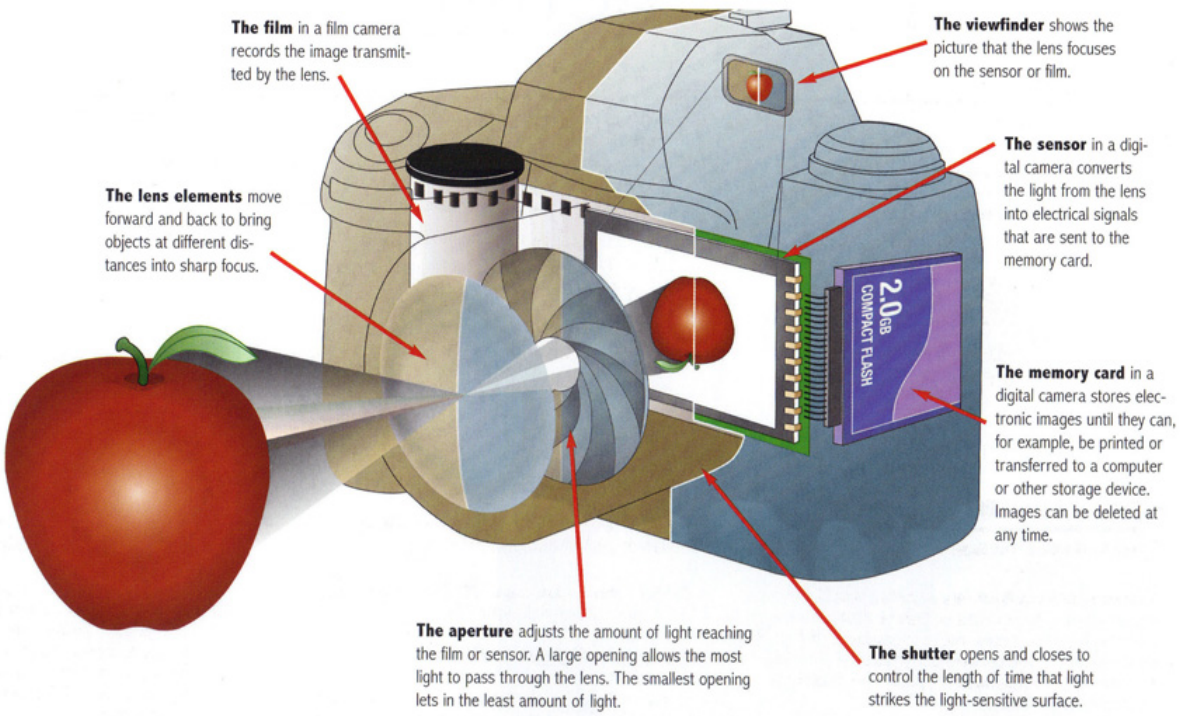
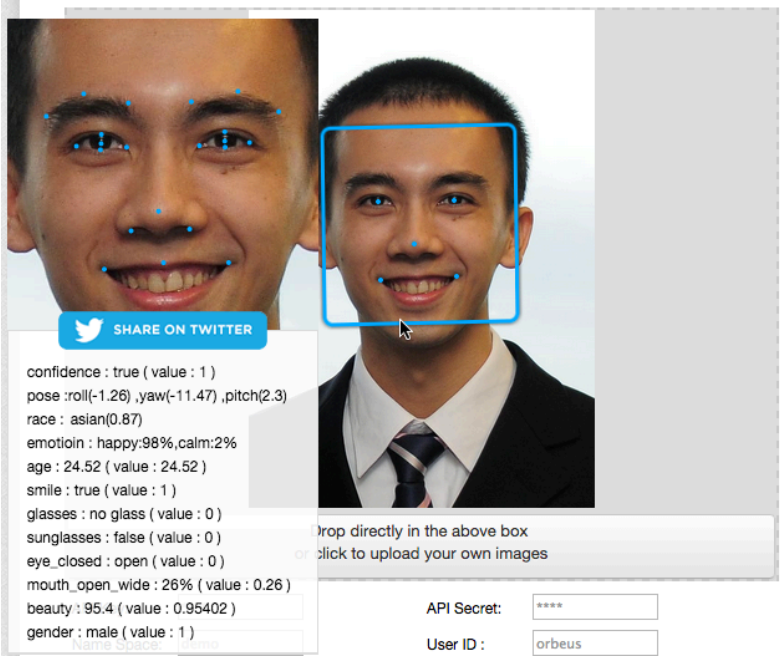
What is a Camera?



Last Time

- What is computer vision?
- Input: digital images
- Output: information about the world



What is a Camera?

Outline for Today

- What is a digital image?
- What is a pin-hole camera?
- Lens & optics
- Geometric transformation
- Accidental camera

Outline for Today

- What is a digital image?
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What is a Digital Image?

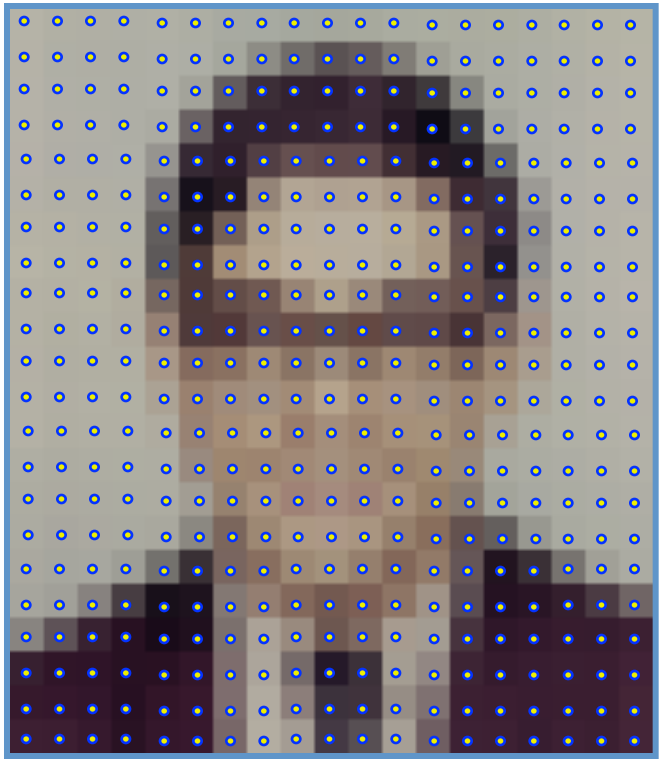
What is a Digital Image?

http://en.wikipedia.org/wiki/Lenna
From **Lawrence G. Roberts's** master's thesis at MIT 1961

What is a Digital Image?

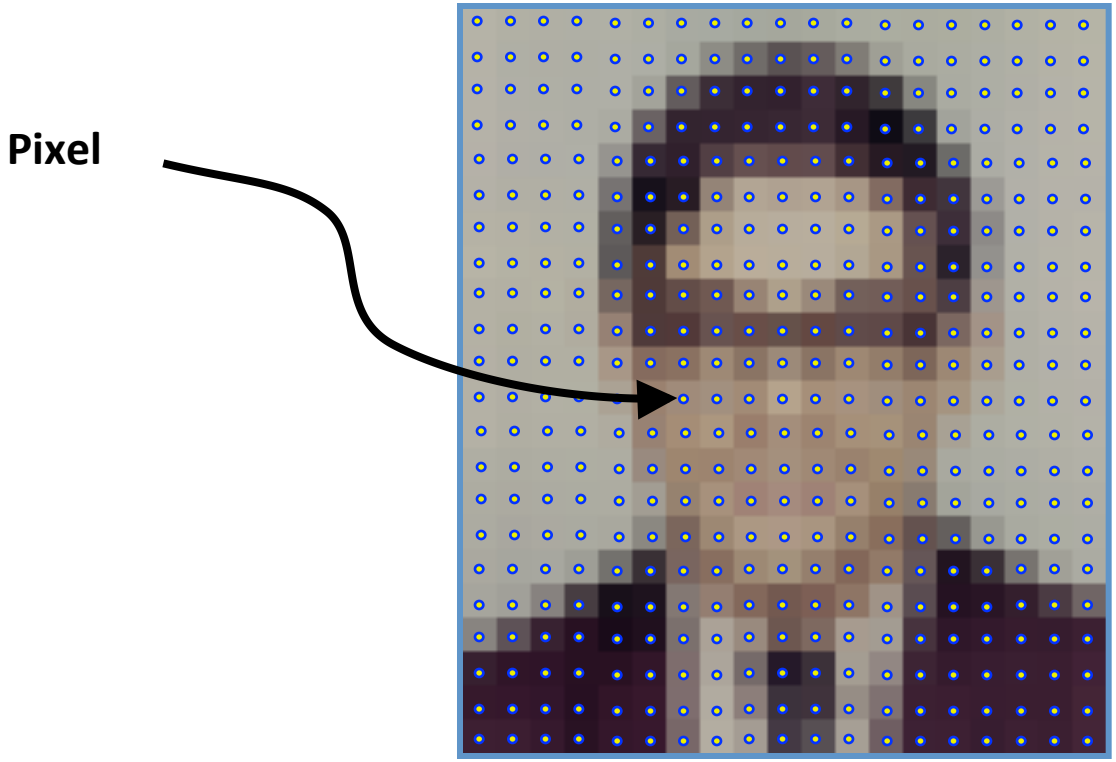
- An image is a 2D rectilinear array of pixels

Continuous image



Digital image

What is a Pixel?

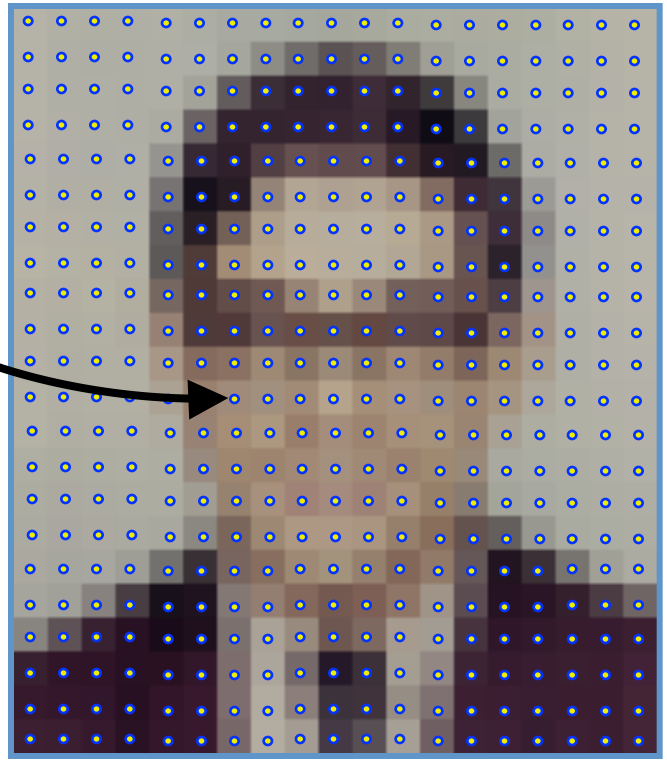


Digital image

What is a Pixel?

- Sample of a continuous (color) function at a position

e.g., Color at (x,y)



Digital image

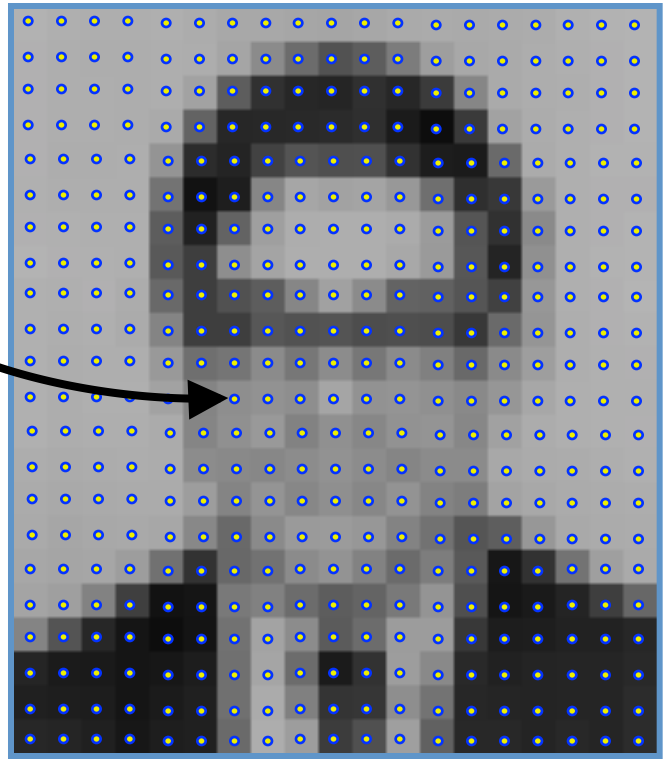
What is a Pixel?

- Sample of a continuous (color) function at a position

e.g., Intensity at (x,y)

Larger value = brighter
Smaller value = darker

Brightest White = 1.0
Darkest Black = 0.0



Digital image

Outline for Today

- What is a digital image?
- What is a pin-hole camera?
- Lens & optics
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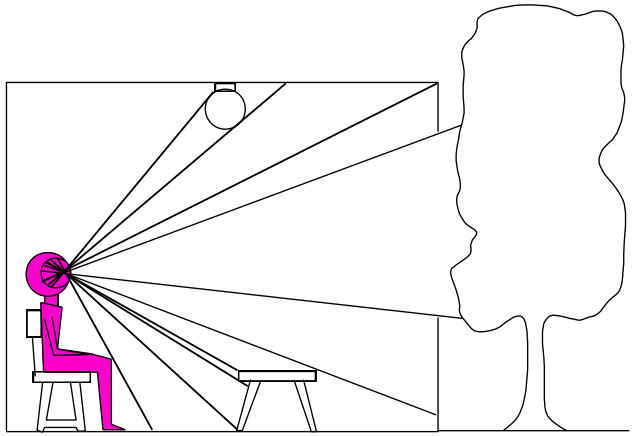
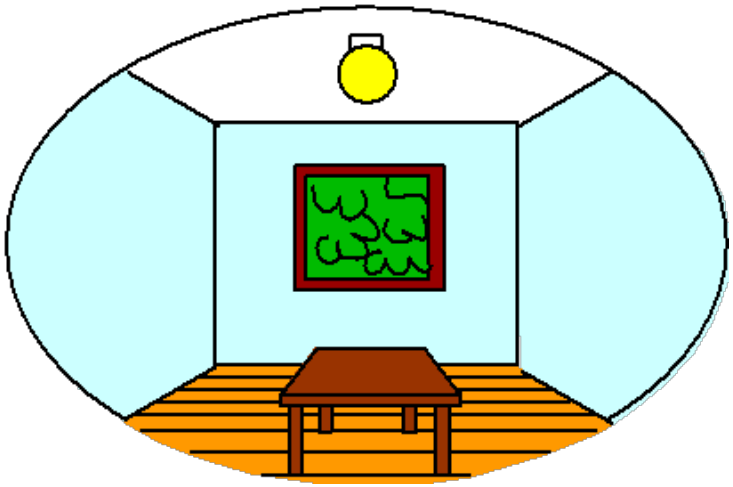
Image formation

3D world



Point of observation

2D image

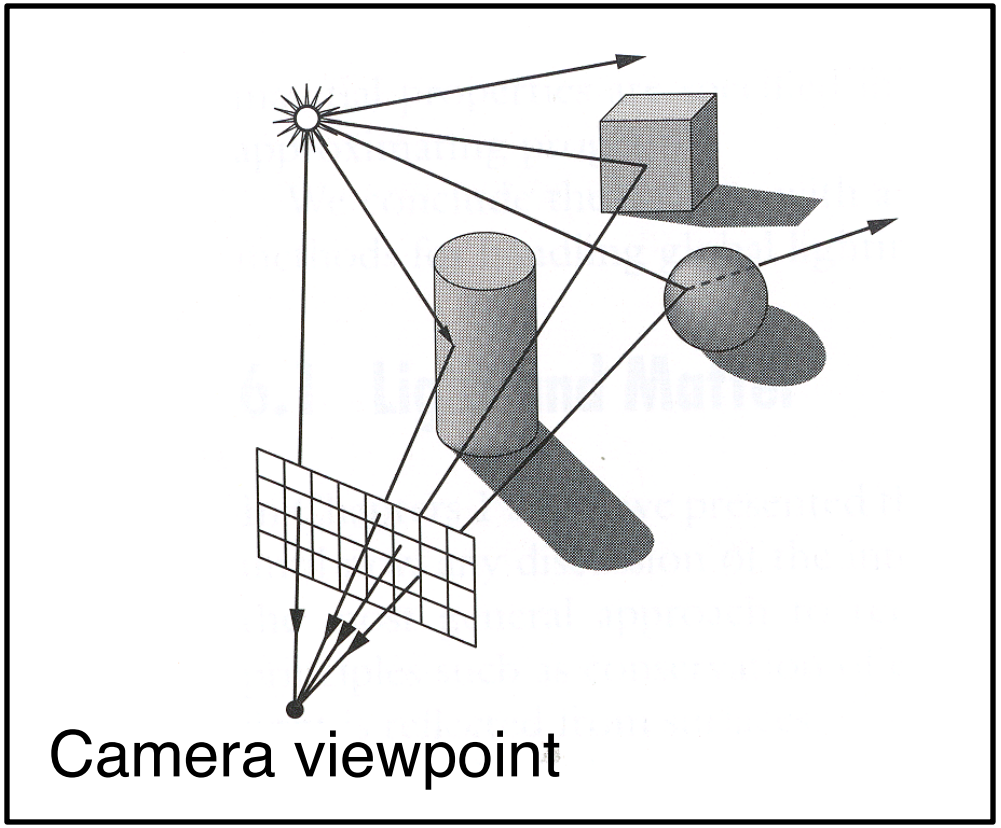


What Is a Photographic Image?

- What does each pixel represent?

What Is a Photographic Image?

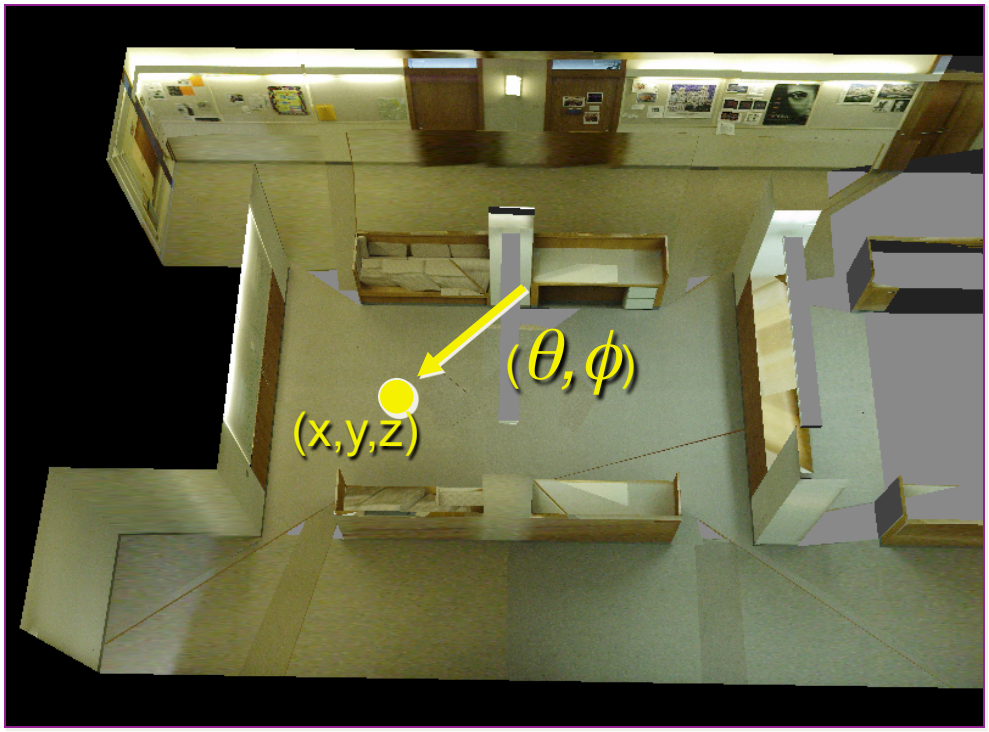
Conceptually, each pixel is a sample of radiance arriving at a camera viewpoint from a direction



Plenoptic Function

The plenoptic function $L(x,y,z,\theta,\phi,t,\lambda)$ describes the radiance arriving …

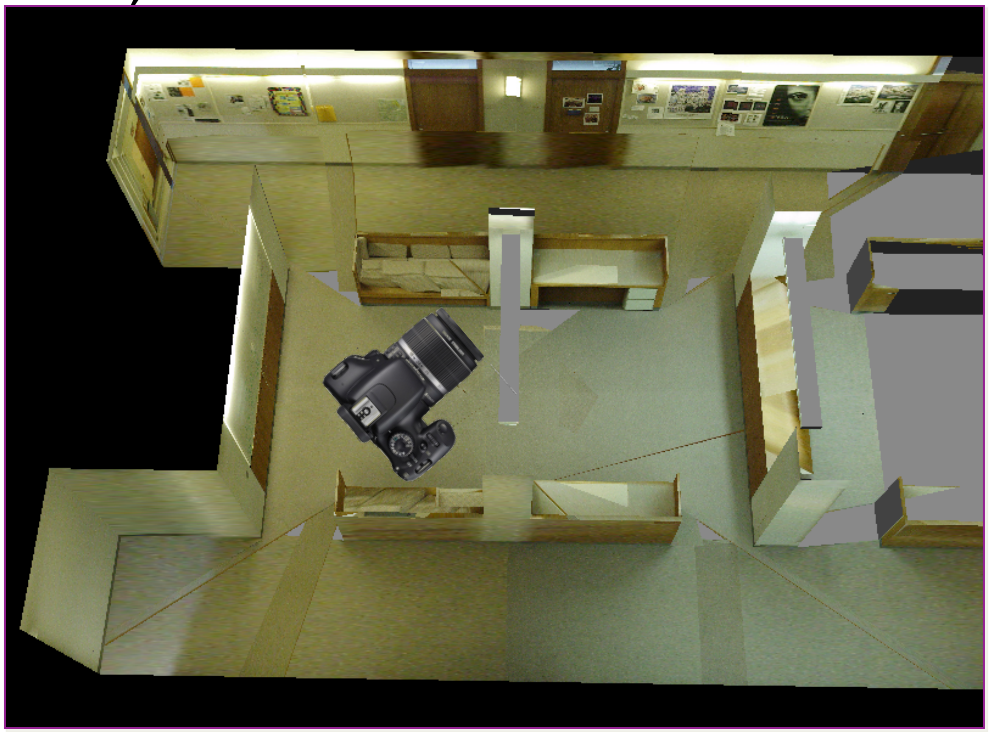
- at any point (x,y,z),
- in any direction (θ,ϕ),
- at any time (t),
- at any frequency (λ)



Photographic Image

Conceptually, a photographic image is a slice of the plenoptic function representing radiance arriving …

- at a particular camera viewpoint,
- in the camera's field of view,
- at a certain time,
- at certain frequencies

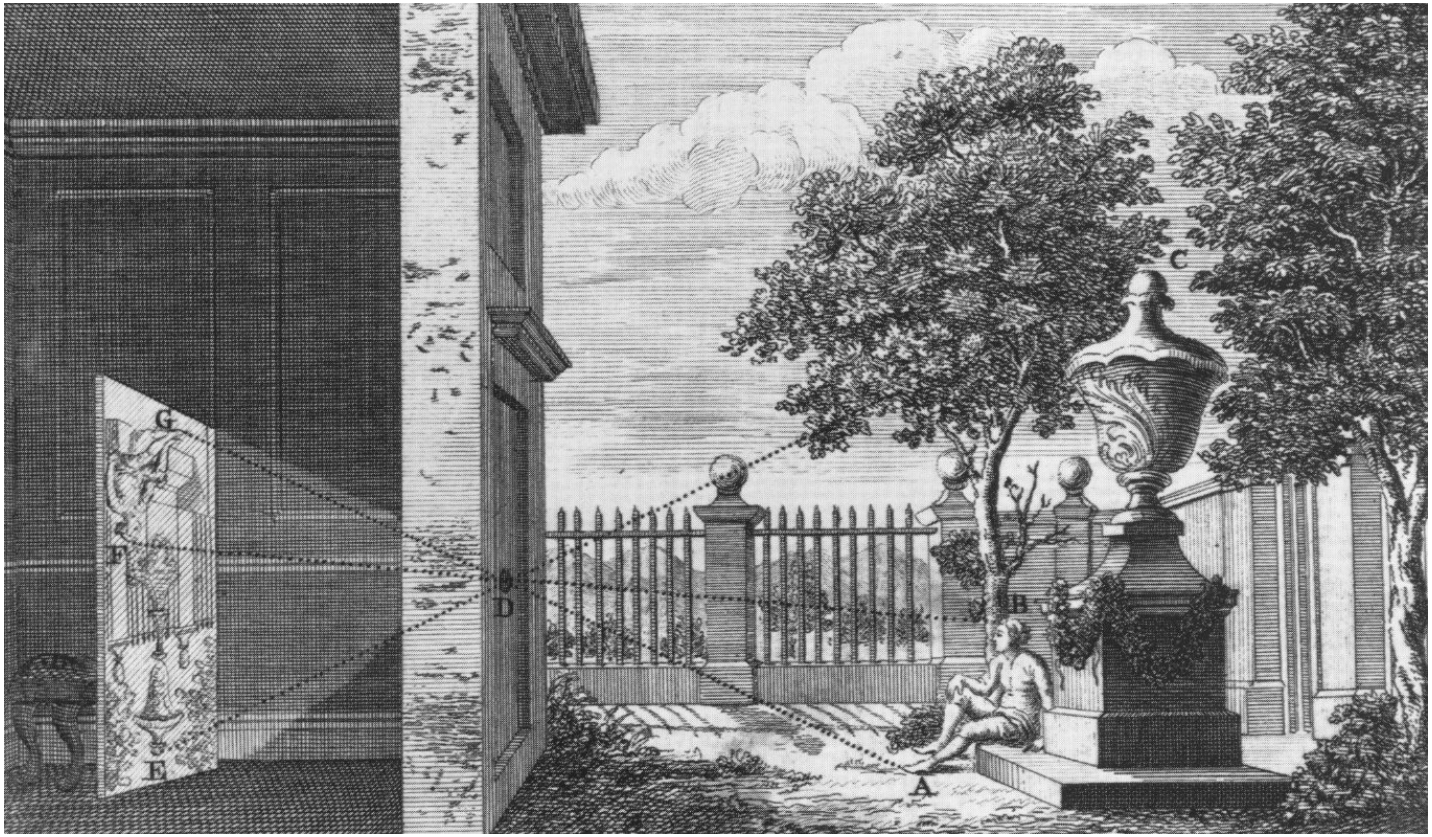


Lightfield Camera

https://pictures.lytro.com

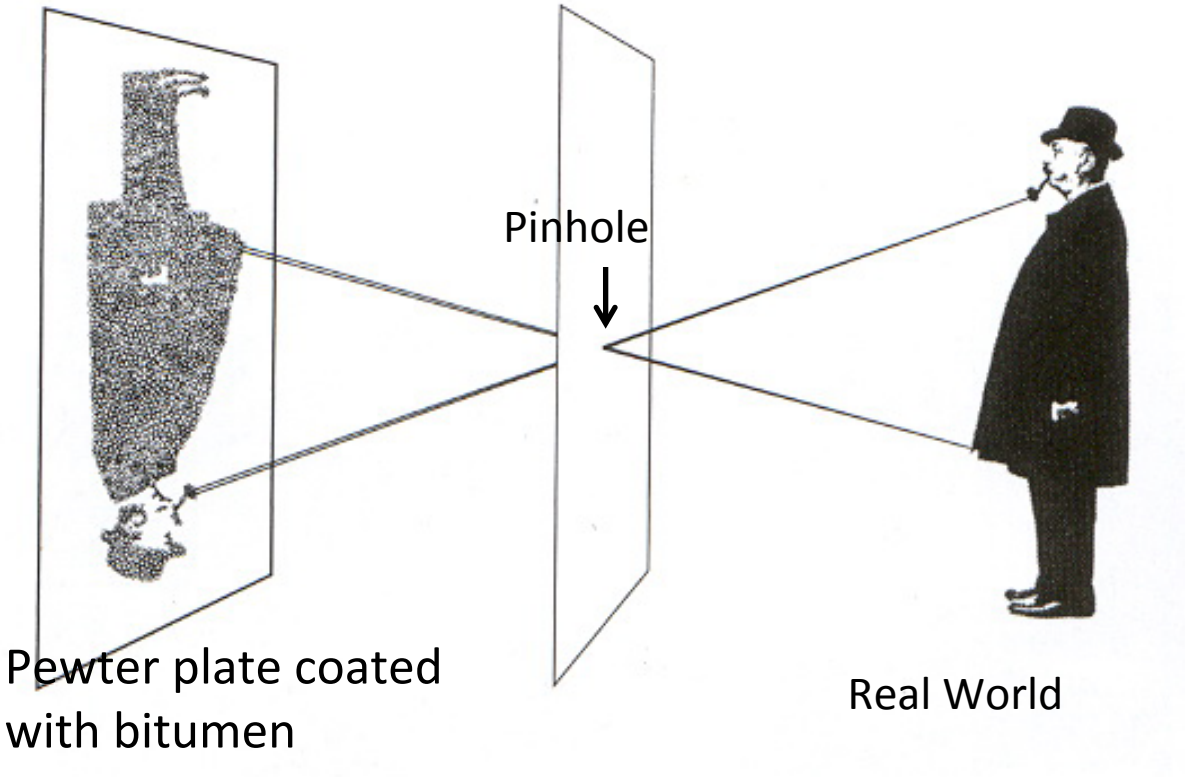
Pinhole Camera

- "Camera obscura" – idea known since antiquity



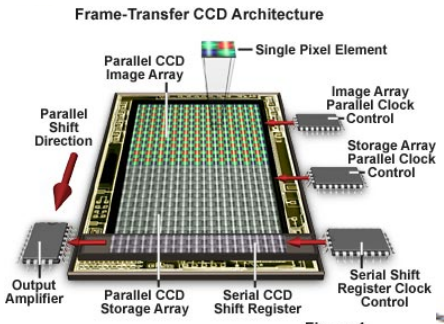
Pinhole Camera

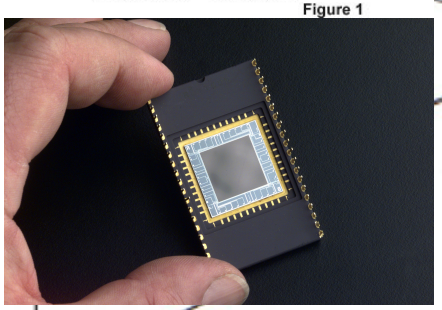
- Joseph Nicéphore Niépce: first recorded image



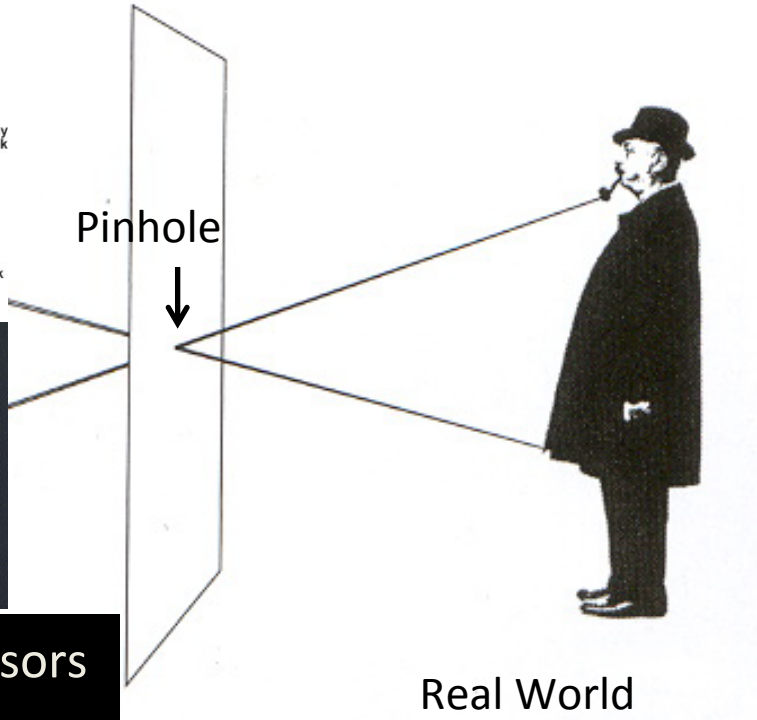
Digital Camera

- Today: photon sensors are CCD, CMOS, etc.

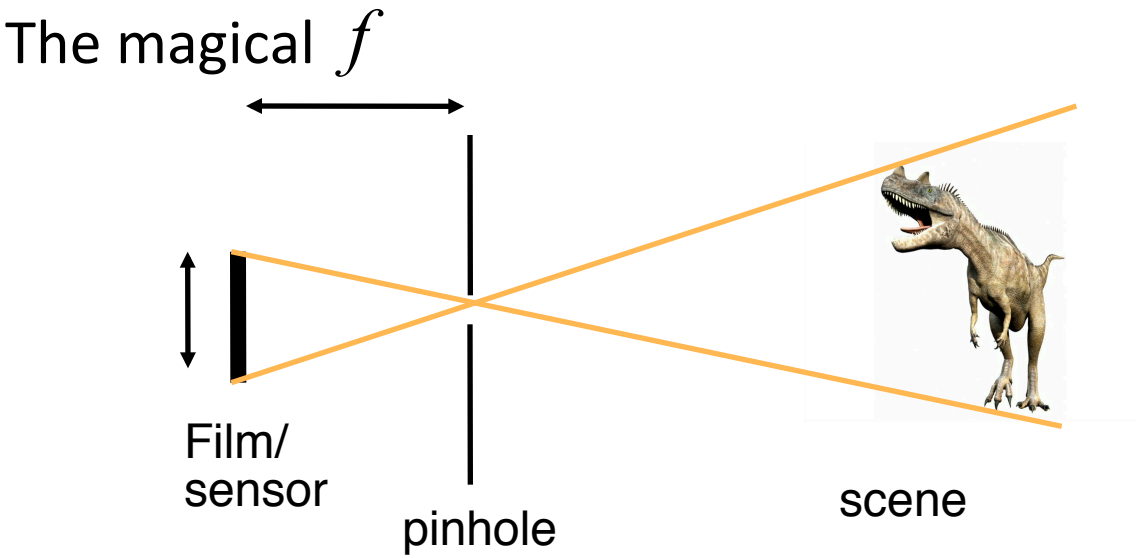




Array of photon sensors with digital readout



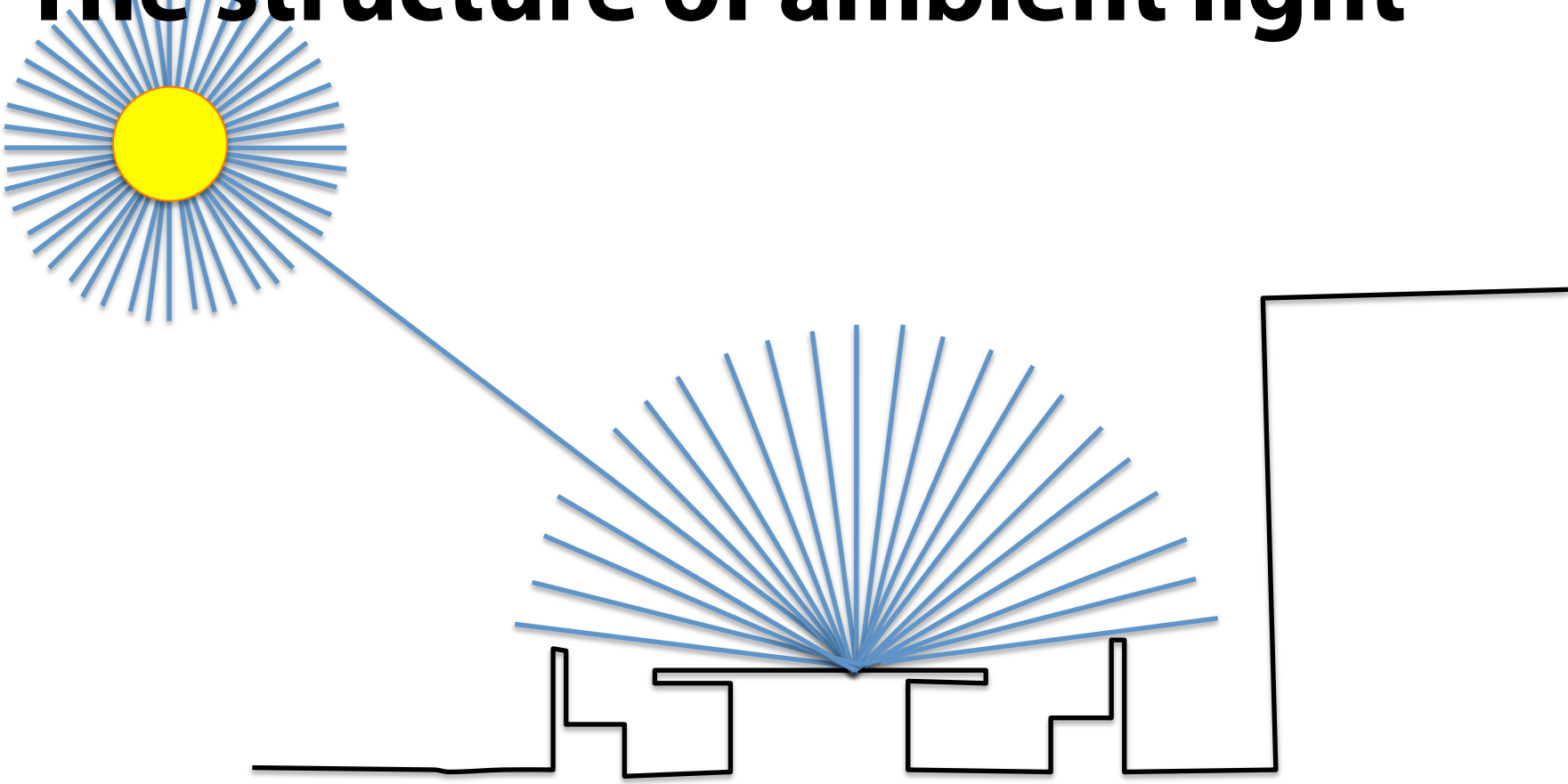
Focal length



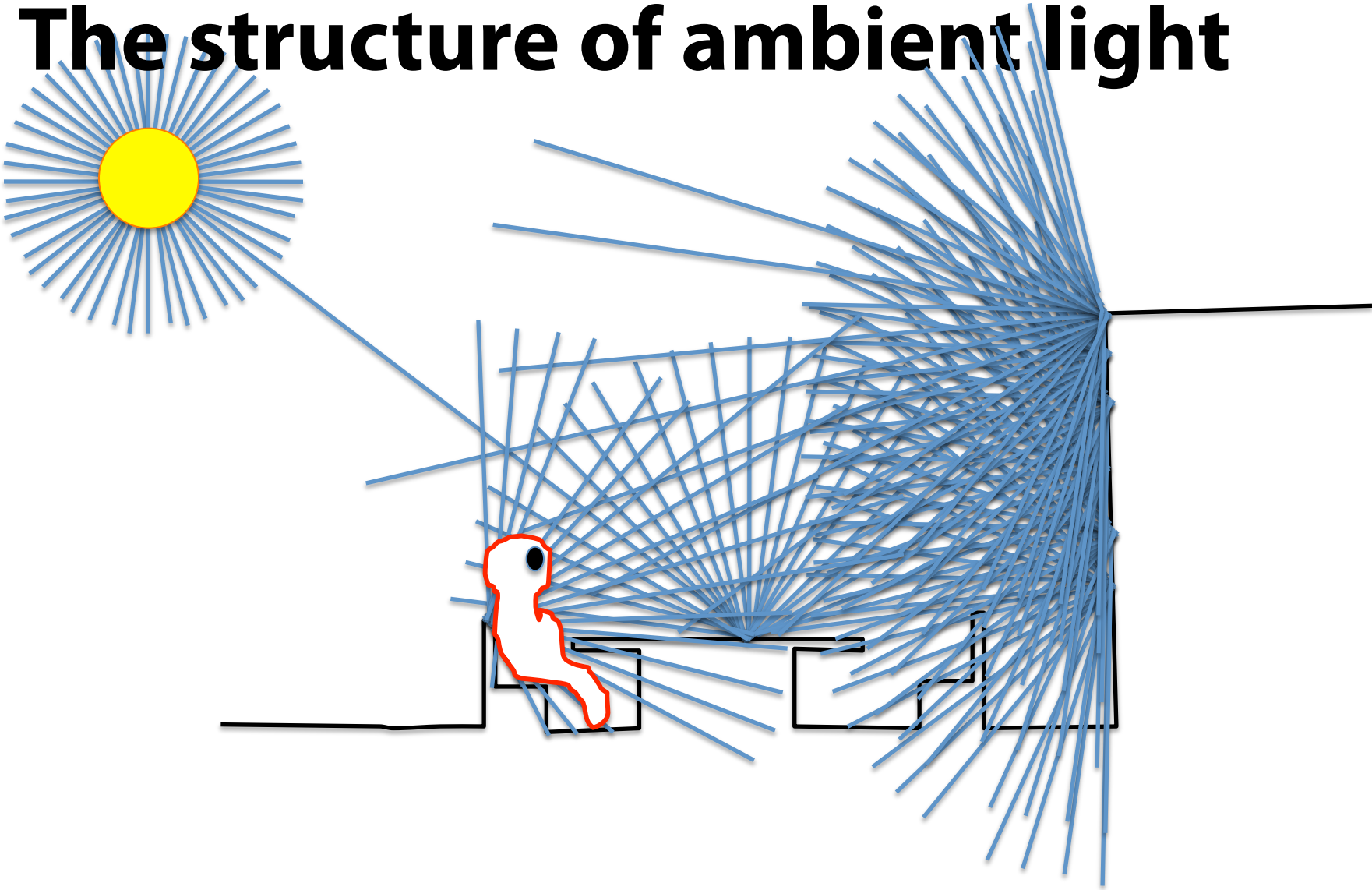
Why do we need a pinhole?

Why is there no image on a white piece of paper?

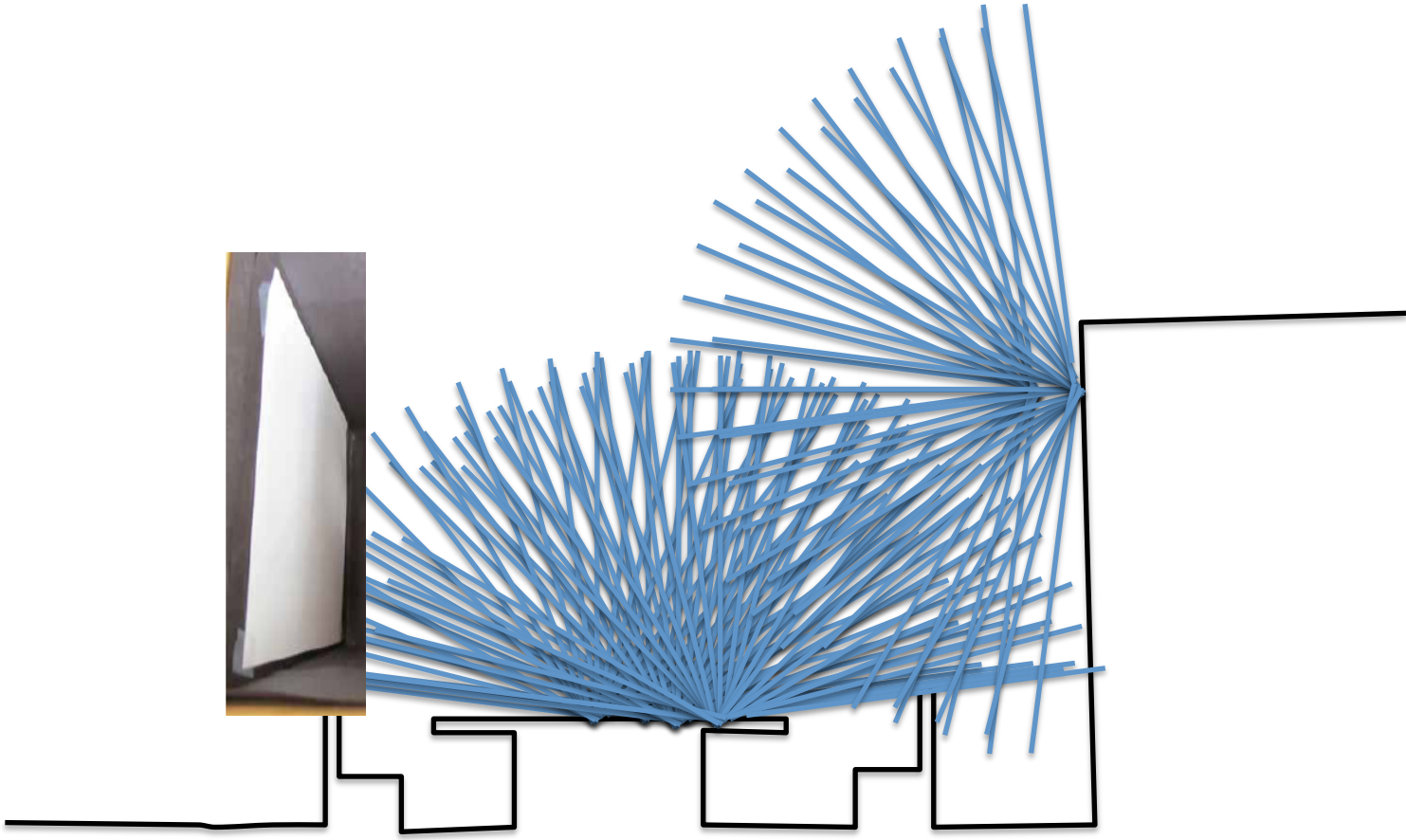
The structure of ambient light



The structure of ambient light

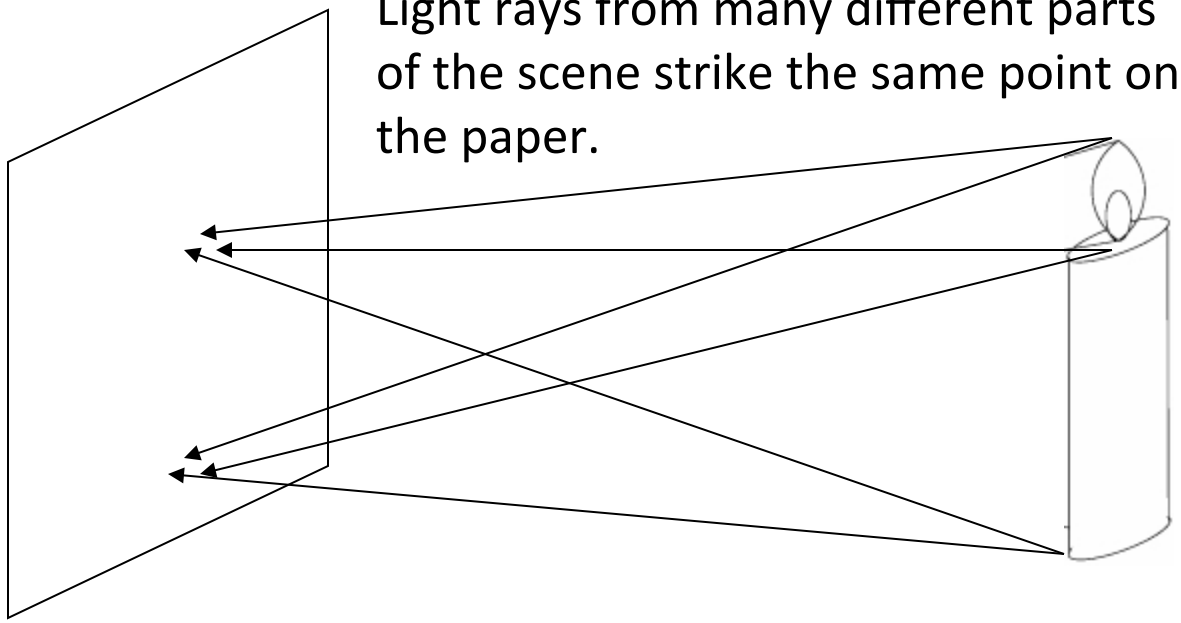


Measuring the Plenoptic function



Why is there no picture appearing on the paper?

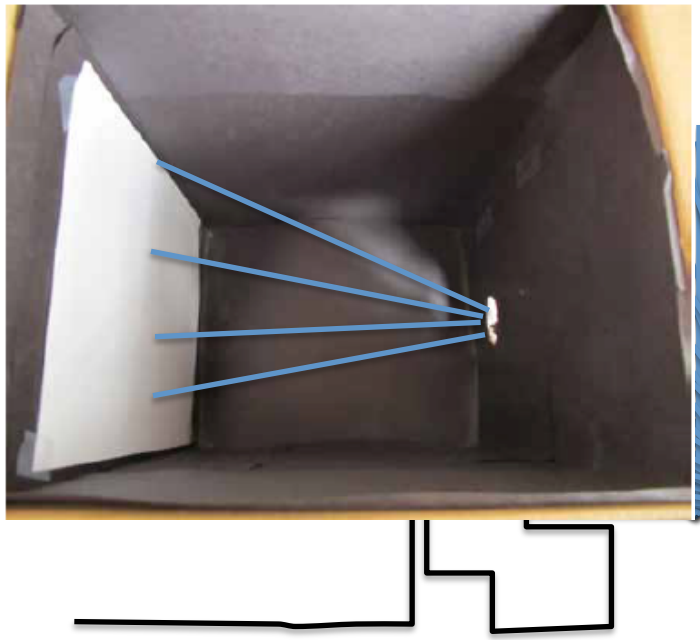
Light rays from many different parts of the scene strike the same point on the paper.

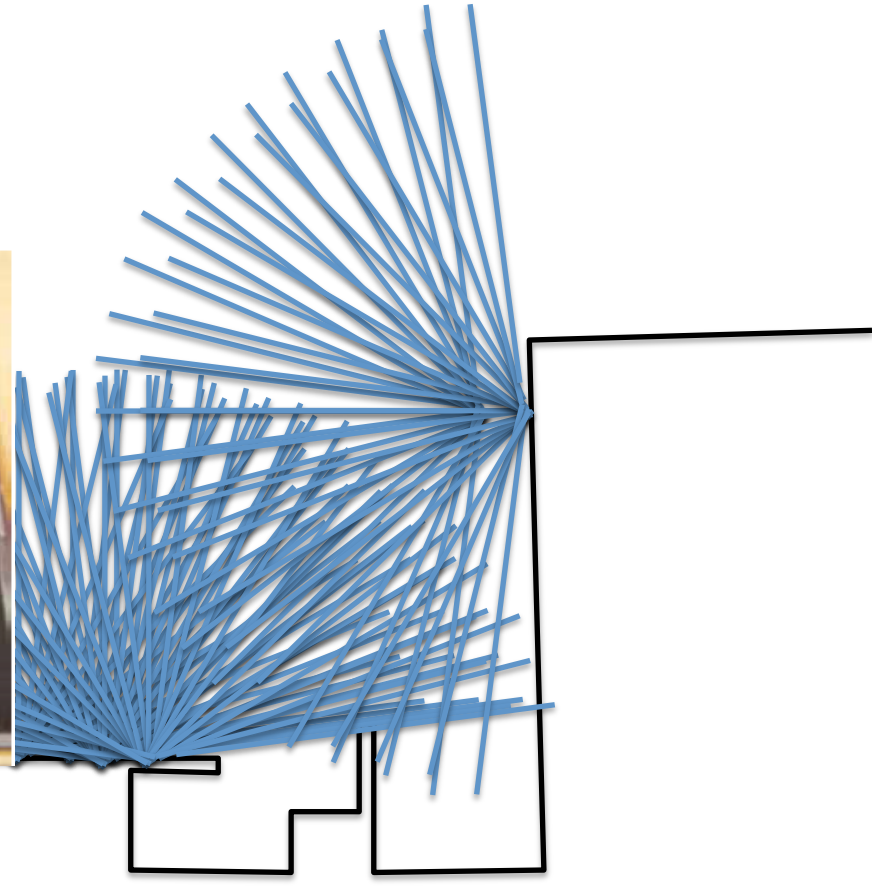


Forsyth & Ponce

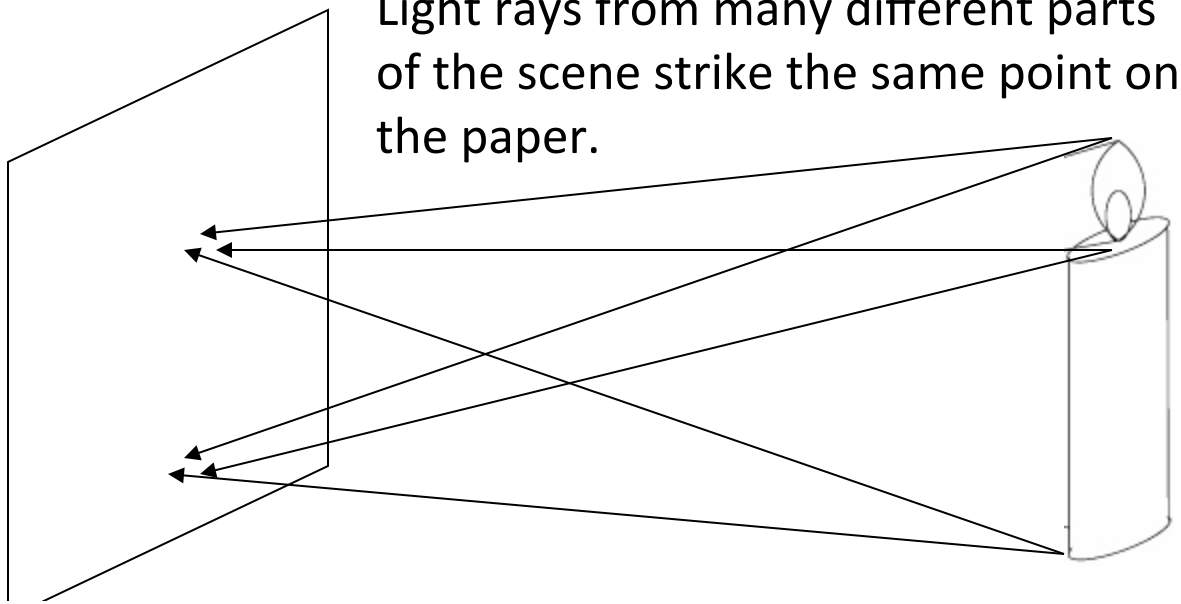
Measuring the Plenoptic function

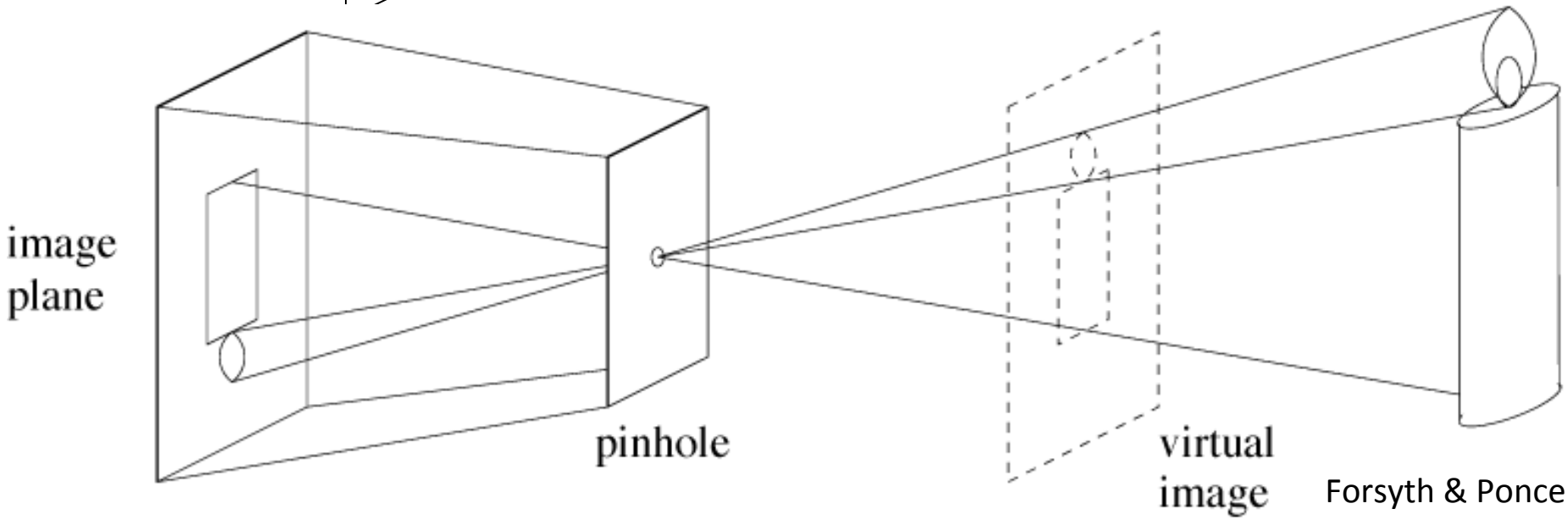
The camera obscura
The pinhole camera





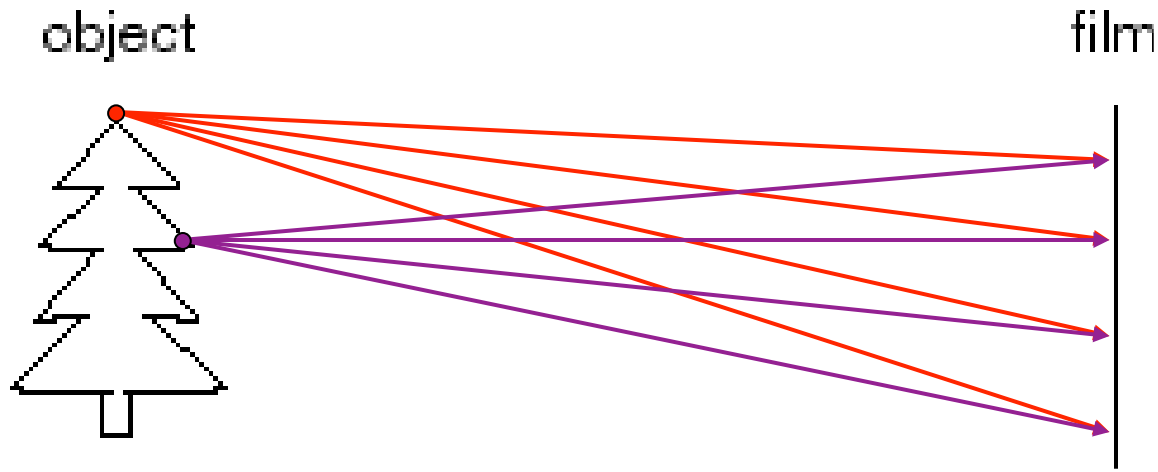
Light rays from many different parts of the scene strike the same point on the paper.

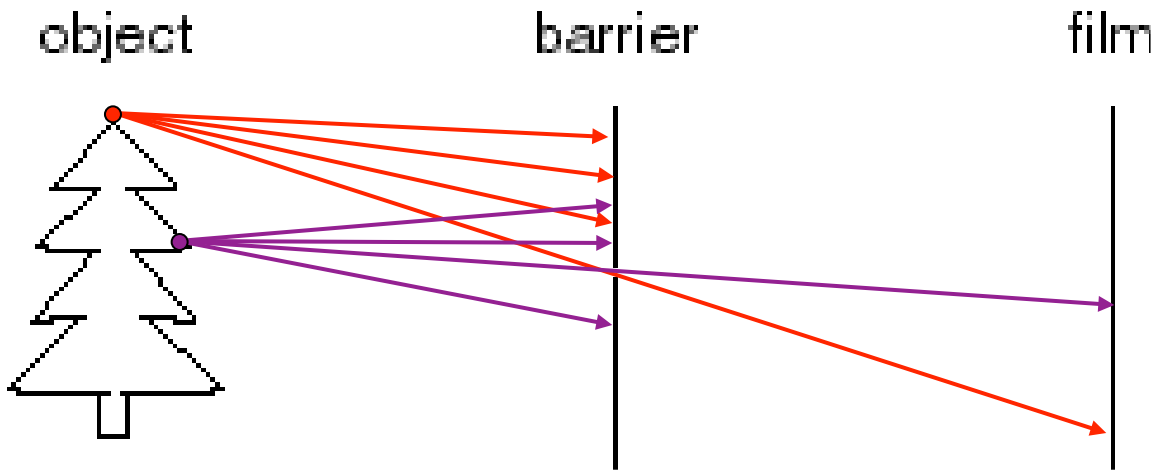




Forsyth & Ponce

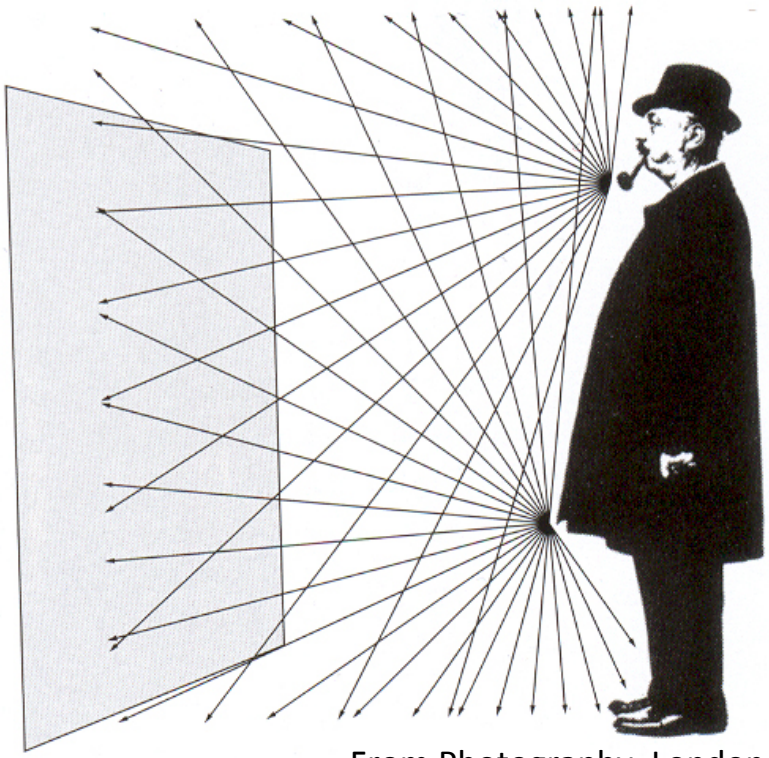
The pinhole camera only allows rays from one point in the scene to strike each point of the paper.


object
film


object
barrier
film

Why not use sensors without optics?

- It receives light from all directions
- It gets all possible images from all possible viewpoints
- We need to be more selective



From Photography, London et al.

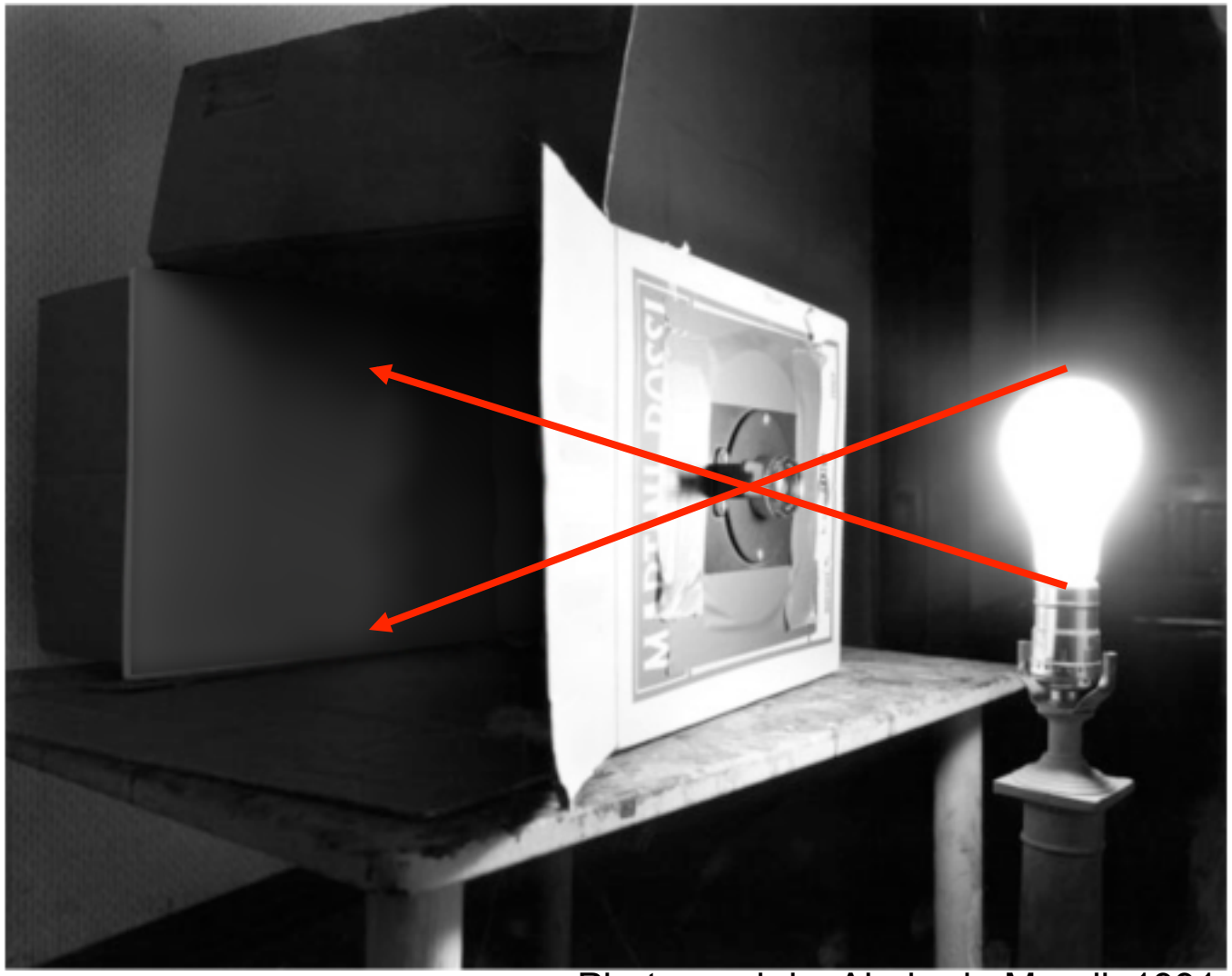
Pinhole camera

Photograph by Abelardo Morell, 1991

Pinhole camera

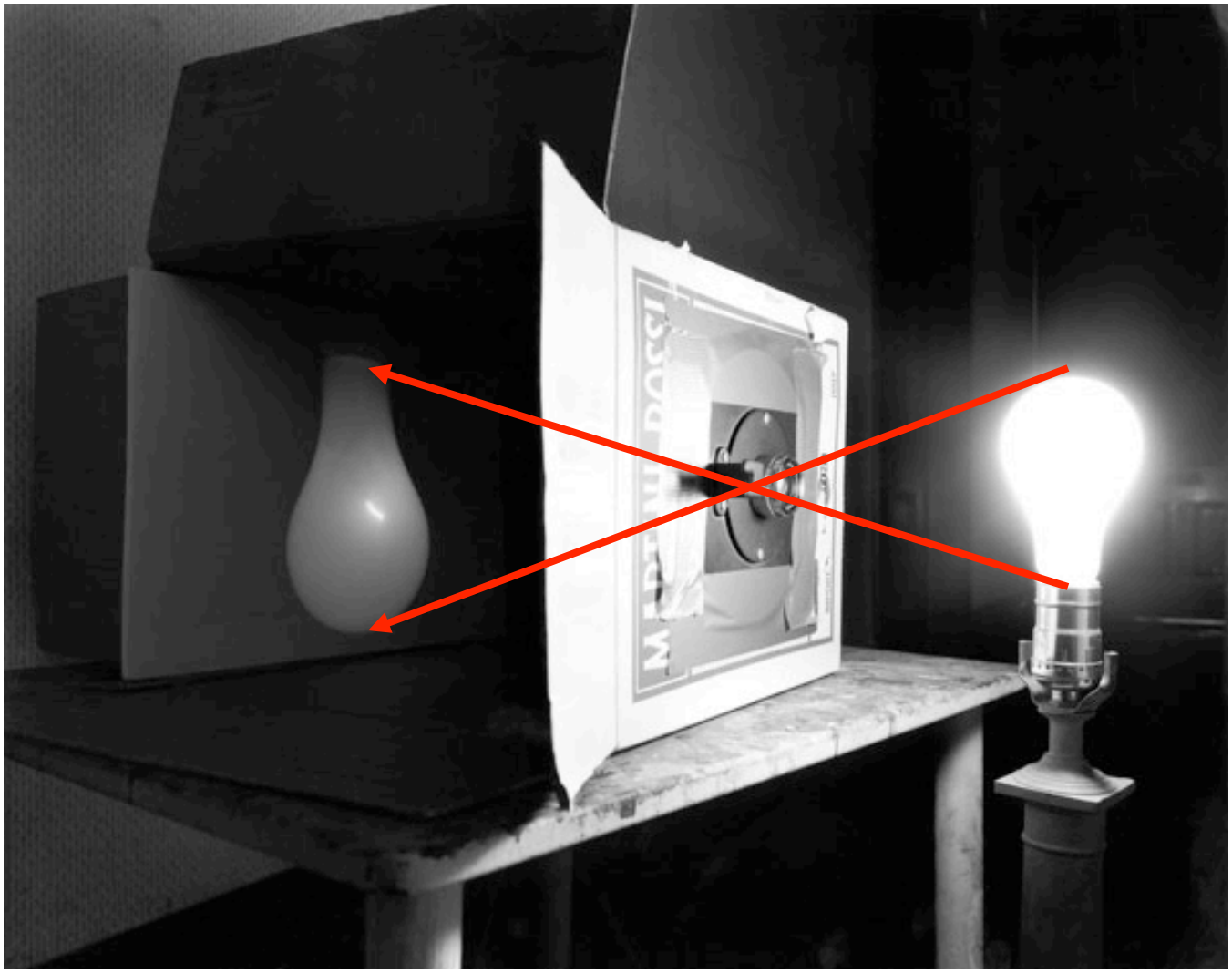
Photograph by Abelardo Morell, 1991

Pinhole camera



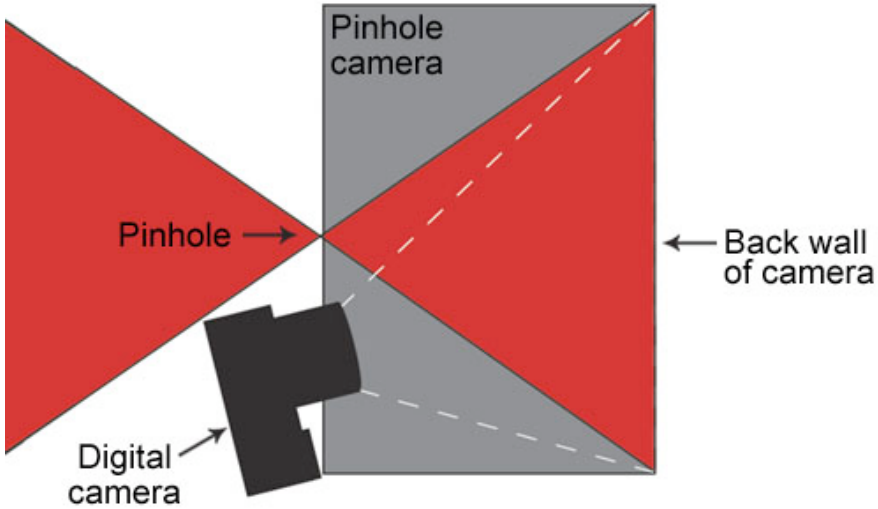
Photograph by Abelardo Morell, 1991

Pinhole camera



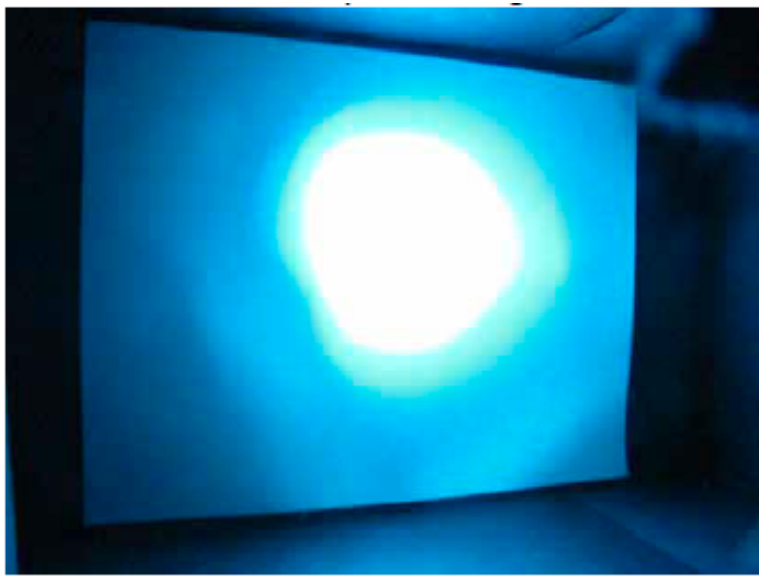
Photograph by Abelardo Morell, 1991

Problem Set 1



http://www.foundphotography.com/PhotoThoughts/archives/2005/04/pinhole_camera_2.html

Problem Set 1



Box? Room!

Cool demo

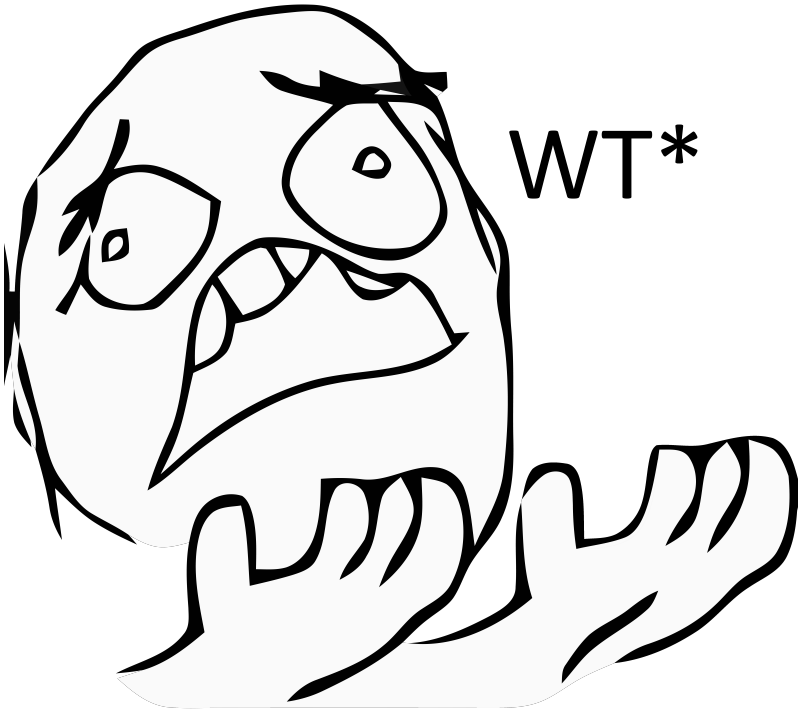
- http://www.youtube.com/watch?v=gvzpu0Q9RTU

Box? Room? Egg!

- http://www.petapixel.com/2011/04/25/eggs-transformed-into-pinhole-cameras/

Pinhole Camera is Awesome

But there are some parameters to tune!

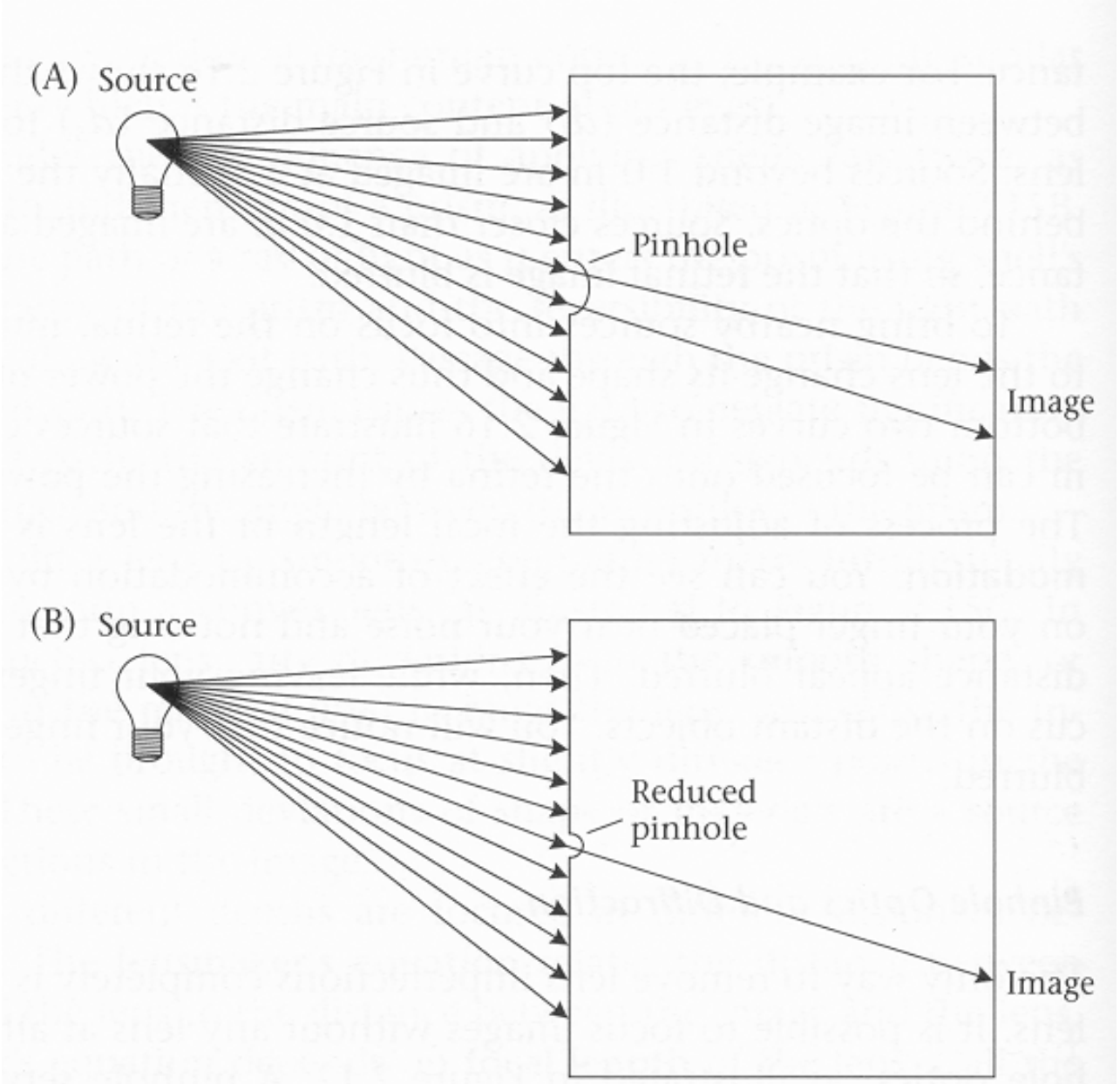


A Grad-student

Pinhole Camera

Only one parameter!

Effect of pinhole size



Wandell, Foundations of Vision, Sinauer, 1995

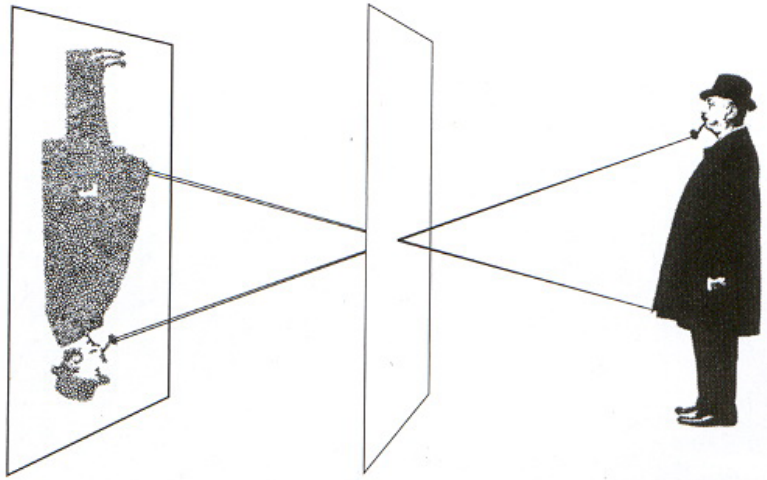
Define: aperture

- In optics, an aperture is a hole or an opening through which light travels.
- More specifically, the aperture of an optical system is the opening that determines the cone angle of a bundle of rays that come to a focus in the image plane.

Pinhole Camera

- What if **aperture** (pinhole size) is very small?
  - long exposure time (static scene)
  - high intensity

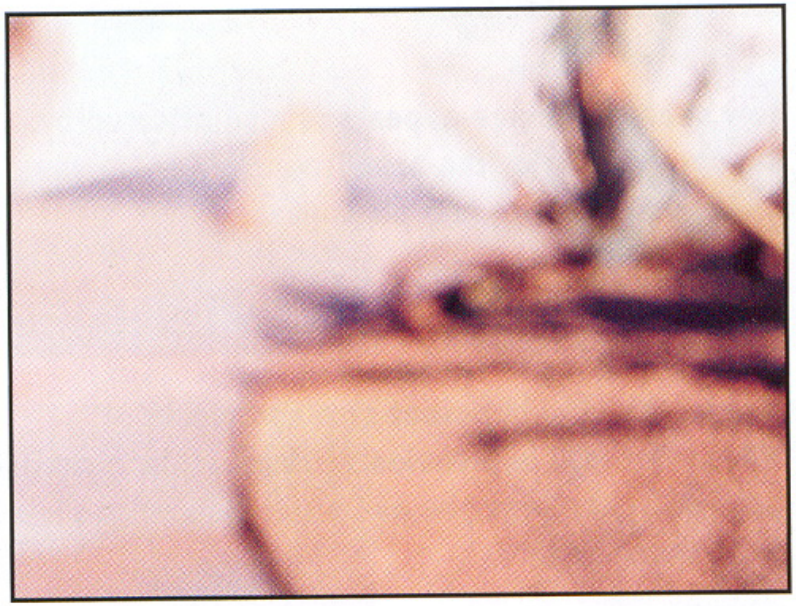
Photograph made with small pinhole

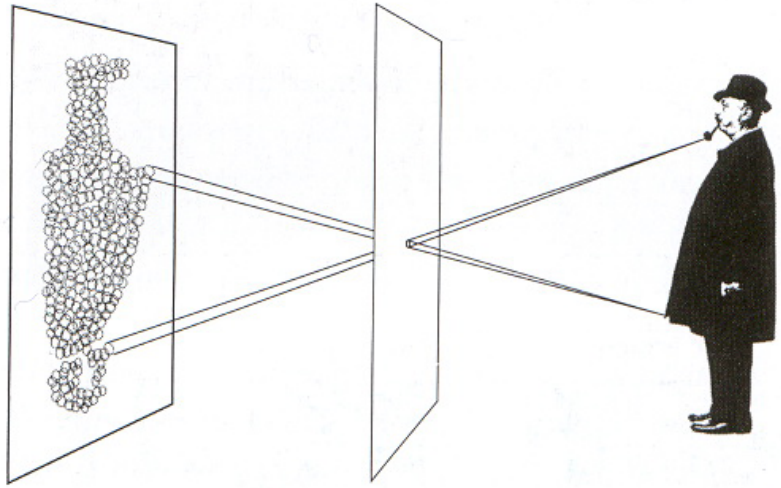


Pinhole Camera

- What if **aperture** (pinhole size) is too big?
  - blurry image

Photograph made with larger pinhole



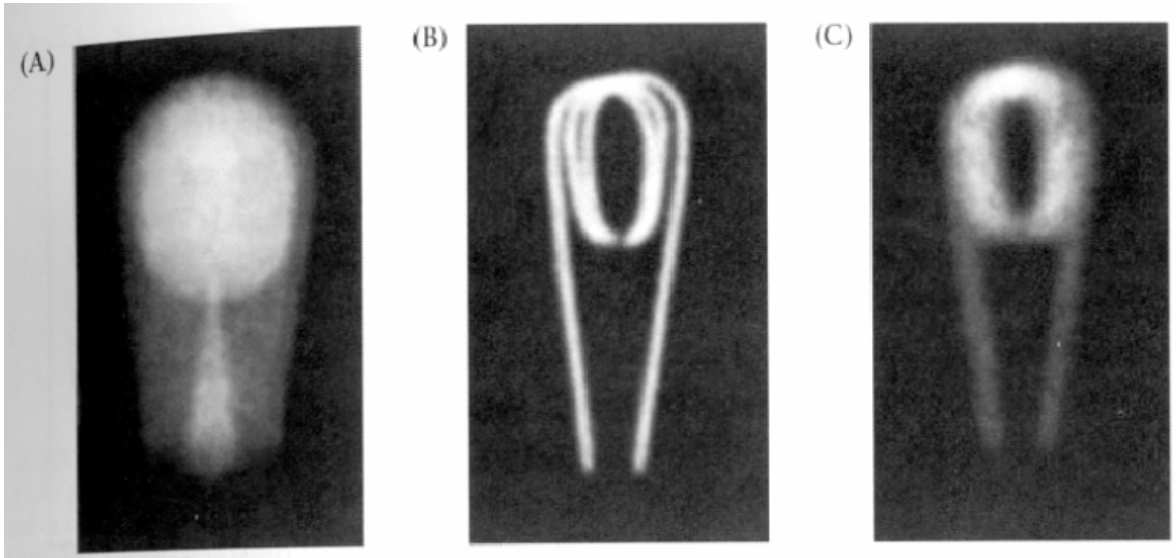


Pinhole Camera

- No aperture is good!
  - If large, blurry
  - If small, not enough light
    - There is no in-between

Pinhole Camera

- What if aperture (pinhole size) is extremely small?
  - diffraction through pinhole ⇒ blurry image

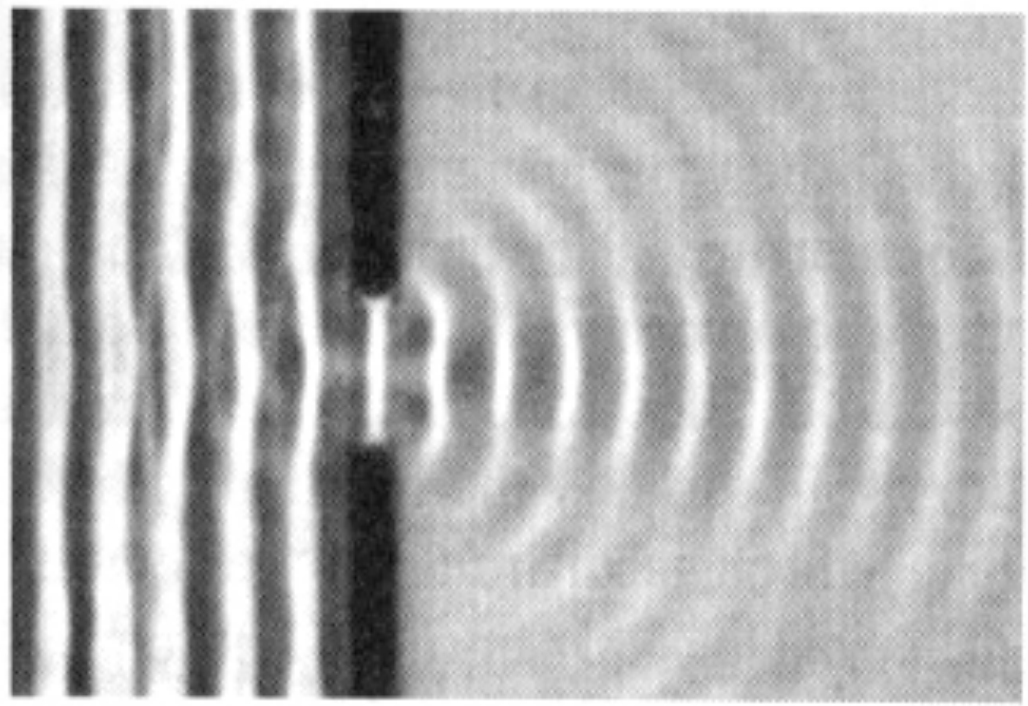


2.18 DIFFRACTION LIMITS THE QUALITY OF PINHOLE OPTICS. These three images of a bulb filament were made using pinholes with decreasing size. (A) When the pinhole is relatively large, the image rays are not properly converged, and the image is blurred. (B) Reducing the size of the pinhole improves the focus. (C) Reducing the size of the pinhole further worsens the focus, due to diffraction. From Ruechardt, 1958.

From Wandell

Diffraction

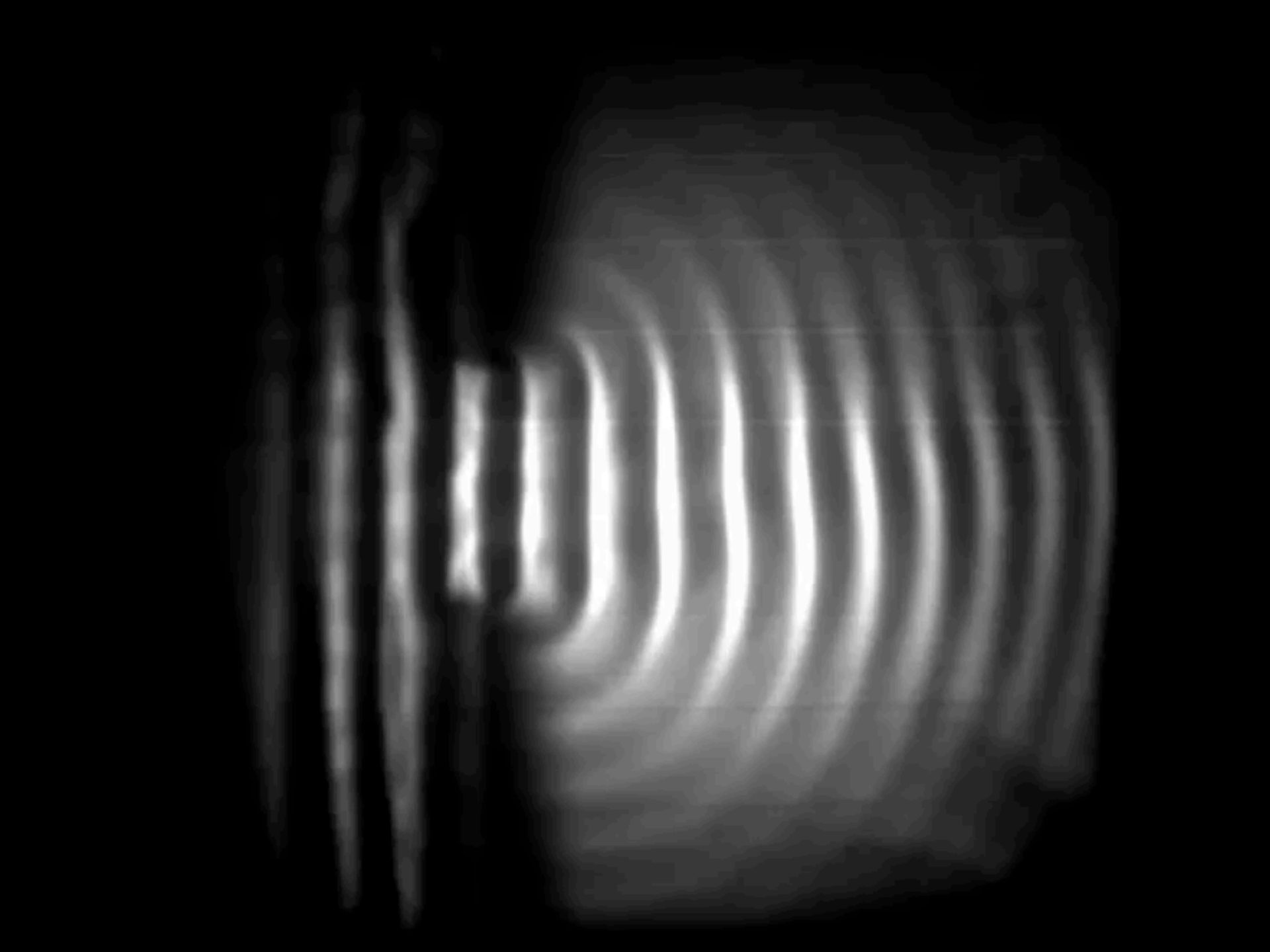
- **Wave nature of light**
- **Smaller aperture means more diffraction**



diffraction of water waves

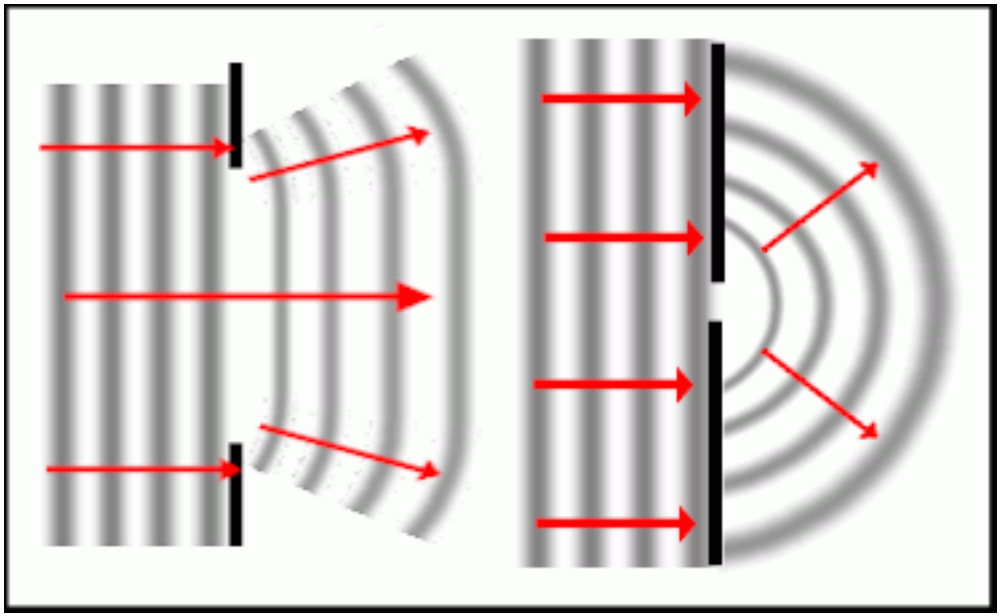
Youtube demos

- http://www.youtube.com/watch?v=kH57Di7Sj0c
- http://www.youtube.com/watch?v=lIn-BLJNXpY
- http://www.brightstorm.com/science/physics/vibration-and-waves/diffraction/
- http://www.youtube.com/watch?v=KSIg_EaIFrw
- http://www.youtube.com/watch?v=sjmBcm84iA4



Bottom line

- **The smaller the hole, the more diffraction**



http://www.mashpedia.com/Ripple_tank

Recap: Problem with pinhole?

- **Not enough light!**
- **Diffraction limits sharpness**

Solution?


I HATE RESEARCH.
yeah, well, life is tough and then you graduate.
get used to it.
JORGE CHAM © 2005
www.phdcomics.com

Solution: refraction!

From Photography, London et al.

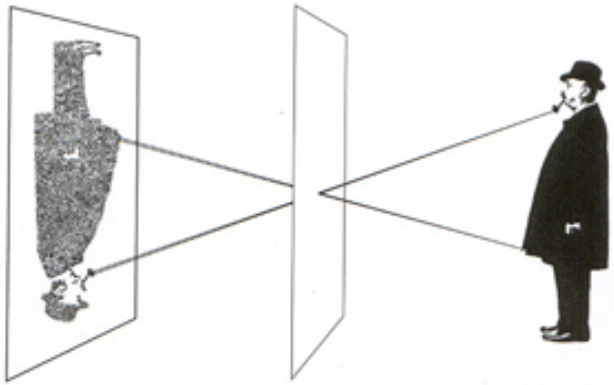
Outline for Today

- What is a digital image?
- What is a pin-hole camera?
- Lens & optics
- Geometric transformation
- Accidental camera

Lenses

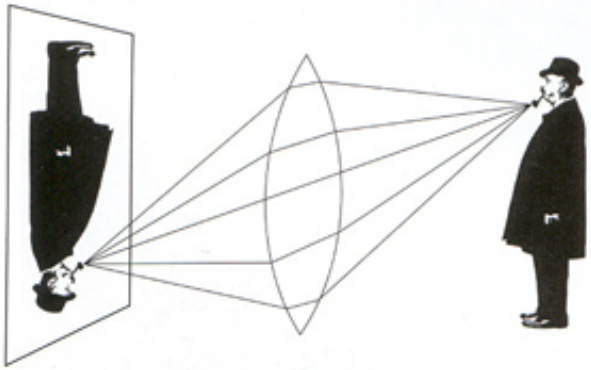
- **Gather more light!**
- **But need to be focused**

Photograph made with small pinhole



To make this picture, the lens of a camera was replaced with a thin metal disk pierced by a tiny pinhole, *equivalent in size to an aperture of f/182. Only a few rays of light from each point on the subject got through the tiny opening, producing a soft but acceptably clear photograph. Because of the small size of the pinhole, the exposure had to be 6 sec long.*

Photograph made with lens



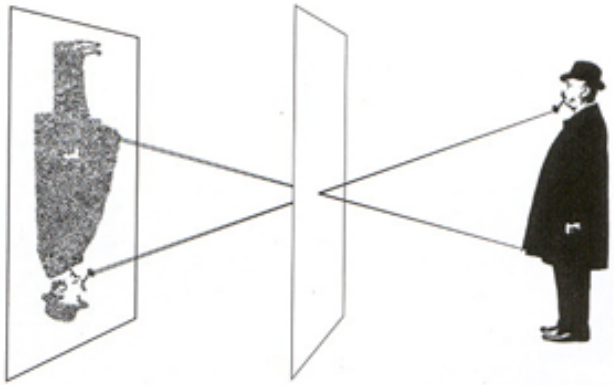
This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec. The lens opening was much bigger than the pinhole, letting in far more light, but it focused the rays from each point on the subject precisely so that they were sharp on the film.*

From Photography, London et al.

Lenses

- Essentially add multiple pinhole images
- ~ shift them to align (refraction)
- Alignment works only for one distance

Photograph made with small pinhole



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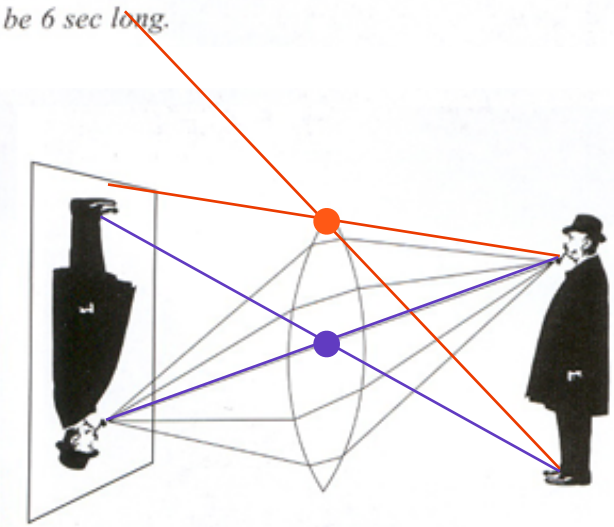

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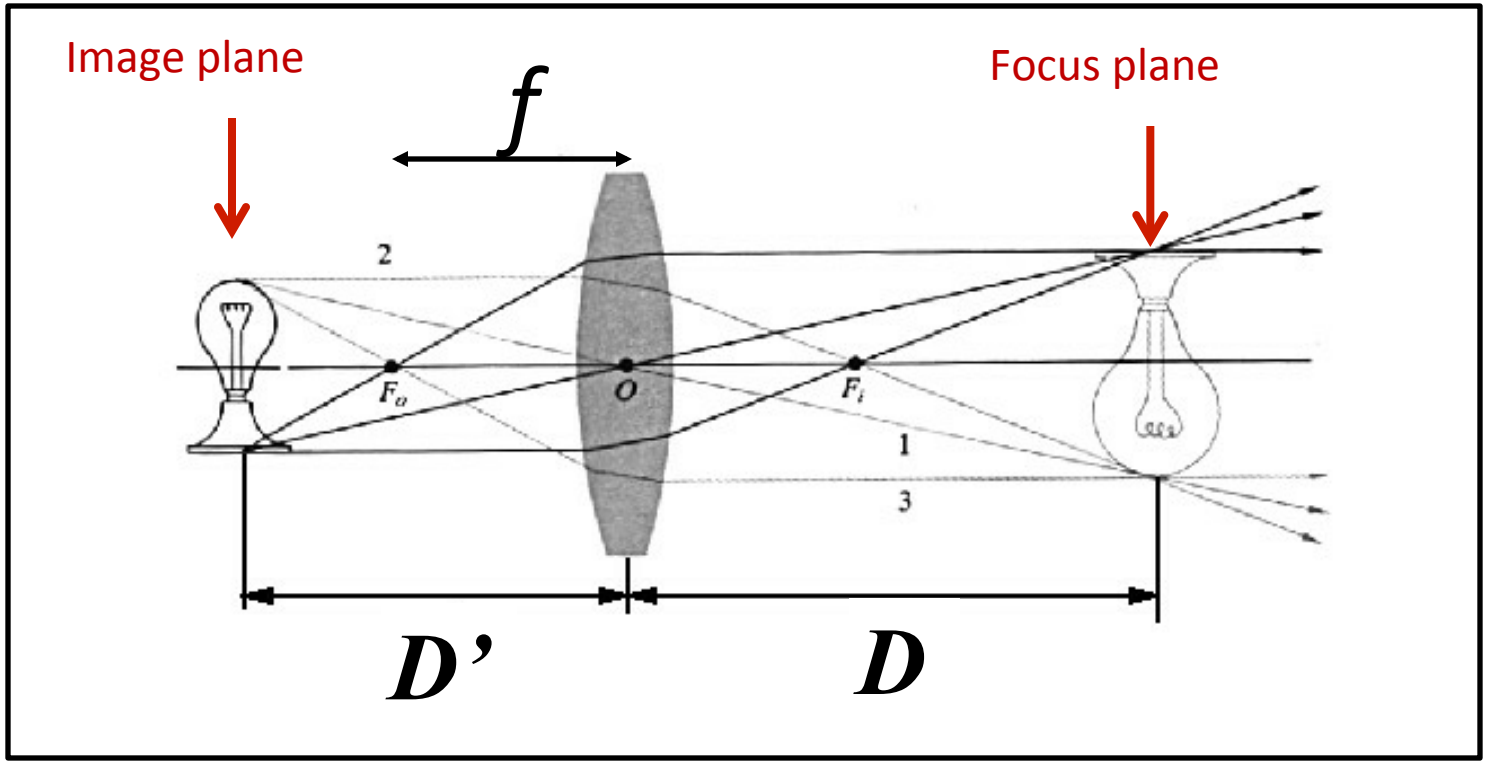
From Photography, London et al.

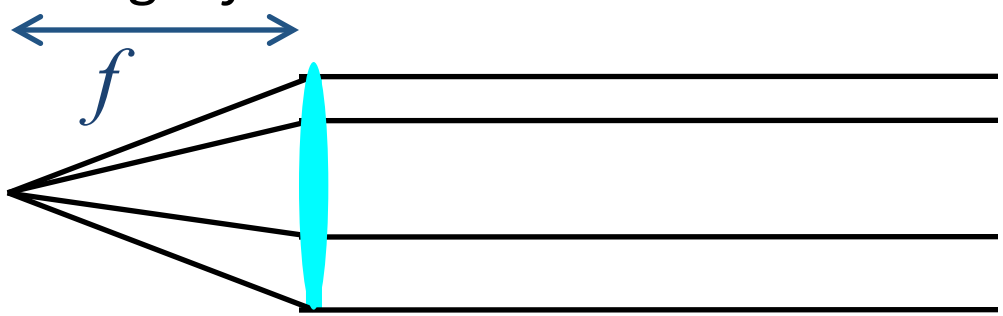
Thin Lens Optics

Rays emanating from one point on focus plane converge at one point on image plane

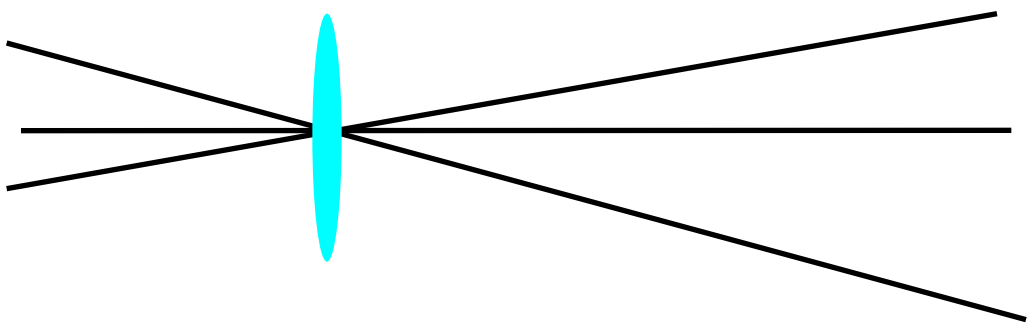


Thin Lens Optics

- All parallel rays converge to one point on a plane located at the focal length *f*

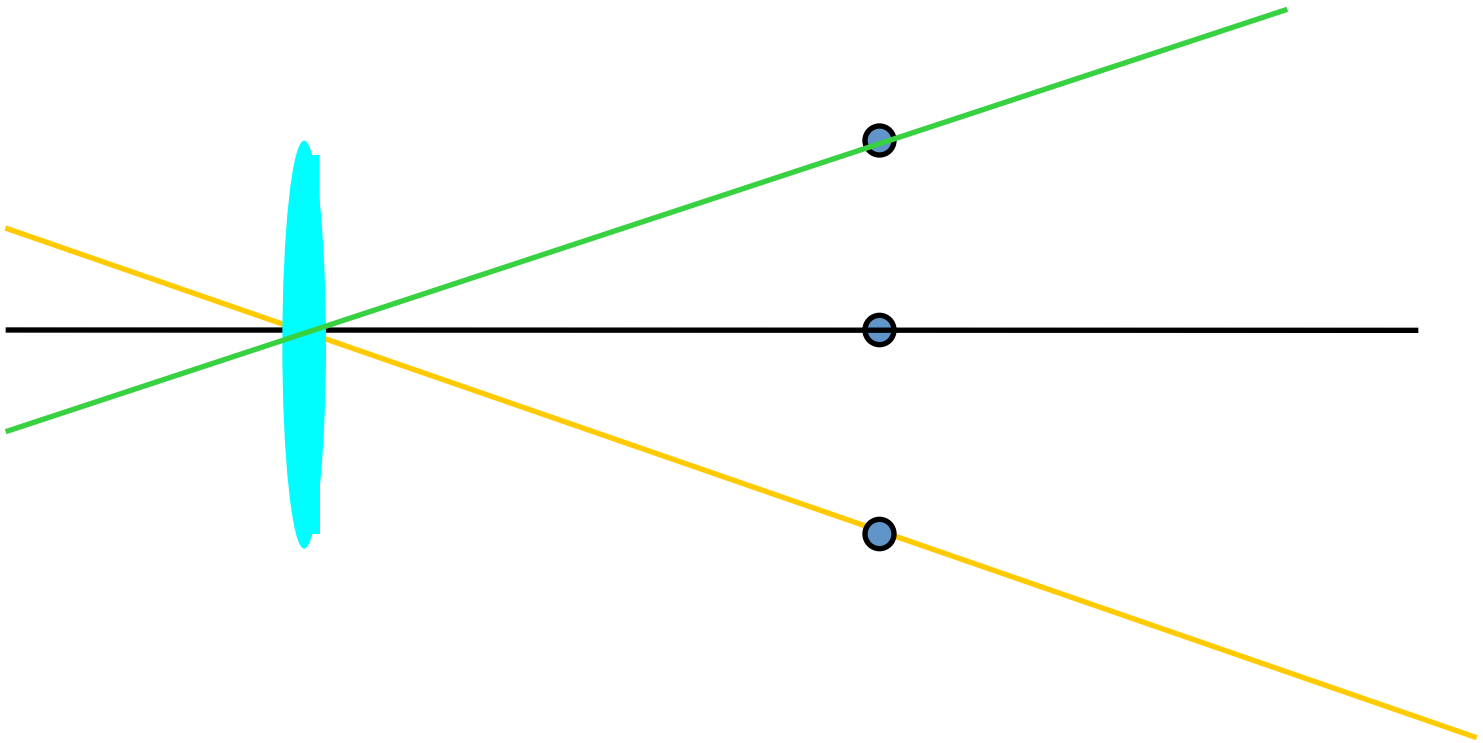


- All rays going through the center are not deviated
  - Hence same perspective as pinhole



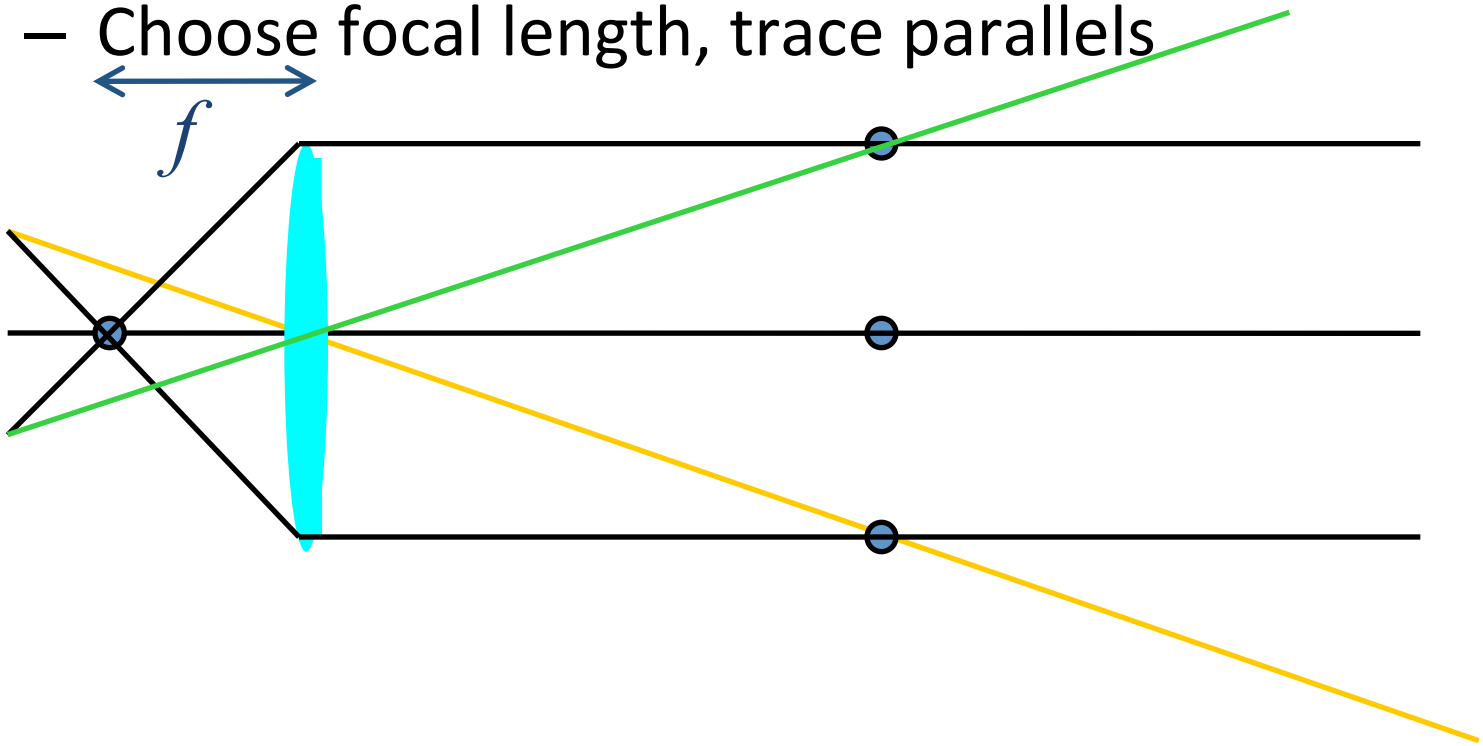
Thin Lens Optics

- Tracing rays through lens
  - Start by rays through the center



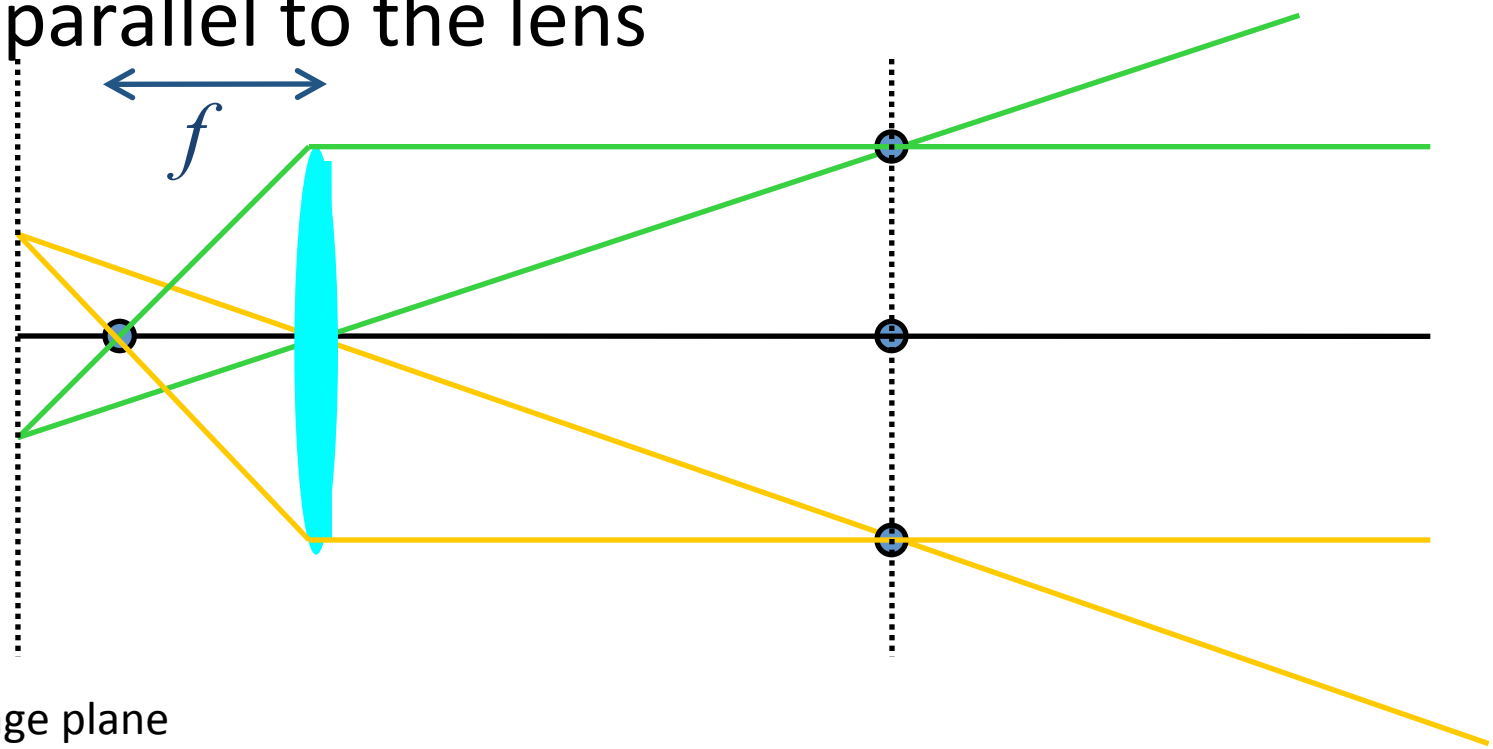
Thin Lens Optics

- Tracing rays through lens
  - Start by rays through the center
  - Choose focal length, trace parallels



Thin Lens Optics

- All rays coming from points on a plane parallel to the lens are focused on another plane parallel to the lens



Thin Lens Optics

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

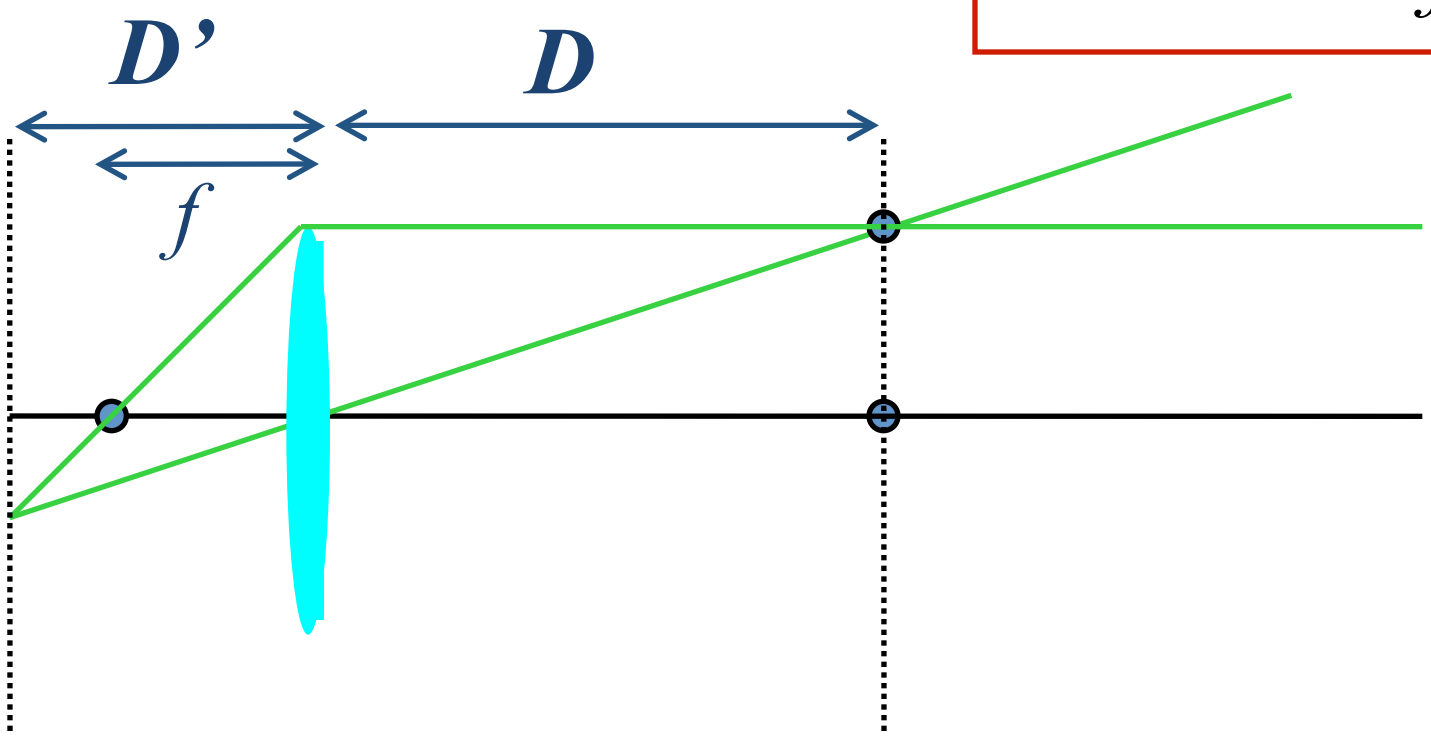


Image plane

Focus plane

Camera Terminology

- Lens parameters:
  - Focal length
- Camera parameters:
  - Aperture
- Camera properties:
  - Depth of field
  - Field of view

Focus Depth (D)

Can control D by changing D'

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

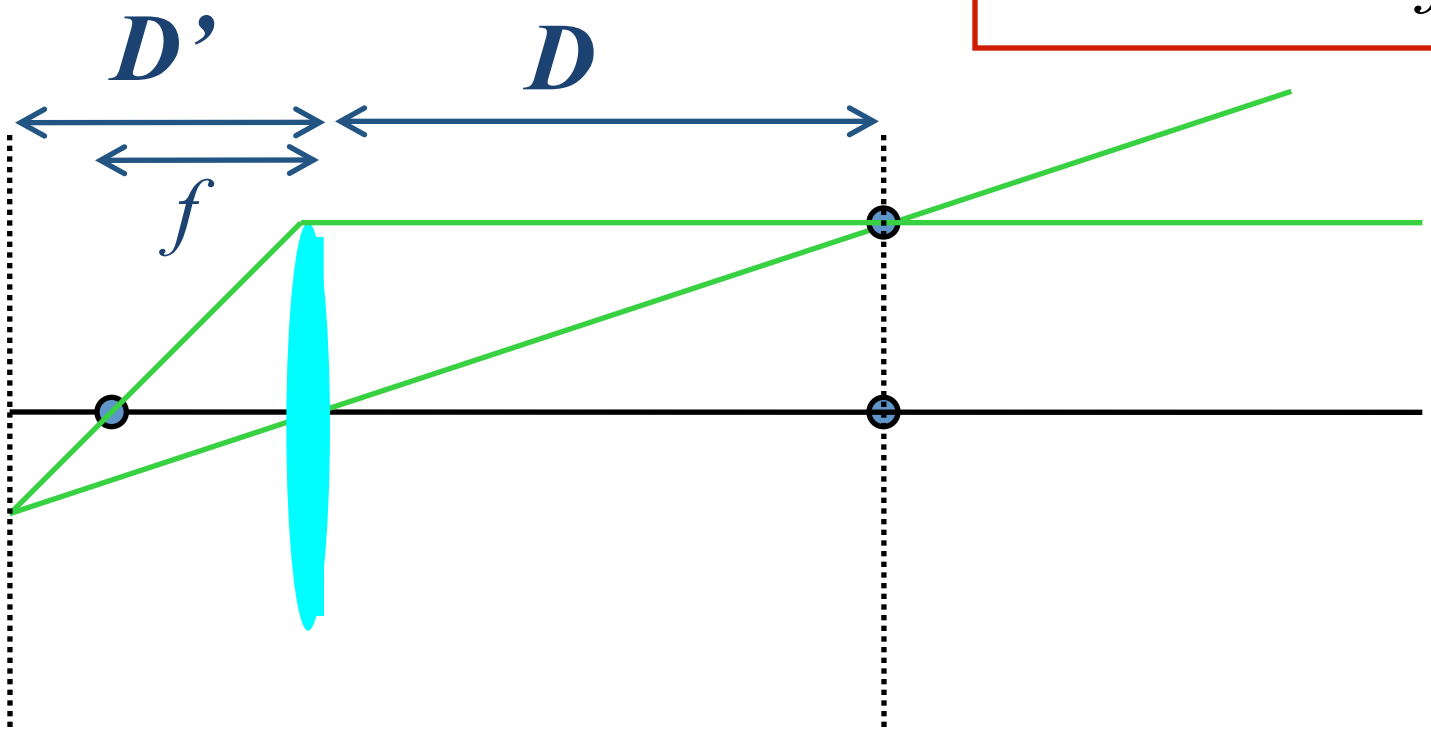


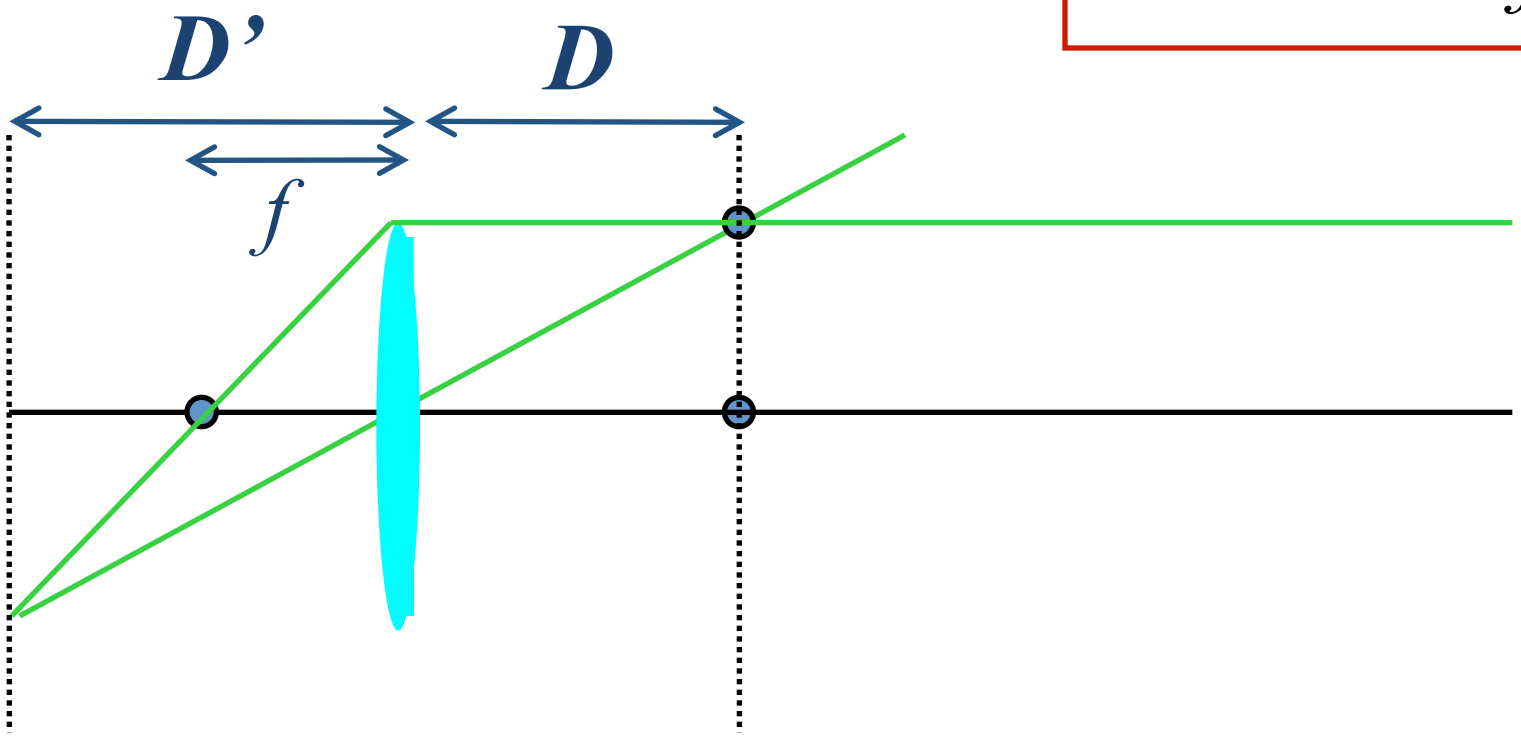
Image plane

Focus plane

Focus Depth (D)

Can control D by changing D'

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



Depth of Field

Only objects on focus plane are in “perfect” focus

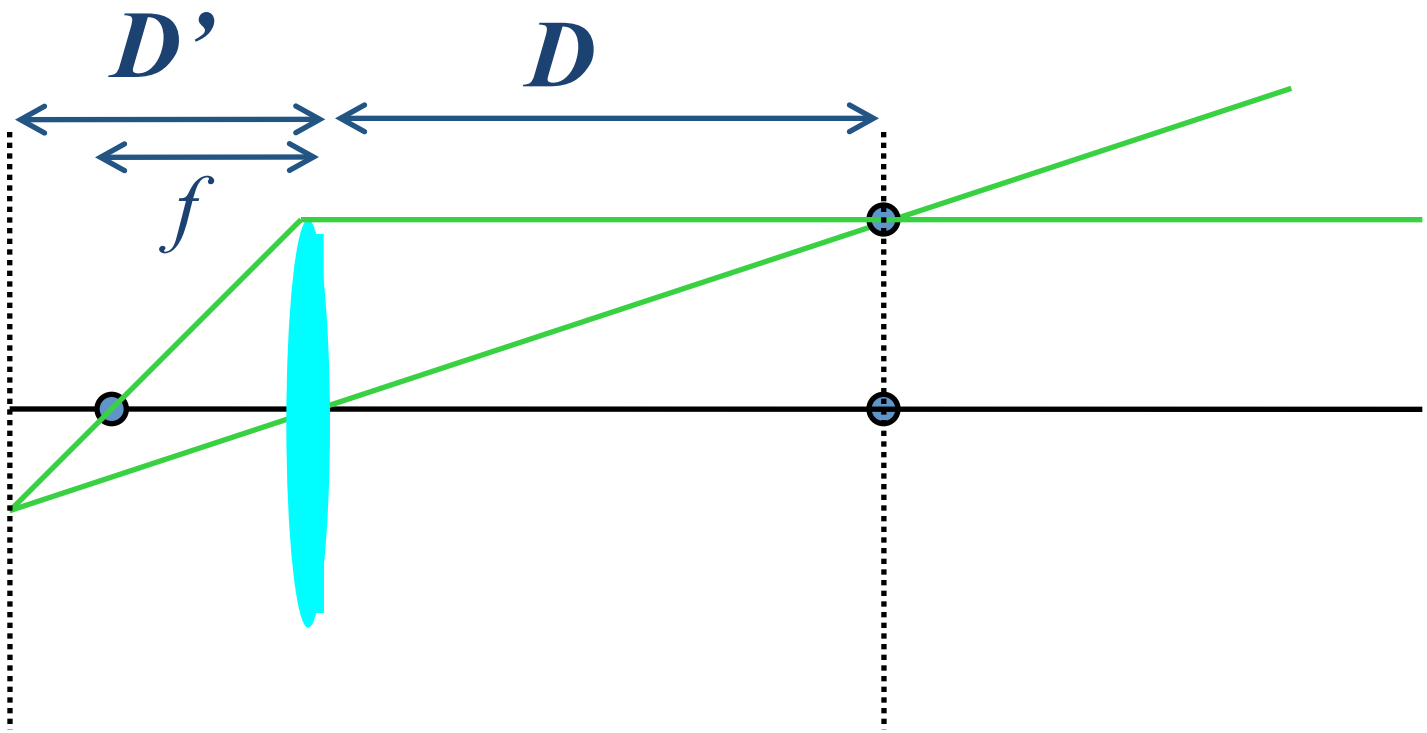


Image plane

Focus plane

Depth of Field

Objects closer to focus plane are in better focus

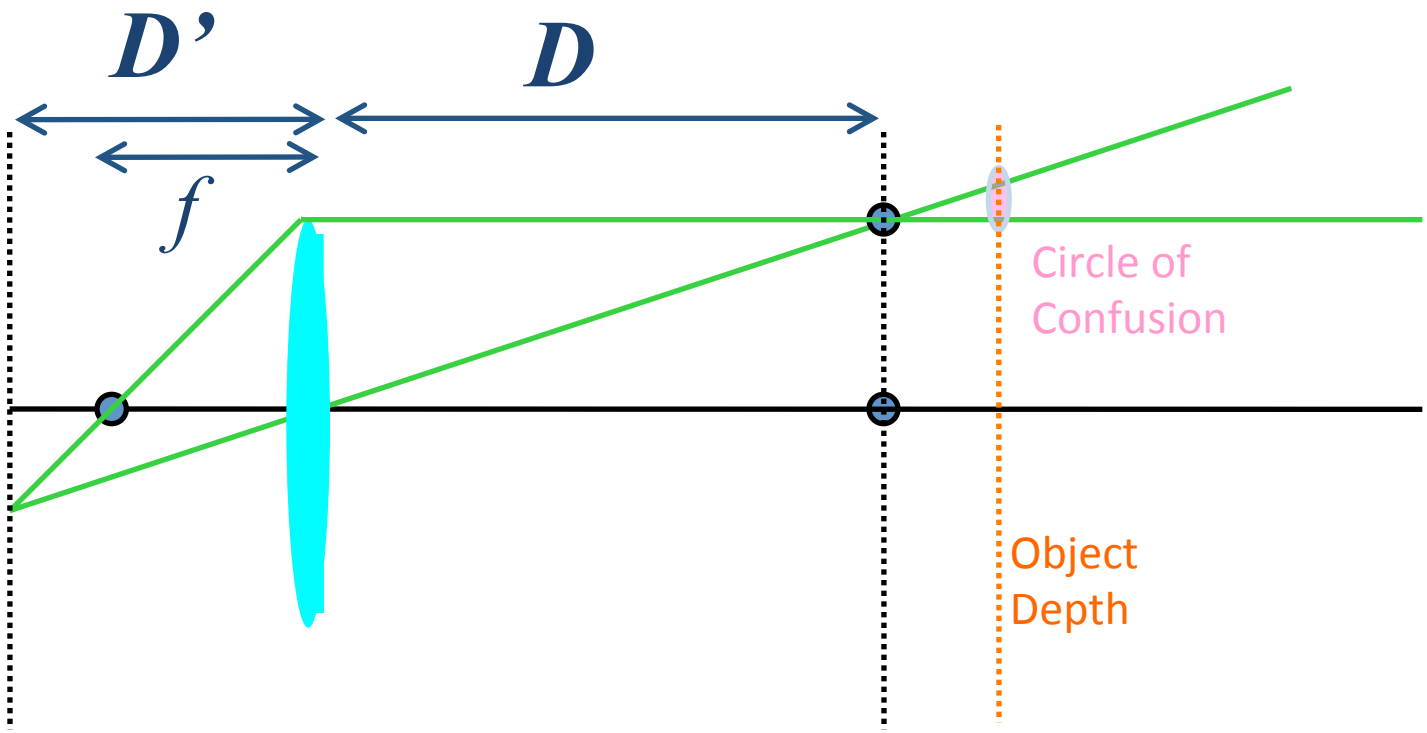


Image plane

Focus plane

Depth of Field

Objects closer to focus plane are in better focus

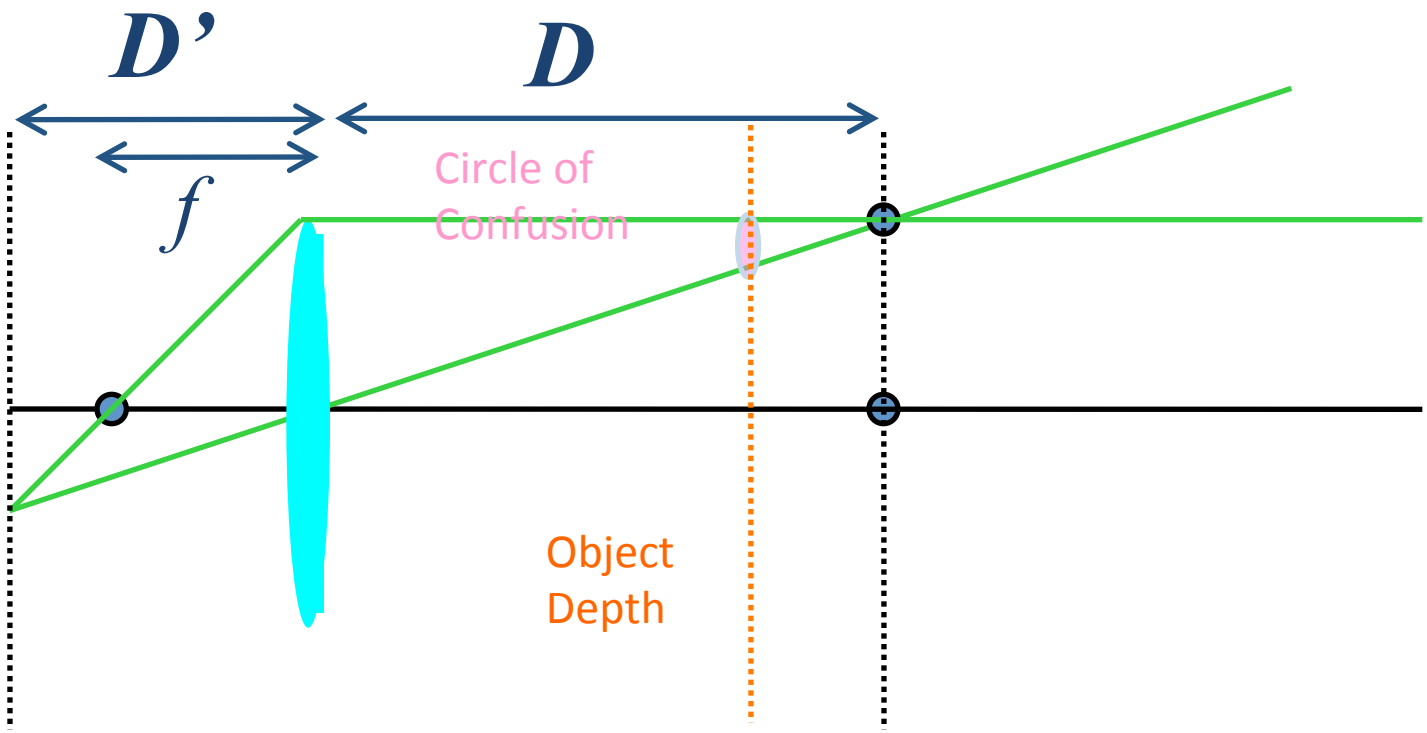


Image plane

Focus plane

Depth of Field

Objects closer to focus plane are in better focus

Slide by Lazebnik

Aperture

Controls radius of hole through which light can pass

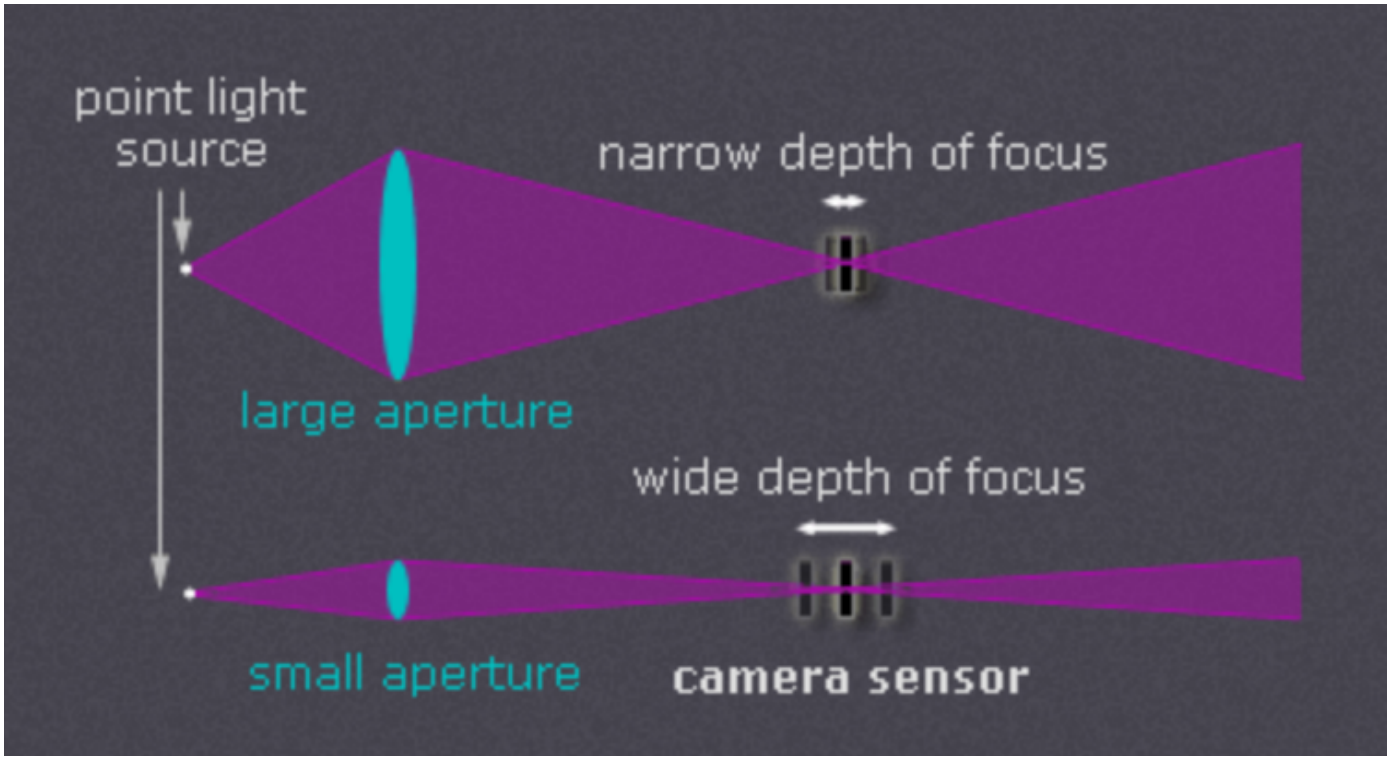
f/1.4 f/5.6 f/16

F-number is diameter of aperture relative to focal length

Aperture

Smaller apertures …

- Let in less light
- Have larger depth of field



Animal Eyes

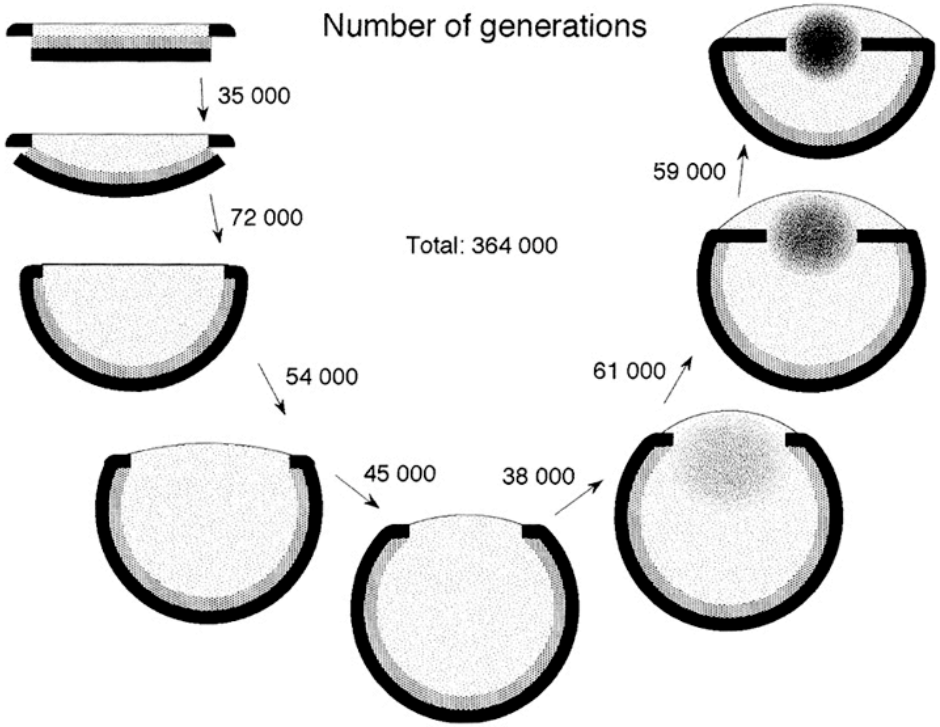
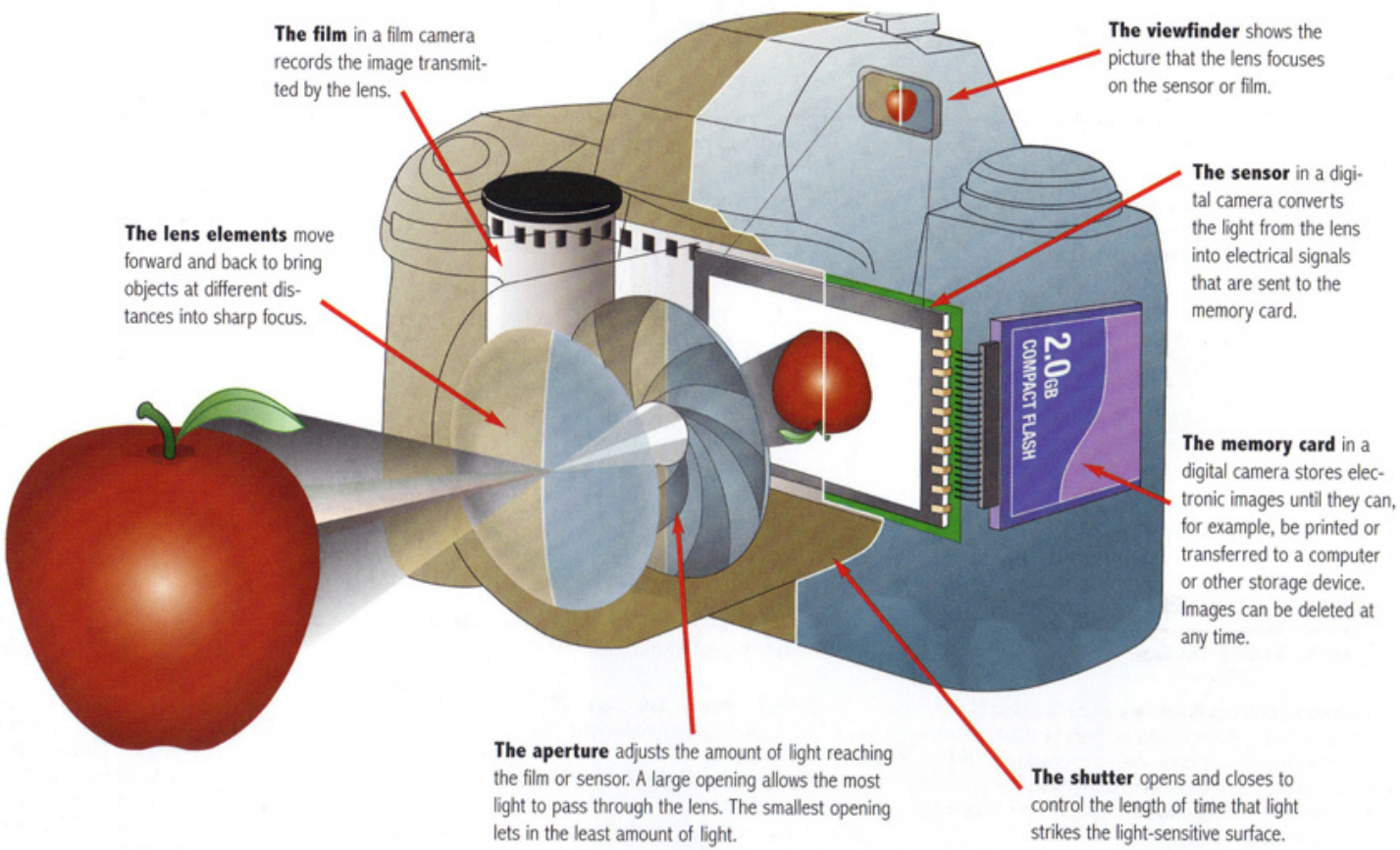


Fig. 1.6 A patch of light sensitive epithelium can be gradually turned into a perfectly focussed camera-type eye if there is a continuous selection for improved spatial vision. A theoretical model based on conservative assumptions about selection pressure and the amount of variation in natural populations suggest that the whole sequence can be accomplished amazingly fast, in less than 400 000 generations. The number of generations is also given between each of the consecutive intermediates that are drawn in the figure. The starting point is a flat piece of epithelium with an outer protective layer, an intermediate layer of receptor cells, and a bottom layer of pigment cells. The first half of the sequence is the formation of a pigment cup eye. When this principle cannot be improved any further, a lens gradually evolves. Modified from Nilsson and Pelger (1994).

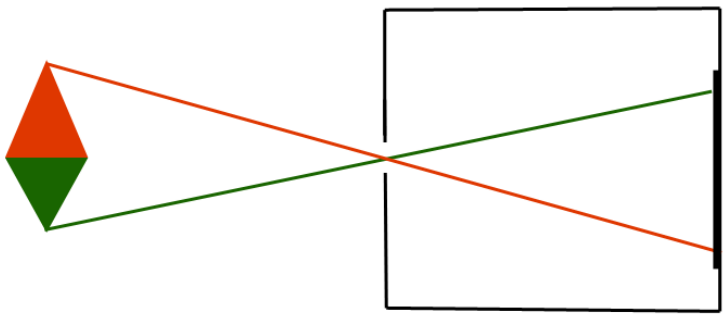
Animal Eyes. Land & Nilsson. Oxford Univ. Press

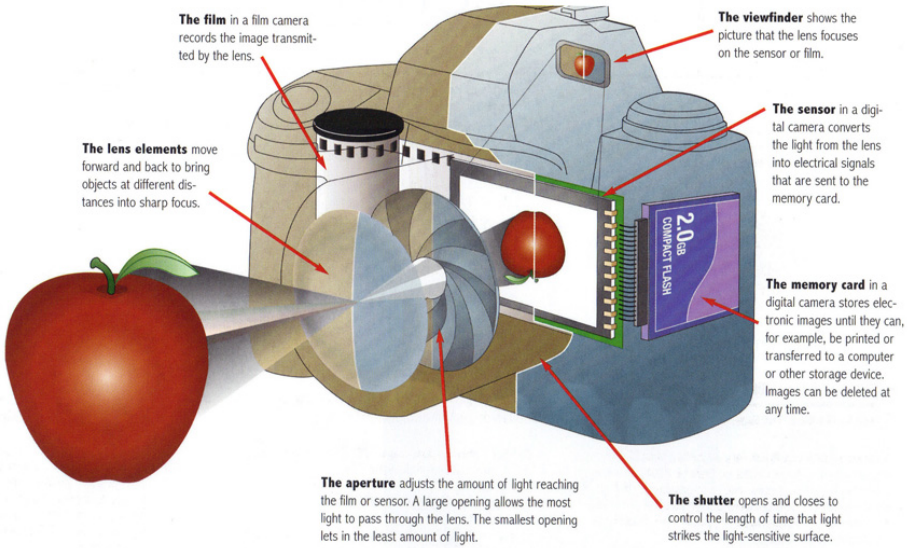
Camera

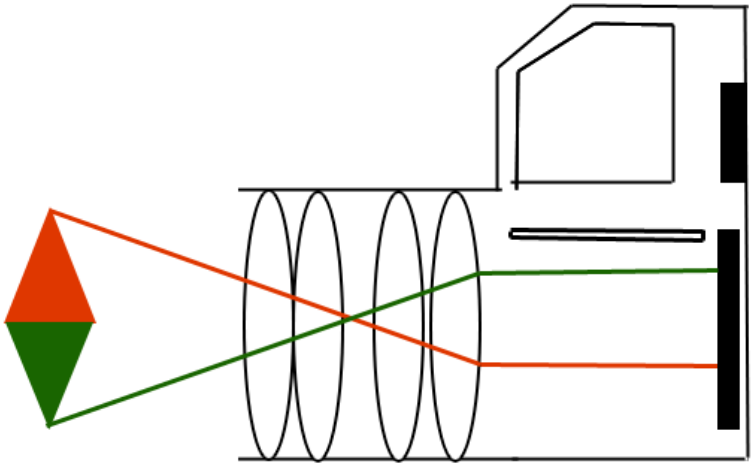


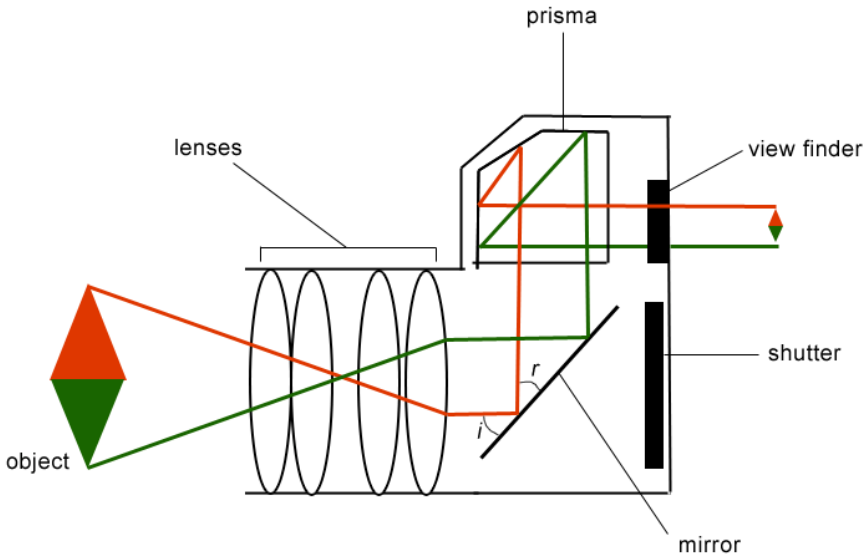
Source: S. Lazebnik, N. Saveley

Camera Anatomy



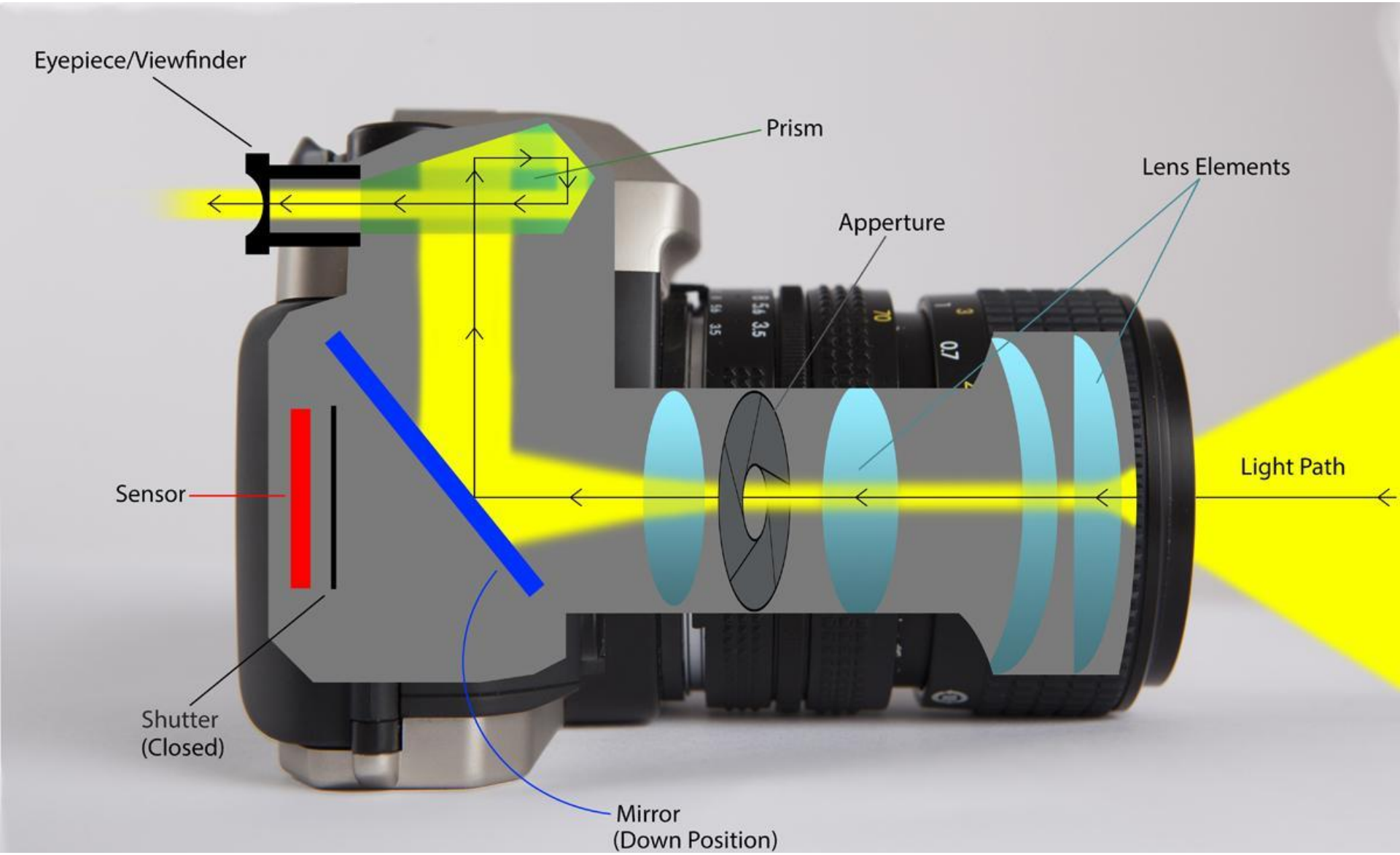






Sensing Parameters

Quiz: how to make an image brighter in a dark room?



Sensor ISO:
How sensitive it is.

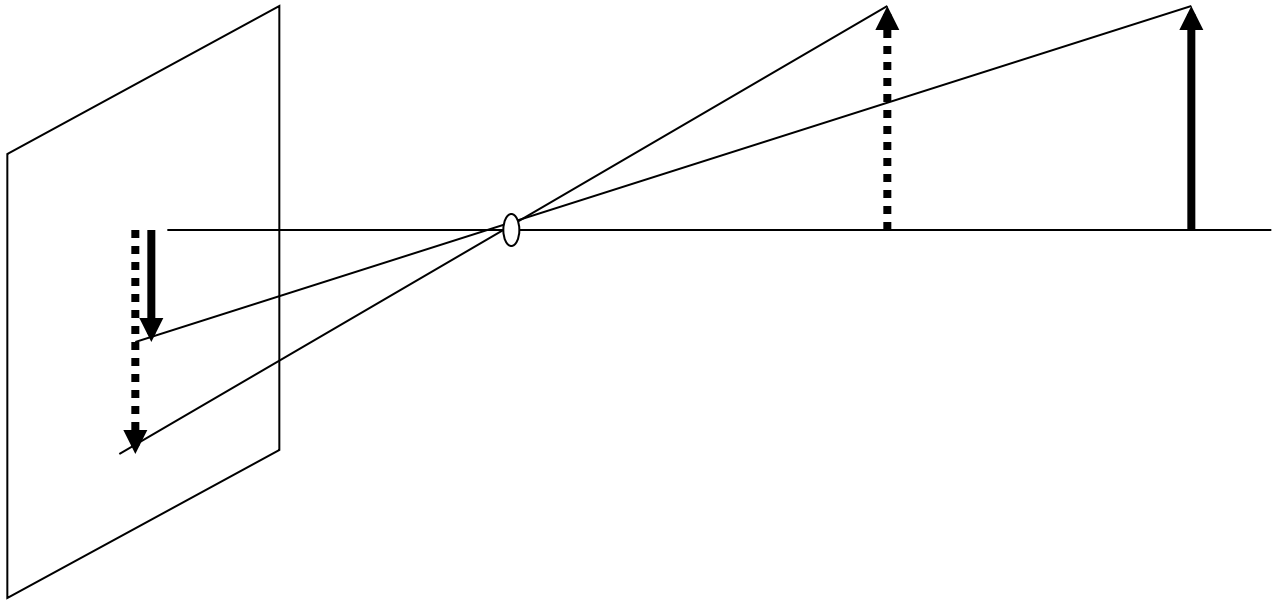
Shutter speed:
time that the sensor receive light

Aperture: size of the hole

Pin-hole Camera

- Physics of real cameras are all different (too tedious to model all of them).
- But they all try their best to approximate pin-hole camera.
- So in most of computer vision subjects, we model all cameras mathematically as a pin-hole camera.
- With some extra parameters that is too much to ignore (e.g. radial distortion).

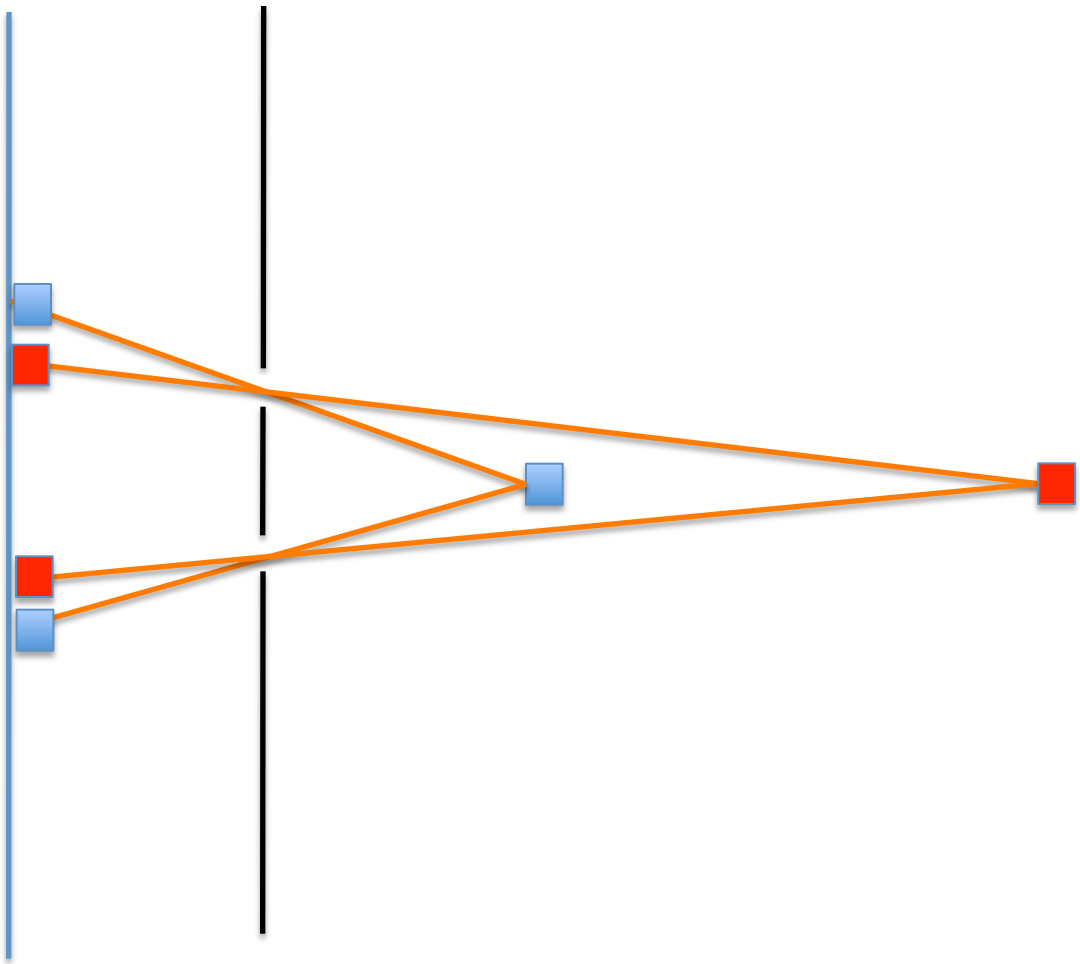
Measuring distance



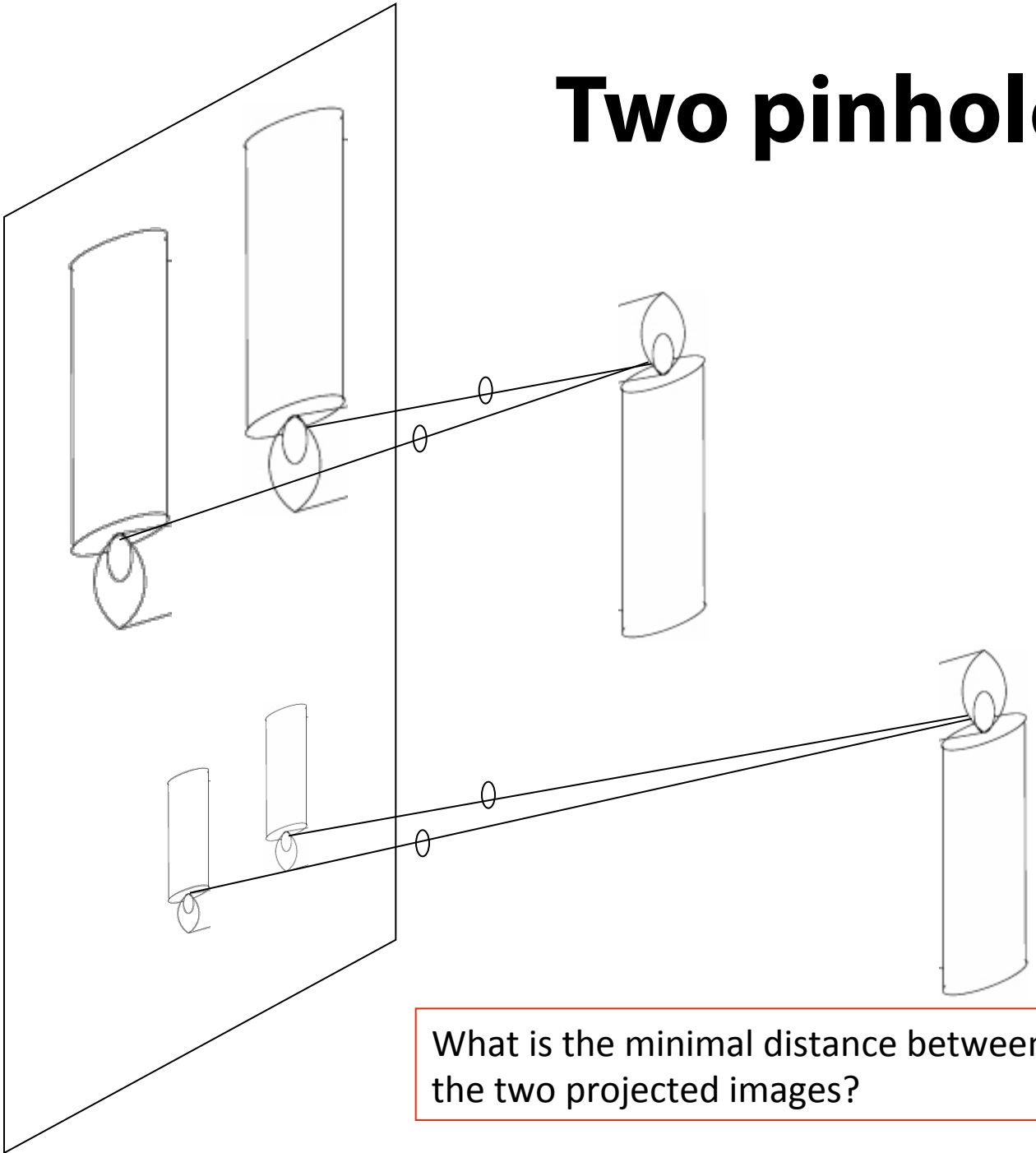
- Object size decreases with distance to the pinhole
- There, given a single projection, if we know the size of the object we can know how far it is.
- But for objects of unknown size, the 3D information seems to be lost.

Playing with pinholes

Two pinholes

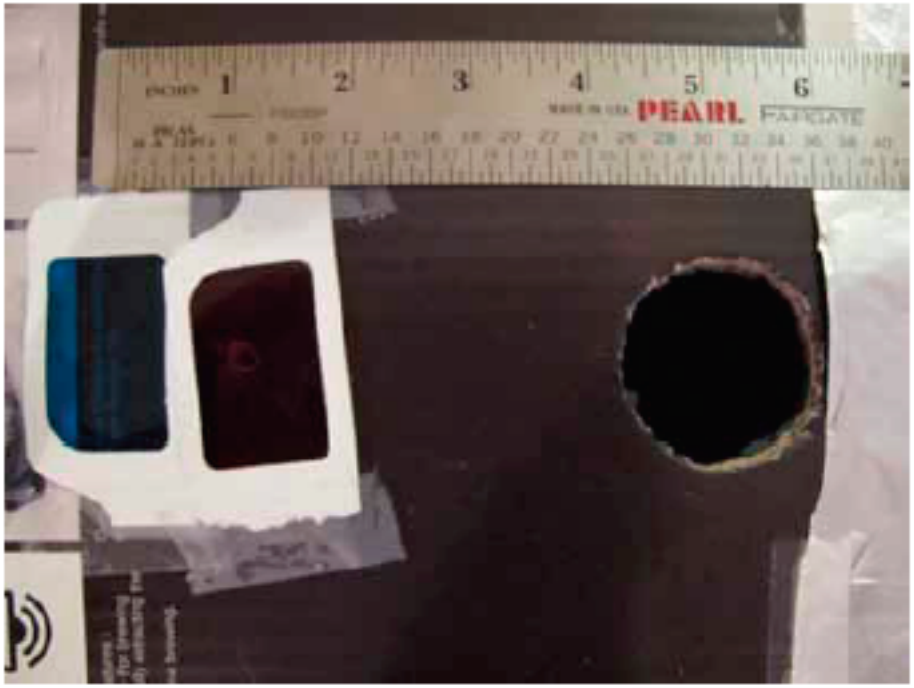


Two pinholes

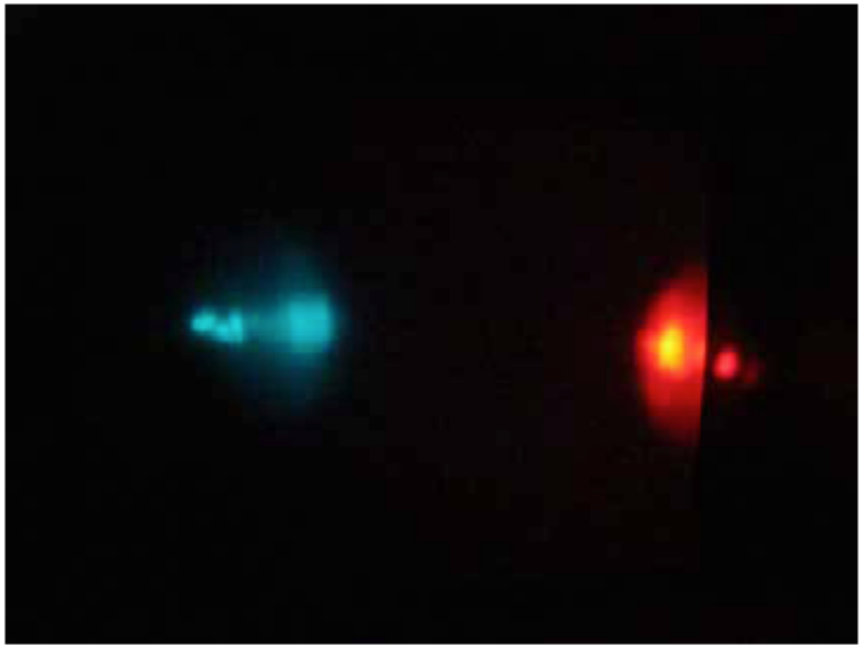


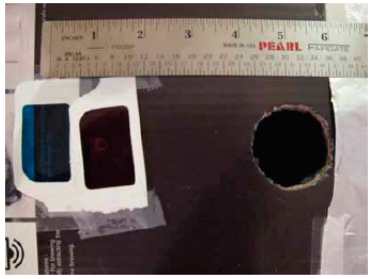
What is the minimal distance between the two projected images?

Anaglyph pinhole camera



Anaglyph pinhole camera

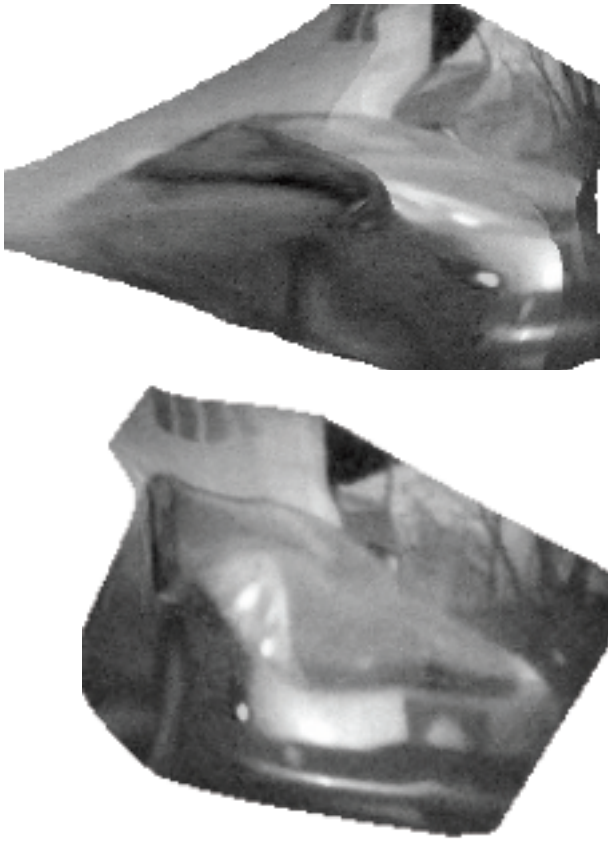




Anaglyph pinhole camera

Anaglyph

Synthesis of new views

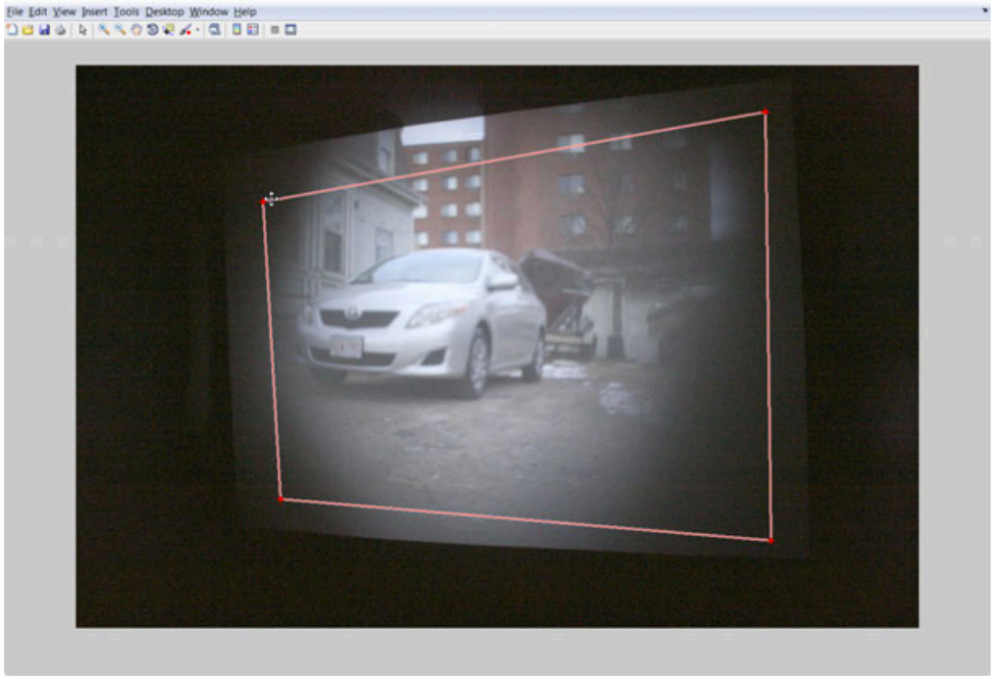


Problem Set 1

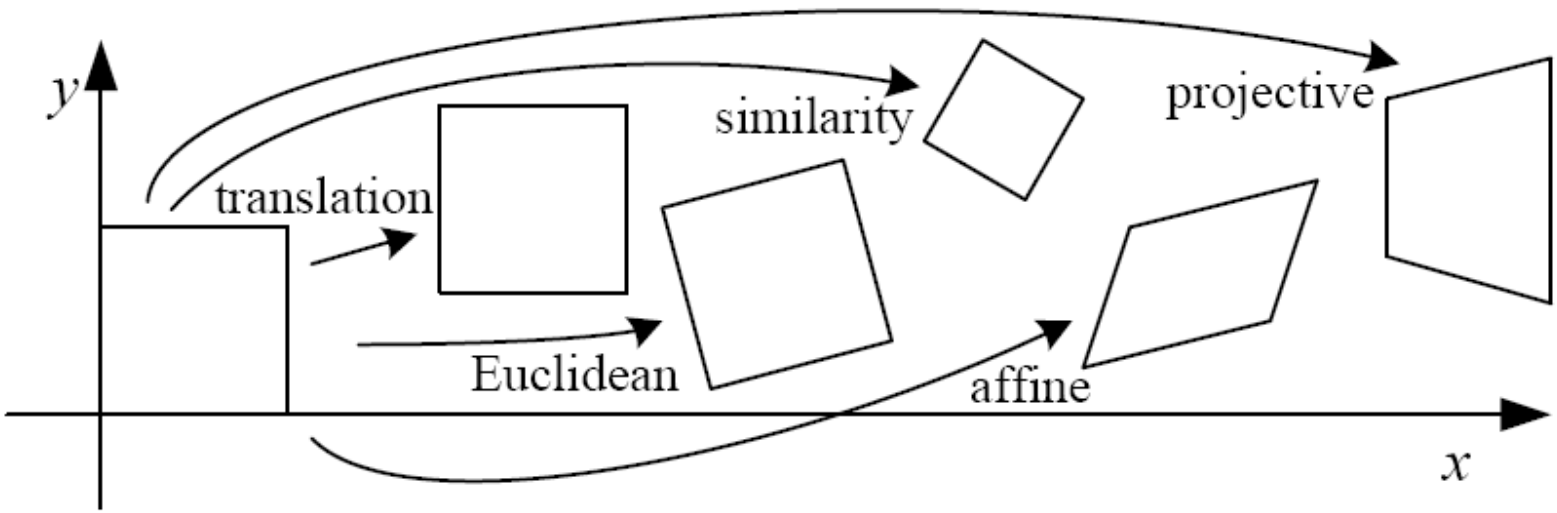
- Build the device
- Take some pictures and put them in the report
- <u>Correct the perspective to a rectangular picture</u>
- Bonus: Take anaglyph images
- Bonus: Work out the geometry
- Bonus: Recover depth for some points in the image

Outline for Today

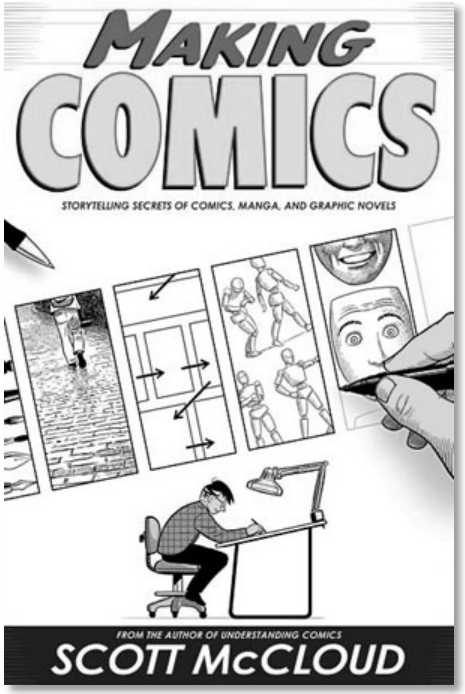
- What is a digital image?
- What is a pin-hole camera?
- Lens & optics
- Geometric transformation
- Accidental camera


File Edit View Insert Tools Desktop Window Help

2D Geometric Transformations



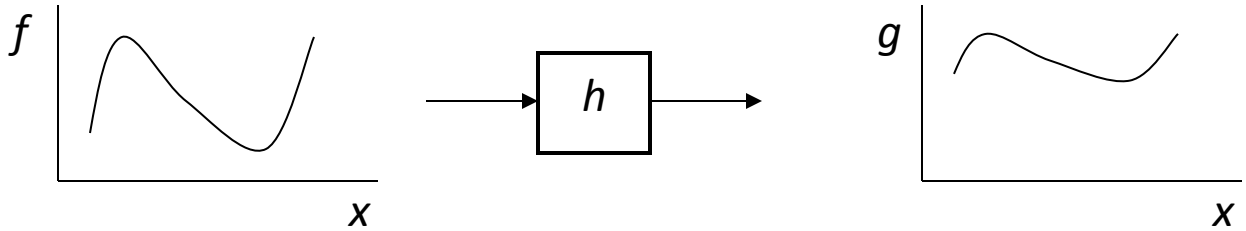
What is the geometric relationship between these two images?



?

Image Transformation

- image filtering: change *range* of image
  - $g(x) = h(f(x))$



- image warping: change *domain* of image
  - $g(x) = f(h(x))$

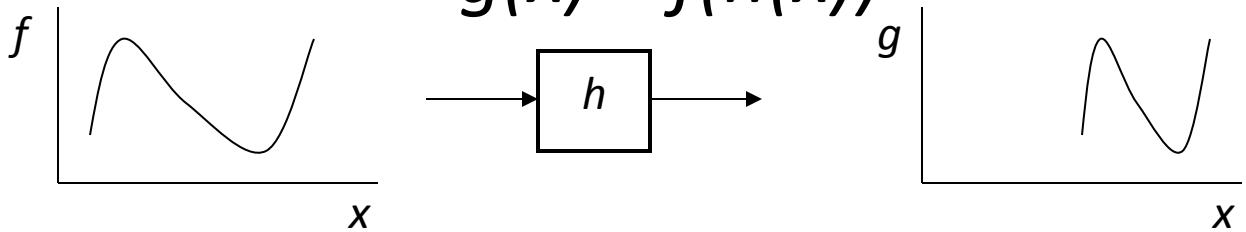
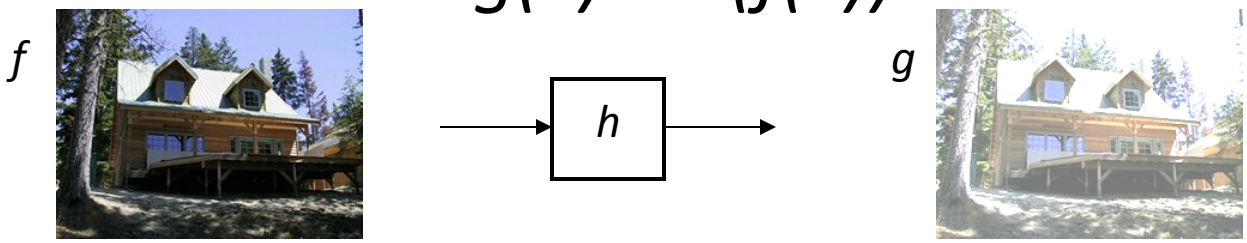
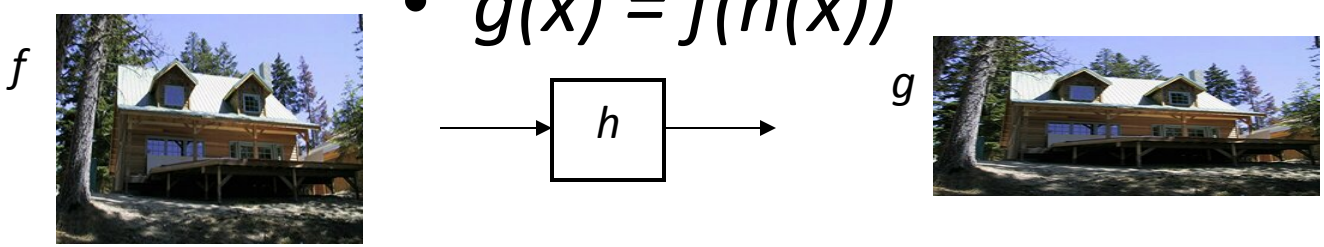


Image Transformation

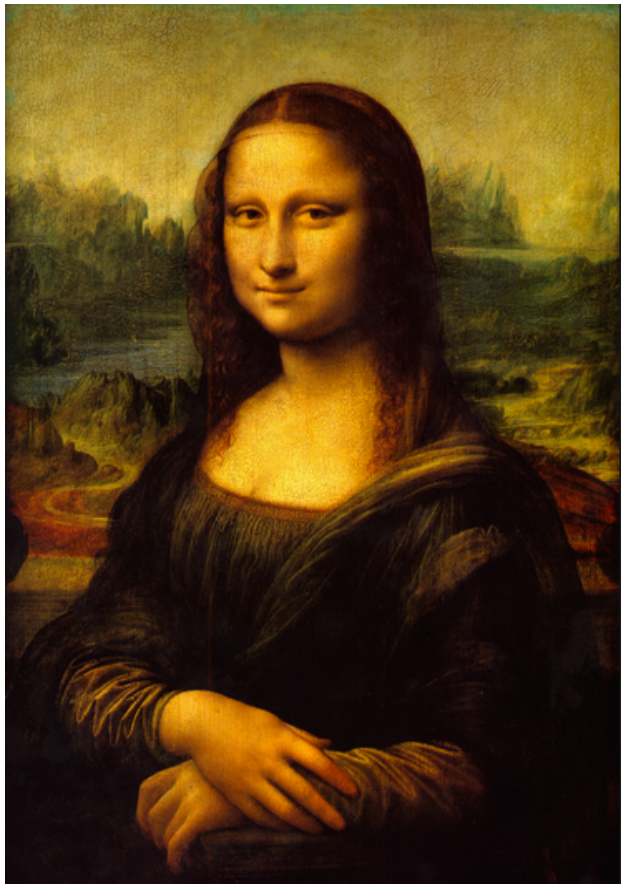
- image filtering: change *range* of image
  - $g(x) = h(f(x))$

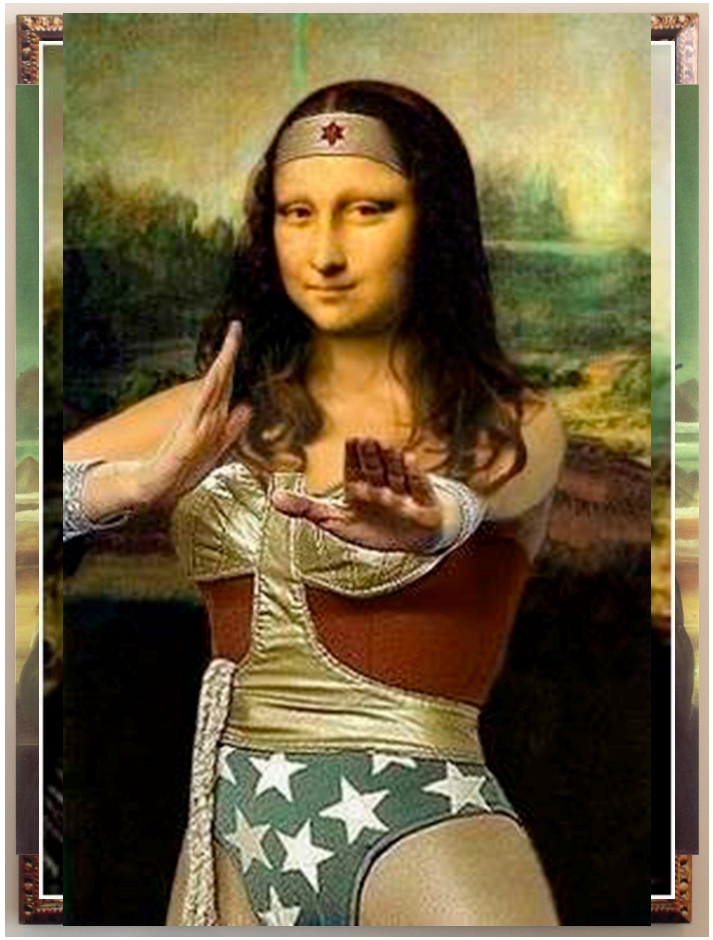


- image warping: change *domain* of image
  - $g(x) = f(h(x))$



Other Image Transformation





Parametric (global) warping

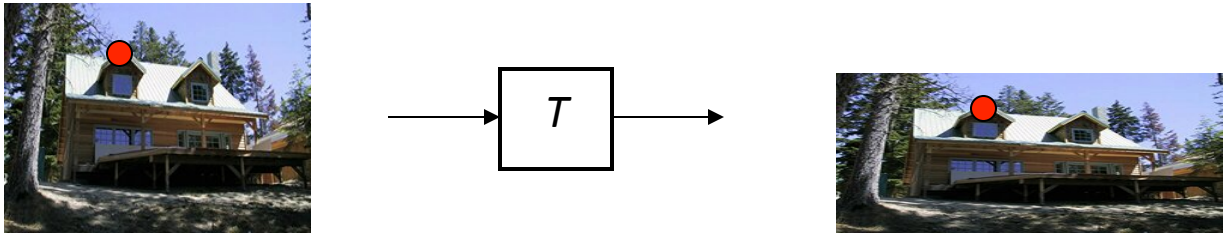
- Examples of parametric warps:

translation

rotation

aspect

Parametric (global) warping



p = (x,y) **p'** = (x',y')

- Transformation T is a coordinate-changing machine:

  p' = *T*(p)

- What does it mean that *T* is global?
  - Is the same for any point p
  - can be described by just a few numbers (parameters)
- Let's consider *linear* xforms (can be represented by a 2D matrix):

$$\mathbf{p}' = \mathbf{T}\mathbf{p} \qquad \begin{bmatrix} x' \\ y' \end{bmatrix} = \mathbf{T} \begin{bmatrix} x \\ y \end{bmatrix}$$

Common linear transformations

- Uniform scaling by *s*:

(0,0)

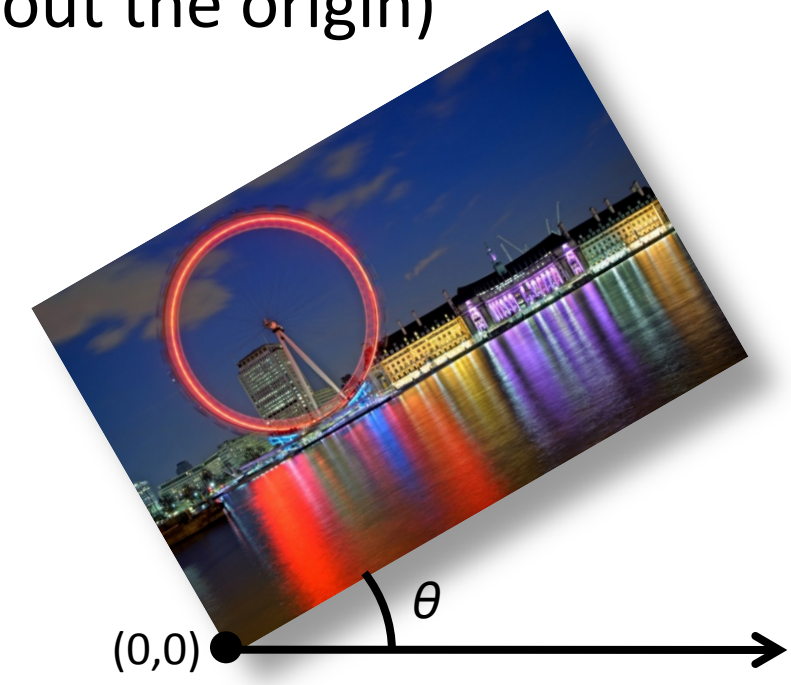
(0,0)

$$\mathbf{S} = \begin{bmatrix} s & 0 \\ 0 & s \end{bmatrix}$$

What is the inverse?

Common linear transformations

- Rotation by angle θ (about the origin)



$$\mathbf{R} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

What is the inverse?

For rotations:

$$\mathbf{R}^{-1} = \mathbf{R}^T$$

2x2 Matrices

- What types of transformations can be represented with a 2x2 matrix?

2D mirror about Y axis?

$$\begin{aligned} x' &= -x \\ y' &= y \end{aligned} \qquad \mathbf{T} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$

2D mirror across line y = x?

$$\begin{aligned} x' &= y \\ y' &= x \end{aligned} \qquad \mathbf{T} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

2x2 Matrices

- What types of transformations can be represented with a 2x2 matrix?

2D Translation?

$$x' = x + t_x$$
$$y' = y + t_y$$

NO!

Translation is not a linear operation on 2D coordinates

All 2D Linear Transformations

- Linear transformations are combinations of …
  - Scale,
  - Rotation,
  - Shear, and
  - Mirror

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

- Properties of linear transformations:
  - Origin maps to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition

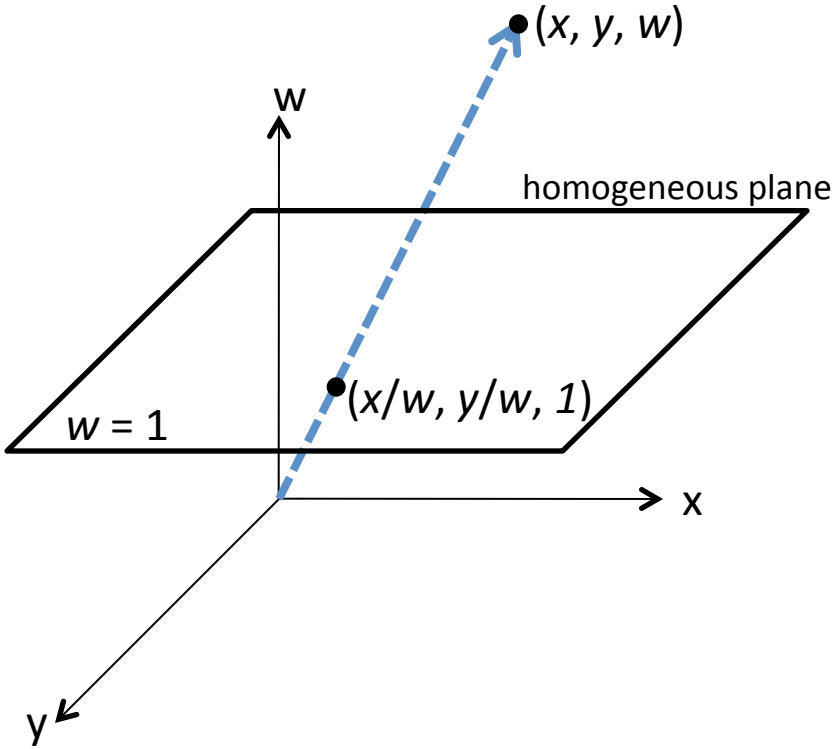
$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} e & f \\ g & h \end{bmatrix} \begin{bmatrix} i & j \\ k & l \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

Homogeneous coordinates

Trick: add one more coordinate:

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

homogeneous image coordinates



Converting *from* homogeneous coordinates

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

Translation

- Solution: homogeneous coordinates to the rescue

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} x + t_x \\ y + t_y \\ 1 \end{bmatrix}$$

Affine transformations

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix}$$

any transformation with last row [0 0 1] we call an *affine* transformation

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix}$$

Basic affine transformations

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & t_x \\ 0 & 1 & t_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

Translate

$$\begin{bmatrix} \boldsymbol{x}' \\ \boldsymbol{y}' \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{s_x} & 0 & 0 \\ 0 & \boldsymbol{s_y} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ 1 \end{bmatrix}$$

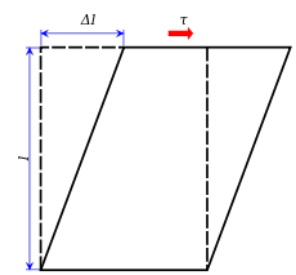
Scale

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$$

2D *in-plane* rotation

$$\begin{bmatrix} \boldsymbol{x}' \\ \boldsymbol{y}' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & \boldsymbol{sh_x} & 0 \\ \boldsymbol{sh_y} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \boldsymbol{y} \\ 1 \end{bmatrix}$$

Shear



Affine Transformations

- Affine transformations are combinations of …
  - Linear transformations, and
  - Translations

$$\begin{bmatrix} x' \\ y' \\ w \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

- Properties of affine transformations:
  - Origin does not necessarily map to origin
  - Lines map to lines
  - Parallel lines remain parallel
  - Ratios are preserved
  - Closed under composition

Where do we go from here?

$$\begin{bmatrix} a & b & c \\ d & e & f \\ 0 & 0 & 1 \end{bmatrix}$$

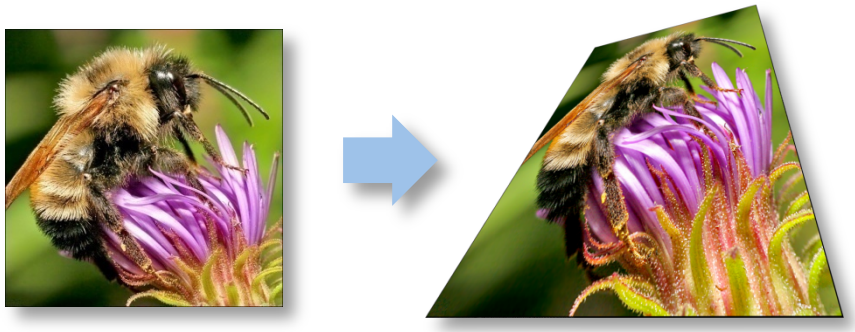
what happens when we mess with this row?

affine transformation

Projective Transformations aka Homographies aka Planar Perspective Maps

$$\mathbf{H} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{bmatrix}$$

Called a *homography*
(or *planar perspective map*)



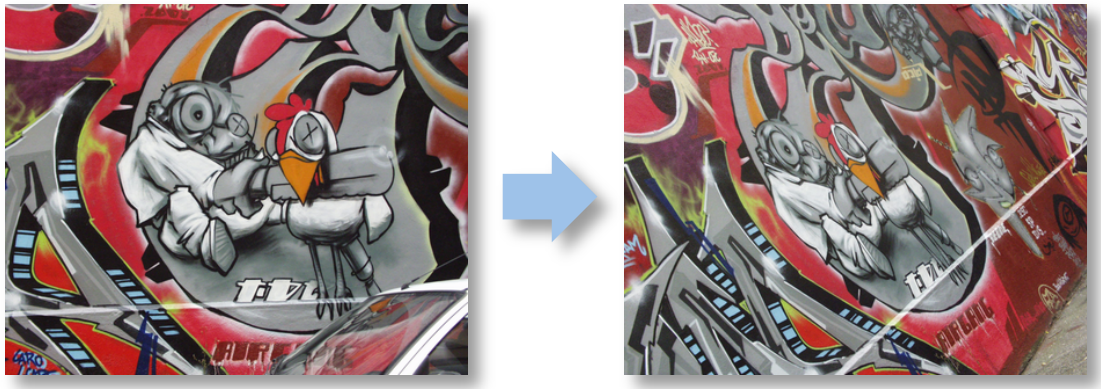
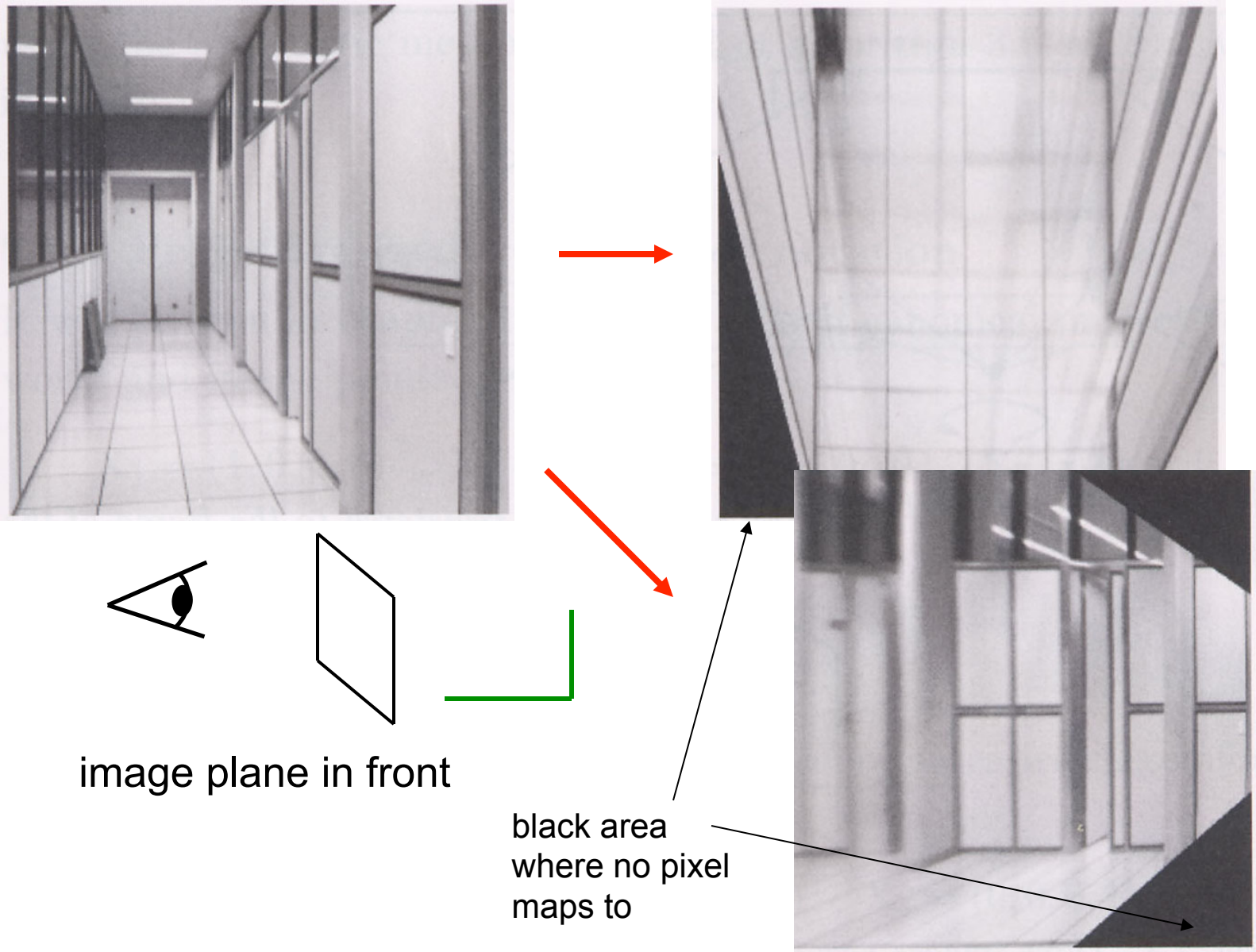


Image warping with homographies



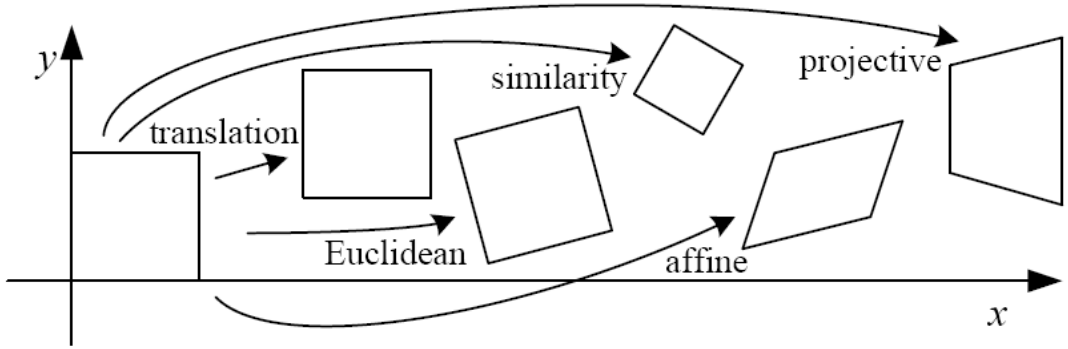
Projective Transformations

- Projective transformations …
  - Affine transformations, and
  - Projective warps

$$\begin{bmatrix} x' \\ y' \\ w' \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \begin{bmatrix} x \\ y \\ w \end{bmatrix}$$

- Properties of projective transformations:
  - Origin does not necessarily map to origin
  - Lines map to lines
  - Parallel lines do not necessarily remain parallel
  - Ratios are not preserved
  - Closed under composition

2D image transformations



Name	Matrix	# D.O.F.	Preserves:	Icon
translation	$\begin{bmatrix} \boldsymbol{I} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	2	orientation $+\cdots$	
rigid (Euclidean)	$\begin{bmatrix} \boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	3	lengths $+\cdots$	
similarity	$\begin{bmatrix} s\boldsymbol{R} \mid \boldsymbol{t} \end{bmatrix}_{2\times 3}$	4	angles $+\cdots$	
affine	$\begin{bmatrix} \boldsymbol{A} \end{bmatrix}_{2\times 3}$	6	parallelism $+\cdots$	
projective	$\begin{bmatrix} \tilde{\boldsymbol{H}} \end{bmatrix}_{3\times 3}$	8	straight lines	

These transformations are a nested set of groups

- Closed under composition and inverse is a member

Outline for Today

- What is a digital image?
- What is a pin-hole camera?
- Lens & optics
- Geometric transformation
- Accidental camera

Accidental Camera

http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0083325

The Great Torralba

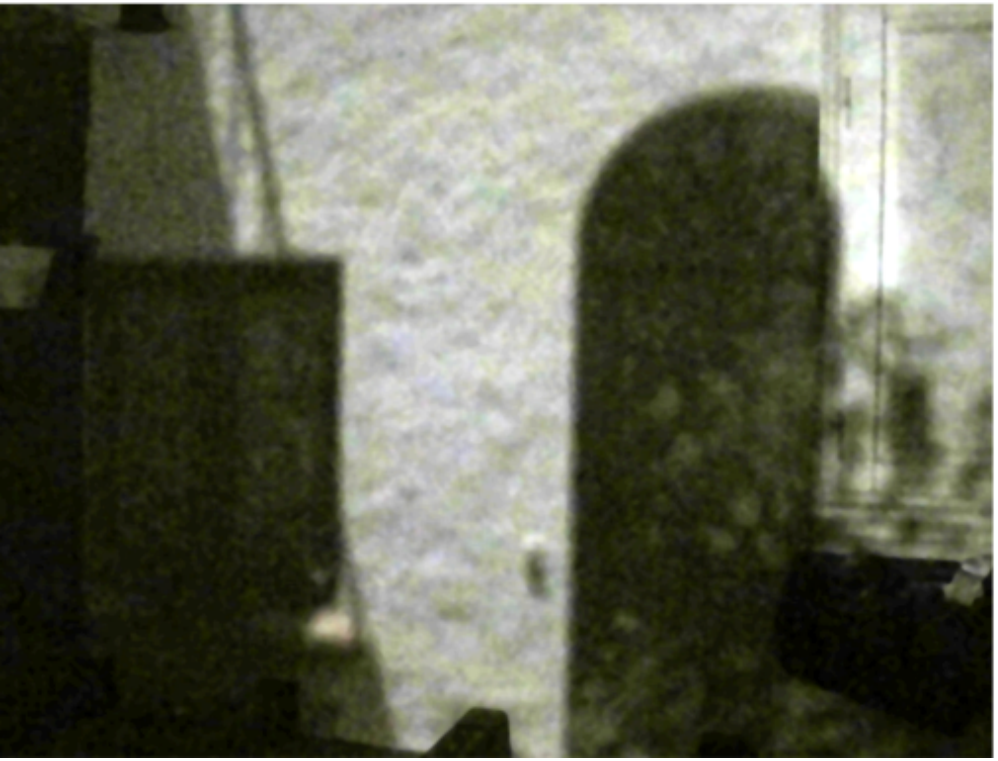
http://techtalks.tv/beta/talks/accidental-pinhole-and-pinspeck-cameras-revealing-the-scene-outside-the-picture/56216/


Shadows?


SALA
CHANCA

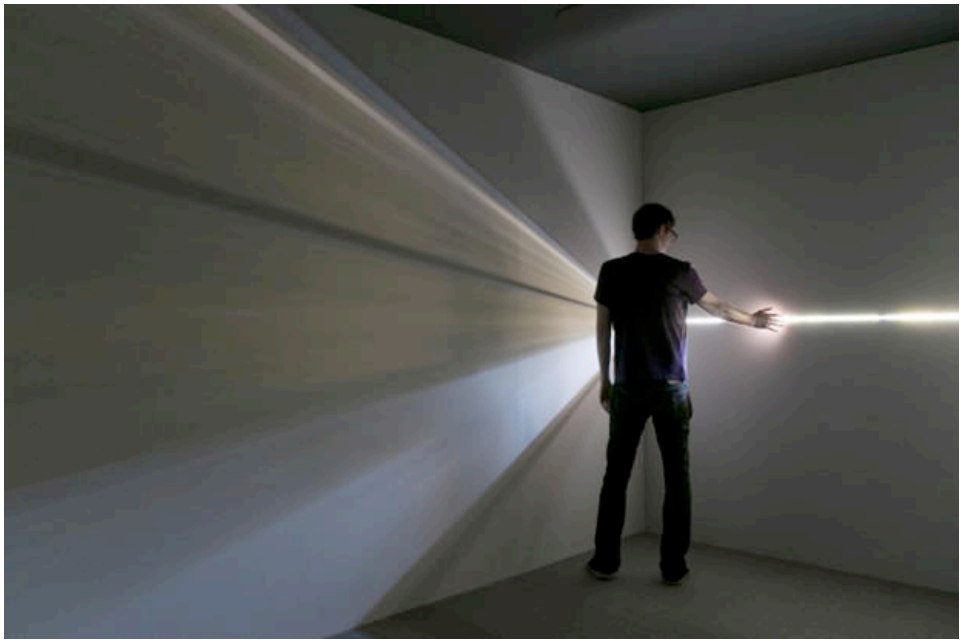
Accidental pinhole camera

Window turned into a pinhole



View outside

Source: wikipedia



Chris Fraser

”a camera obscura has been used ... to bring images from the outside into a darkened room”

Aberlado Morell

Window open

Window turned into a pinhole

Making a pinhole with home materials

Making a pinhole with home materials

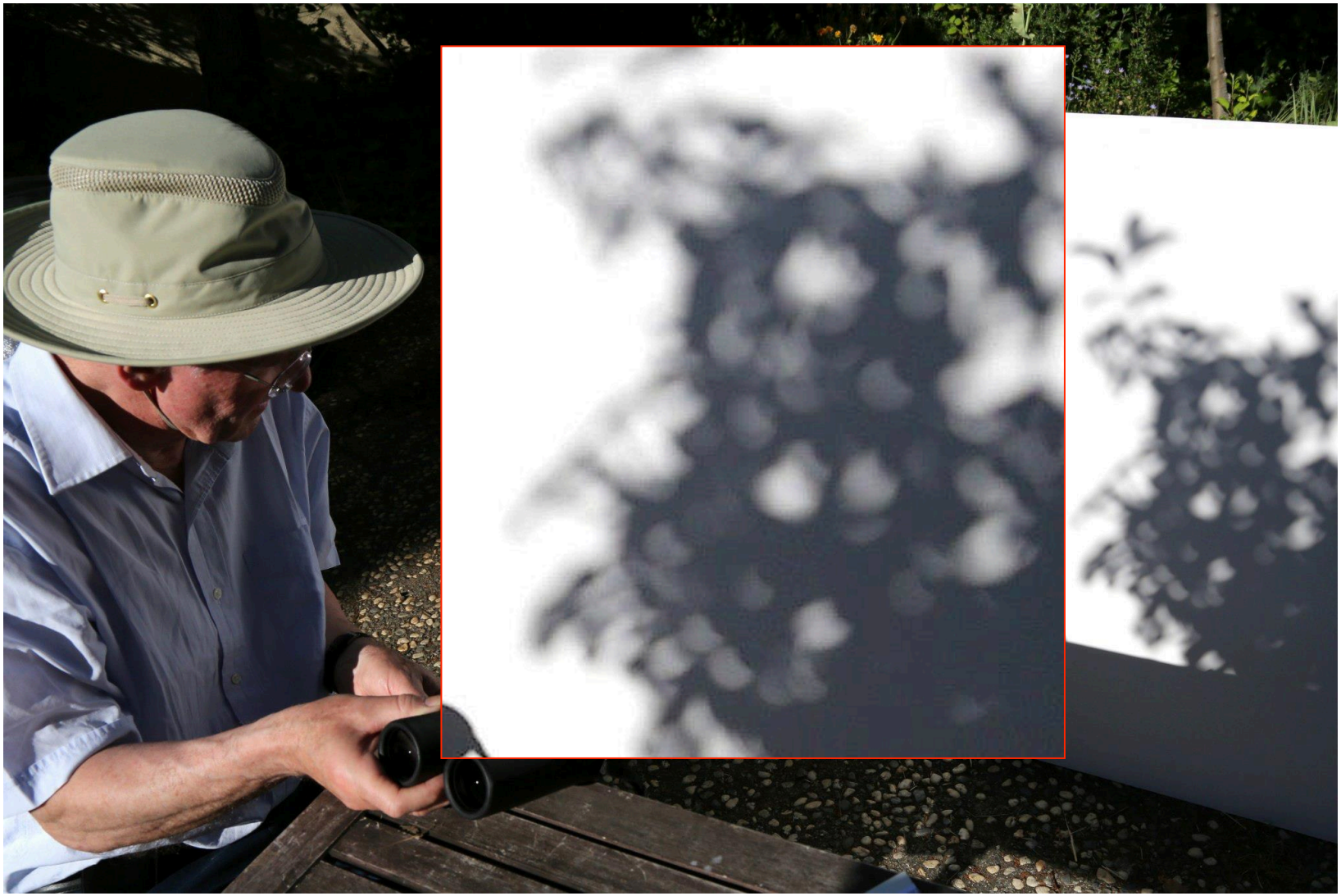
An hotel room,
contrast enhanced.

The view from my window

Accidental pinholes produce images that are unnoticed or misinterpreted as shadows

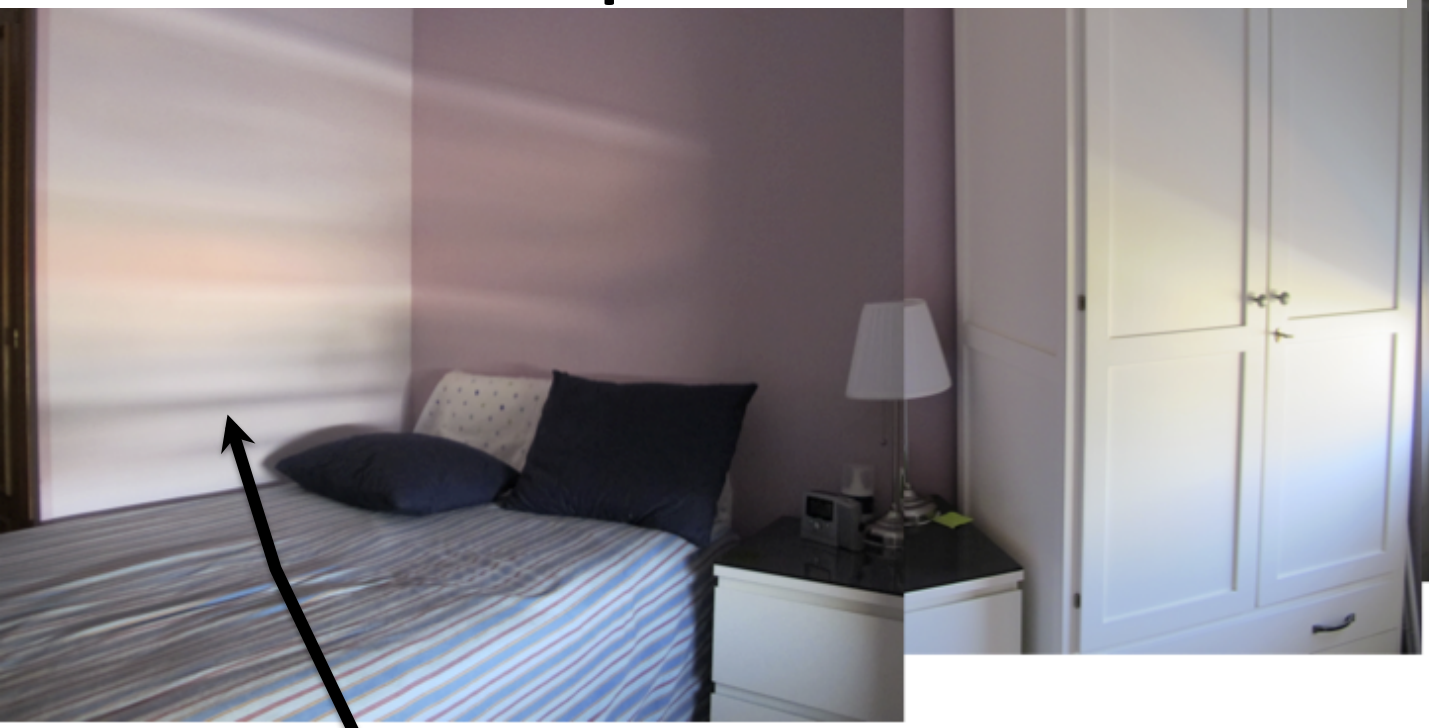
Another hotel room

Accidental pinholes in outdoor scenes



Pierre Moreels father (source: facebook)

Accidental pinhole camera

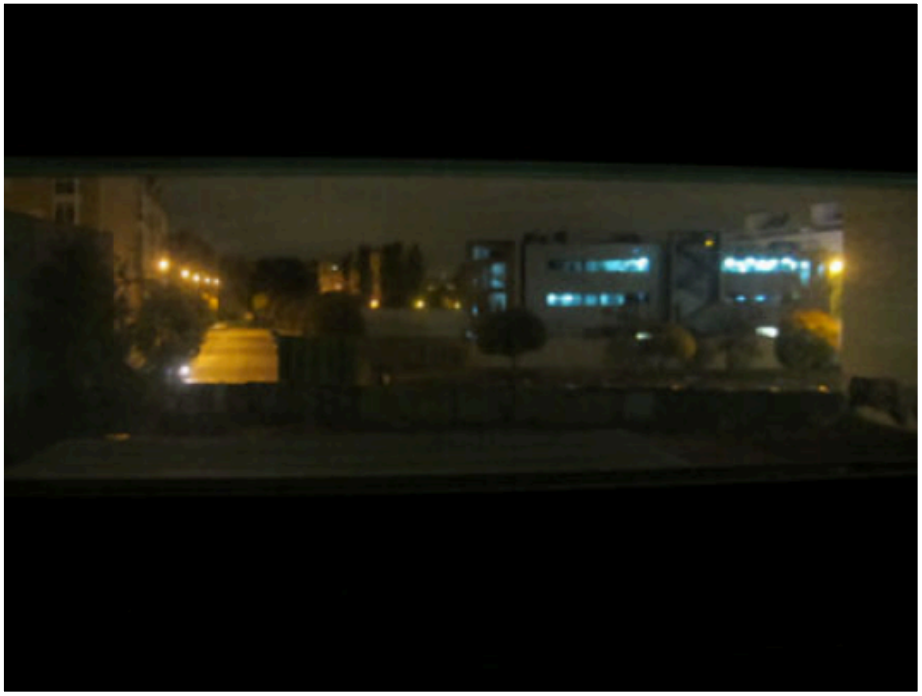


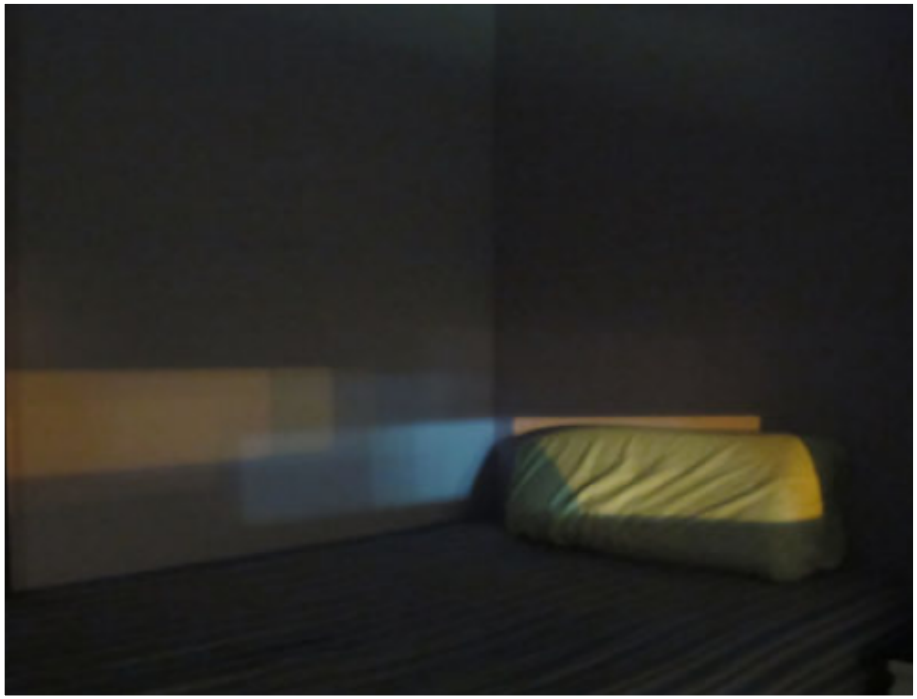
Outside scene

*

Aperture

See Zomet, A.; Nayar, S.K. CVPR 2006 for a detailed analysis.





Anti-pinhole or Pinspeck cameras

Anti-pinhole or Pinspeck cameras

Adam L. Cohen, 1982

OPTICA ACTA, 1982, VOL. 29, NO. 1, 63–67

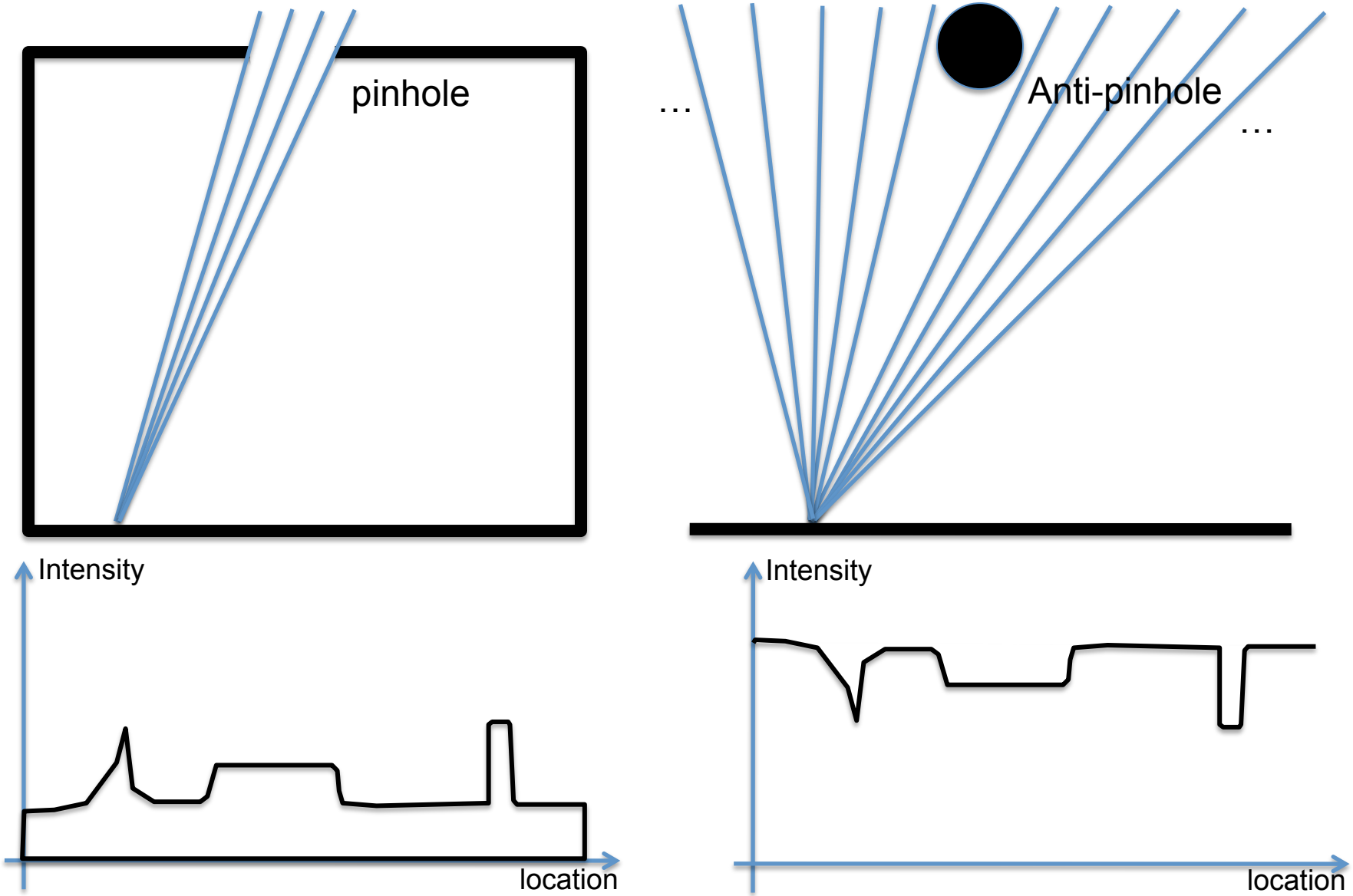
Anti-pinhole imaging

ADAM LLOYD COHEN
Parmly Research Institute, Loyola University of Chicago,
Chicago, Illinois 60626, U.S.A.

(*Received 16 April 1981; revision received 8 July 1981*)

Abstract. By complementing a pinhole to produce an isolated opaque spot, the light ordinarily blocked from the pinhole image is transmitted, and the light ordinarily transmitted is blocked. A negative geometrical image is formed, distinct from the familiar 'bright-spot' diffraction image. Anti-pinhole, or 'pinspeck' images are visible during a solar eclipse, when the shadows of objects appear crescent-shaped. Pinspecks demonstrate unlimited depth of field, freedom from distortion and large angular field. Images of different magnification may be formed simultaneously. Contrast is poor, but is improvable by averaging to remove noise and subtraction of a d.c. bias. Pinspecks may have application in X-ray space optics, and might be employed in the eyes of simple organisms.

Pinhole and Anti-pinhole cameras



Adam L. Cohen, 1982

Natural eyes

Lenses

Pinholes

Anti-pinholes

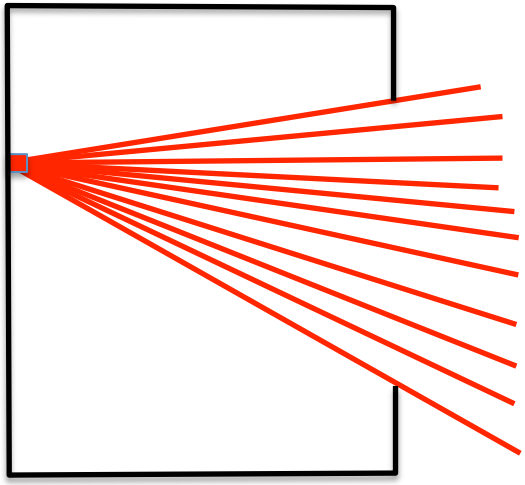
Mixed accidental pinhole and anti-pinhole cameras

Mixed accidental pinhole and anti-pinhole cameras

Mixed accidental pinhole and anti-pinhole cameras

Mixed accidental pinhole and anti-pinhole cameras

Room with a window



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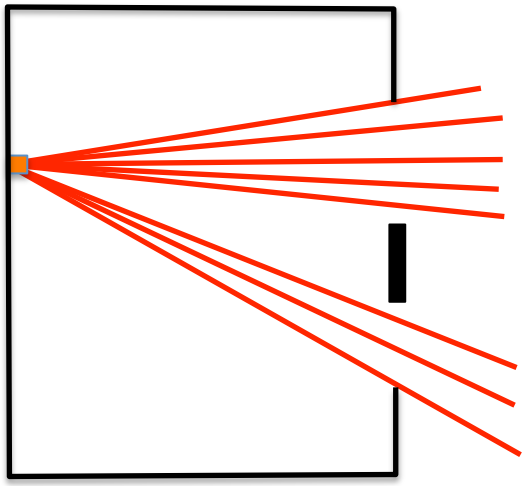
Person in front of the window



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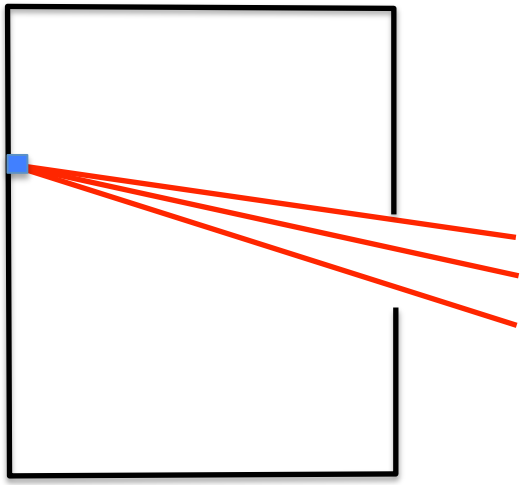
Difference image



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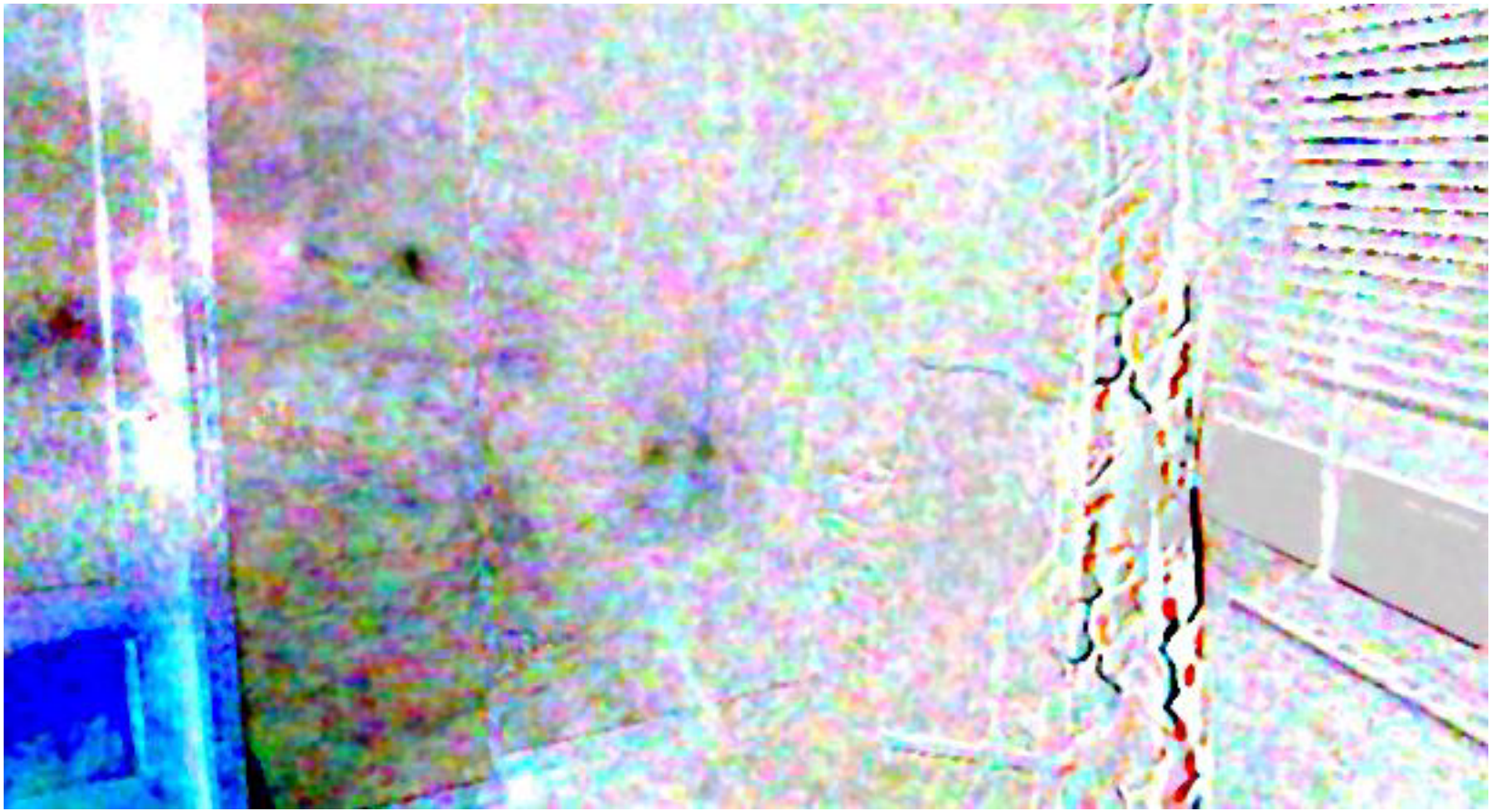
Mixed accidental pinhole and anti-pinhole cameras

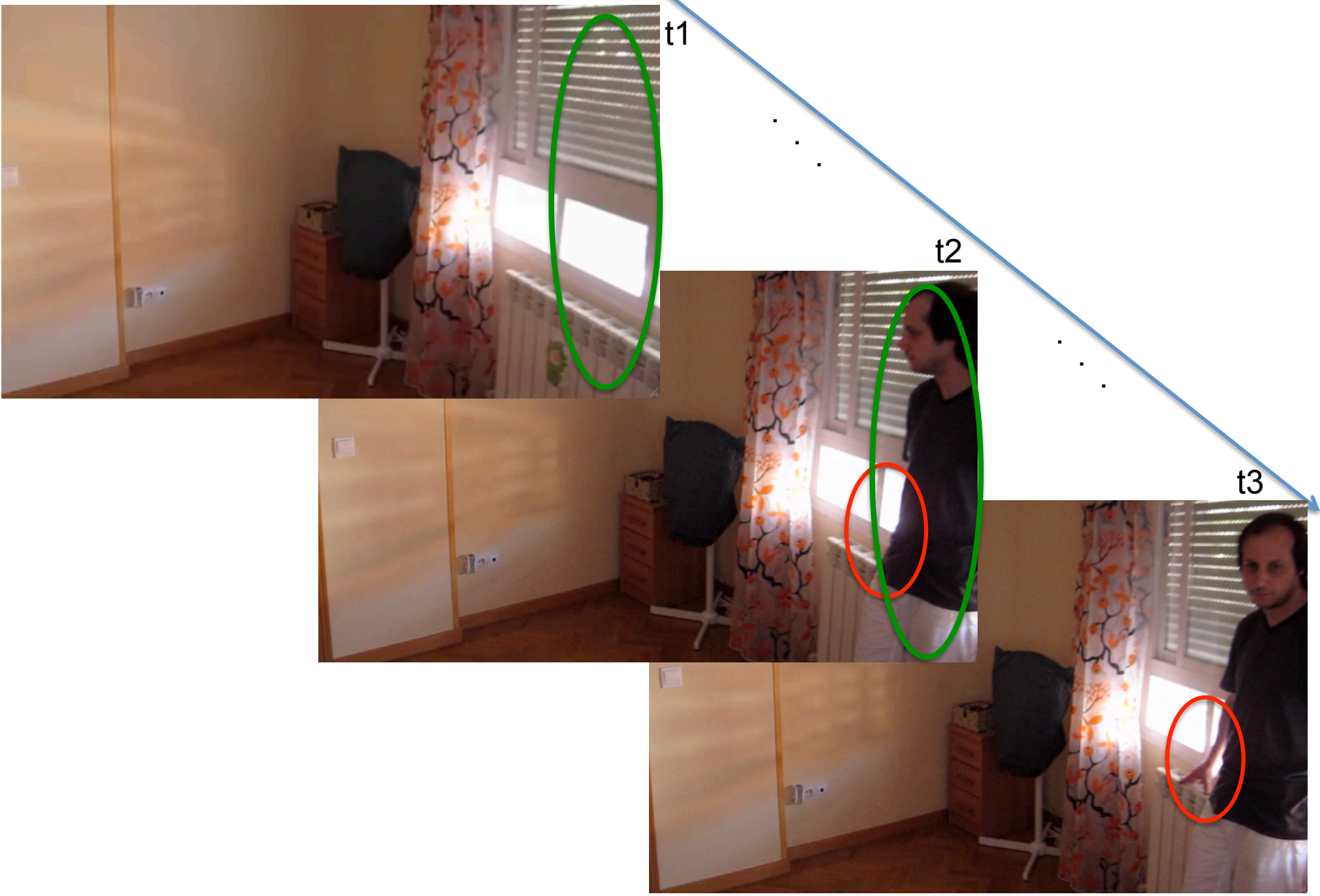


Mixed accidental pinhole and anti-pinhole cameras

Body as the occluder

View outside the window

Looking for a small accidental occluder



Reference

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Video

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Looking for a small accidental occluder

Body as the occluder

Hand as the occluder

View outside the window

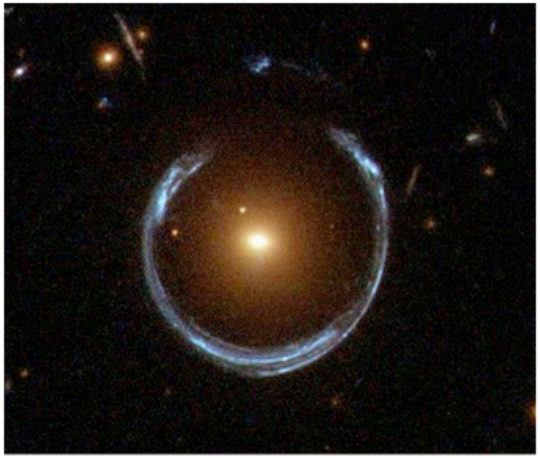
Accidental cameras reveal parts of the scene not directly visible

Mirrors

Nishino and Nayar, IJCV 2006

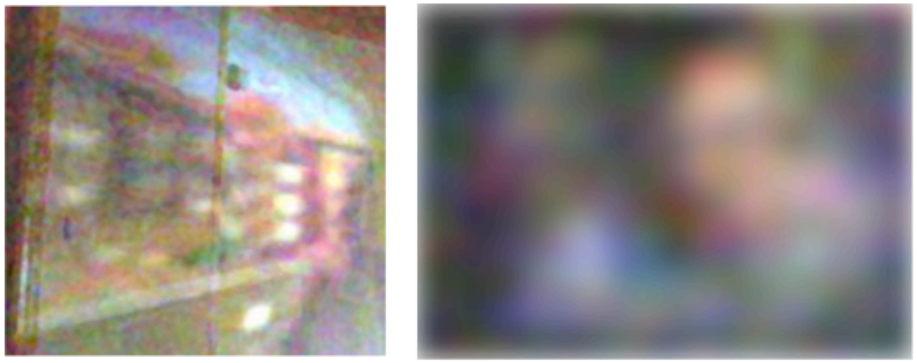
Pinholes

Lenses



Gravitational lensing

Anti-pinholes



Applications

- Computer graphics for better light models
- Image forensics (J. O'Brian & H. Farid, 2012)

Did man actually land on the moon?

Did man actually land on the moon?