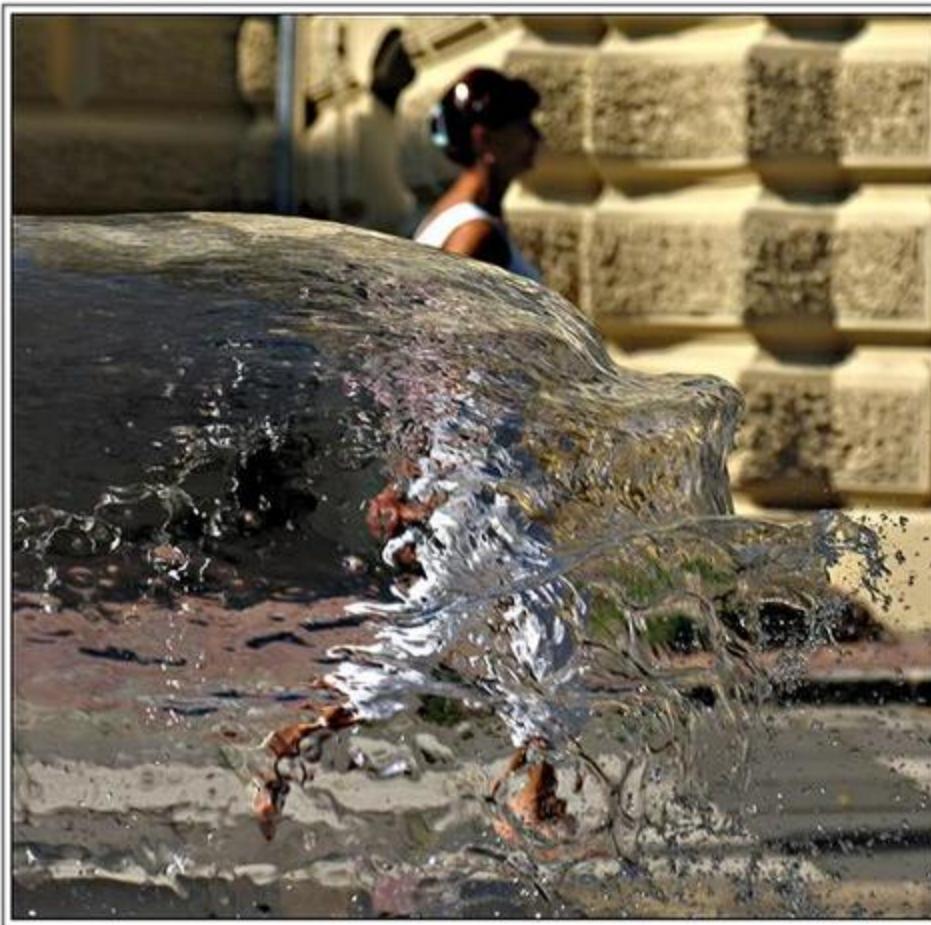


The Camera

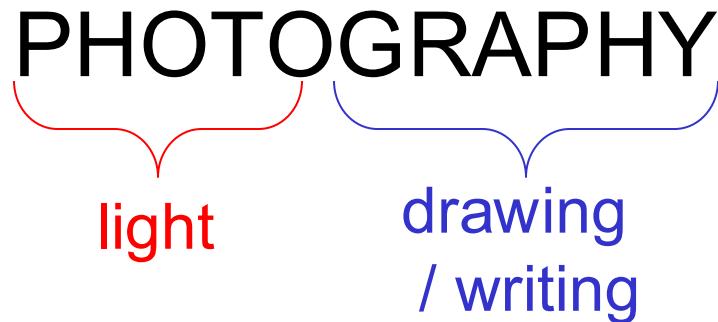


(c) Tomasz Pluciennik

CS180: Intro to Comp. Vision, and Comp. Photo
Efros & Kanazawa, UC Berkeley, Fall 2025

Etymology

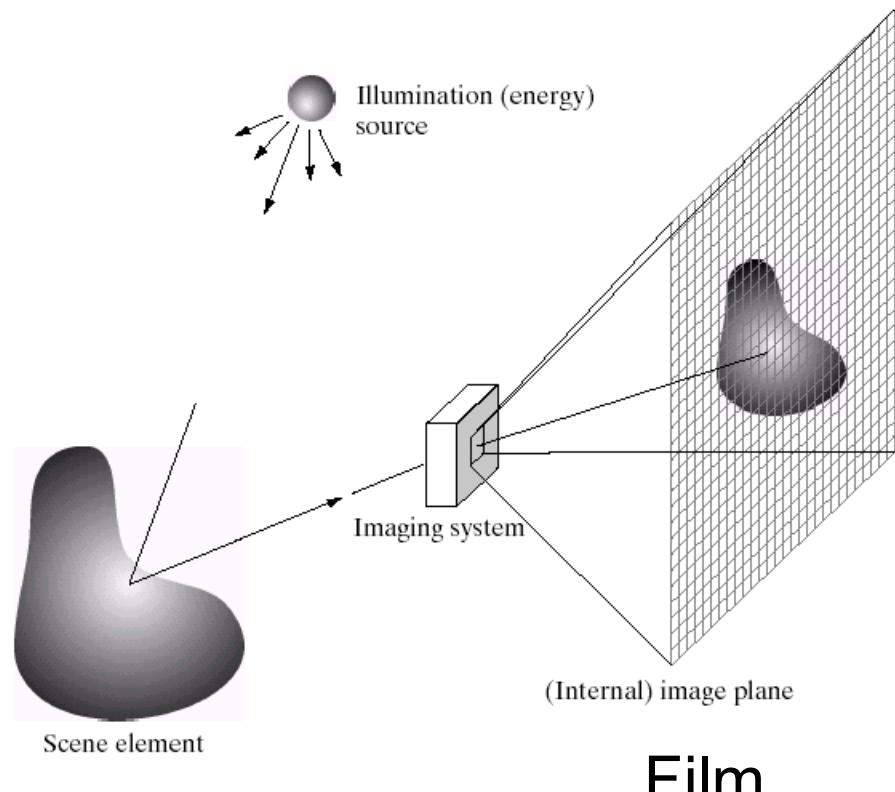
PHOTOGRAPHY



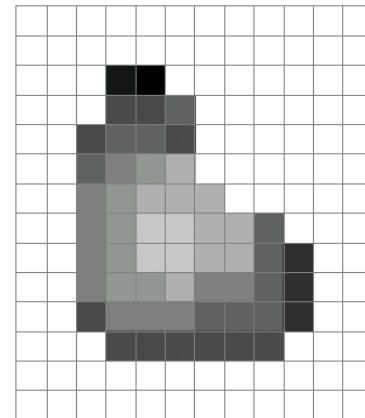
light

drawing
/ writing

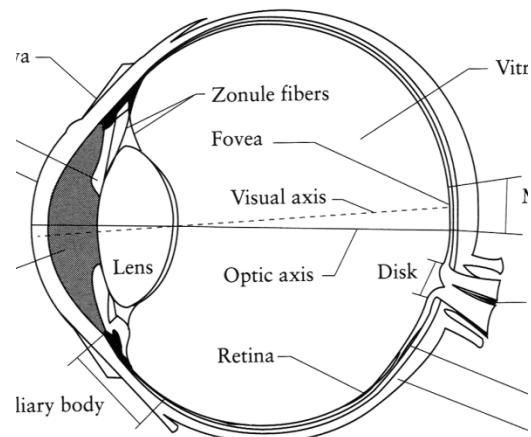
Image Formation



Film

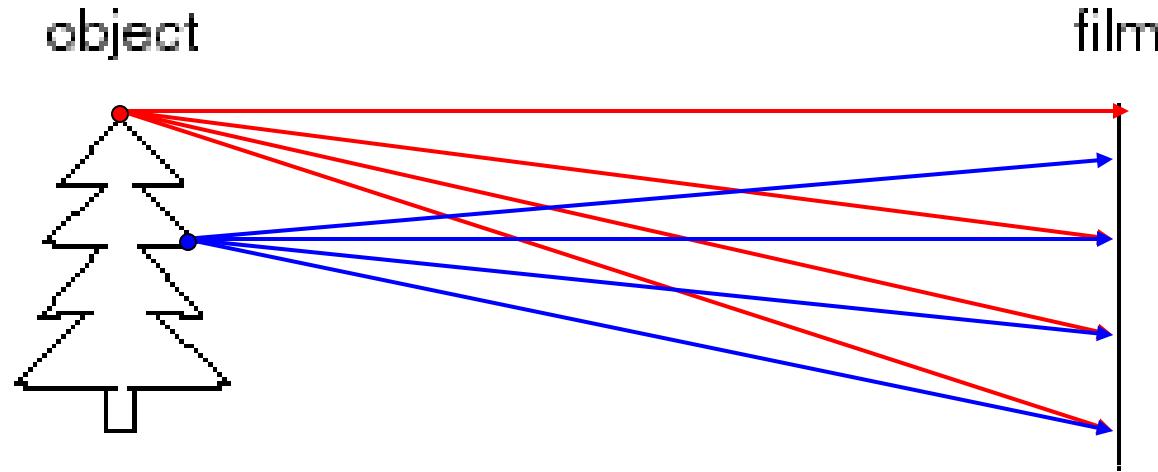


Digital Camera



The Eye

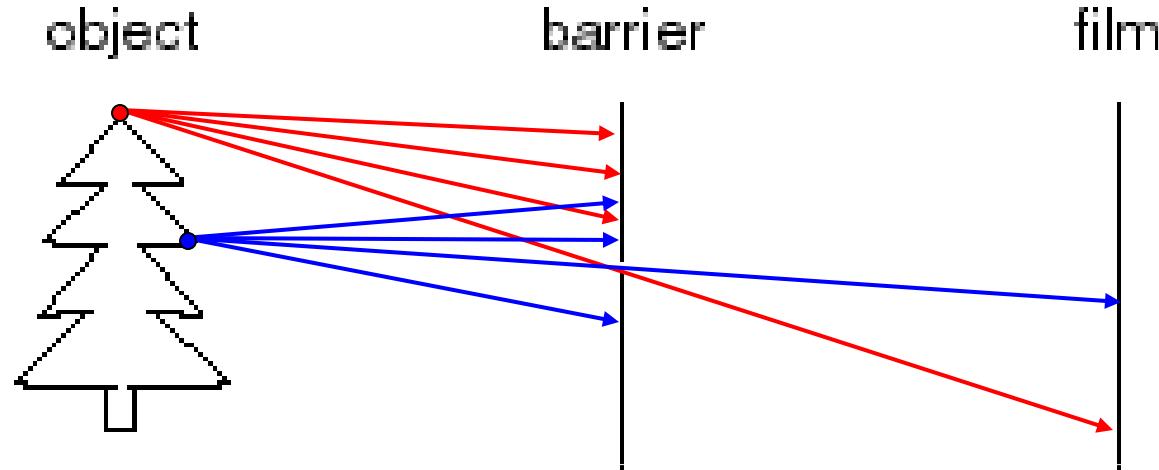
How do we see the world?



Let's design a camera

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

Pinhole camera

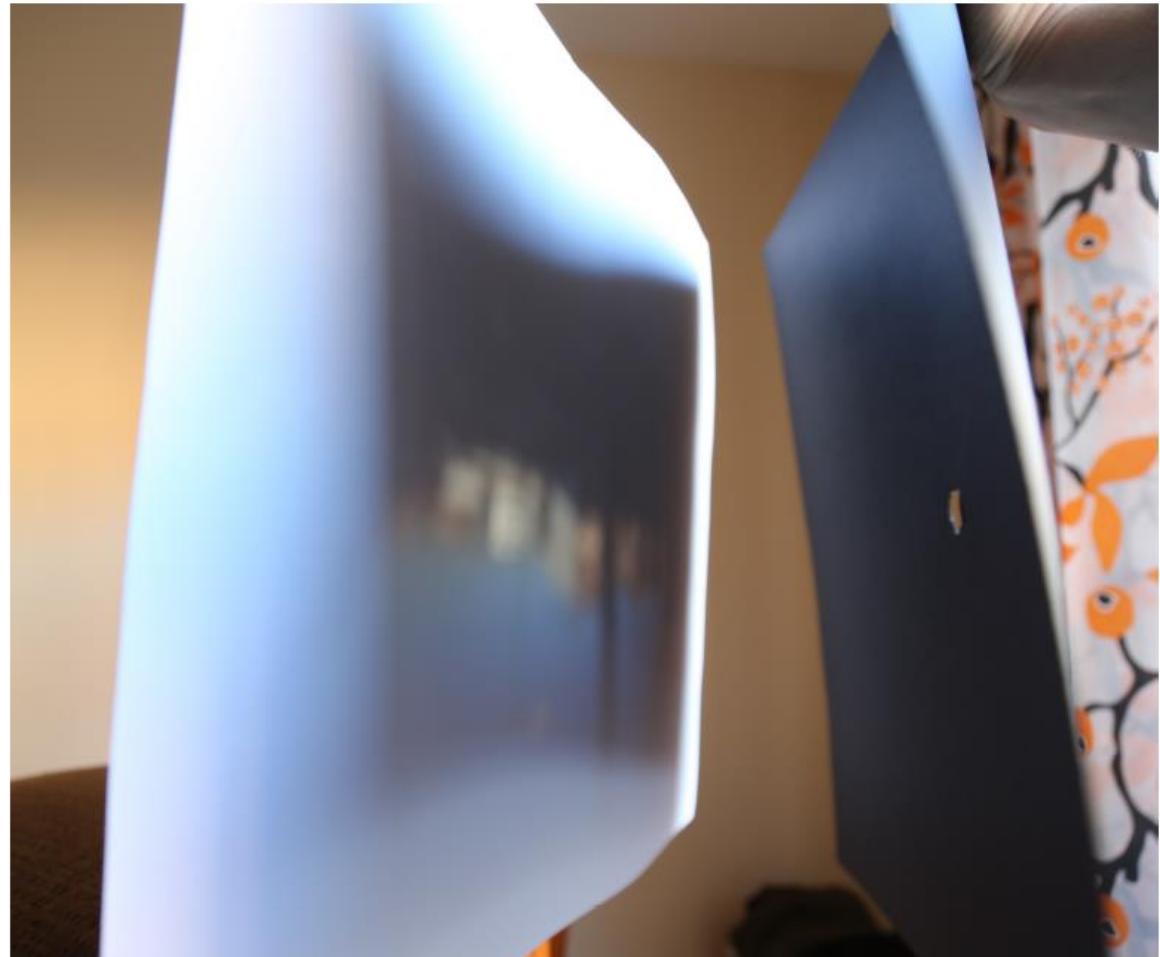


Add a barrier to block off most of the rays

- This reduces blurring
- The opening known as the **aperture**
- How does this transform the image?

DIY Pinhole Camera

Figure 5.4: A simple setting for creating images on a white piece of paper. In front of the white piece of paper we place another piece of black paper with a hole in the middle. The black paper projects a shadow on the white paper and, in the middle of the shadow, appears a picture of the scene in front of the hole. By making the hole large you will get a brighter, but blurrier image.



Camera Obscura: the pre-camera

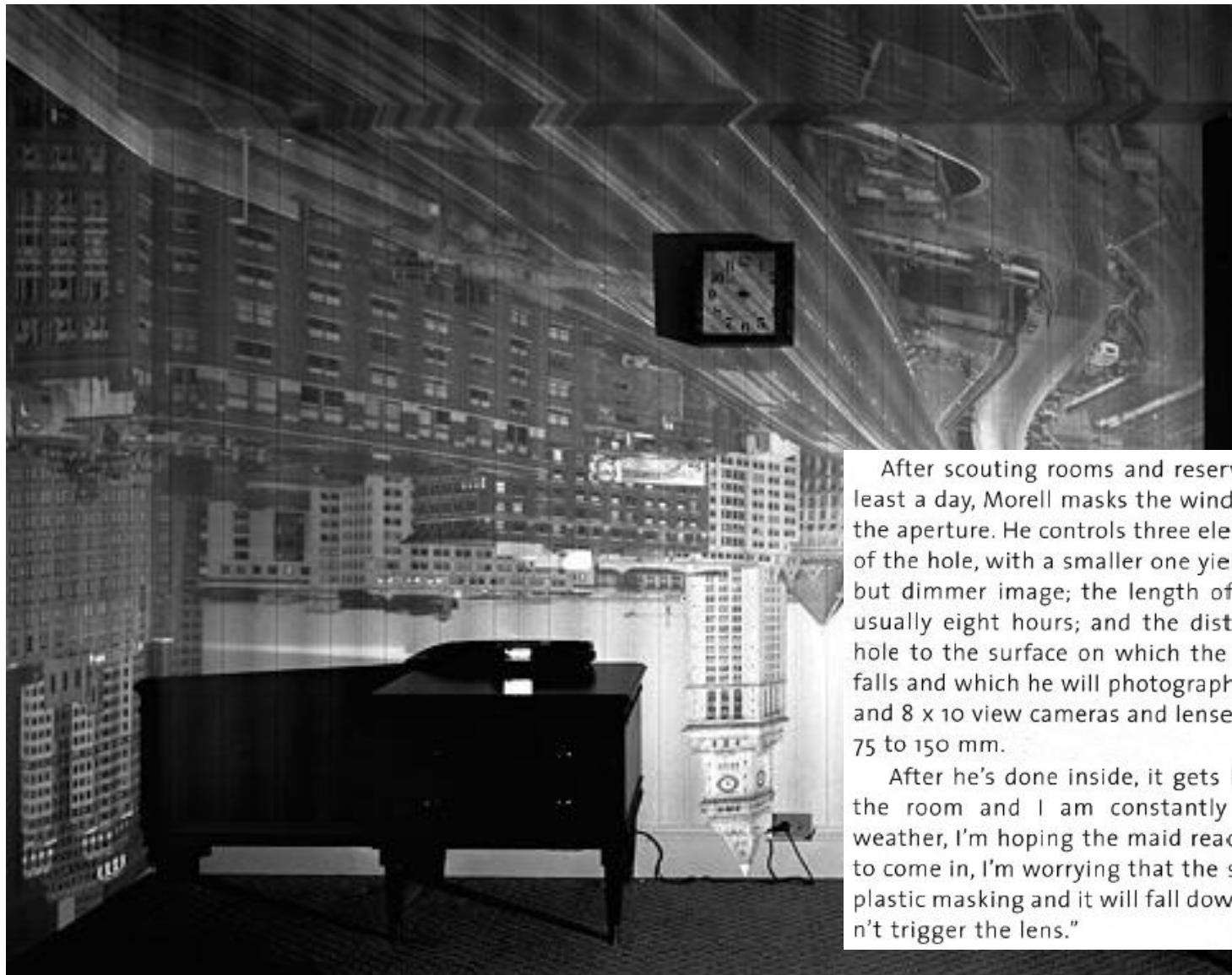
- First Idea: Mo-Ti, China (470-390 BC)
- First build: Al Hacen, Iraq/Egypt (965-1039 AD)

Drawing aid for artists:
described by Leonardo da Vinci (1452-1519)



Camera Obscura near Cliff House

8-hour exposure (Abelardo Morell)



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."



“Trashcam” Project



<http://petapixel.com/2012/04/18/german-garbage-men-turn-dumpsters-into-giant-pinhole-cameras/>

Pinhole cameras everywhere



Tree shade

photo
<http://v>

© Trina Singley

Accidental pinhole cameras

My hotel room,
contrast enhanced.



The view from my window



Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

Accidental pinhole camera







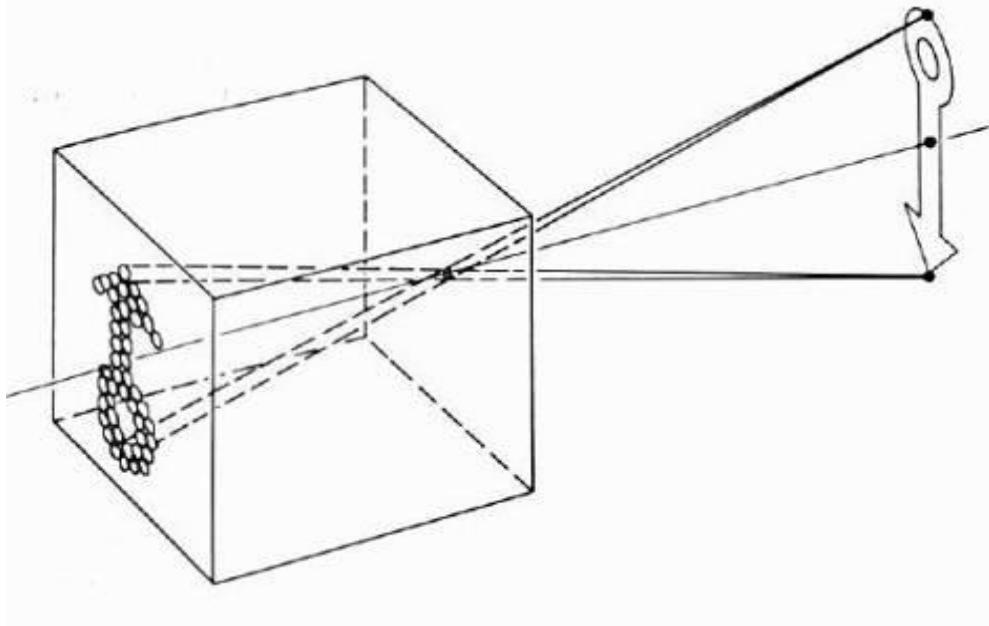
Window turned into a pinhole



View outside



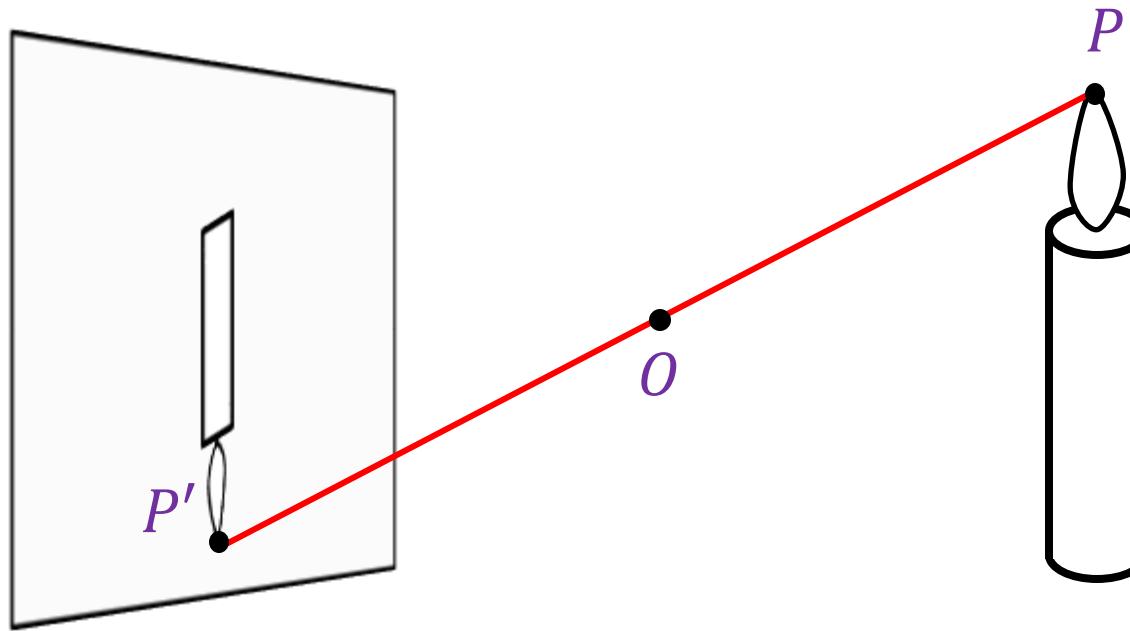
Pinhole camera model



Pinhole model:

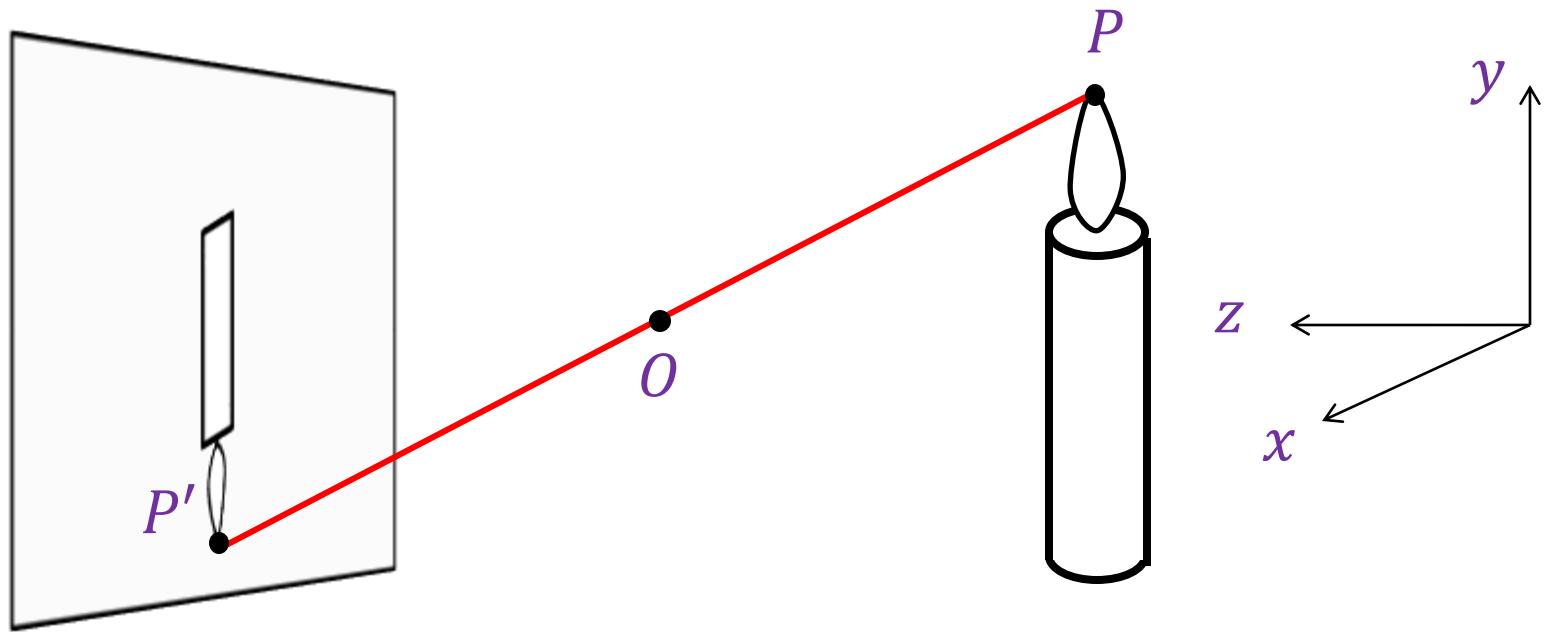
- Captures **pencil of rays** – all rays through a single point
- The point is called **Center of Projection (COP)**
- The image is formed on the **Image Plane**
- **Effective focal length f** is distance from COP to Image Plane

Modeling Projection



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

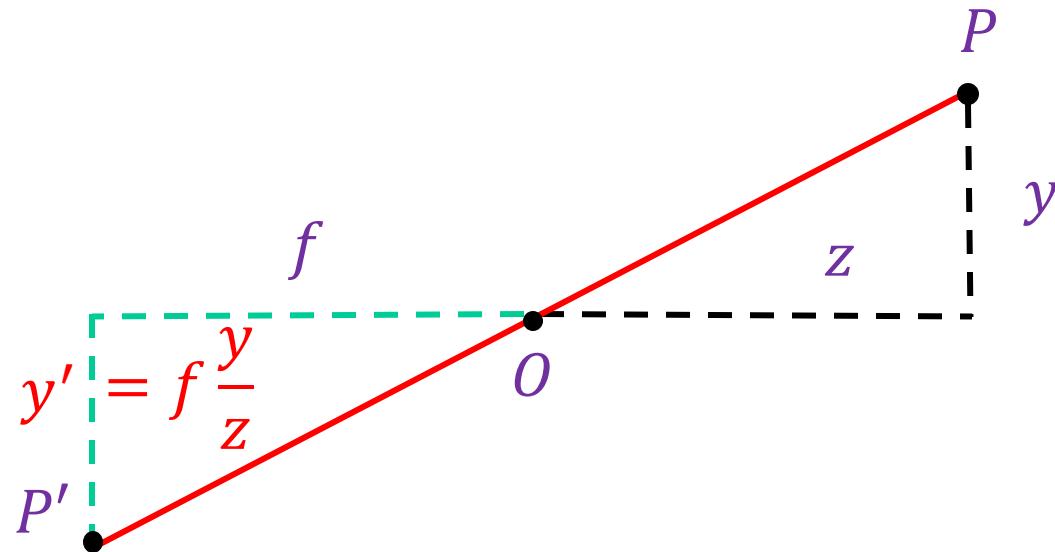
Modeling Projection



Canonical coordinate system

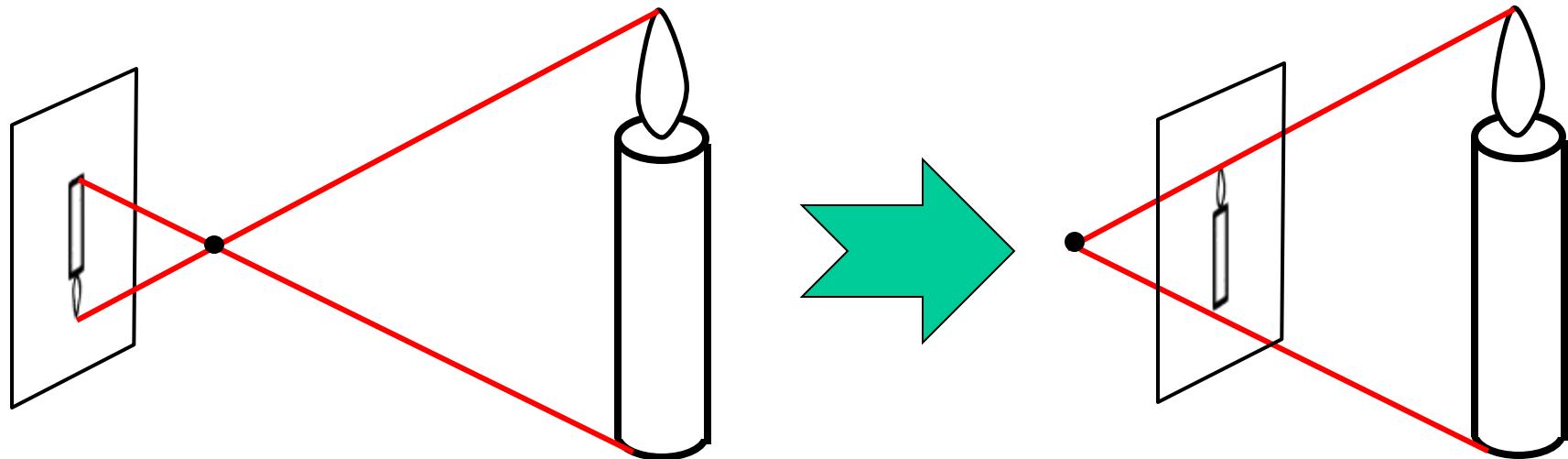
- The optical center (O) is at the origin
- The z axis is the *optical axis* perpendicular to the image plane
- The xy plane is parallel to the image plane, x and y axes are horizontal and vertical directions of the image plane

Deriving perspective projection



$$(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

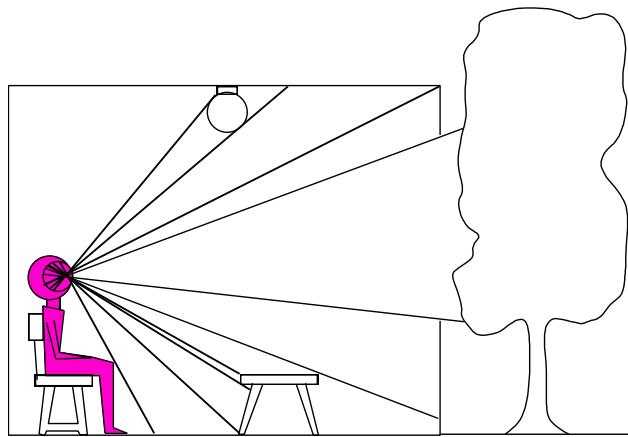
Avoiding Inversion



Instead of dealing with an image that is **upside down**, most of the time we will pretend that the image plane is **in front** of the camera center

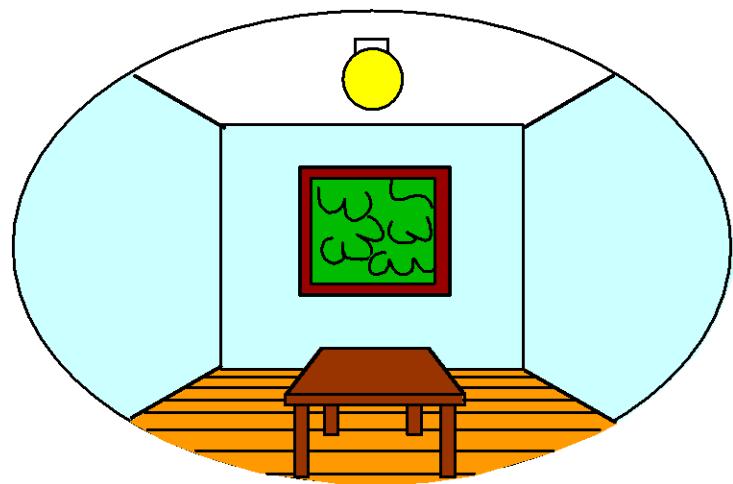
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image

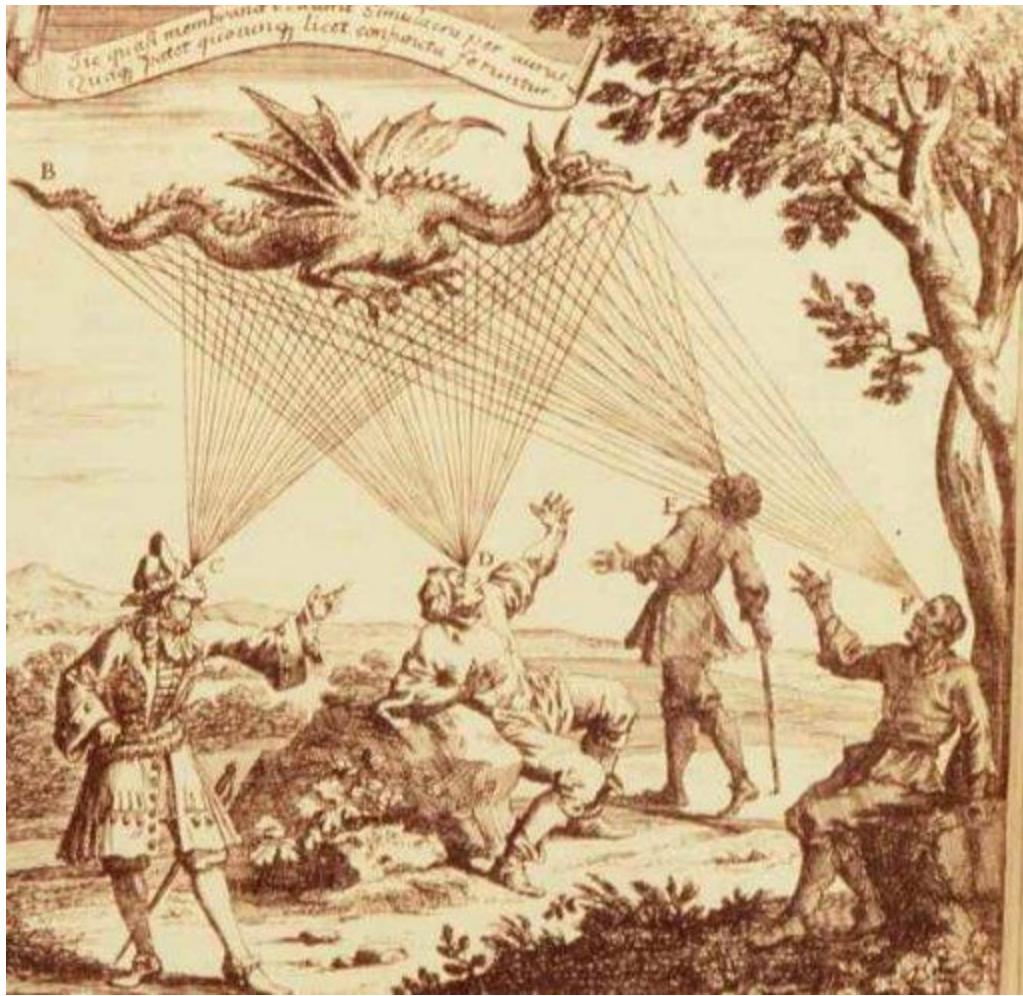


But there is a problem...

Emission Theory of Vision

“For every complex problem there is an answer that is clear, simple, and wrong.”

-- H. L. Mencken



Eyes send out “feeling rays” into the world

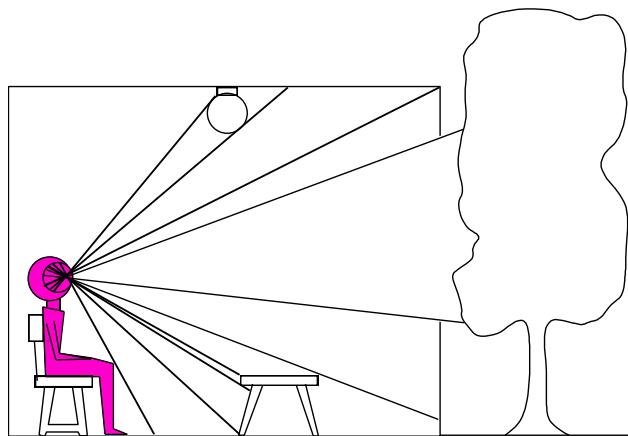
- Supported by:
- Empedocles
- Plato
- Euclid (kinda)
- Ptolemy
- ...
- 50% of US college students*

*<http://www.ncbi.nlm.nih.gov/pubmed/12094435?dopt=Abstract>



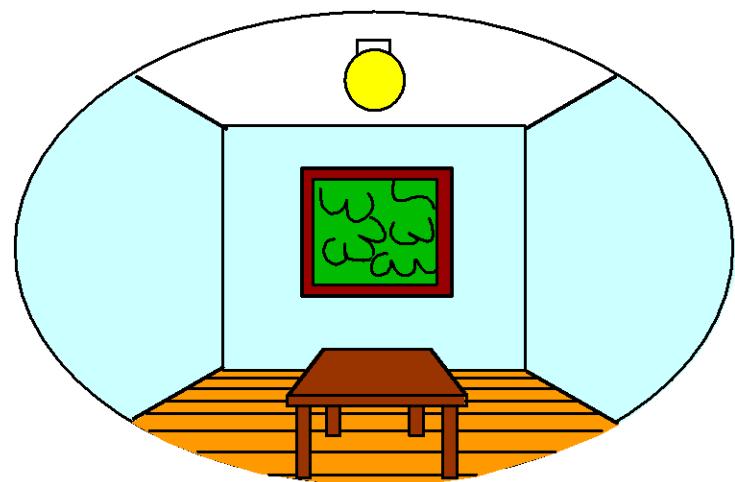
How we see the world

3D world



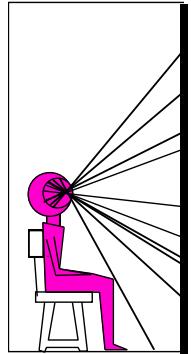
Point of observation

2D image



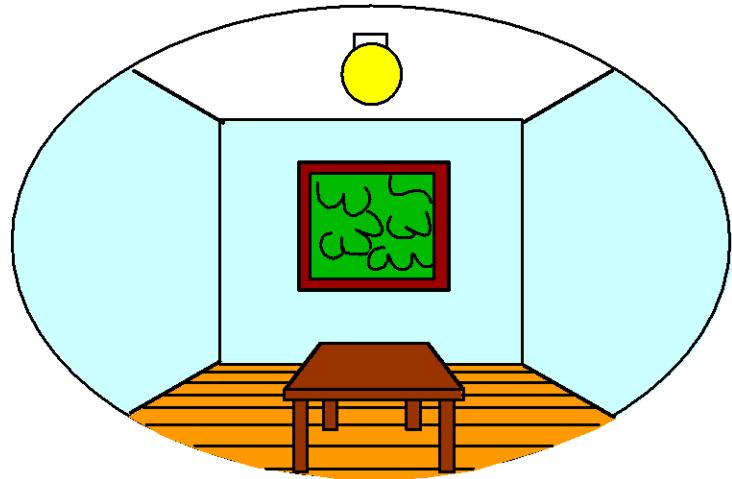
How we see the world

3D world



Painted
backdrop

2D image



$$(x, y, z) \rightarrow \left(f \frac{x}{z}, f \frac{y}{z} \right)$$

Fooling the eye



CoolOpticalIllusions.com

PLANET GLOBE
BY JEFFREY L. COOPER

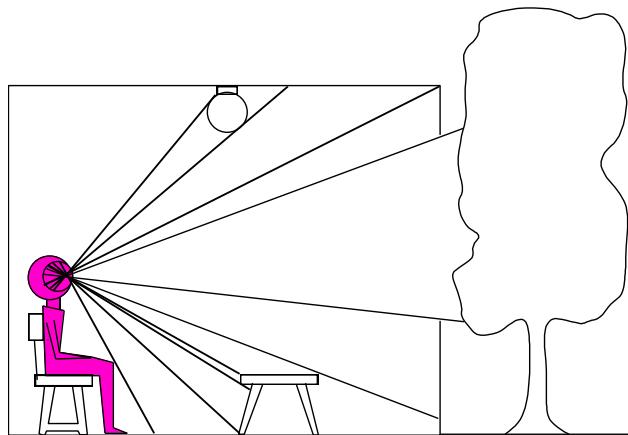
Fooling the eye



Making of 3D sidewalk art: <http://www.youtube.com/watch?v=3SNYtd0Ayt0>

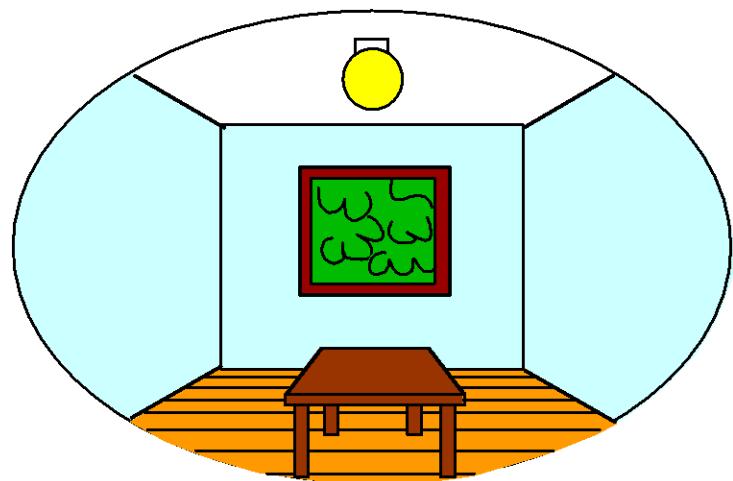
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image

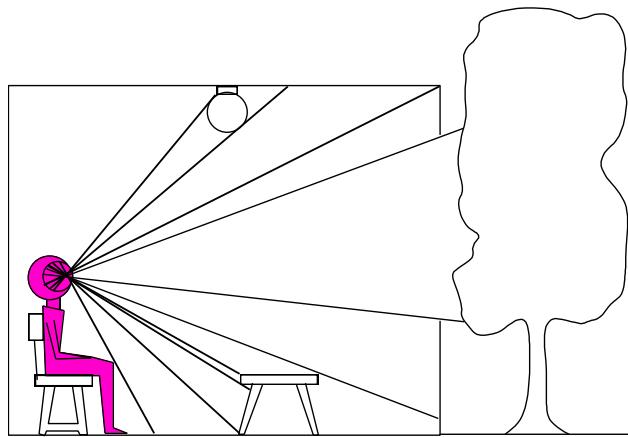


Why did evolution opt for such strange solution?

- Nice to have a passive, long-range sensor
- Can get 3D with stereo or by moving around, plus experience

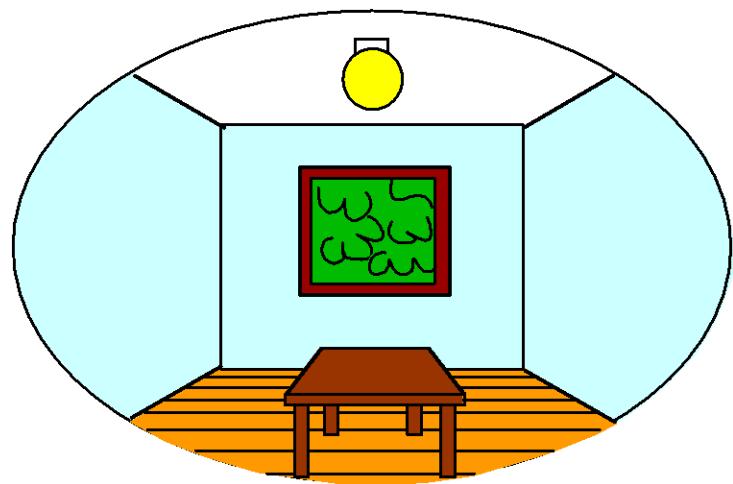
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

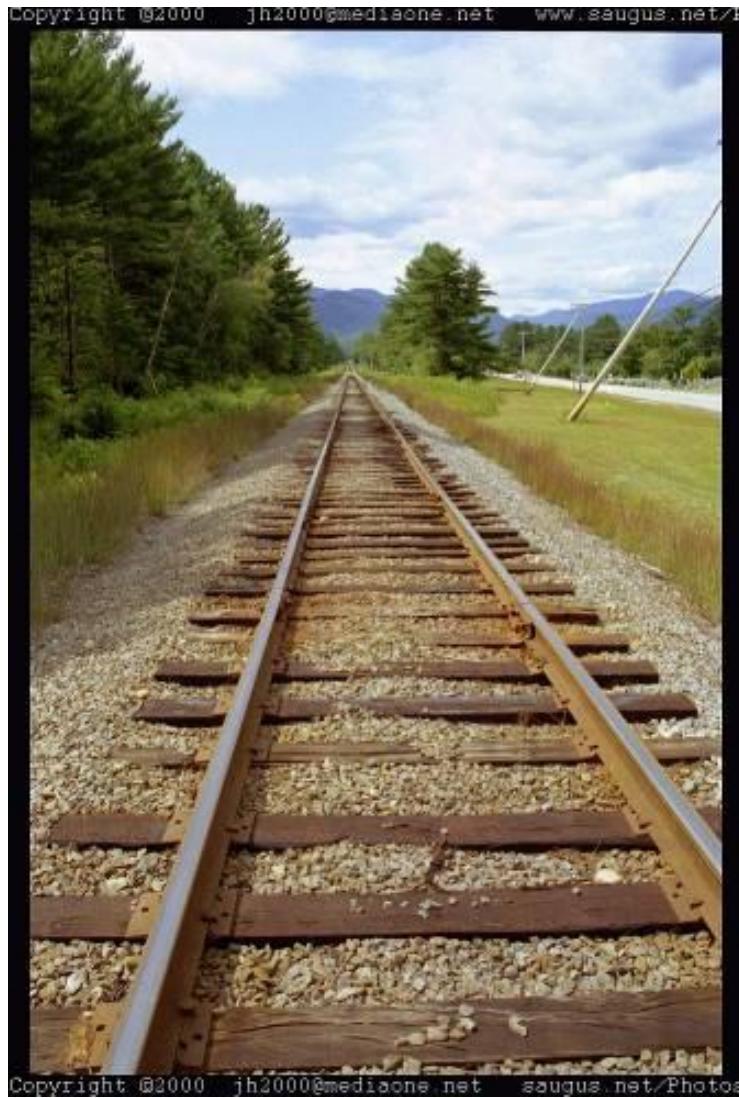
2D image



What have we lost?

- Angles
- Distances (lengths)

Funny things happen...



Parallel lines aren't...

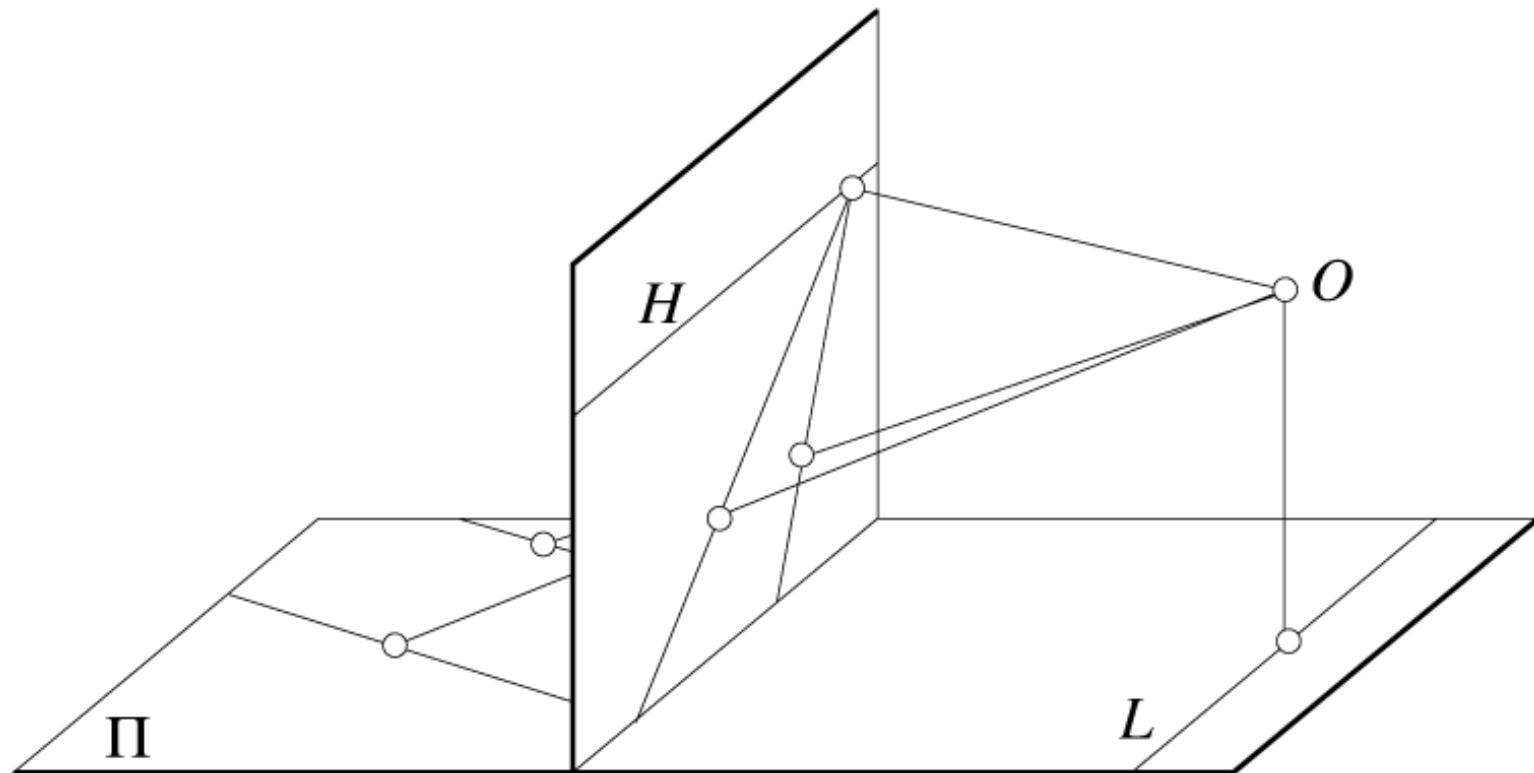


Figure by David Forsyth

Exciting New Study!



Sailors Take Warning



A.V. CLUB



VIDEO

POLITICS

SPORTS

BUSINESS

SCIENCE/TECH

ENTERTAINMENT

LOCAL

Q search

RECENT NEWS

Ariel Castro Failed By System

New Skin Cream To Do Something

Assad Unable To Convince Putin
That He Used Chemical Weapons
On Syrians

Royal Baby Already Making New
Friends

College-Aged Female Finds
Unlikely Kindred Spirit In Audrey
Hepburn

Personal Trainer Has Desk

Bruce Springsteen On Fence About
Playing Assad's Birthday Gig

Study: People Far Away From You Not Actually Smaller

NEWS • Science & Technology • ISSUE 49•34 • Aug 22, 2013



Researchers say that, contrary to prior assertions, the subject above stands at equal height at left and at right, and does not grow smaller as he walks away from the camera.

Lengths can't be trusted...

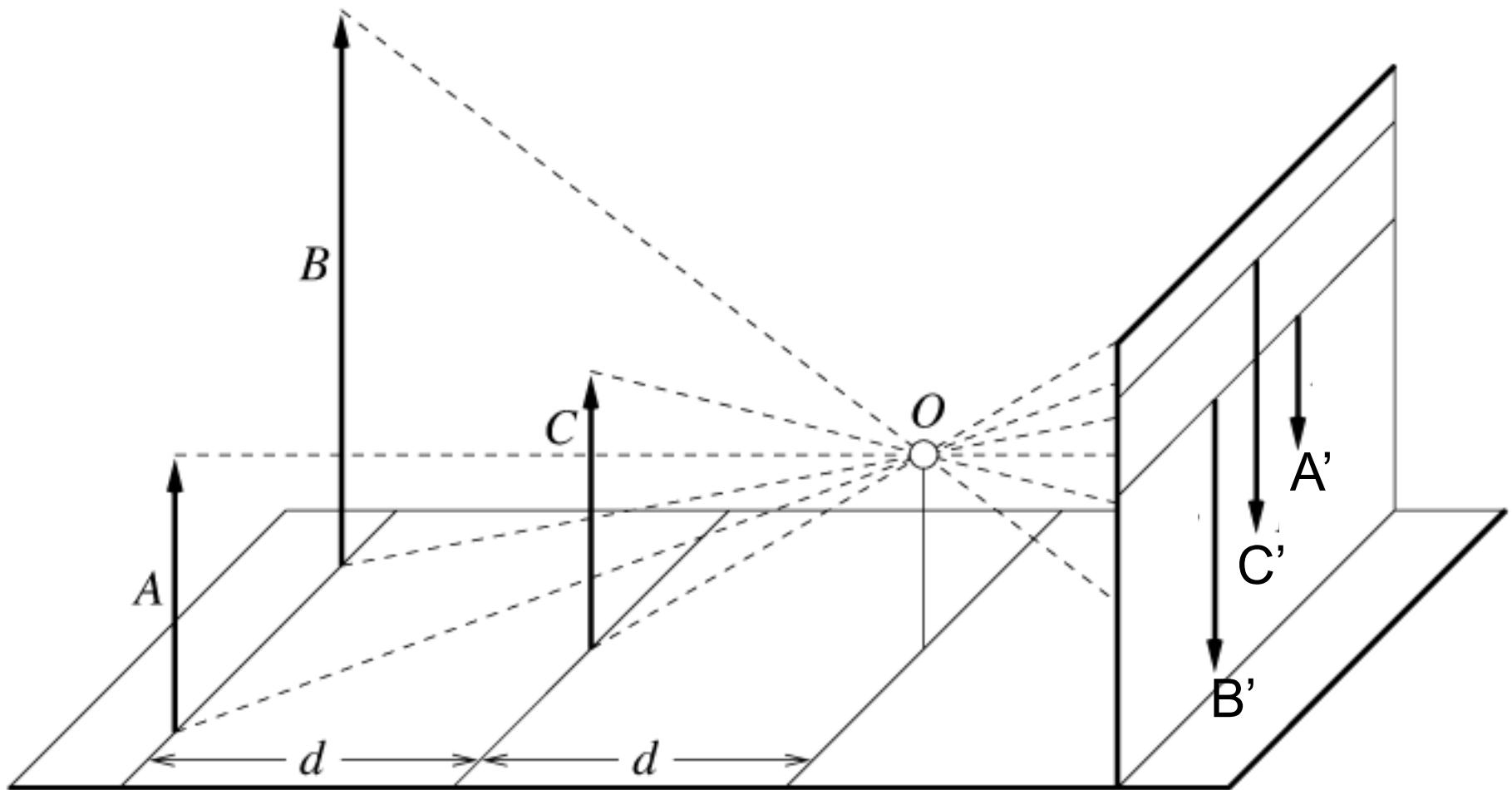
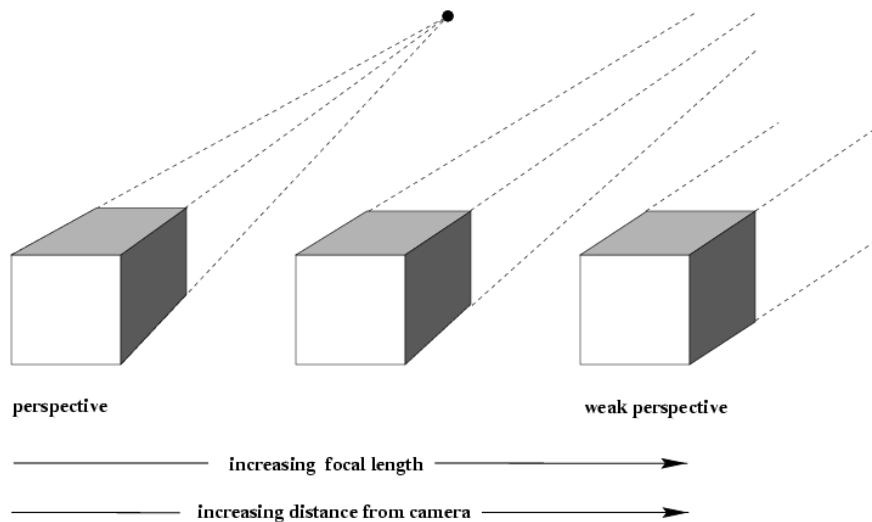


Figure by David Forsyth

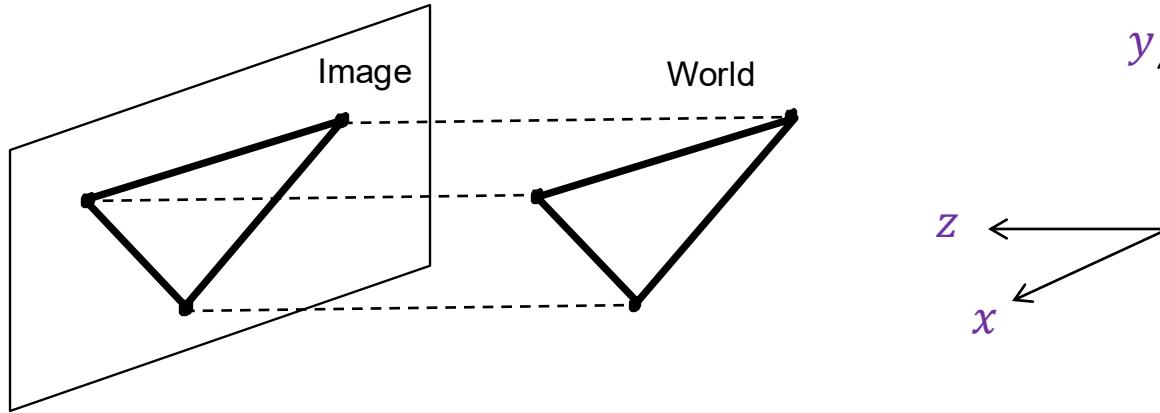
Orthographic or parallel projection

- What happens if we walk infinitely far away and zoom infinitely far in?



Orthographic or parallel projection

- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!



$$(x, y, z) \rightarrow (x, y)$$

Orthographic or parallel projection

- Special case of perspective projection
 - Distance from center of projection to image plane is infinite
 - Projection equation: simply drop the z coordinate!

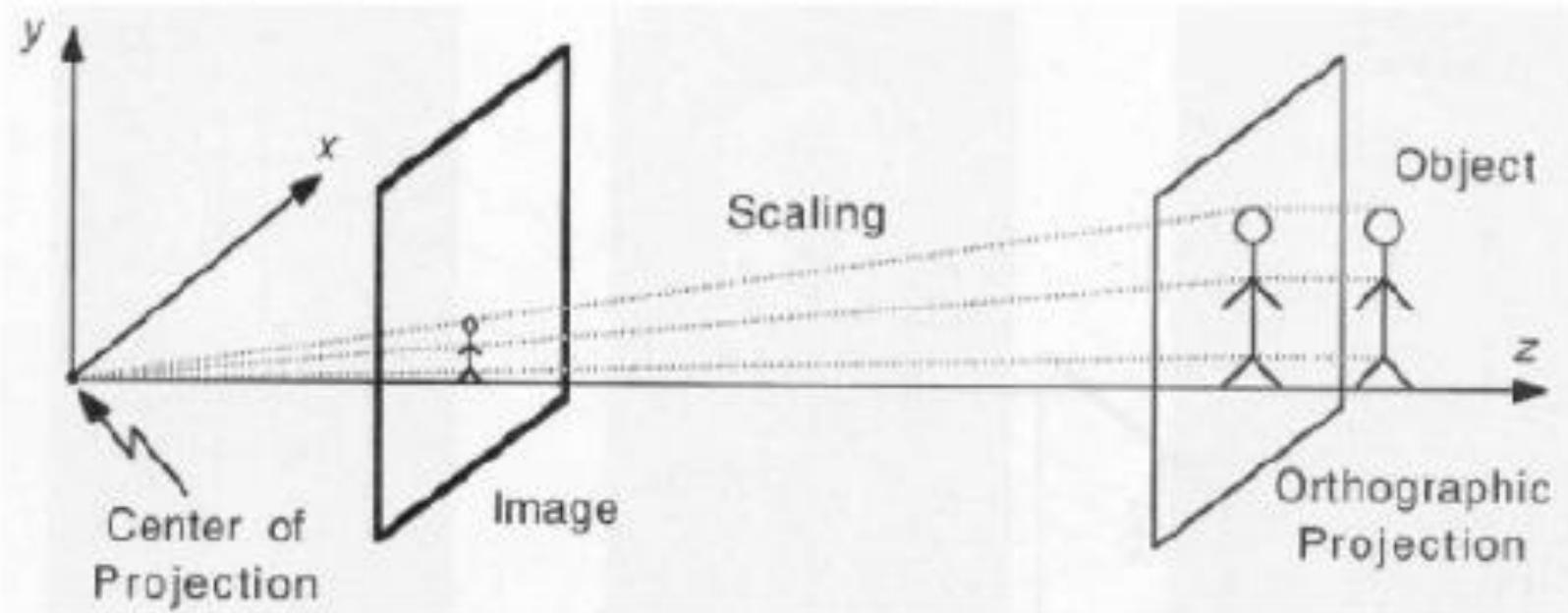


SimCity 2000

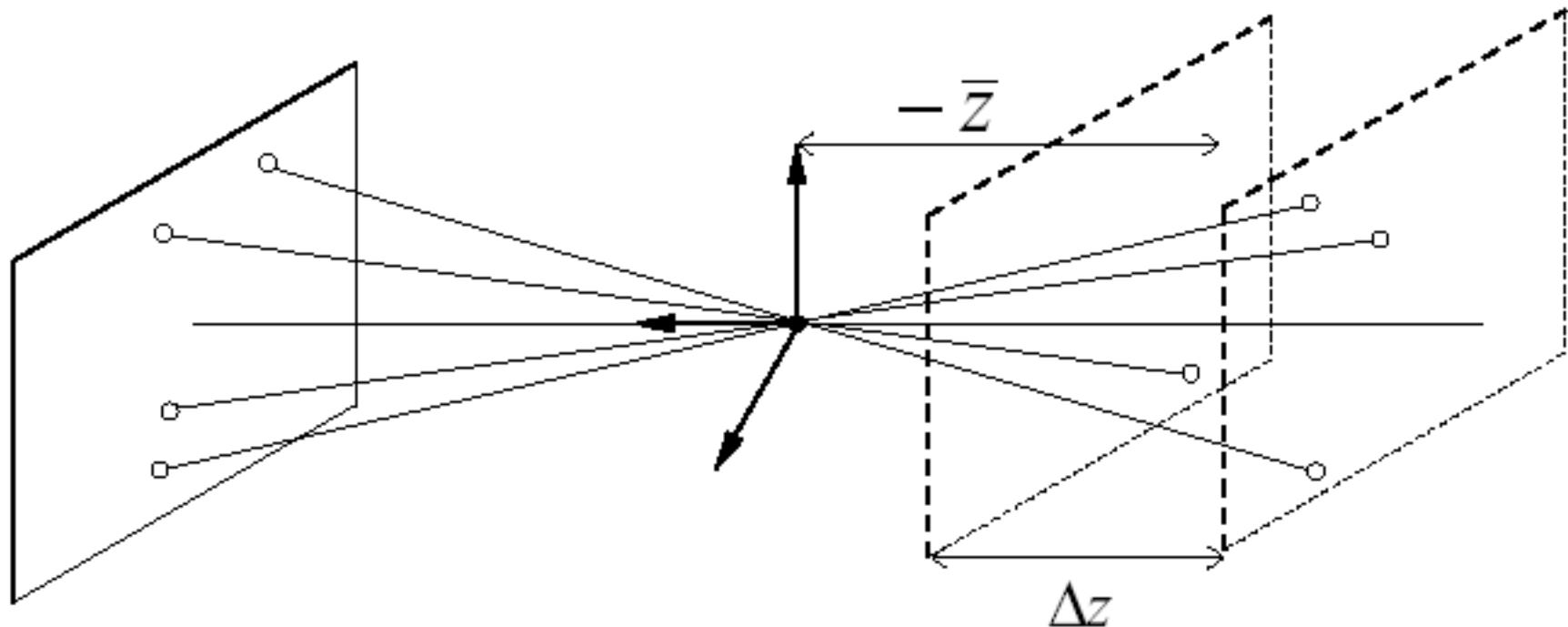


12th century Chinese scroll
(via [A. Hertzmann](#))

Scaled Orthographic or “Weak Perspective”



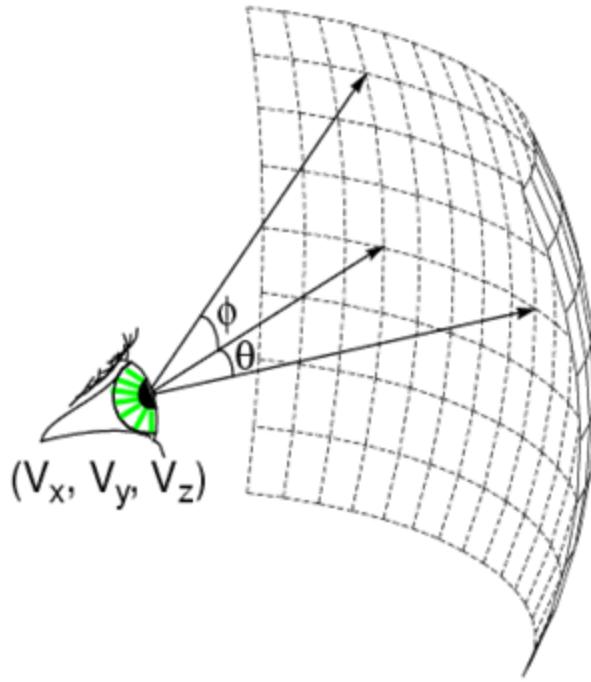
Scaled Orthographic or “Weak Perspective”



$$\text{If } \Delta z \ll -\bar{z} : \begin{aligned} x' &\approx -mx & m &= -\frac{f}{\bar{z}} \\ y' &\approx -my \end{aligned}$$

Justified if scene depth is small relative to average distance from camera

Spherical Projection



What if PP is spherical with center at COP?
In spherical coordinates, projection is trivial:

$$(\theta, \phi, f) \rightarrow (\theta, \phi)$$

Note: doesn't depend on focal length f !

Building a real camera

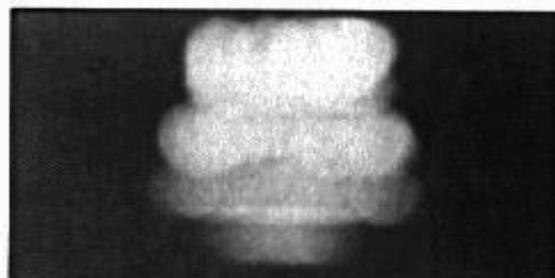


Another way to make pinhole camera



Why so
blurry?

Shrinking the aperture



2 mm



1 mm



0.6mm



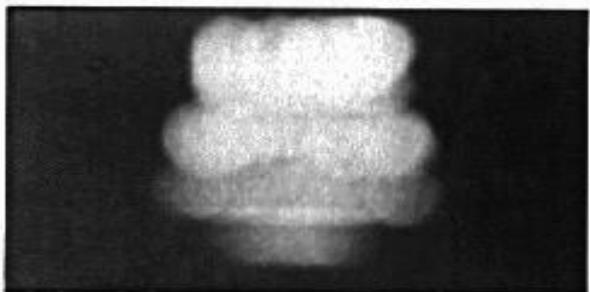
0.35 mm

Less light gets through

Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects...

Shrinking the aperture



2 mm



1 mm



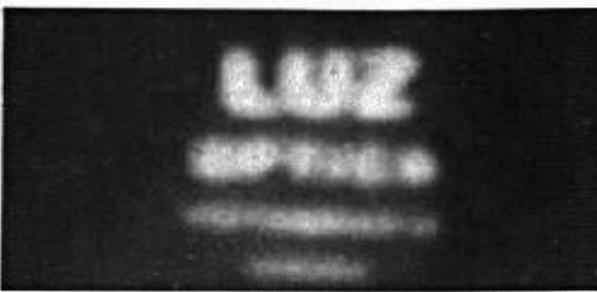
0.6mm



0.35 mm

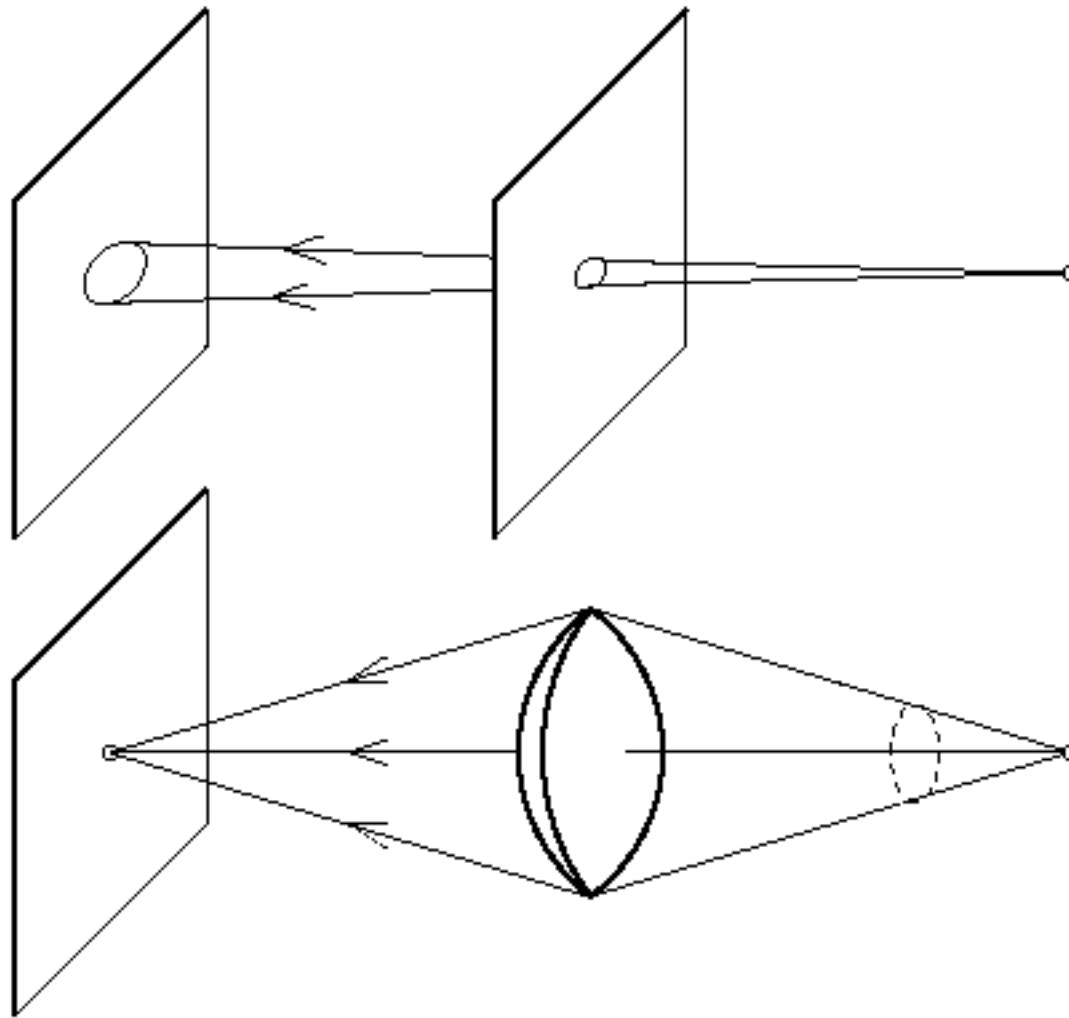


0.15 mm

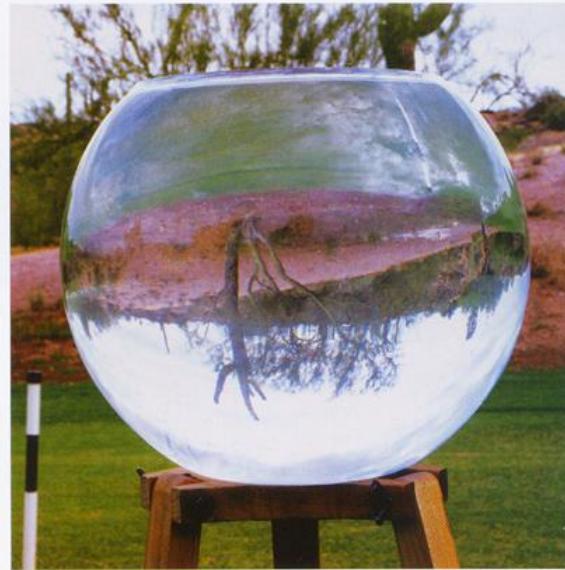
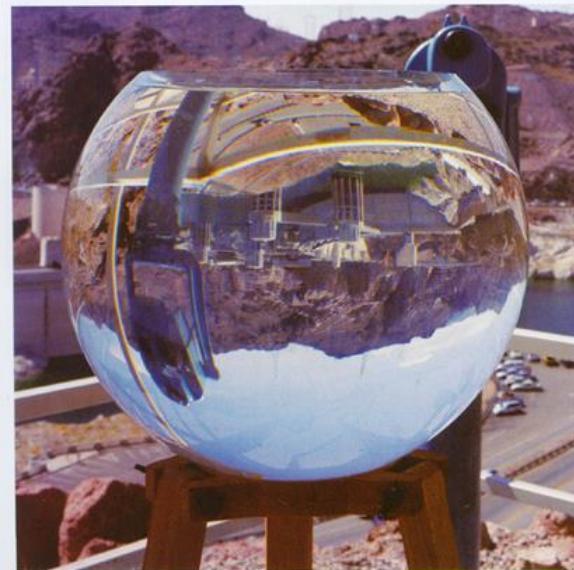
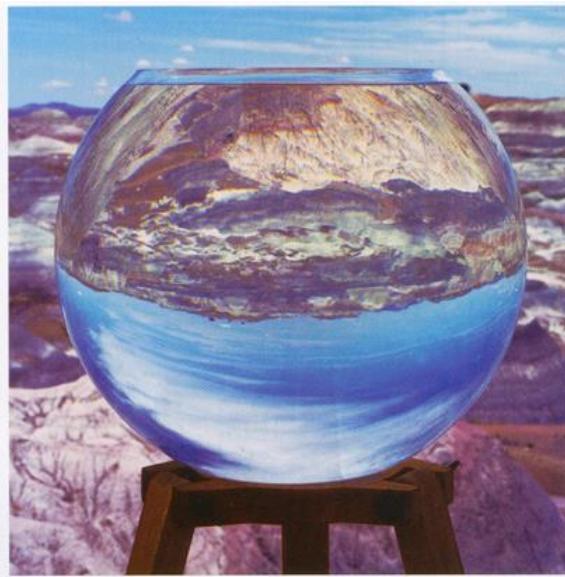
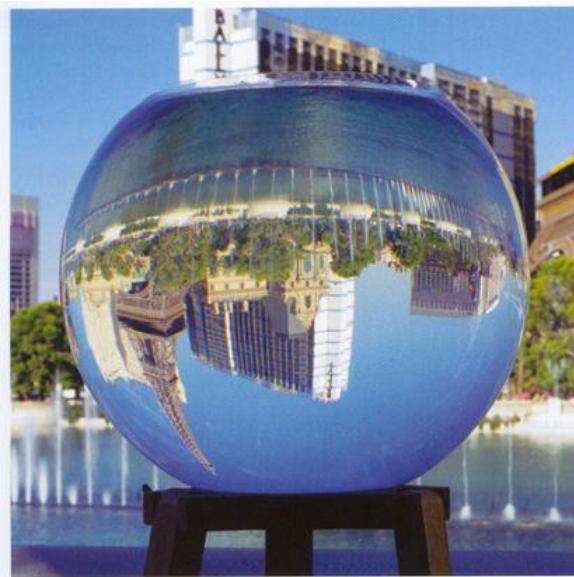


0.07 mm

The reason for lenses



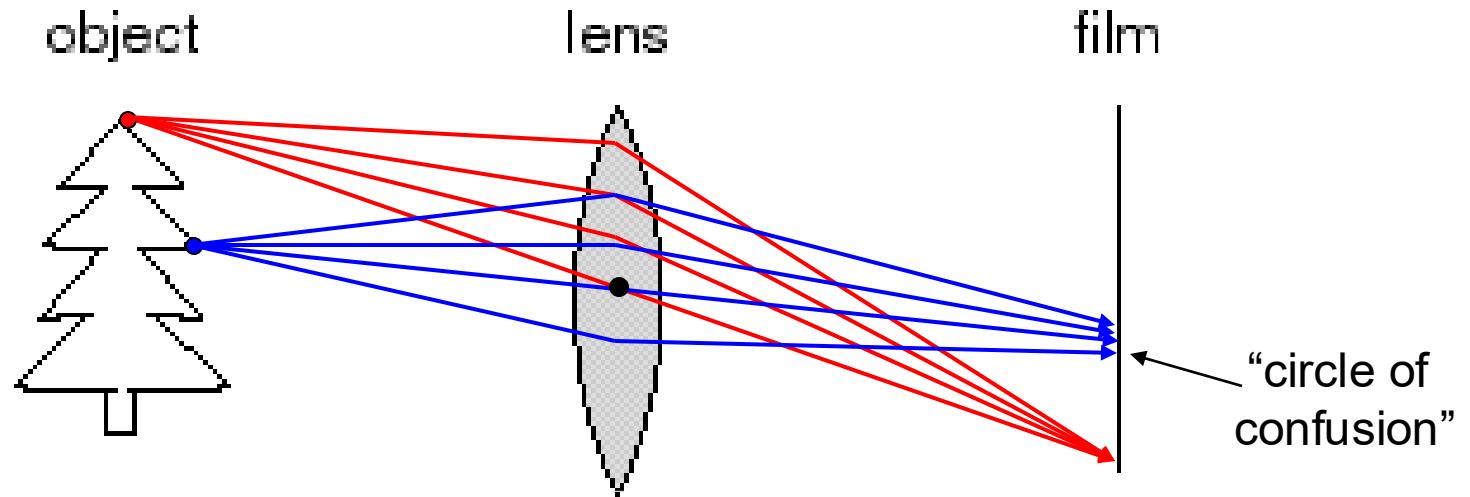
Replacing pinholes with lenses



Photography,
London et al

Focus

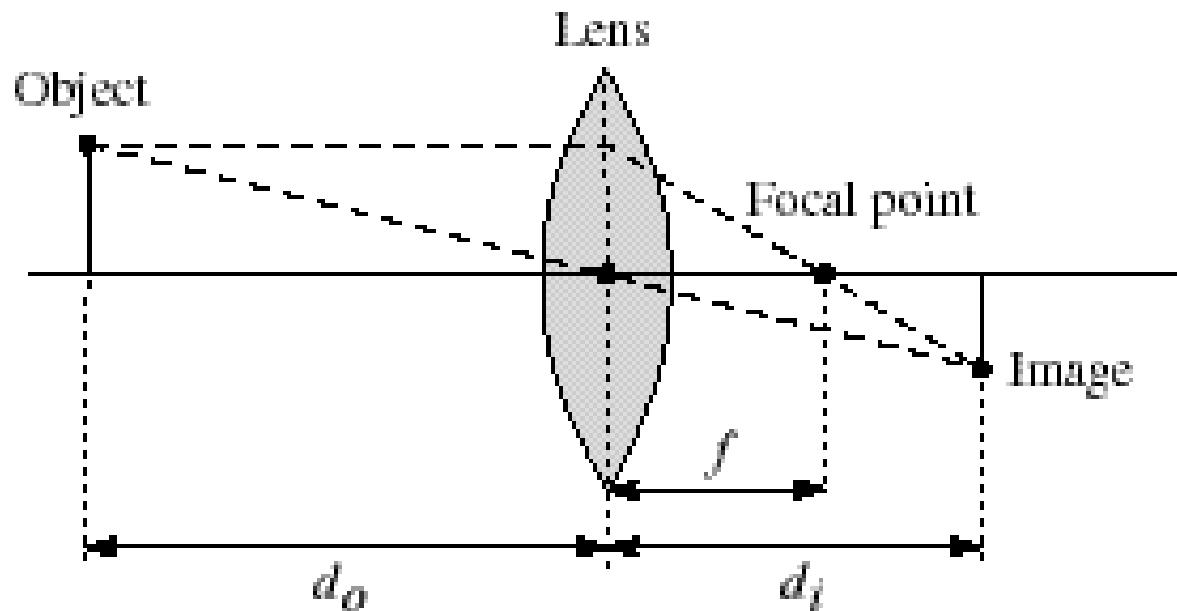
Focus and Defocus



A lens focuses light onto the film

- There is a specific distance at which objects are “in focus”
 - other points project to a “circle of confusion” in the image
- Changing the shape of the lens changes this distance

Thin lenses



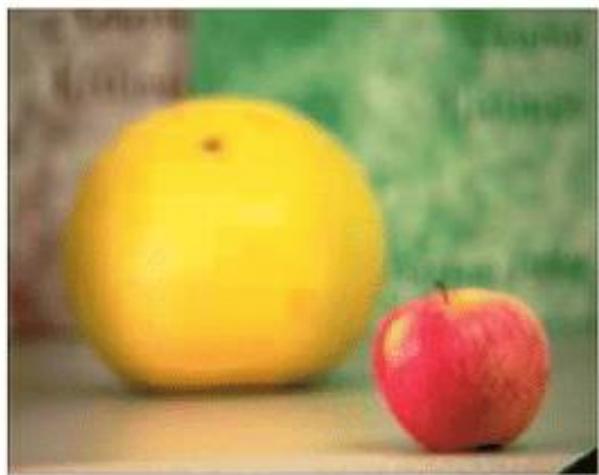
$$\text{Thin lens equation: } \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

- Any object point satisfying this equation is in focus
- What is the shape of the focus region?
- Thin lens applet: http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html (by Fu-Kwun Hwang)

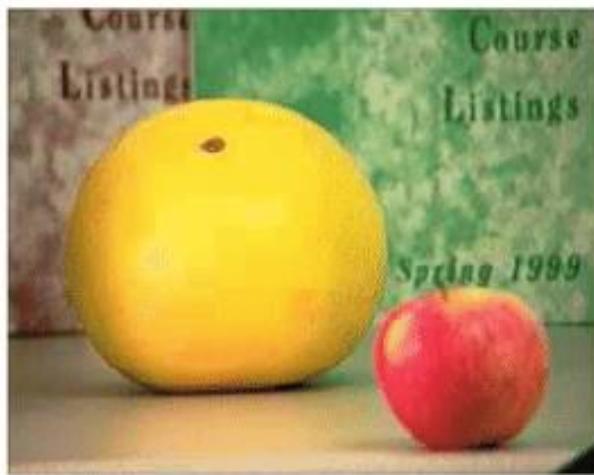
Varying Focus



Varying Focus



(a)



(b)



(c)

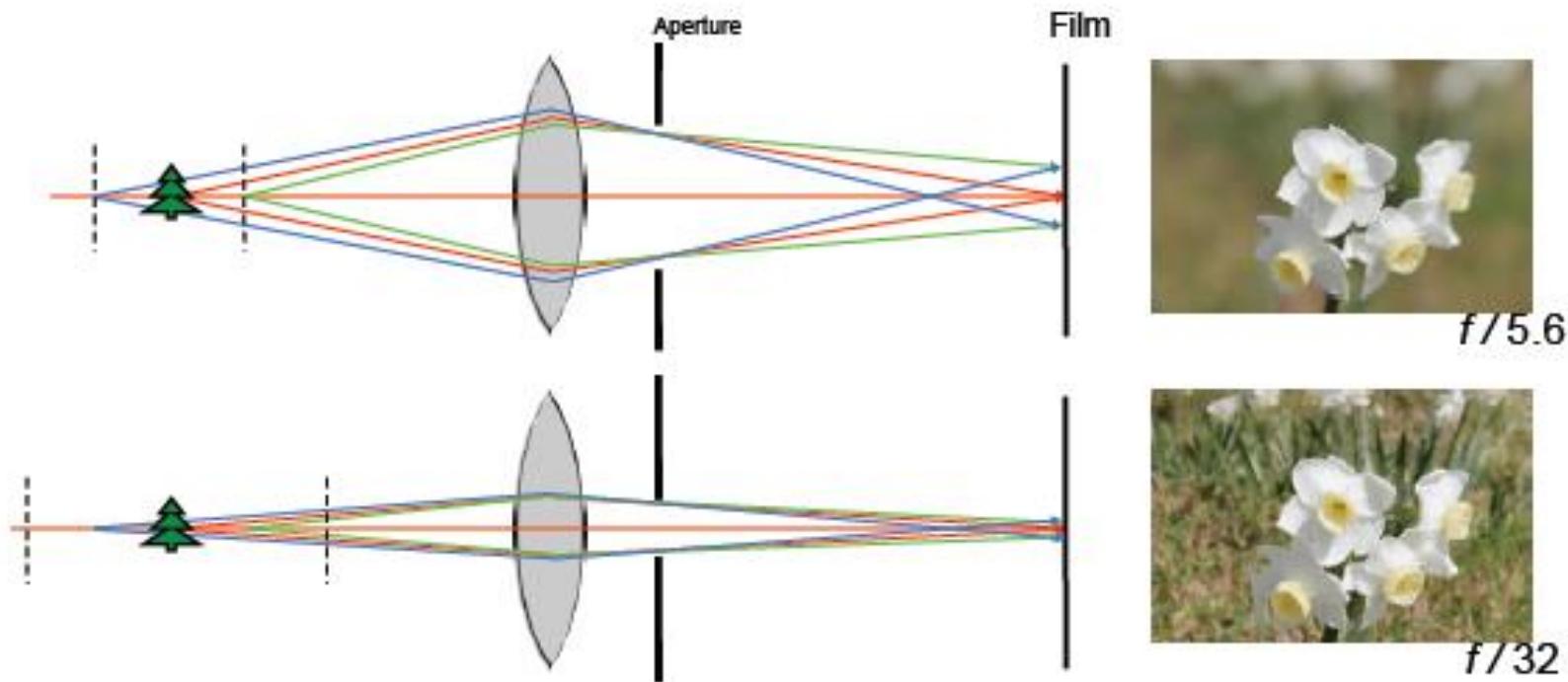
Depth Of Field

Depth of Field



DEPTH OF FIELD
DEPTH OF FIELD

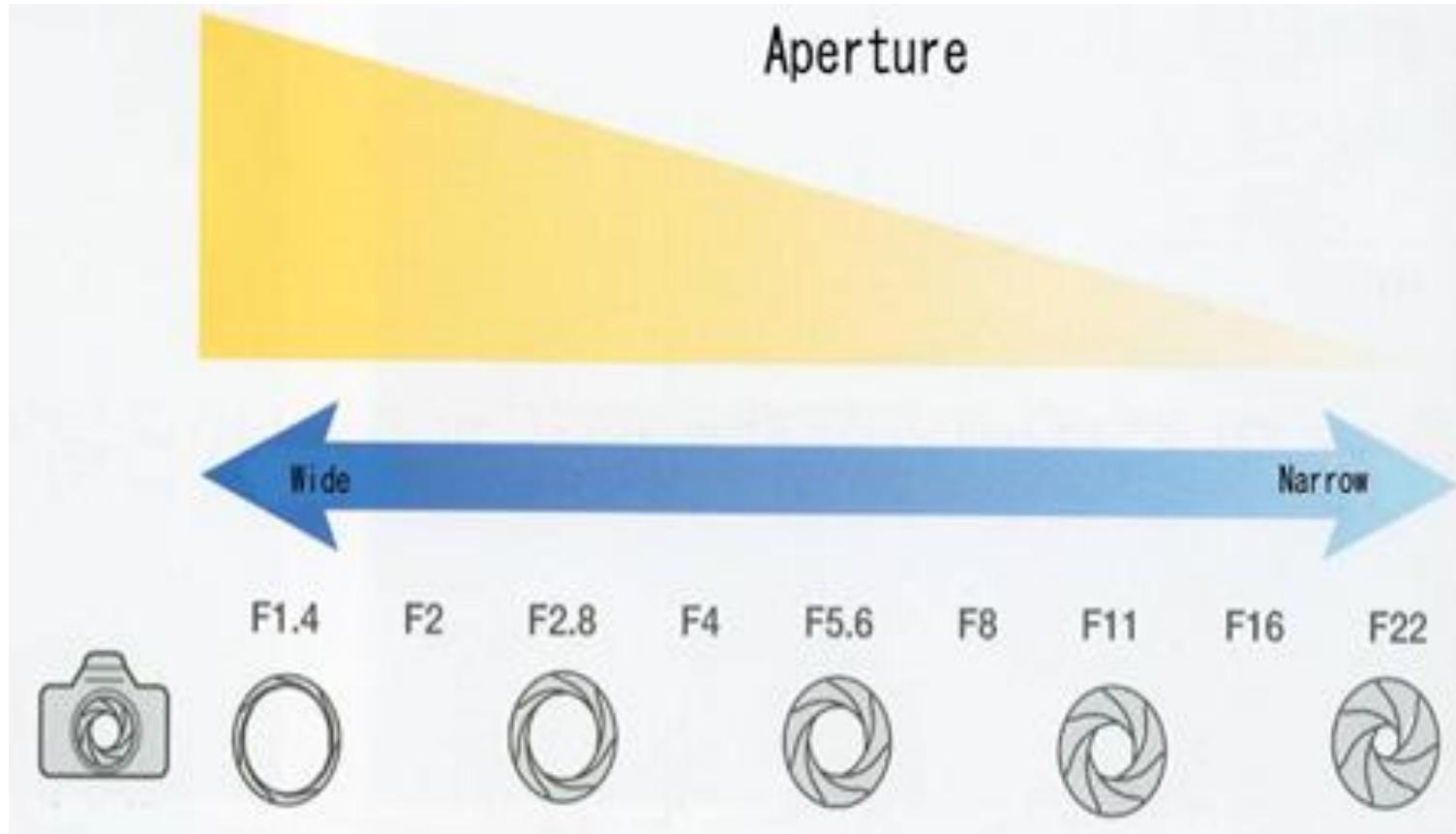
Aperture controls Depth of Field



Changing the aperture size affects depth of field

- A smaller aperture increases the range in which the object is approximately in focus
- But small aperture reduces amount of light – need to increase exposure

F-number: focal length / aperture diameter



Varying the aperture



Wide aperture = small DOF



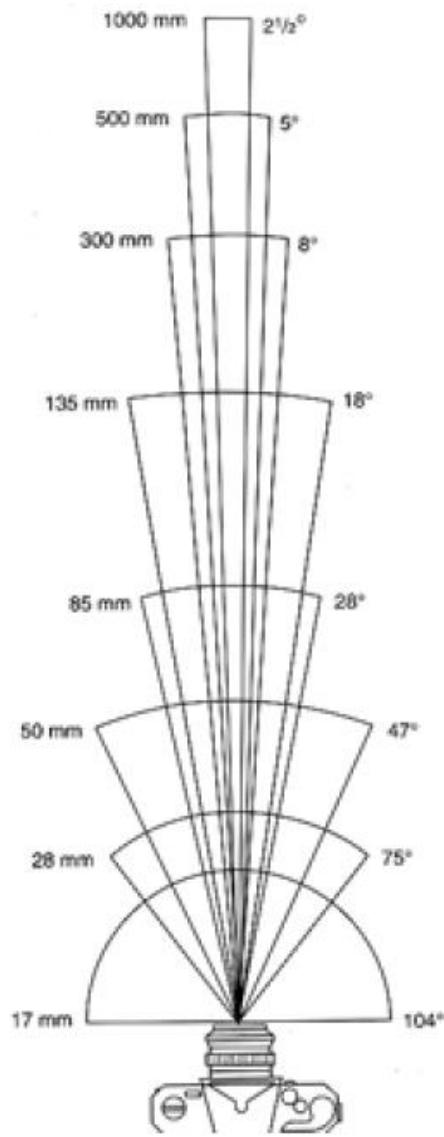
Narrow aperture = large DOF

Nice Depth of Field effect



Field of View (Zoom)

Field of View (Zoom)



17mm



28mm



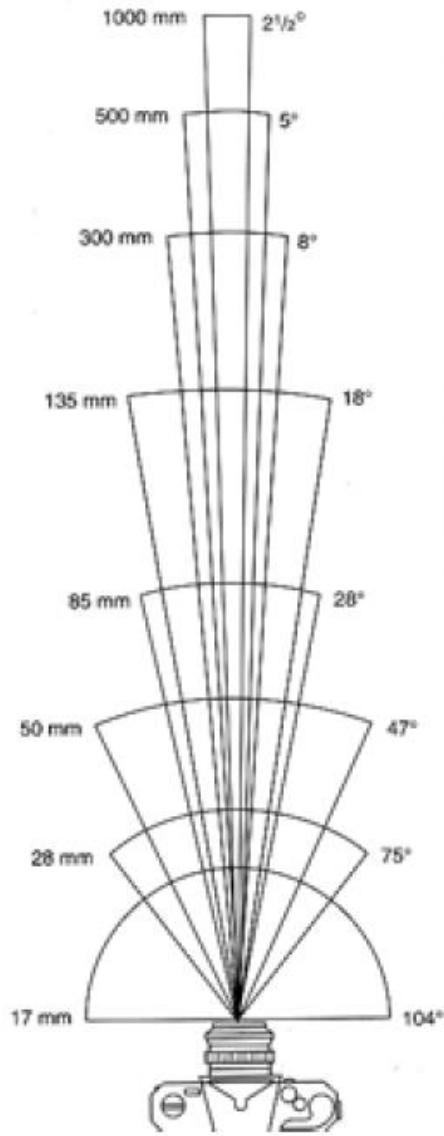
50mm



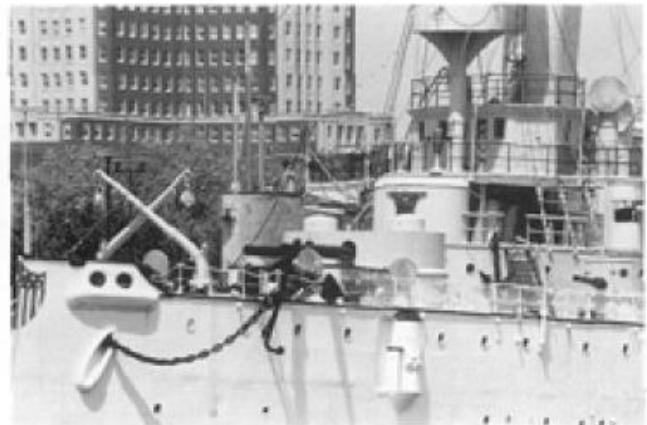
85mm

From London and Upton

Field of View (Zoom) = Cropping



135mm



300mm



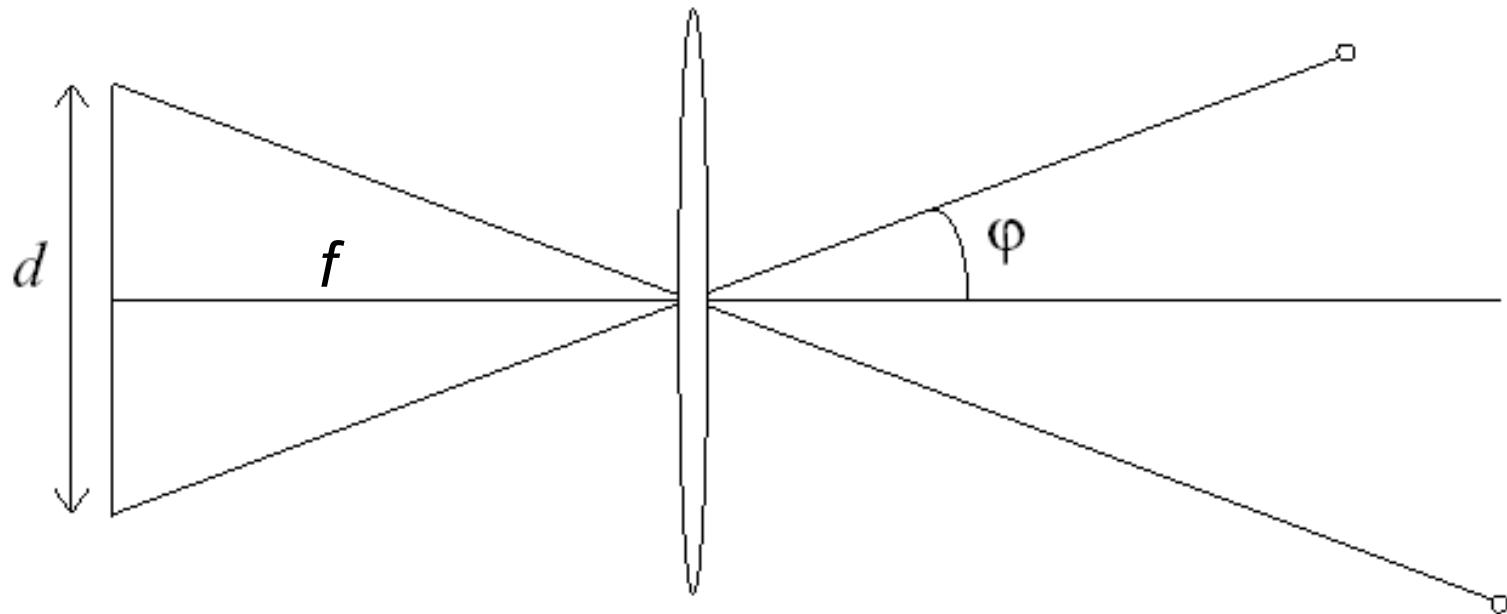
135mm



300mm

From London and Upton

FOV depends of Focal Length



Size of field of view governed by size of the camera retina:

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

Smaller FOV = larger Focal Length

Expensive toys...

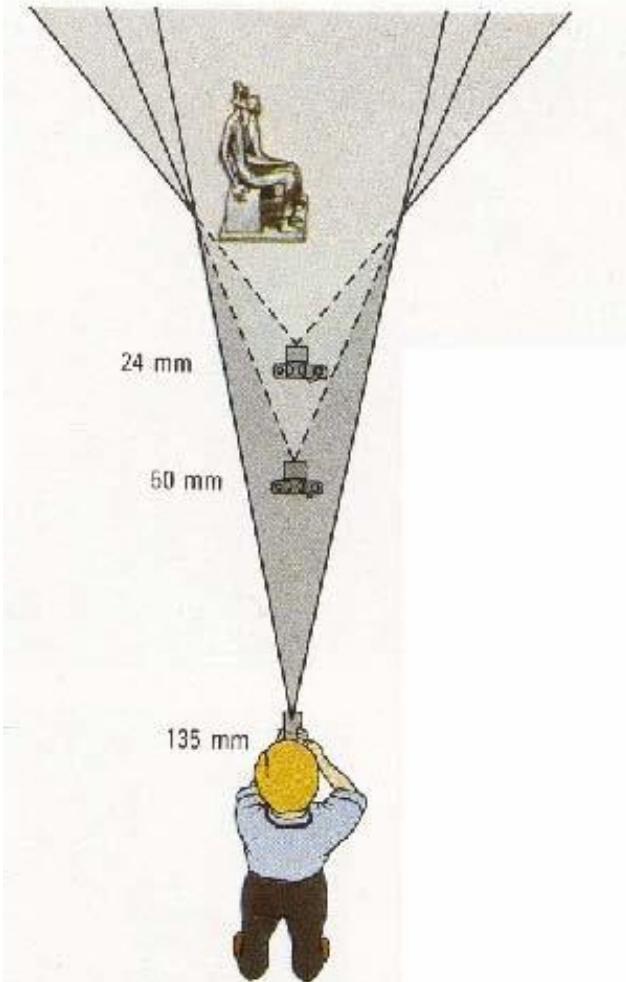


Sigma 200-500mm F2.8 EX DG lens

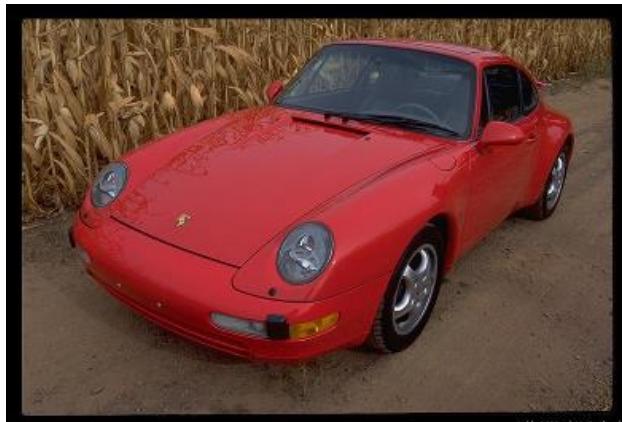
What does 1600mm lens look like?



Field of View / Focal Length

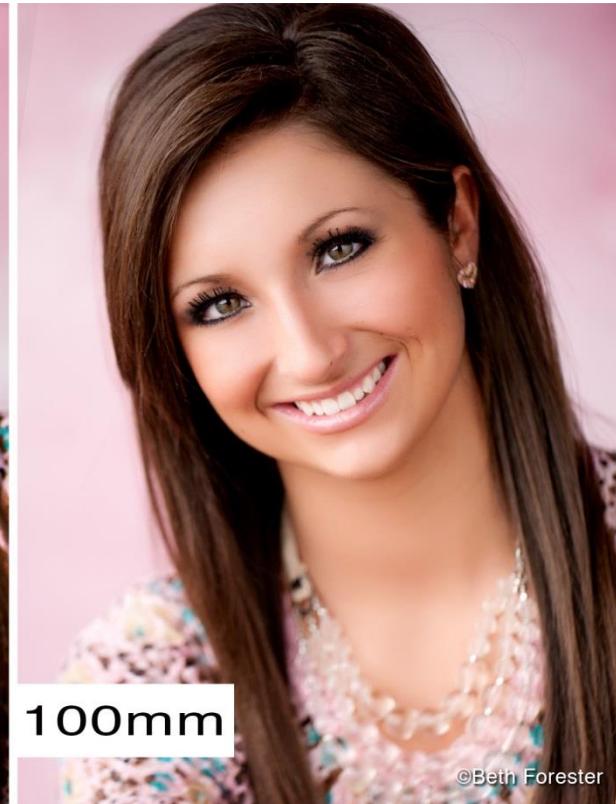


Large FOV, small f
Camera close to car



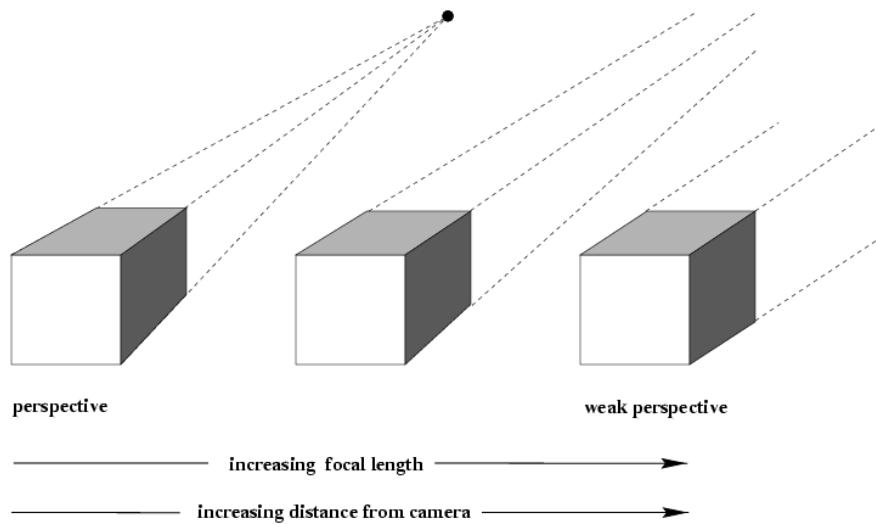
Small FOV, large f
Camera far from the car

Focal length / distance in portraiture



©Beth Forester

Perspective Compression



Dolly Zoom (“Vertigo Shot”)



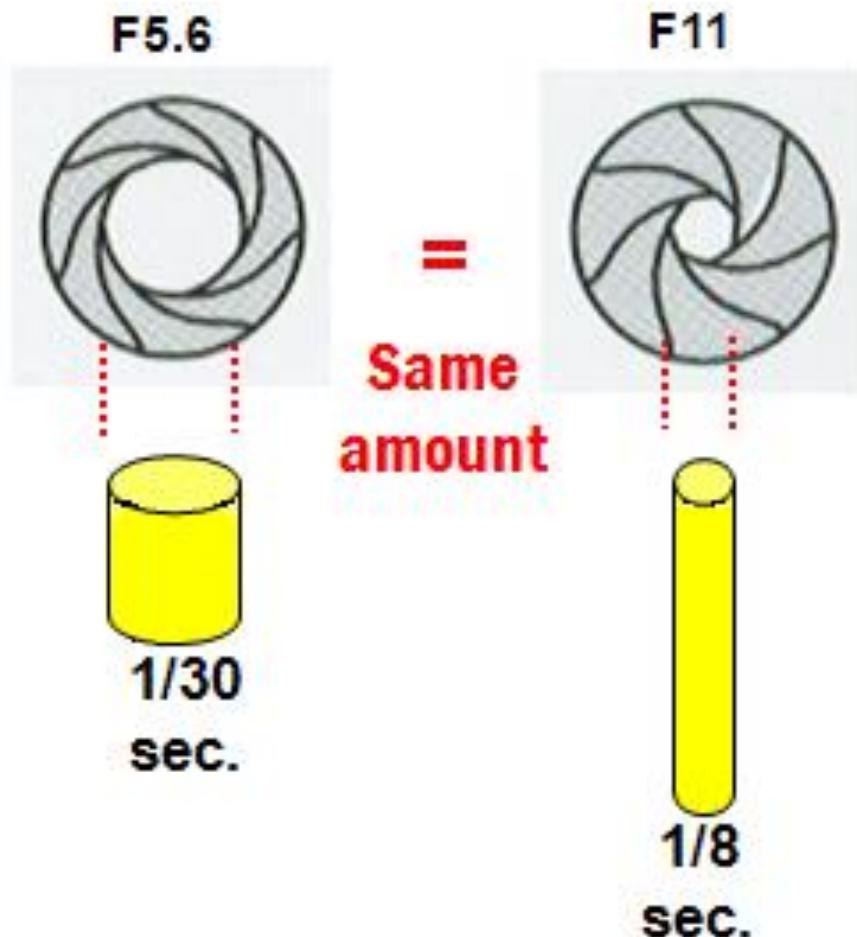
http://filmmakermagazine.com/83872-hitchcock-to-scorcese-47-years-of-the-dolly-zoom/#.VBNtn_IdVac

Exposure

Shutter Speed



Exposure: shutter speed vs. aperture





Fun with slow shutter speeds



Photos by Fredo Durand

More fun



<http://vimeo.com/14958082>

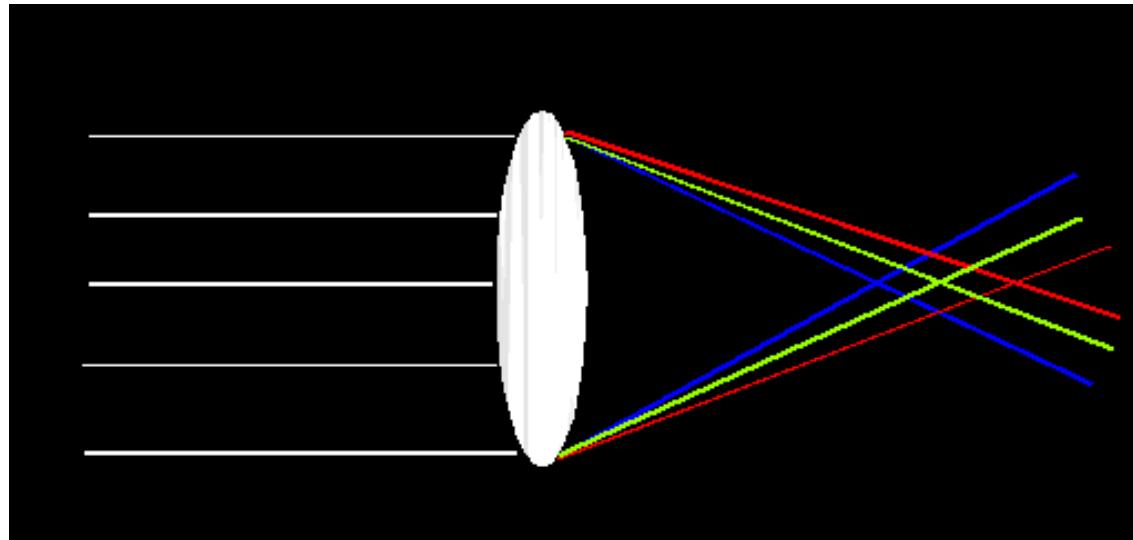
Lens Flaws

Lens Flaws: Chromatic Aberration

Dispersion: wavelength-dependent refractive index

- (enables prism to spread white light beam into rainbow)

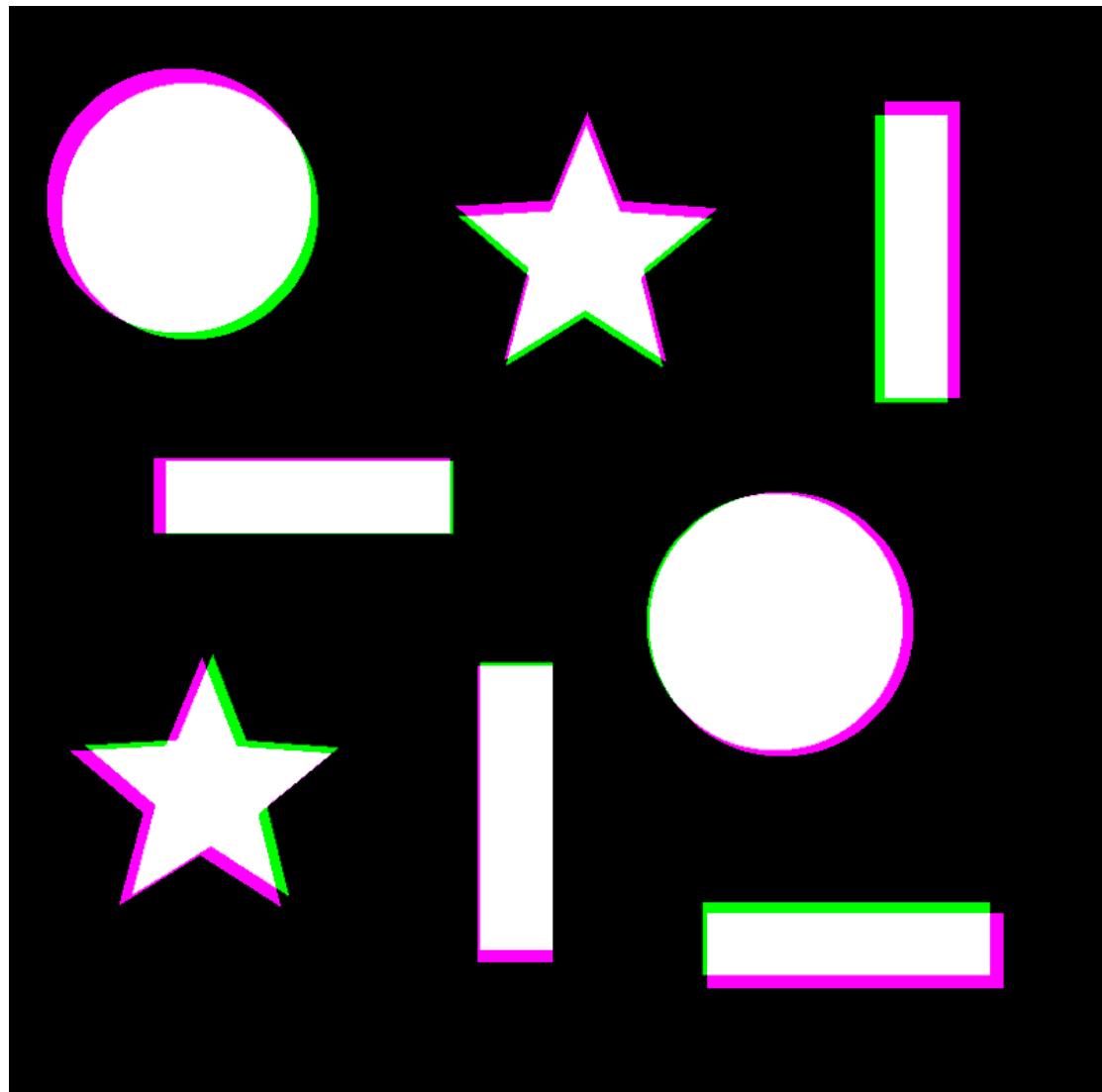
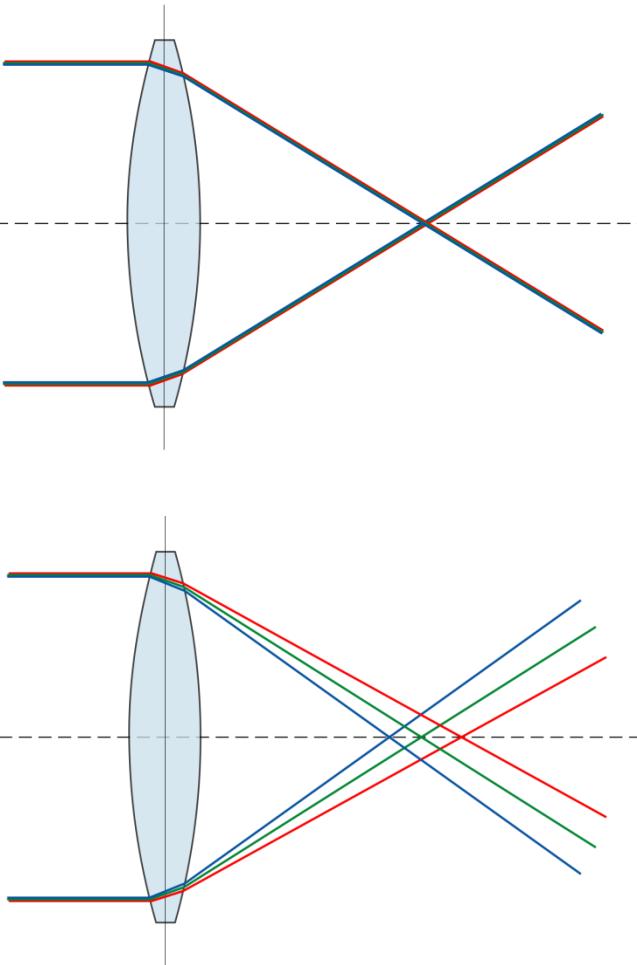
Modifies ray-bending and lens focal length: $f(\lambda)$



color fringes near edges of image

Corrections: add ‘doublet’ lens of flint glass, etc.

Chromatic Aberration



Chromatic Aberration

Near Lens Center



Near Lens Outer Edge

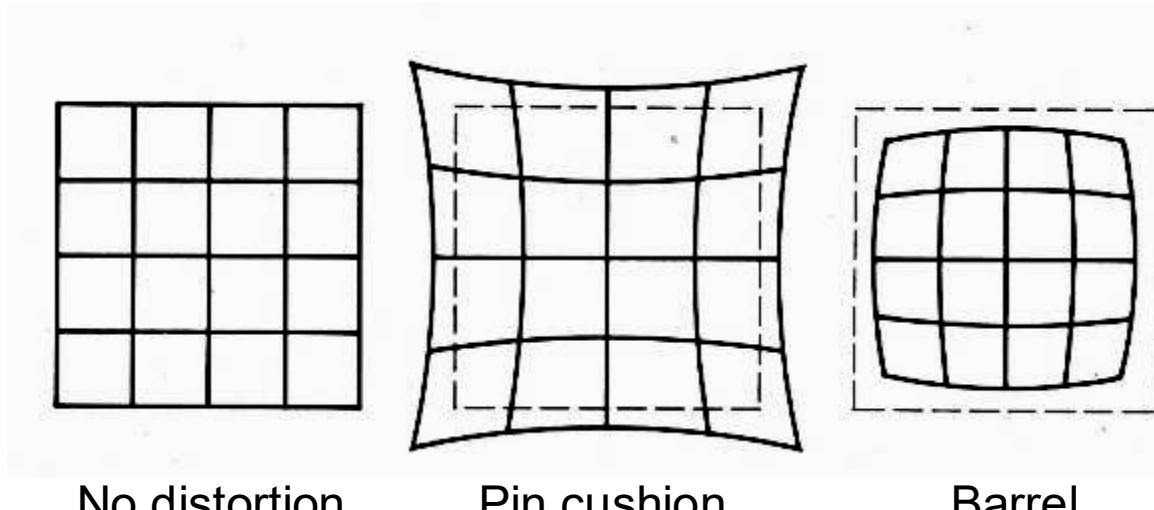


Radial Distortion (*e.g.* ‘Barrel’ and ‘pin-cushion’)

straight lines curve around the image center



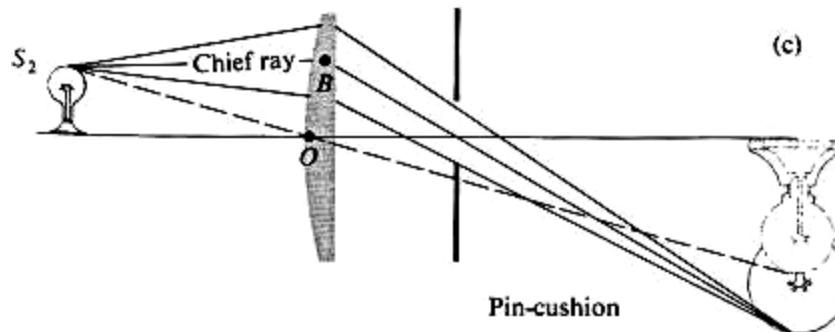
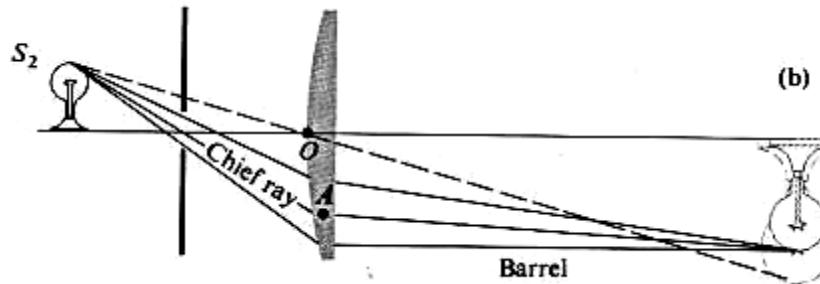
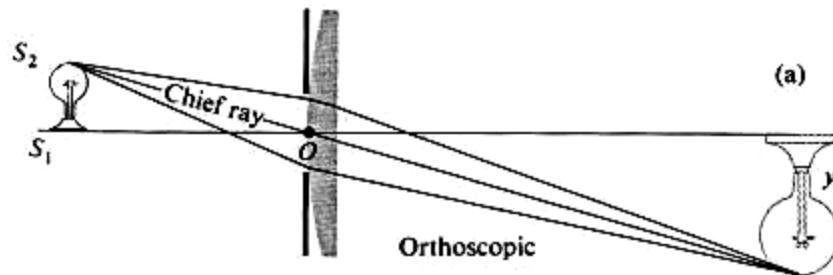
Radial Distortion



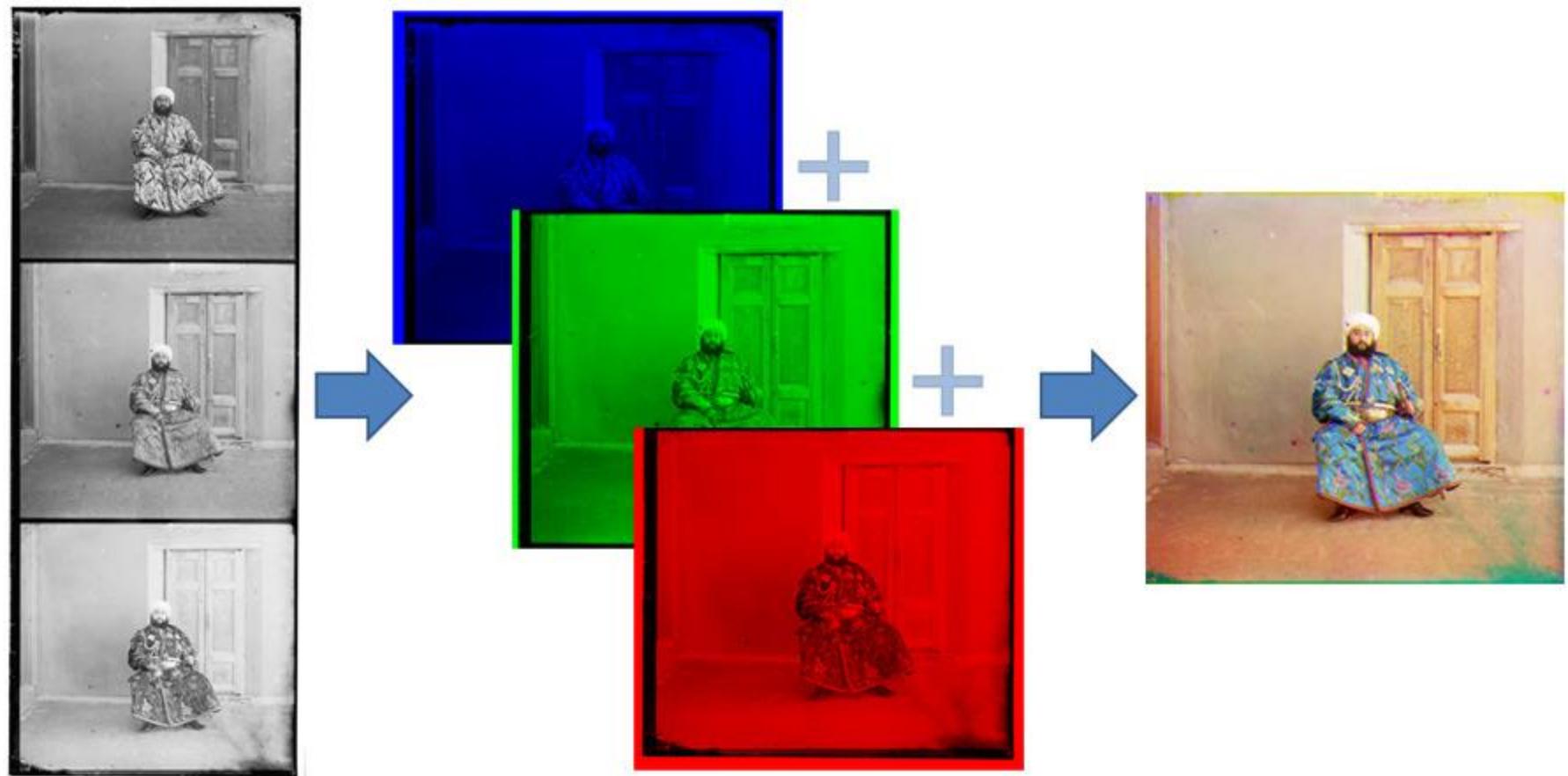
Radial distortion of the image

- Caused by imperfect lenses
- Deviations are most noticeable for rays that pass through the edge of the lens

Radial Distortion



Programming Project #1



Project out TONIGHT!