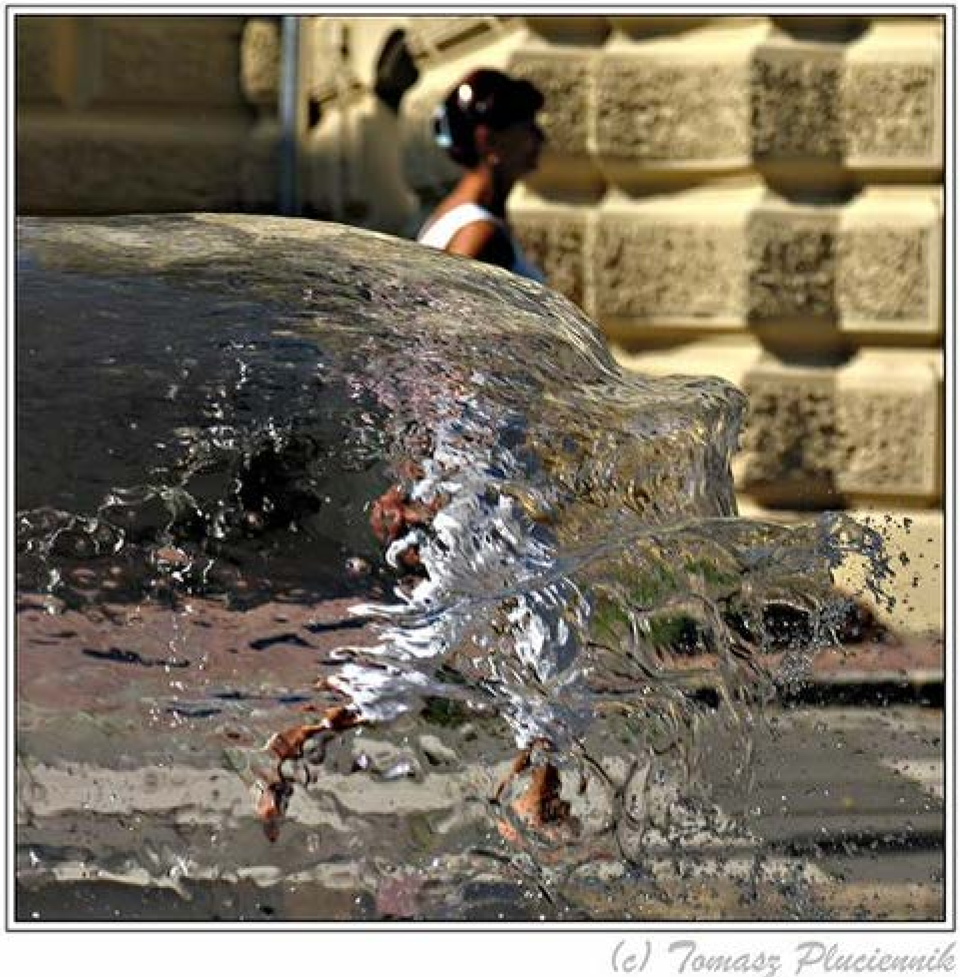
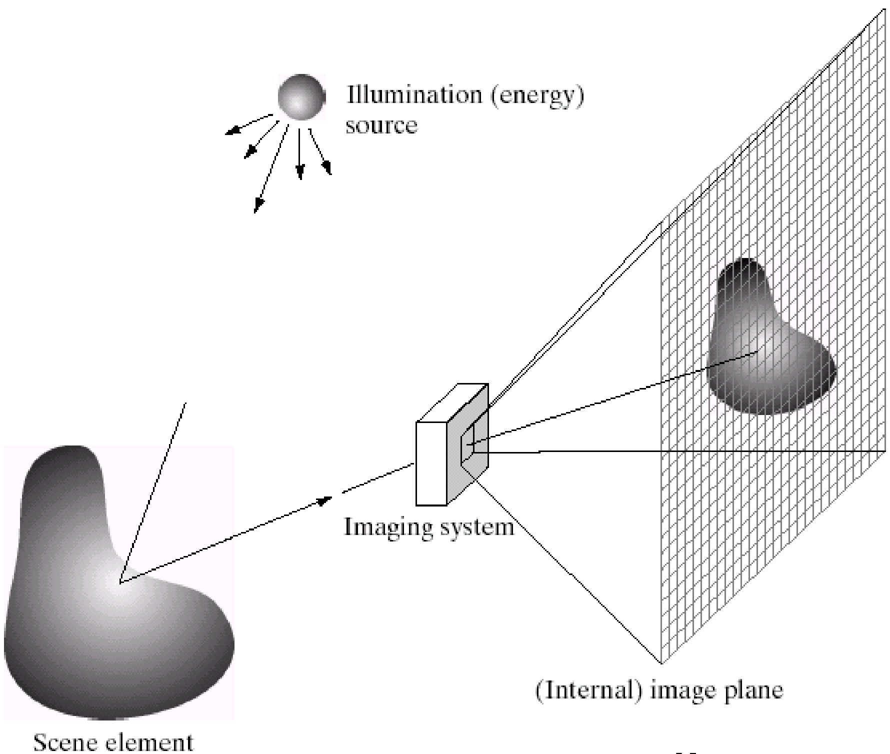
The Camera



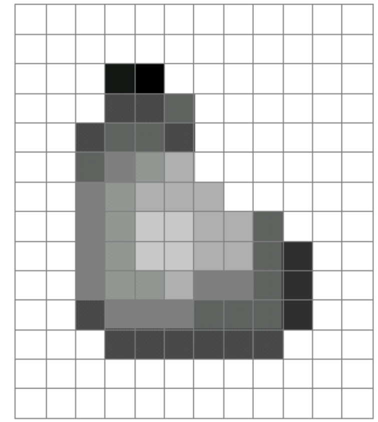
CS194: Image Manipulation & Computational Photography

Alexei Efros, UC Berkeley, Fall 2015

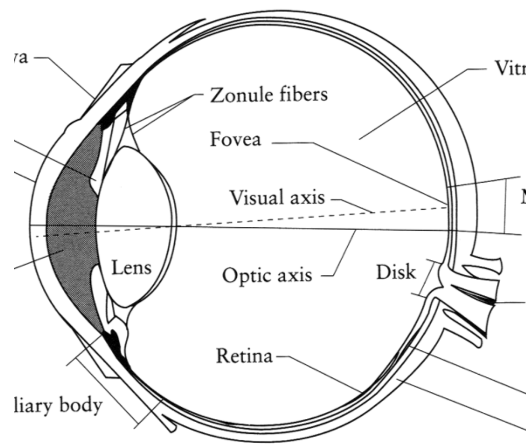
Image Formation



Film

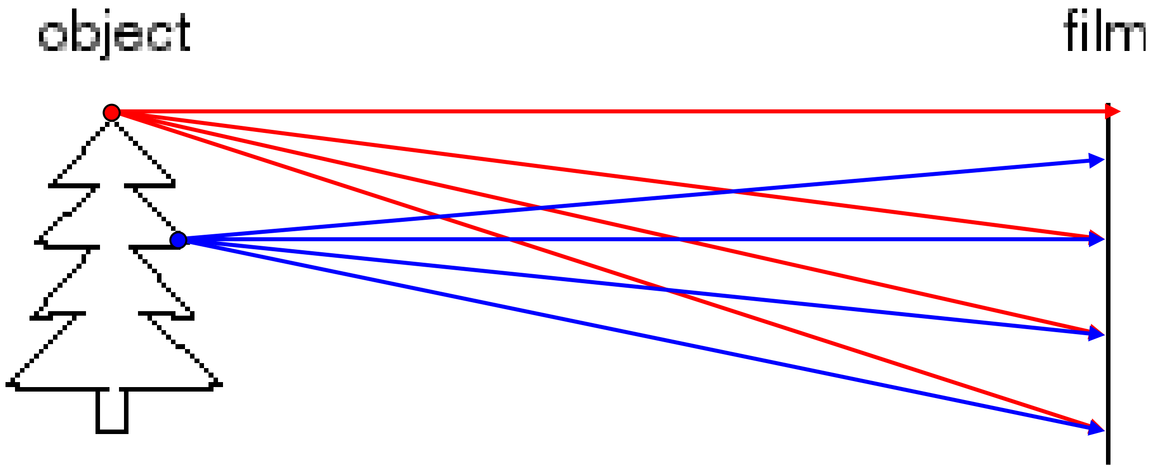


Digital Camera



The Eye

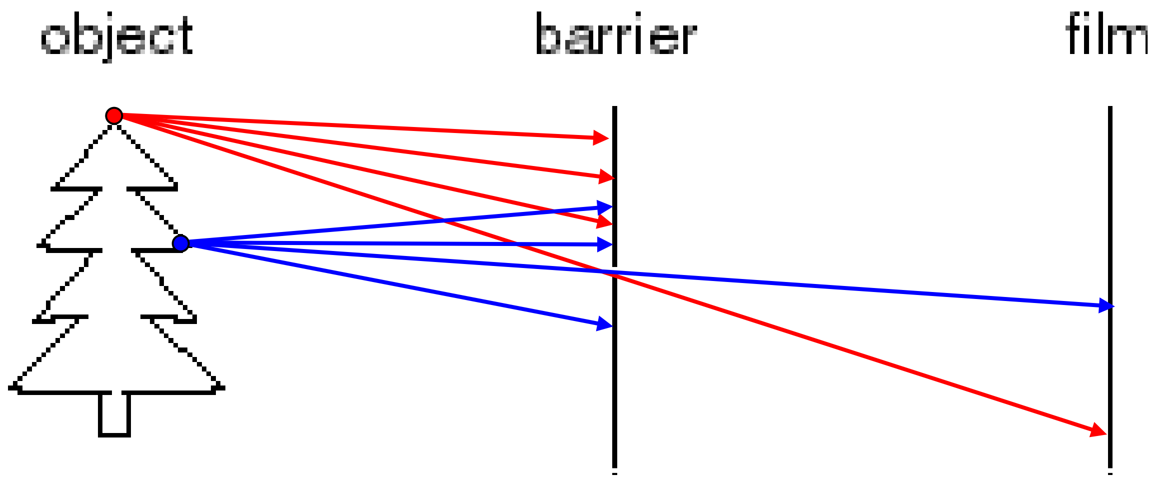
How do we see the world?



Let’s design a camera

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

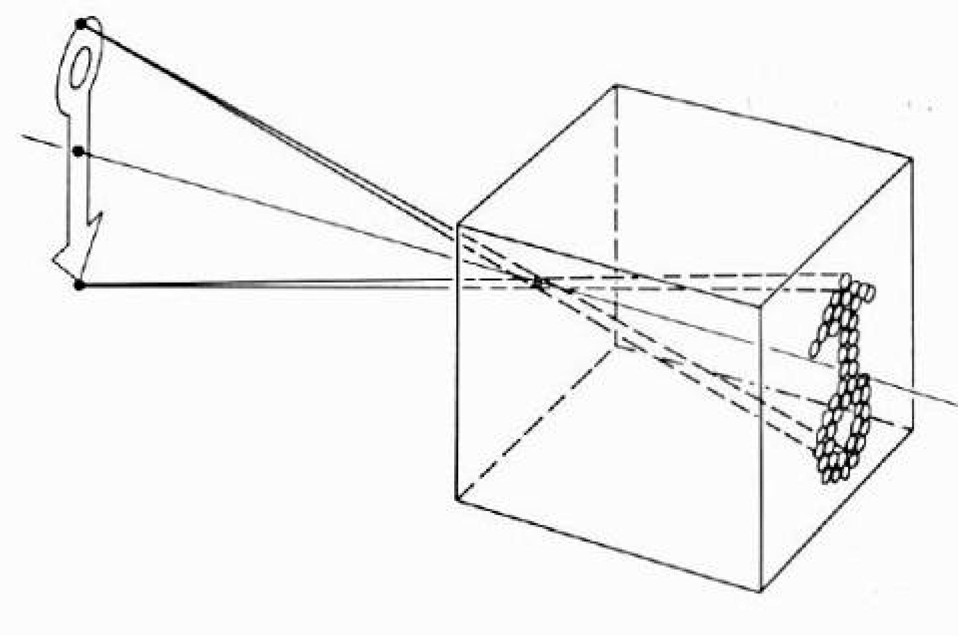
Pinhole camera



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?

Pinhole camera model



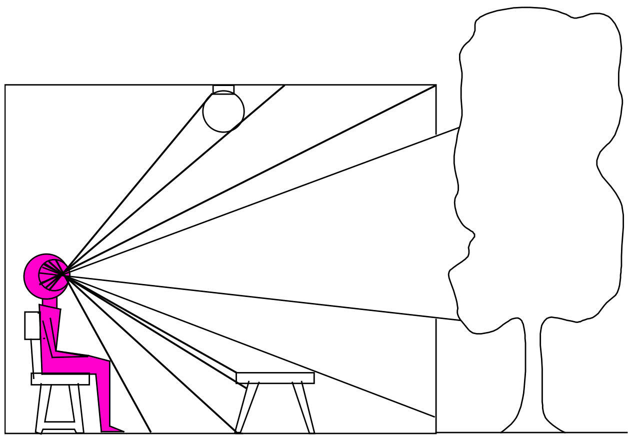
Pinhole model:

- 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

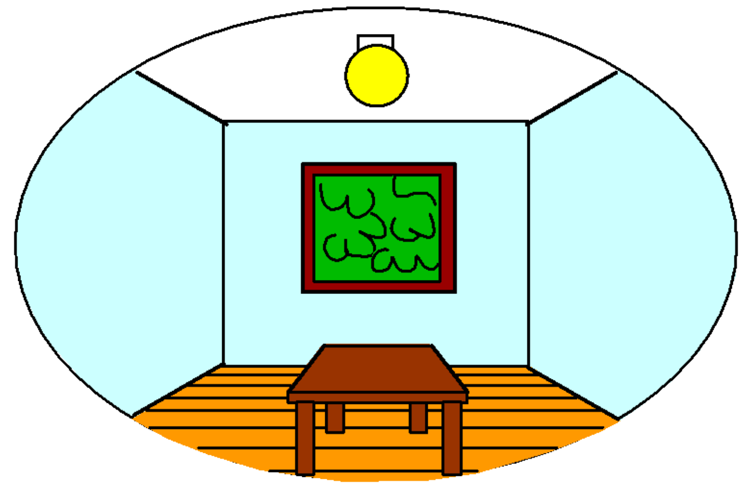
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

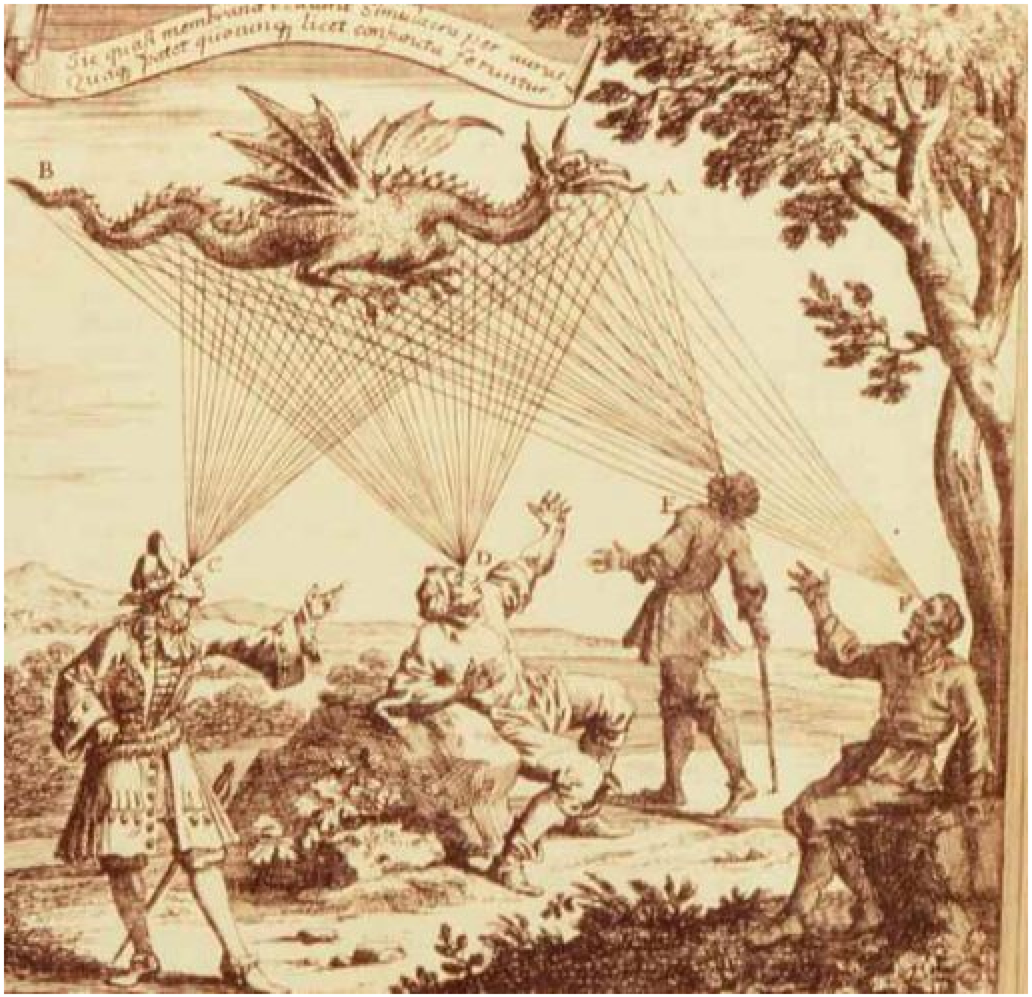
2D image



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

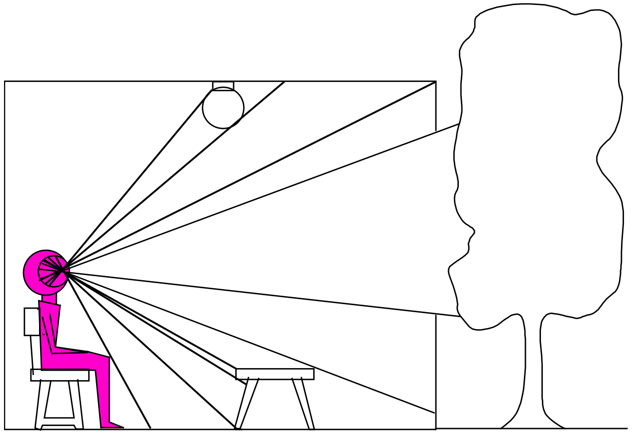
Supported by:

- Empedocles
- Plato
- Euclid (kinda)
- Ptolemy
- …
- 50% of US college students*

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

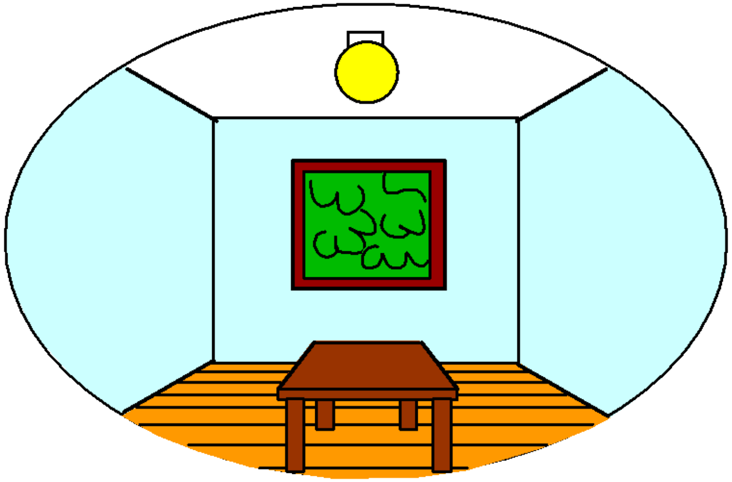
How we see the world

3D world



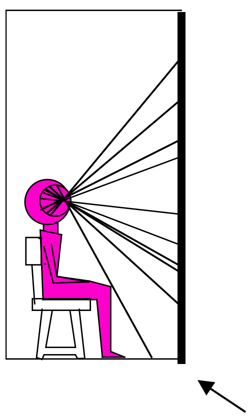
Point of observation

2D image

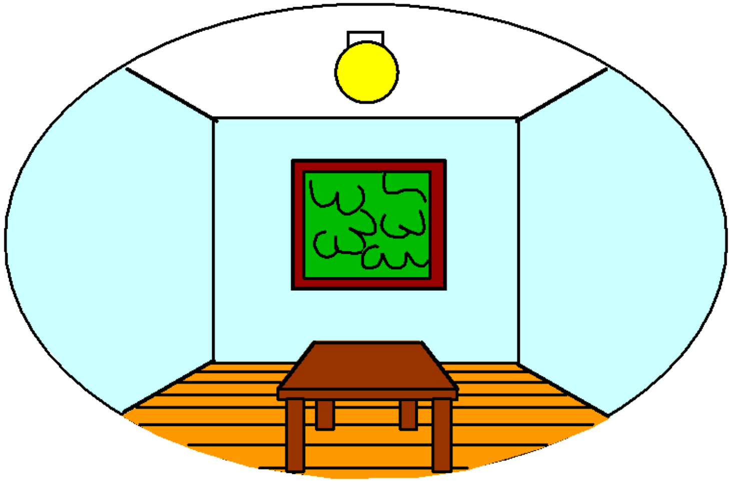


How we see the world

3D world



2D image



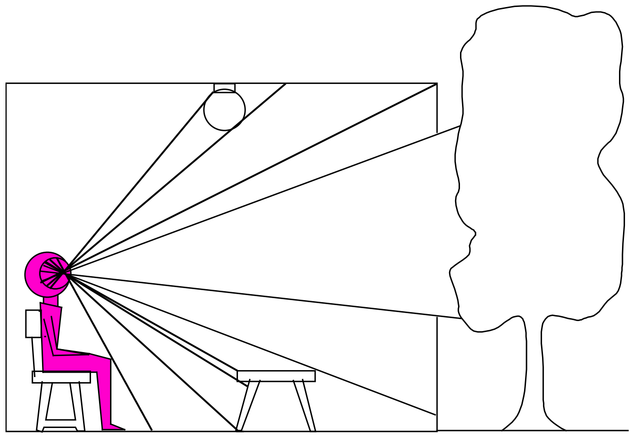
Fooling the eye

Fooling the eye

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

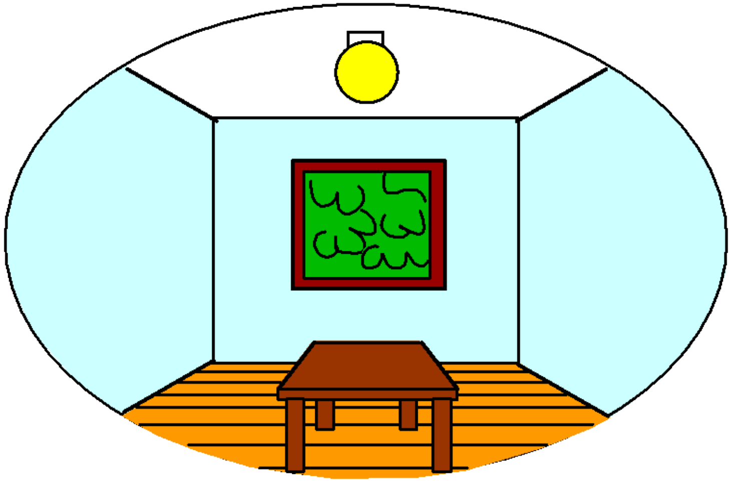
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

2D image

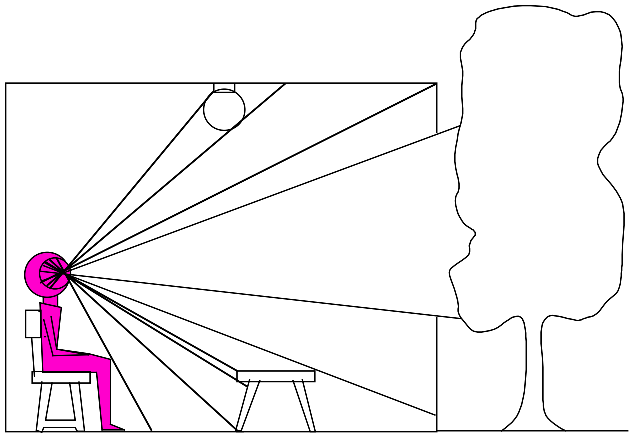


Why did evolution opt for such strange solution?

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

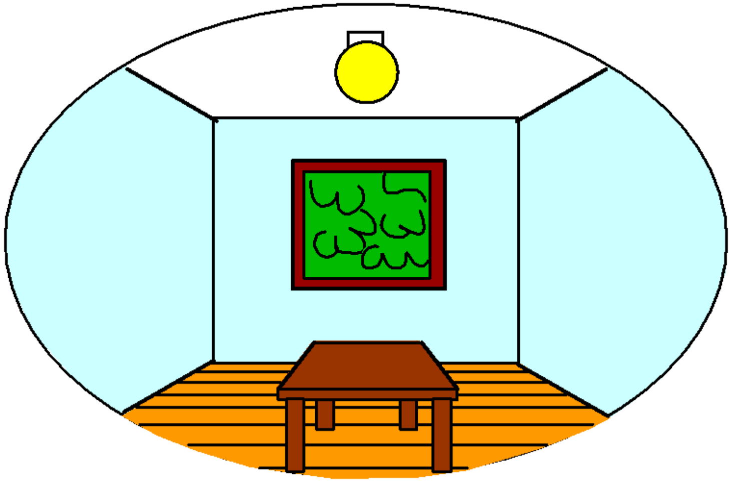
Dimensionality Reduction Machine (3D to 2D)

3D world



Point of observation

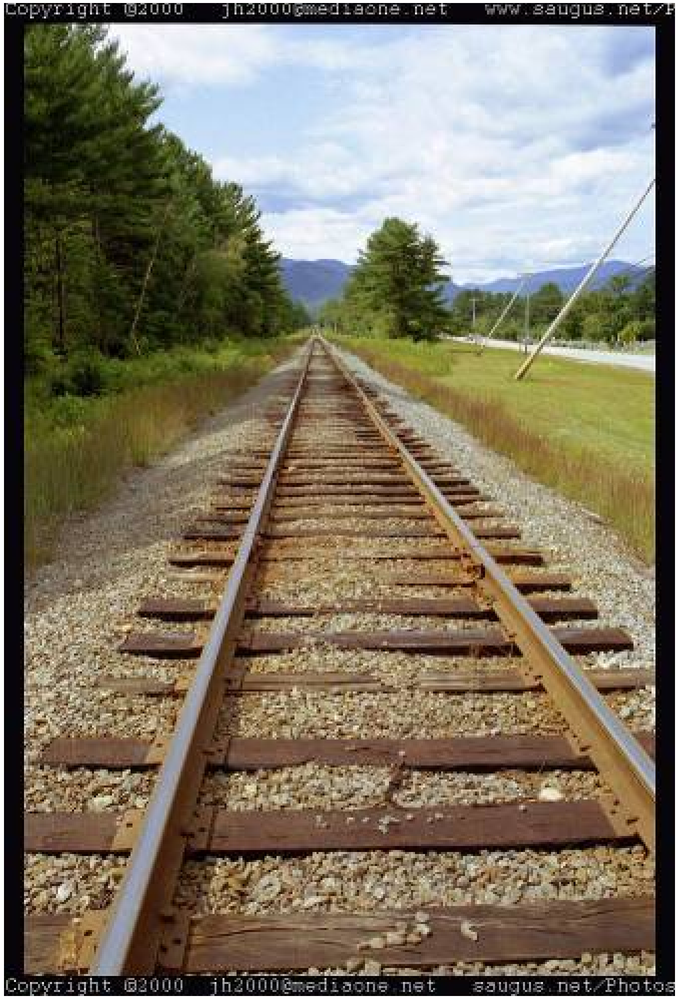
2D image



What have we lost?

- Angles
- Distances (lengths)

Funny things happen…



Parallel lines aren't…

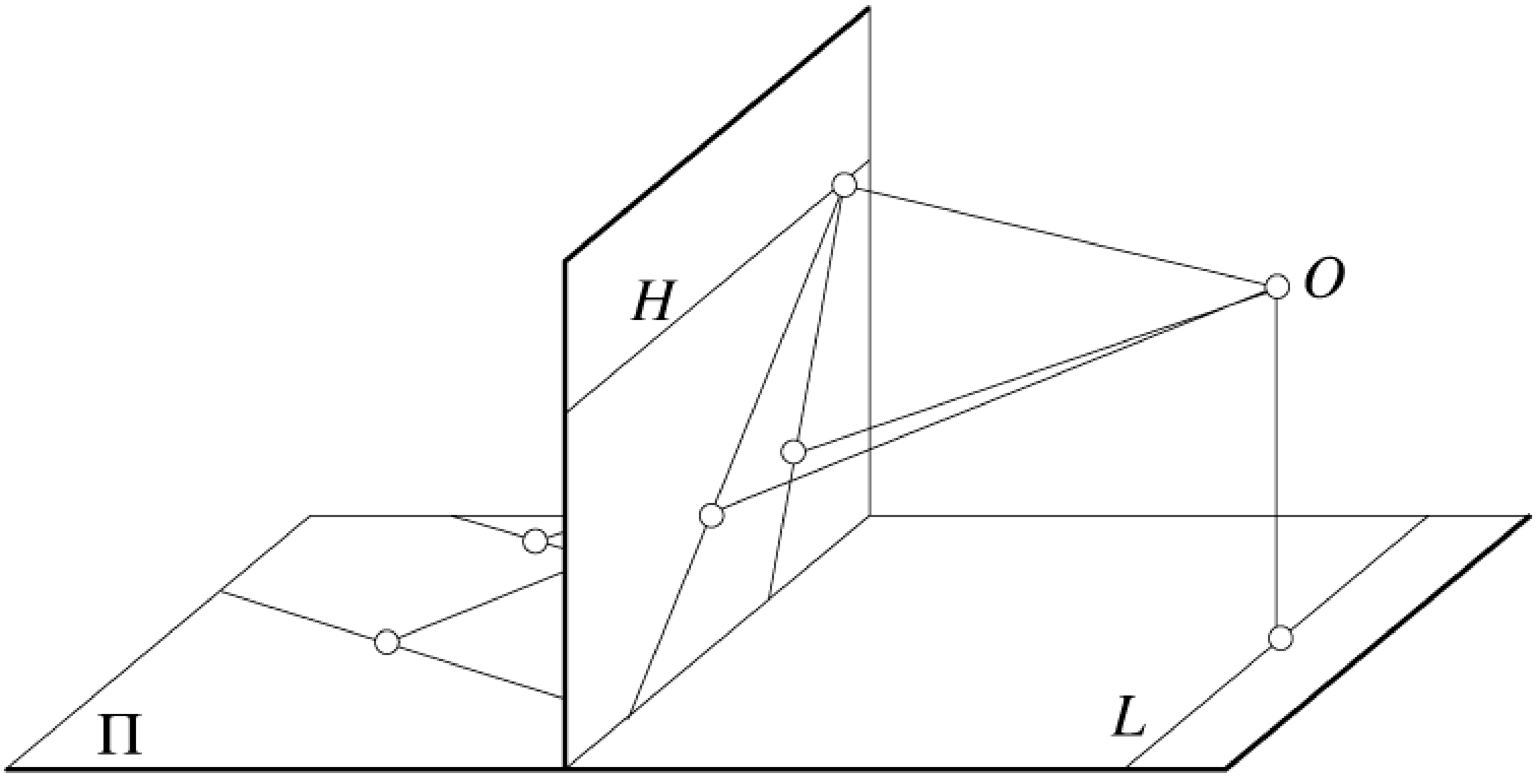


Figure by David Forsyth

Exciting New Study!

99° Sailors Take Warning

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- 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

10.2K

688

332

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...

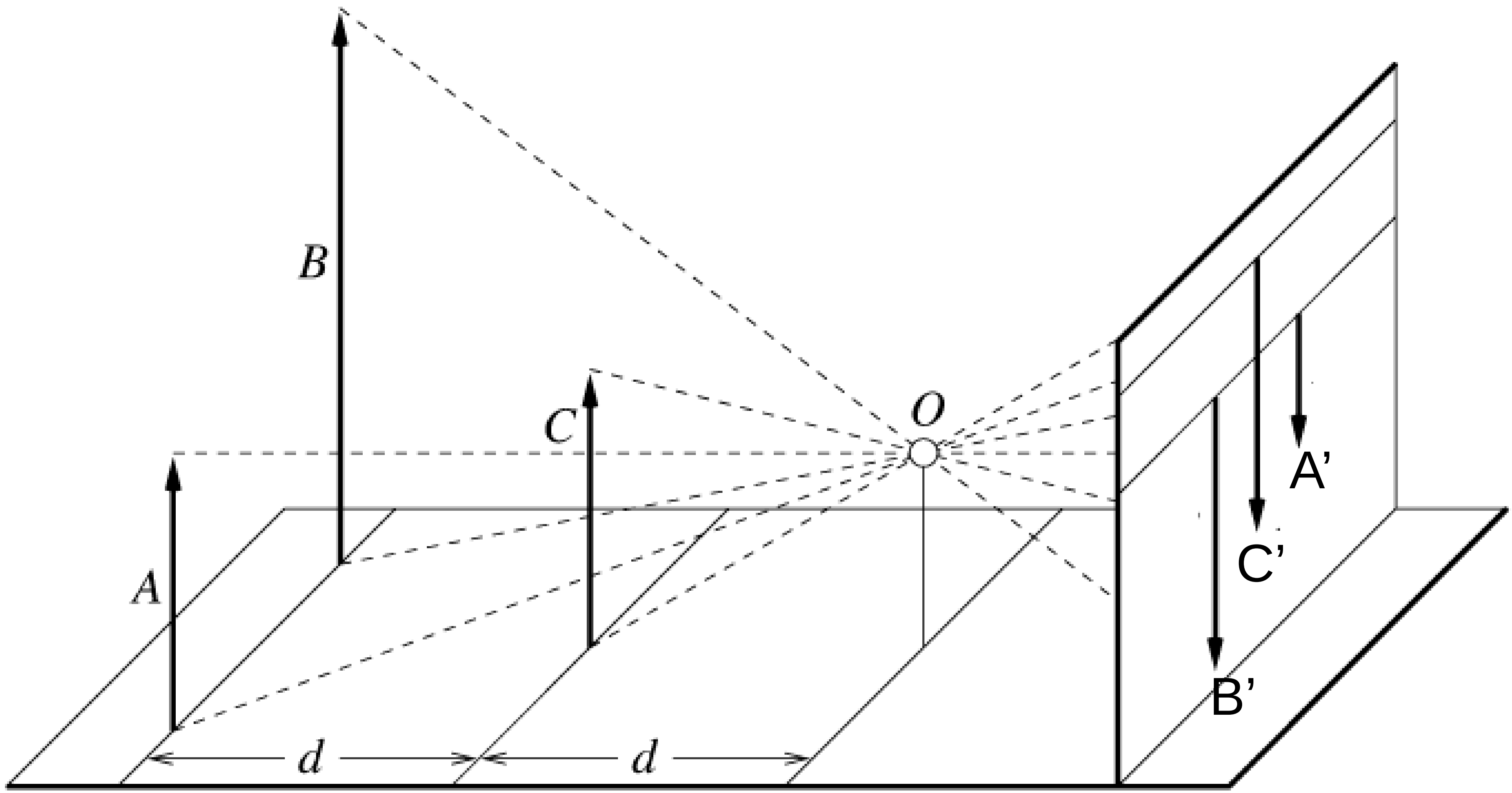
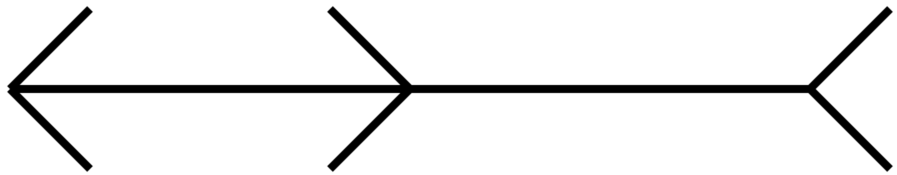
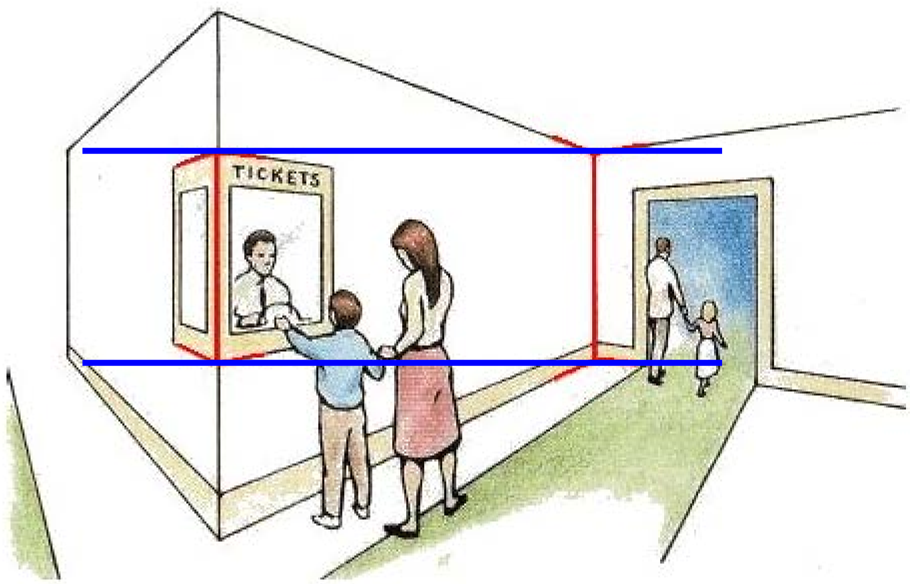


Figure by David Forsyth

…but humans adopt!



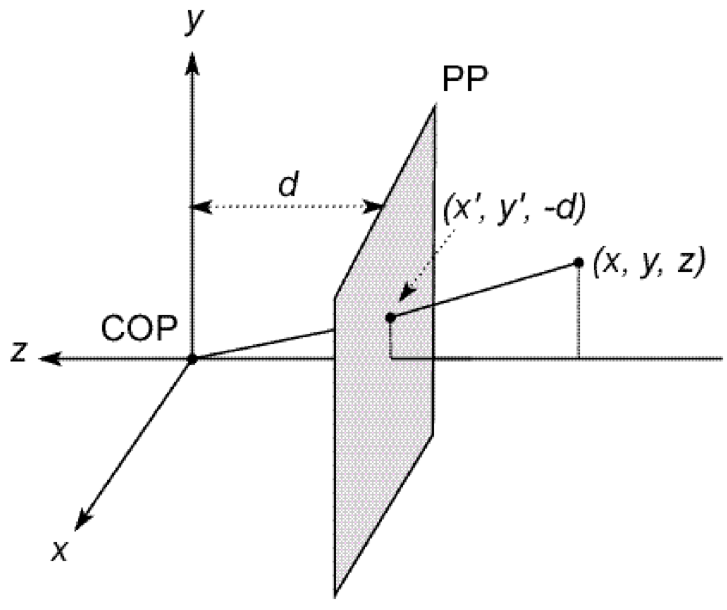
Müller-Lyer Illusion



We don’t make measurements in the image plane

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

Modeling projection

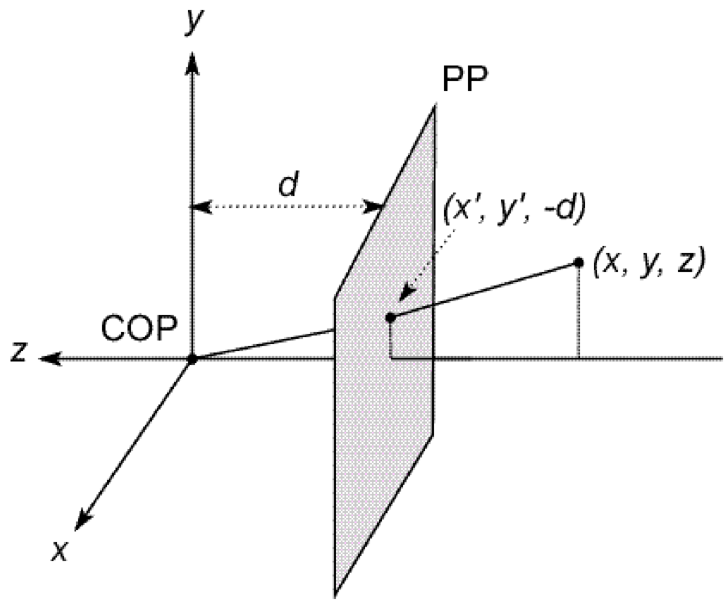


The coordinate system

- 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:

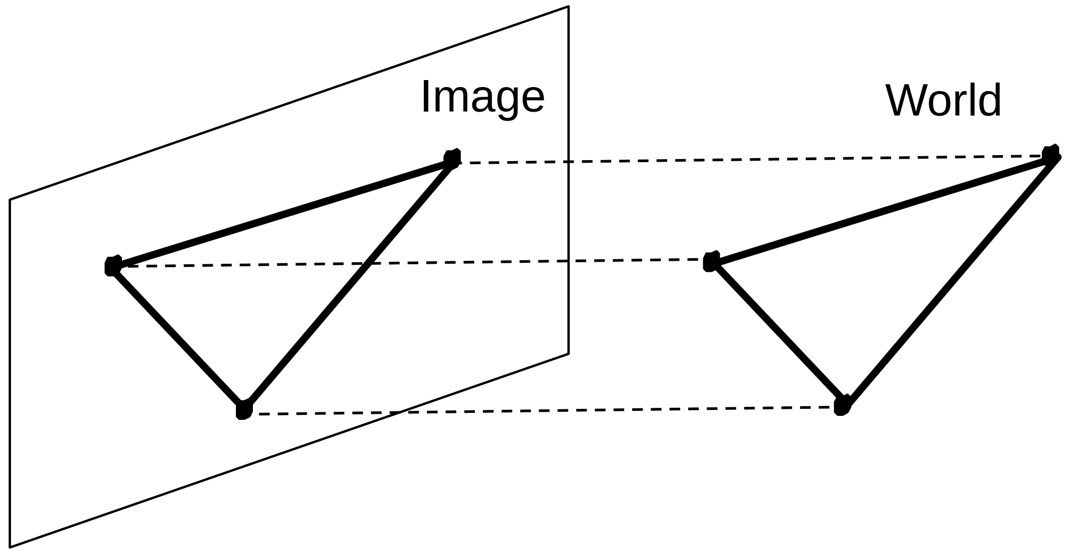
$$(x, y, z) \rightarrow (-d\frac{x}{z},\ -d\frac{y}{z})$$

Slide by Steve Seitz

Orthographic Projection

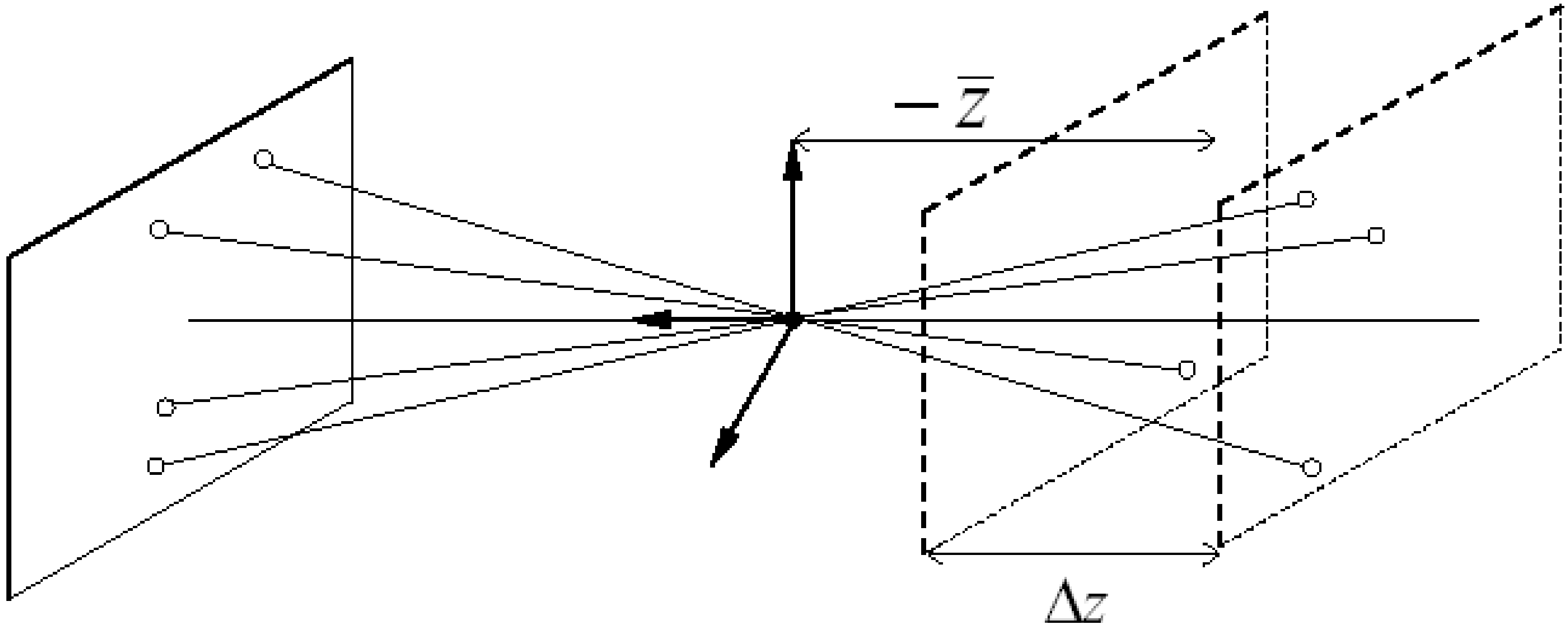
Special case of perspective projection

- Distance from the COP to the PP is infinite



- Also called “parallel projection”
- x’ = x
- y’ = y

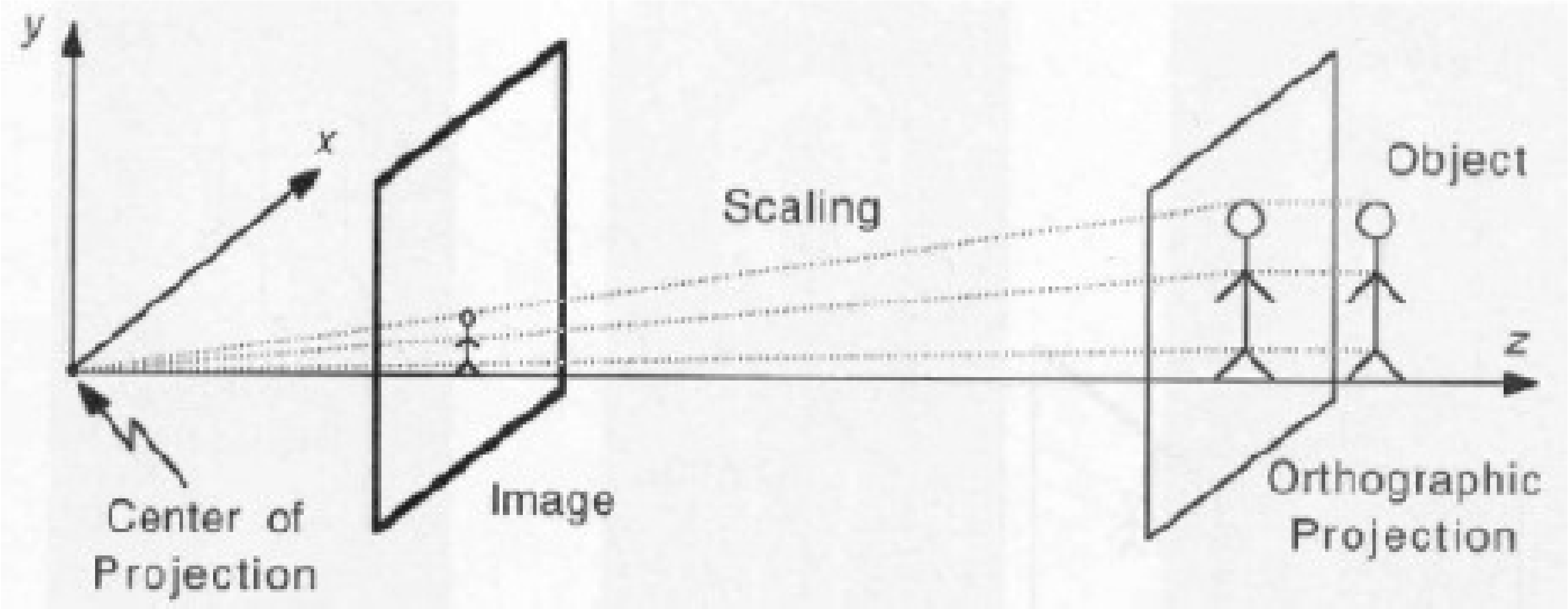
Scaled Orthographic or “Weak Perspective”



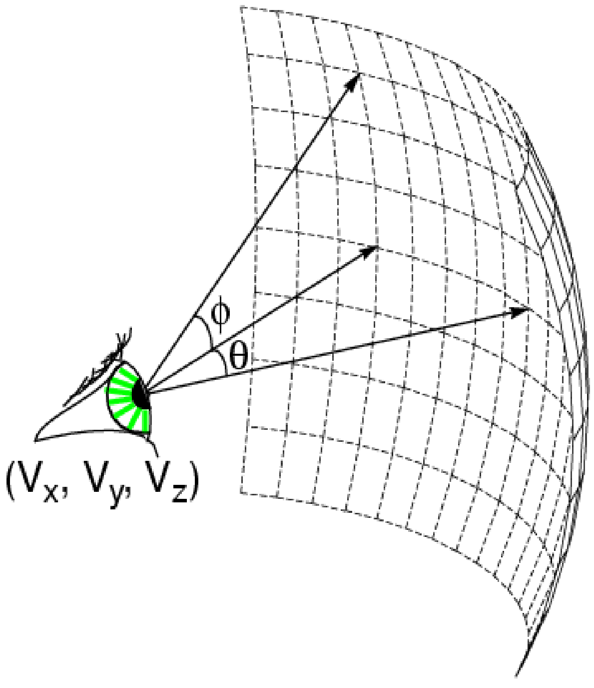
If $\Delta z << -\bar{z}$: $x' \approx -mx$, $y' \approx -my$ $\quad m = -\frac{f'}{\bar{z}}$

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

Scaled Orthographic or “Weak Perspective”



Spherical Projection



What if PP is spherical with center at COP?

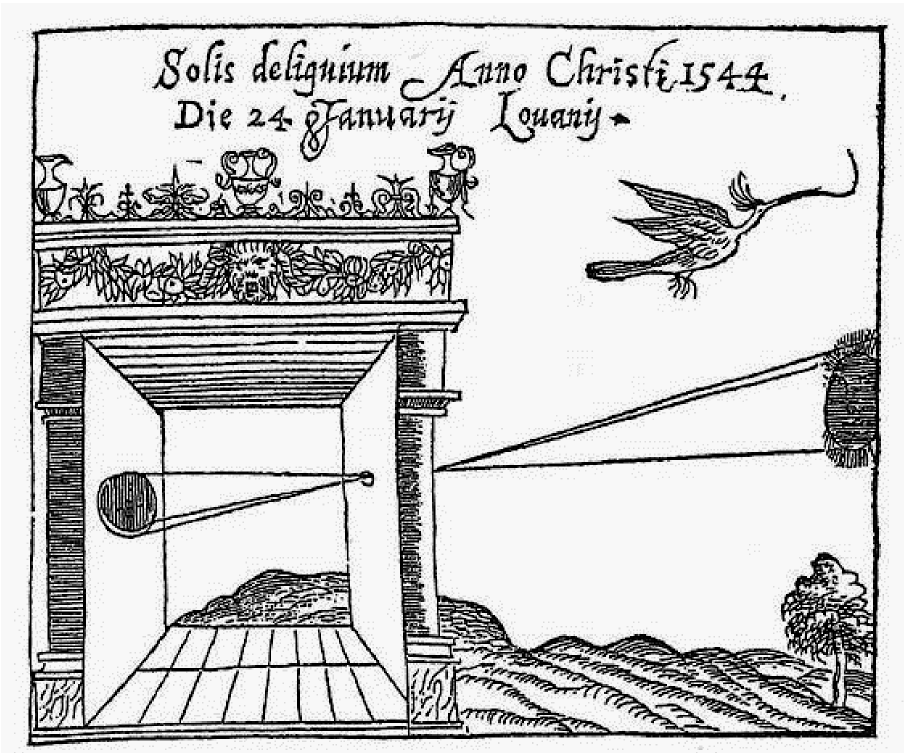
In spherical coordinates, projection is trivial:

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

Note: doesn’t depend on focal length f!

Building a real camera

Camera Obscura: the pre-camera



Gemma Frisius, 1558

- 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)

http://www.abelardomorell.net/books/books_m02.html

Pinhole cameras everywhere

Tree shadow during a solar eclipse

photo credit: Nils van der Burg

http://www.physicstogo.org/index.cfm

Slide by Steve Seitz

Accidental pinhole cameras

My hotel room, contrast enhanced.

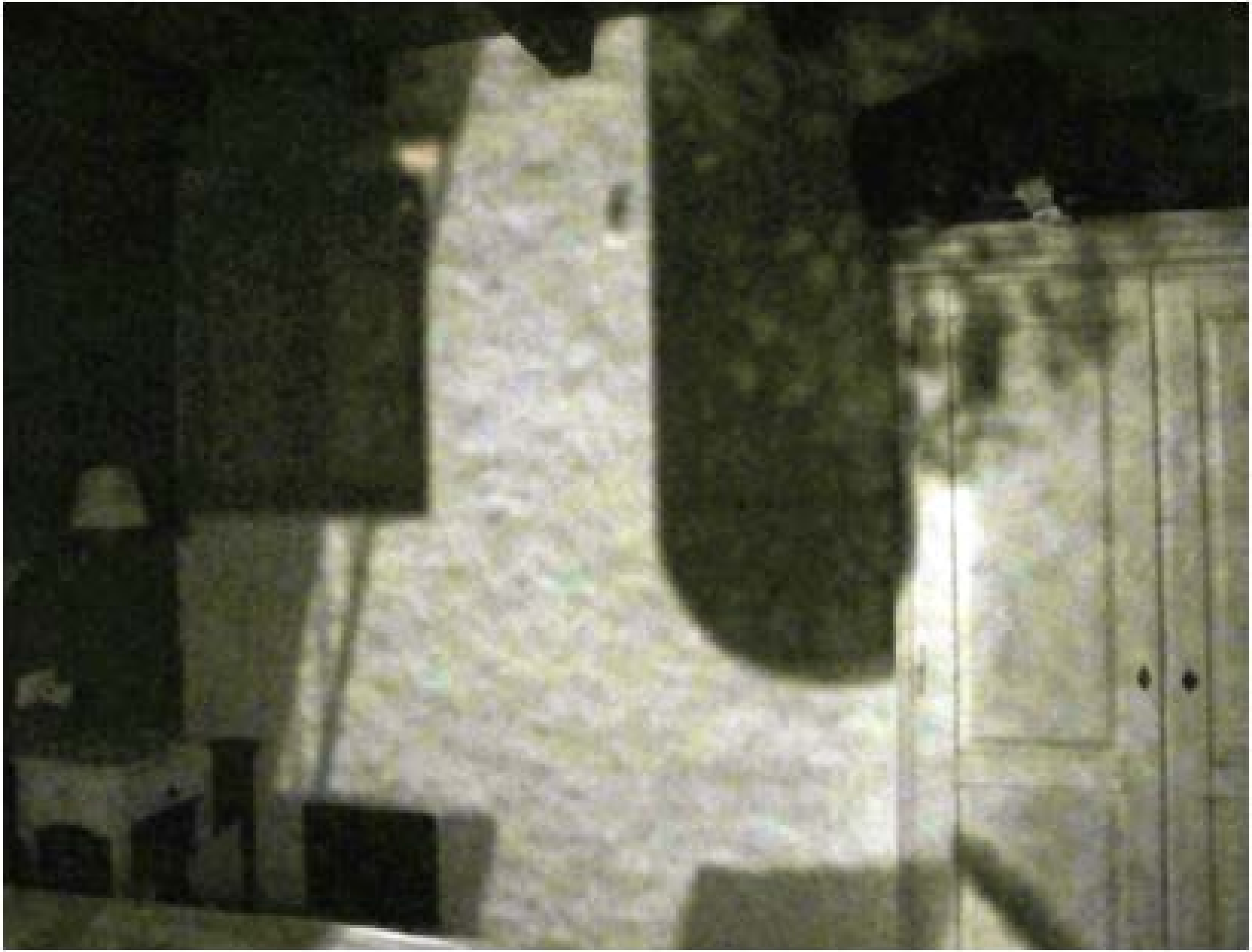
The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

A. Torralba and W. Freeman, Accidental Pinhole and Pinspeck Cameras, CVPR 2012

Torralba and Freeman, CVPR'12

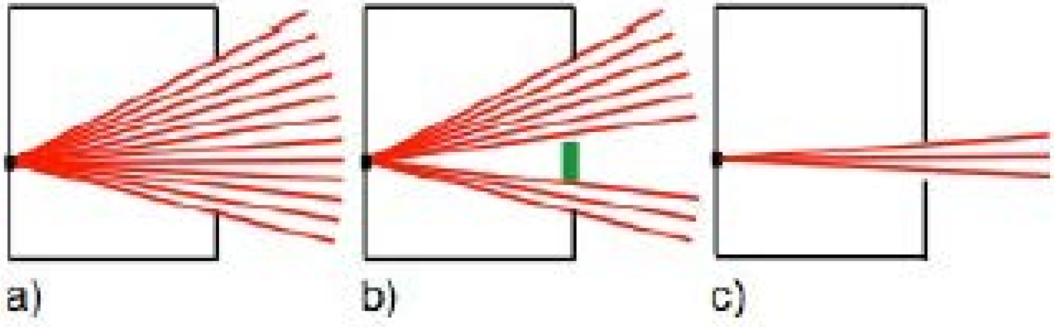
Accidental pinhole camera

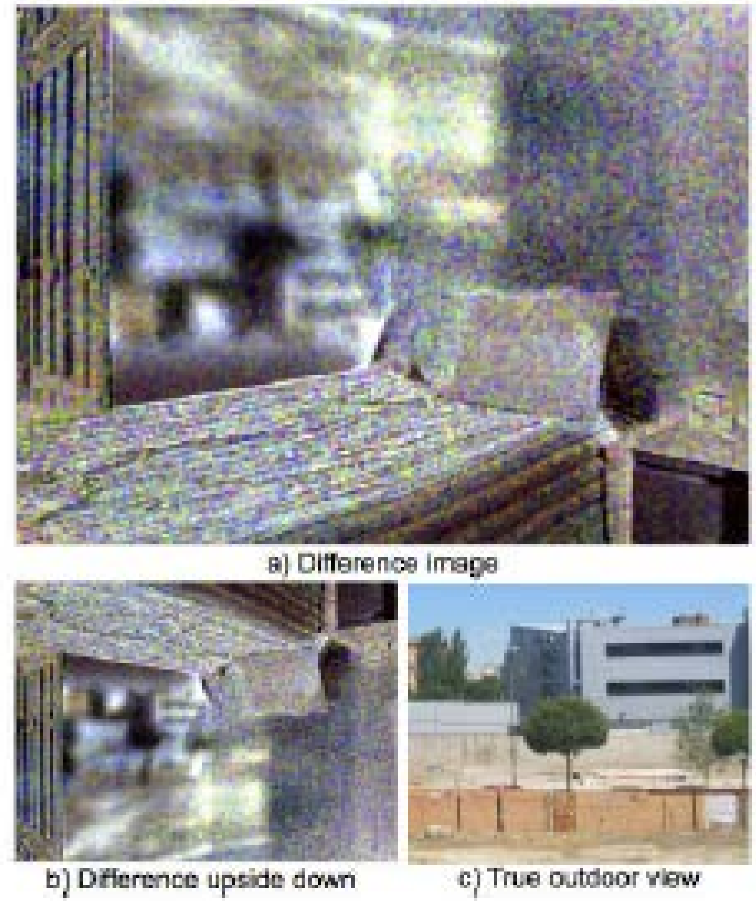


Window turned into a pinhole

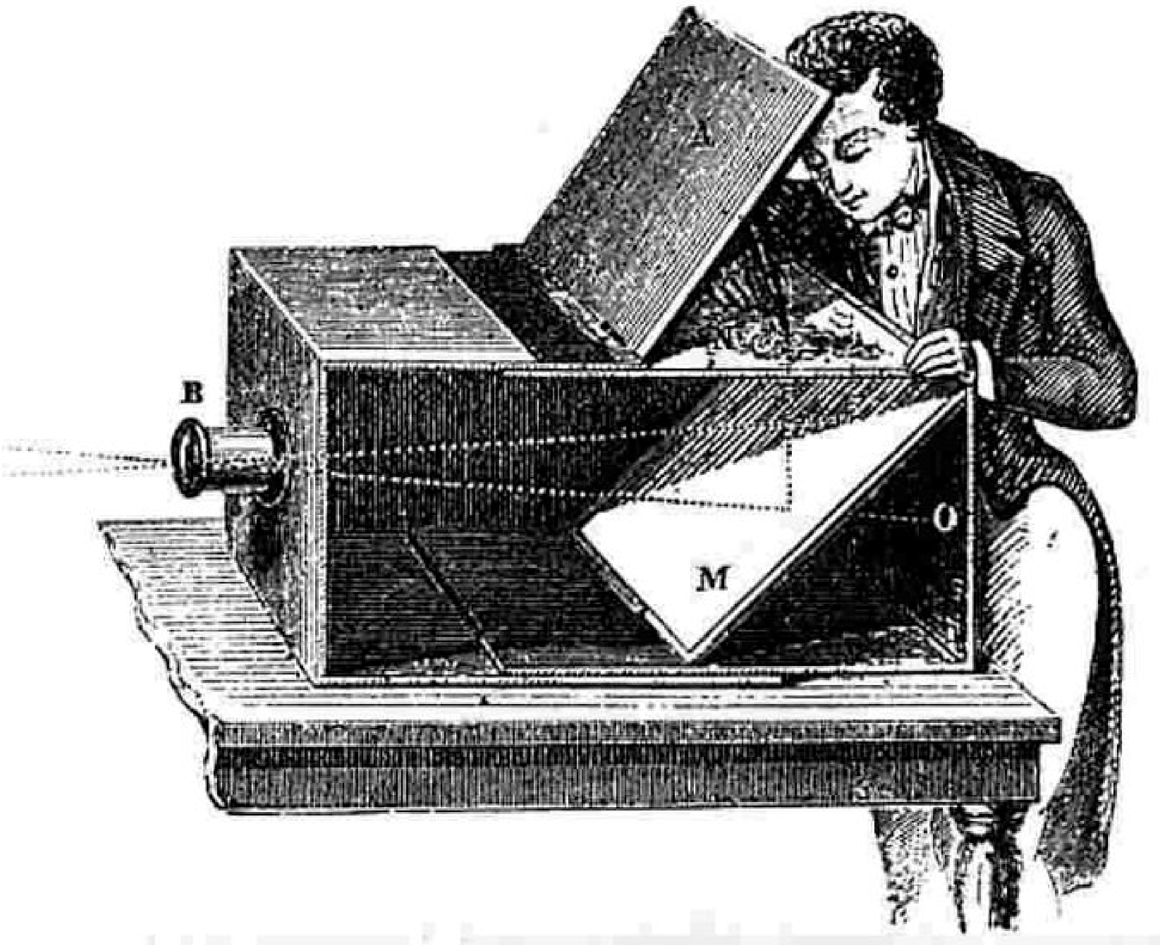
View outside

Pinspeck Camera: the anti-pinhole





Project 2: a Shoe-box Camera Obscura

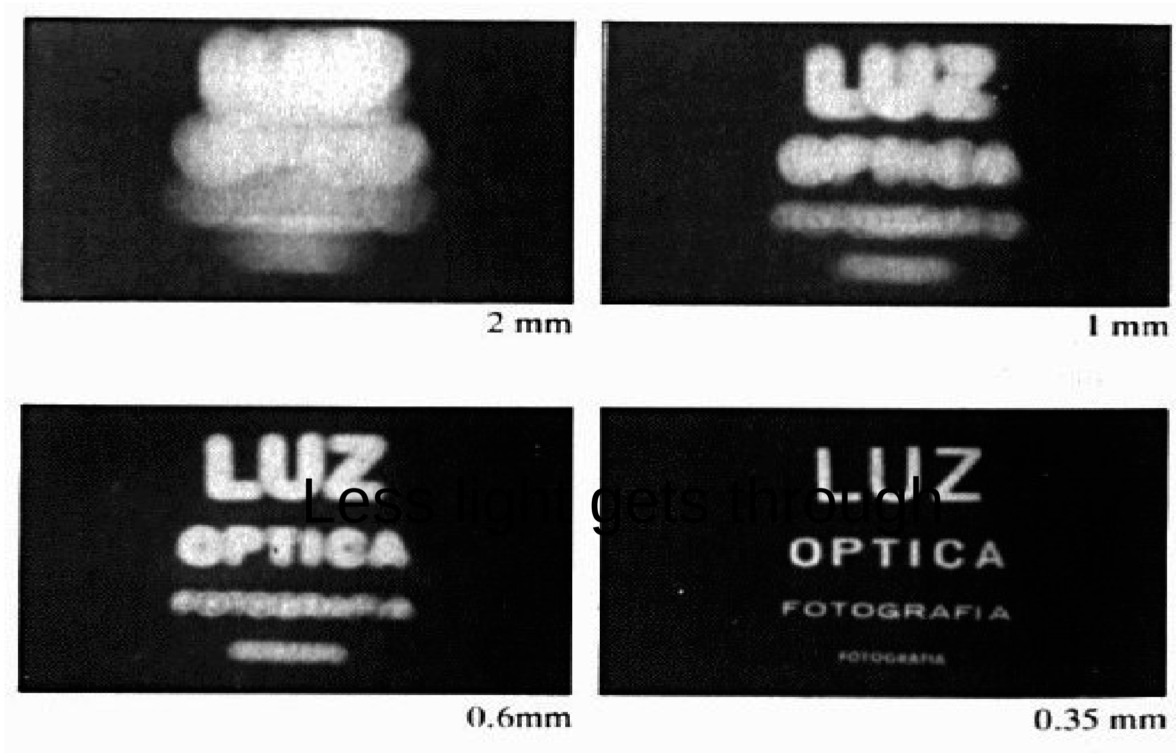


Another way to make pinhole camera

Why so blurry?

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

Shrinking the aperture

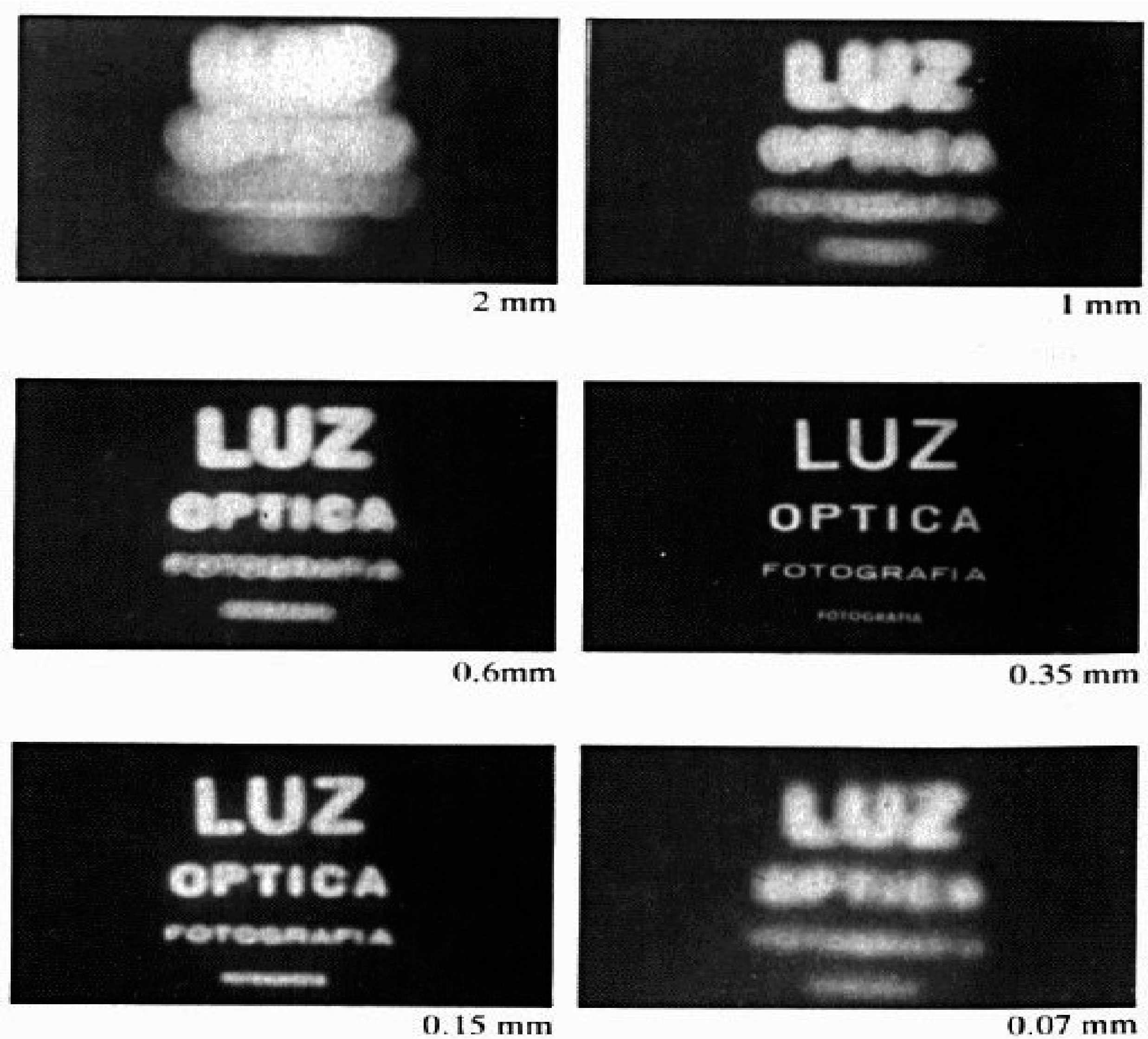


Less light gets through

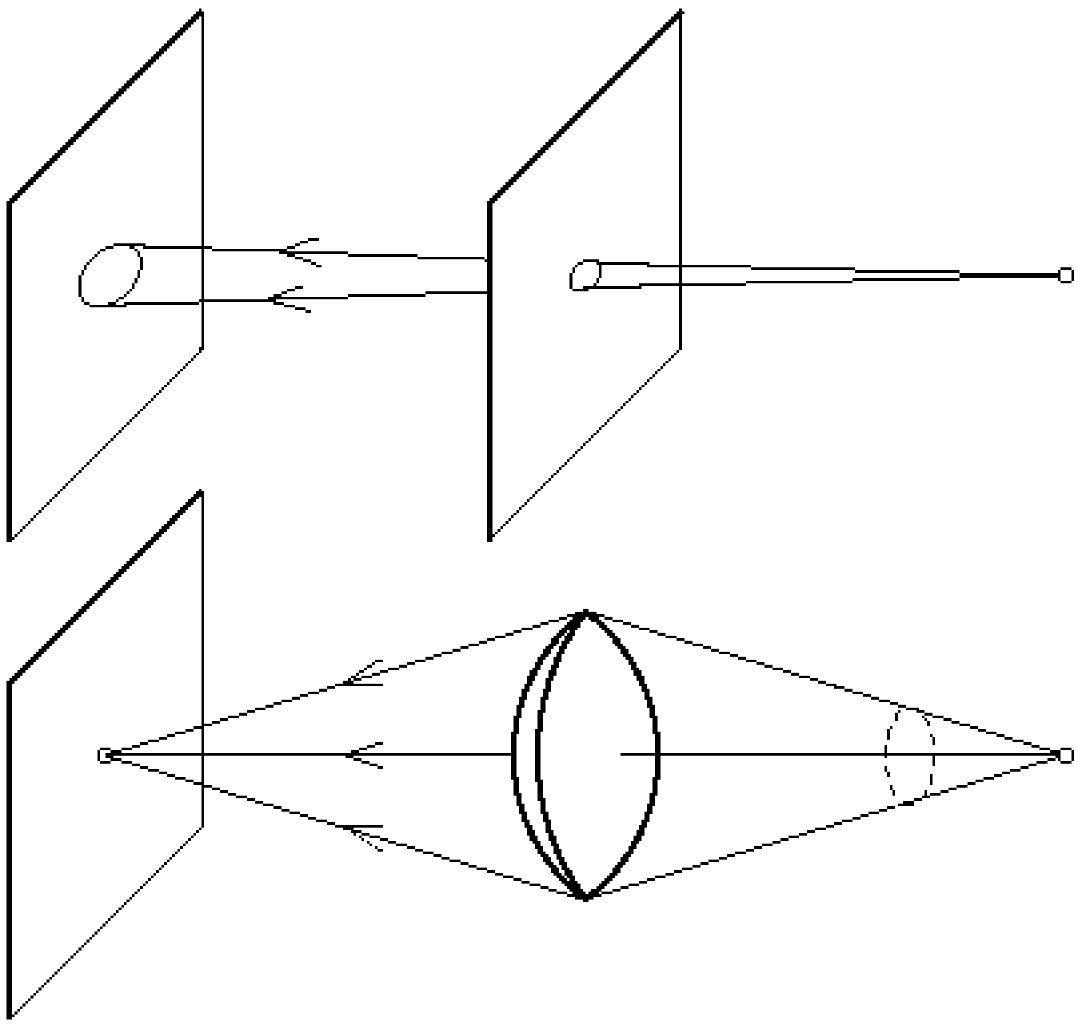
Why not make the aperture as small as possible?

- Less light gets through
- Diffraction effects…

Shrinking the aperture



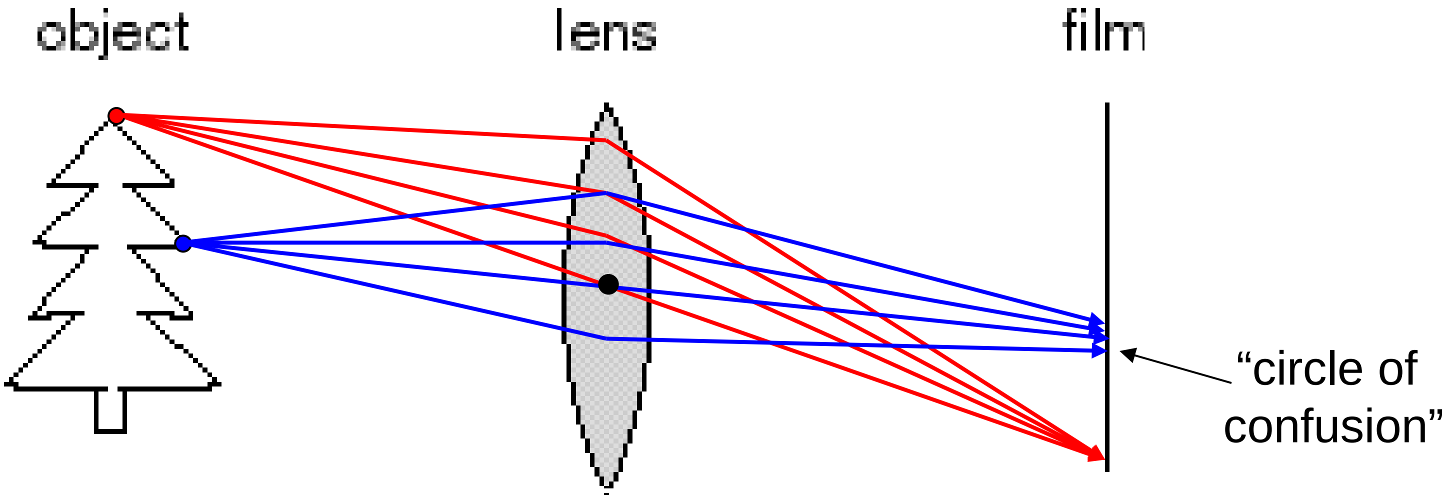
The reason for lenses



Slide by Steve Seitz

Focus

Focus and Defocus

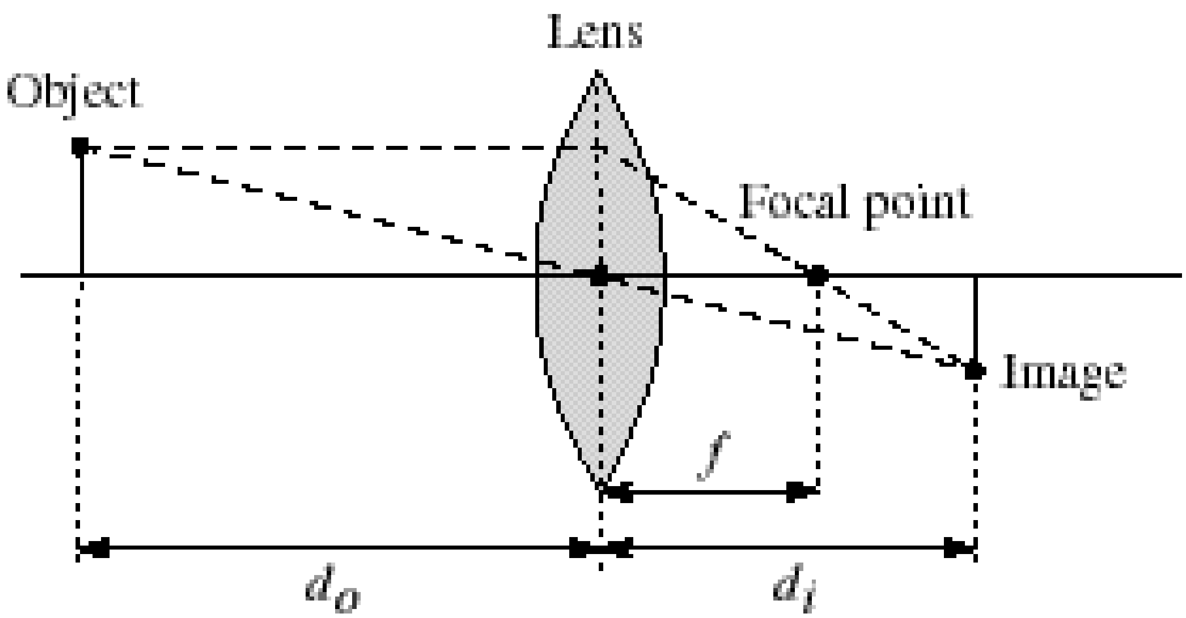


A lens focuses light onto the film

- 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?
- Thin lens applet: http://www.phy.ntnu.edu.tw/java/Lens/lens_e.html (by Fu-Kwun Hwang)

Slide by Steve Seitz

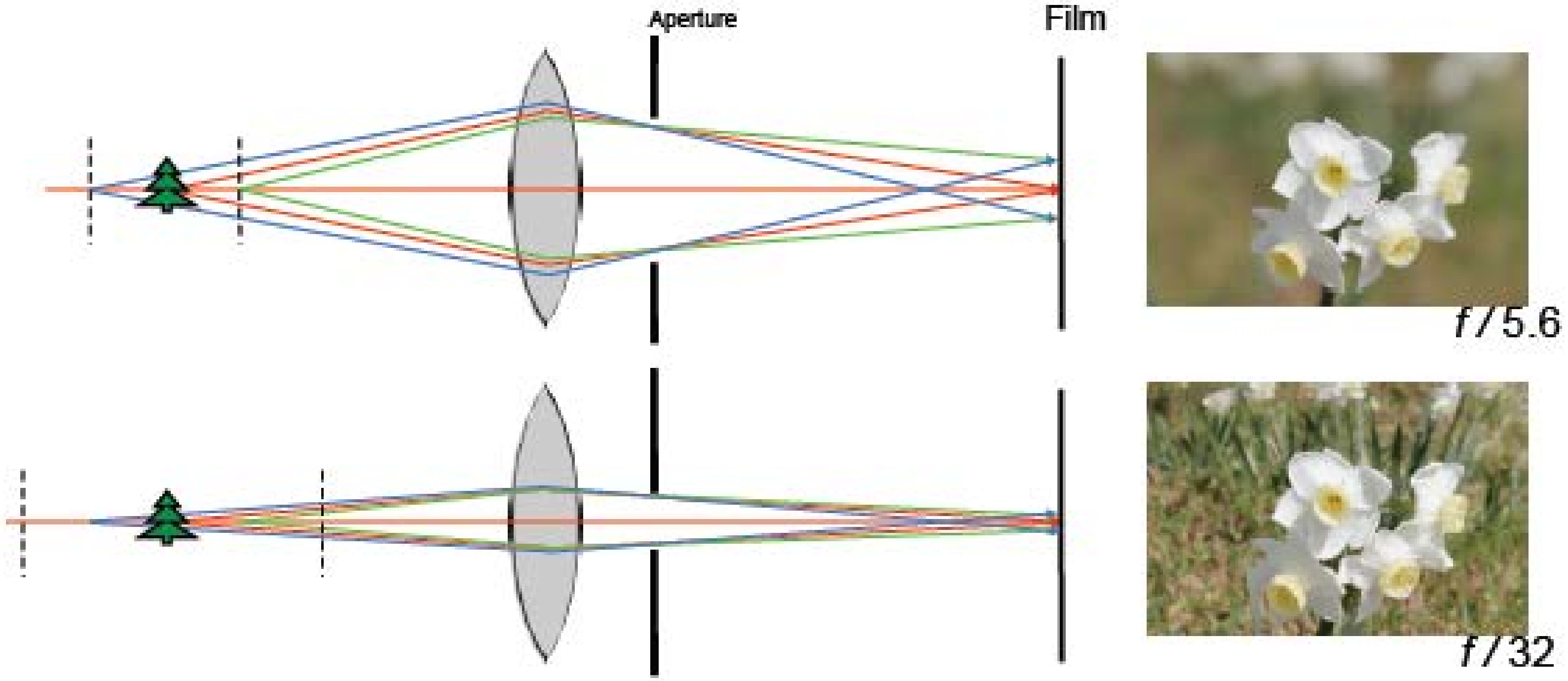
Varying Focus

Depth Of Field

Depth of Field

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

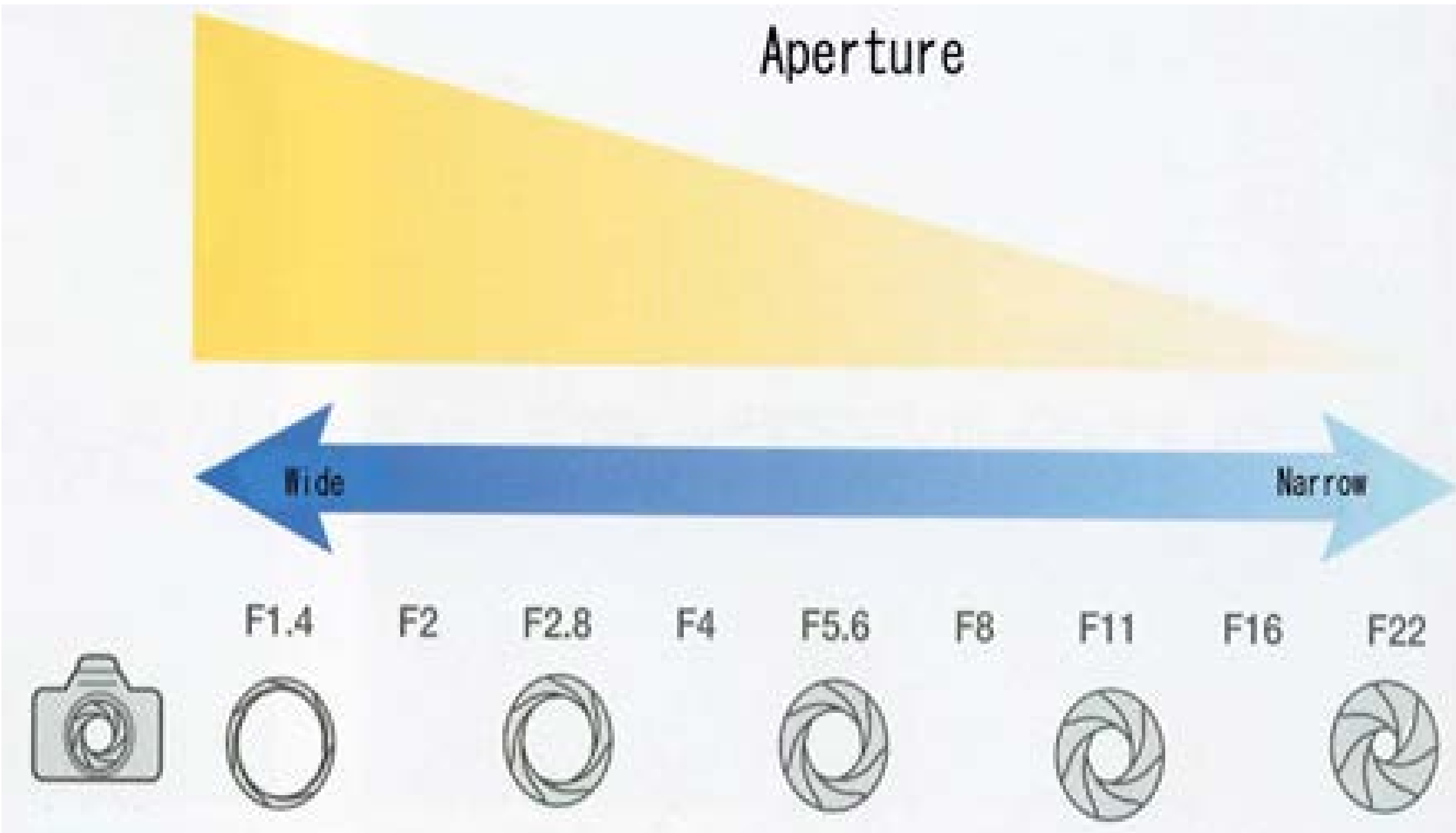
Aperture controls Depth of Field



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

F-number: focal length / aperture diameter



Varying the aperture

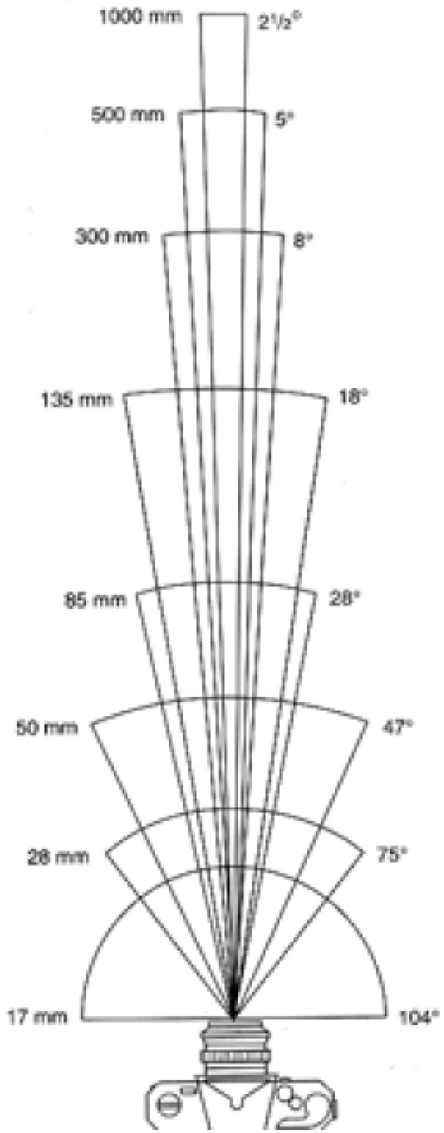
Wide apeture = small DOF

Narrow apeture = large DOF

Nice Depth of Field effect

Field of View (Zoom)

Field of View (Zoom)




17mm

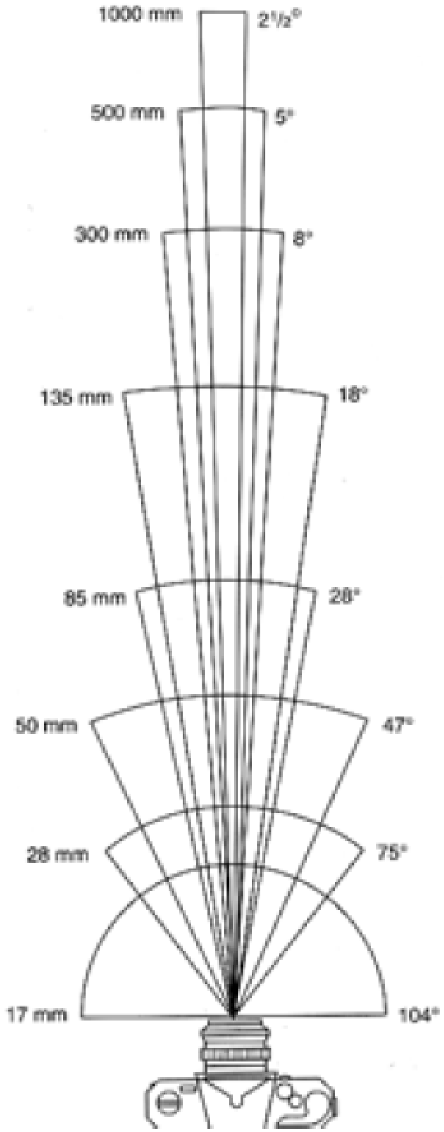

28mm

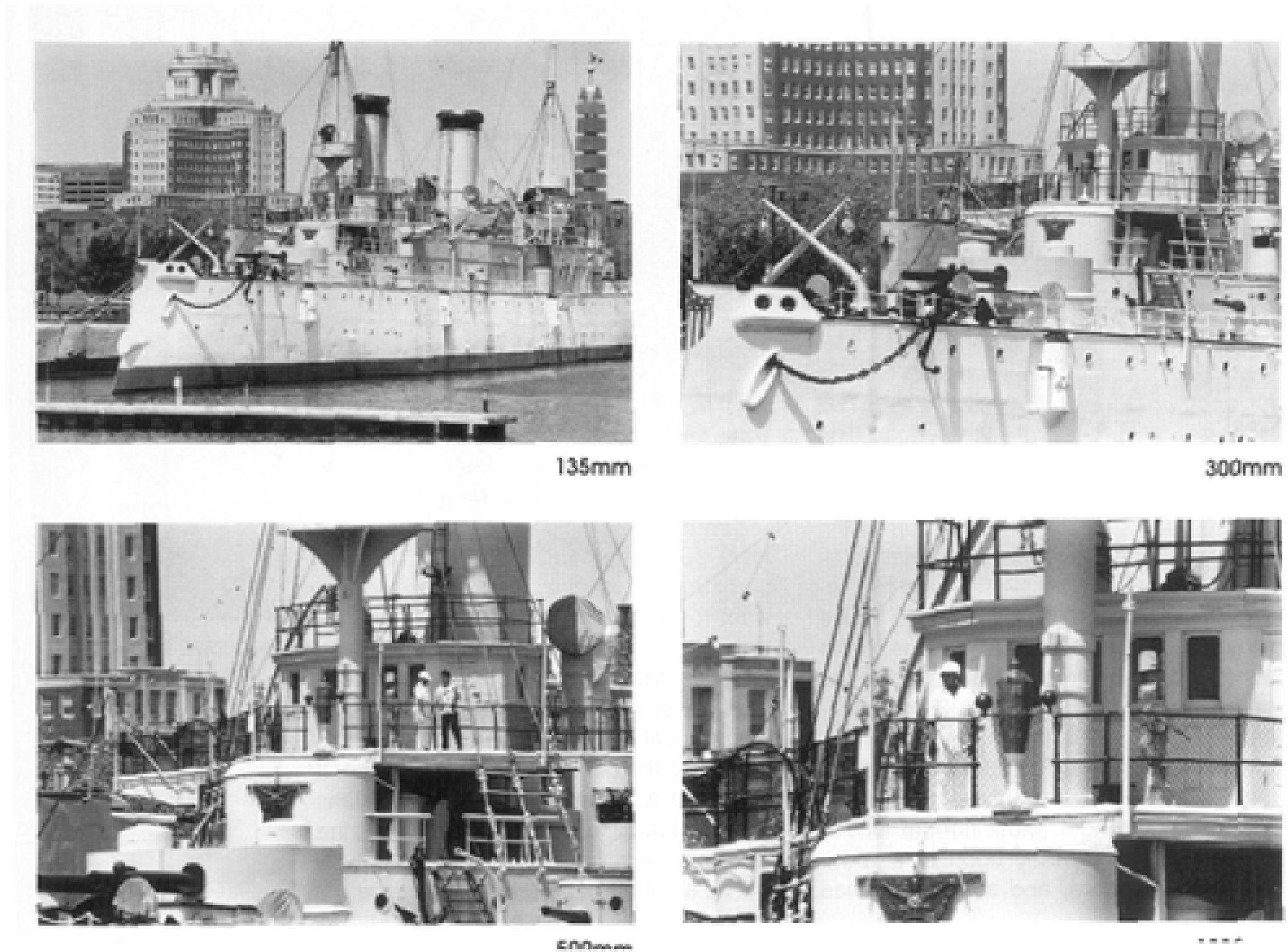

50mm


85mm

From London and Upton

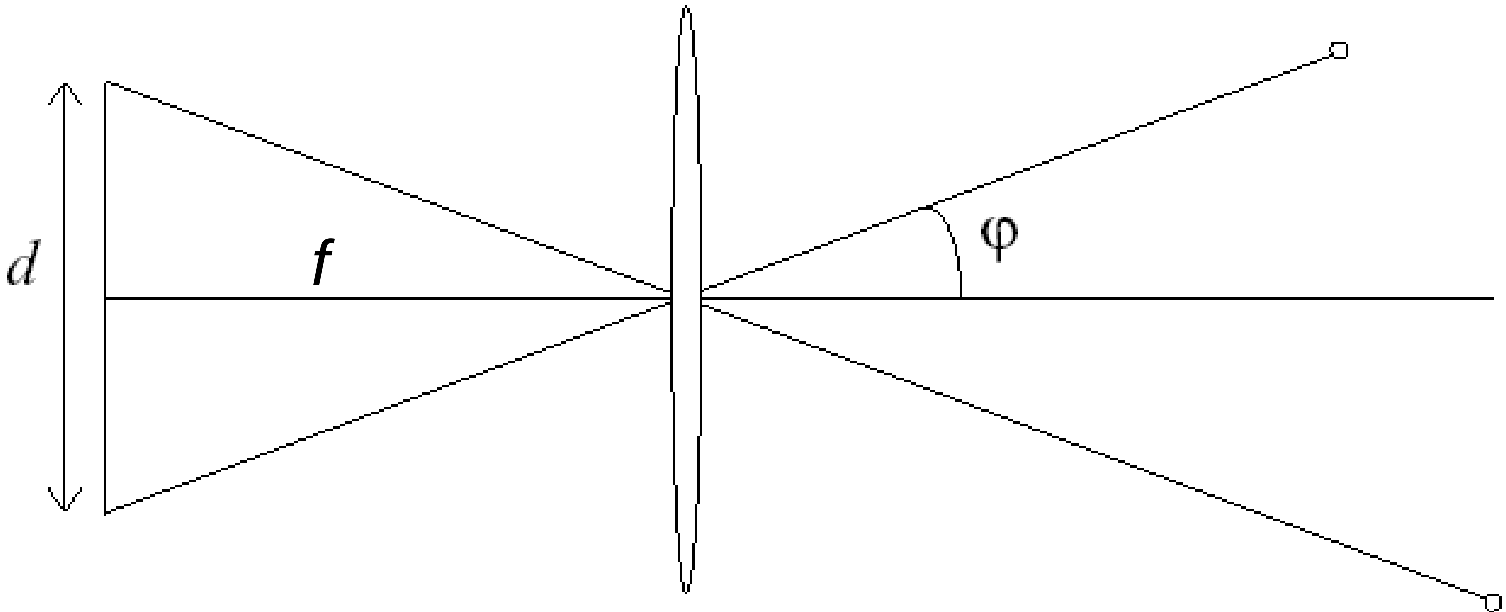
Field of View (Zoom) = Cropping





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

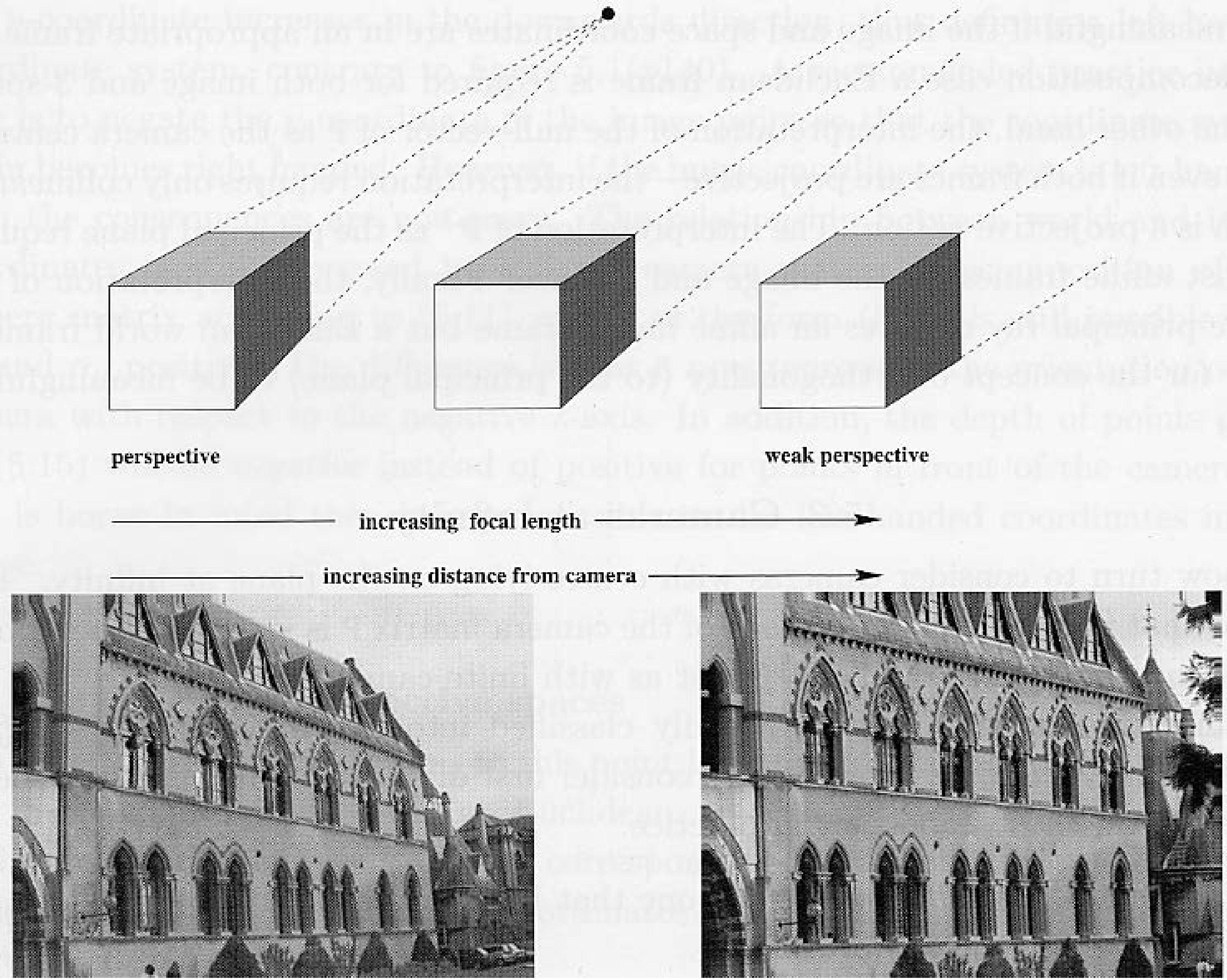
Expensive toys…

Sigma 200-500mm F2.8 EX DG lens

What does 1600mm lens look like?

http://www.digitalpixels.net/varia/the-web/sigma-200-500mm-f28-ex-dg-lens-on-the-field/

http://dancarrphotography.com/blog/wp-content/uploads/2011/05/Canon_super_tele_comparison.jpg



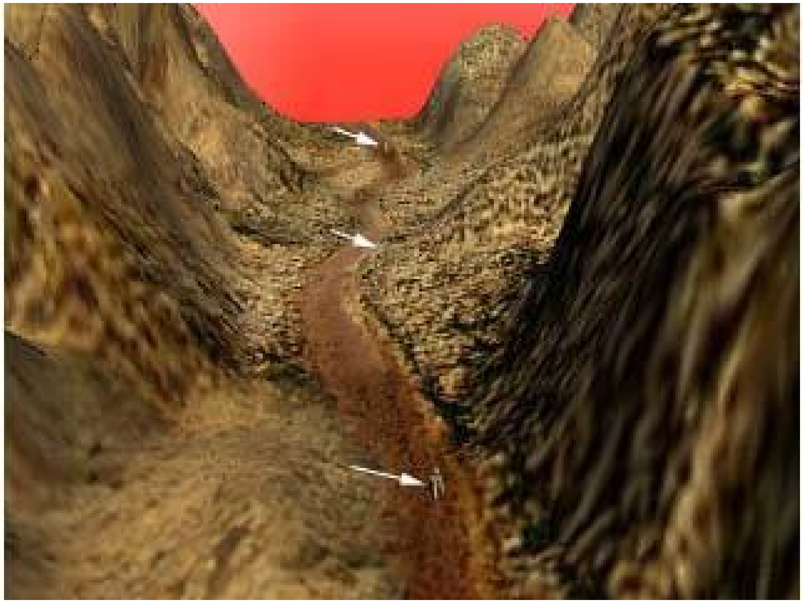
From Zisserman & Hartley

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

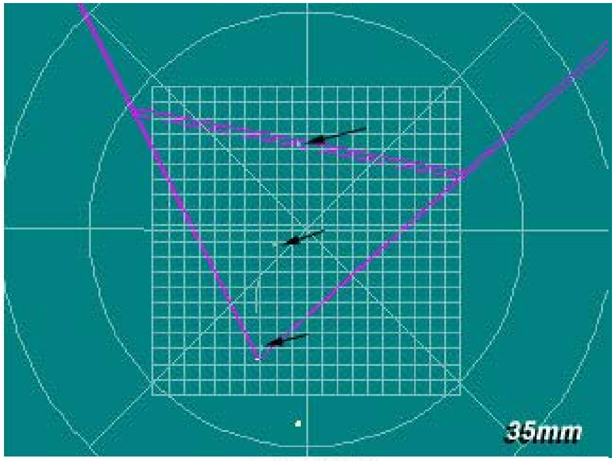


Figure 5.2

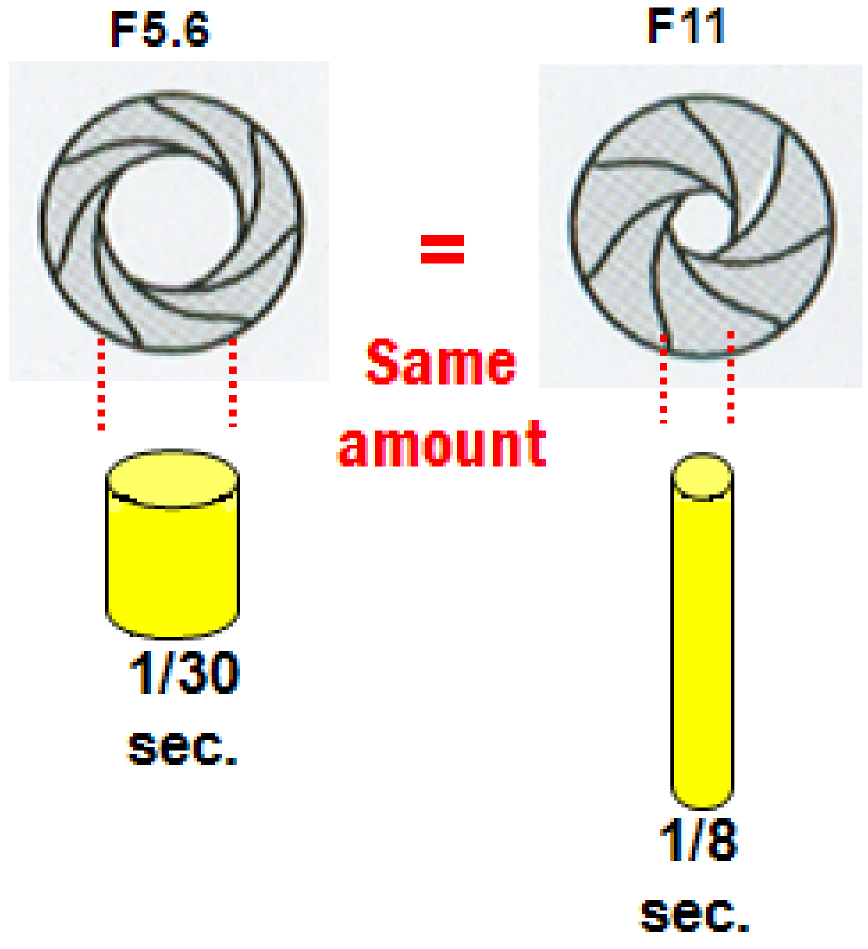
Dolly Zoom ("Vertigo Shot")

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

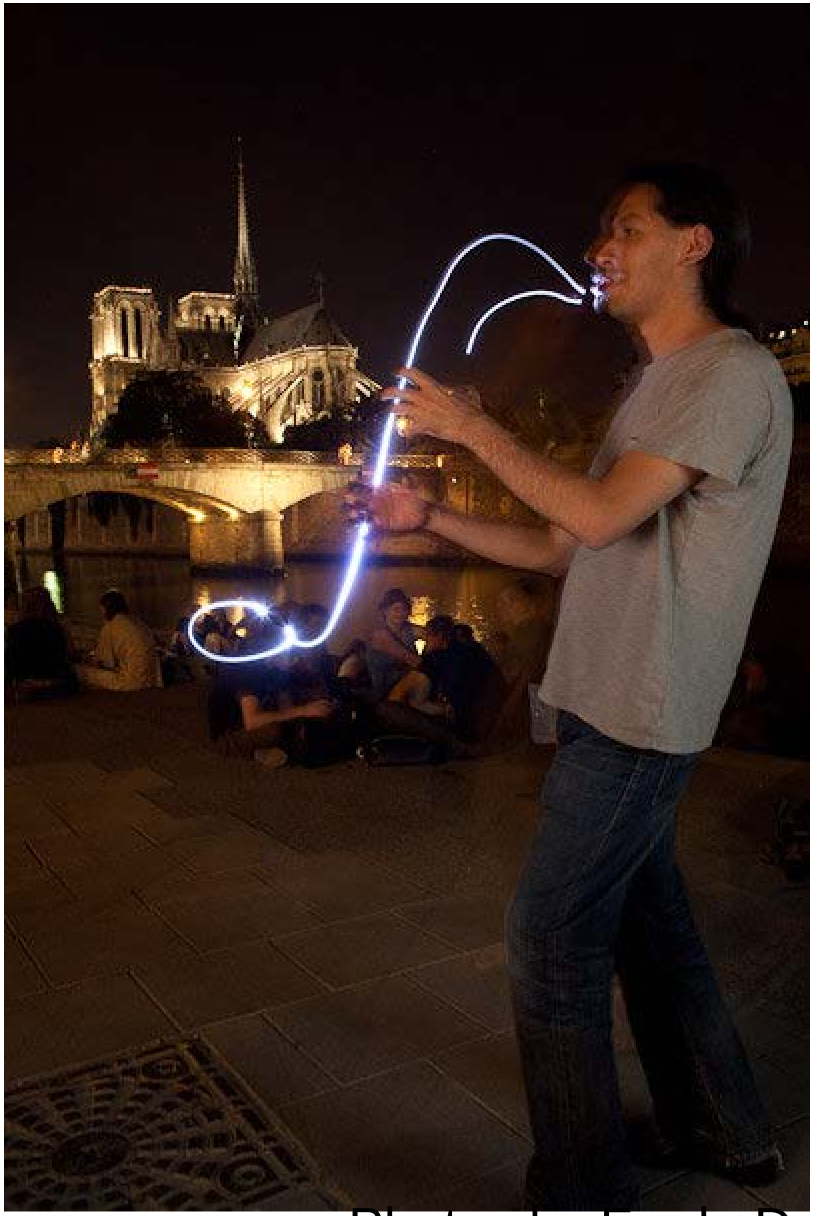
Shutter Speed

http://en.wikipedia.org/wiki/Shutter_speed

Exposure: shutter speed vs. aperture



Fun with slow shutter speeds



Photos by Fredo Durand

More fun

http://vimeo.com/14958082

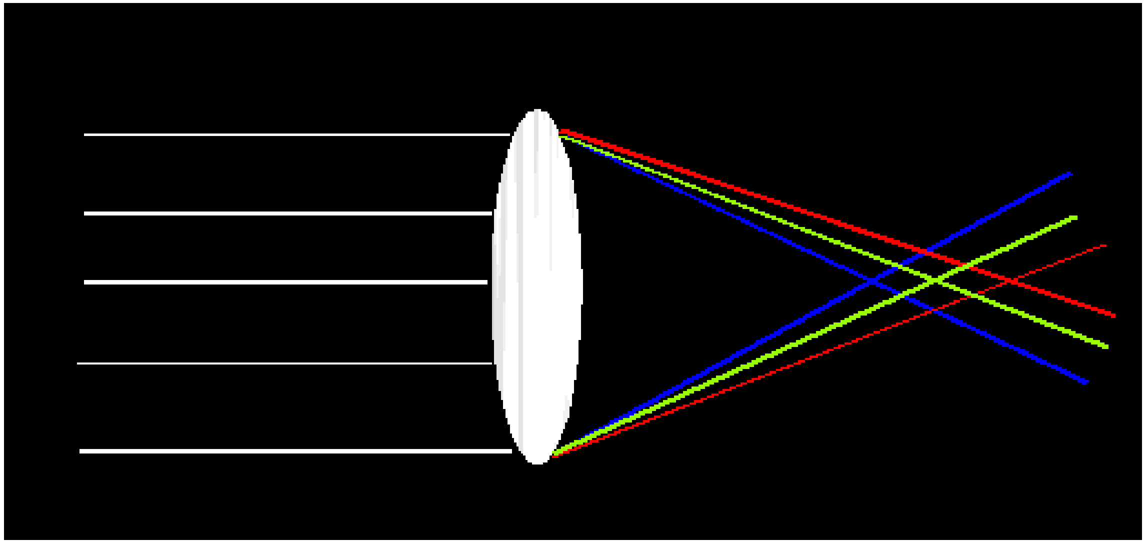
Lens Flaws

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(λ)



color fringes near edges of image

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

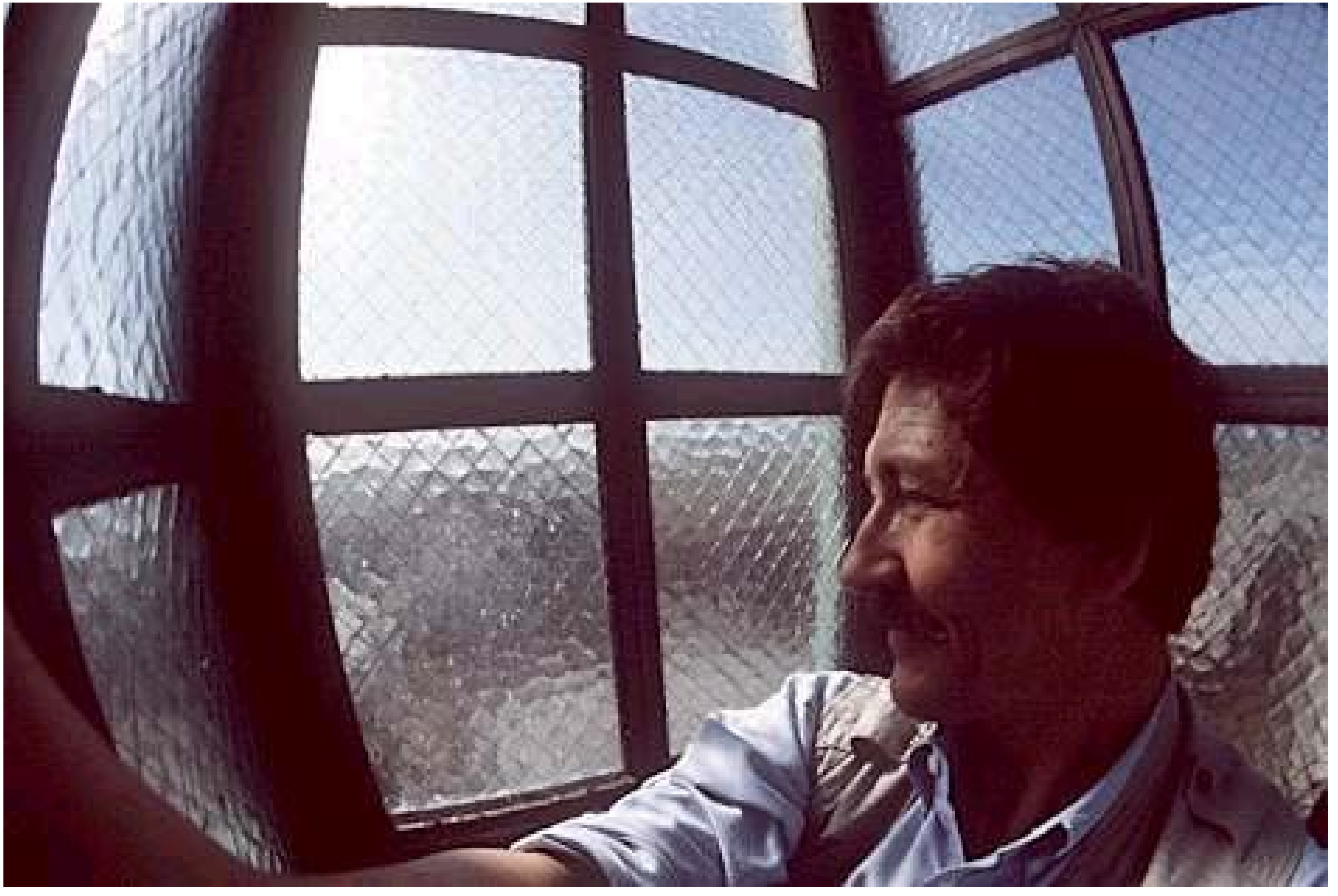
Chromatic Aberration

Near Lens Center

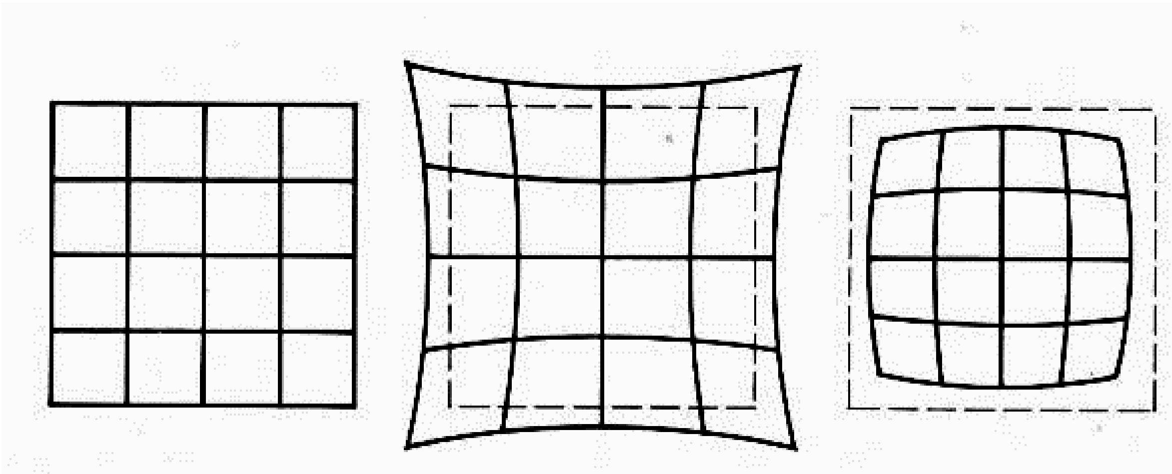
Near Lens Outer Edge

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