BBM 413 Fundamentals of Image Processing

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Image Formation and the Digital Camera

Acknowledgement: The course slides are mostly adapted from the slides prepared by Steve Marschner, James Hays, Ali Farhadi and Anat Levin

Today

- Image formation
- Display devices and digital camera
- Digital images

Today

- Image formation
- Display devices and digital camera
- Digital images

What is an image?

- A photographic print
- A photographic negative
- This projection screen
- Some numbers in RAM

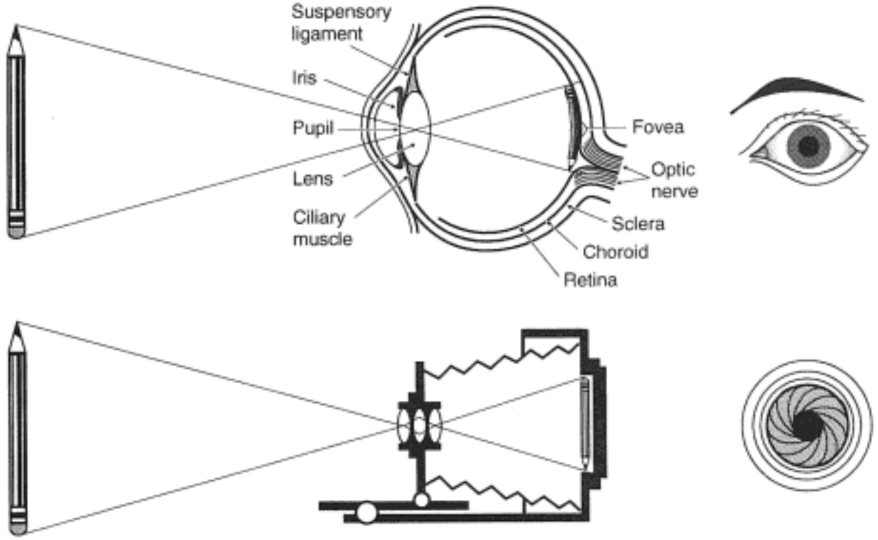
An image is:

- A 2D distribution of intensity or color
- A function defined on a two-dimensional plane

$$I : \mathbb{R}^2 \to \ldots$$

- Note: no mention of pixels yet
- To process images, must:
  - obtain images—capture the scenes via hardware
  - represent images—encode them numerically

Image Formation



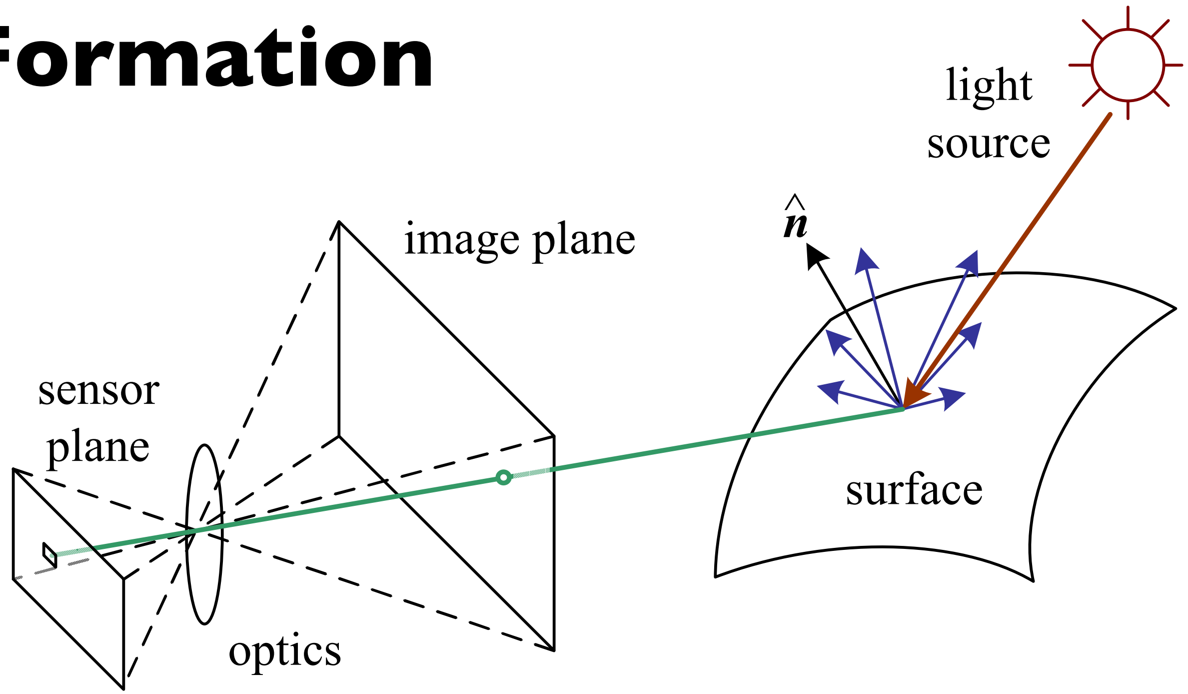
Three Dimensional World ⟶ Two Dimensional Image Space

- What is measured in an image location?
  - brightness
  - color

<< viewpoint, illumination conditions, local geometry, local material properties

Figures: Francis Crick, The Astonishing Hypothesis,

Image Formation



Three Dimensional World ⟶ Two Dimensional Image Space

- What is measured in an image location?
  - brightness
  - color

<< viewpoint
illumination conditions
surface properties
(local geometry and local material properties)

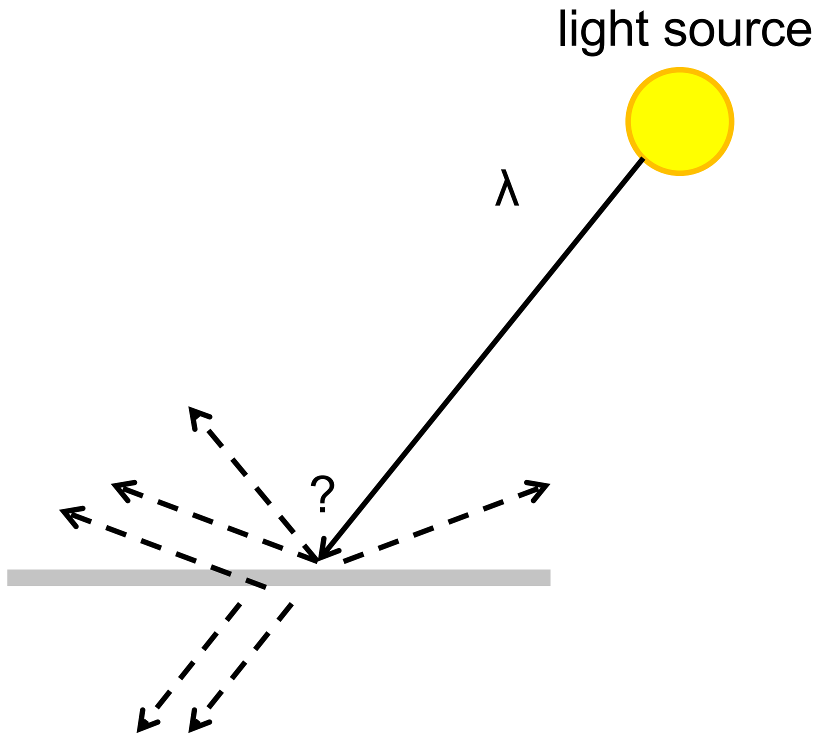
Figures: Francis Crick, The Astonishing Hypothesis,


Slide source: Seitz
MAKE POVERTY HISTORY
JULIAN BEEVER
CoolOpticalIllusions.com


Slide source: Seitz
CoolOpticalIllusions.com

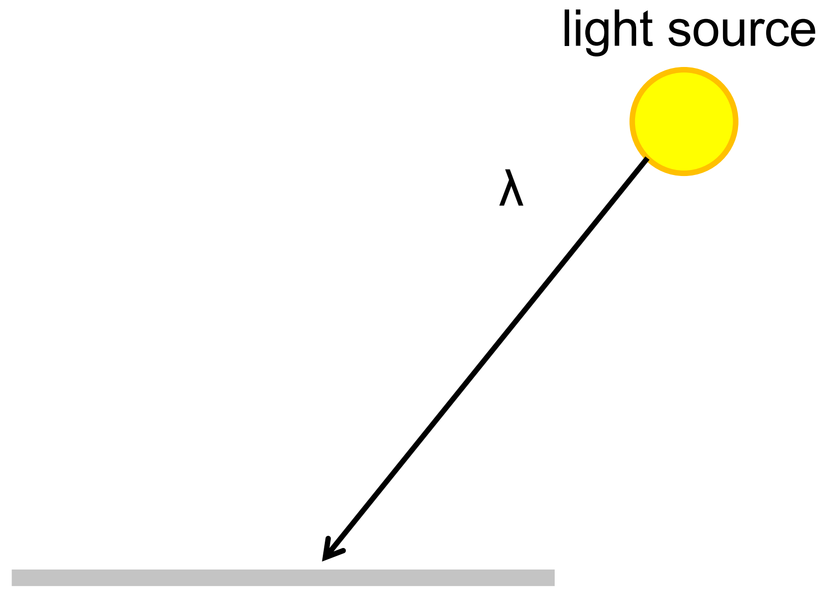
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



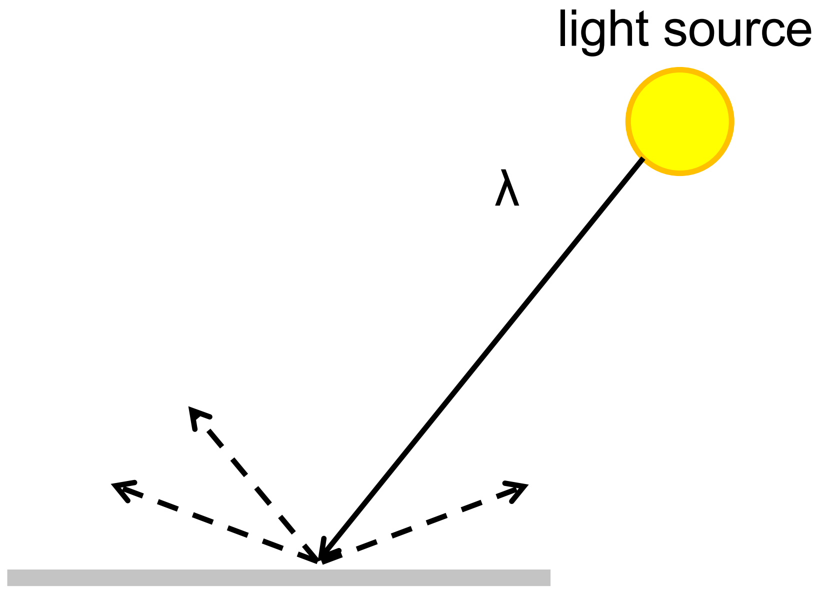
A photon's life choices

- **Absorption**
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



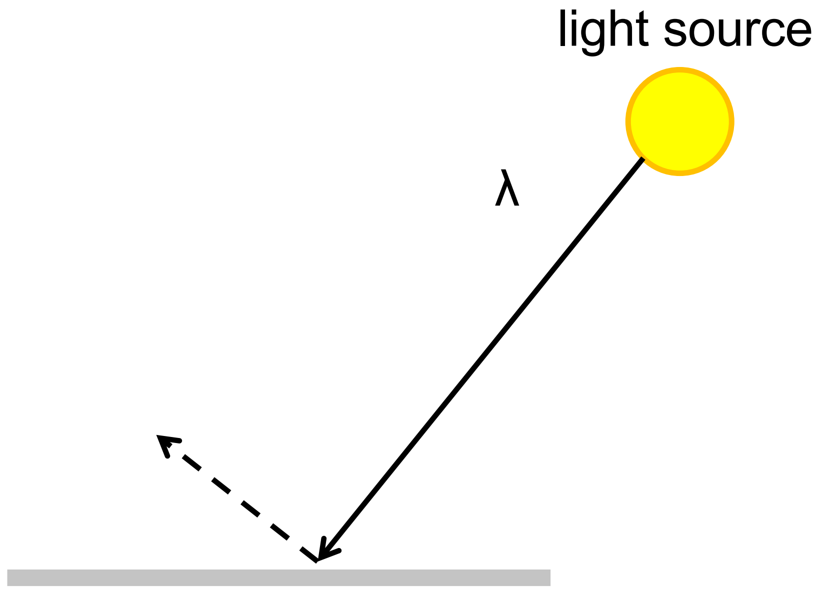
A photon's life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



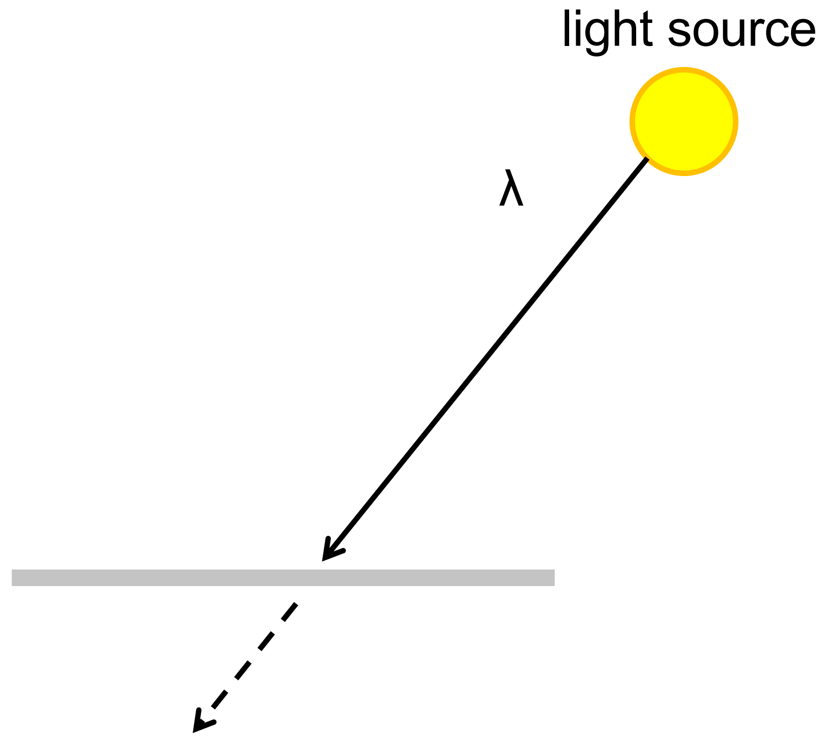
A photon's life choices

- Absorption
- Diffusion
- **Specular Reflection**
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



A photon's life choices

- Absorption
- Diffusion
- Reflection
- **Transparency**
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



A photon's life choices

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- Transparency
- **Refraction**
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- Phosphorescence
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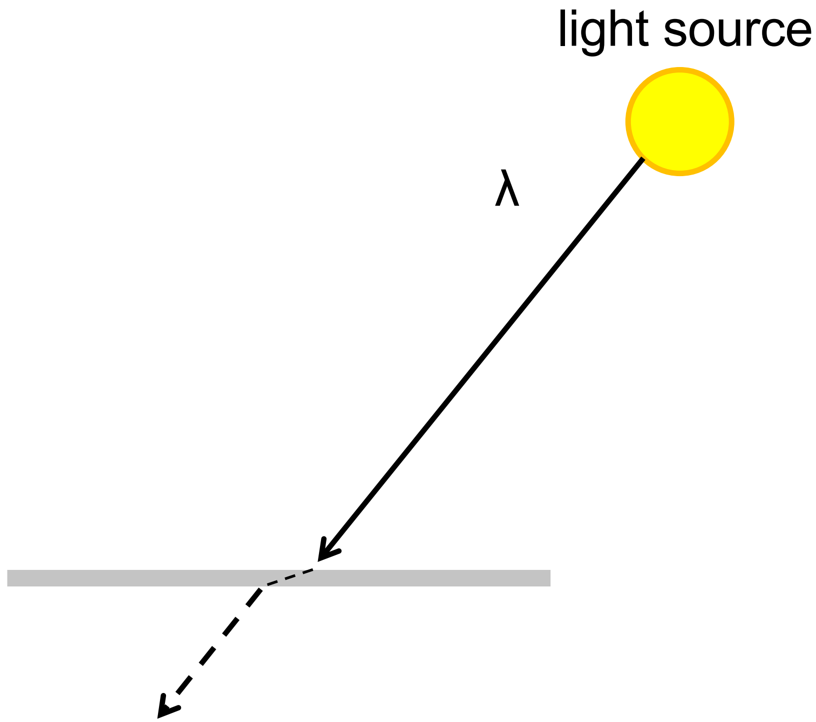

A photon's life choices

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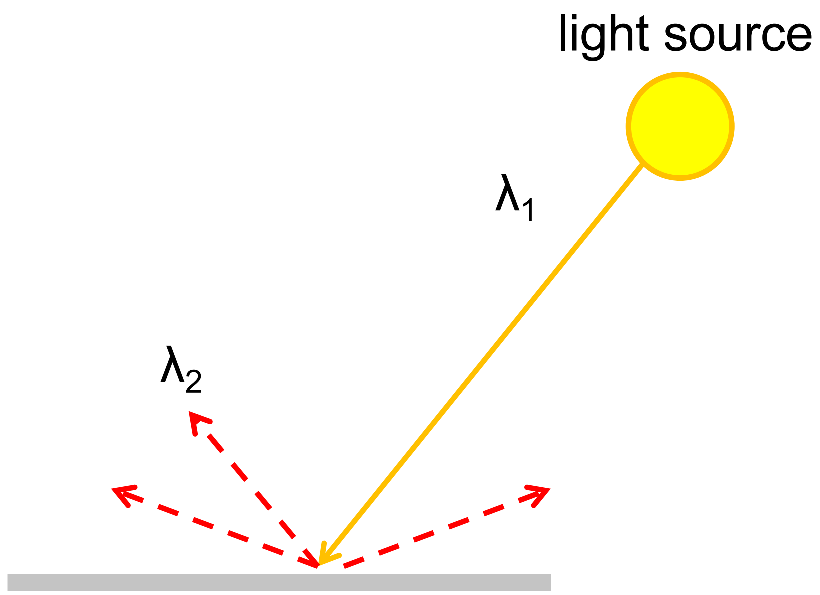

A photon's life choices

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- **Subsurface scattering**
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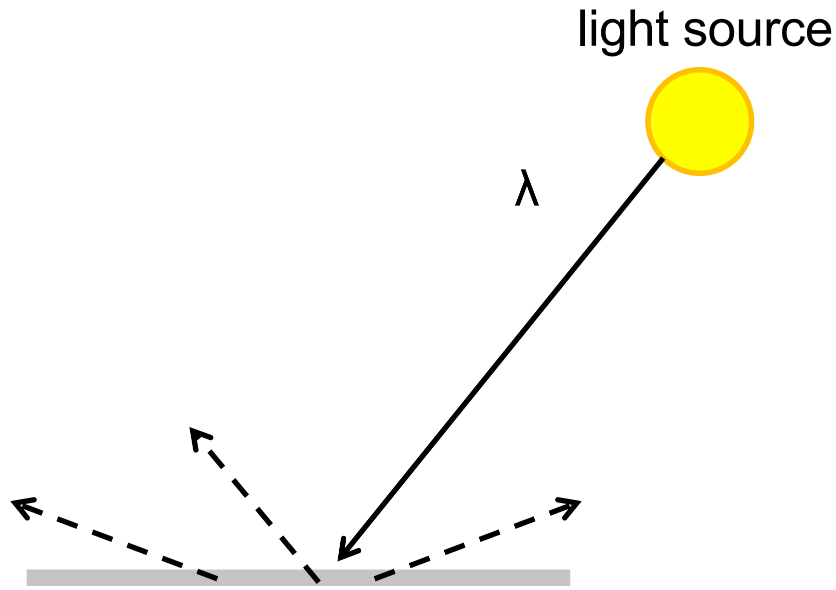

A photon's life choices

- Absorption
- Diffusion
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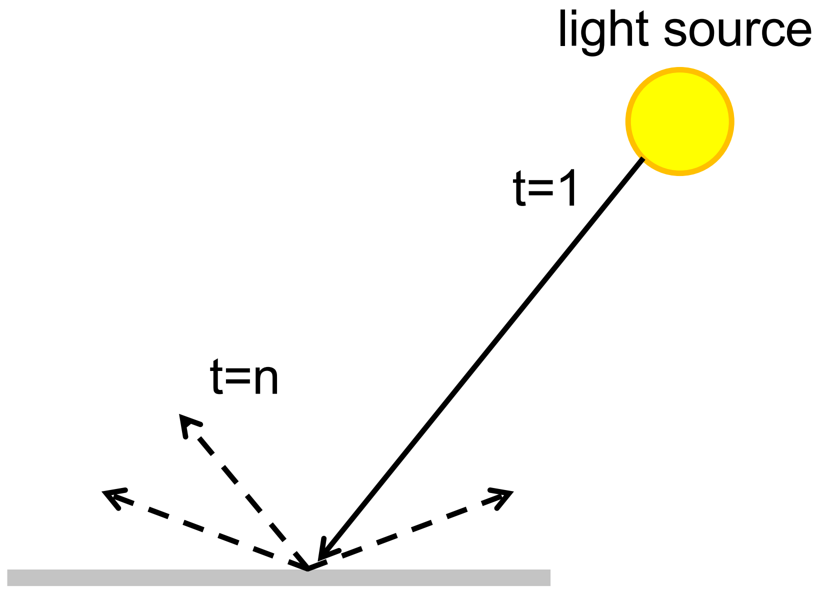
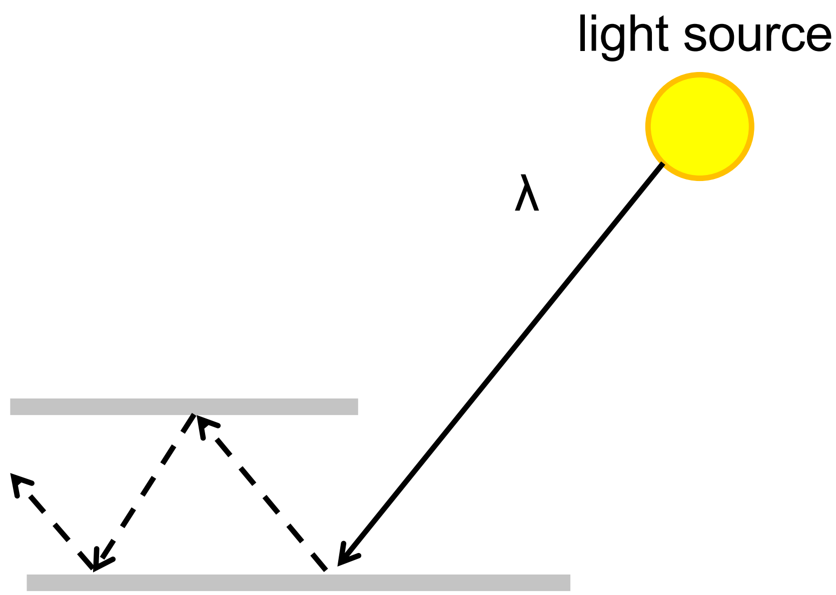
- **Phosphorescence**
- Interreflection



A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- **Interreflection**



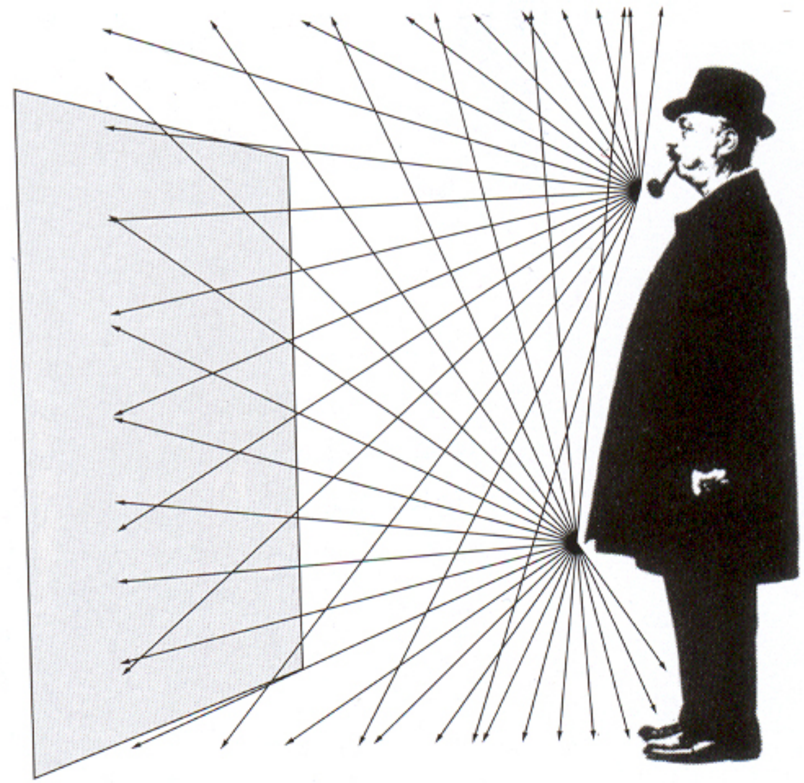
(Specular Interreflection)

Image Formation

Images cannot exist without light!

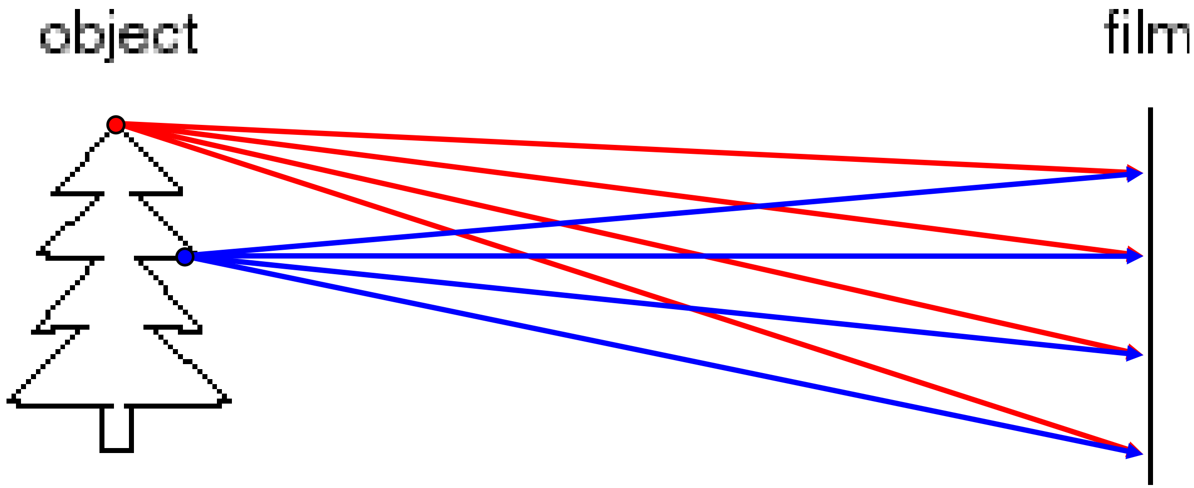
Why is there no image on a white piece of paper?

It receives light from all directions



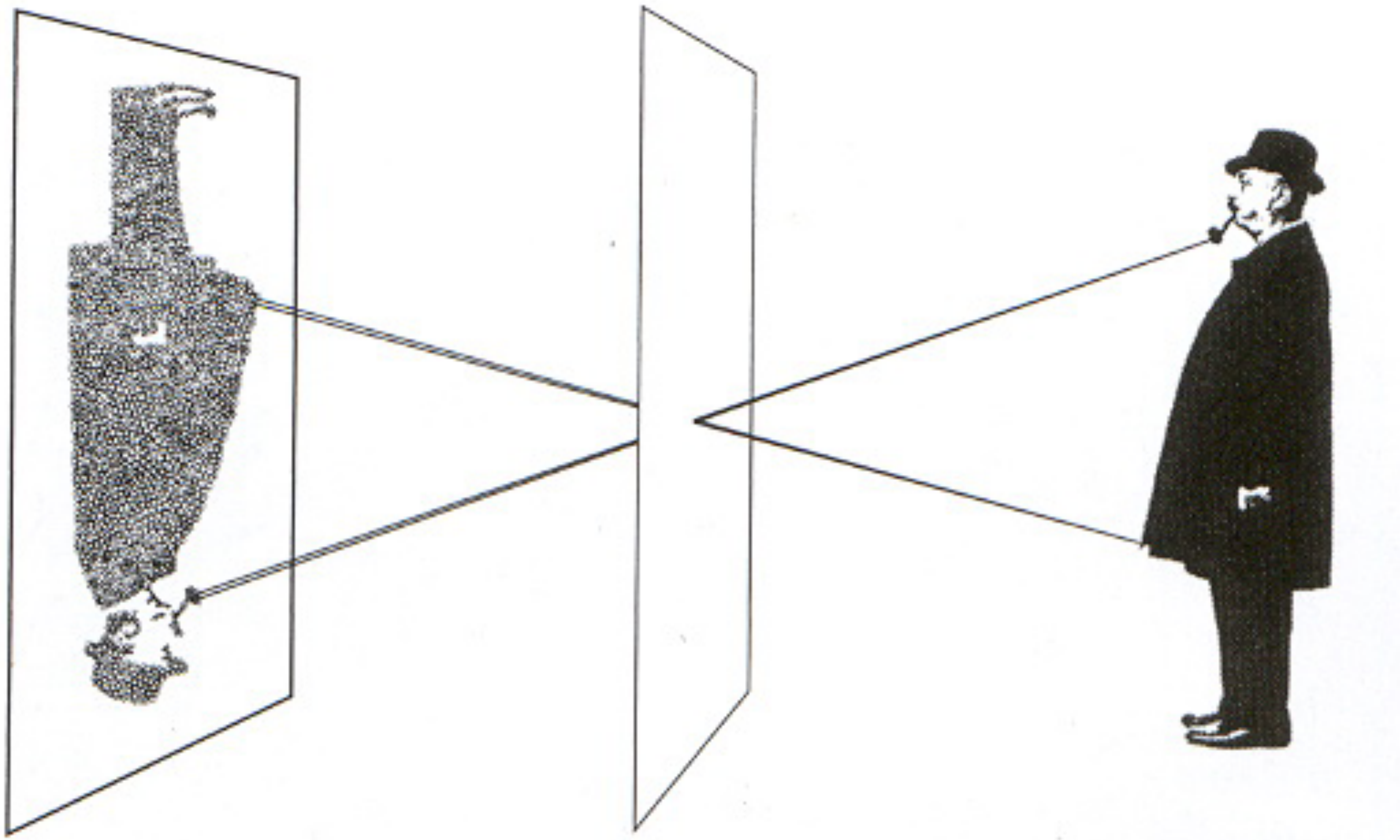
From Photography, London et al.

Image Formation



- Let's design a camera
  - Idea 1: put a piece of film in front of an object
  - Do we get a reasonable image?

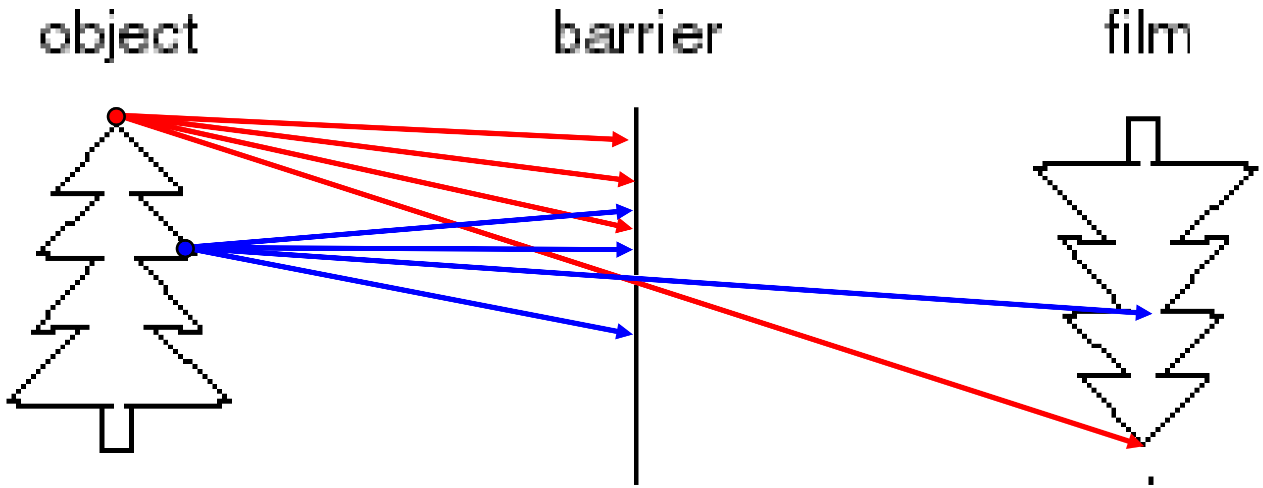
Pinhole camera



A pinhole projects all rays through
a common center of projection.

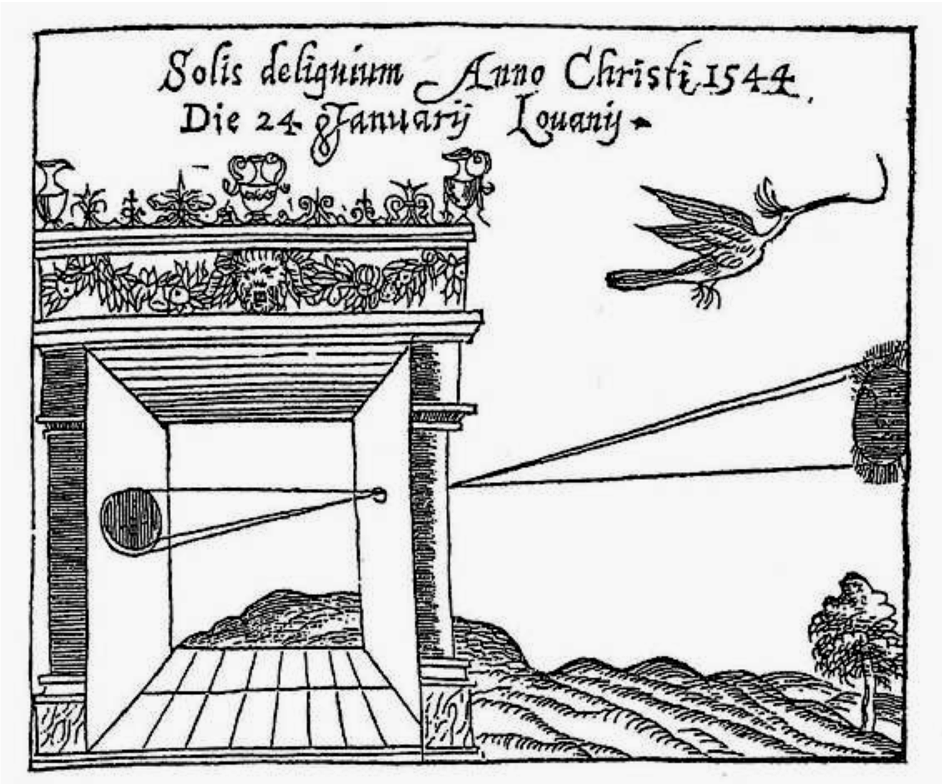
From Photography, London et al.

Pinhole camera



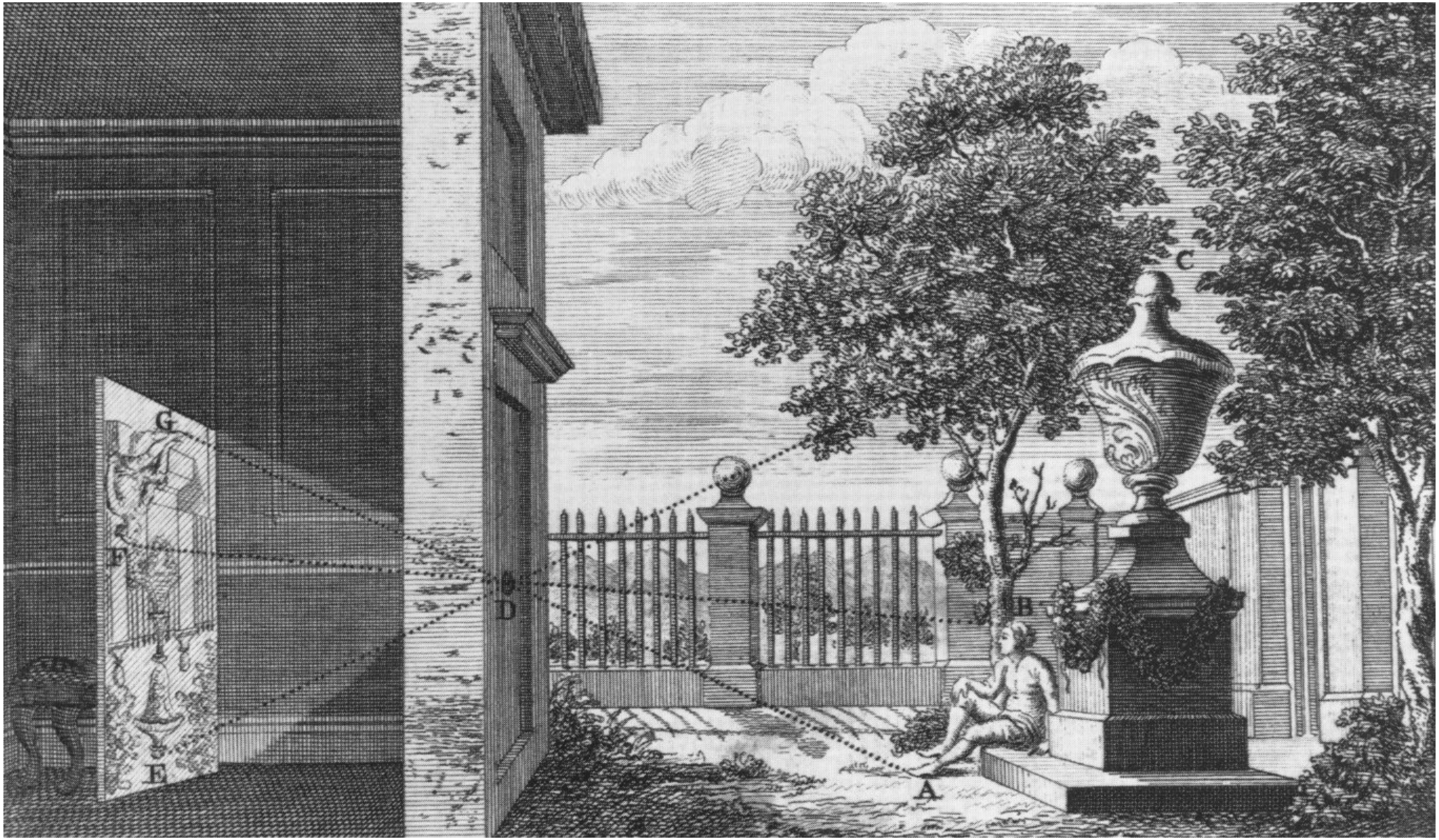
- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening is known as the **aperture**
  - How does this transform the image?

Camera Obscura



- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)

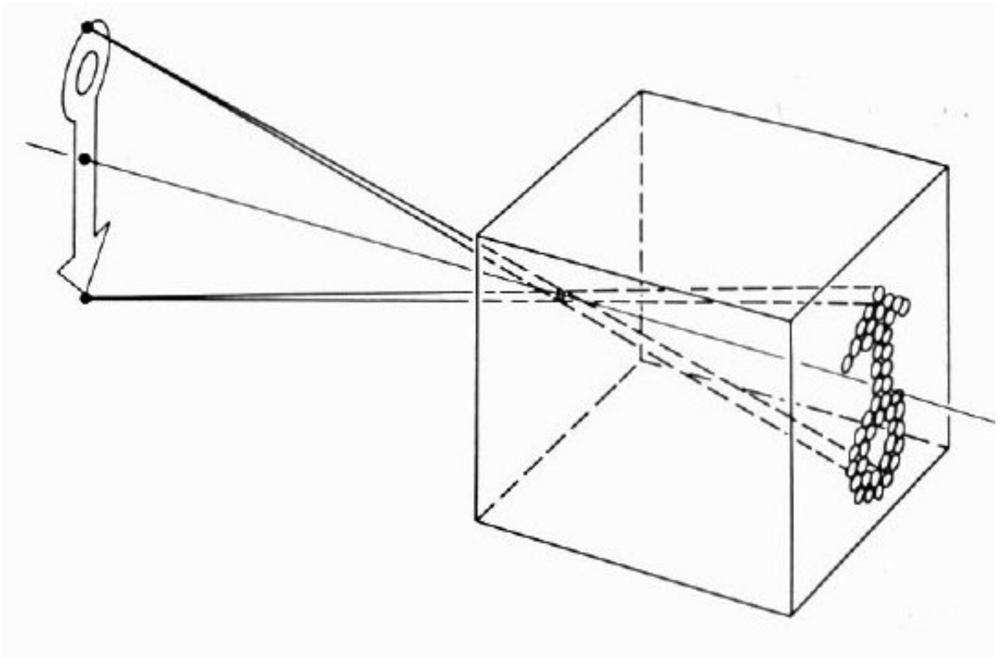
Camera Obscura



Abelardo Morell:
Through the Looking Glass

https://www.youtube.com/watch?v=DTa9wLkaizQ

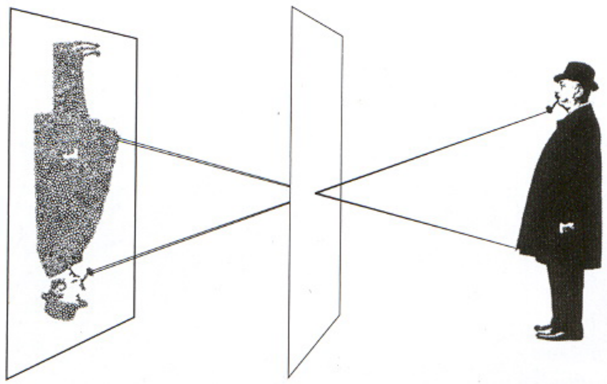
Camera Obscura



- The first camera
  - How does the aperture size affect the image?

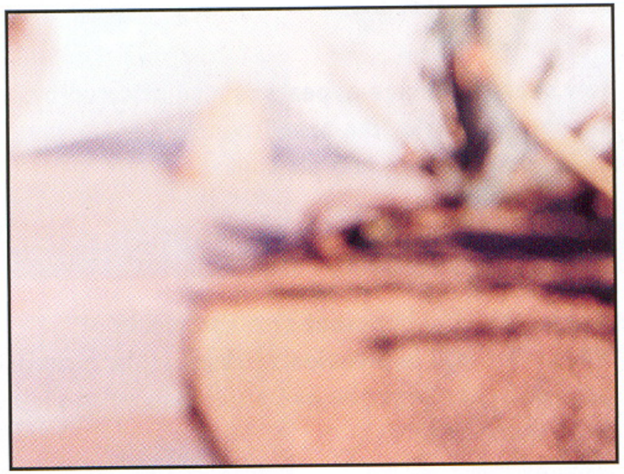
Pinhole Size?

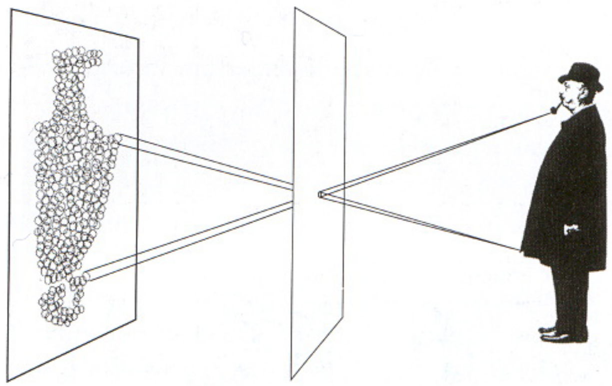
Photograph made with small pinhole



Small pinhole-
sharp but hard to
collect enough light

Photograph made with larger pinhole

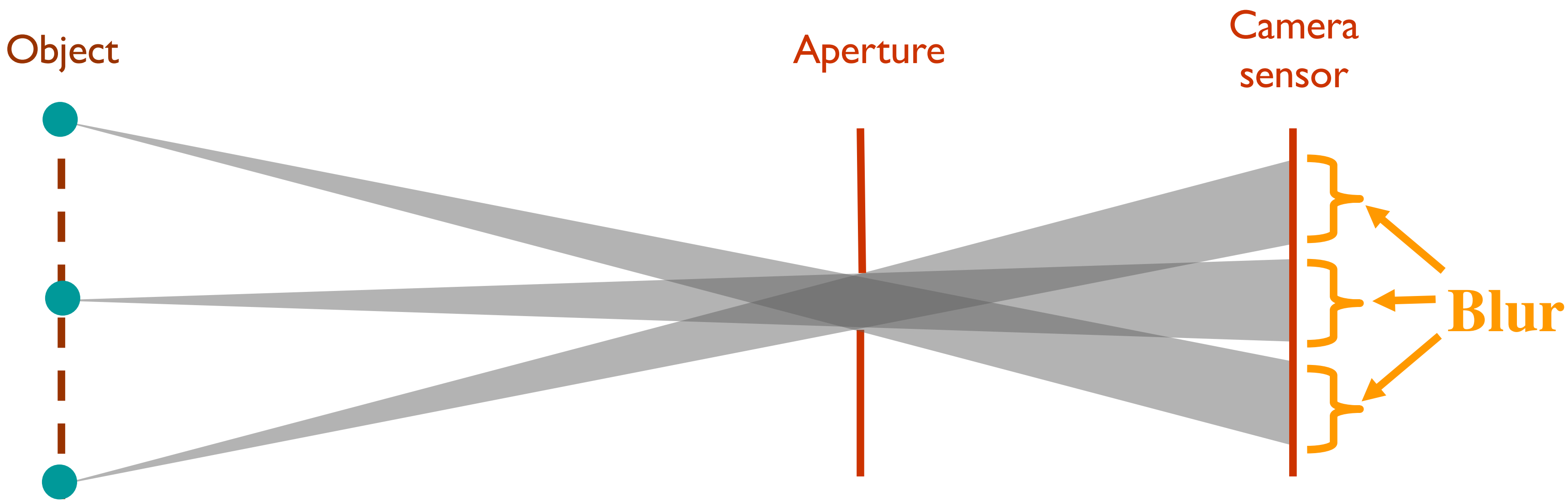




Larger pinhole-
Blur

From Photography, London et al.

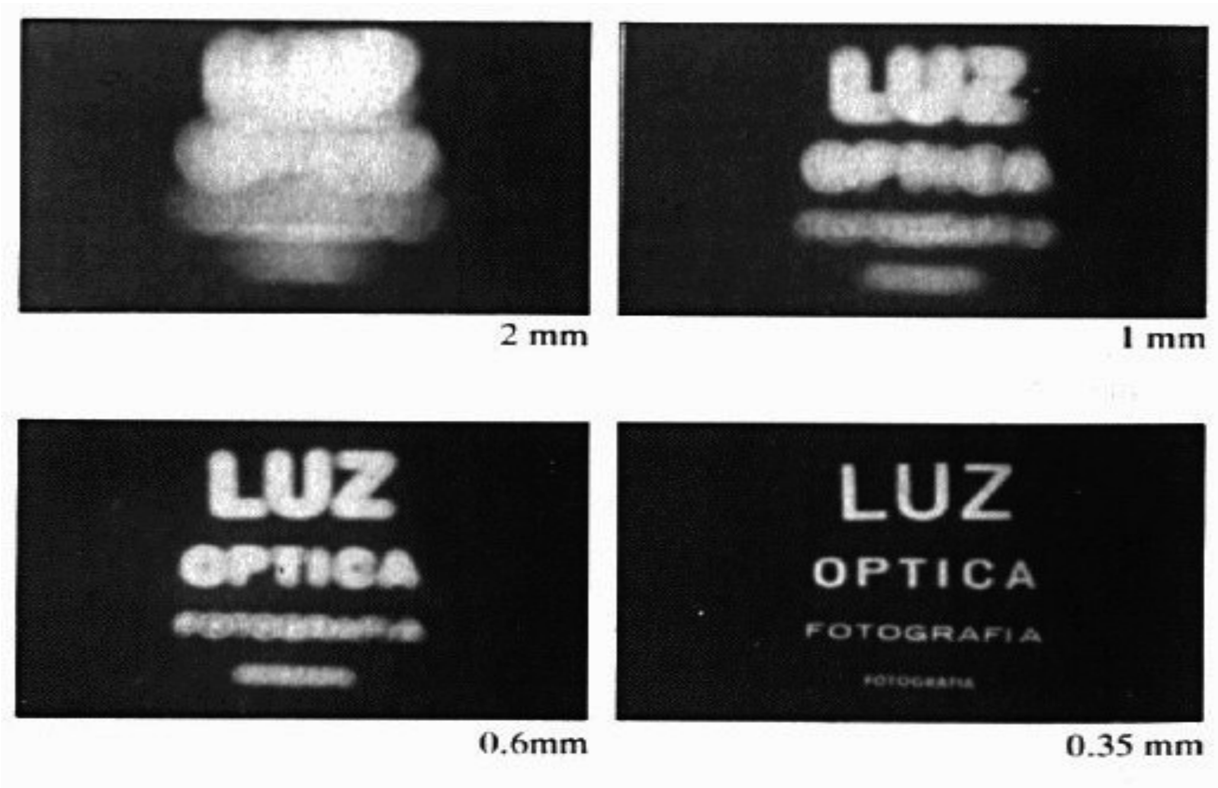
Pinhole Size



small hole => sharp, but doesn't collect enough light (noise)

larger hole => easy to collect enough light, but blur occurs

Pinhole Size



- Why not make the aperture as small as possible?
  - Less light gets through
  - Diffraction effects...

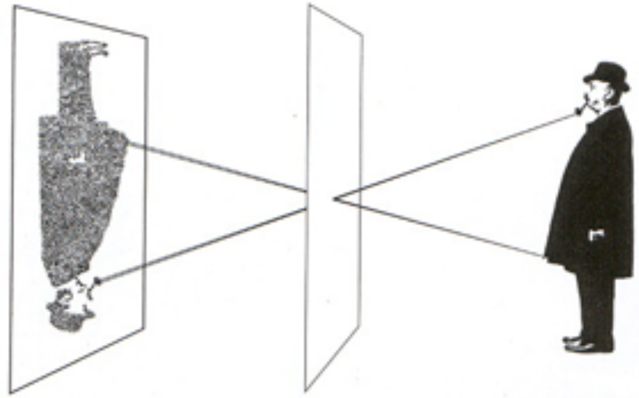
Solution: light refraction!

From Photography, London et al.

Lenses

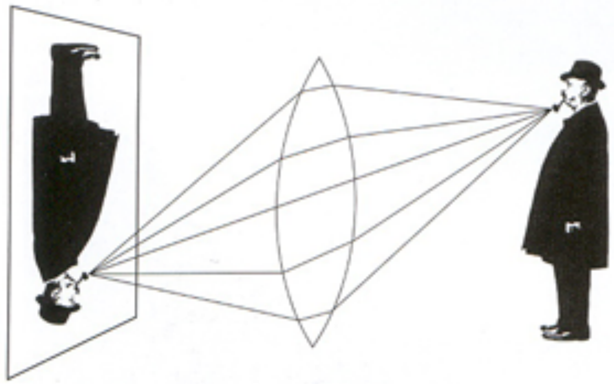
- gather more light!
- But need to be focused

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

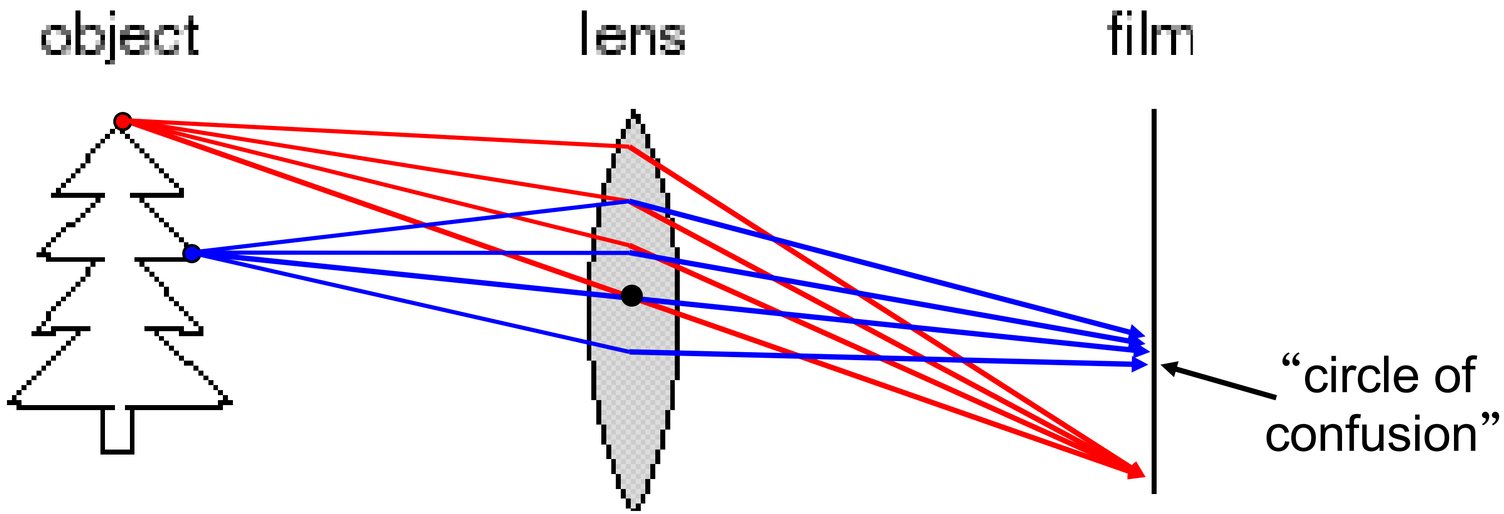


This time, using a simple convex lens with an f/16 aperture, *the scene appeared sharper than the one taken with the smaller pinhole, and the exposure time was much shorter, only 1/100 sec.*

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.

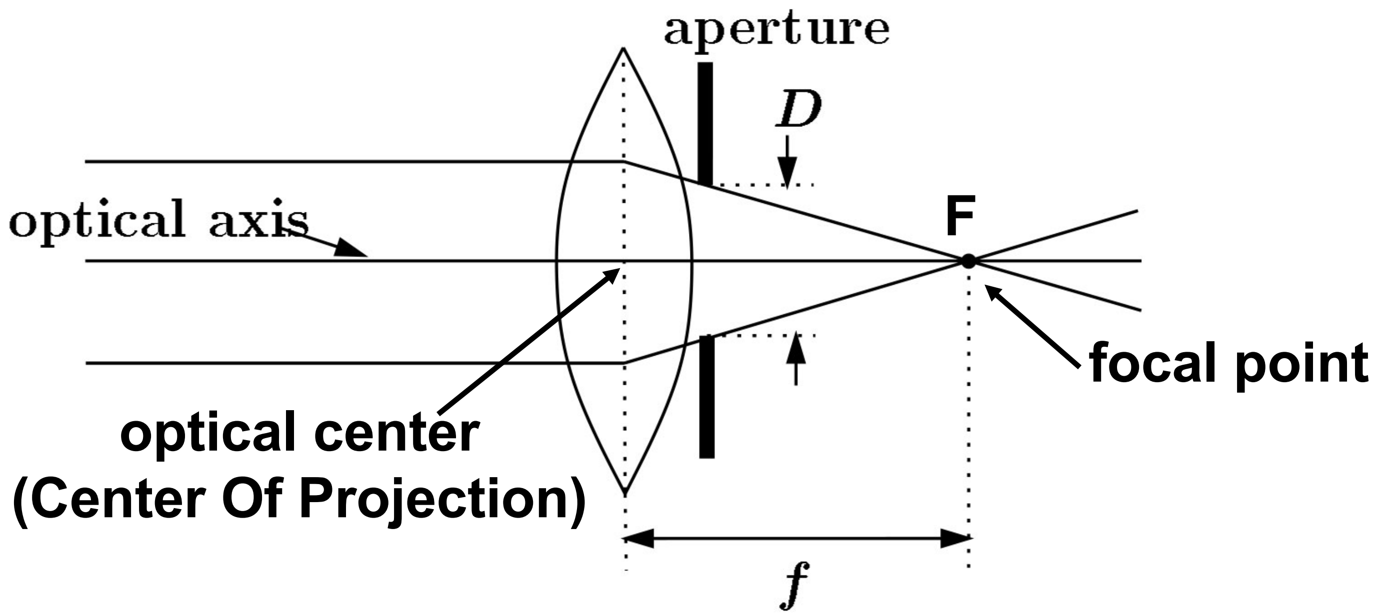
From Photography, London et al.

Adding a lens



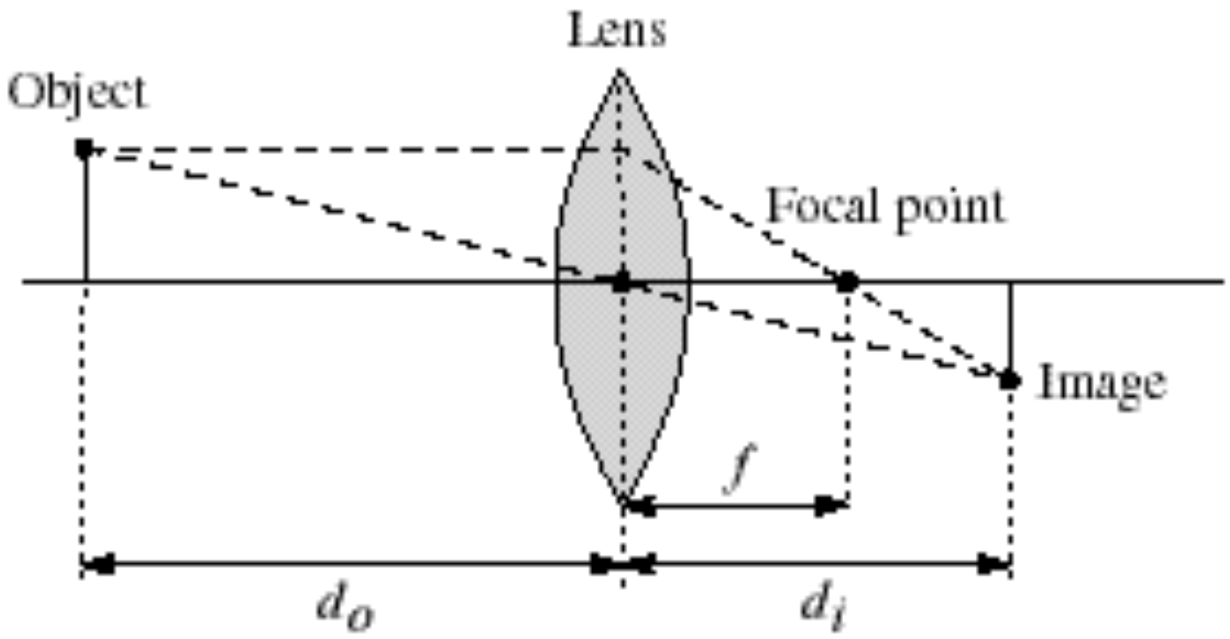
- A lens focuses light onto the film
  - There is a specific distance at which objects are "in focus"
    - other points project to a "circle of confusion" in the image
  - Changing the shape of the lens changes this distance

Lenses



- A lens focuses parallel rays onto a single focal point
  - focal point at a distance *f* beyond the plane of the lens
    - *f* is a function of the shape and index of refraction of the lens
  - Aperture of diameter D restricts the range of rays
    - aperture may be on either side of the lens
  - Lenses are typically spherical (easier to produce)
  - Real cameras use many lenses together (to correct for aberrations)

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?

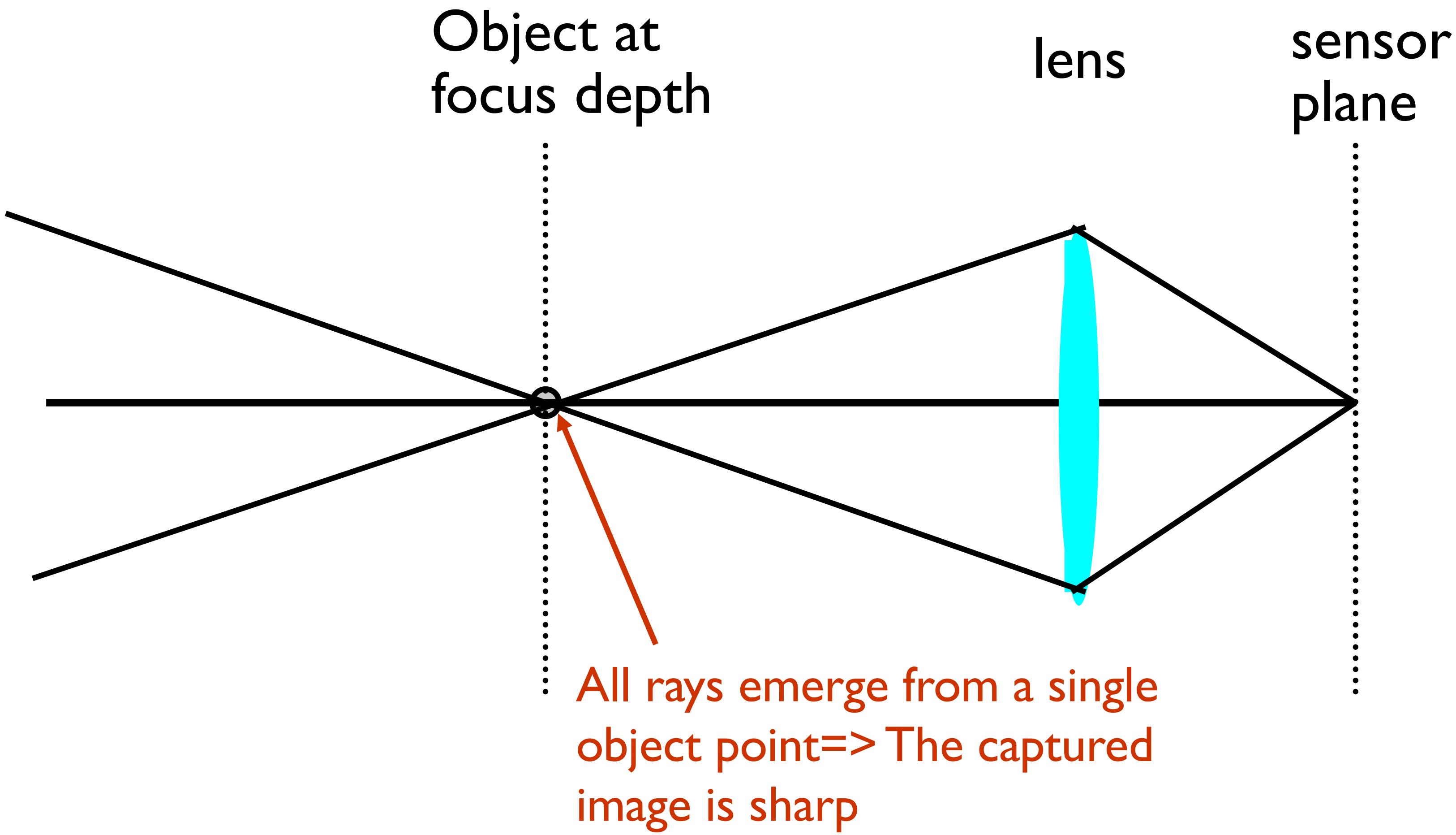
A lens is focused at a single depth

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$$

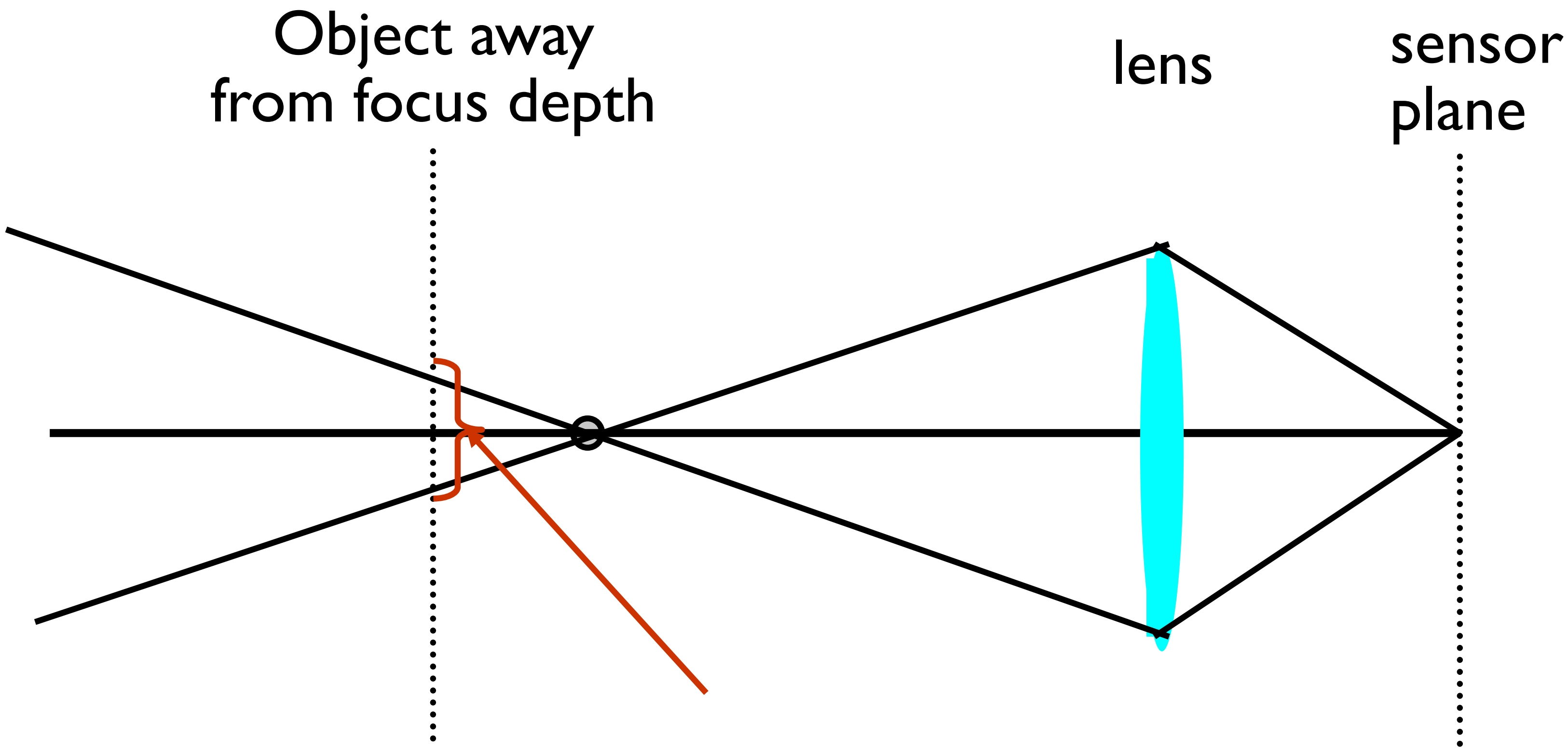
z_0: distance to the (focused) object

z_i: distance behind the lens at which the image is formed

f: focal length



A lens is focused at a single depth



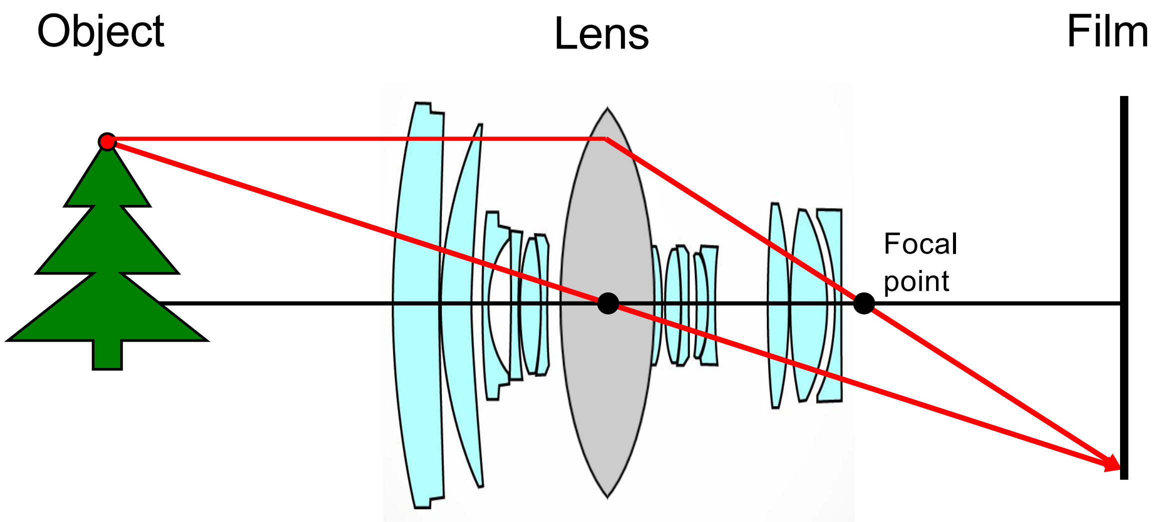
Rays emerge from multiple object points
(circle of confusion) => the captured image is blurred

A lens is focused at a single depth

$$\frac{1}{z_o} + \frac{1}{z_i} = \frac{1}{f}$$

Thin lens assumption

The thin lens assumption assumes the lens has no thickness, but this isn't true…



By adding more elements to the lens, the distance at which a scene is in focus can be made roughly planar.

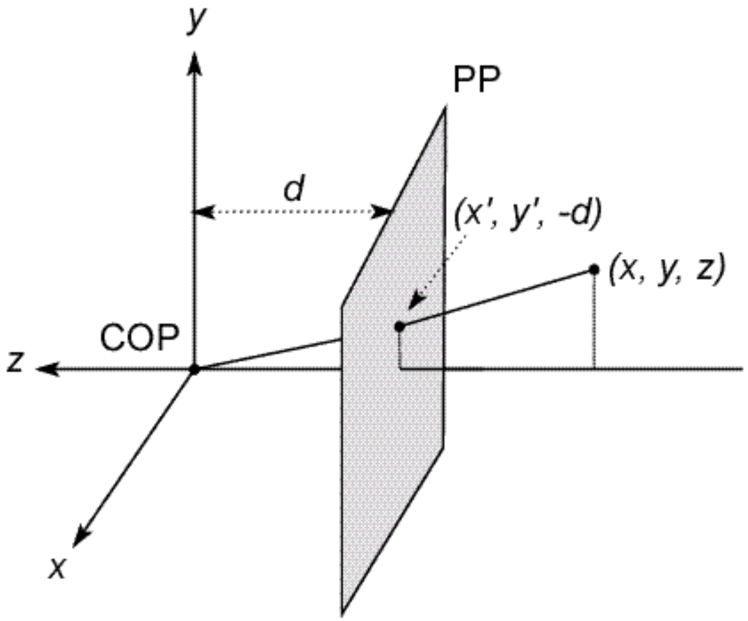
Projection

- Mapping from the world (3d) to an image (2d)
- Can we have a 1-to-1 mapping?
- How many possible mappings are there?

- An optical system defines a particular projection.
- Two examples:

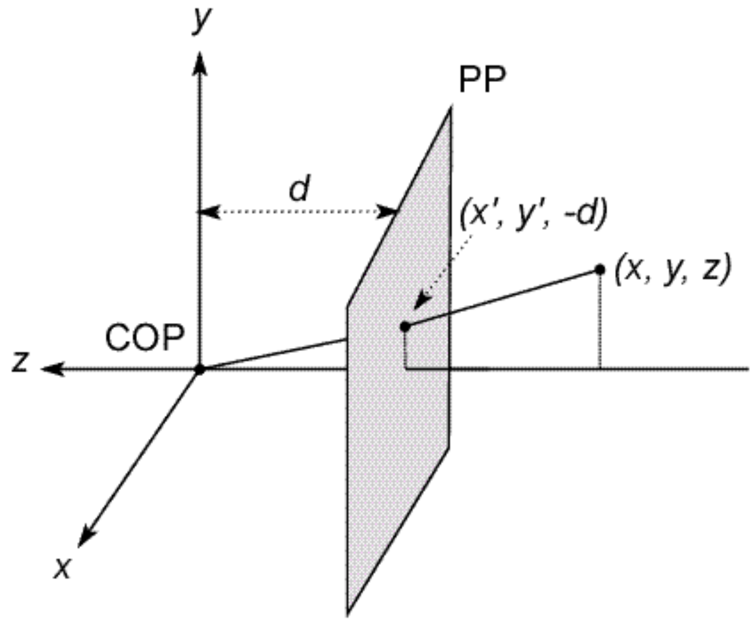
1. Perspective projection (how we see “normally”)
2. Orthographic projection (e.g., telephoto lenses)

Modeling projection



- The coordinate system
  - We will use the pin-hole model as an approximation
  - Put the optical center (Center Of Projection) at the origin
  - Put the image plane (Projection Plane) in front of the COP
  - The camera looks down the negative z axis
    - we need this if we want right-handed-coordinates

Modeling projection



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

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

- 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

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

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

Perspective Projection

- Projection is a matrix multiply using homogeneous coordinates:

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

divide by third coordinate

This is known as **perspective projection**

- The matrix is the **projection matrix**

Perspective Projection Example

1. Object point at (10, 6, 4), d=2

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \end{bmatrix} \begin{bmatrix} 10 \\ 6 \\ 4 \\ 1 \end{bmatrix} = \begin{bmatrix} 10 & 6 & -2 \end{bmatrix}$$

$$\Rightarrow x' = -5,\ y' = -3$$

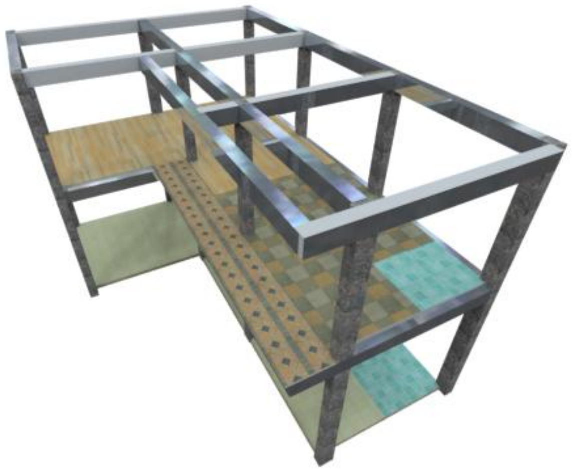
2. Object point at (25, 15, 10)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/d & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1/2 & 0 \end{bmatrix} \begin{bmatrix} 25 \\ 15 \\ 10 \\ 1 \end{bmatrix} = \begin{bmatrix} 25 & 15 & -5 \end{bmatrix}$$

$$\Rightarrow x' = -5,\ y' = -3$$

Perspective projection is not 1-to-1!

Perspective Projection



- preserves lines (collinearity), cross ratio
- does not always preserve parallel lines.
- Lines parallel to projection plane remain parallel.
- Lines not parallel to projection plane converge to a single point on the horizon called the <u>vanishing point</u>.

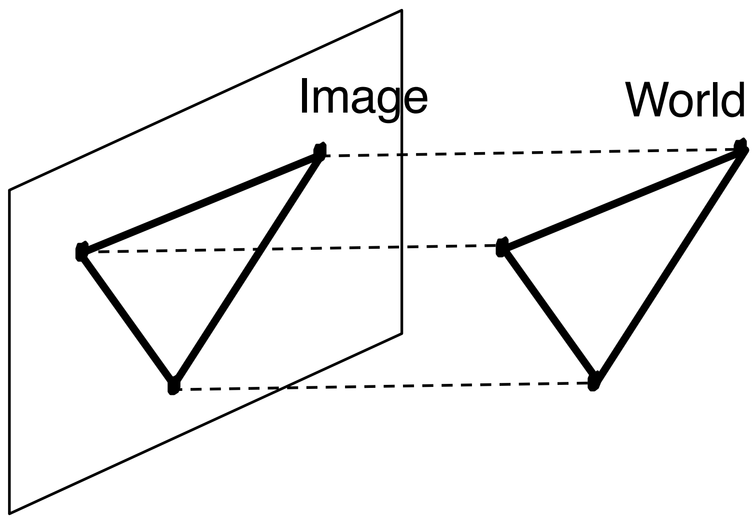
Perspective Projection

- What happens when d➔∞?

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

Orthographic projection

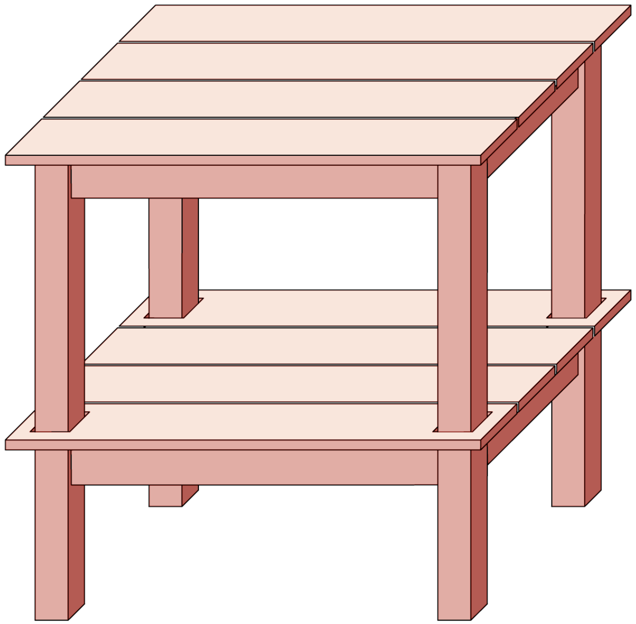
- Special case of perspective projection
  - Distance from the COP to the PP is infinite

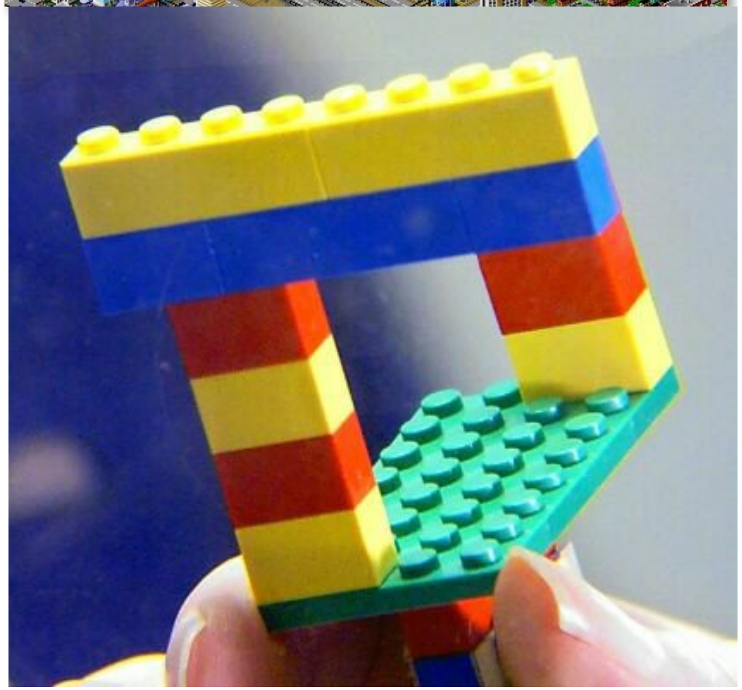


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \Rightarrow (x, y)$$

  - Good approximation for telephoto optics
  - Also called "parallel projection":
    (x, y, z) → (x, y)

Orthographic projection

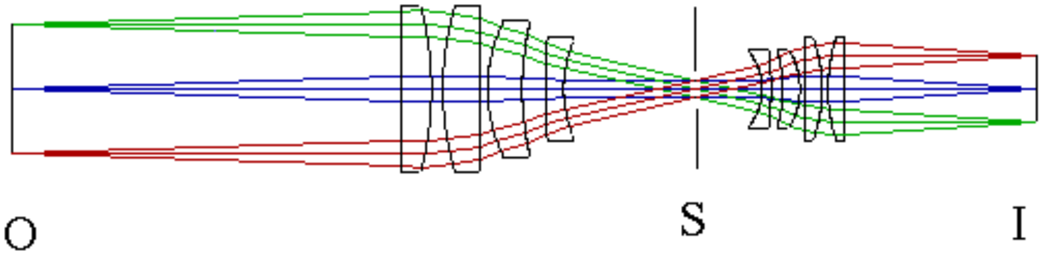




- preserves ratios, but not angles.
- parallel lines remain parallel.
- loses depth information.

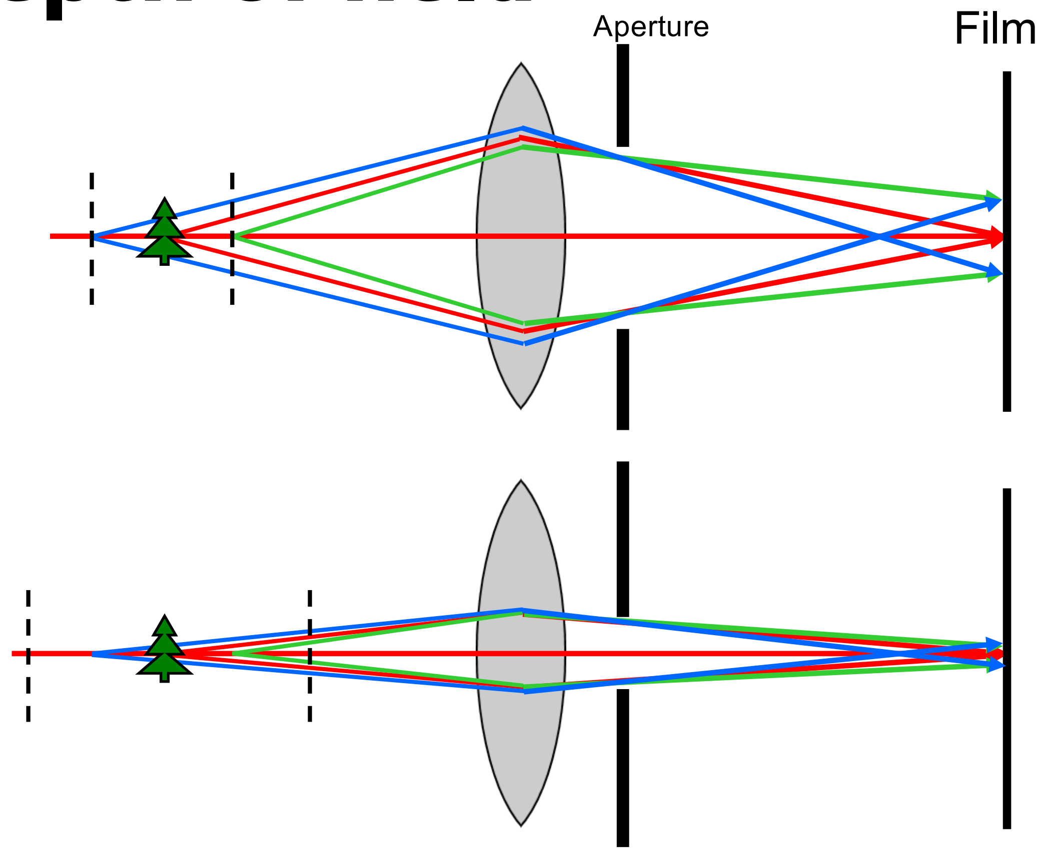
Orthographic ("telecentric") lenses

Navitar telecentric zoom lens



http://www.lhup.edu/~dsimanek/3d/telecent.htm

Depth of field



f / 5.6

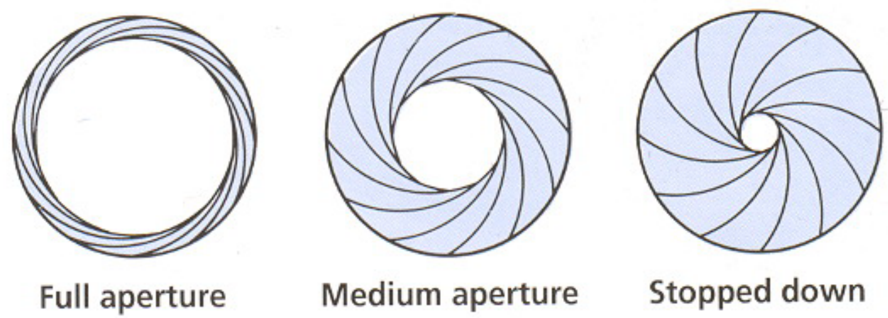
f / 32

- Changing the aperture size affects depth of field
  - A smaller aperture increases the range in which the object is approximately in focus

Flower images from Wikipedia http://en.wikipedia.org/wiki/Depth_of_field

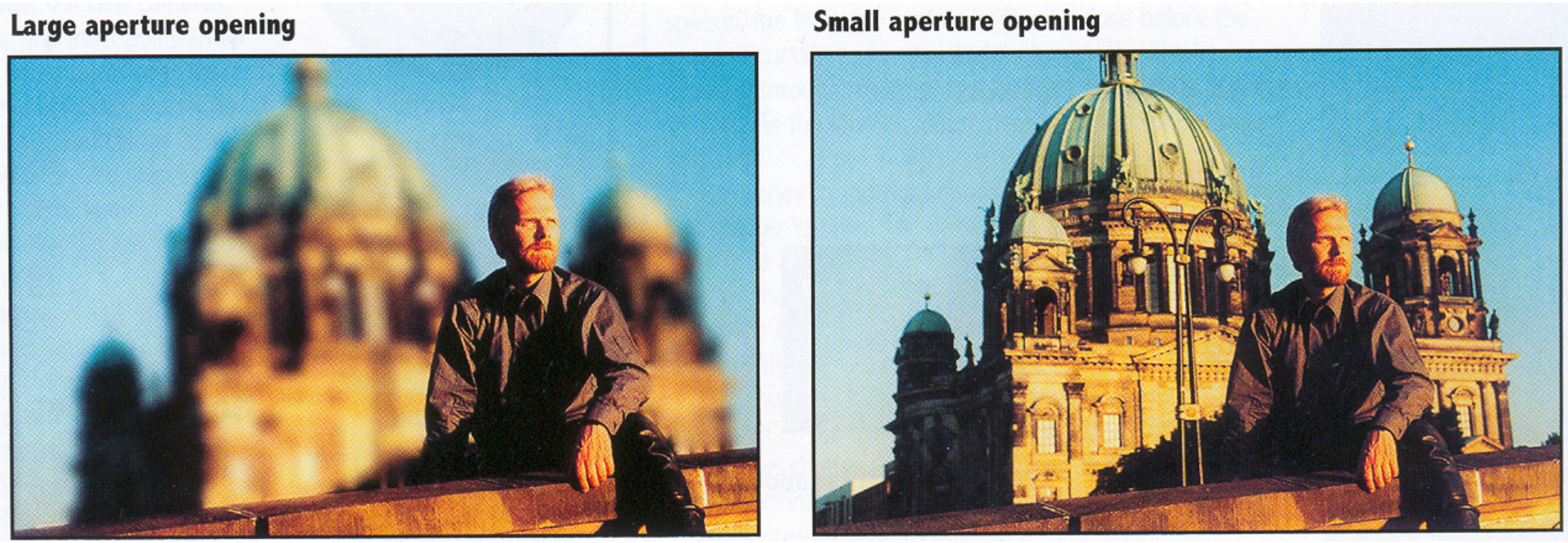
Aperture

- Diameter of the lens opening (controlled by diaphragm)
- Controls depth of field
- Expressed as a fraction of focal length, in f-number
  - f/2.0 on a 50mm means that the aperture is 25mm
  - f/2.0 on a 100mm means that the aperture is 50mm
- Disconcerting: small f number = big aperture
- What happens to the area of the aperture when going from f/2.0 to f/4.0?
- Typical f numbers are f/2.0, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22, f/32



Main effect of aperture

- **Depth of field:** Allowable depth variation in the scene that limits the circle of confusion to a tolerable number



From Photography, London et al.

Depth of field

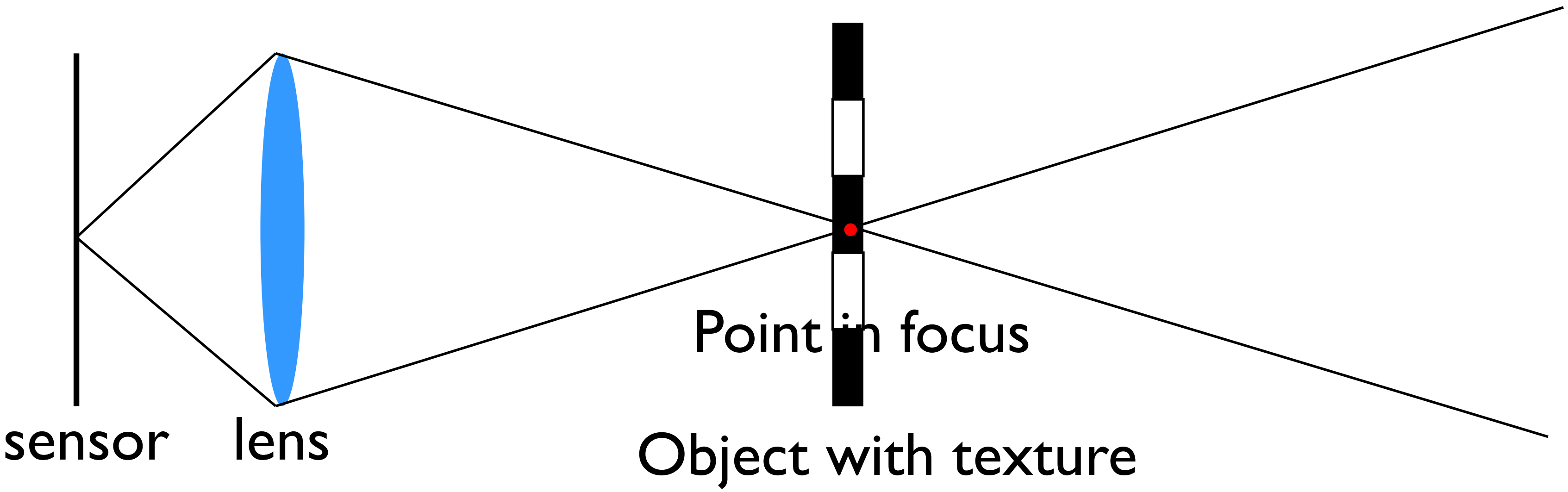


Image of object in focus- sharp (all rays hitting a single sensor point emerge from a single point on the object)

Depth of field

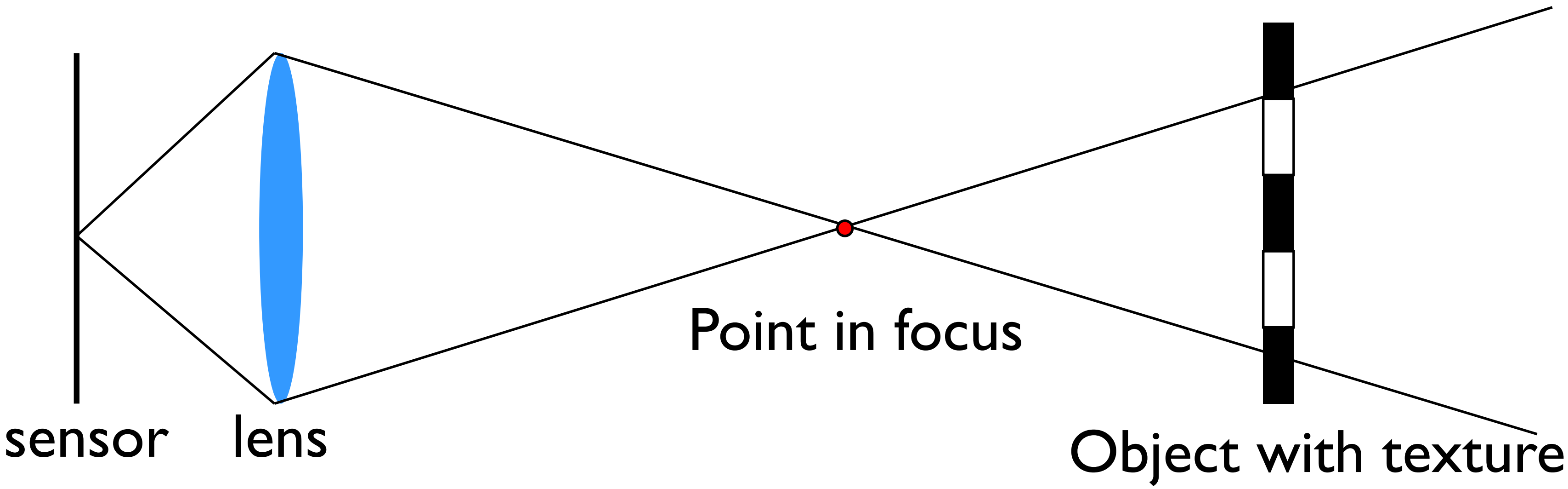
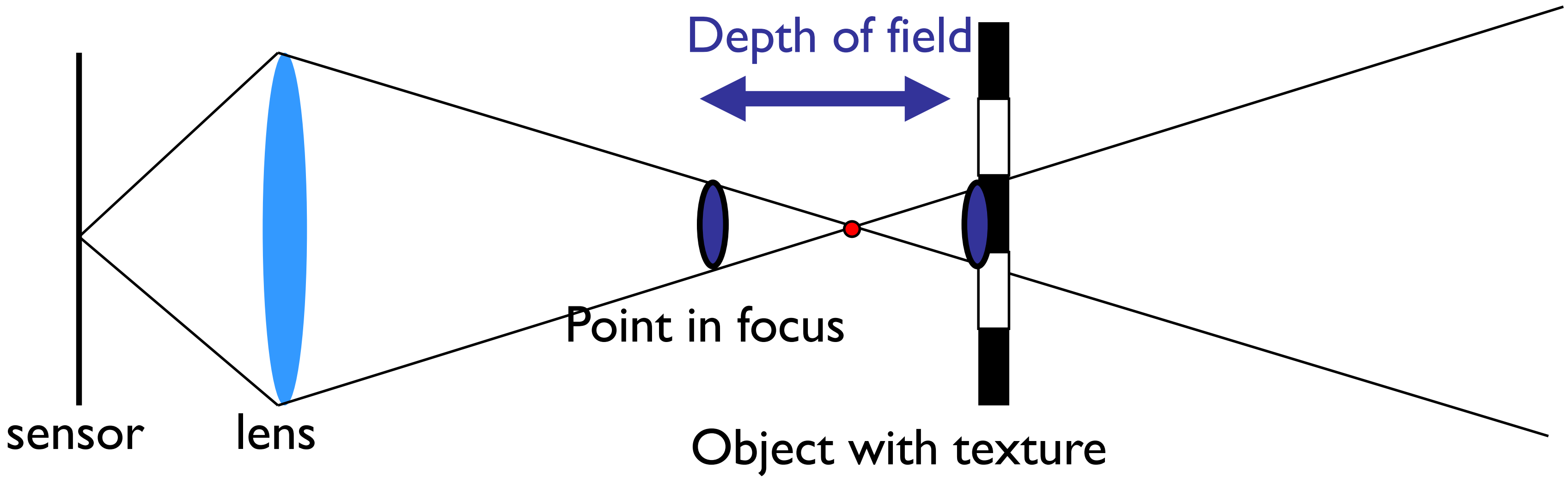


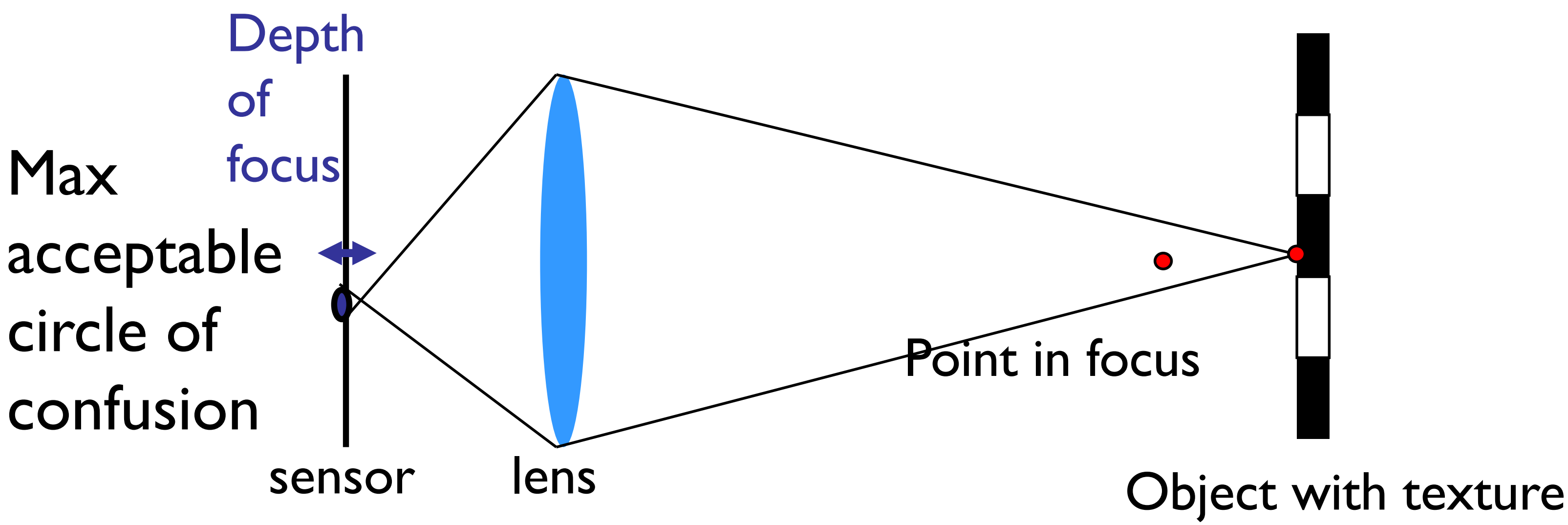
Image of object in focus- sharp (all rays hitting a single sensor point emerge from a single point on the object)

Image of an object away from focus depth- blurred (rays hitting a single sensor point emerge from multiple points on the object)

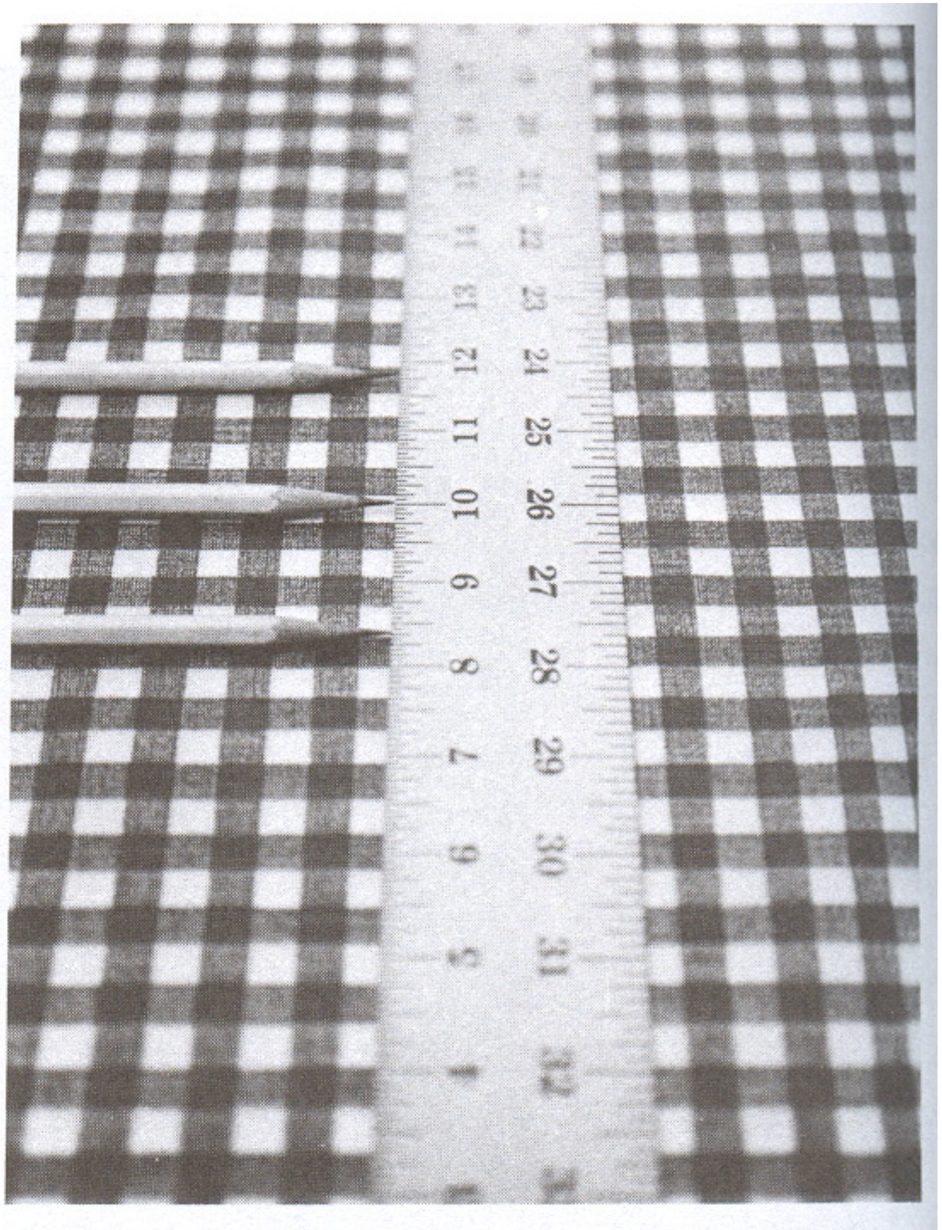
Depth of field

- We allow for some tolerance





Depth of Field



Depth of Field

Portrait

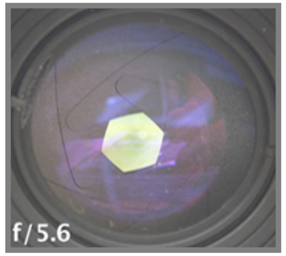
Landscape

Shallow Depth of Field

Large Aperture

Large Depth of Field

Small Aperture

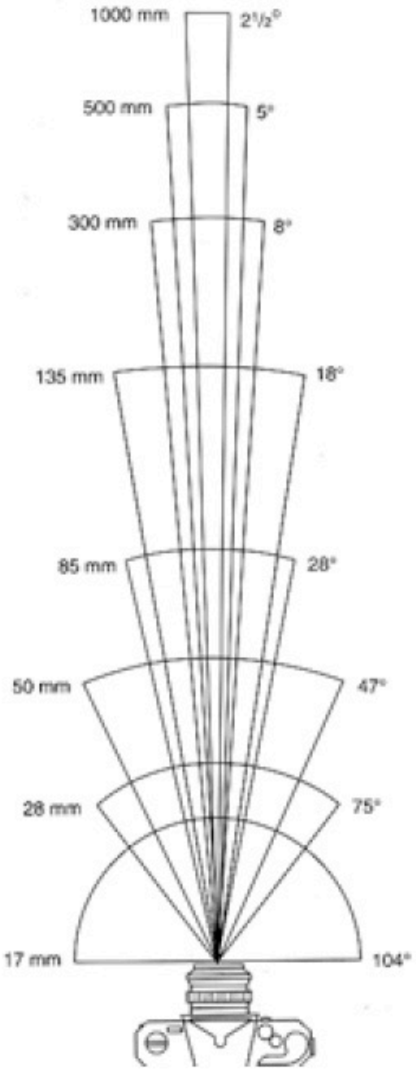


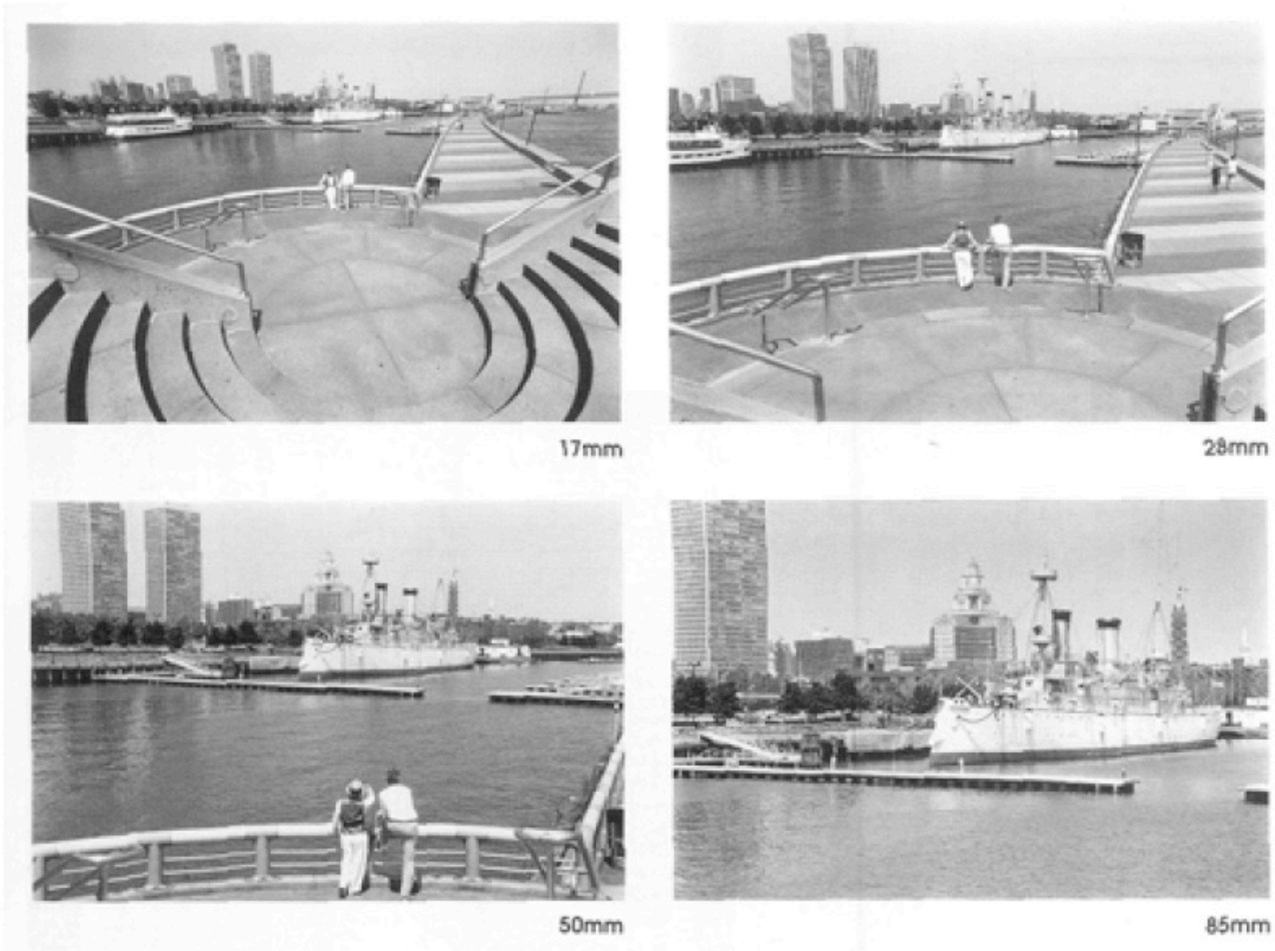
http://photographertips.net

Exposure

- Exposure: How much light falls on sensor
- Get the right amount of light to sensor/film
- Main parameters:
  - Shutter speed: How long sensor is exposed to light
  - Aperture (area of lens): How much light can pass through from the lens
  - Sensitivity: How much light is needed by the sensor
  - Lighting conditions

Field of View (Zoom, focal length)





From London and Upton

Shutter speed

- Controls how long the film/sensor is exposed, i.e. the amount of light reaching the sensor
- Pretty much linear effect on exposure
- Usually in fraction of a second:
  - 1/30, 1/60, 1/125, 1/250, 1/500
  - Get the pattern ?
- Faster shutter (e.g. 1/500th sec) = less light
- Slower shutter (e.g. 1/30th sec) = more light
- On a normal lens, normal humans can hand-hold down to 1/60
  - In general, the rule of thumb says that the limit is the inverse of focal length, e.g. 1/500 for a 500mm

Shutter speed

Short exposure- dark

medium exposure

long exposure- saturation

Shutter speed

Short exposure after contrast adjustment- noise

medium exposure

long exposure- saturation

Main effect of slower shutter speed

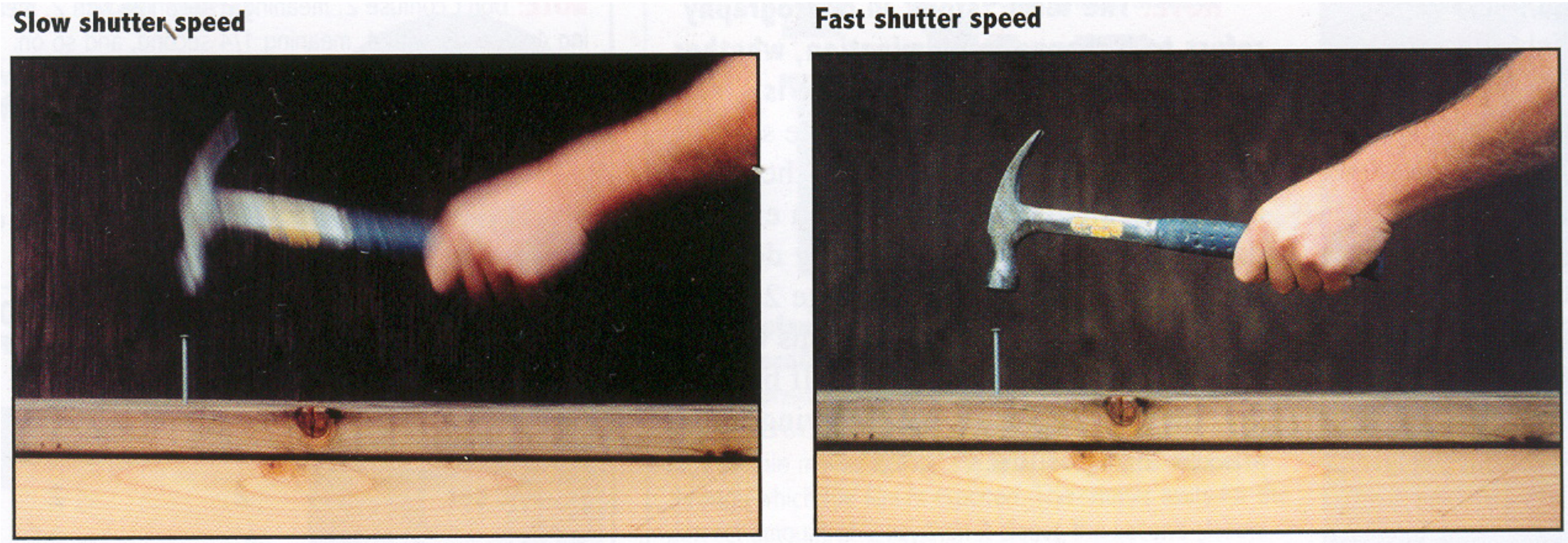
- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.
- Camera shake

Image taken with a tripod

Image taken with a hand held camera

Main effect of slower shutter speed

- For dynamic scenes, the shutter speed also determines the amount of *motion blur* in the resulting picture.
- Scene motion

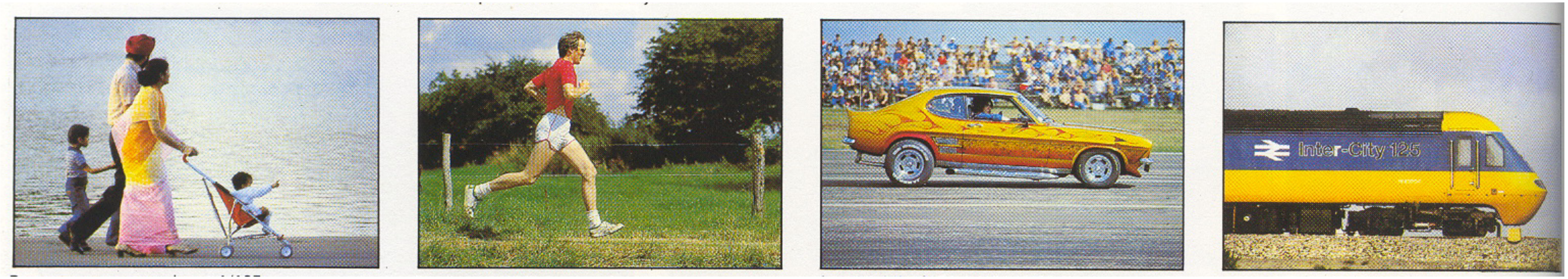


From Photography, London et al.

Effect of Shutter Speed

- Freezing motion

Walking people | Running people | Car | Fast train



1/125 | 1/250 | 1/500 | 1/1000

Today

- Image formation
- Display devices and digital camera
- Digital images

Representative display technologies

Computer displays

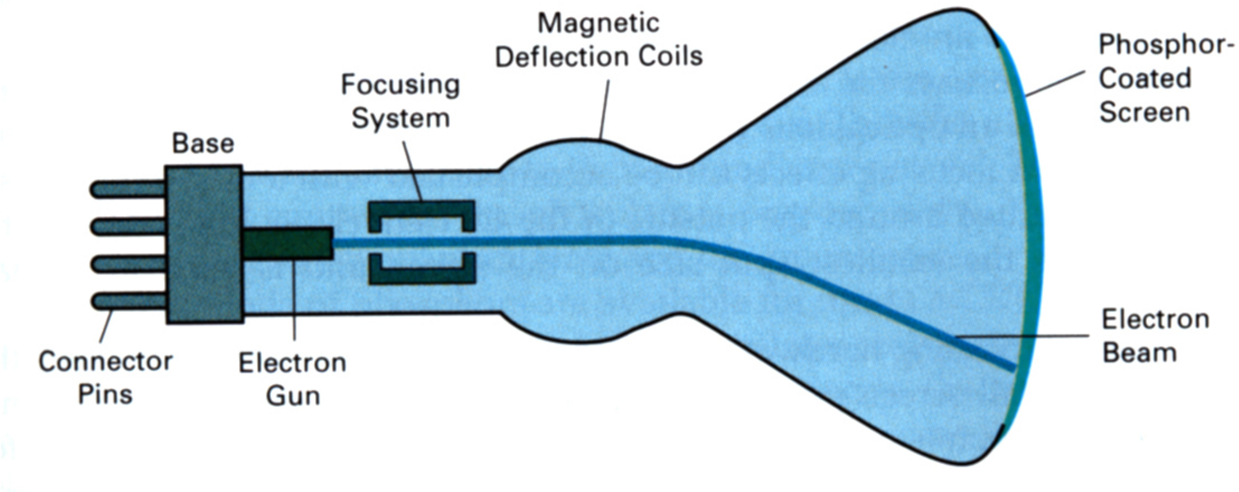
- Raster CRT display
- LCD display

Printers

- Laser printer
- Inkjet printer

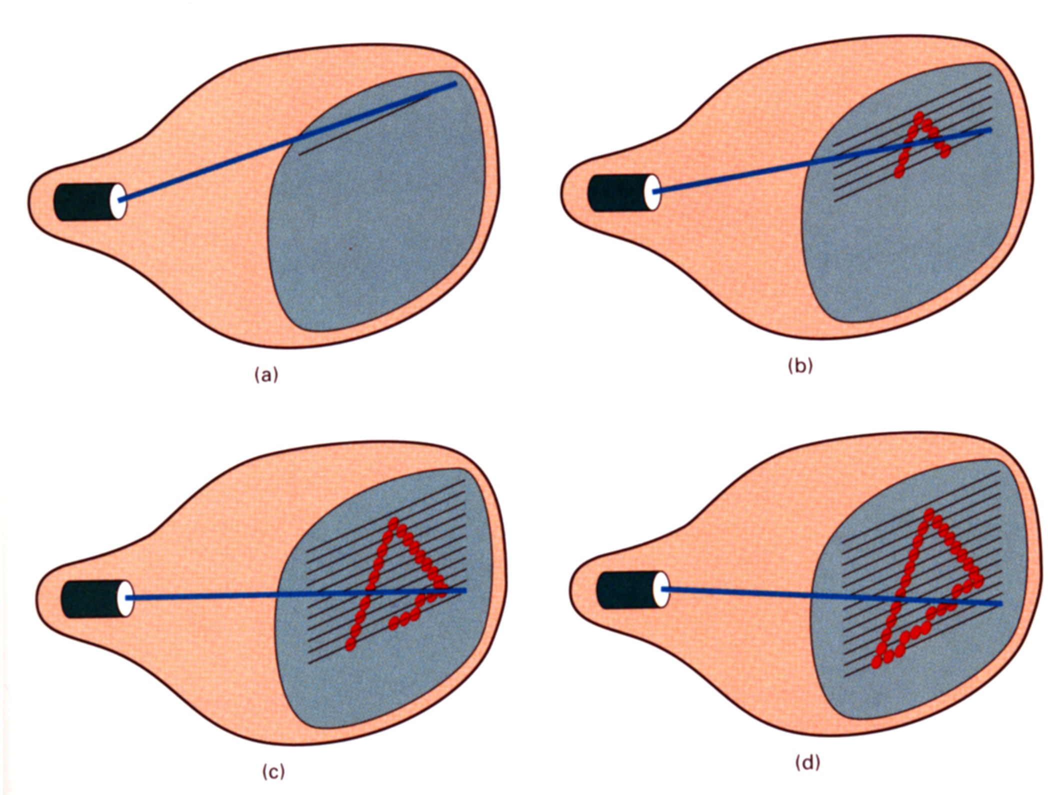
Cathode ray tube

- First widely used electronic display
  - developed for TV in the 1920s–1930s



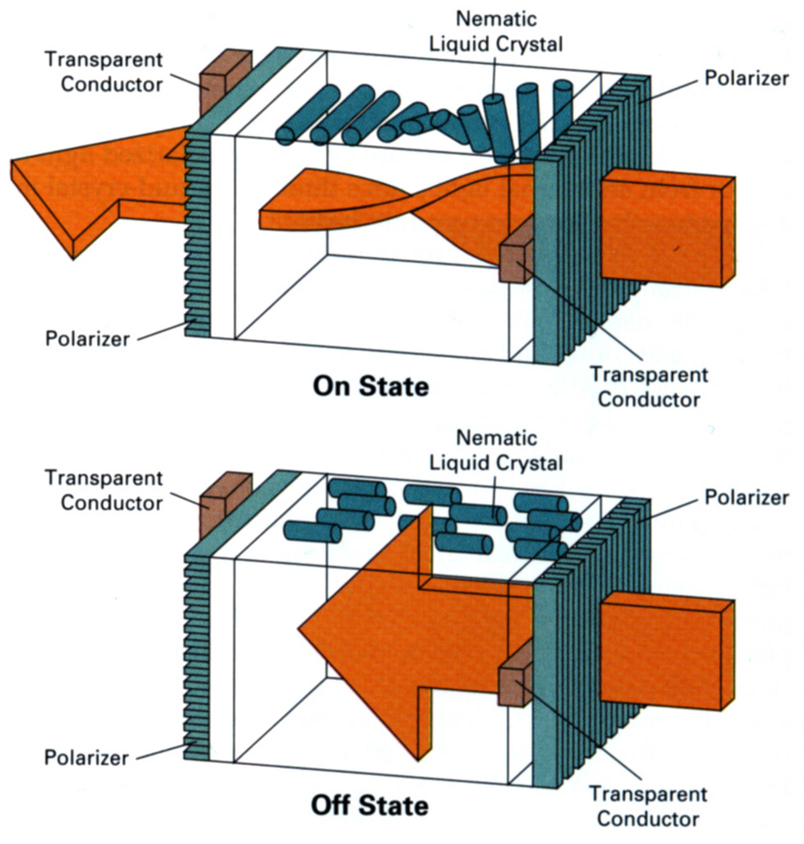
Raster CRT display

- Scan pattern fixed in display hardware
- Intensity modulated to produce image
- Originally for TV
  - (continuous analog signal)
- For computer, intensity determined by contents of *framebuffer*



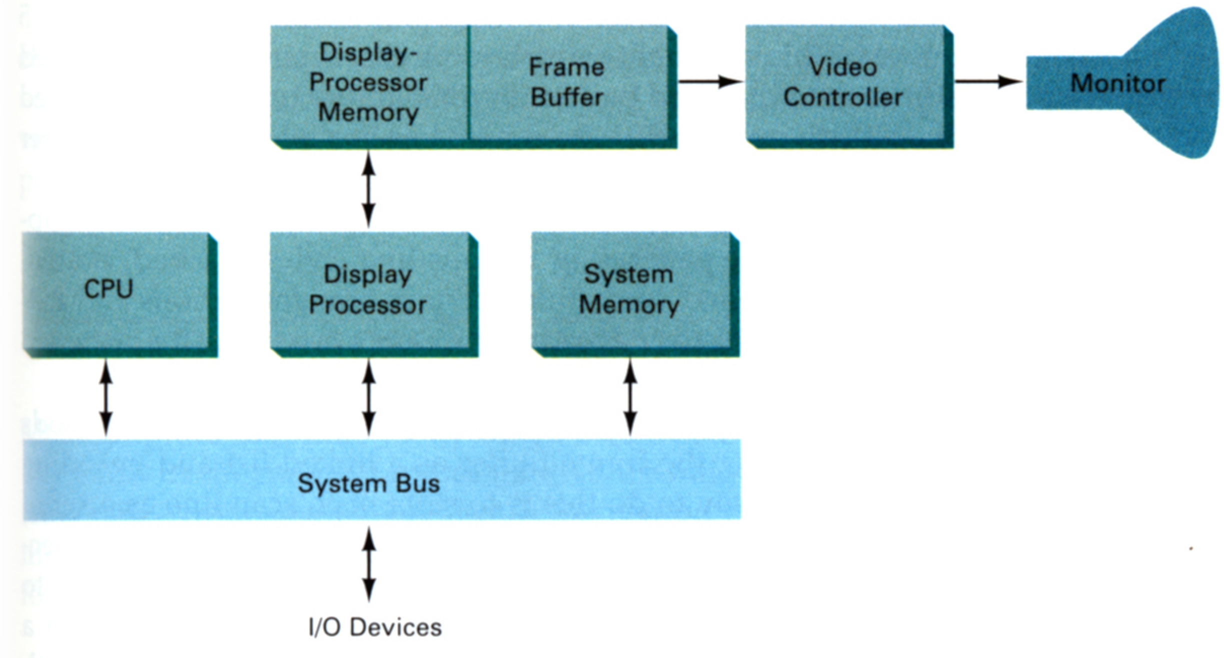
LCD flat panel or projection display

- Principle: block or transmit light by twisting its polarization
- Intermediate intensity levels possible by partial twist
- Fundamentally raster technology
- Fixed format



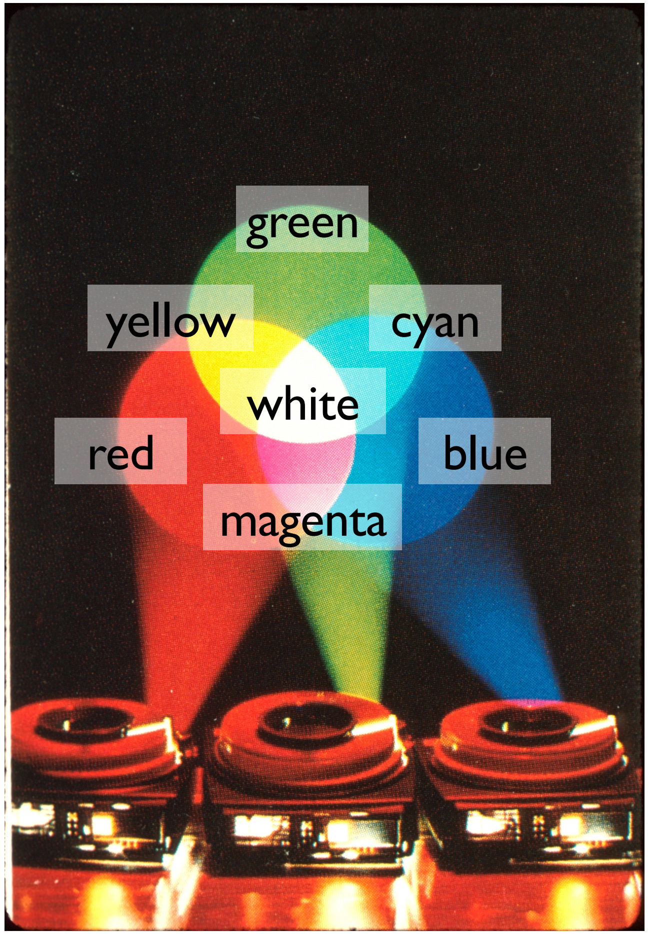
Raster display system

- Screen image defined by a 2D array in RAM
  - for CRT, read out and convert to analog in sync with scan
- In most systems today, it's in a separate memory
- The memory area that maps to the screen is called the *frame buffer*



Color displays

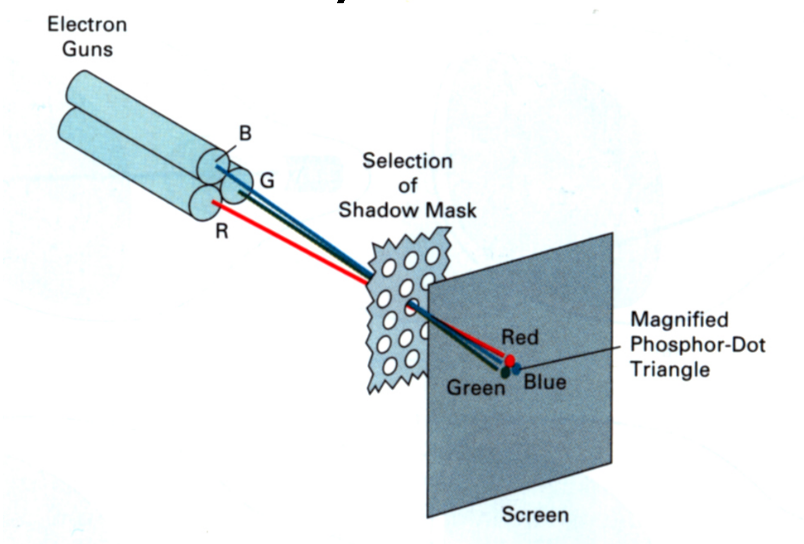
- Operating principle: humans are trichromatic
  - match any color with blend of three
  - therefore, problem reduces to producing 3 images and blending
- Additive color
  - blend images by sum
  - e.g. overlapping projection
  - e.g. unresolved dots
  - R, G, B make good primaries



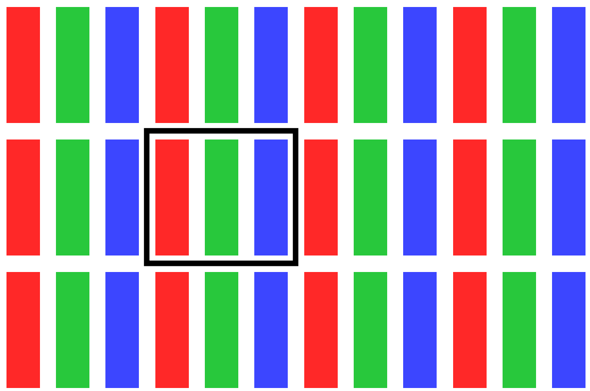
[source unknown]

Color displays

- CRT: phosphor dot pattern to produce finely interleaved color images

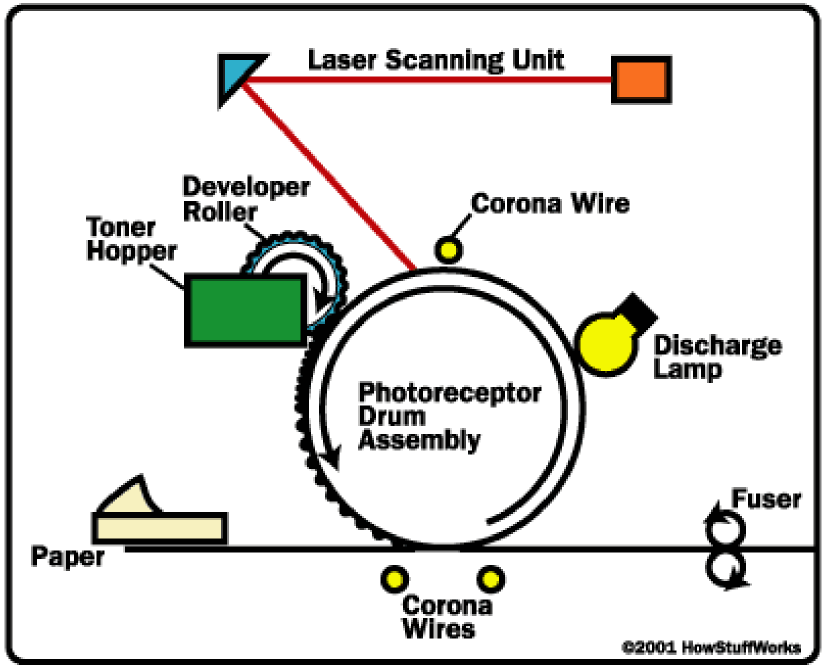


- LCD: interleaved R,G,B pixels



Laser printer

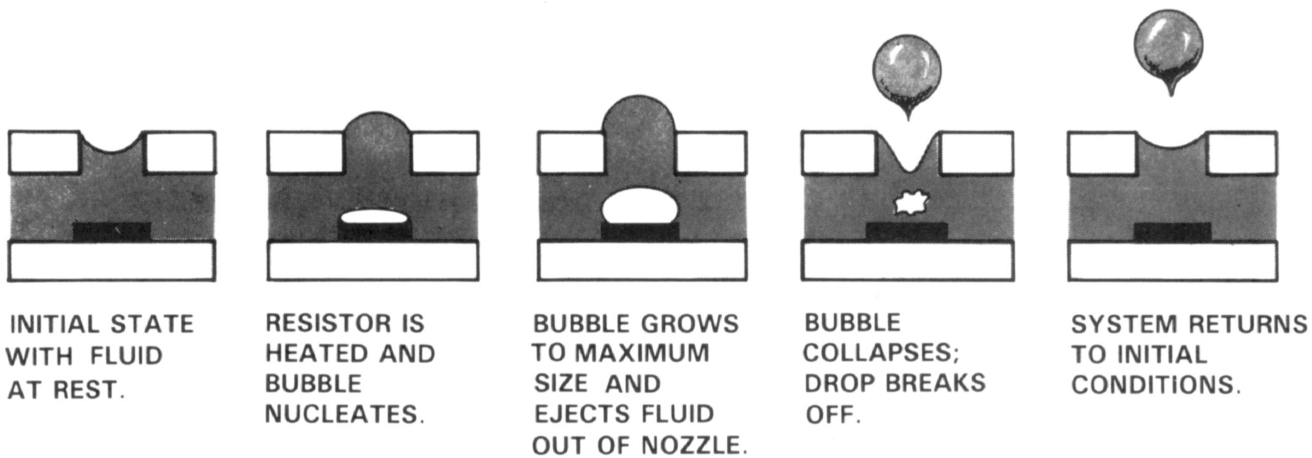
- Xerographic process
- Like a photocopier but with laser-scanned raster as source image
- Key characteristics
  - image is binary
  - resolution is high
  - very small, isolated dots are not possible



[howstuffworks.com]

Inkjet printer

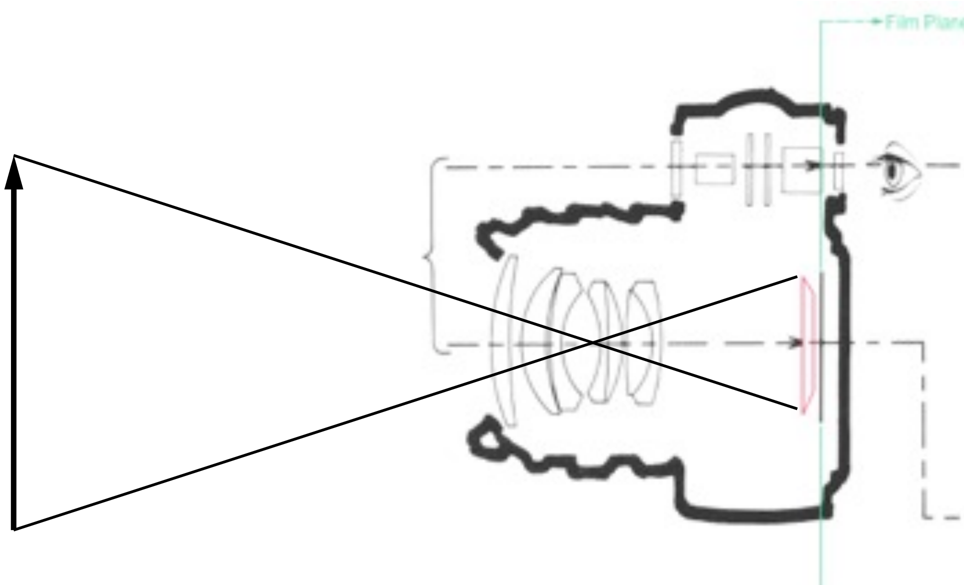
- Liquid ink sprayed in small drops
  - very small—measured in picoliters
- Head with many jets scans across paper
- Key characteristics:
  - image is binary (drop or no drop; no partial drops)
  - isolated dots are reproduced well



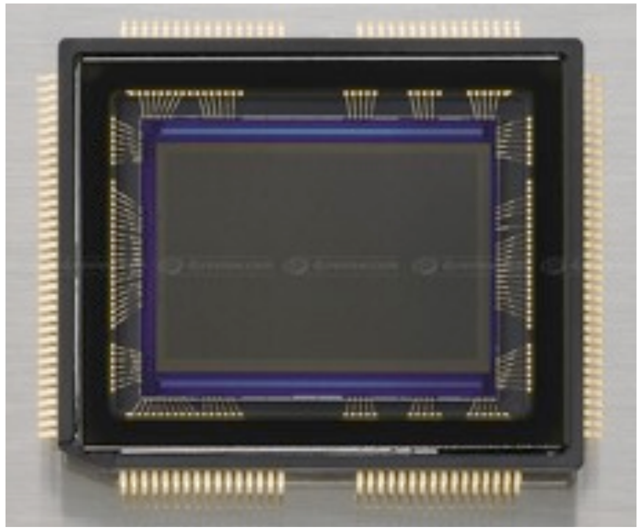
[source unknown]

Digital camera

- A raster input device
- Image sensor contains 2D array of photosensors



[CS 417 Spring 2002]



[dpreview.com]

Today

- Image formation
- Display devices and digital camera
- Digital images

Raster image representation

- All these devices suggest 2D arrays of numbers
- Big advantage: represent arbitrary images
  - approximate arbitrary functions with increasing resolution
  - works because memory is cheap (brute force approach!)

[Philip Greenspun]

Meaning of a raster image

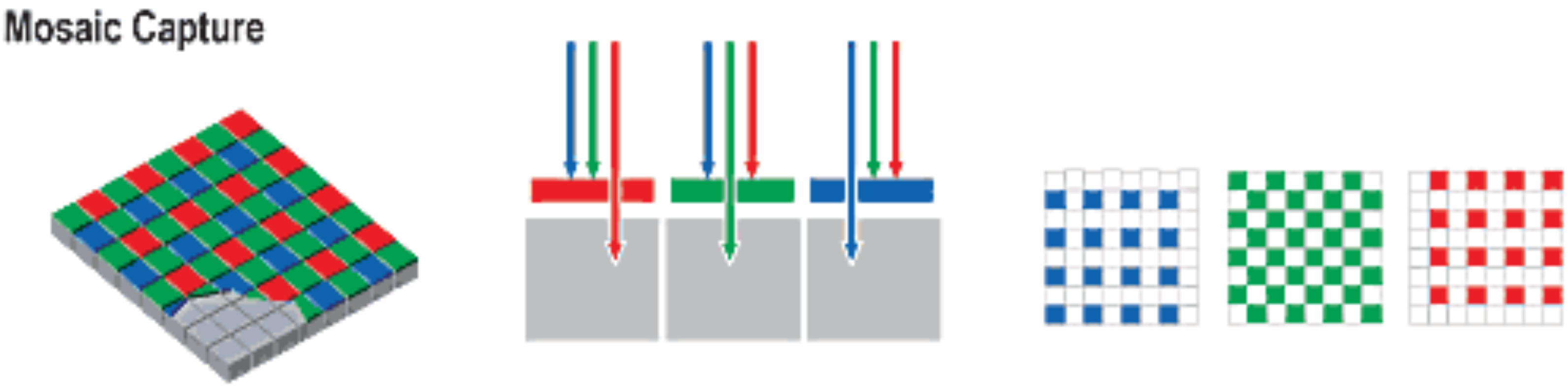
- Meaning of a given array is a function on 2D
- Define meaning of array = result of output device?
  - that is, piecewise constant for LCD, blurry for CRT
  - but: we don't have just one output device
  - but: want to define images we can't display (e.g. too big)
- Abstracting from device, problem is reconstruction
  - image is a sampled representation
  - pixel means "this is the intensity around here"
    - LCD: intensity is constant over square regions
    - CRT: intensity varies smoothly across pixel grid

Digital camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - CMOS
  - http://electronics.howstuffworks.com/digital-camera.htm

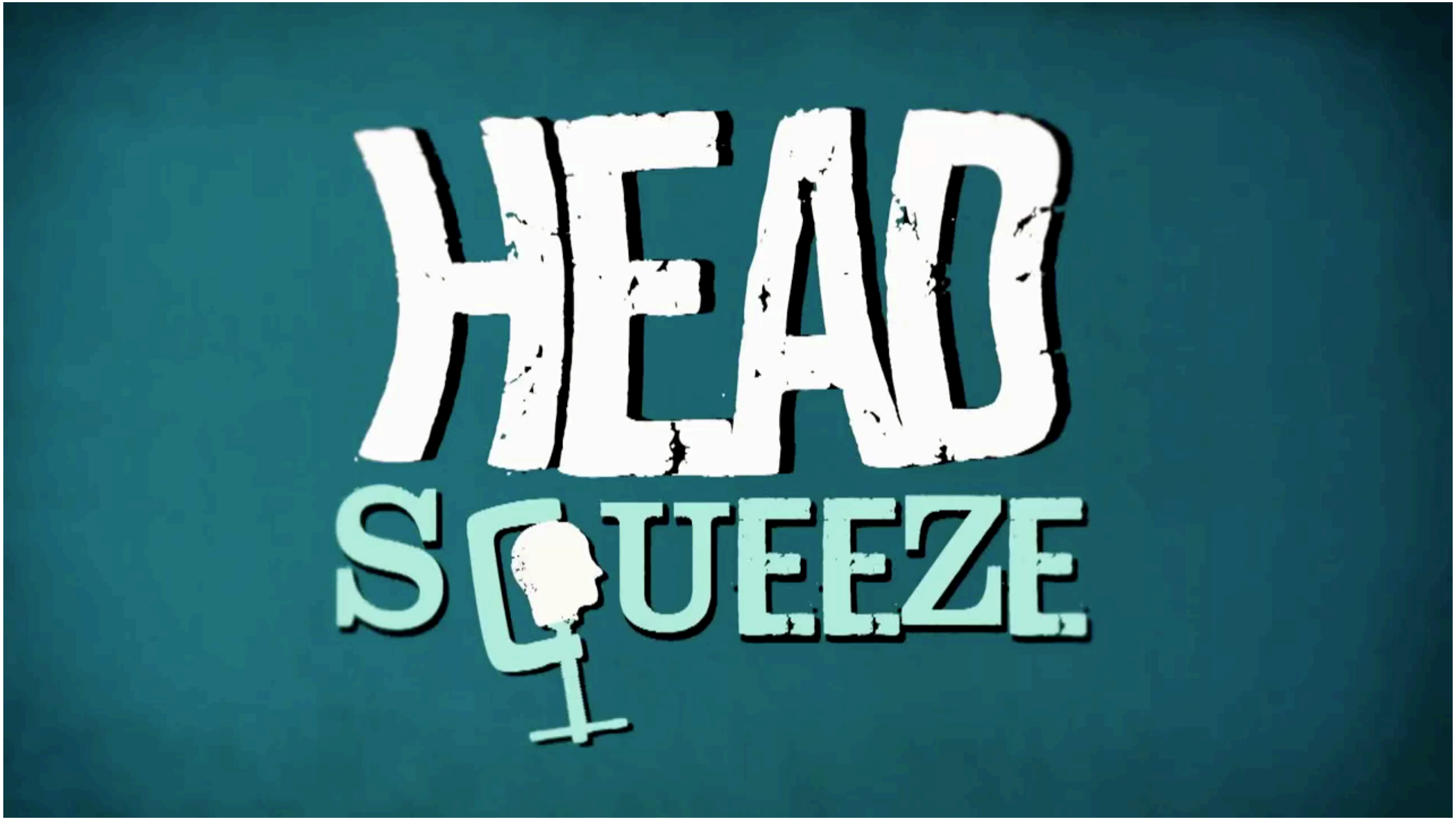
Digital camera

- Color typically captured using color mosaic
- Demosaicing



[Foveon]

Digital camera



How do digital cameras work? https://www.youtube.com/watch?v=Ic0czeUJrGE

Sensor Array

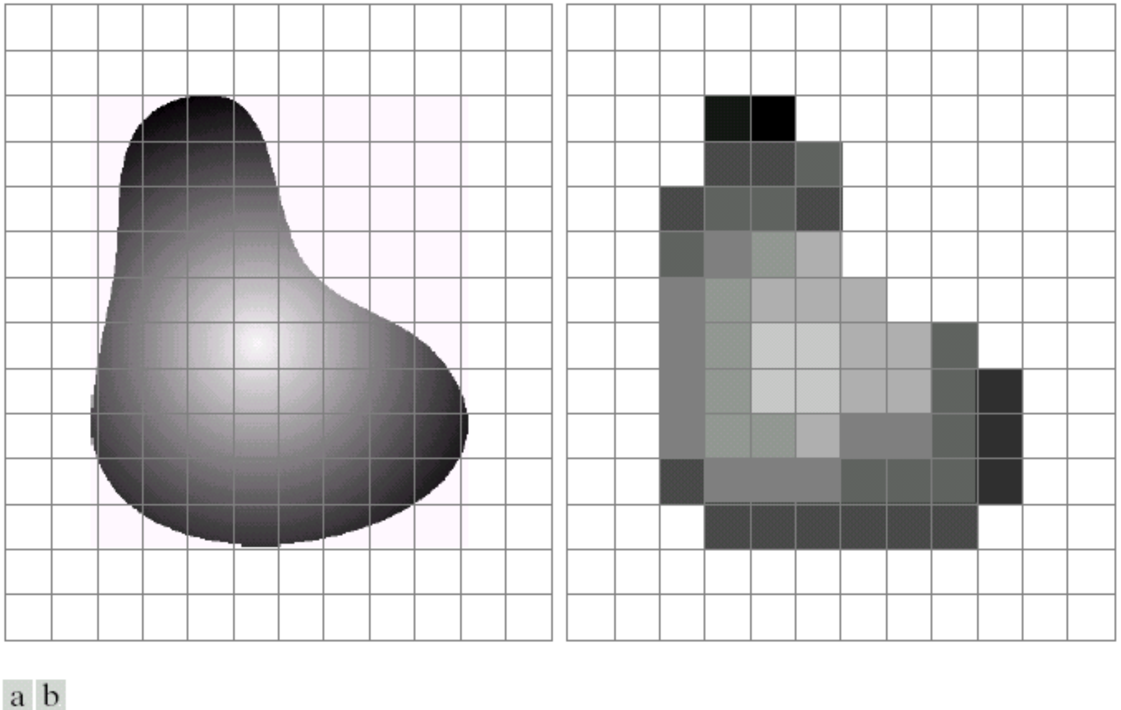
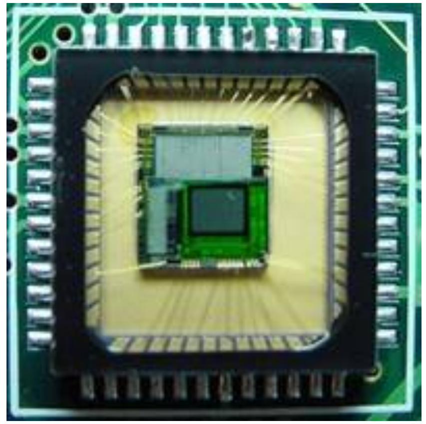


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

Issues with digital cameras

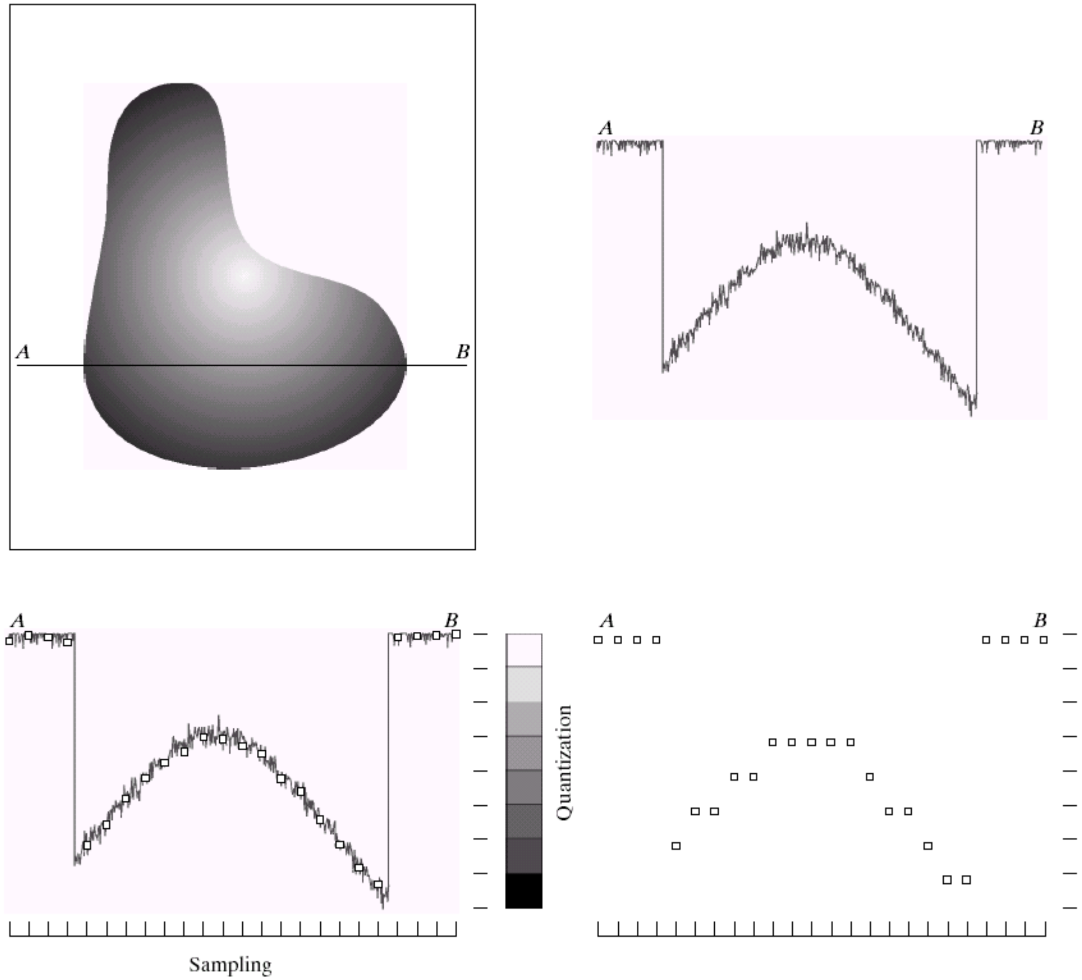
- Noise
  - big difference between consumer vs. SLR-style cameras
  - low light is where you most notice noise
- Compression
  - creates artifacts except in uncompressed formats (tiff, raw)
- Color
  - color fringing artifacts from Bayer patterns
- Blooming
  - charge overflowing into neighboring pixels
- In-camera processing
  - oversharpening can produce halos
- Interlaced vs. progressive scan video
  - even/odd rows from different exposures
- Are more megapixels better?
  - requires higher quality lens
  - noise issues
- Stabilization
  - compensate for camera shake (mechanical vs. electronic)

More info online, e.g.,

http://electronics.howstuffworks.com/digital-camera.htm

http://www.dpreview.com/

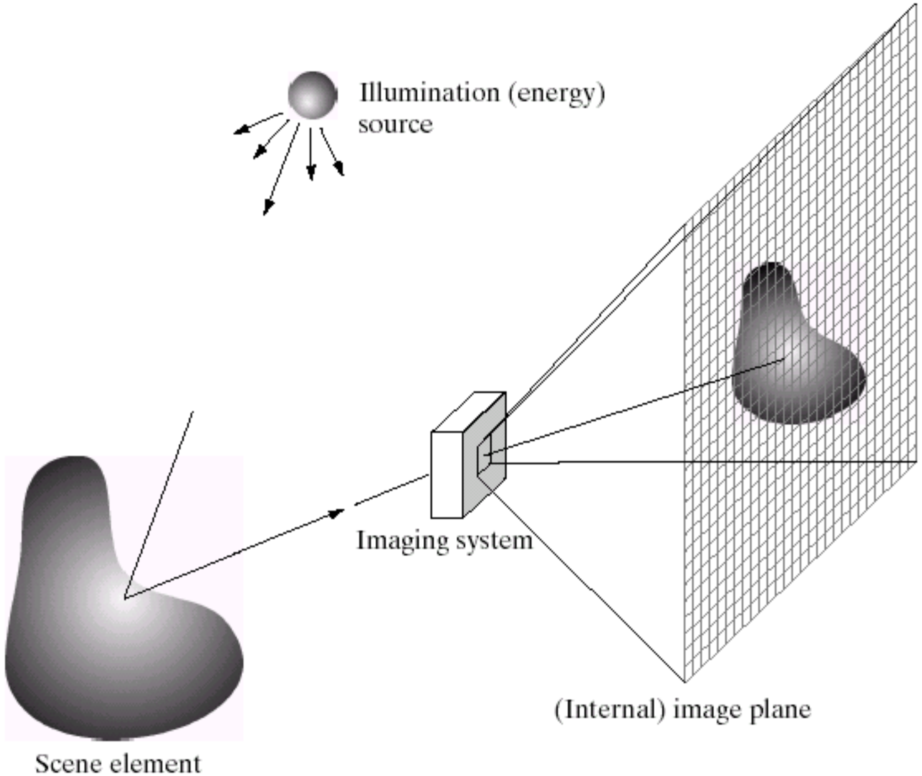
Sampling and Quantization

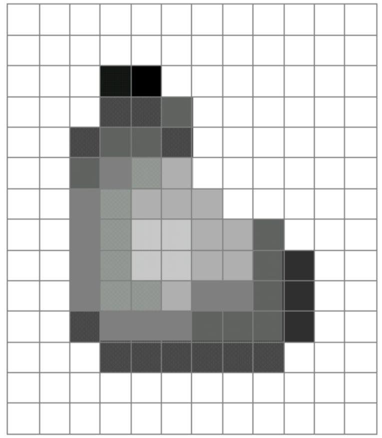


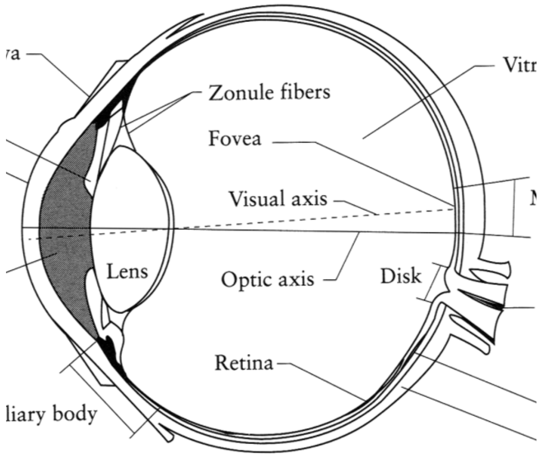
a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from A to B in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

Image Representation







- Discretization
  - in image space - sampling
  - In image brightness - quantization

Figures: Gonzalez and Woods, Digital Image Processing, 3rd Edition, 2008

Image Representation

- **Digital image:** 2D discrete function f
- **Pixel**: Smallest element of an image f(x,y)

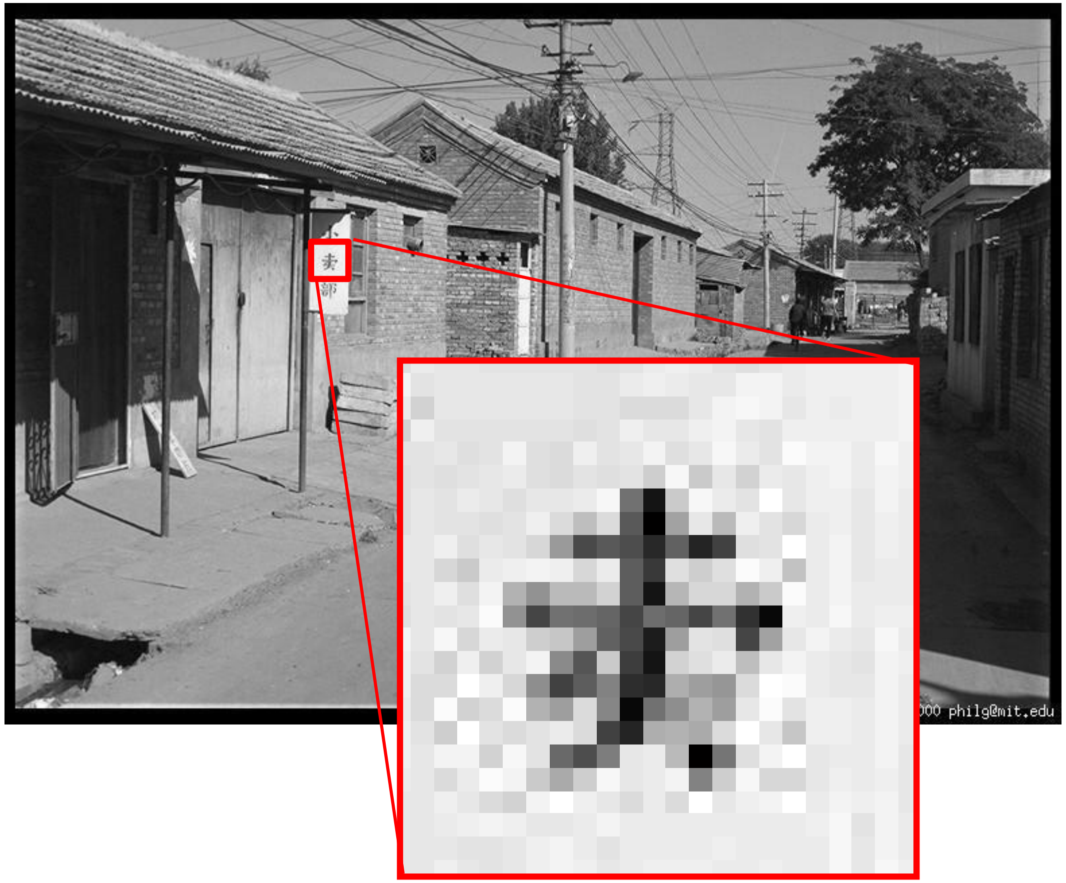


Figure: M. J. Black

Image Representation

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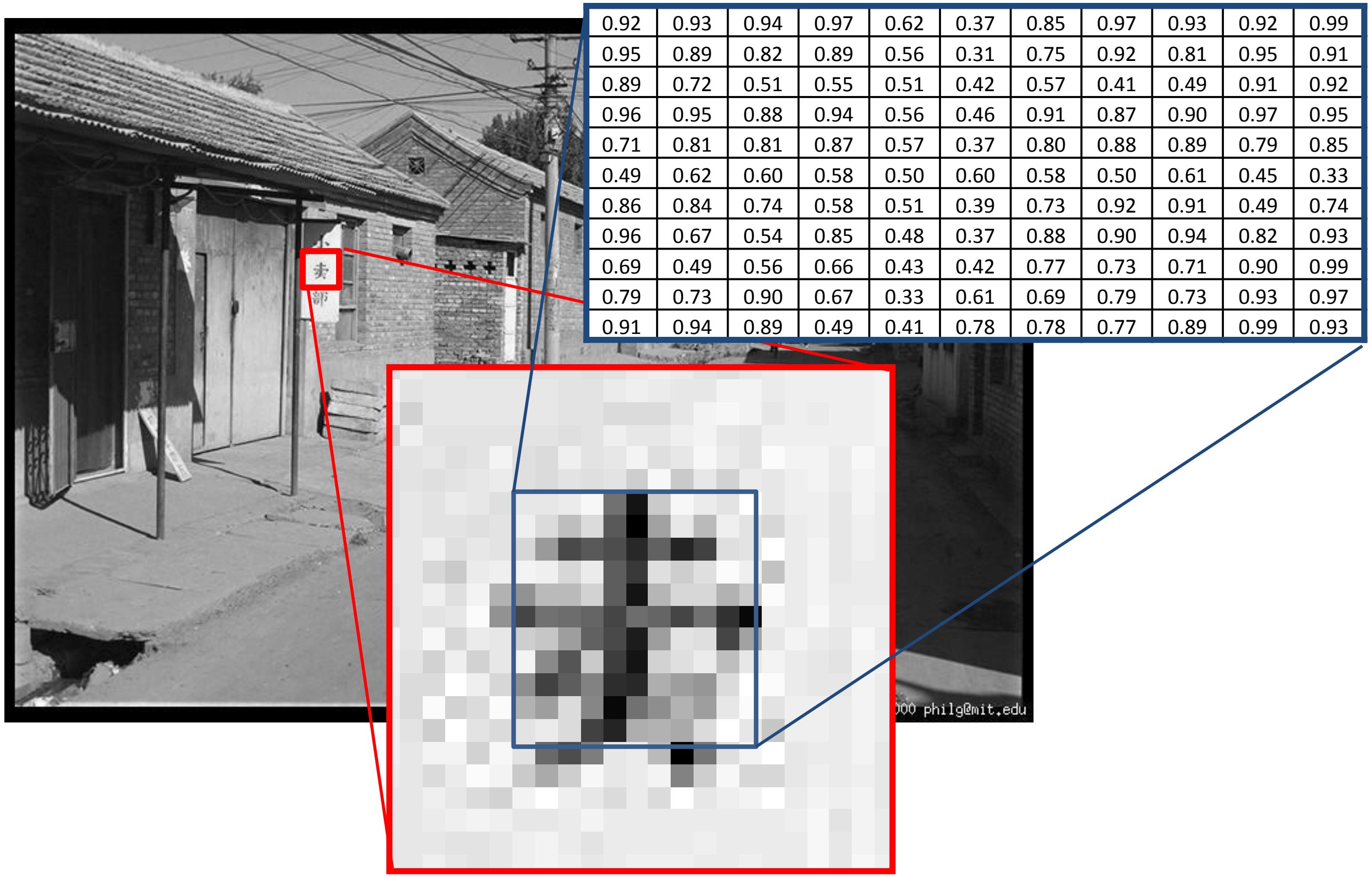
- **Pixel**: Smallest element of an image f(x,y)



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Figure: M. J. Black

Datatypes for raster images

- Bitmaps: `boolean` per pixel (1 bpp): $I : \mathbb{R}^2 \rightarrow \{0, 1\}$
  - interp. = black and white; e.g. fax
- Grayscale: integer per pixel: $I : \mathbb{R}^2 \rightarrow [0, 1]$
  - interp. = shades of gray; e.g. black-and-white print
  - precision: usually `byte` (8 bpp); sometimes 10, 12, or 16 bpp
- Color: 3 integers per pixel: $I : \mathbb{R}^2 \rightarrow [0, 1]^3$
  - interp. = full range of displayable color; e.g. color print
  - precision: usually `byte[3]` (24 bpp)
  - sometimes 16 (5+6+5) or 30 or 36 or 48 bpp
  - indexed color: a fading idea

Datatypes for raster images

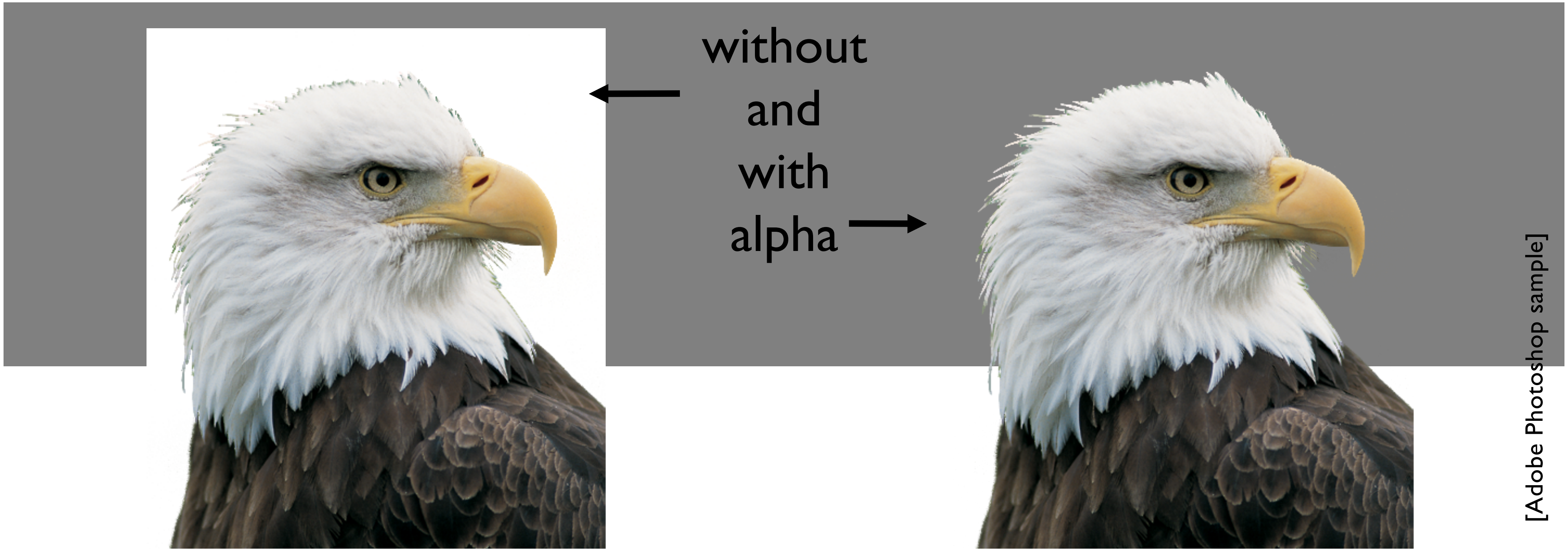
- Floating point: $I : \mathbb{R}^2 \rightarrow \mathbb{R}_+$ or $I : \mathbb{R}^2 \rightarrow \mathbb{R}^3_+$
  - more abstract, because no output device has infinite range
  - provides *high dynamic range* (HDR)
  - represent real scenes independent of display
  - becoming the standard intermediate format in graphics processors
- Clipping and white point
  - common to compute FP, then convert to integer
  - full range of values may not "fit" in display's output range
  - simplest solution: choose a maximum value, scale so that value becomes full intensity (2^n–1 in an *n*-bit integer image)

Intensity encoding in images

- What do the numbers in images (pixel values) mean?
  - they determine how bright that pixel is
  - bigger numbers are (usually) brighter

Datatypes for raster images

- For color or grayscale, sometimes add *alpha* channel
  - describes transparency of images



[Adobe Photoshop sample]

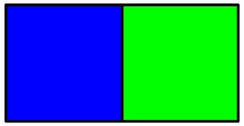
Storage requirements for images

- 1024x1024 image (1 megapixel)
  - bitmap: 128KB
  - grayscale 8bpp: 1MB
  - grayscale 16bpp: 2MB
  - color 24bpp: 3MB
  - floating-point HDR color: 12MB

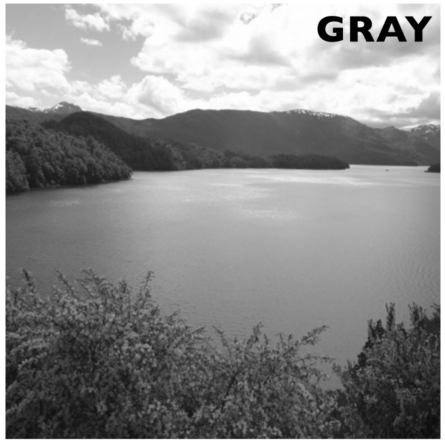
Converting pixel formats

- Color to gray
  - could take one channel (blue, say)
    - leads to odd choices of gray value
  - combination of channels is better
    - but different colors contribute differently to lightness
    - which is lighter, full blue or full green?
    - good choice: gray = 0.2 R + 0.7 G + 0.1 B
    - more on this in color, later on

Same pixel values.

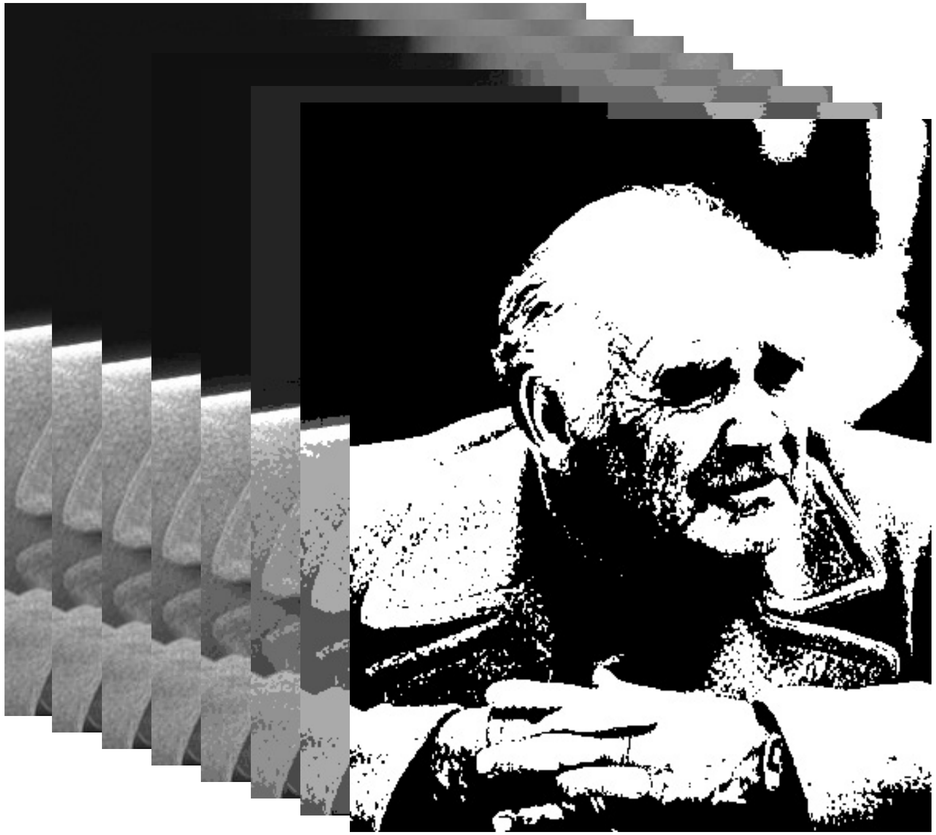


Same luminance?



Converting pixel precision

- Up is easy; down loses information—be careful



1 bpp (2 grays)

[photo: Philip Greenspun]

Today

- Image formation
- Display devices and digital camera
- Digital images

Next class

- Color perception
- Color spaces