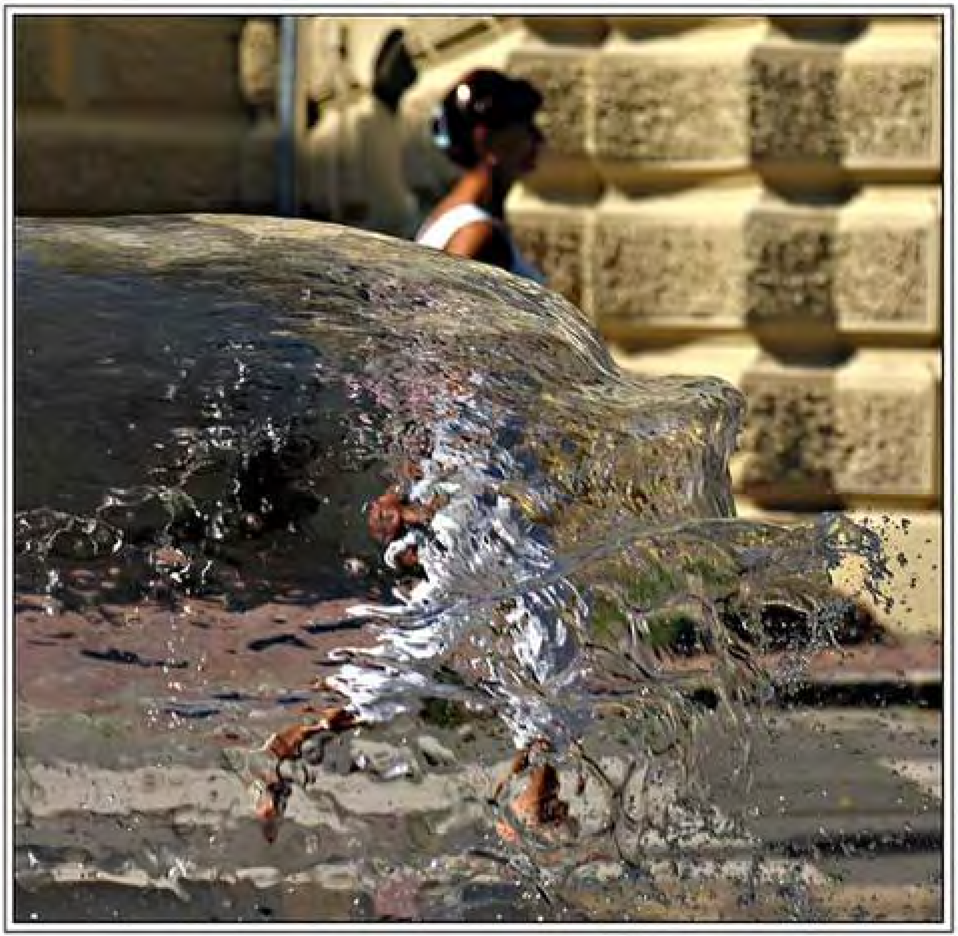
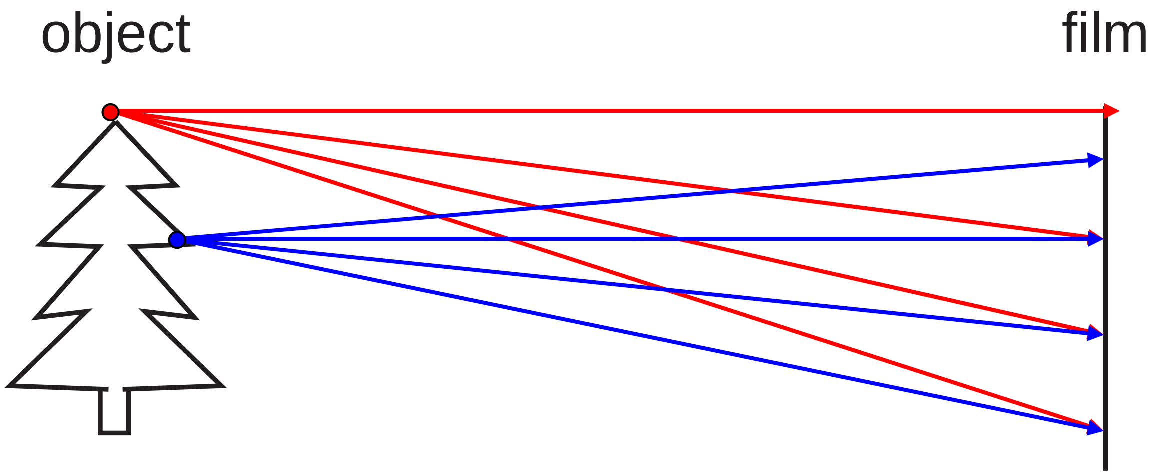
The Camera



15-463: Computational Photography
Alexei Efros, CMU, Fall 2007

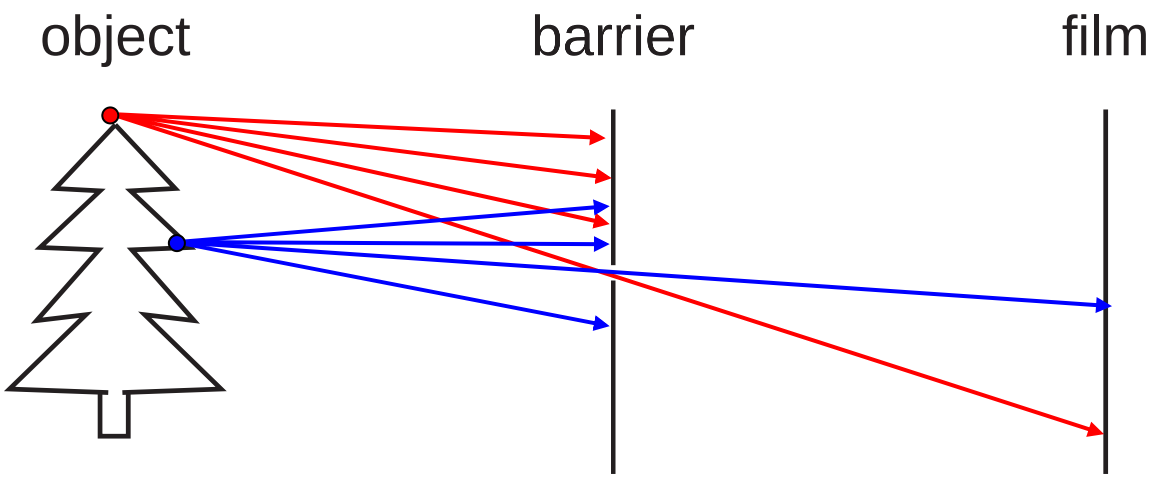
How do we see the world?



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

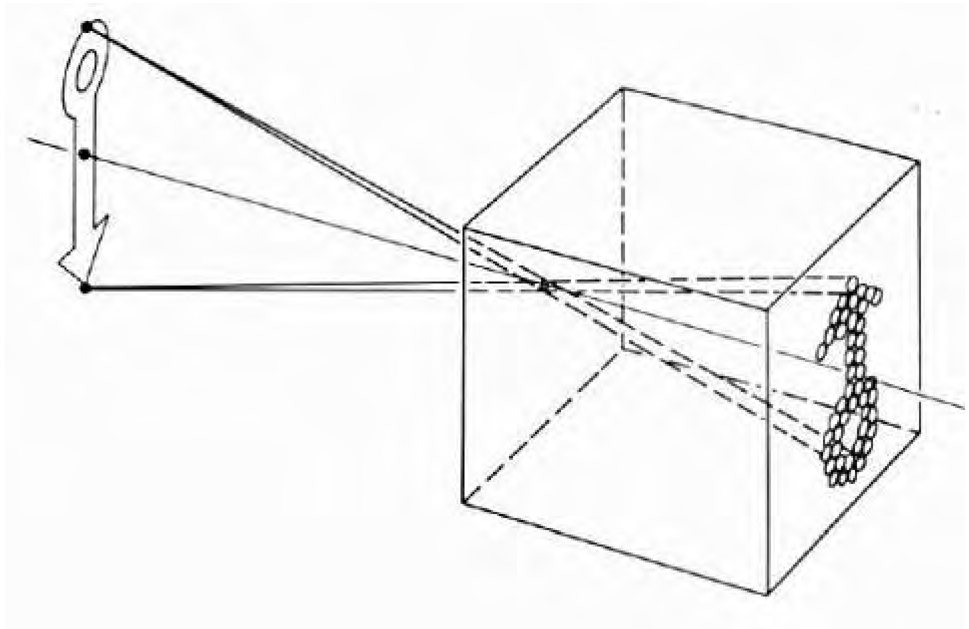


Add a barrier to block off most of the rays

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

Slide by Steve Seitz

Pinhole camera model



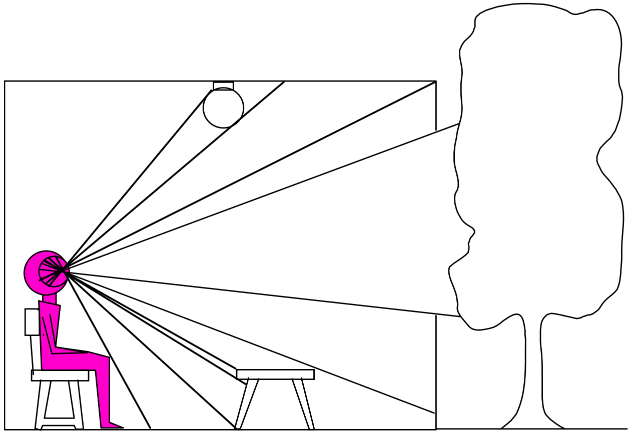
Pinhole model:

- 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

Slide by Steve Seitz

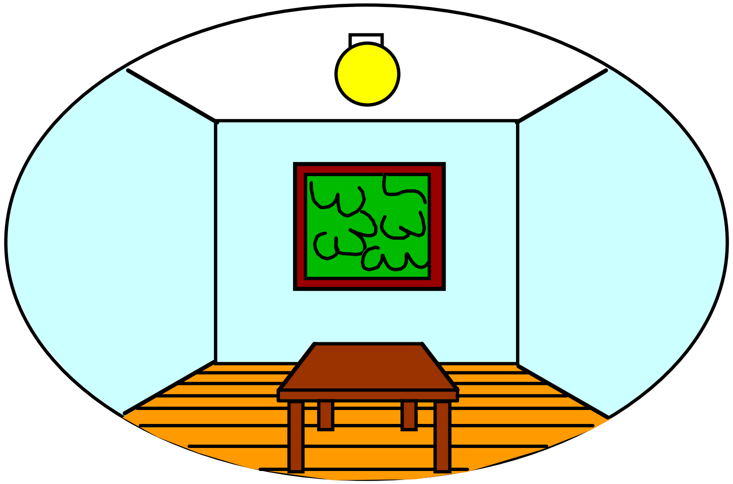
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image

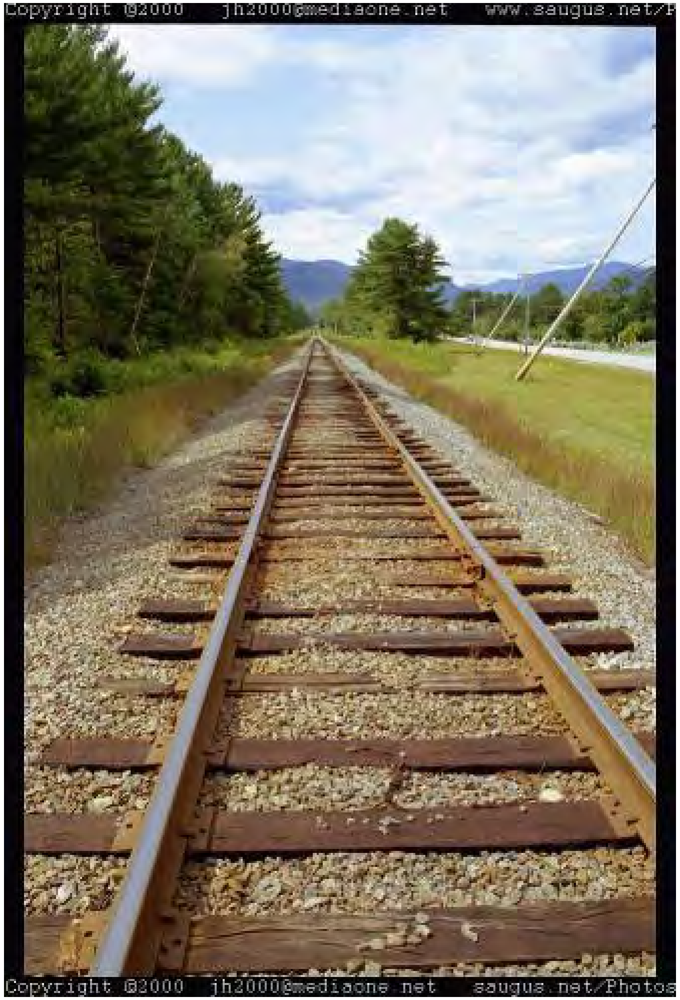


What have we lost?

- Angles
- Distances (lengths)

Figures © Stephen E. Palmer, 2002

Funny things happen…



Parallel lines aren't…

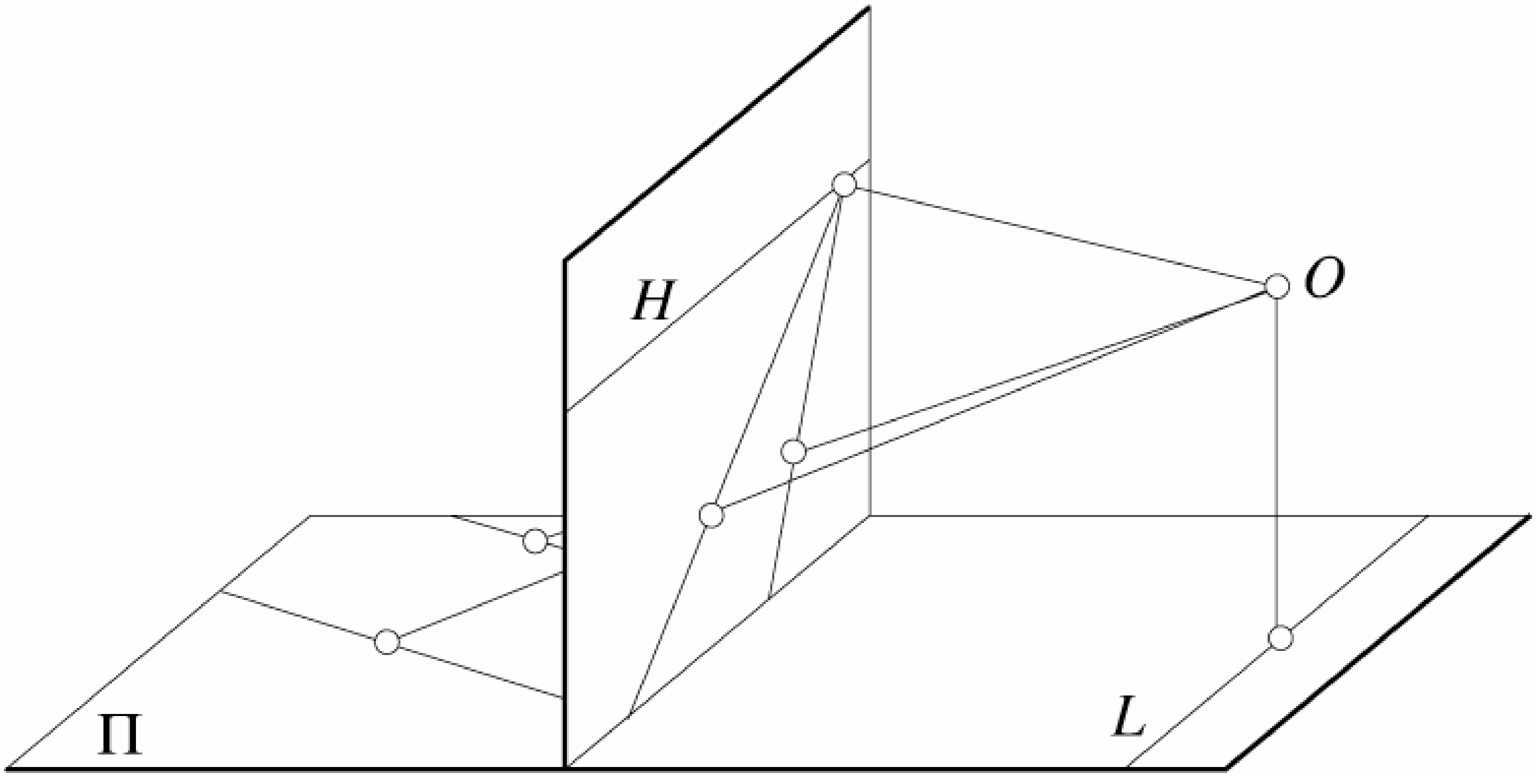


Figure by David Forsyth

Lengths can't be trusted...

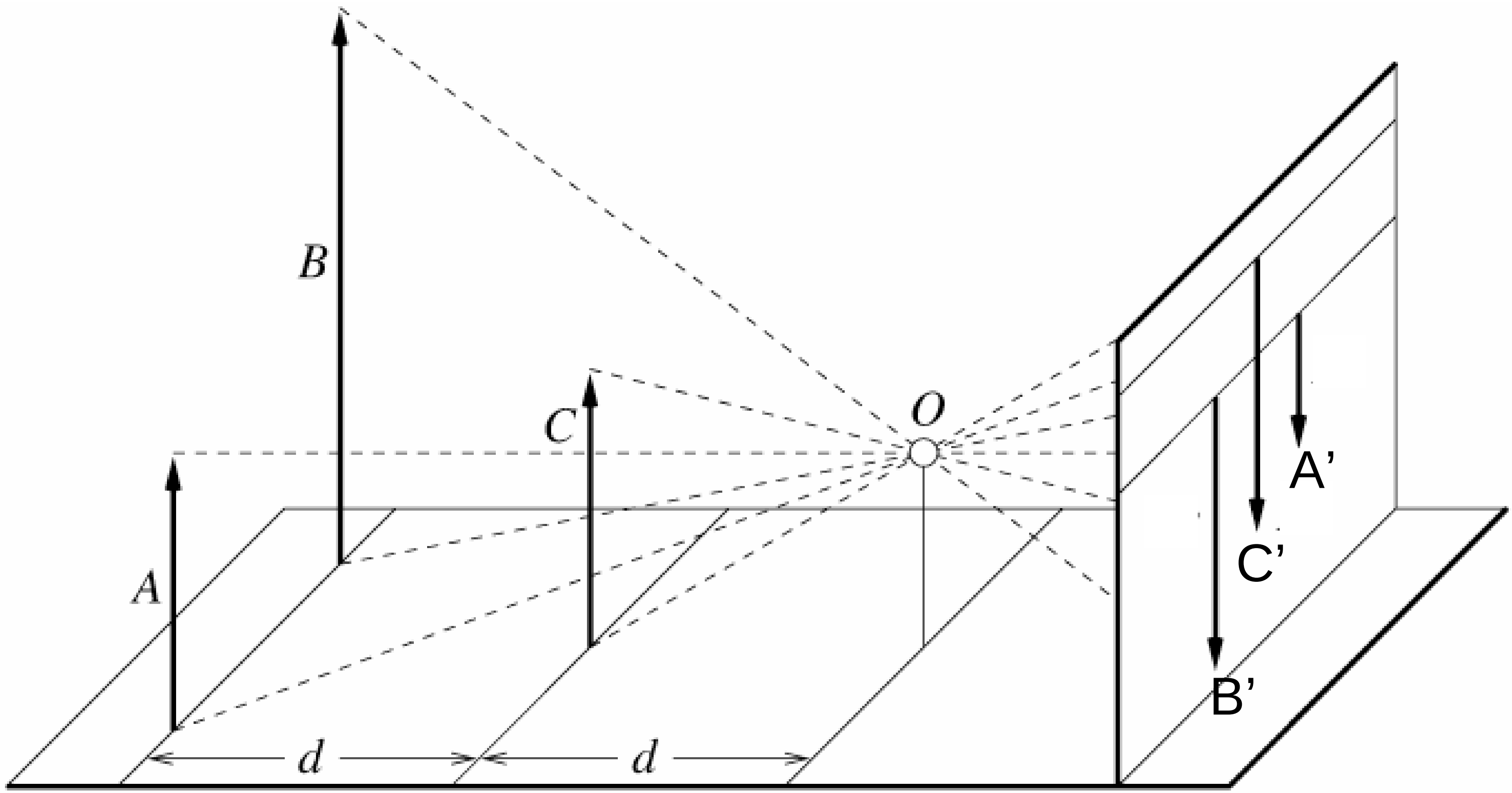
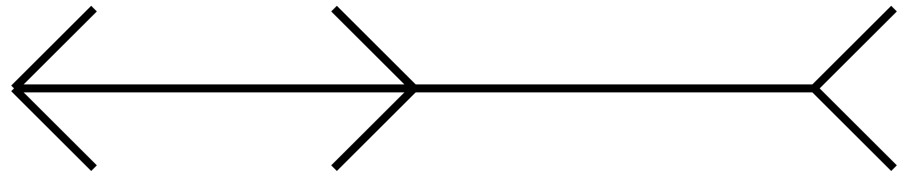
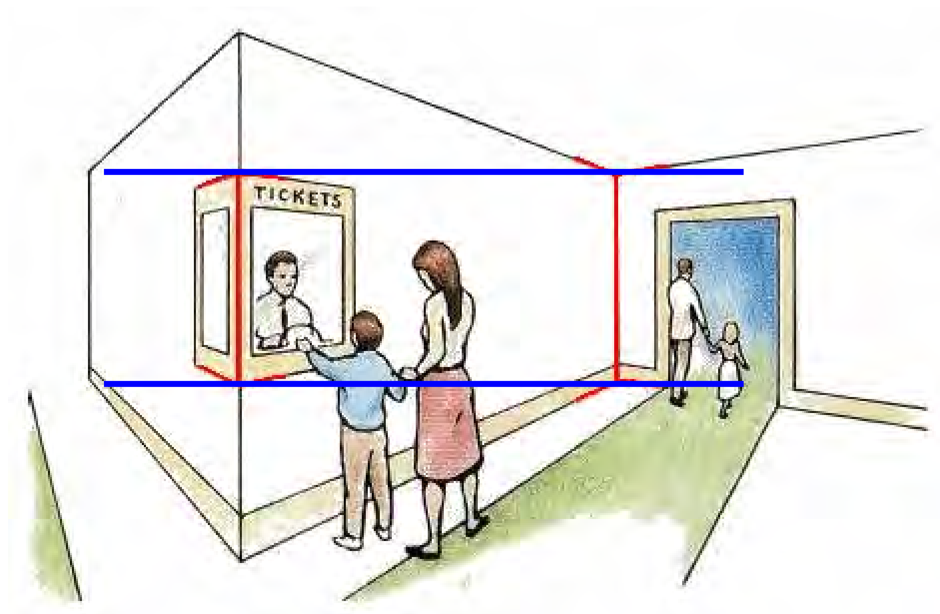


Figure by David Forsyth

…but humans adopt!



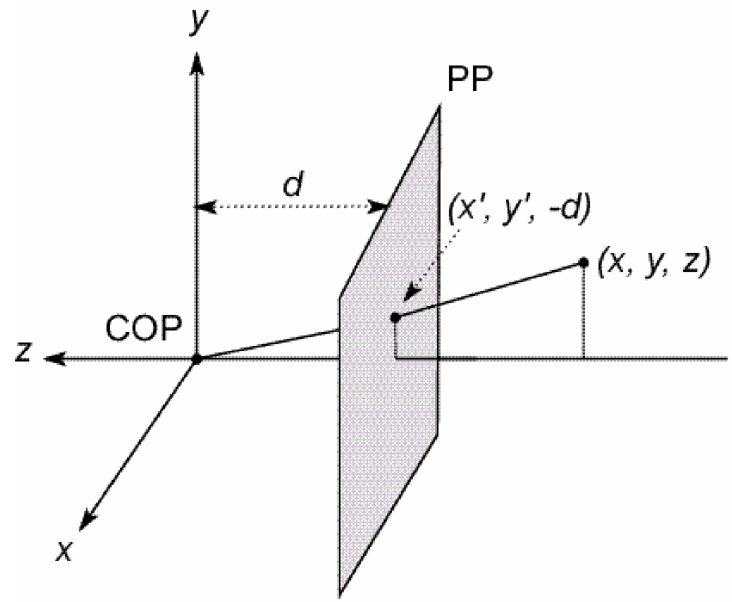
Müller-Lyer Illusion



We don’t make measurements in the image plane

http://www.michaelbach.de/ot/sze_muelue/index.html

Modeling projection

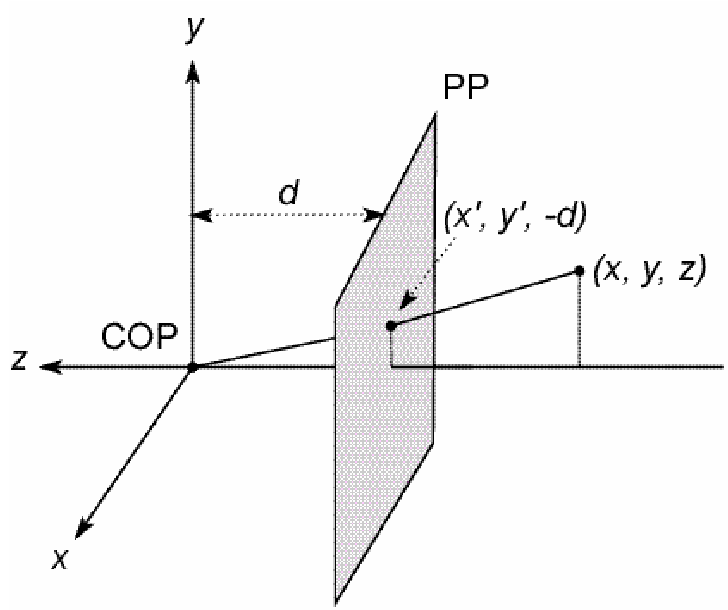


The coordinate system

- We will use the pin-hole model as an approximation
- Put the optical center (**C**enter **O**f **P**rojection) at the origin
- Put the image plane (**P**rojection **P**lane) *in front* of the COP
  - Why?
- The camera looks down the *negative* z axis
  - we need this if we want right-handed-coordinates

Slide by Steve Seitz

Modeling projection



Projection equations

- Compute intersection with PP of ray from (x,y,z) to COP
- Derived using similar triangles (on board)

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z},\ -d)$$

- We get the projection by throwing out the last coordinate:

$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z})$$

Slide by Steve Seitz

Homogeneous coordinates

Is this a linear transformation?

- no—division by z is nonlinear

Trick: add one more coordinate:

$$(x, y) \Rightarrow \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

homogeneous image coordinates

$$(x, y, z) \Rightarrow \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

homogeneous scene coordinates

Converting *from* homogeneous coordinates

$$\begin{bmatrix} x \\ y \\ w \end{bmatrix} \Rightarrow (x/w, y/w)$$

$$\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \Rightarrow (x/w, y/w, z/w)$$

Slide by Steve Seitz

Perspective Projection

Projection is a matrix multiply using homogeneous coordinates:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ -z/d \end{bmatrix} \Rightarrow (-d\frac{x}{z}, \;\; -d\frac{y}{z})$$

divide by third coordinate

This is known as **perspective projection**

- The matrix is the **projection matrix**
- Can also formulate as a 4x4

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ -z/d \end{bmatrix} \Rightarrow (-d\frac{x}{z}, \;\; -d\frac{y}{z})$$

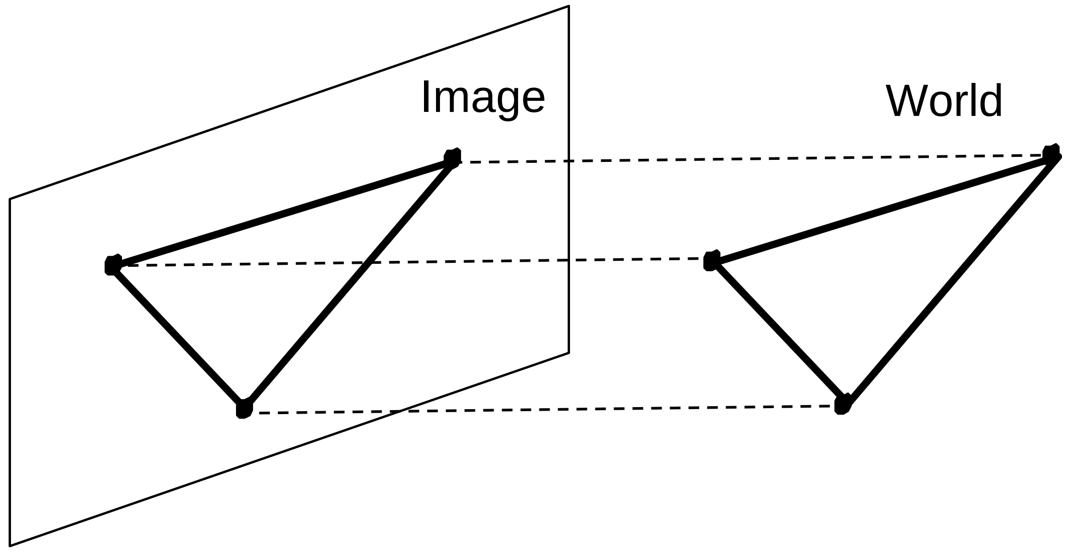
divide by fourth coordinate

Slide by Steve Seitz

Orthographic Projection

Special case of perspective projection

- Distance from the COP to the PP is infinite

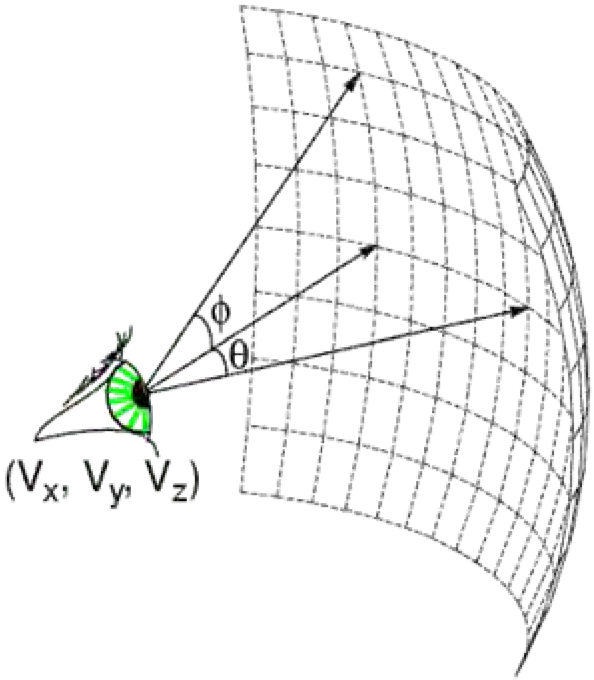


- Also called “parallel projection”
- What’s the projection matrix?

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$

Slide by Steve Seitz

Spherical Projection



What if PP is spherical with center at COP?

In spherical coordinates, projection is trivial:

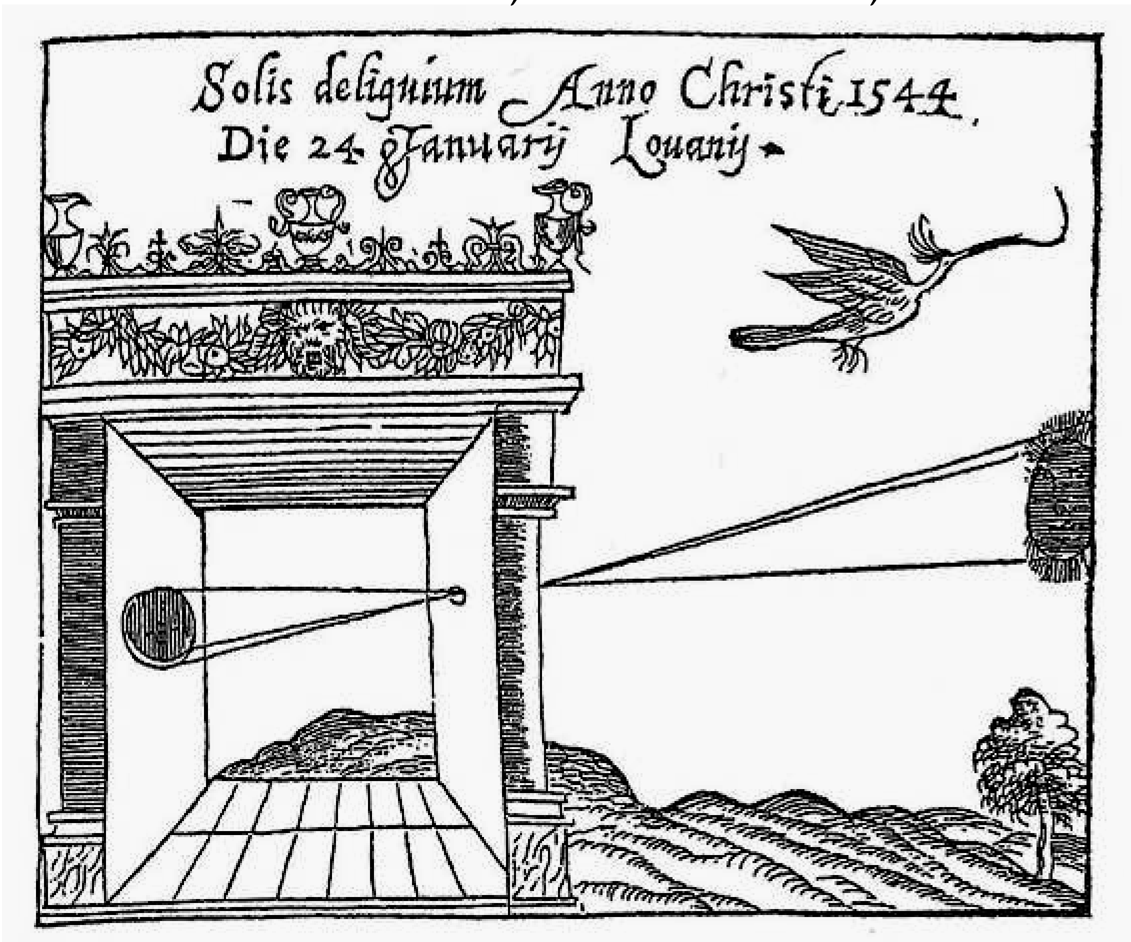
$$(\theta,\phi) = (\theta,\phi,\mathrm{d})$$

Note: doesn't depend on focal length d!

Building a real camera

Camera Obscura

Camera Obscura, Gemma Frisius, 1558



The first camera

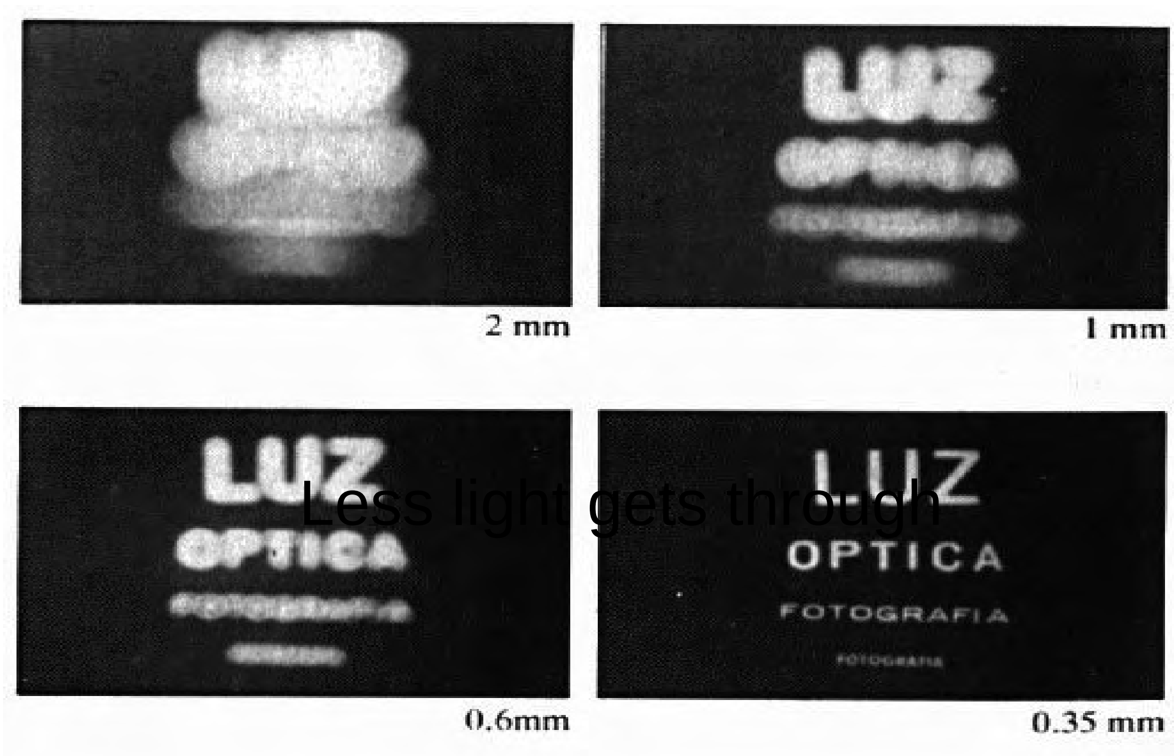
- Known to Aristotle
- Depth of the room is the effective focal length

Home-made pinhole camera

Why so
blurry?

http://www.debevec.org/Pinhole/

Shrinking the aperture

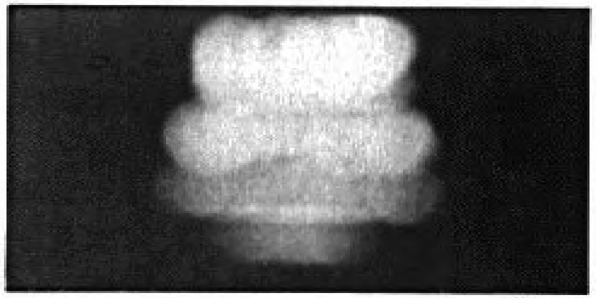


Less light gets through

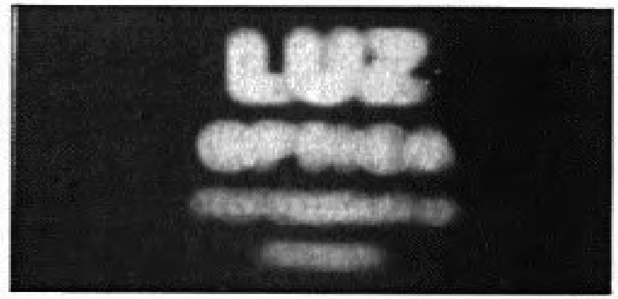
Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…

Shrinking the aperture



2 mm

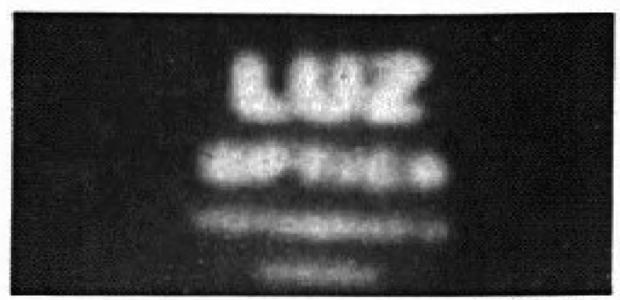


1 mm

0.6mm

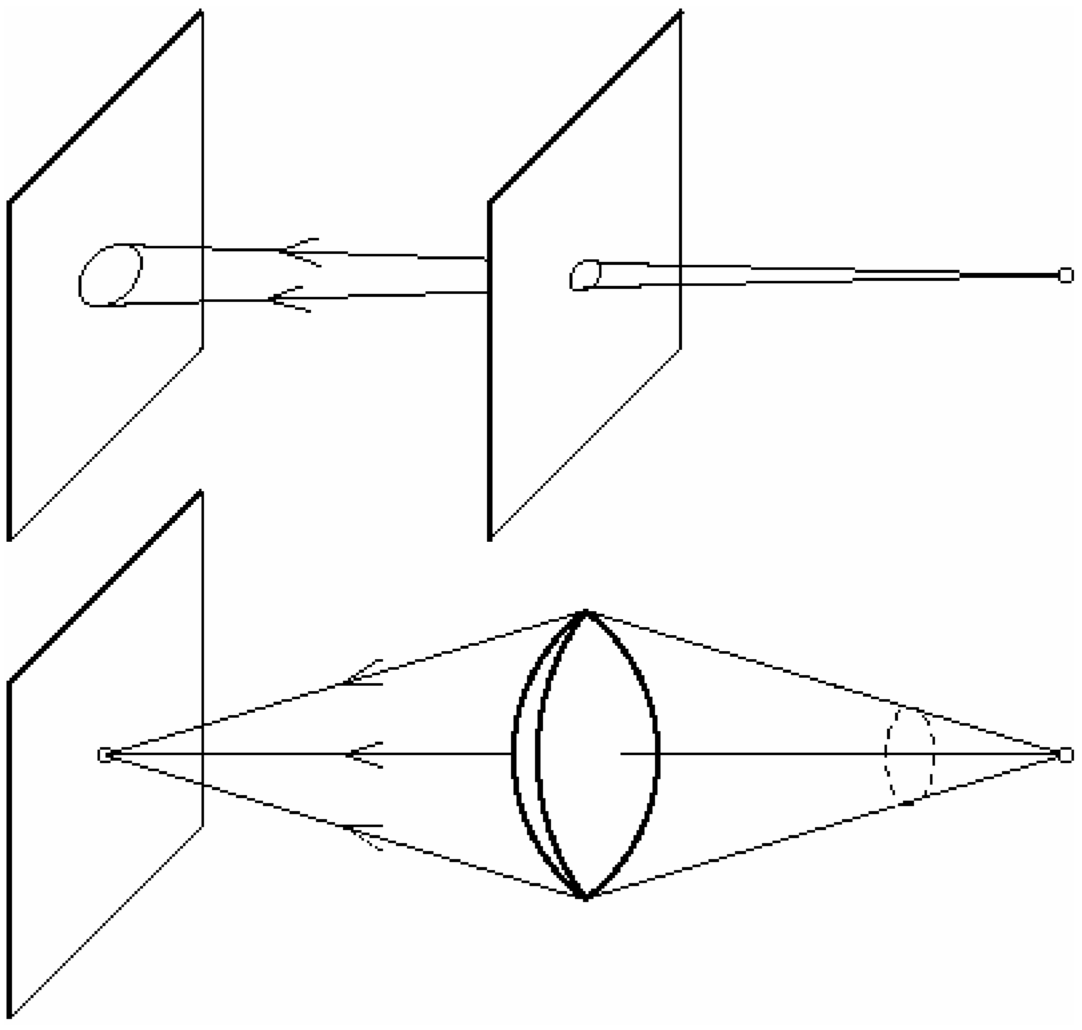
0.35 mm

0.15 mm



0.07 mm

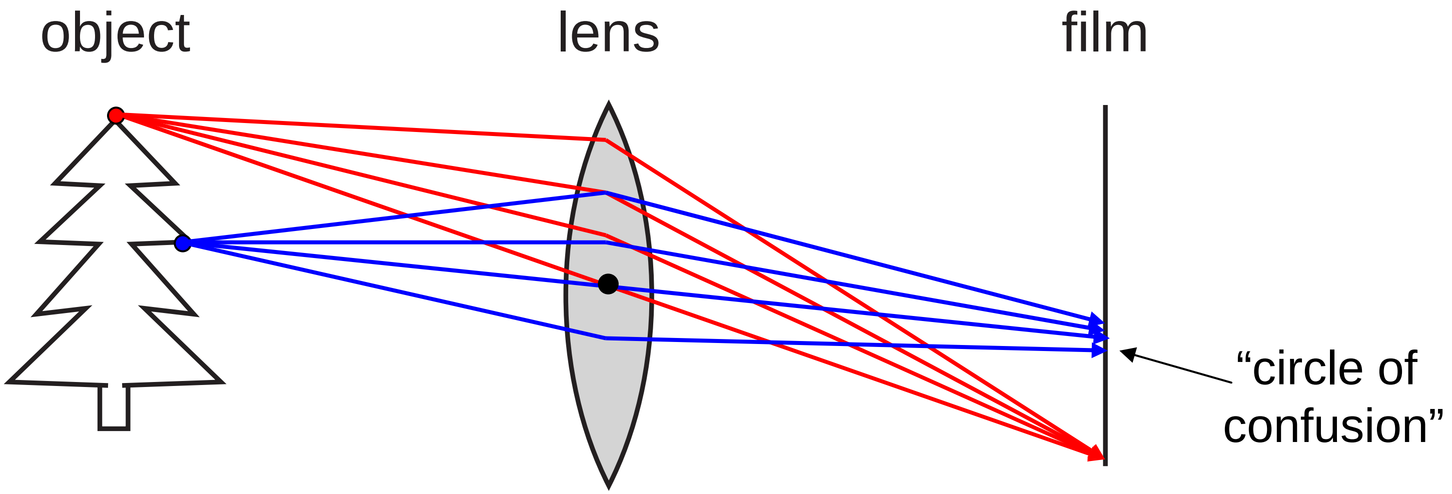
The reason for lenses



Slide by Steve Seitz

Focus

Focus and Defocus

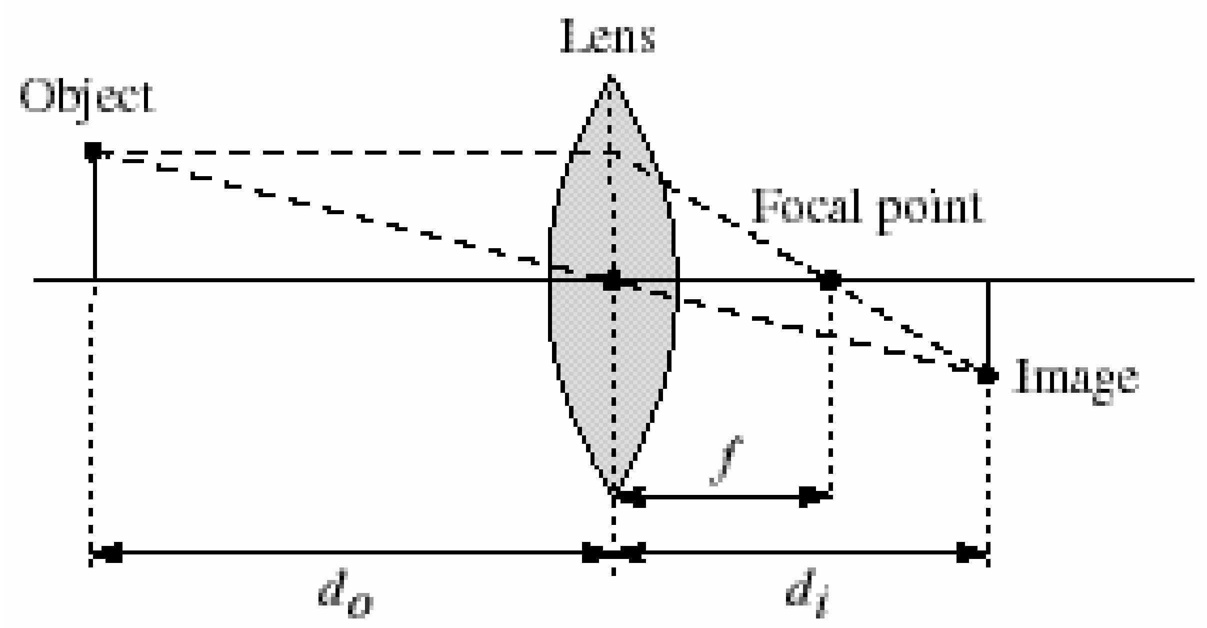


A lens focuses light onto the film

- 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

Slide by Steve Seitz

Thin lenses

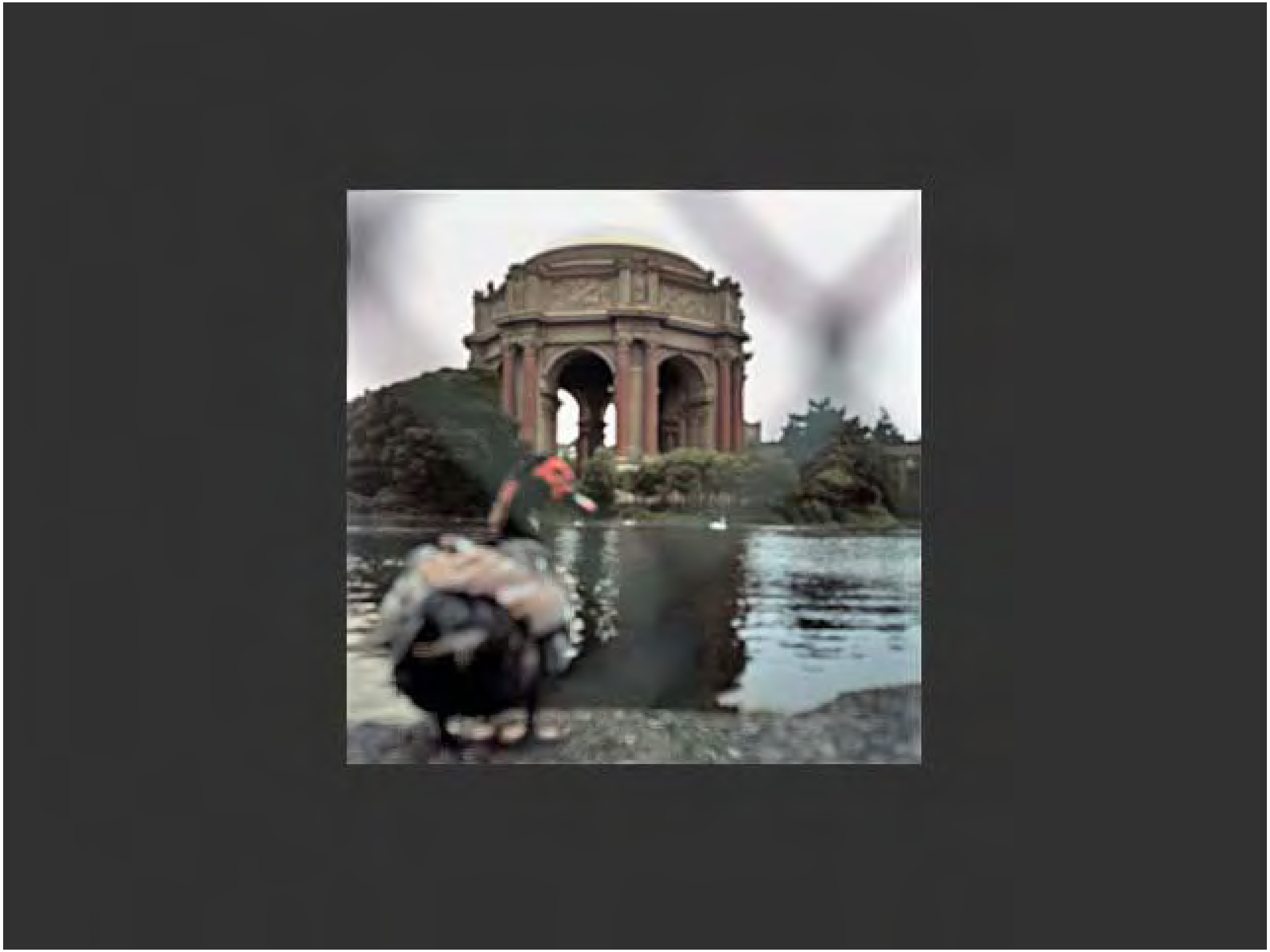


Thin lens equation: $$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

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

Slide by Steve Seitz

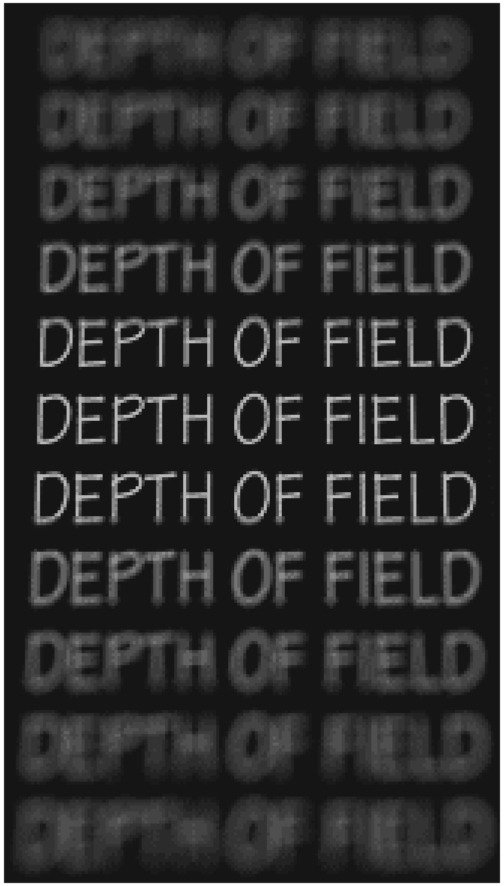
Varying Focus



Ren Ng

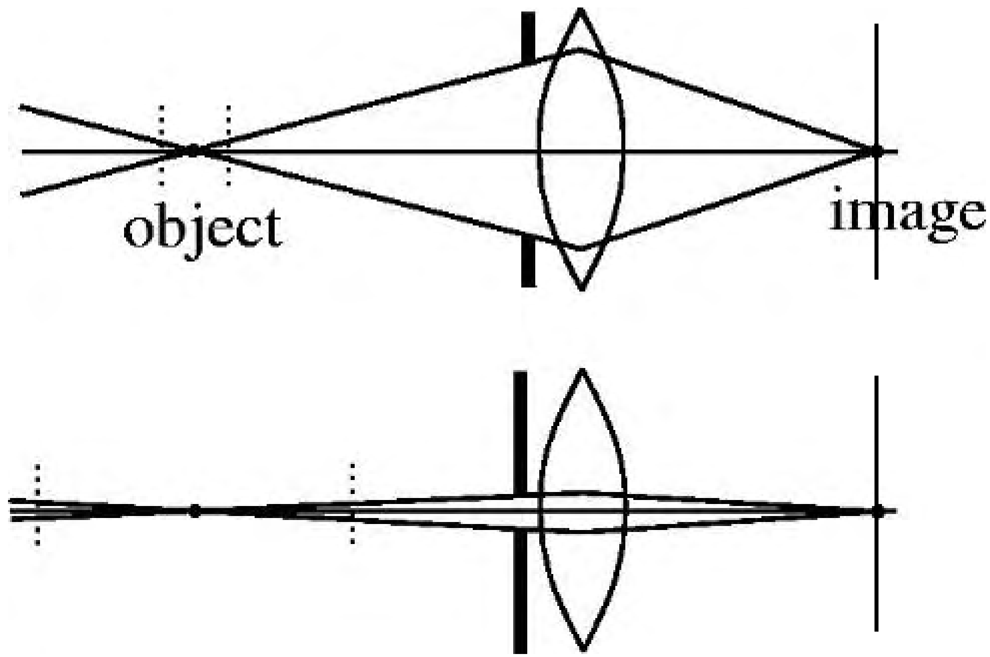
Depth Of Field

Depth of Field



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

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

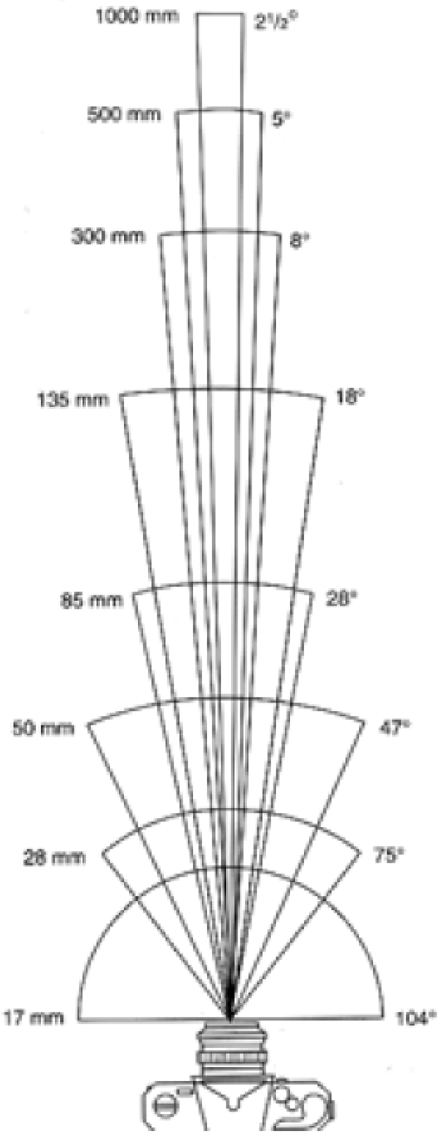
Varying the aperture

Large apeture = small DOF   Small apeture = large DOF

Nice Depth of Field effect

Field of View (Zoom)

Field of View (Zoom)



17mm

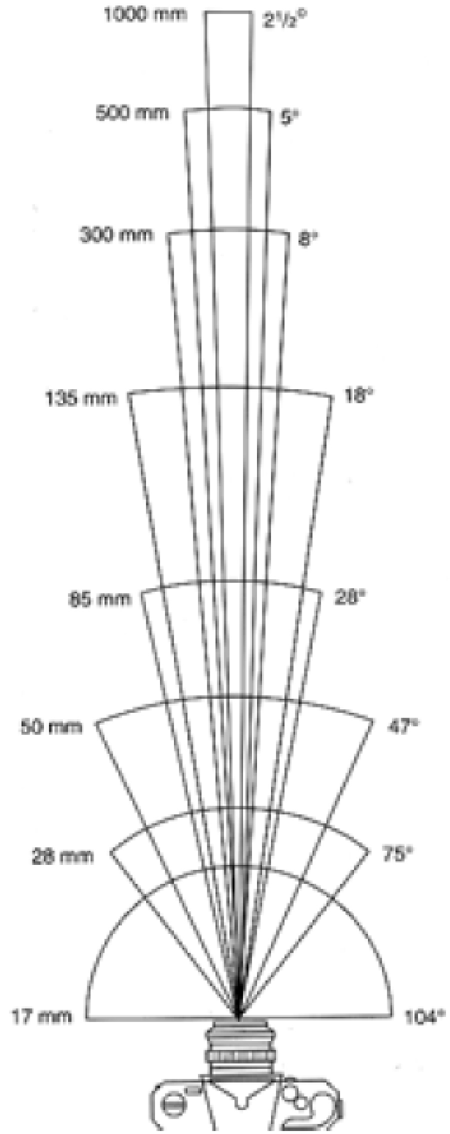
28mm

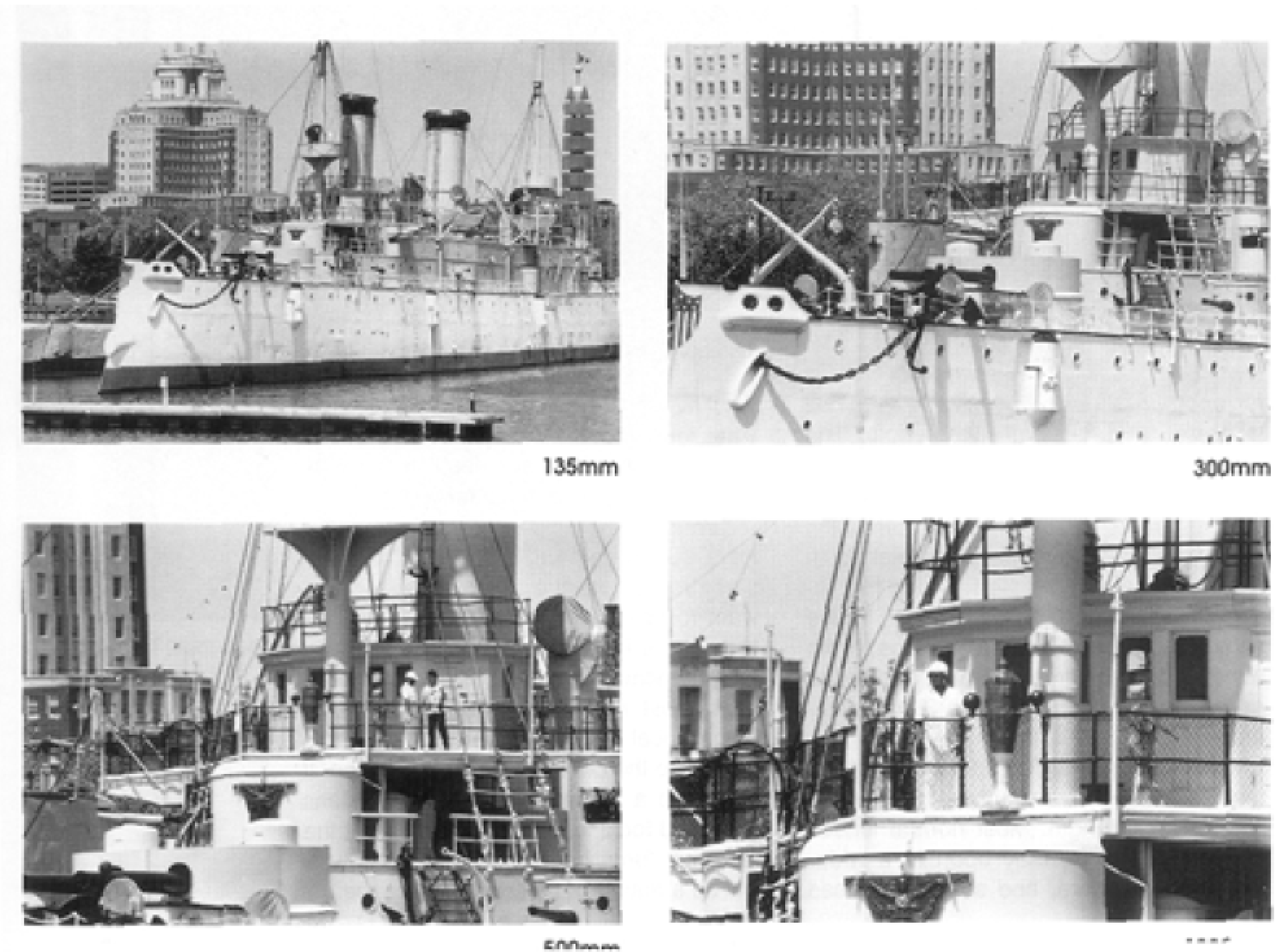
50mm

85mm

From London and Upton

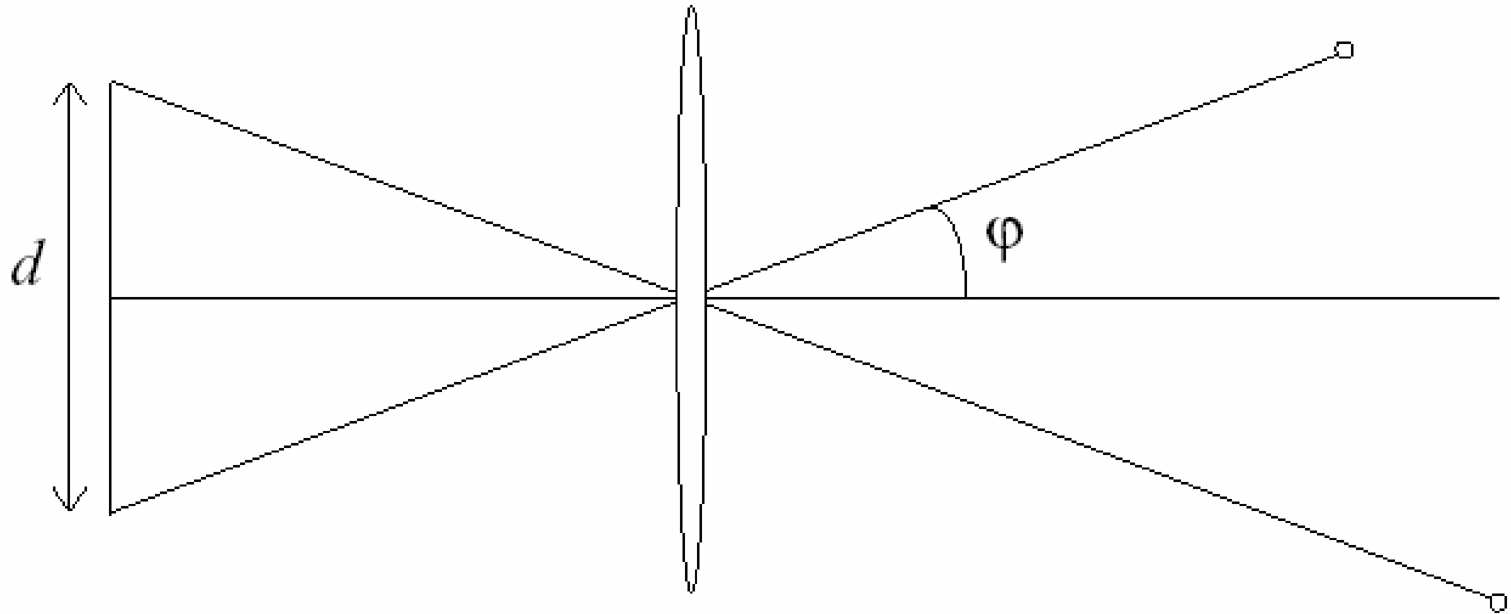
Field of View (Zoom)





From London and Upton

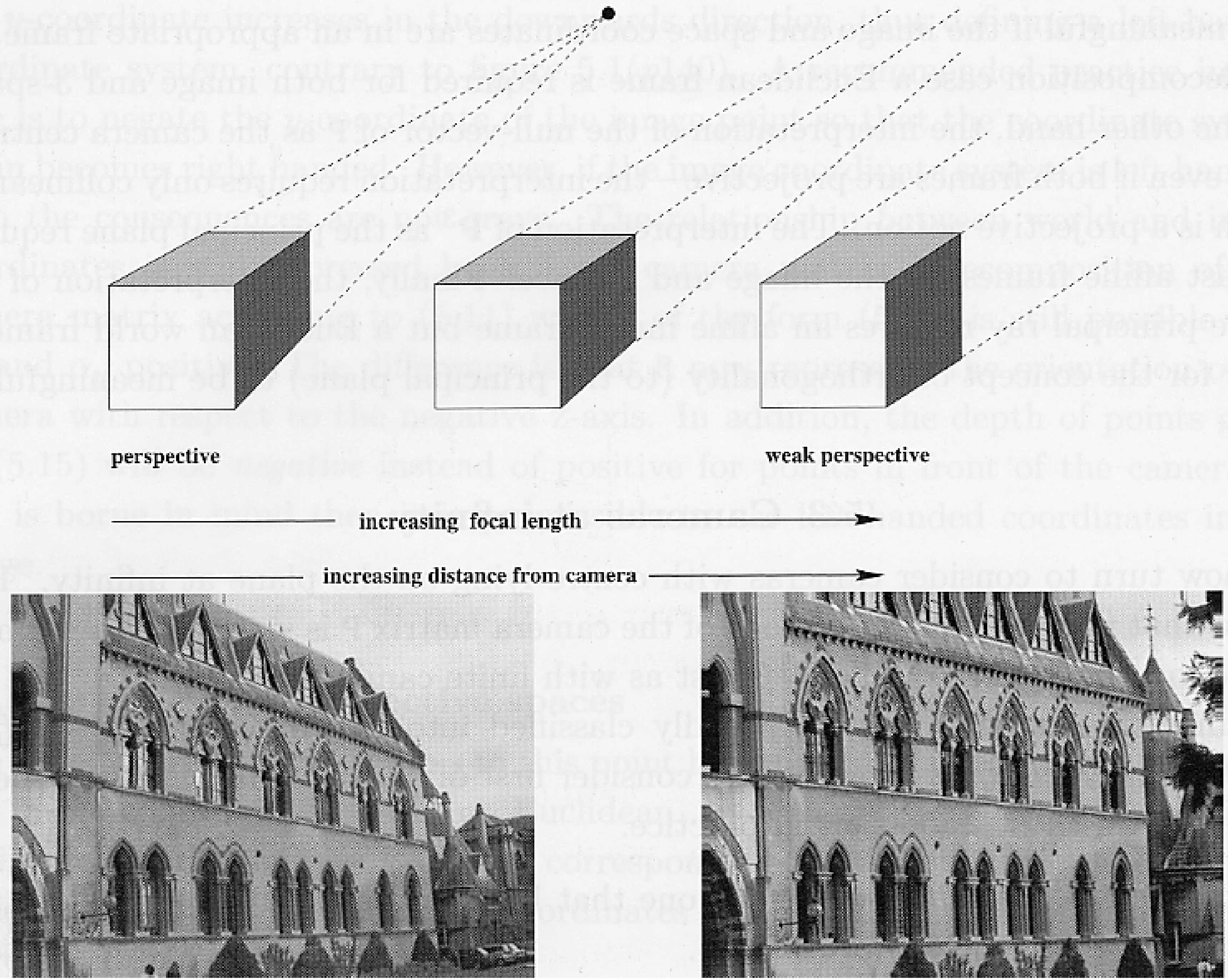
FOV depends of Focal Length



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



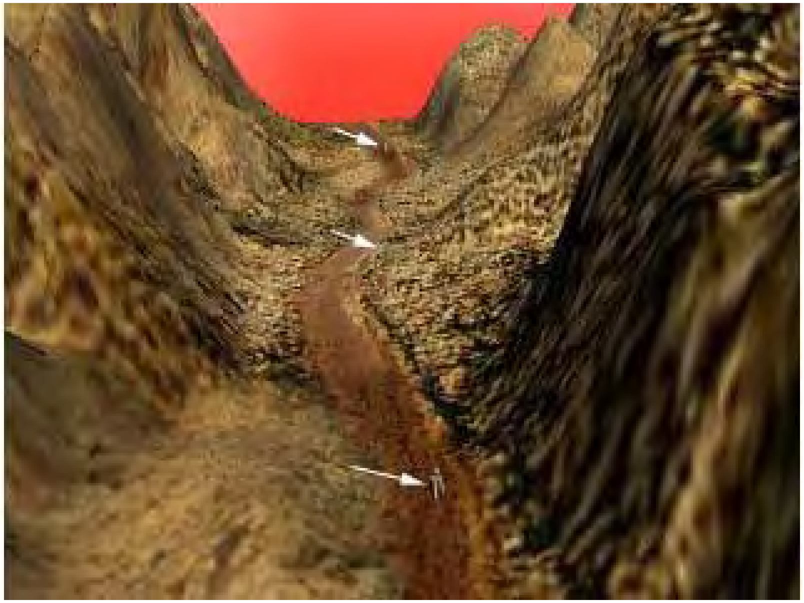
From Zisserman & Hartley

Field of View / Focal Length

Large FOV, small f
Camera close to car

Small FOV, large f
Camera far from the car

Fun with Focal Length (Jim Sherwood)



http://www.hash.com/users/jsherwood/tutes/focal/Zoomin.mov

Figure 5.1

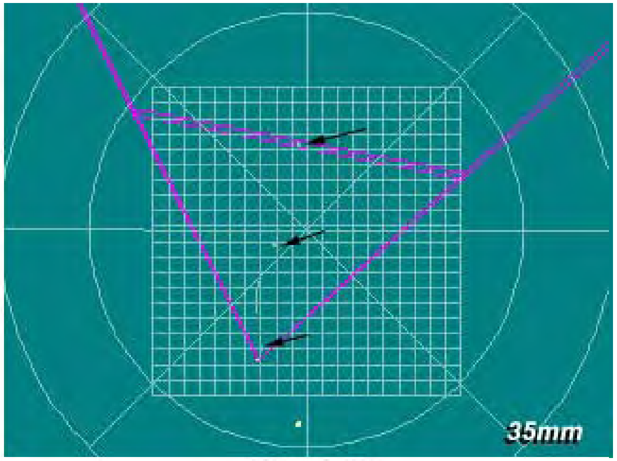


Figure 5.2

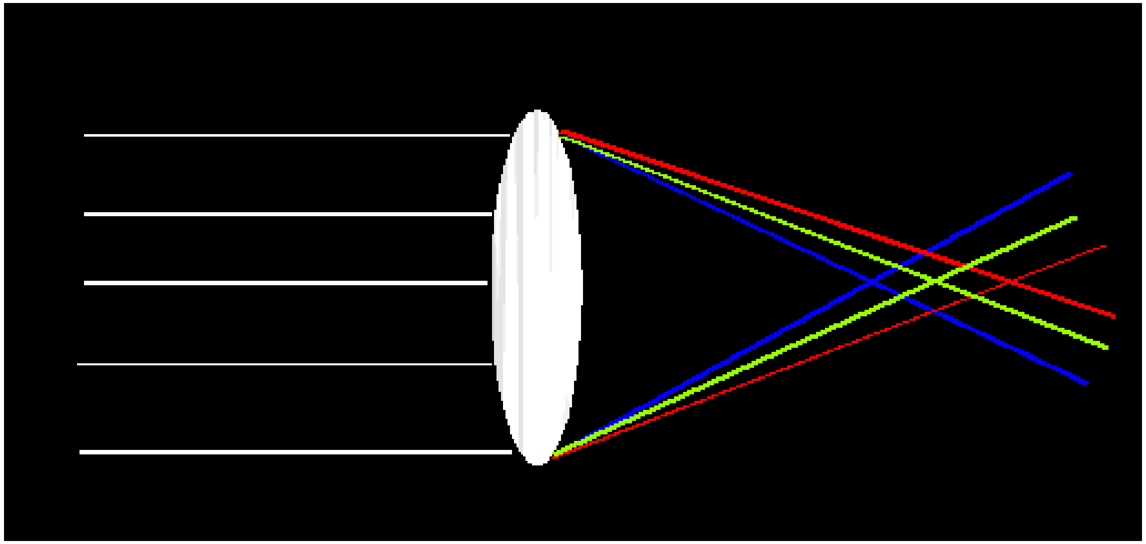
Lens Flaws

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

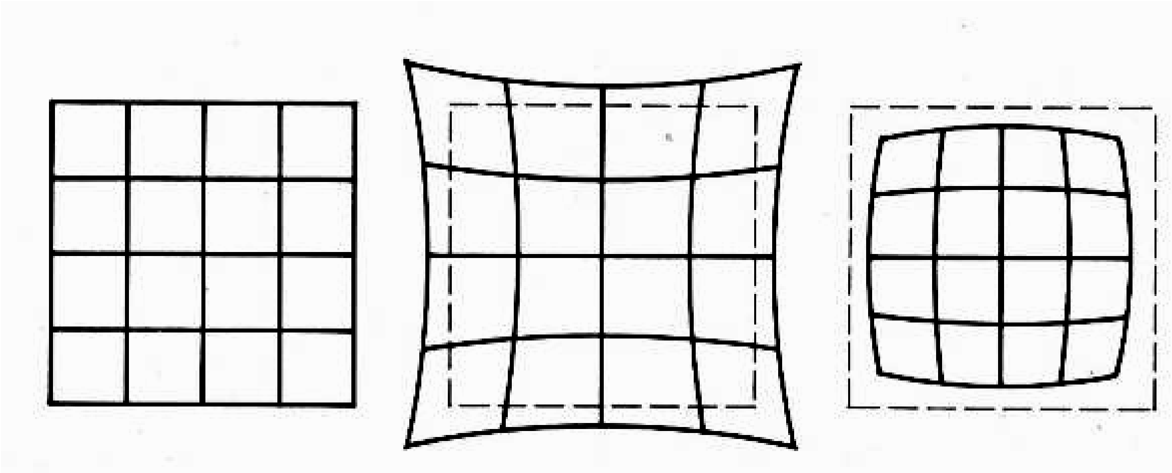
Near Lens Center

Near Lens Outer Edge

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

straight lines curve around the image center

Radial Distortion



No distortion Pin cushion Barrel

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