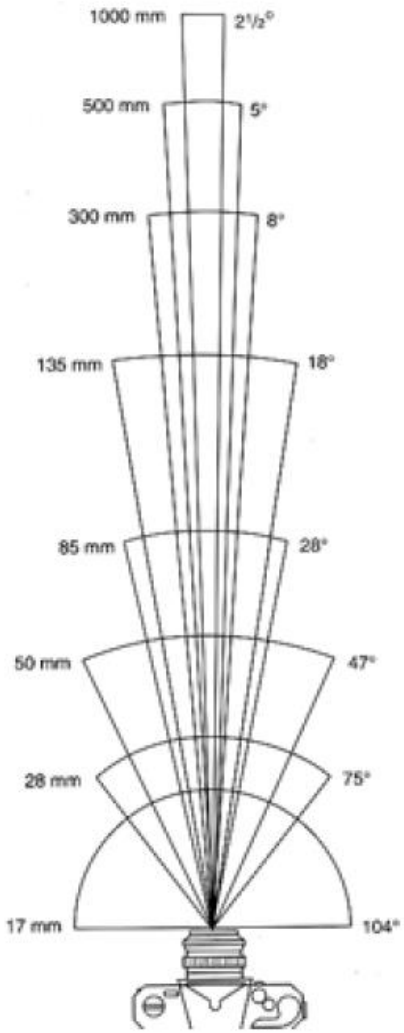


$$\phi = \tan^{-1}\left(\frac{d}{2f}\right)$$

$\tan^{-1}$ is monotonic increasing.

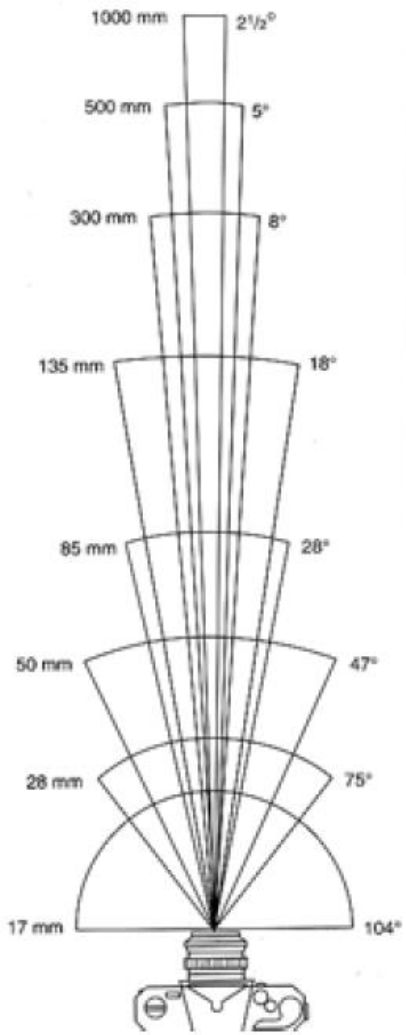
How can I get the FOV bigger?

Field of View

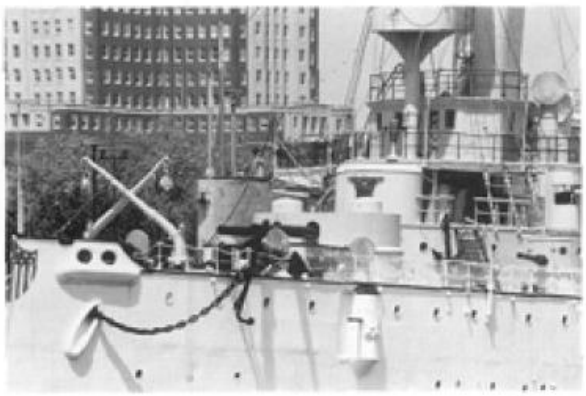


Slide Credit: A. Efros

Field of View



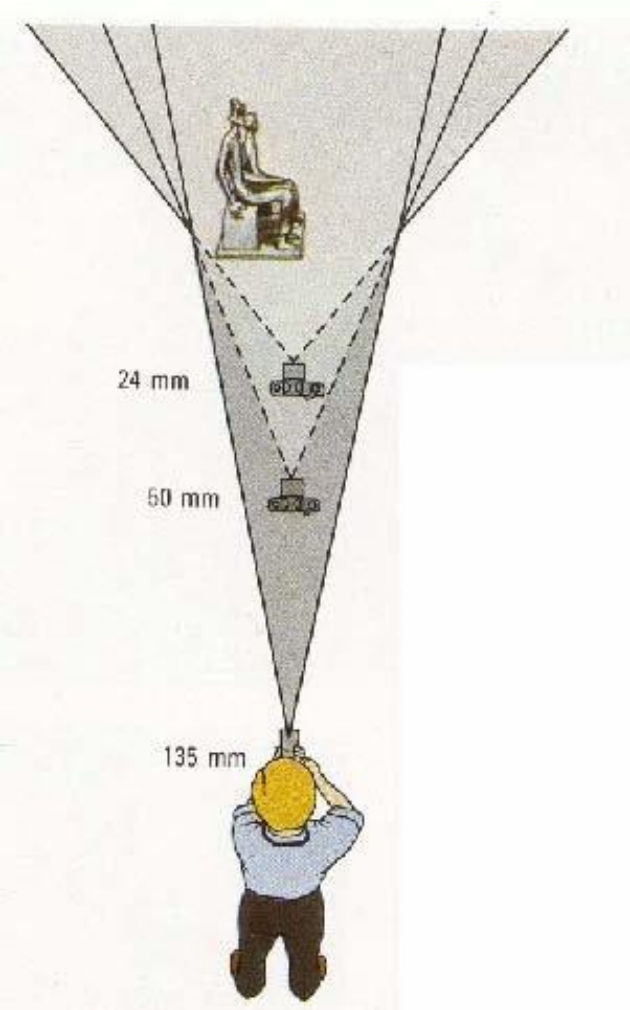
135mm



300mm

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

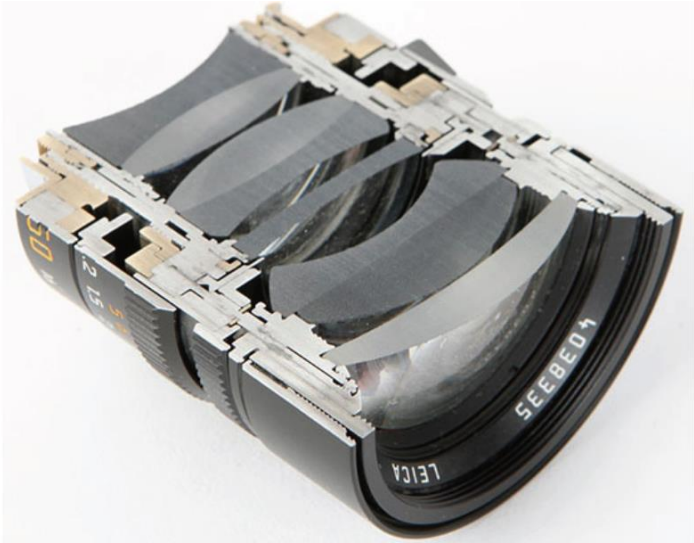
Dolly Zoom

Change f and distance at the same time

Video Credit: Goodfellas 1990

More Bad News!

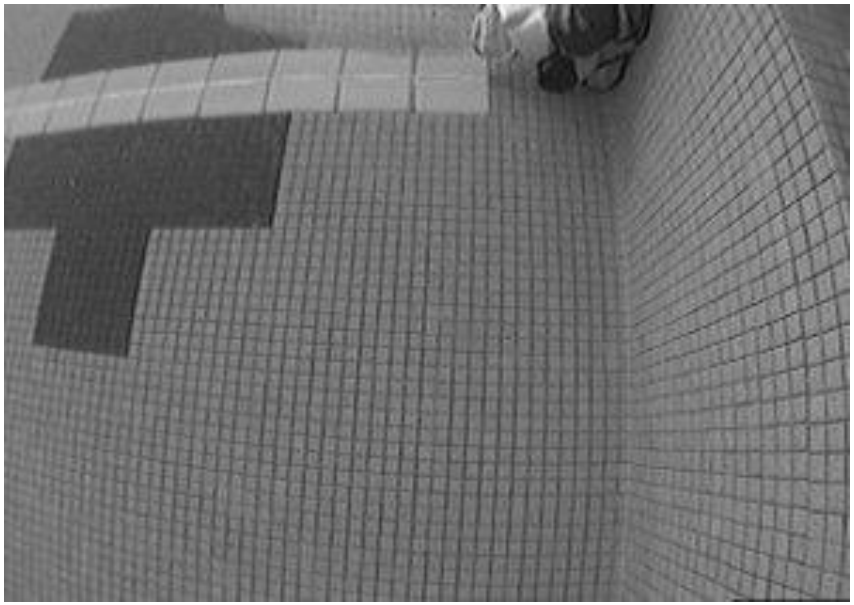
- First a pinhole…
- Then a thin lens model….

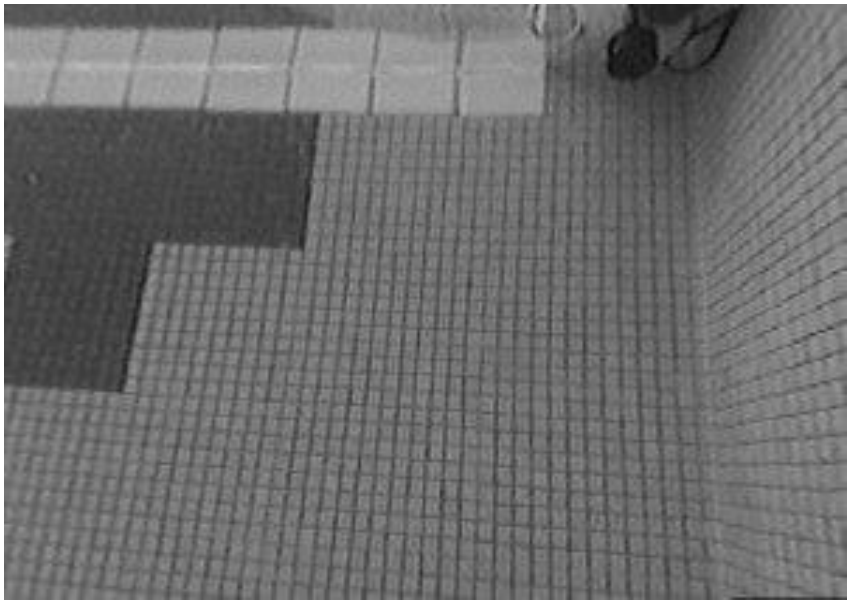


Slide: L. Lazebnik

Lens Flaws: Radial Distortion

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

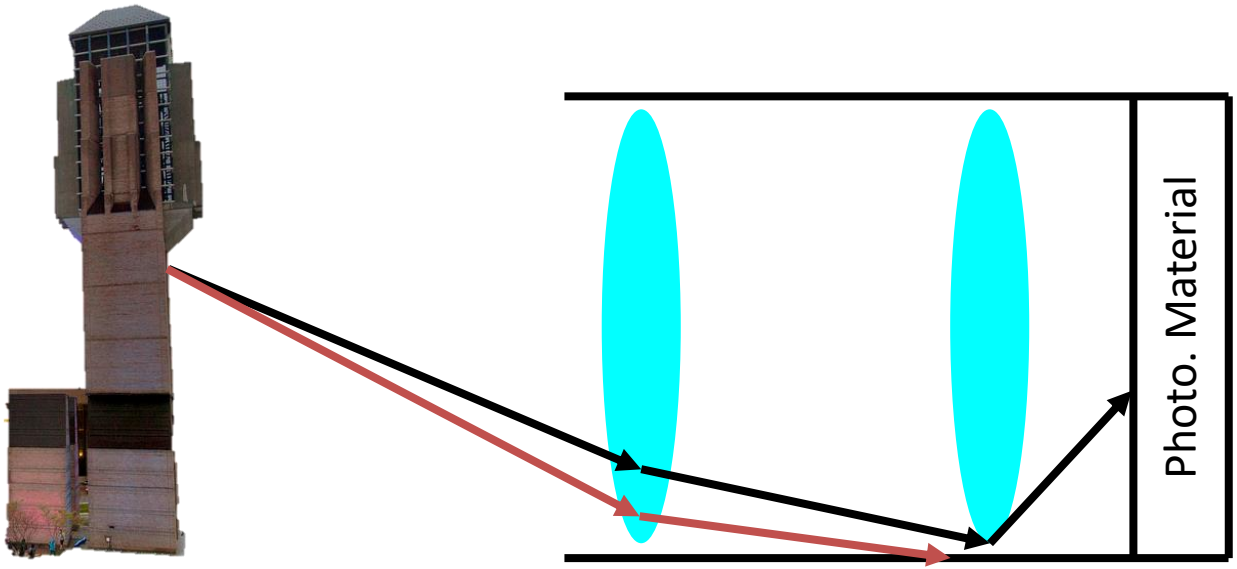




Less common these days in consumer devices

Photo: Mark Fiala, U. Alberta

Vignetting



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

Slide inspired by L. Lazebnik Slide

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

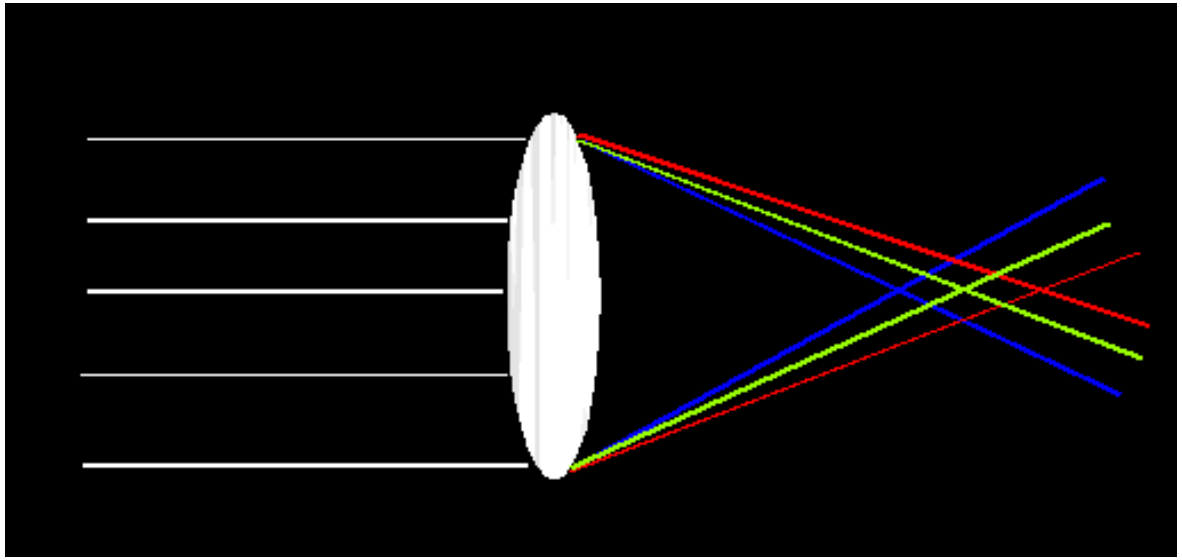
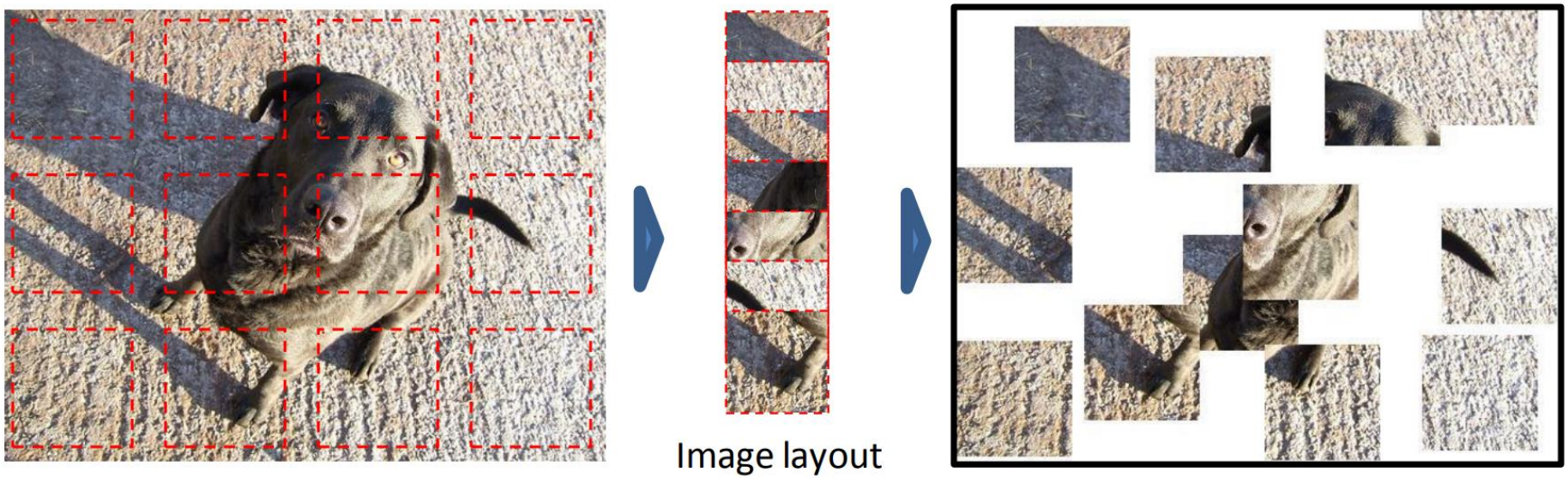


Image credits: L. Lazebnik, Wikipedia

Lens Flaws: Chromatic Abberation

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



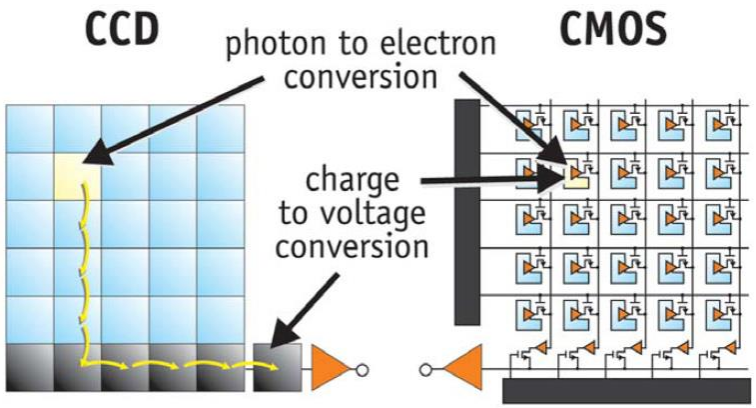
Initial layout, with sampled patches in red

Image layout is discarded

We can recover image layout automatically

Slide Credit: C. Doersch

From Photon to Photo



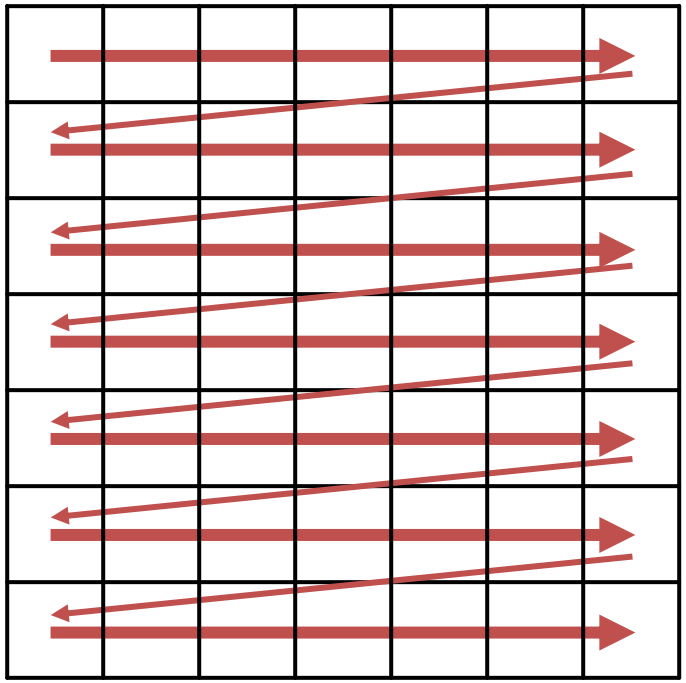
CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

- 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)**

Slide Credit: L. Lazebnik, Photo Credit: Wikipedia, Stefano Meroli

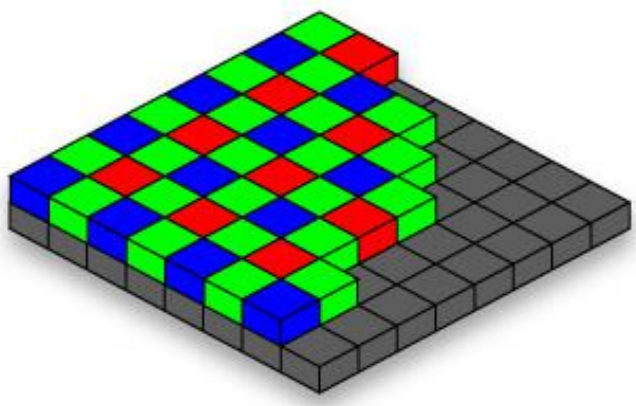
From Photon to Photo

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



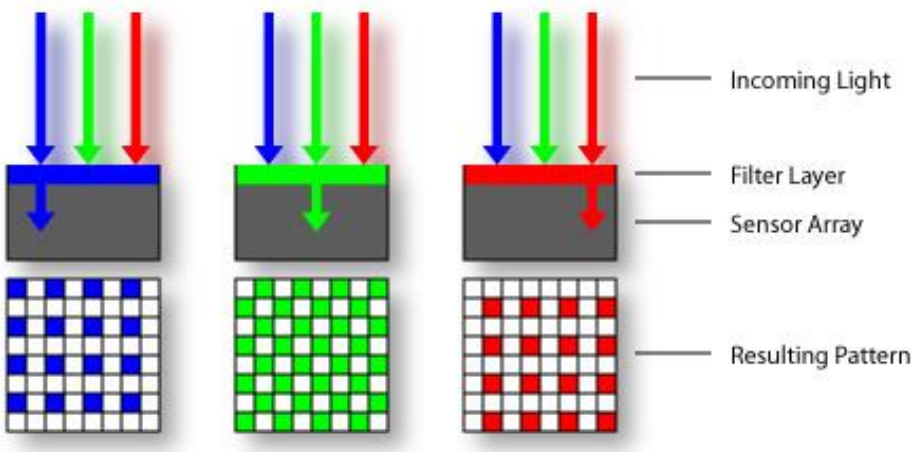
Preview of What's Next

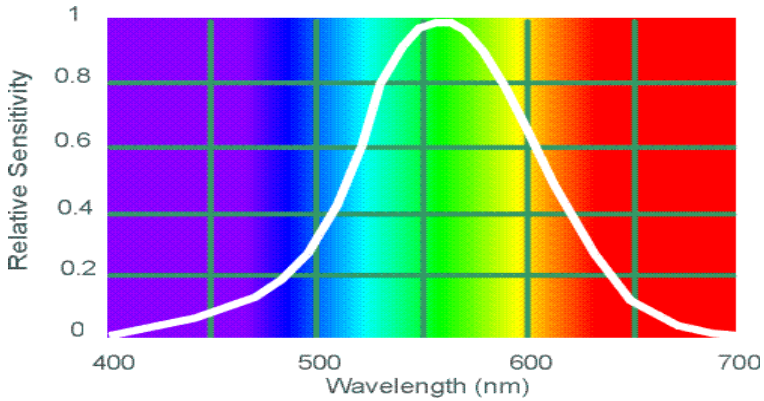
Bayer grid



Demosaicing:

Estimation of missing components from neighboring values





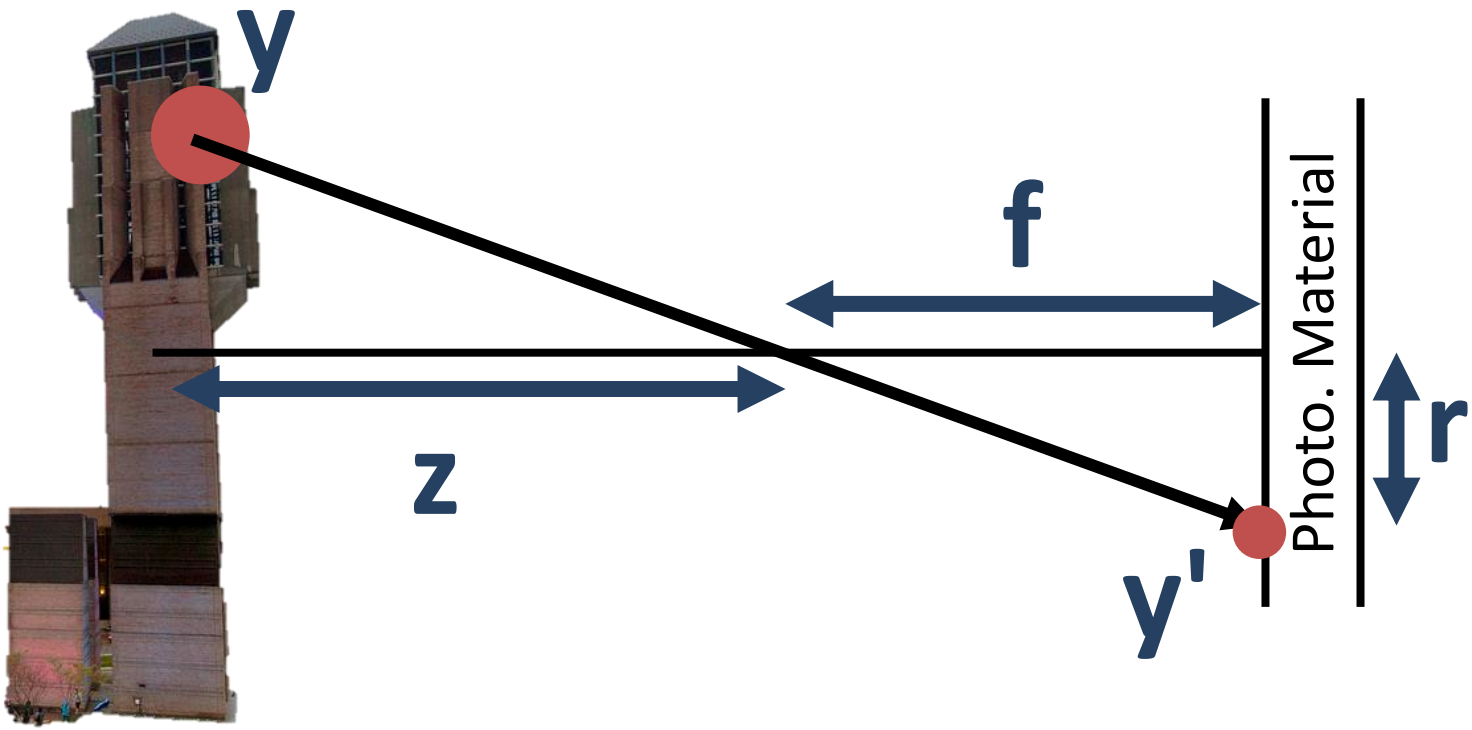
Slide Credit: S. Seitz

Human Luminance Sensitivity Function

For the Curious

- Cut in the interest of time

Radial Distortion Correction



Ideal

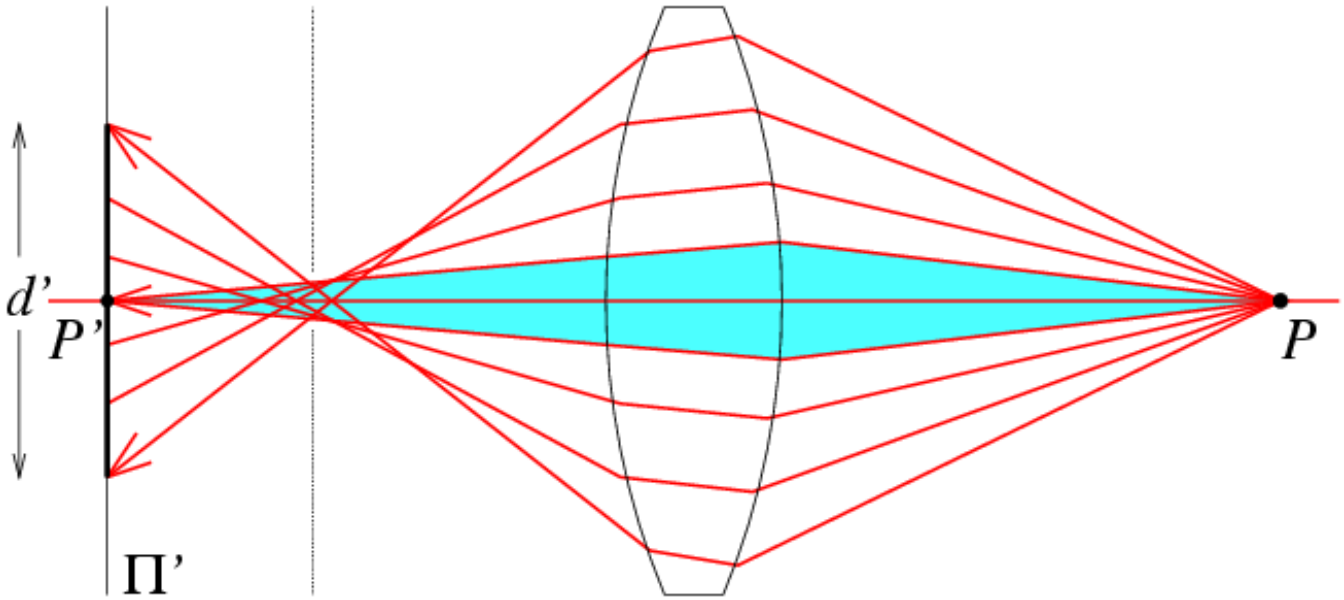
$$y' = f\frac{y}{z}$$

Distorted

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

Lens Flaws: Spherical Abberation

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

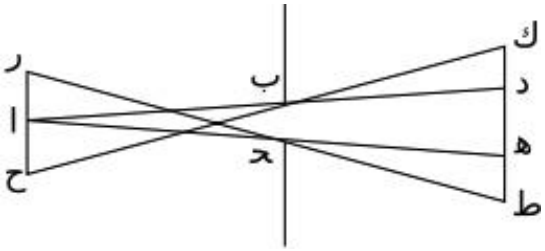


Slide: L. Lazebnik

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



Alhacen's notes

Niepce, "La Table Servie," 1822

Old television camera

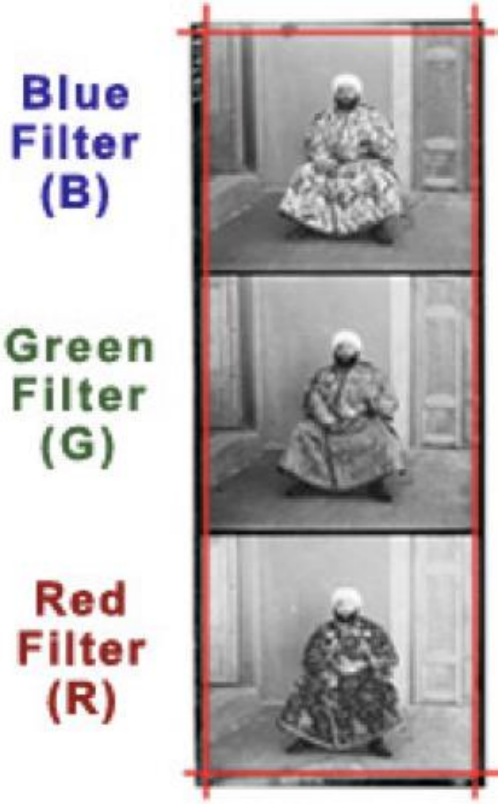
First digitally scanned photograph

- 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)



Slide Credit: S. Maji

Historic Milestone

Slide Credit: S. Maji

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