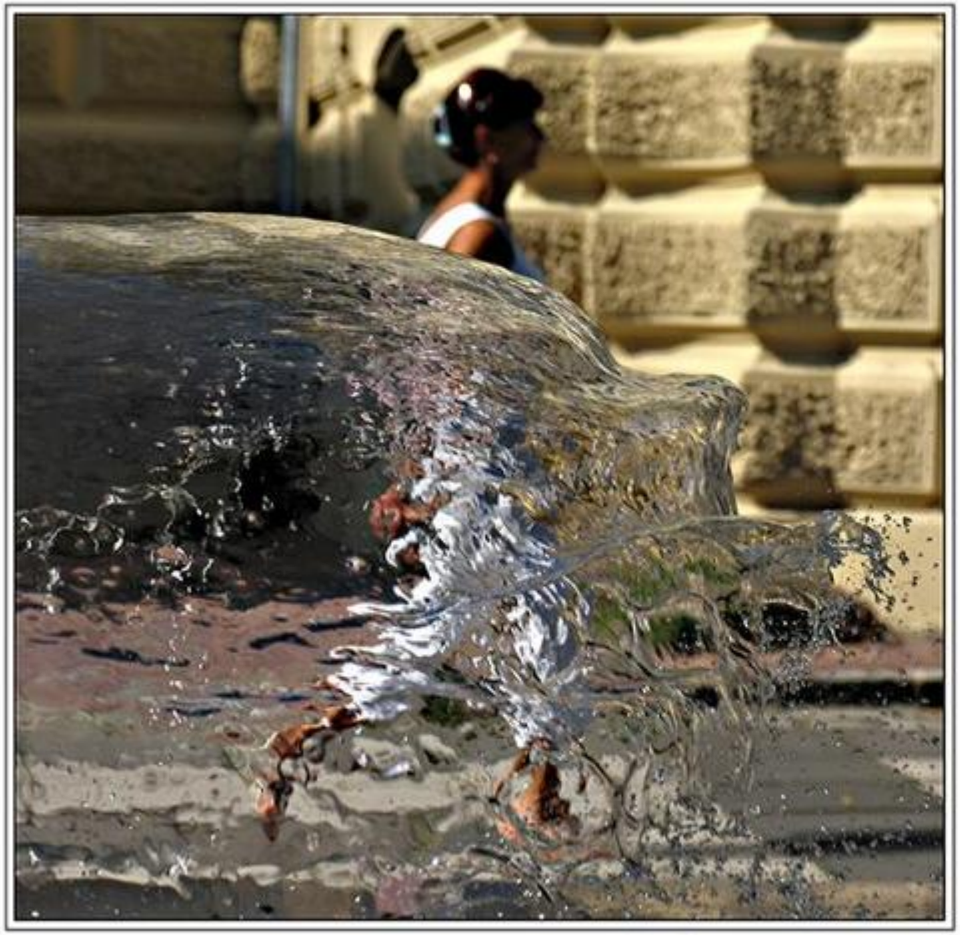
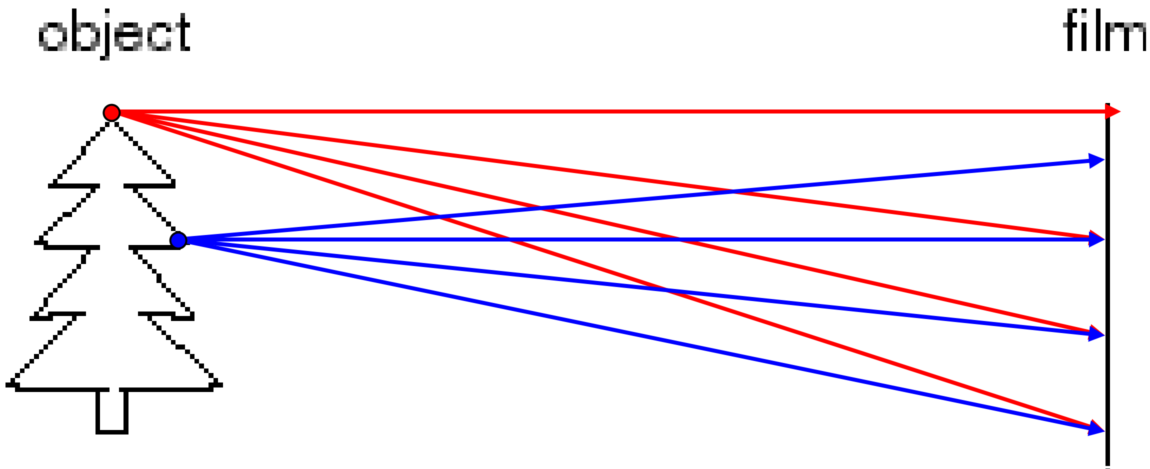
The Camera



(c) Tomasz Plucienník

15-463: Computational Photography
Alexei Efros, CMU, Spring 2010

How do we see the world?

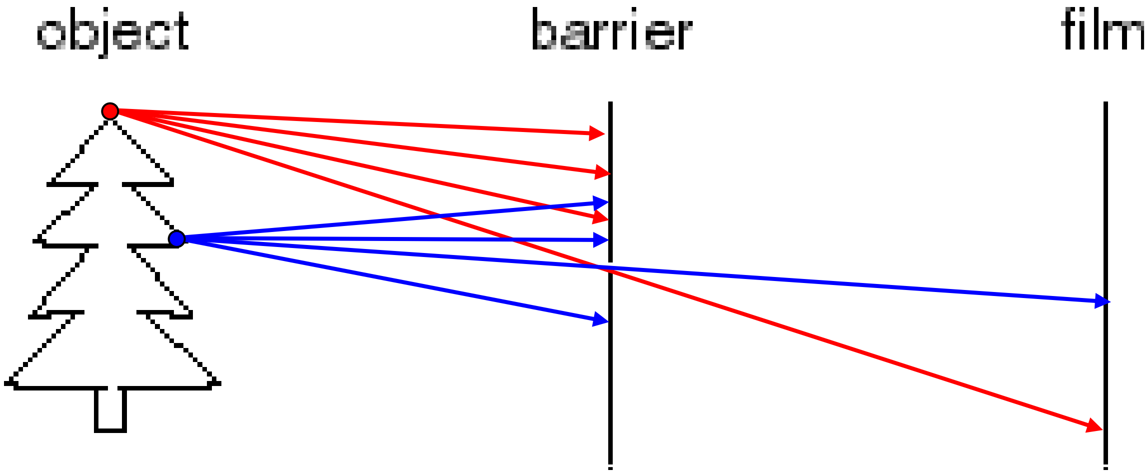


Let’s design a camera

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

Slide by Steve Seitz

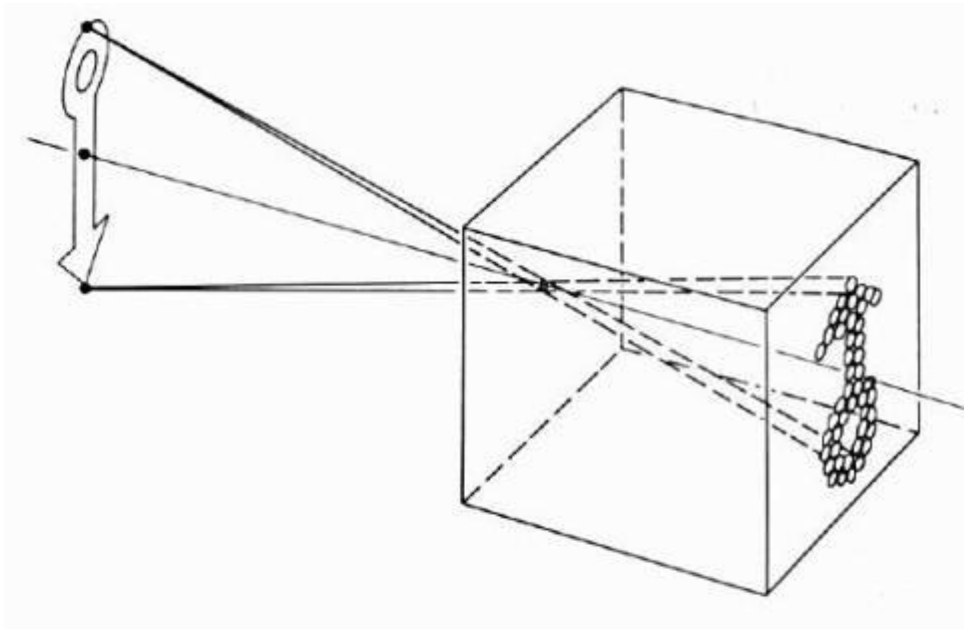
Pinhole camera



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?

Pinhole camera model



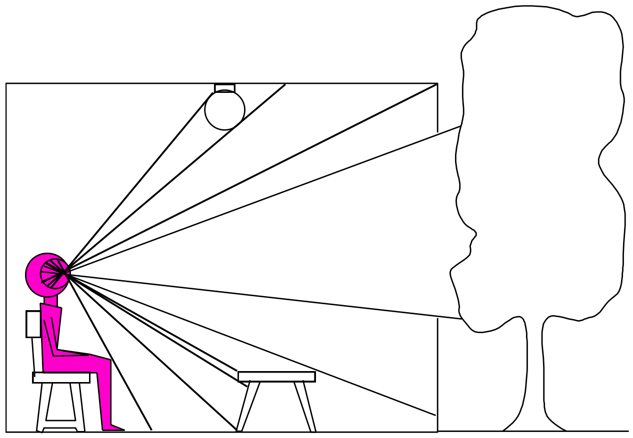
Pinhole model:

- 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

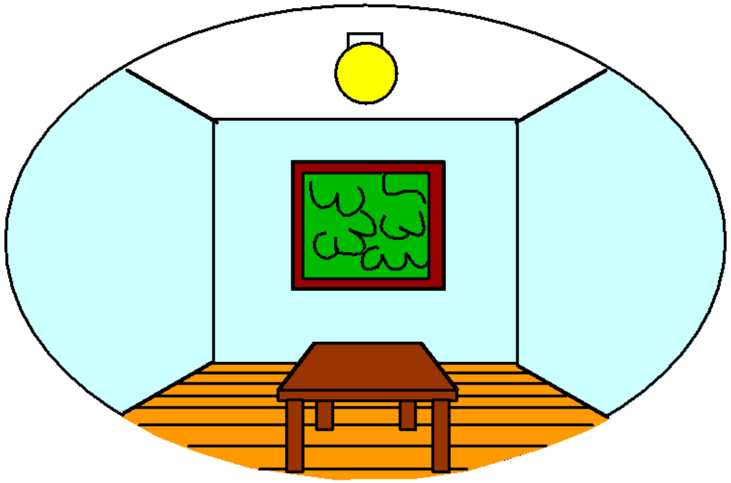
Slide by Steve Seitz

Dimensionality Reduction Machine (3D to 2D)

3D world *2D image*



Point of observation

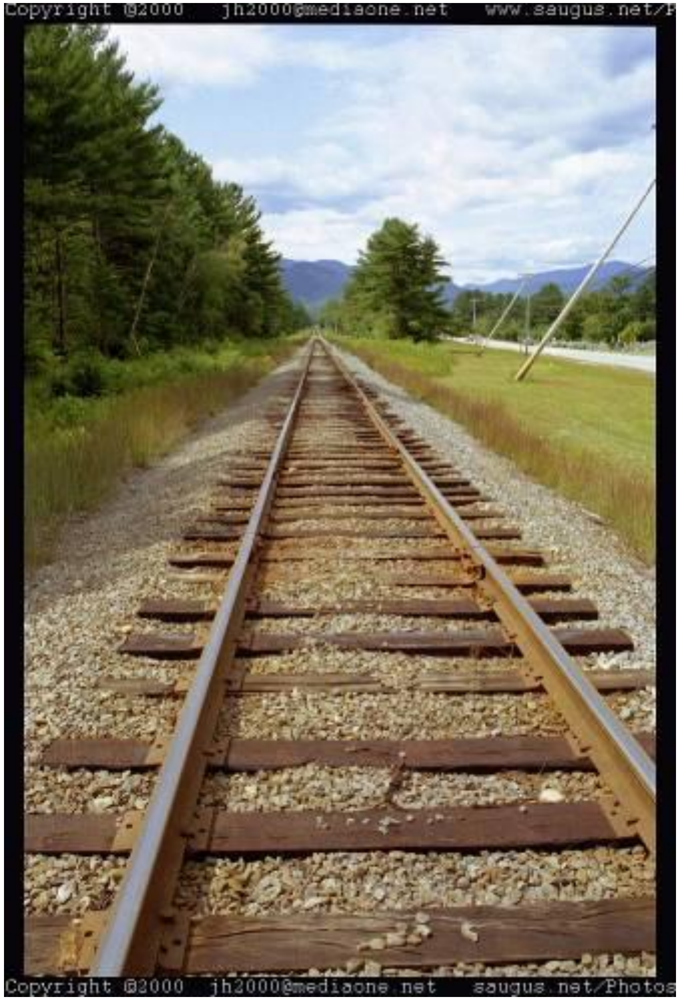


What have we lost?

- Angles
- Distances (lengths)

Figures © Stephen E. Palmer, 2002

Funny things happen…



Parallel lines aren't…

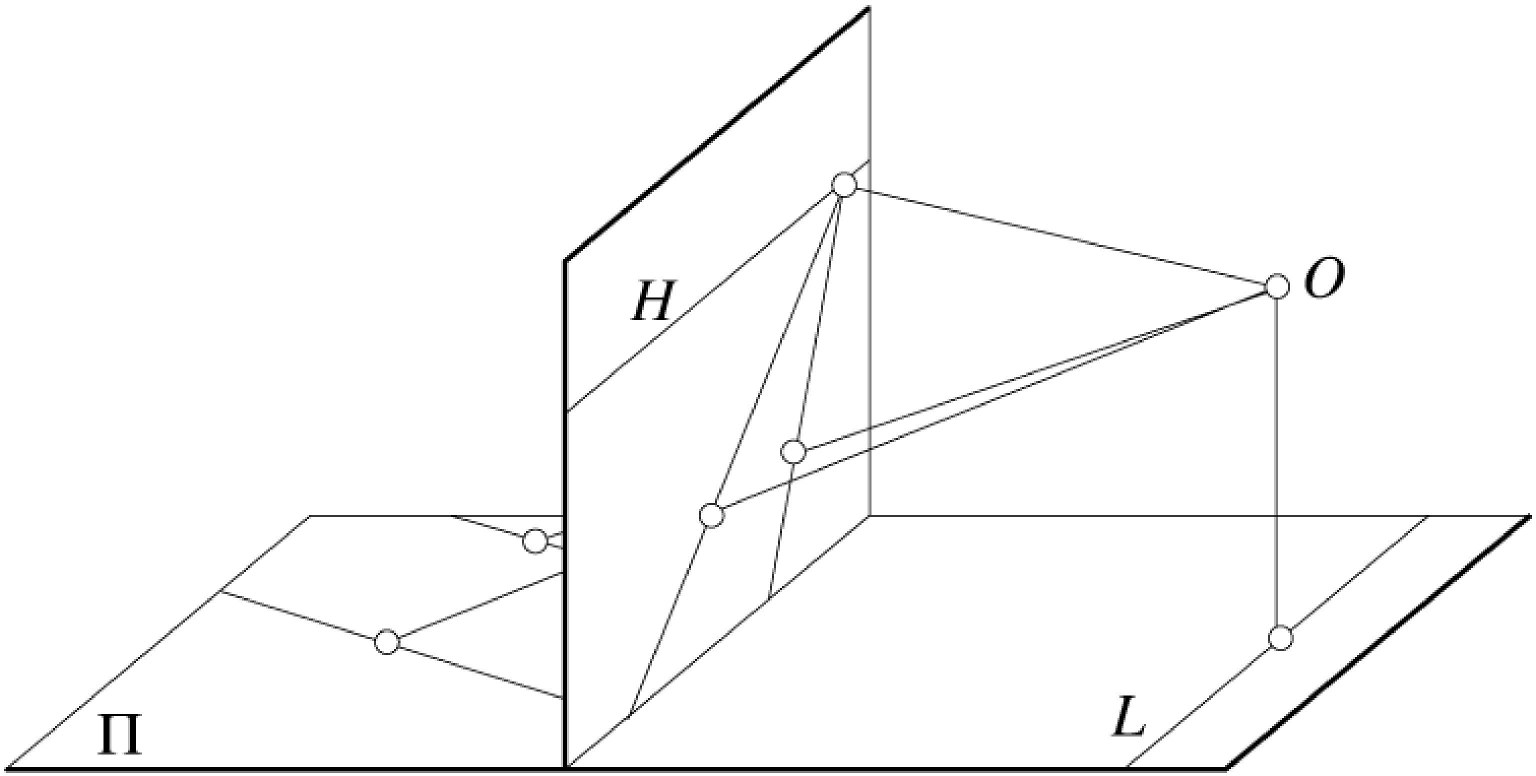


Figure by David Forsyth

Lengths can’t be trusted...

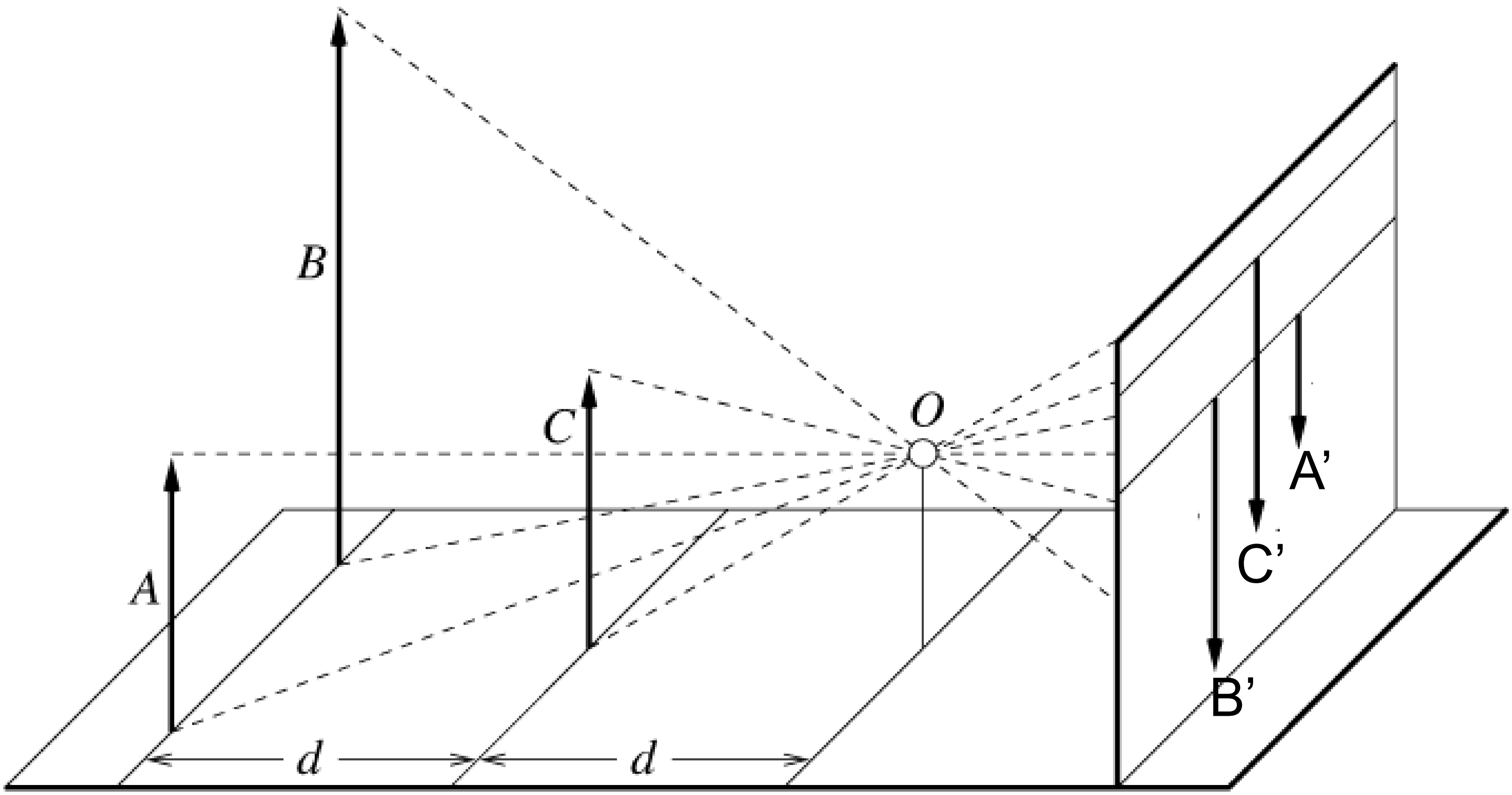
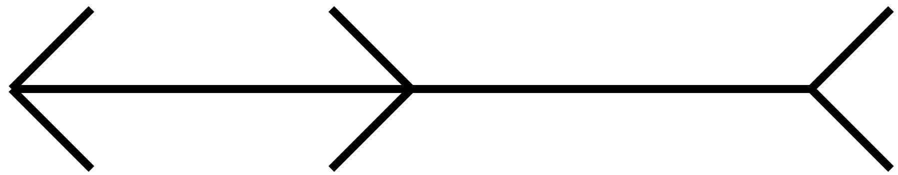
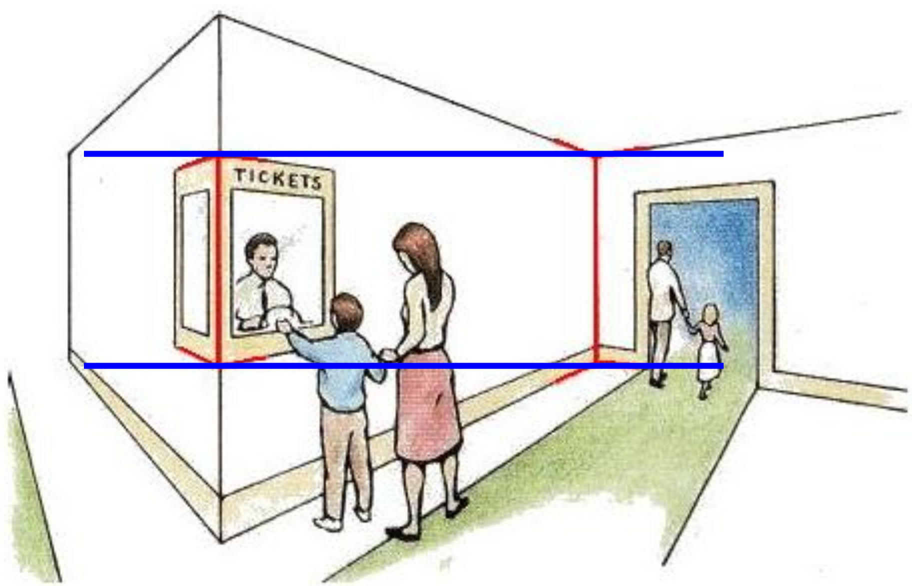


Figure by David Forsyth

…but humans adopt!



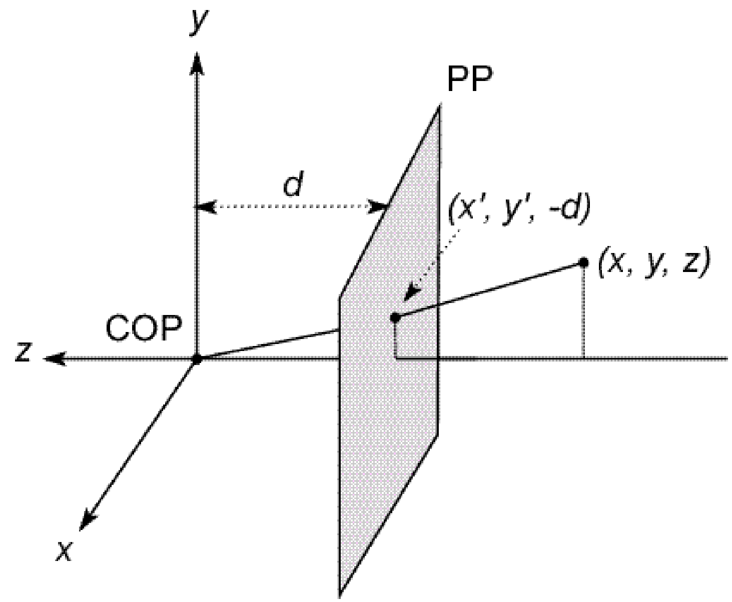
Müller-Lyer Illusion



We don't make measurements in the image plane

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

Modeling projection

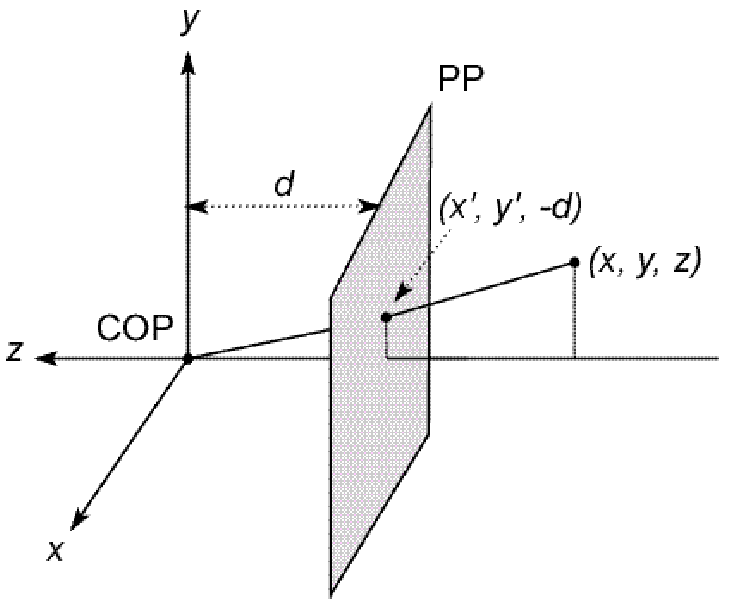


The coordinate system

- 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:

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

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

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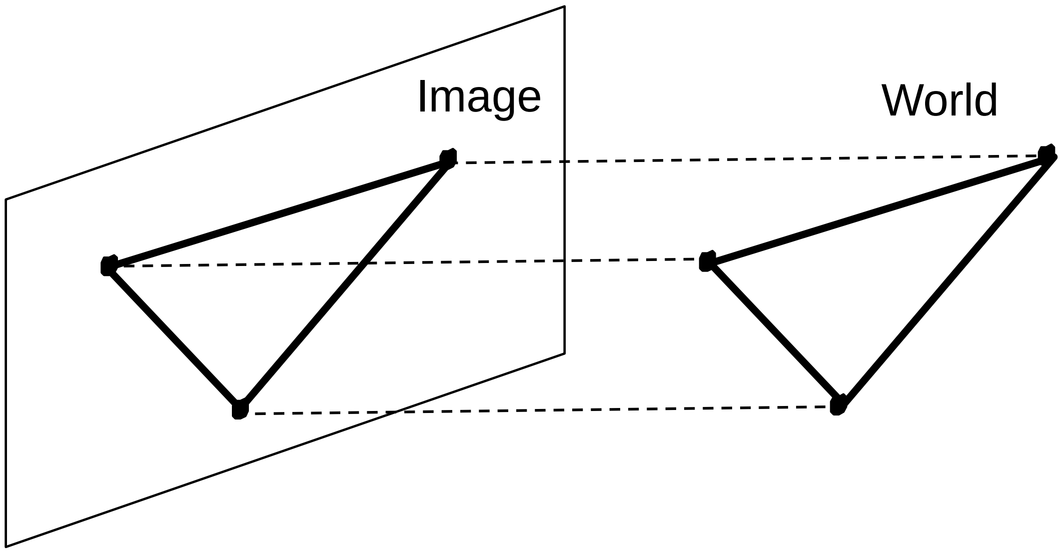
Orthographic Projection

Special case of perspective projection

- Distance from the COP to the PP is infinite

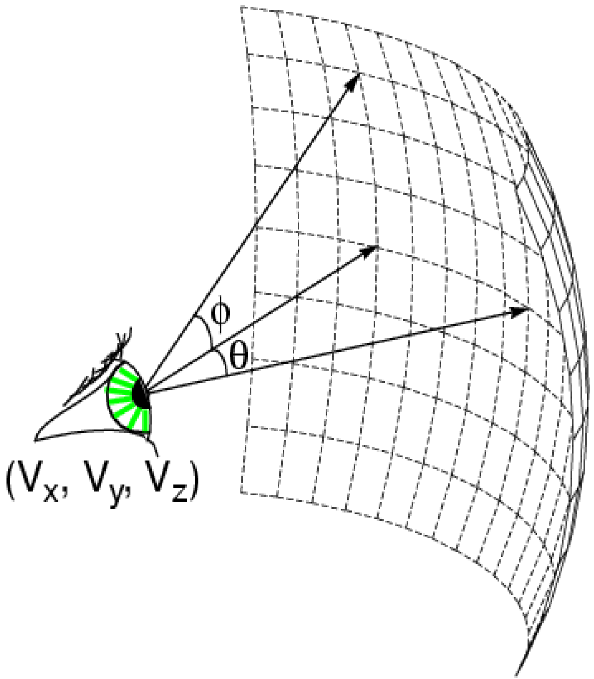


- Also called "parallel projection"
- What's the projection matrix?

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

Slide by Steve Seitz

Spherical Projection



What if PP is spherical with center at COP?

In spherical coordinates, projection is trivial:

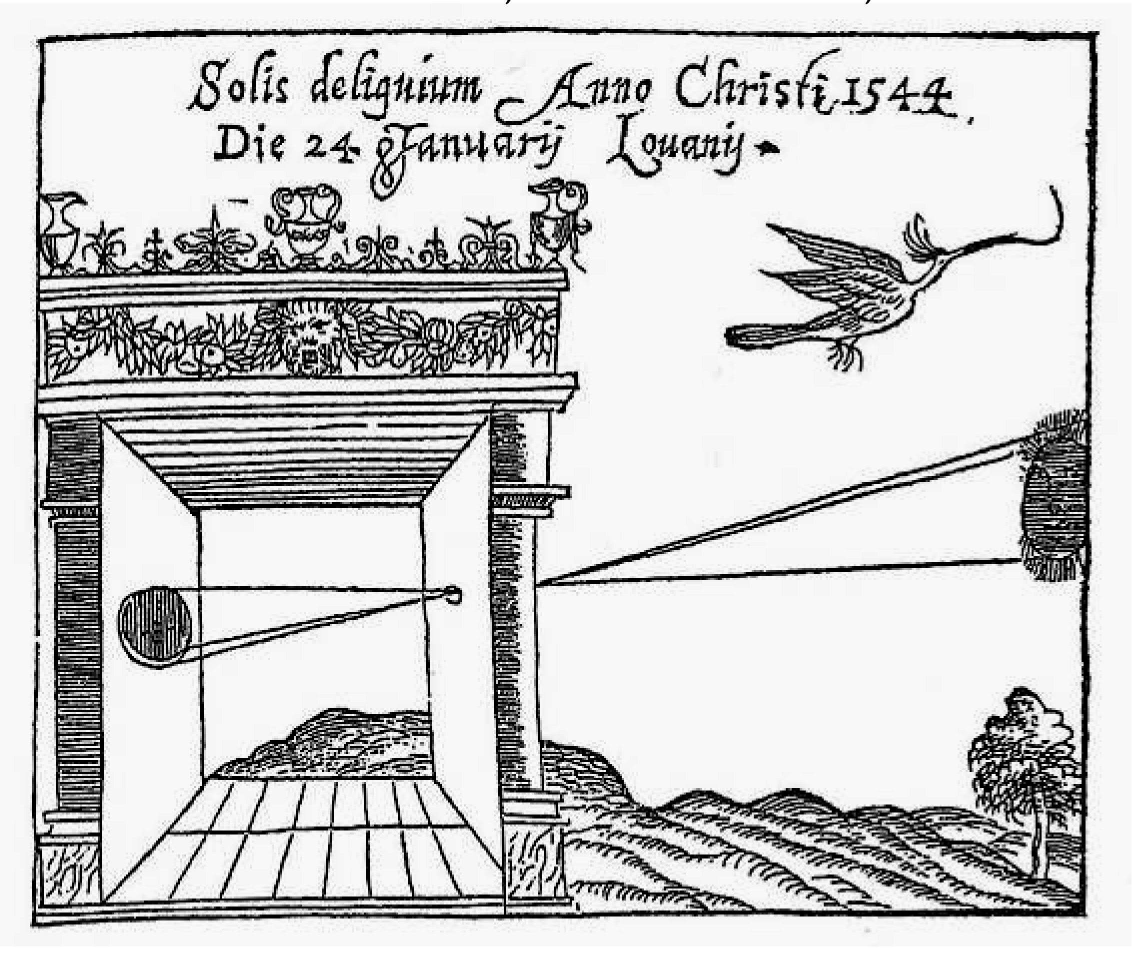
$$(\theta,\phi) = (\theta,\phi,\mathrm{d})$$

Note: doesn't depend on focal length d!

Building a real camera

Camera Obscura

Camera Obscura, Gemma Frisius, 1558



The first camera

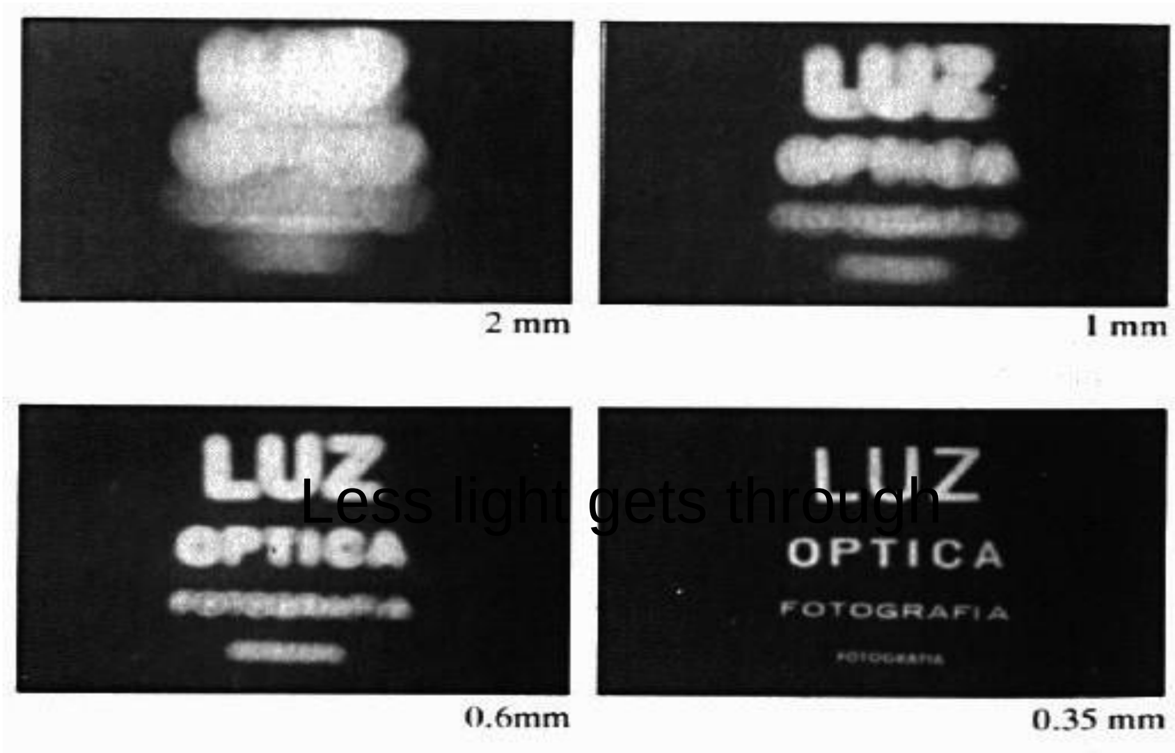
- Known to Aristotle
- Depth of the room is the effective focal length

Home-made pinhole camera

Why so blurry?

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

Shrinking the aperture



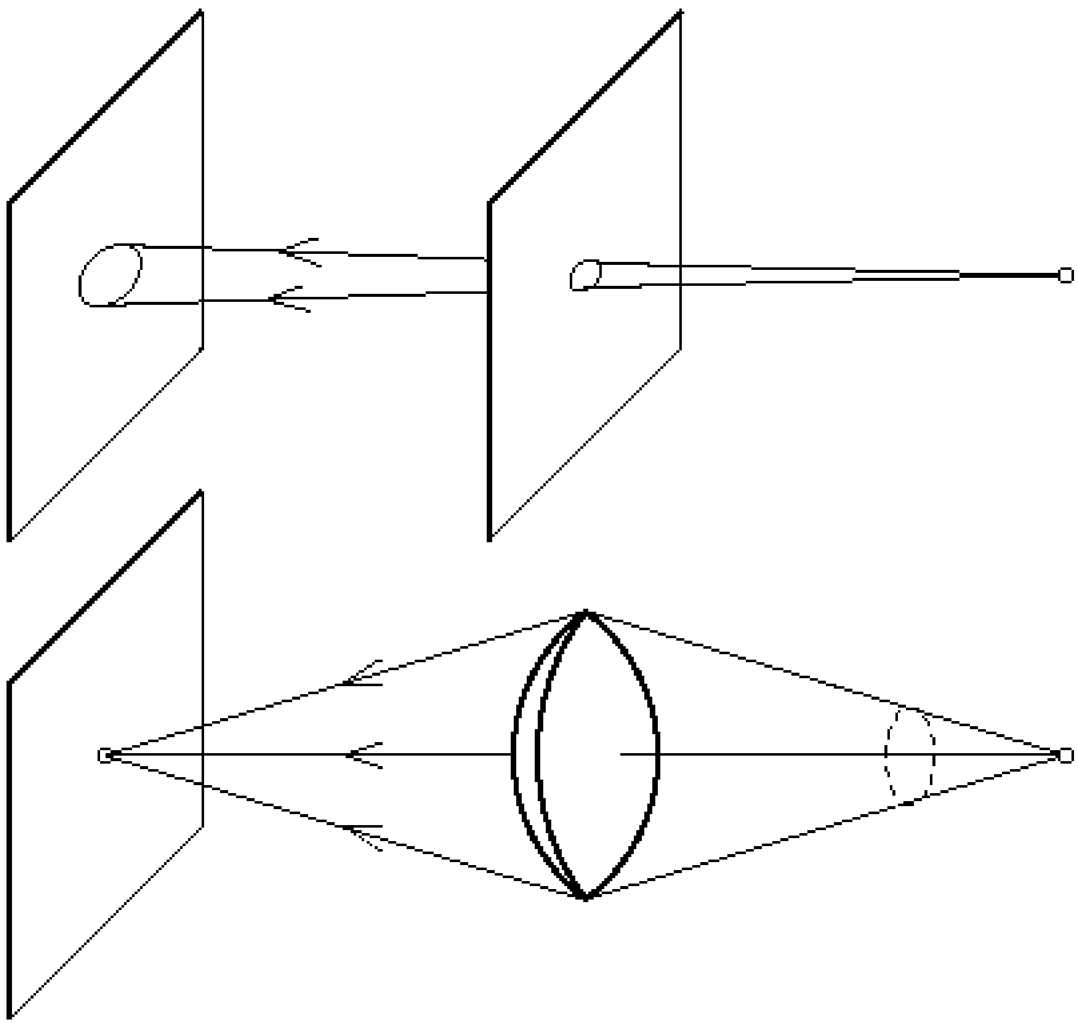
Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…

Slide by Steve Seitz

Shrinking the aperture

The reason for lenses



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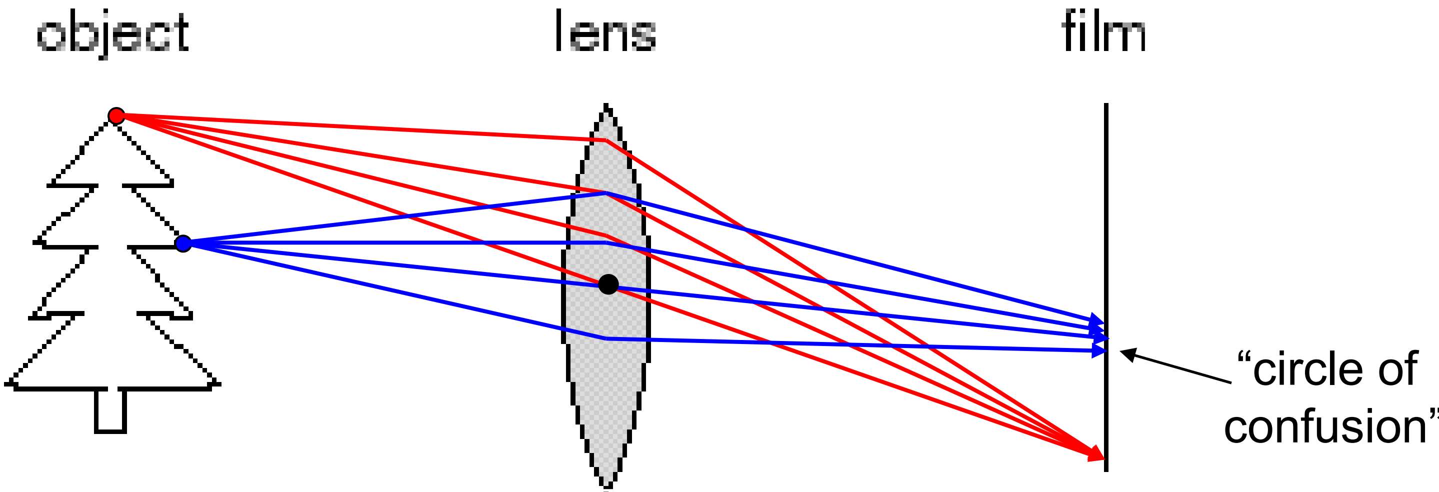
Focus

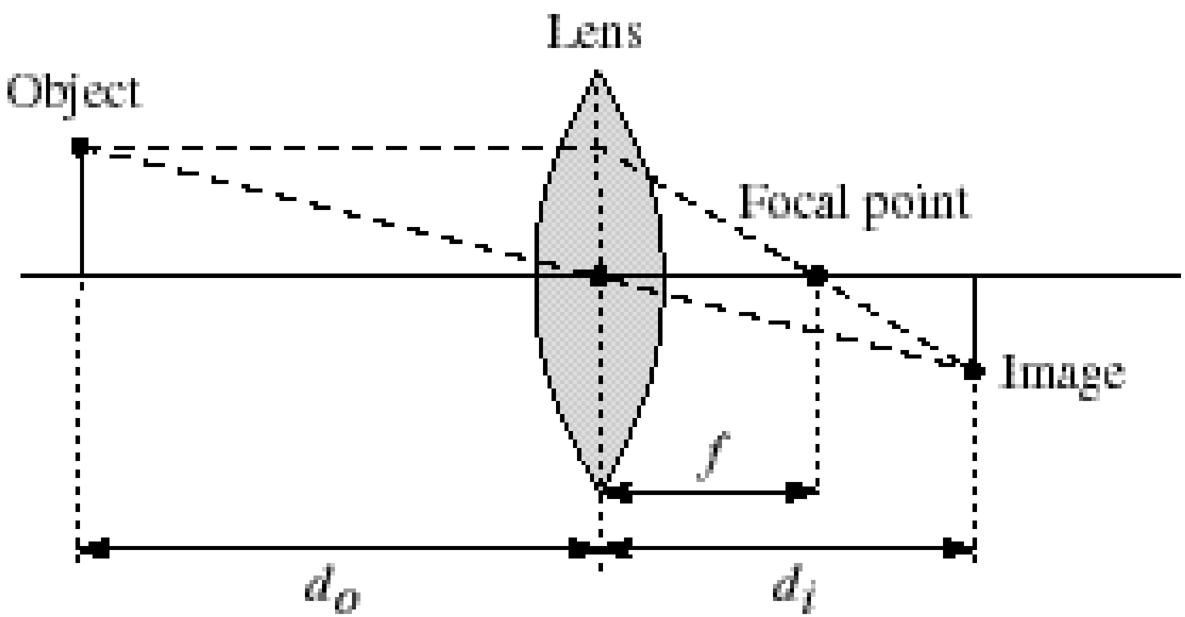
Focus and Defocus



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



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

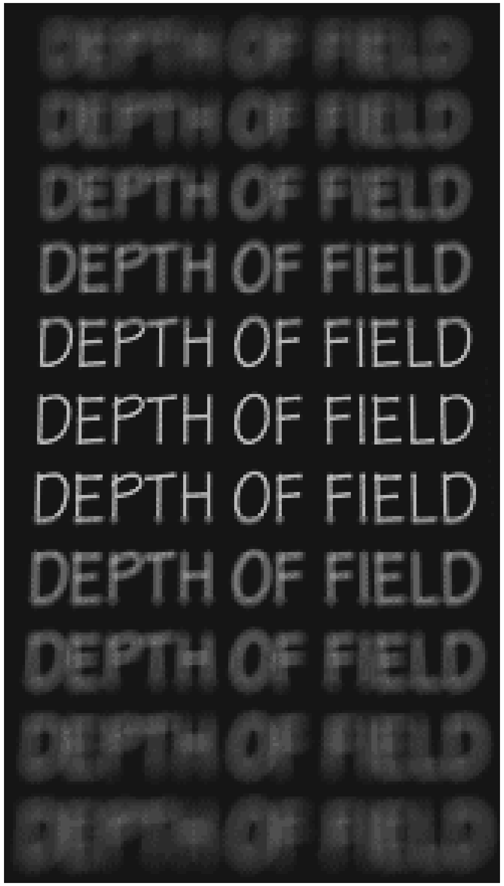
- Any object point satisfying this equation is in focus
- What is the shape of the focus region?
- How can we change the focus region?
- Thin lens applet: http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html (by Fu-Kwun Hwang)

Slide by Steve Seitz

Varying Focus

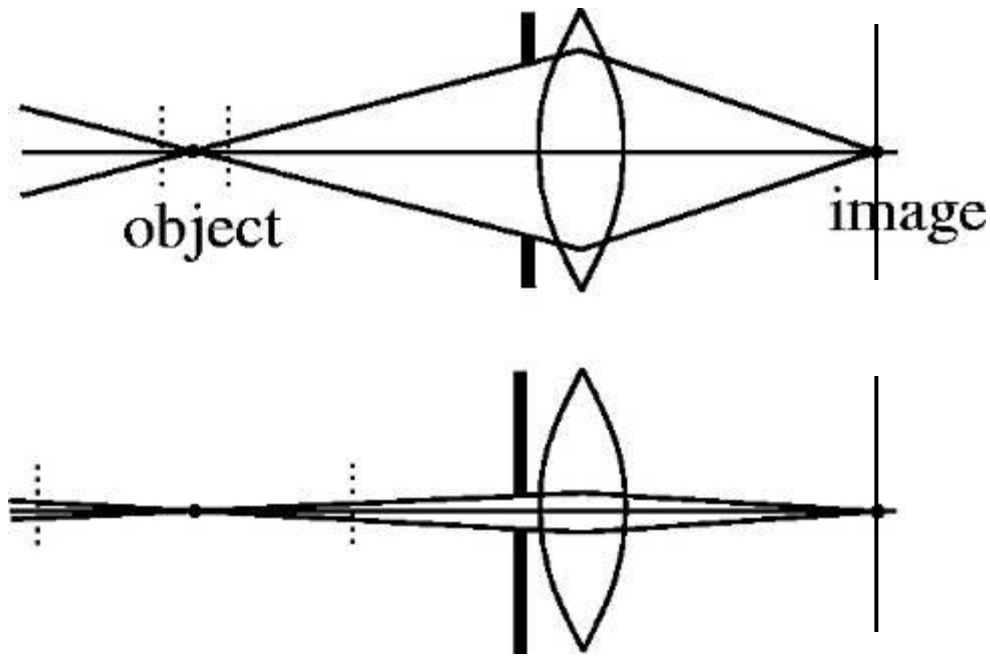
Depth Of Field

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

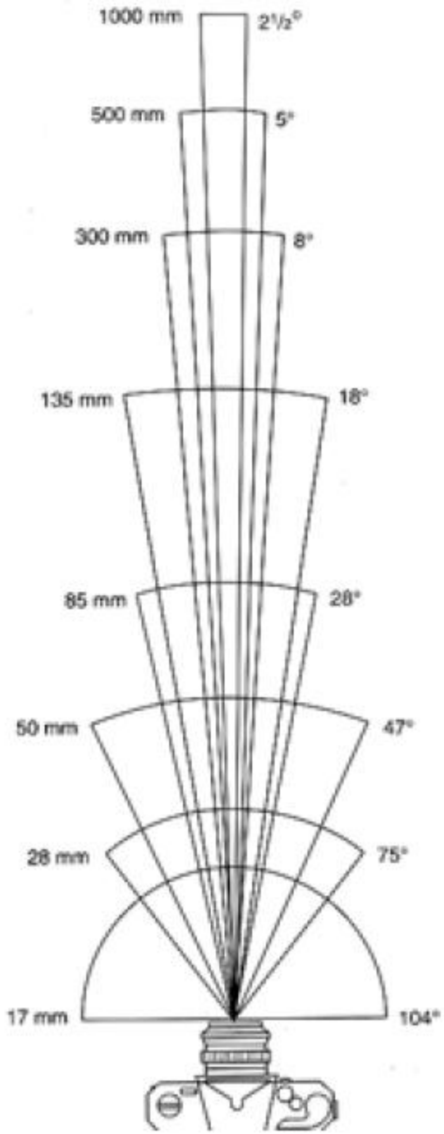
Large apeture = small DOF

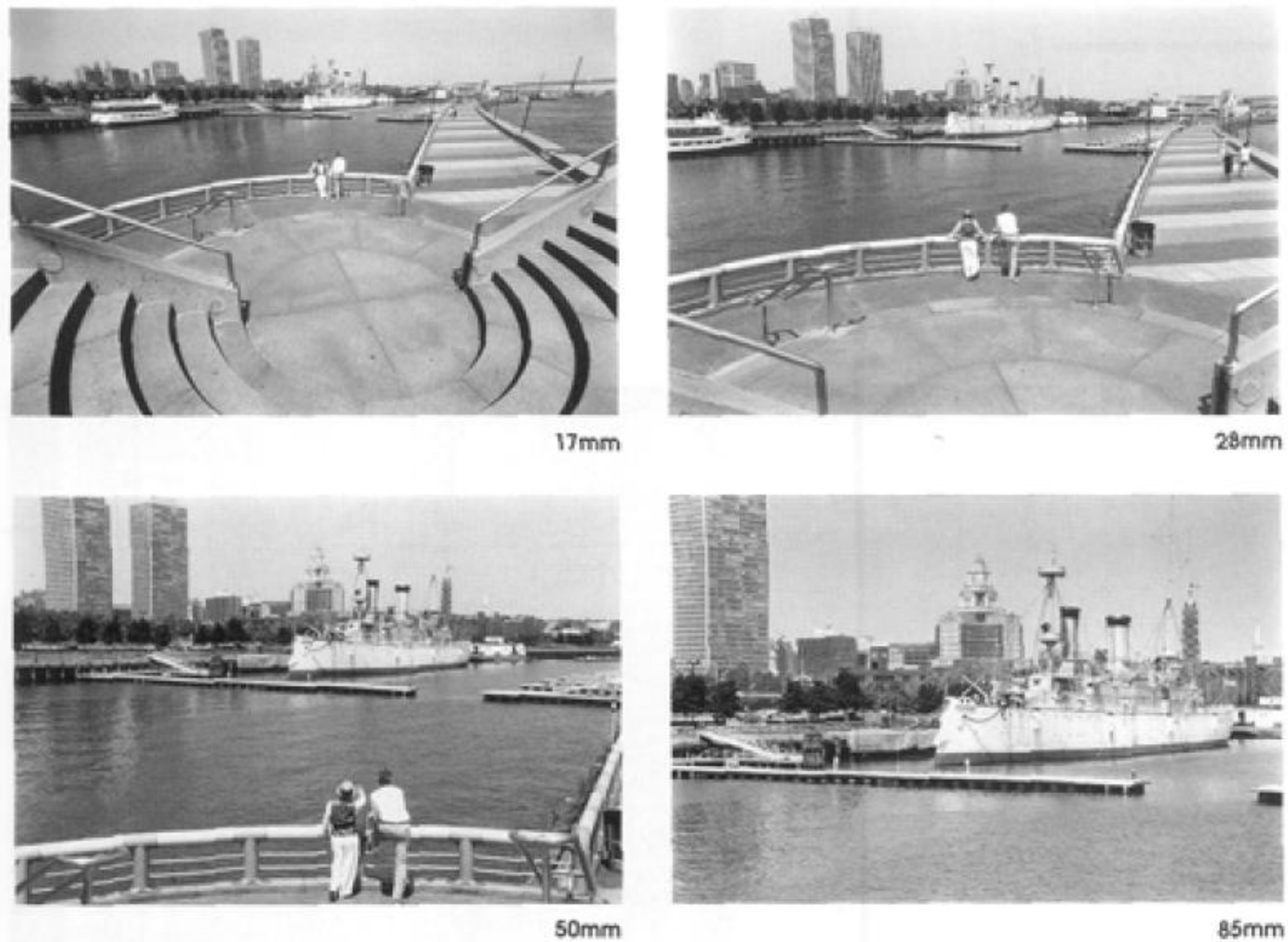
Small apeture = large DOF

Nice Depth of Field effect

Field of View (Zoom)

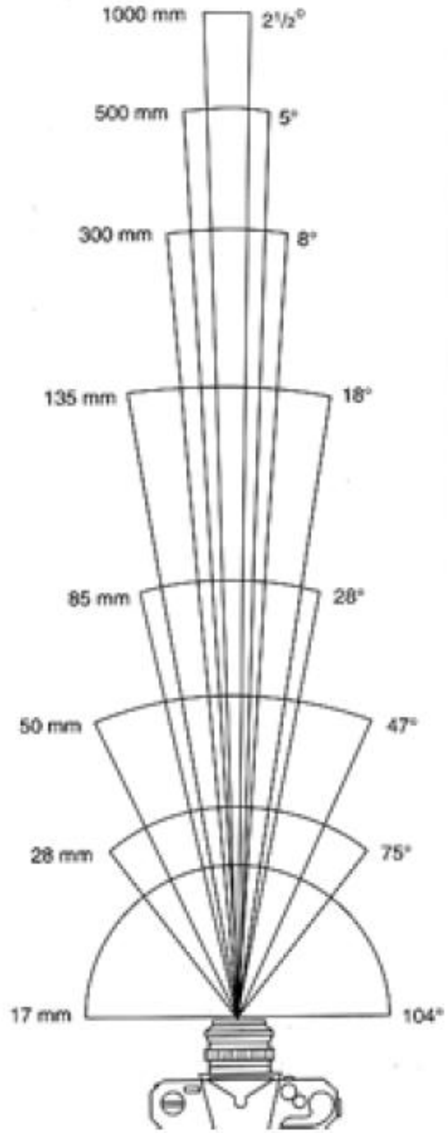
Field of View (Zoom)

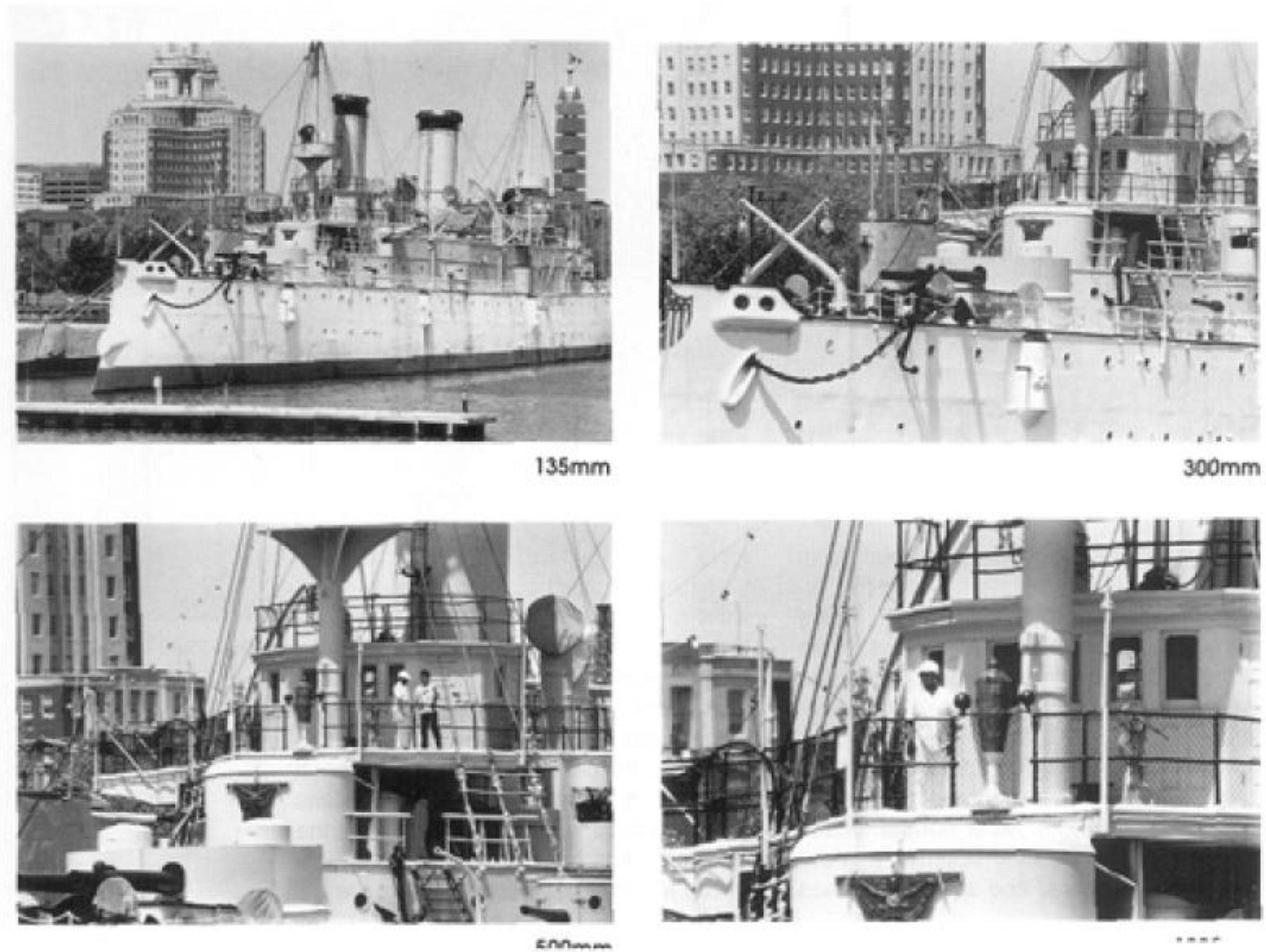




From London and Upton

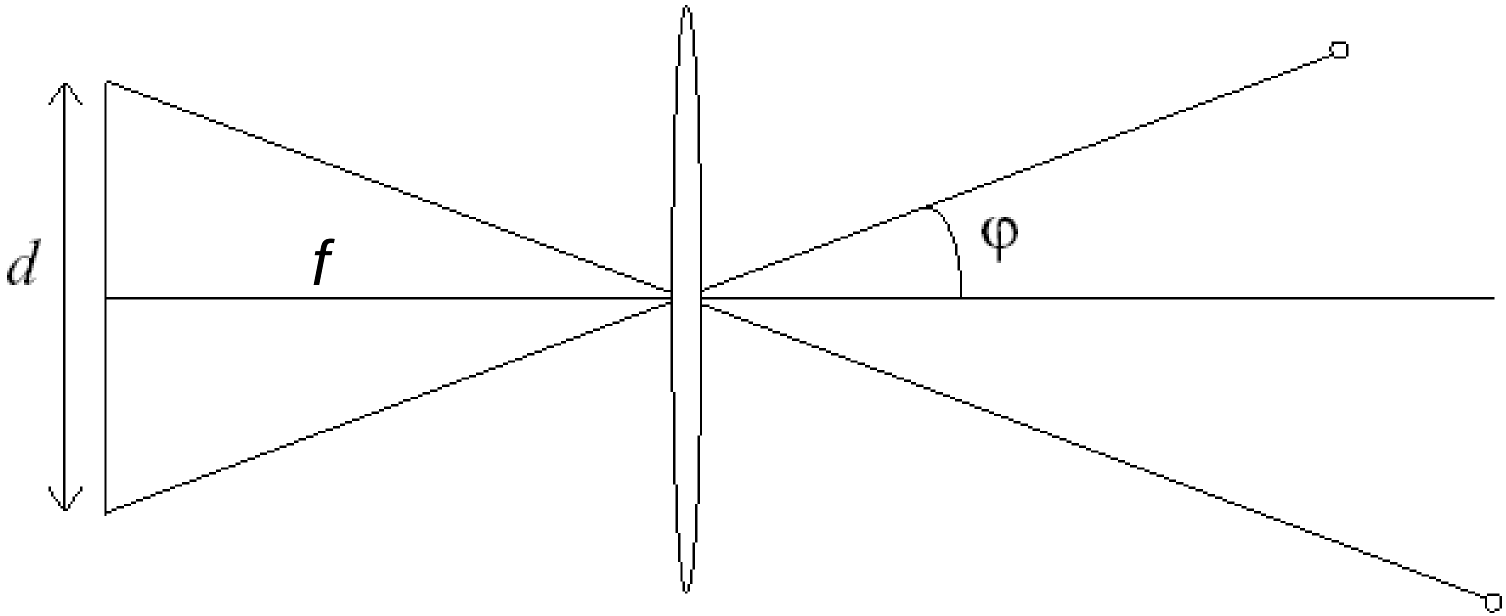
Field of View (Zoom) = Cropping





From London and Upton

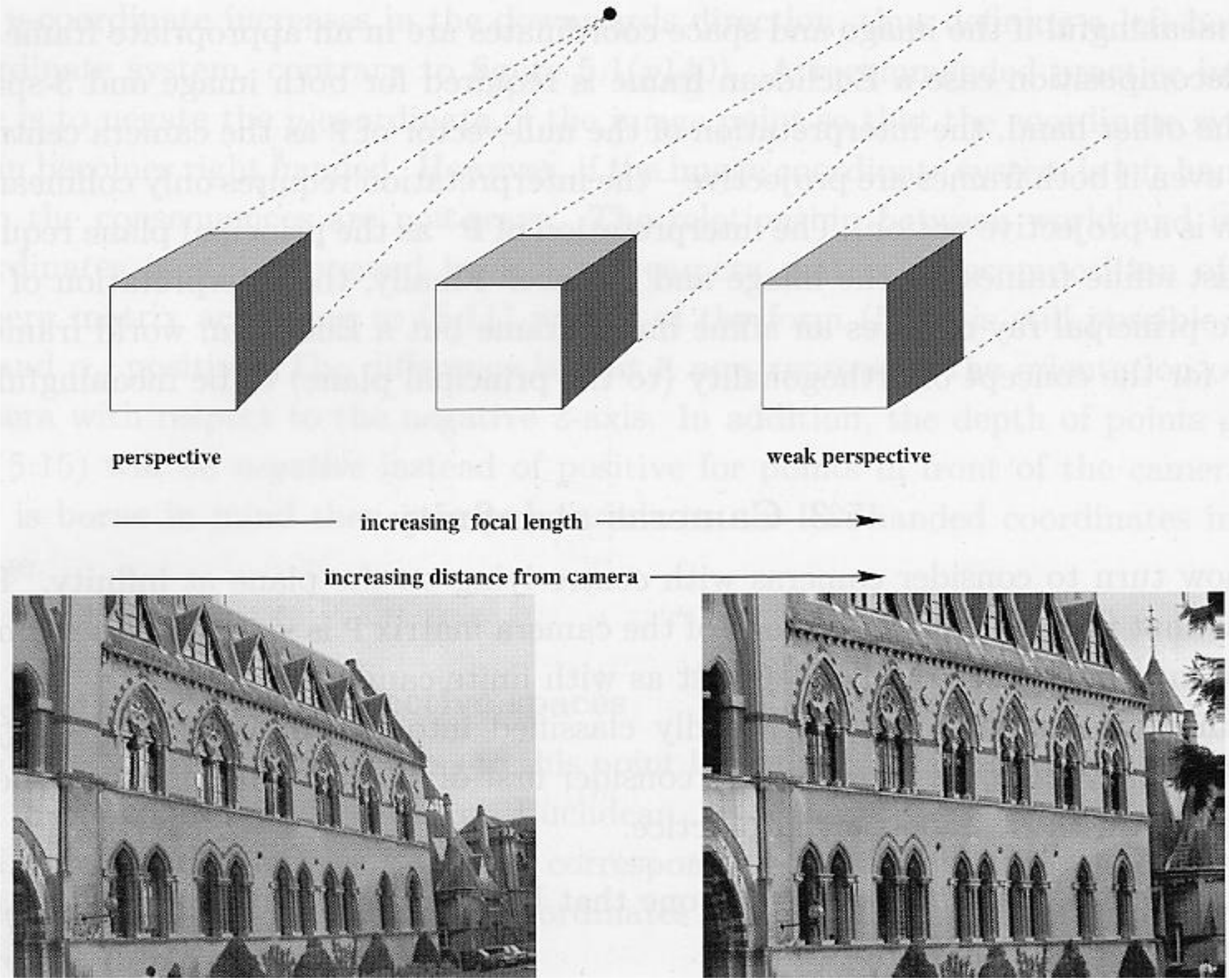
FOV depends of Focal Length



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



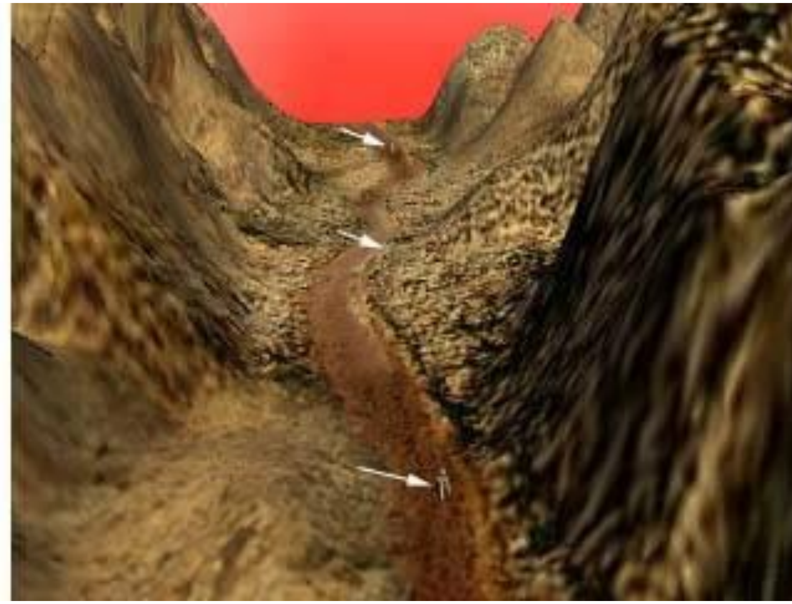
From Zisserman & Hartley

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

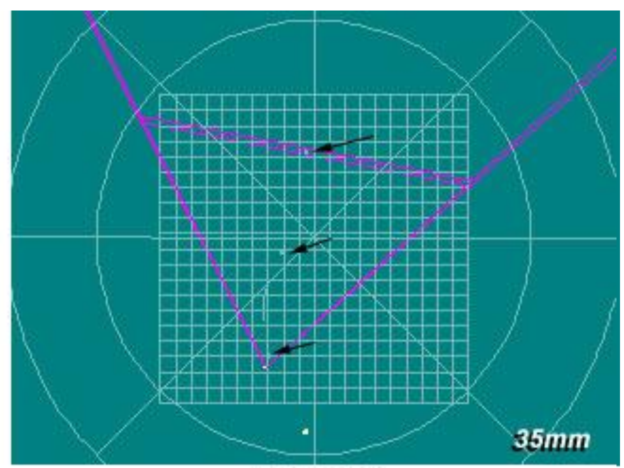


Figure 5.2

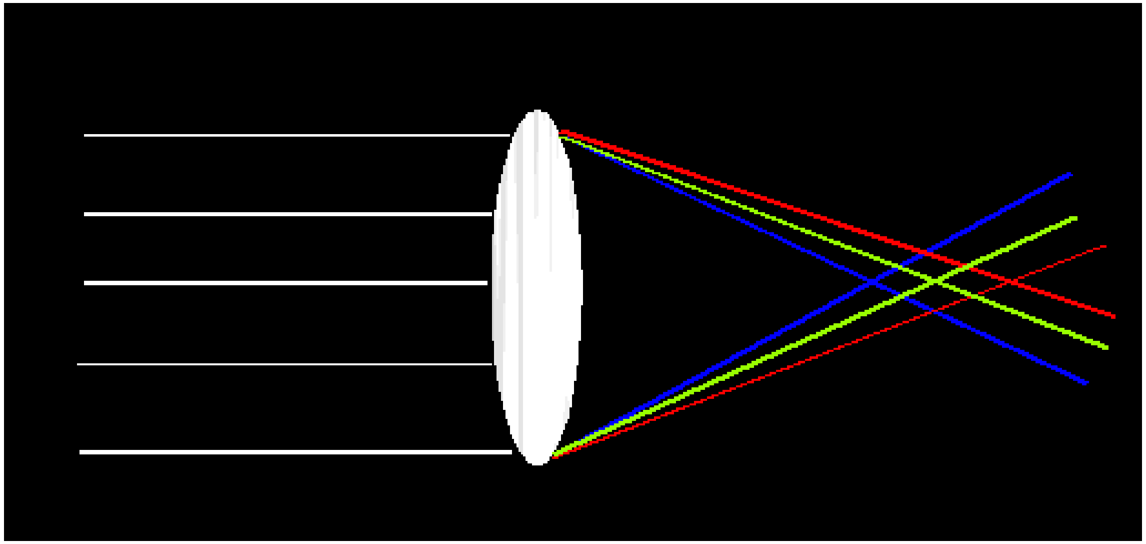
Lens Flaws

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

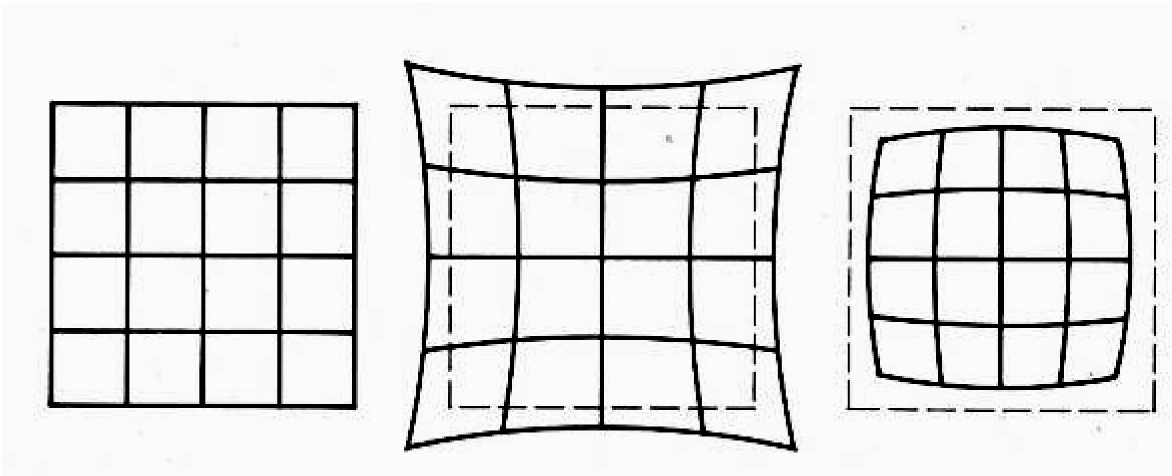
Near Lens Center

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