CS 484/684

Computational Vision

Image Modalities

most slides are shamelessly stolen from

Steven Seitz, Aleosha Efros, and Terry Peters

CS 484/684

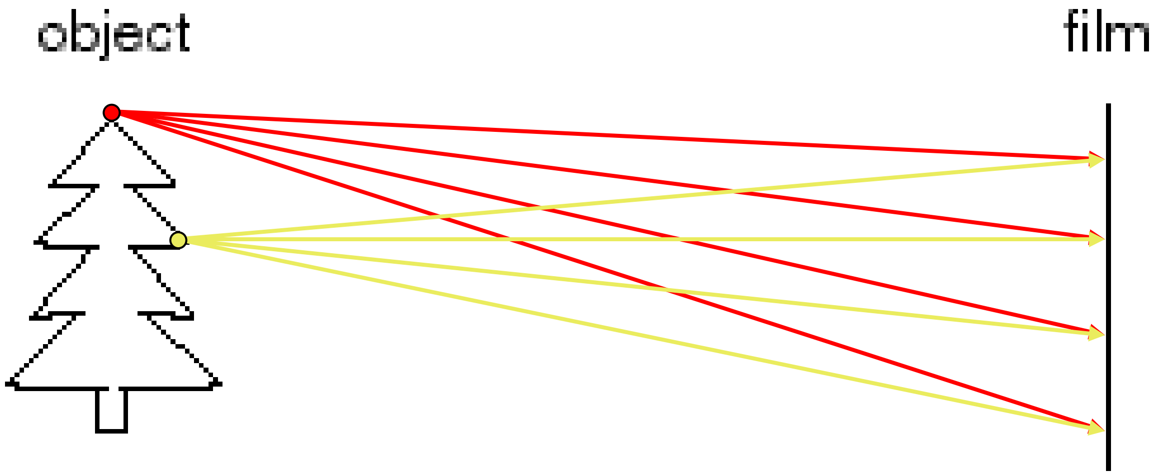
Computational Vision

- Photo/Video data
  - Lenses
  - *Pin-hole* camera model – the basics
  - Digital images and volumes
- Medical Images and Volumes
  - X-ray, MRI, CT, and Ultrasound

Extra Reading: **Szeliski, Ch. 2**,
Gonzalez & Woods, Ch. 1

Slide by Steve Seitz

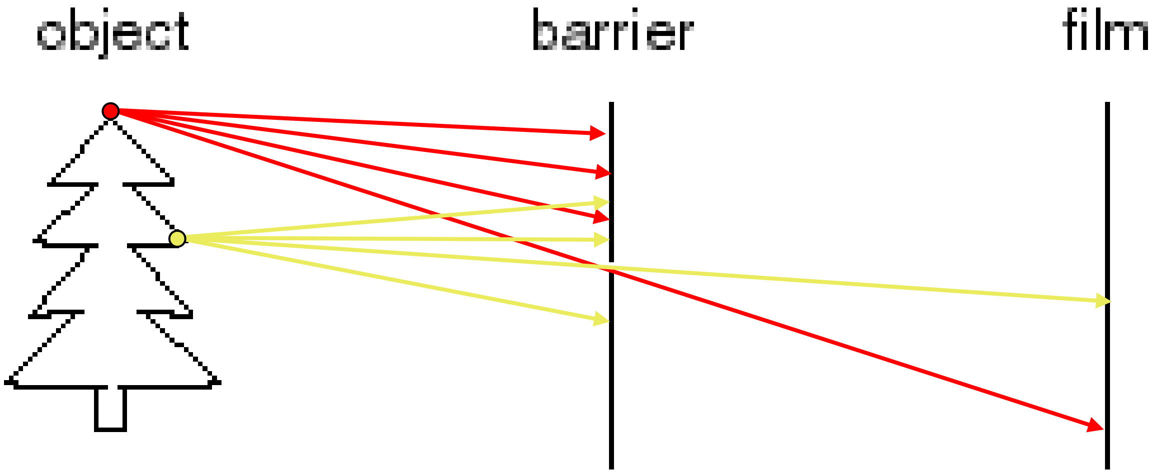
How do we see the world?



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

Slide by Steve Seitz

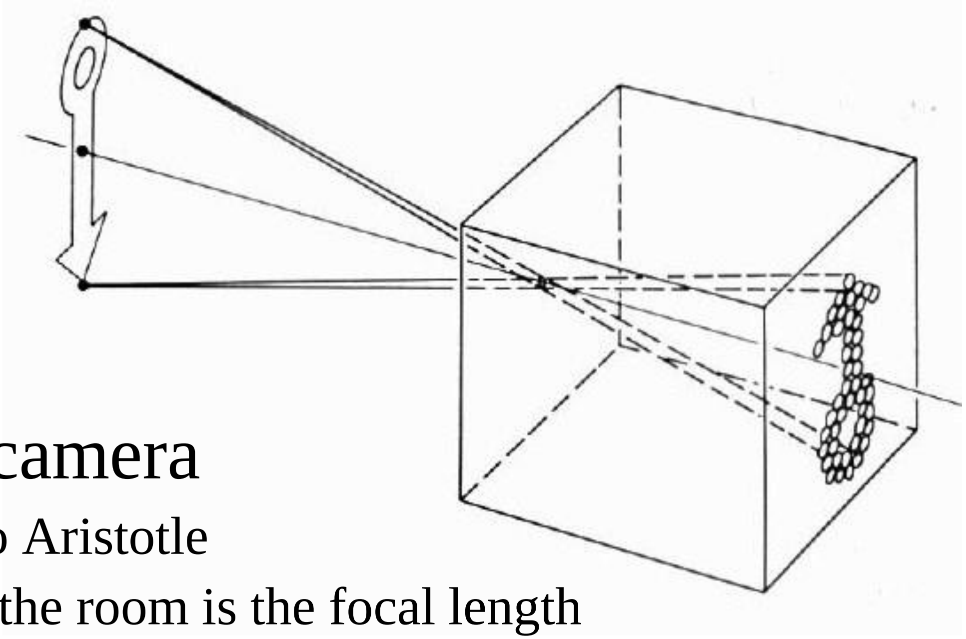
Pinhole camera



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

Slide by Steve Seitz

Camera Obscura (a.k.a. darkroom)

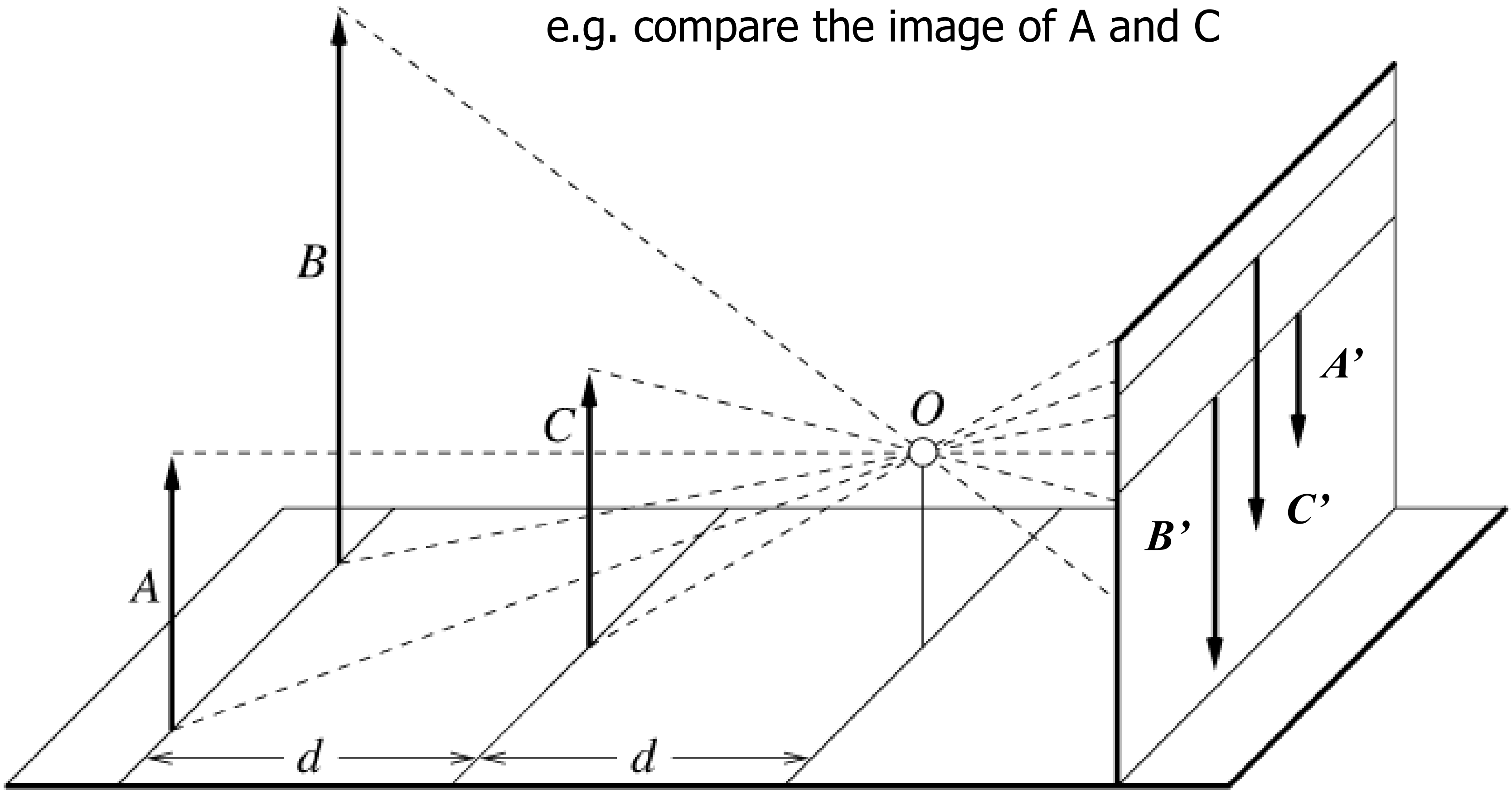


- The first camera
  - Known to Aristotle
  - Depth of the room is the focal length
  - *Pencil of rays* – all rays through a point
- 3D world is projected on an image plane (2D)
- Can we restore 3D points from their image?
  - That is, **can we measure distances** (the lost 3^{rd} dimension)?

Figure by David Forsyth

Depth is ambiguous as distant objects appear smaller

e.g. compare the image of A and C



- Eventually, we will learn methods for restoring depth

  (prior knowledge about 3D world, geometric constraints, learning)

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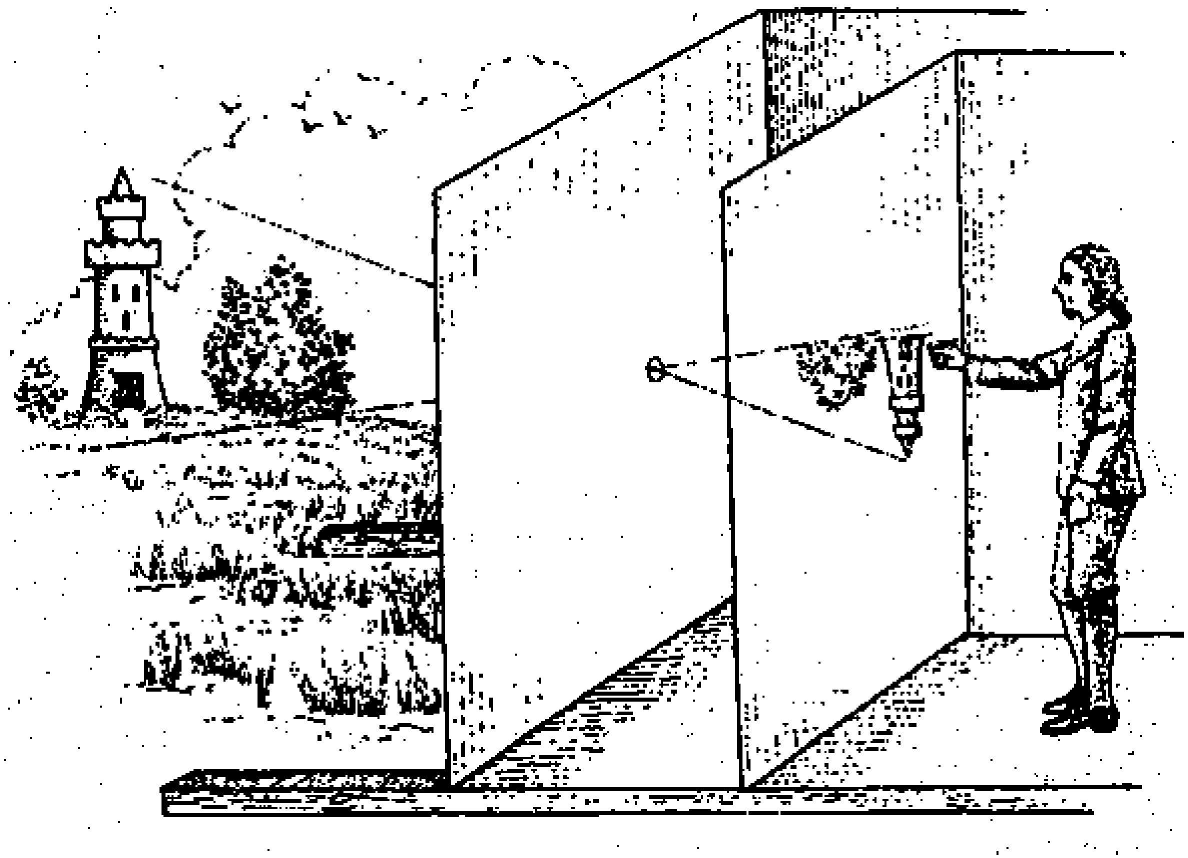
Slide by Aleosha Efros

How to record an image

Drawing from "The Great Art of Light and Shadow "

Jesuit Athanasius Kircher, 1646.



Camera Obscura

Slide by Aleosha Efros

Home-made pinhole camera

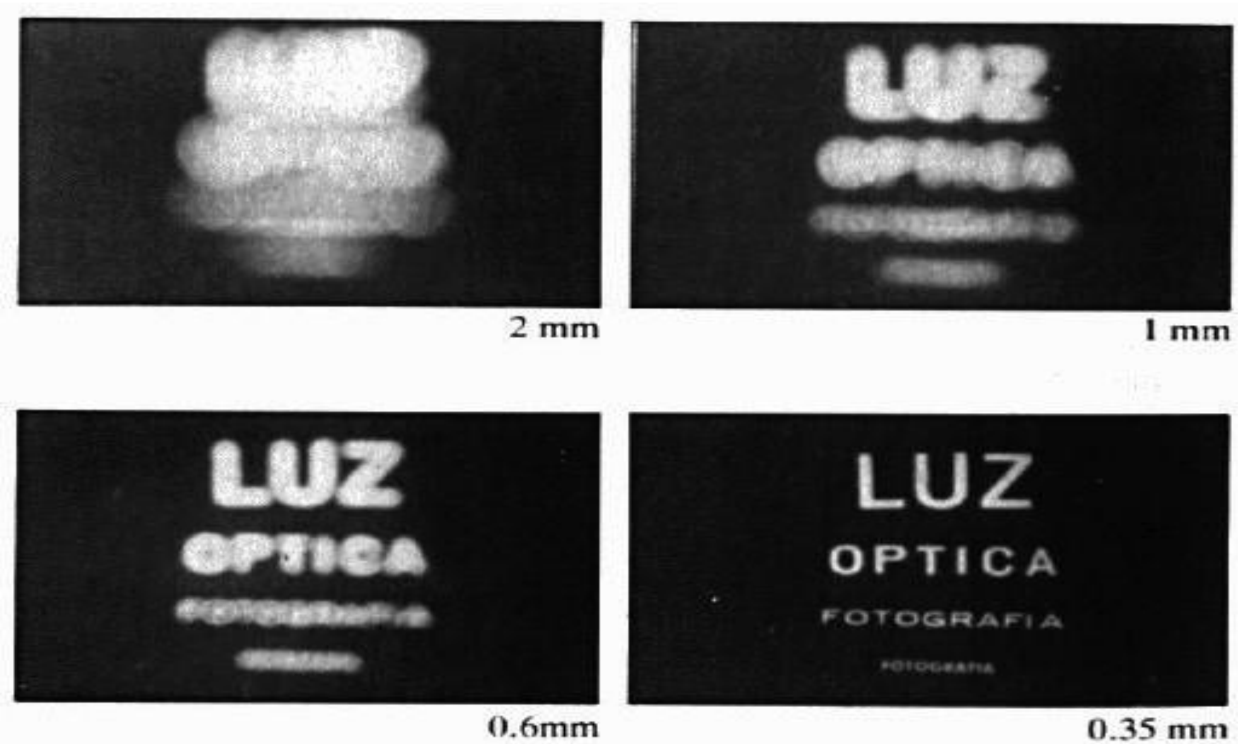
electronic CCD or CMOS image sensors

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

How does the aperture size affect the image?

Slide by Steve Seitz

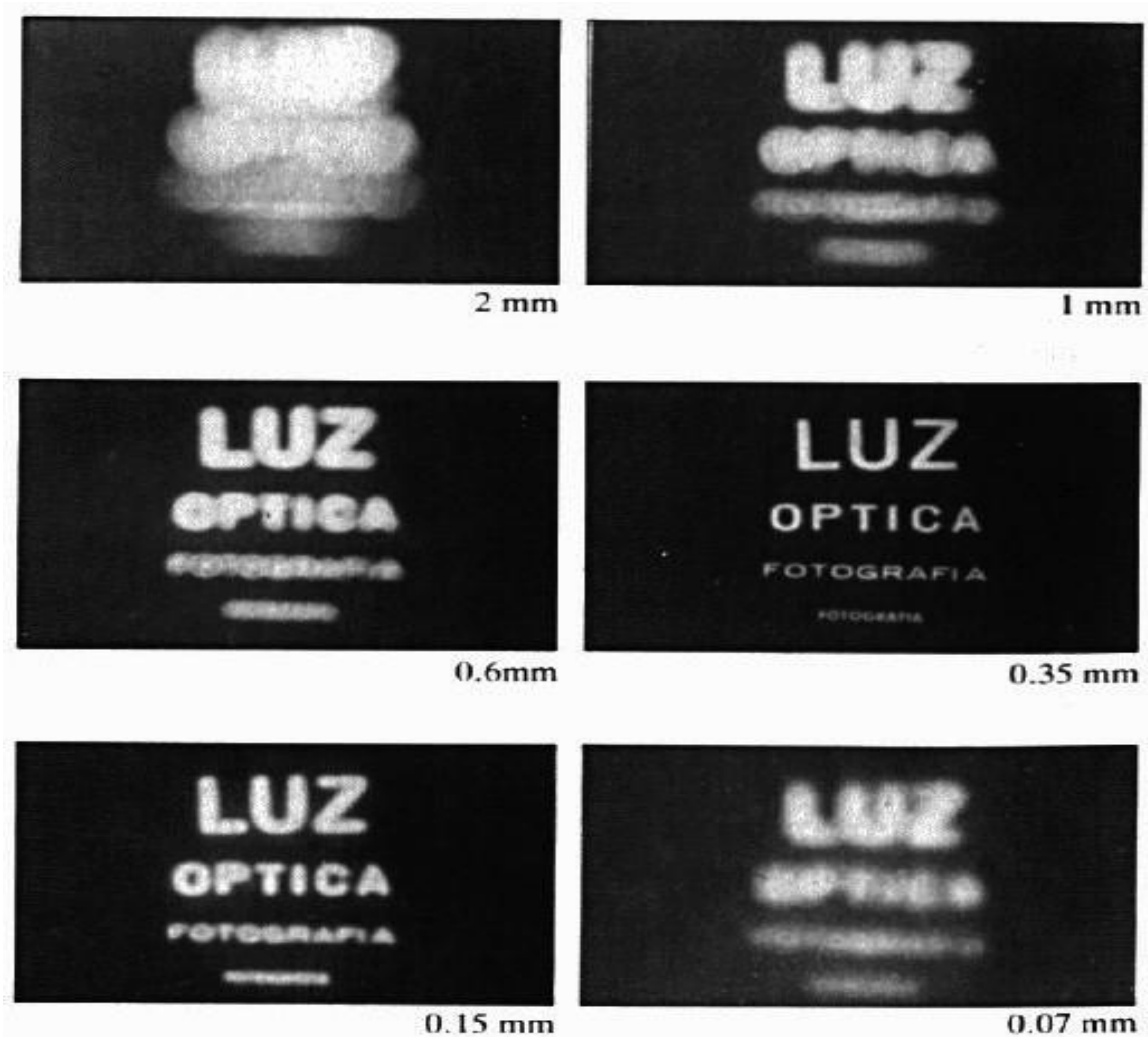
Shrinking the aperture



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

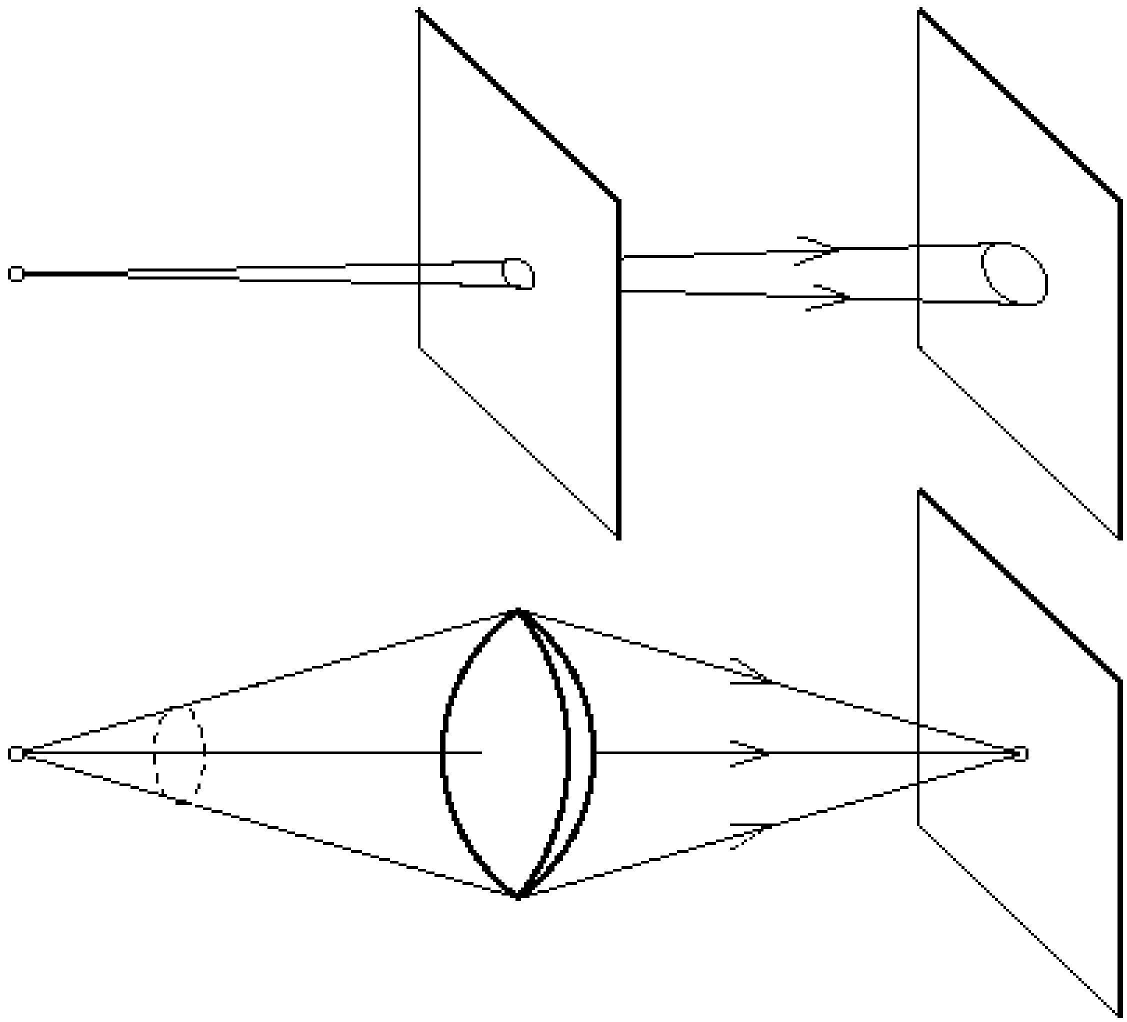
Slide by Steve Seitz

Shrinking the aperture



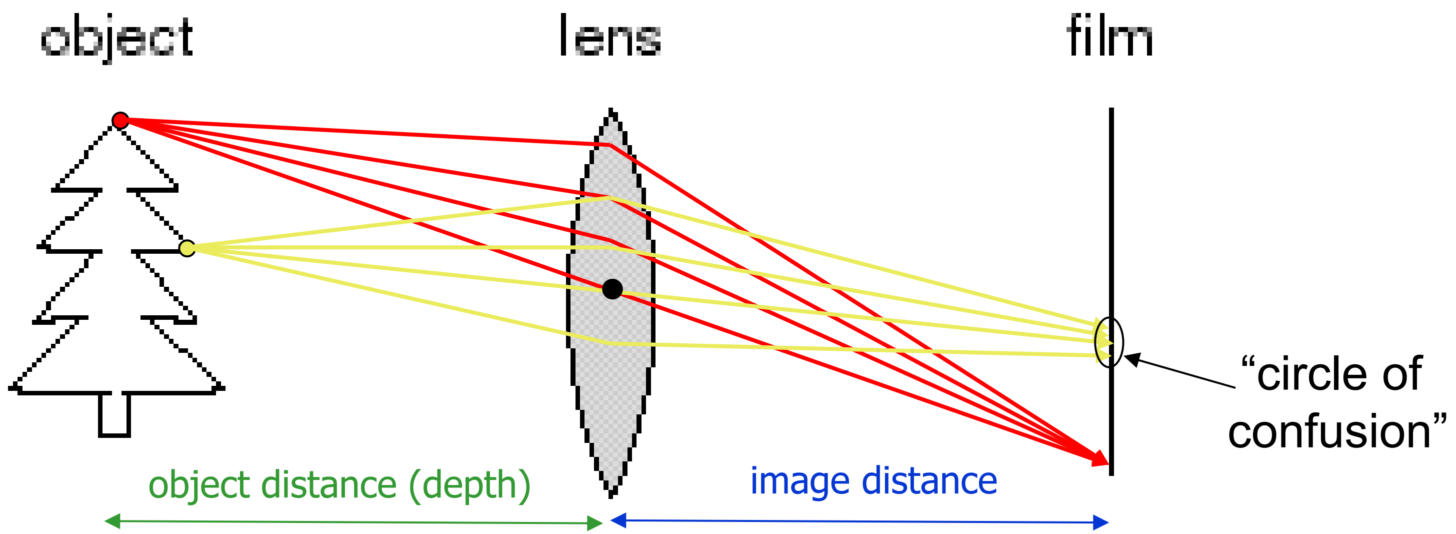
Slide by Steve Seitz

The reason for lenses



Slide by Steve Seitz

Adding a lens

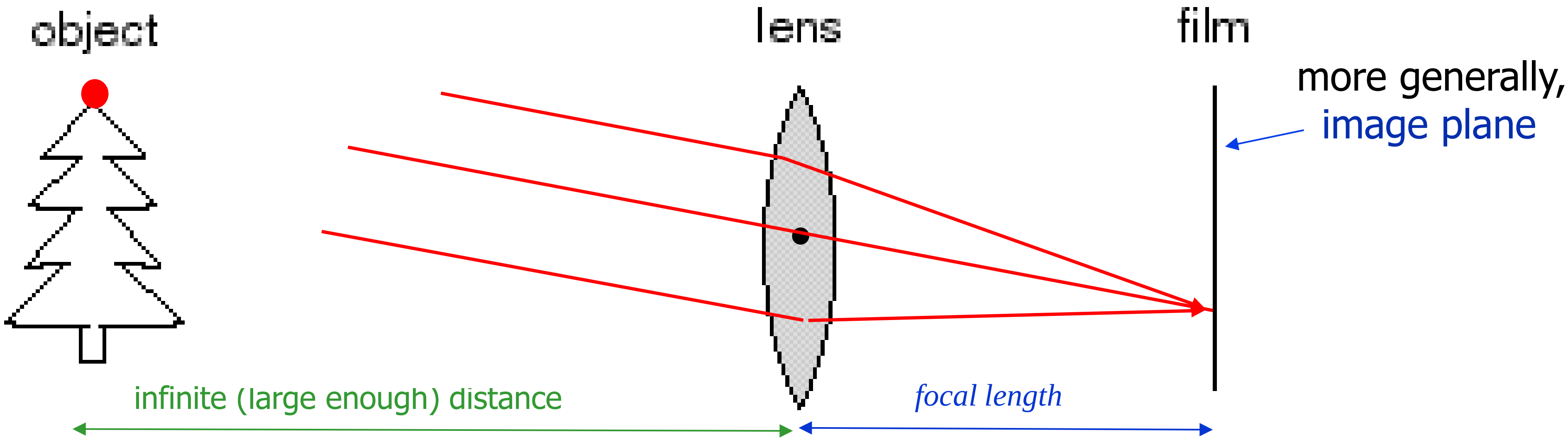


- A lens focuses light onto the film
  - There is a specific depth at which objects are "in focus"
    - other points project to a "circle of confusion" in the image
  - Changing image distance changes this depth (see a problem in HW0)

NOTE: *depth-from-focus* - estimate "depth map" by finding "sharp" image regions while changing either image distance or lens' *focal length*.

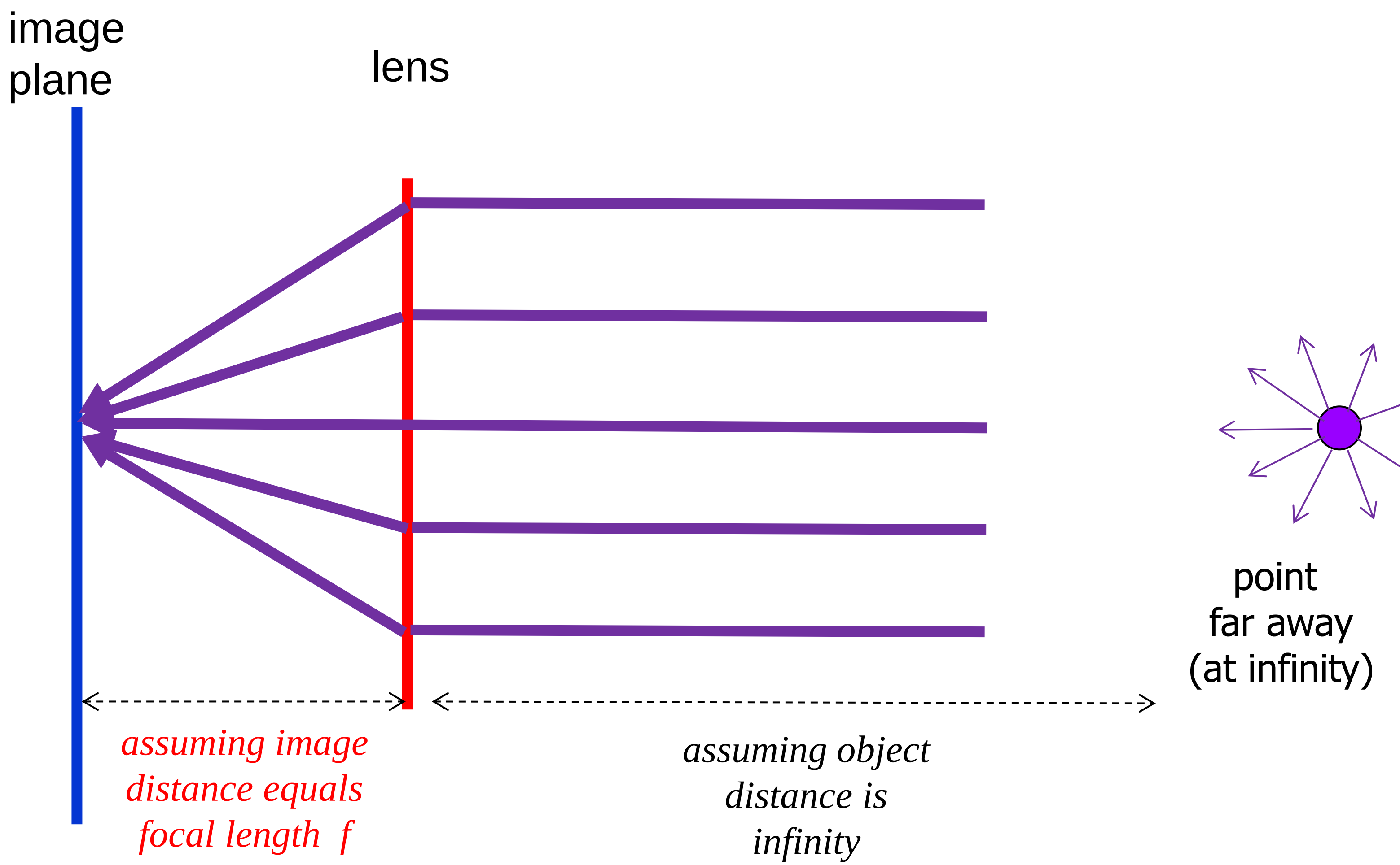
Slide by Steve Seitz

Adding a lens

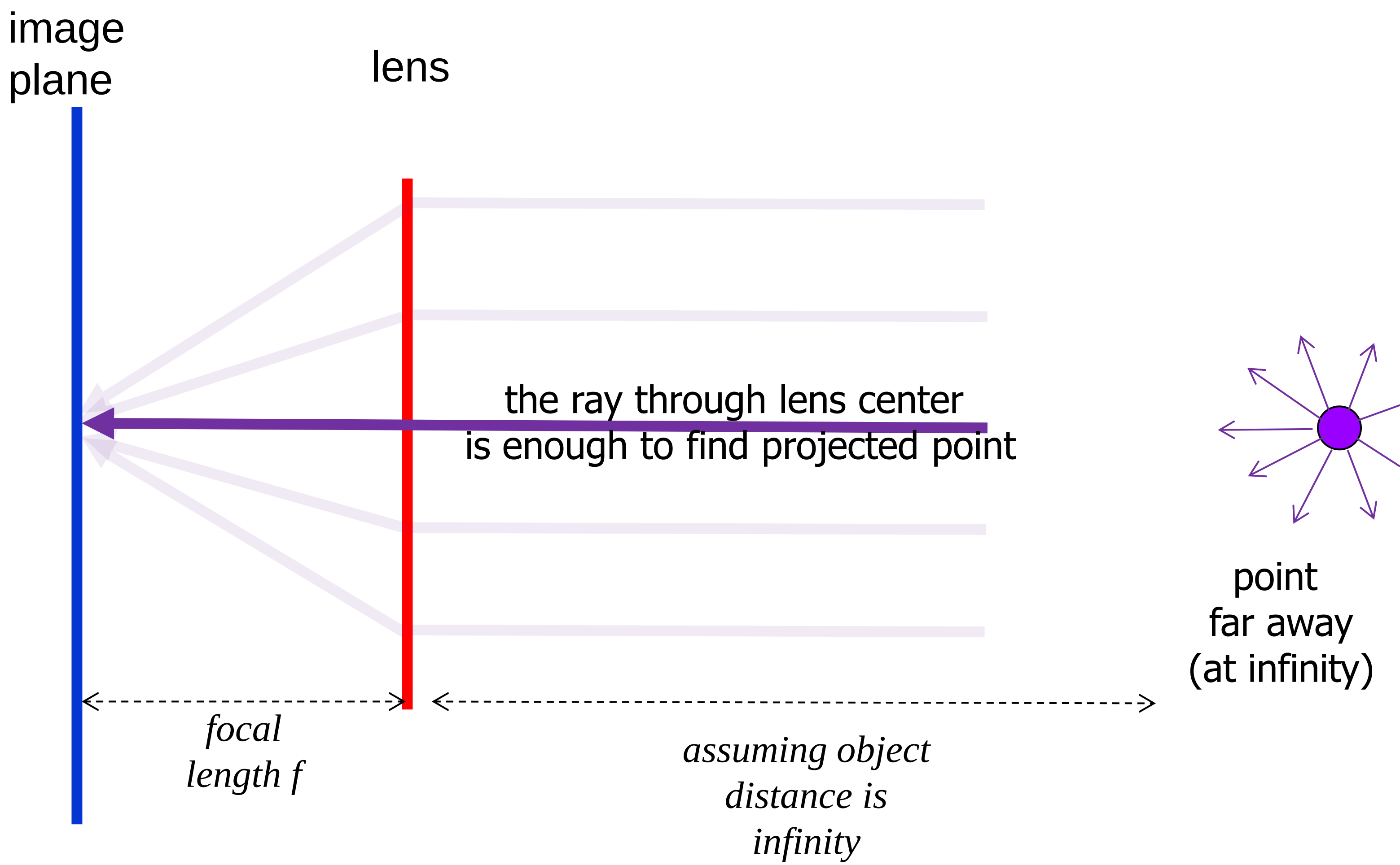


- Lens' **focal length** is image distance where objects at infinity appear in focus.
    - Focal length depends on lens' construction (e.g. surface radius). Some lenses may allow changing their focal length (typically, these are multi-lens constructions).
    - To focus on closer objects, image distance should differ from lens' focal length (see a problem in HW0)

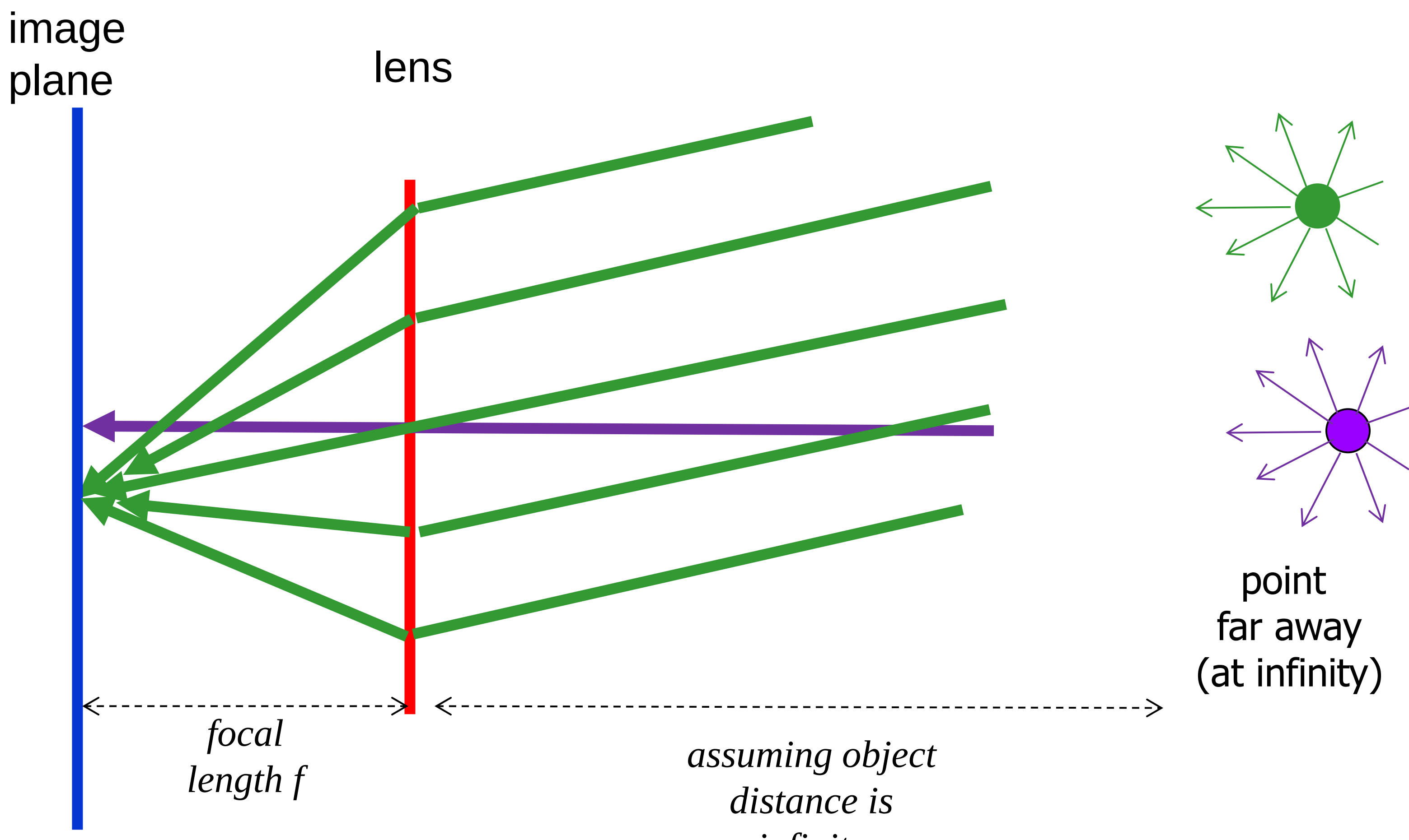
Basic lens camera



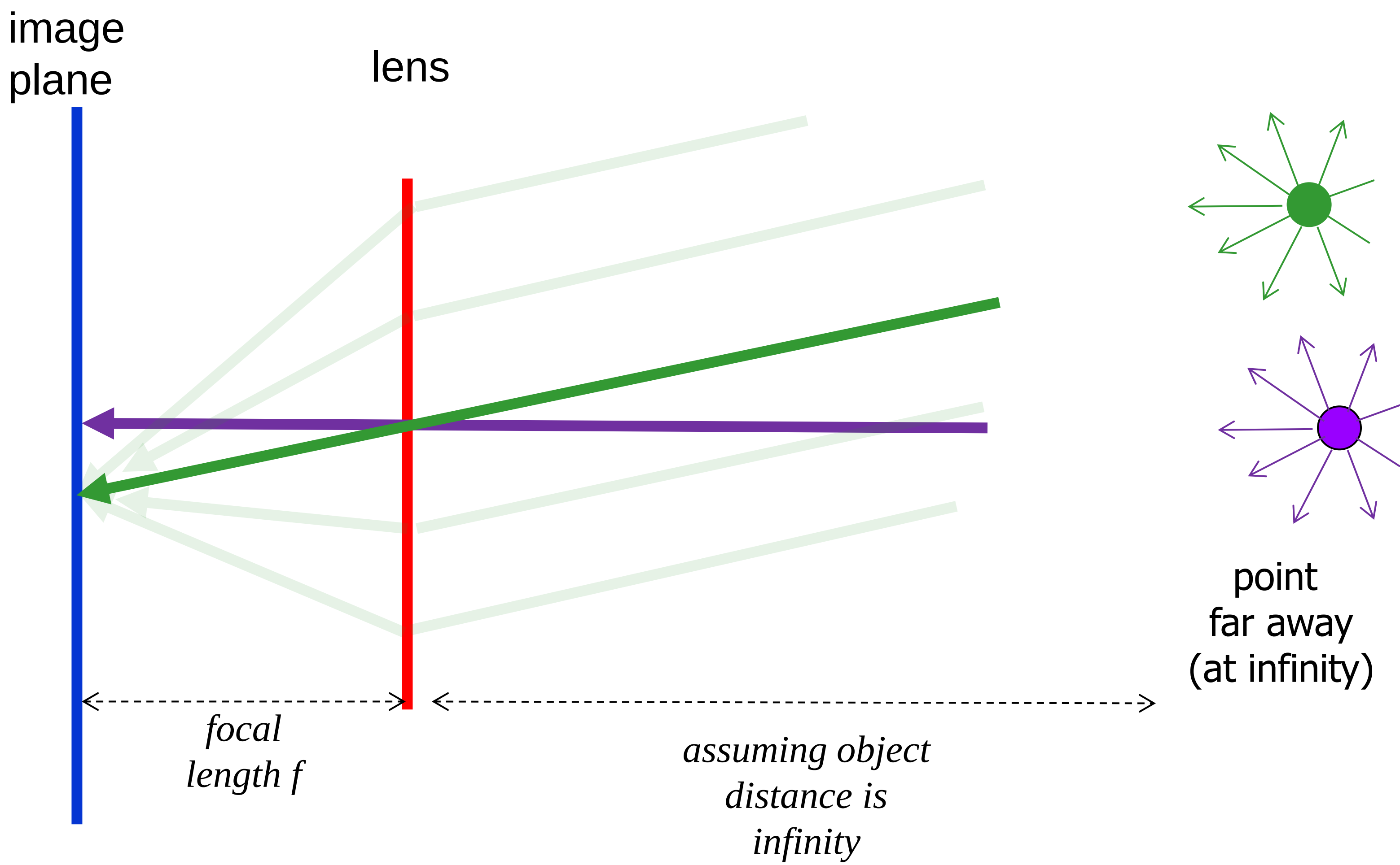
Basic lens camera



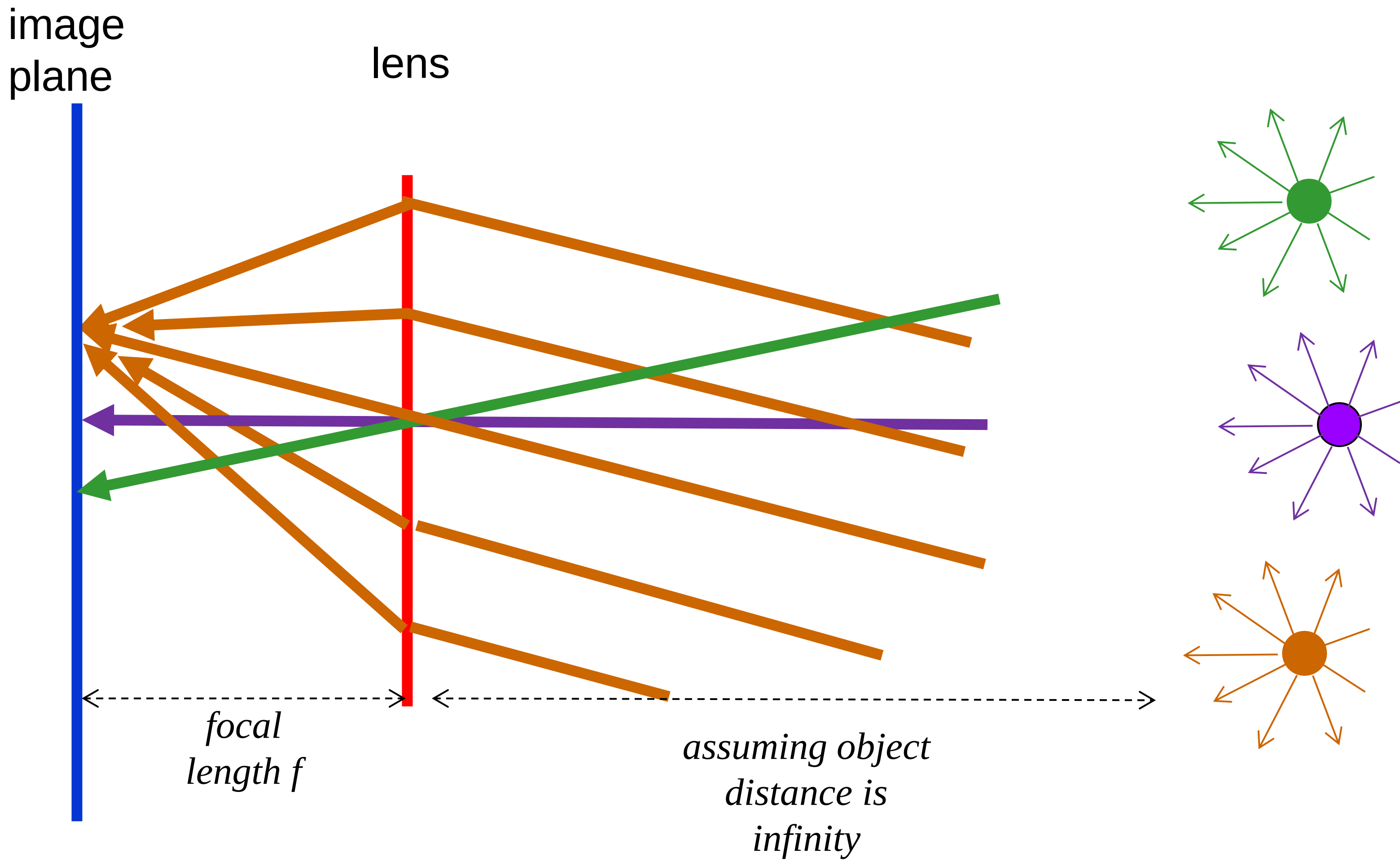
Basic lens camera



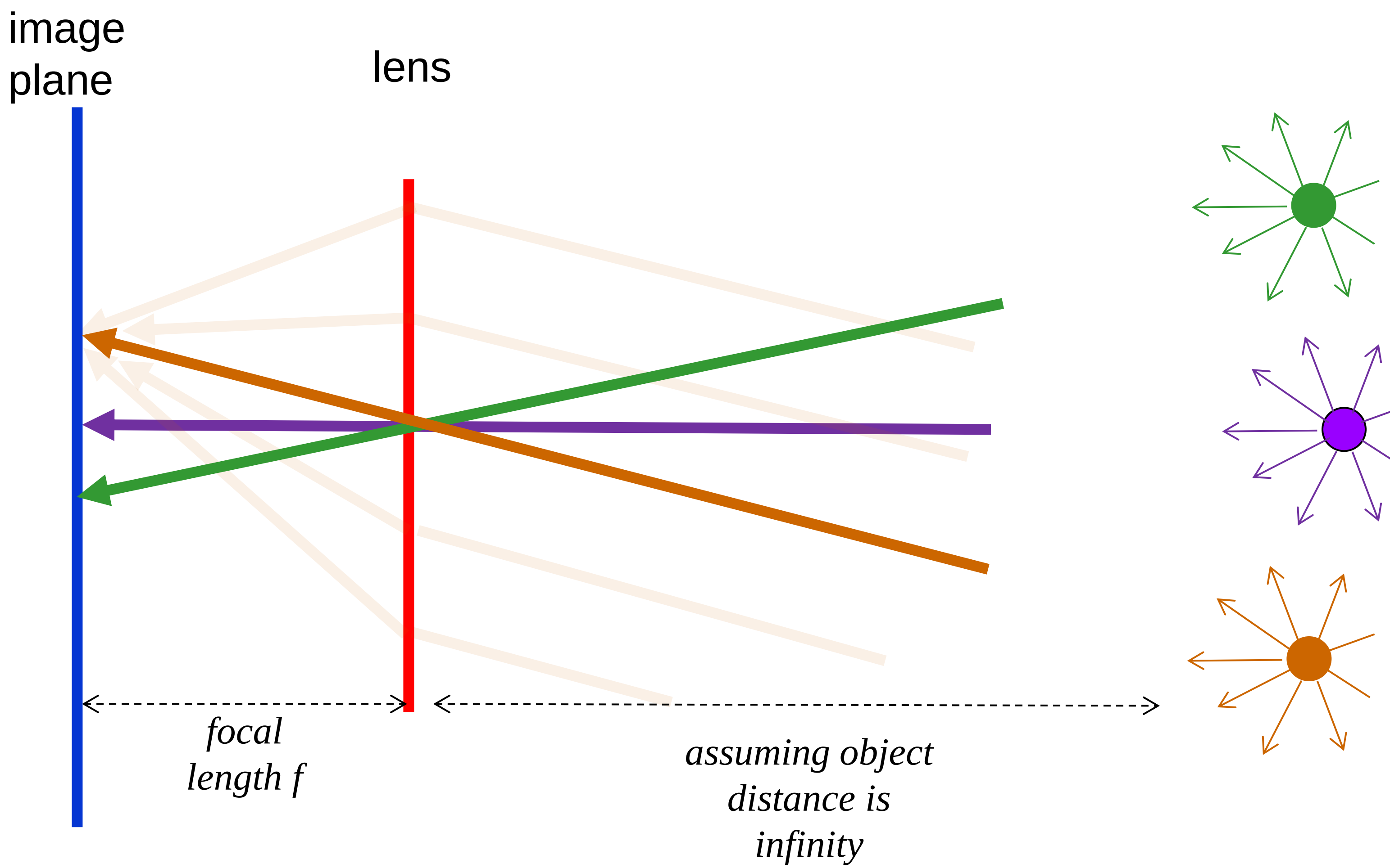
Basic lens camera



Basic lens camera

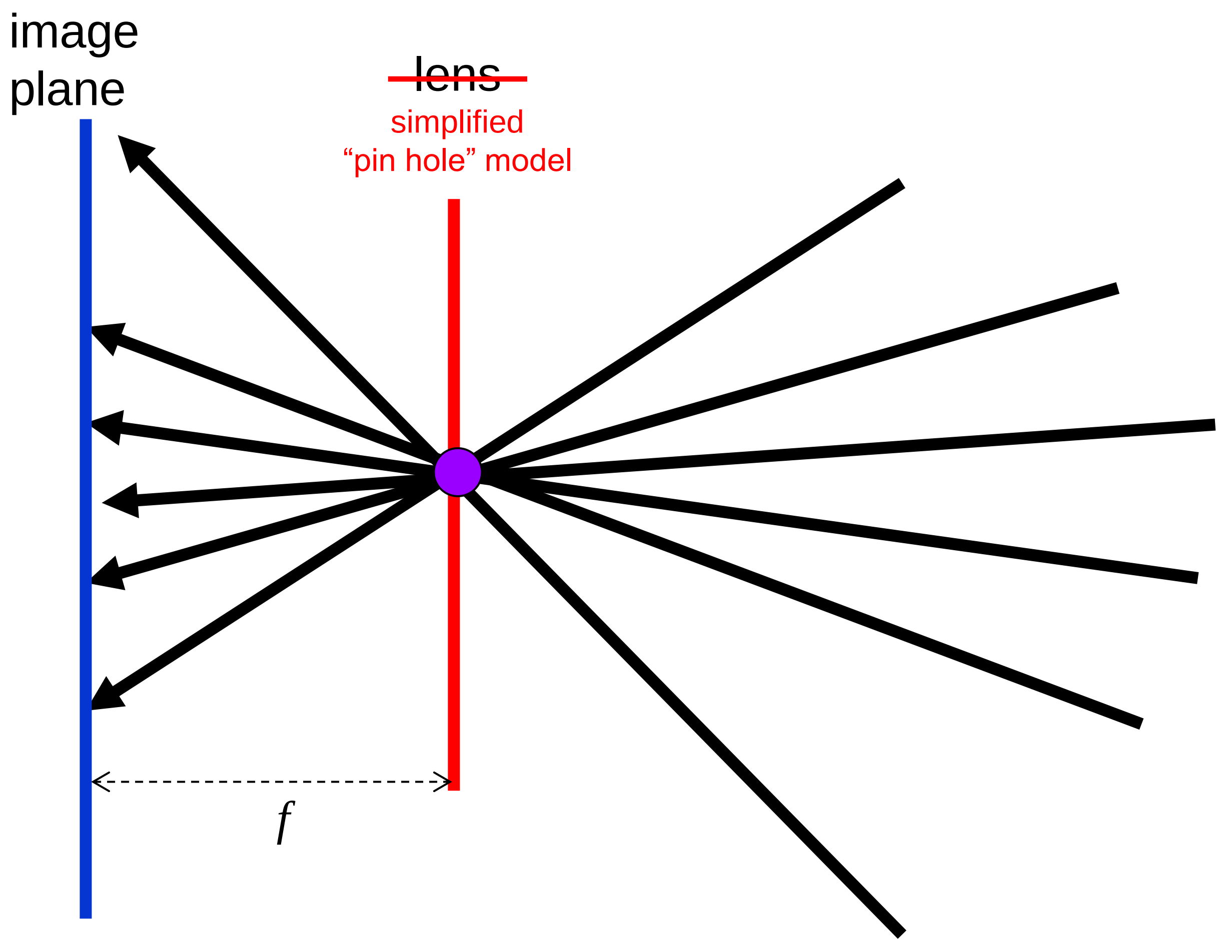


Basic lens camera



NOTE: - Rays from closer 3D points converge at a "circle of confusion" if image distance is lens' focal length.
- In-focus points can be adjusted by changing image distance.
- We use simplified "**pin hole camera model**" ignoring "out-of-focus" issues assuming 3D points are far enough.

Basic camera model: “pin hole”

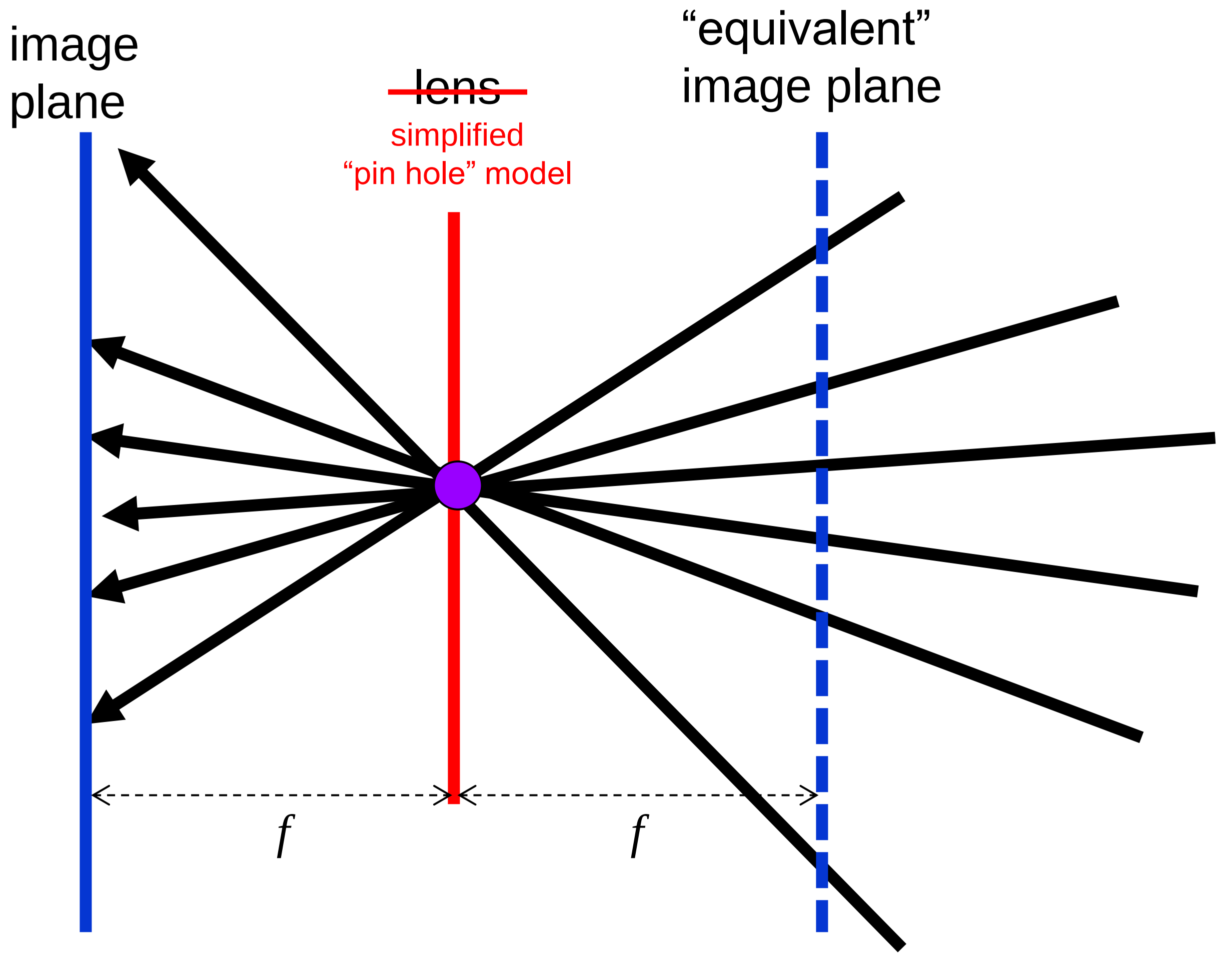


NOTE:

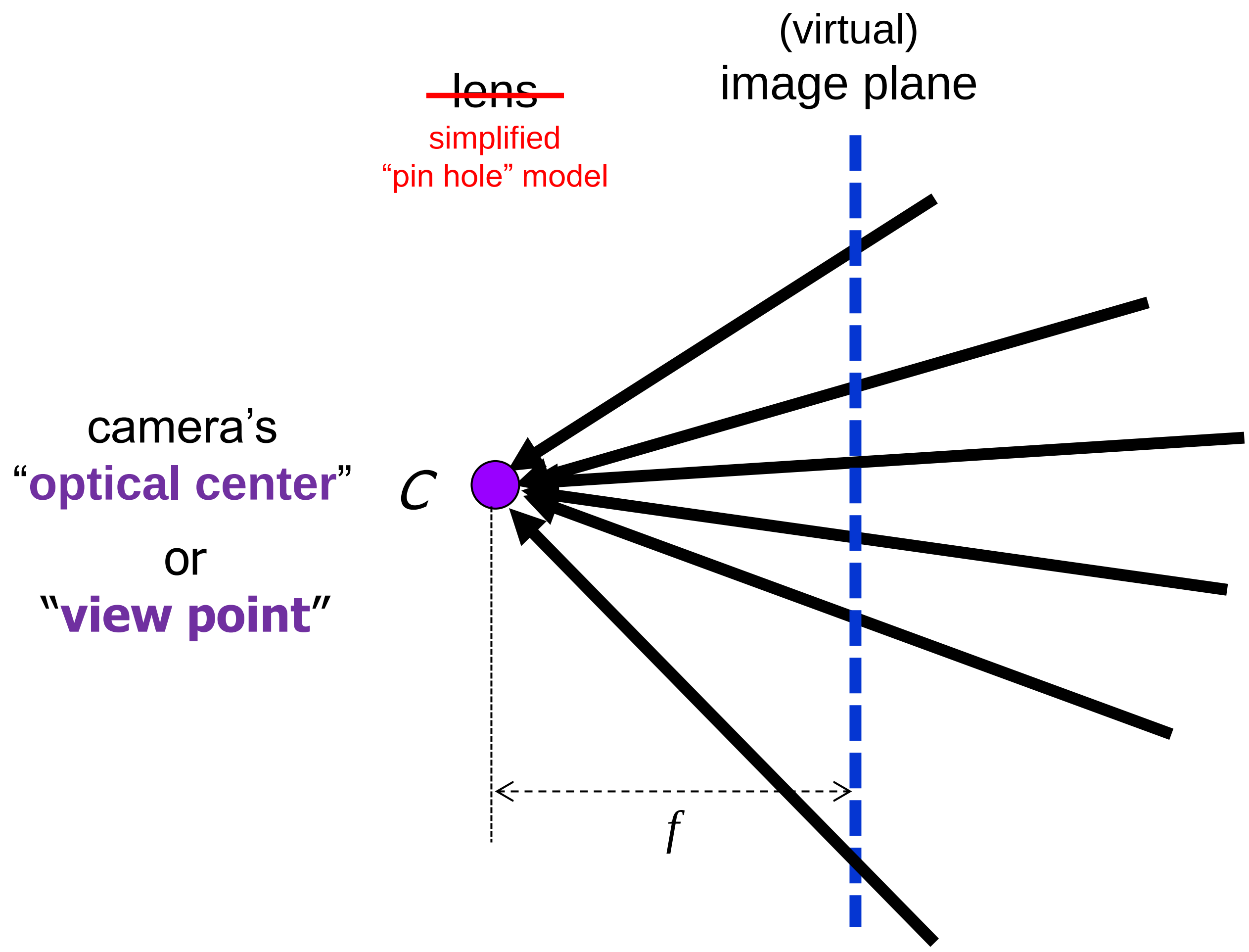
for pin hole camera model “focal length” (f) is defined as image distance (to the “hole”).

As mentioned earlier, focal length of a lens does not have to be equal to the image distance (to the lens).

Basic camera model: “pin hole”



Basic camera model: "pin hole"



Simplified camera representation: image plane is drawn in front of the optical center.
We will use such "**pin hole" camera model** later in the course.

Simple example of projective geometry (from 3D point to 2D pixel)

Consider a simple example of so-called **camera-centered 3D world coordinate system** (x,y,z):

for world points (3D)

camera-centered world coordinate system

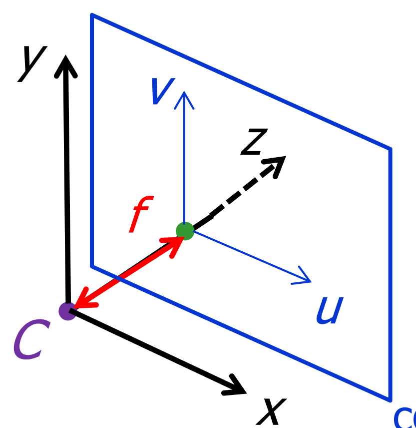


image coordinate system

for image pixels locations (2D)

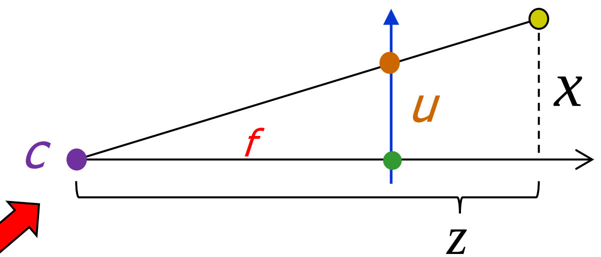
Simplifying Assumptions

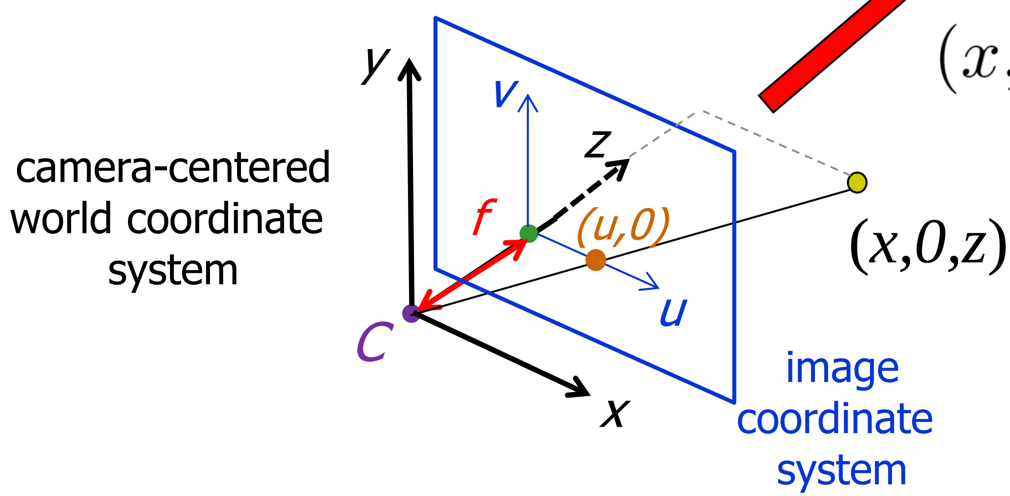
(more general case in Topic 7)

- world coordinate system center (0,0,0) is at optical center C
- x-y plane is parallel to the image plane
- x and y axis parallel to u and v axis of the image coordinate system
- axis z (called ***optical axis***) intersects image at its coordinate center (0,0)

Simple example of projective geometry (from 3D point to 2D pixel)

First, consider arbitrary world point inside x-z plane





$$(x, 0, z) \rightarrow (f\frac{x}{z},\ \ 0\ )$$

u v

image-based coordinates of the **projection point**

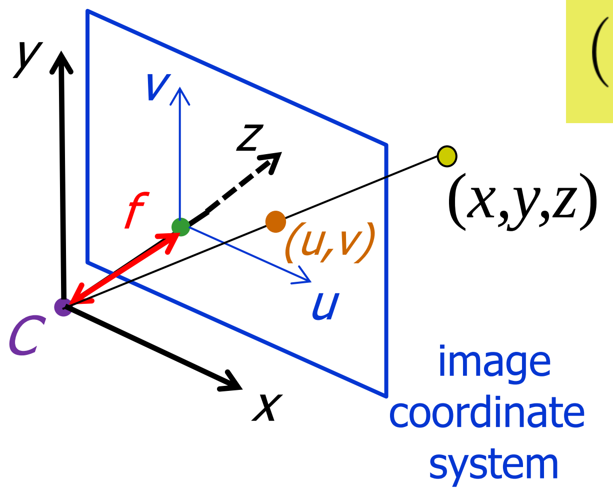
It projects onto some image point/pixel (*u*,0) on axis *u*

(by construction, intersection of x-z plane with the image plane is axis *u*)

Simple example of projective geometry (from 3D point to 2D pixel)

For a general point (x,y,z) in 3D

camera-centered world coordinate system



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

u v

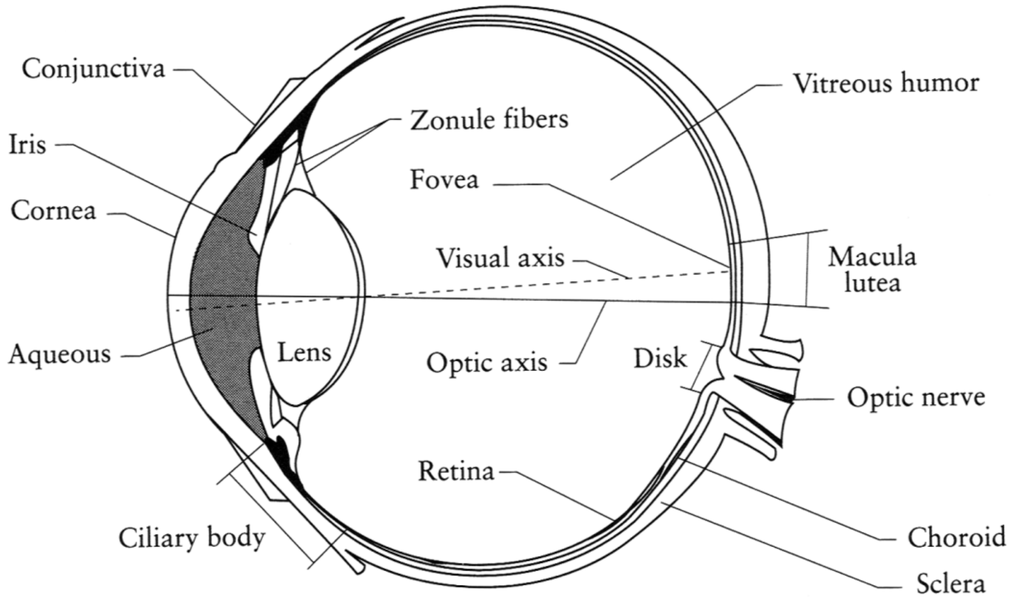
image-based coordinates of the **projection point**

Simple observation: size of any 3D object image is inversely proportional to object's distance from the camera (z-coordinate value)

We will further study projective camera models in topics 5 and 7

Slide by Aleosha Efros

The eye



- The human eye is a camera!
  - **Iris -** colored annulus with radial muscles
  - **Pupil -** the hole (aperture) whose size is controlled by the iris
  - What's the "film"?
    - photoreceptor cells (rods and cones) in the **retina**

Slide by Aleosha Efros

Cameras

- Widely available

Figure by Gonzalez & Woods

Digital Image Formation

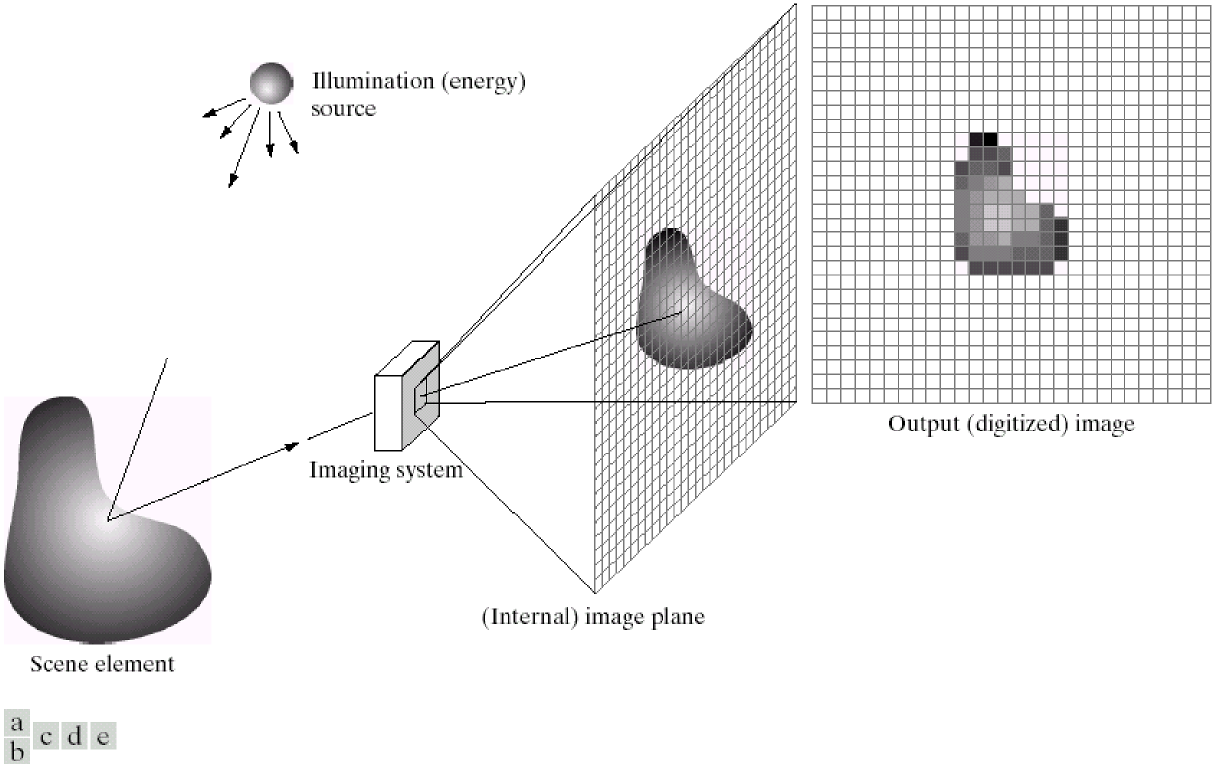


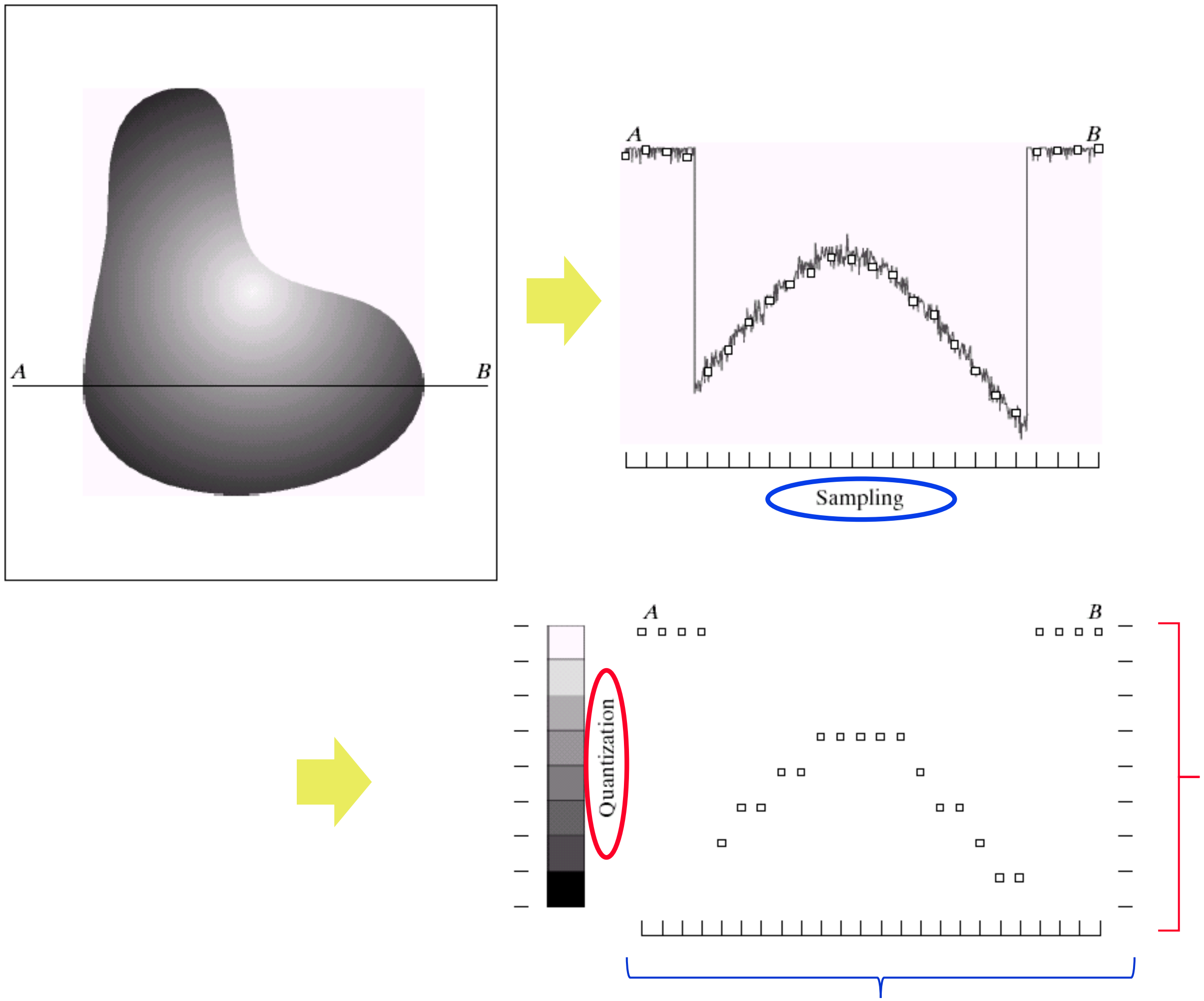
FIGURE 2.15 An example of the digital image acquisition process. (a) Energy ("illumination") source. (b) An element of a scene. (c) Imaging system. (d) Projection of the scene onto the image plane. (e) Digitized image.

*f(x,y) = reflectance(x,y) * illumination(x,y)*

Reflectance in [0,1], illumination in [0,inf]

Figure by Gonzalez & Woods

Sampling and Quantization

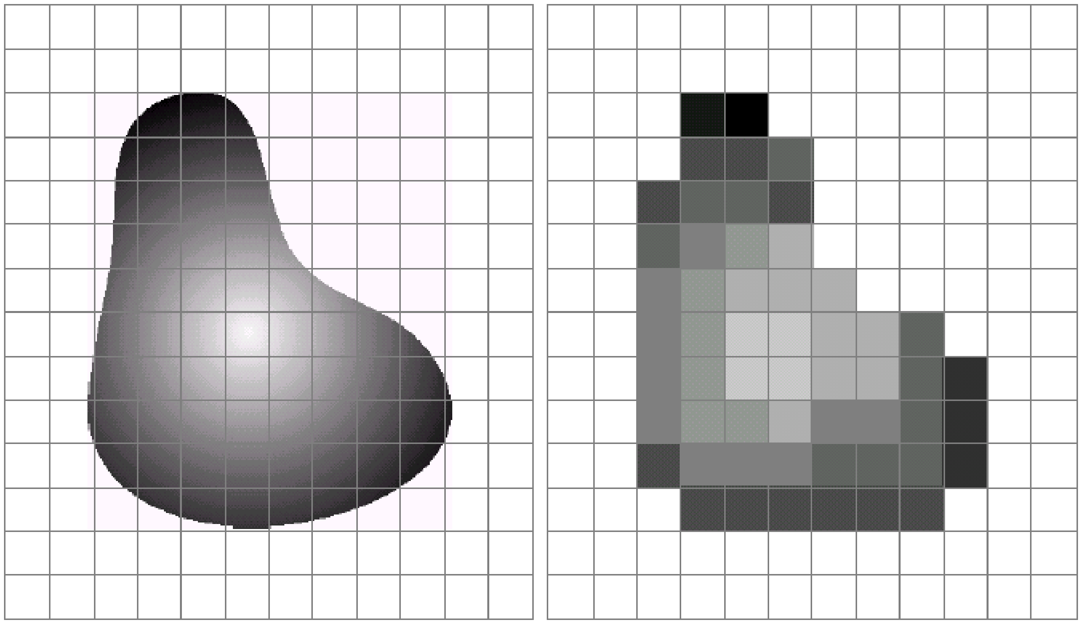


intensity (color) depth
a.k.a. bit depth

spatial resolution
(number of pixels, pixel size)

Figure by Gonzalez & Woods

Sampling and Quantization



a b

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

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Slide by Aleosha Efros

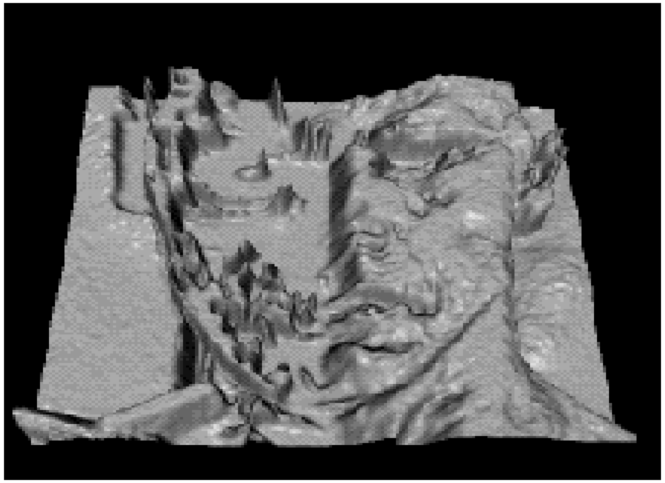
What is an image?

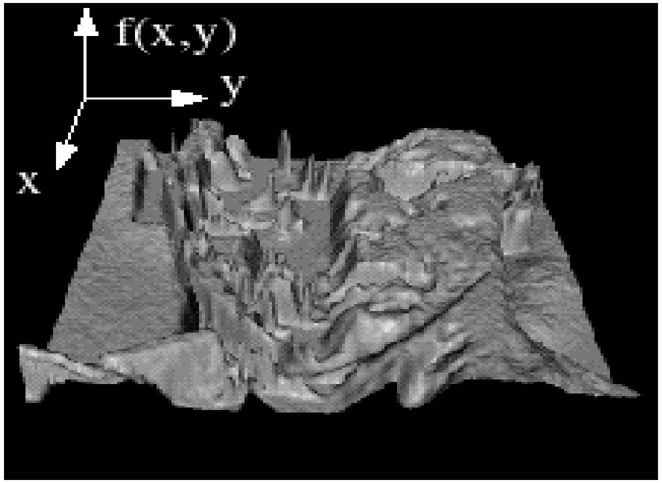
- We can think of an **image** as a function $f(x,y)$ from R^2 to R:
  - $f(x, y)$ gives the **intensity** at position (x, y)
  - Realistically, we expect the image only to be defined over a rectangle, with a finite range:
    - $f: [a,b]\times[c,d] \rightarrow [0,1]$
- A color image is just three functions pasted together. We can write this as a "vector-valued" function:

$$f(x,y) = \begin{bmatrix} r(x,y) \\ g(x,y) \\ b(x,y) \end{bmatrix}$$

Slide by Aleosha Efros

Images as functions $f(x, y) : \mathcal{R}^2 \rightarrow \mathcal{R}$





Slide by Aleosha Efros

What is a digital image?

- We usually operate on **digital** (**discrete**) images:
  - **Sample** the 2D space (XY) on a regular grid
  - **Quantize** each intensity sample (round to nearest integer)
- If our samples are Δ apart, we can write this as:

$$f[i, j] = \text{Quantize}\{ f(i\,\Delta, j\,\Delta) \}$$

- The image can be represented as a matrix (2D array) of integers

$j \rightarrow$, $i \downarrow$

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

quantized intensities

Image Data "Tensors" (multidimensional arrays)

- We usually operate on **digital** (**discrete**) images:
  - **Sample** the 2D space (XY) on a regular grid
  - **Quantize** each intensity sample (round to nearest integer)
- If our samples are Δ apart, we can write this as:

$$f[i, j] = \text{Quantize}\{ f(i\,\Delta, j\,\Delta) \}$$

- **Color image** can be stored as a 3D array (tensor) of integers

j →

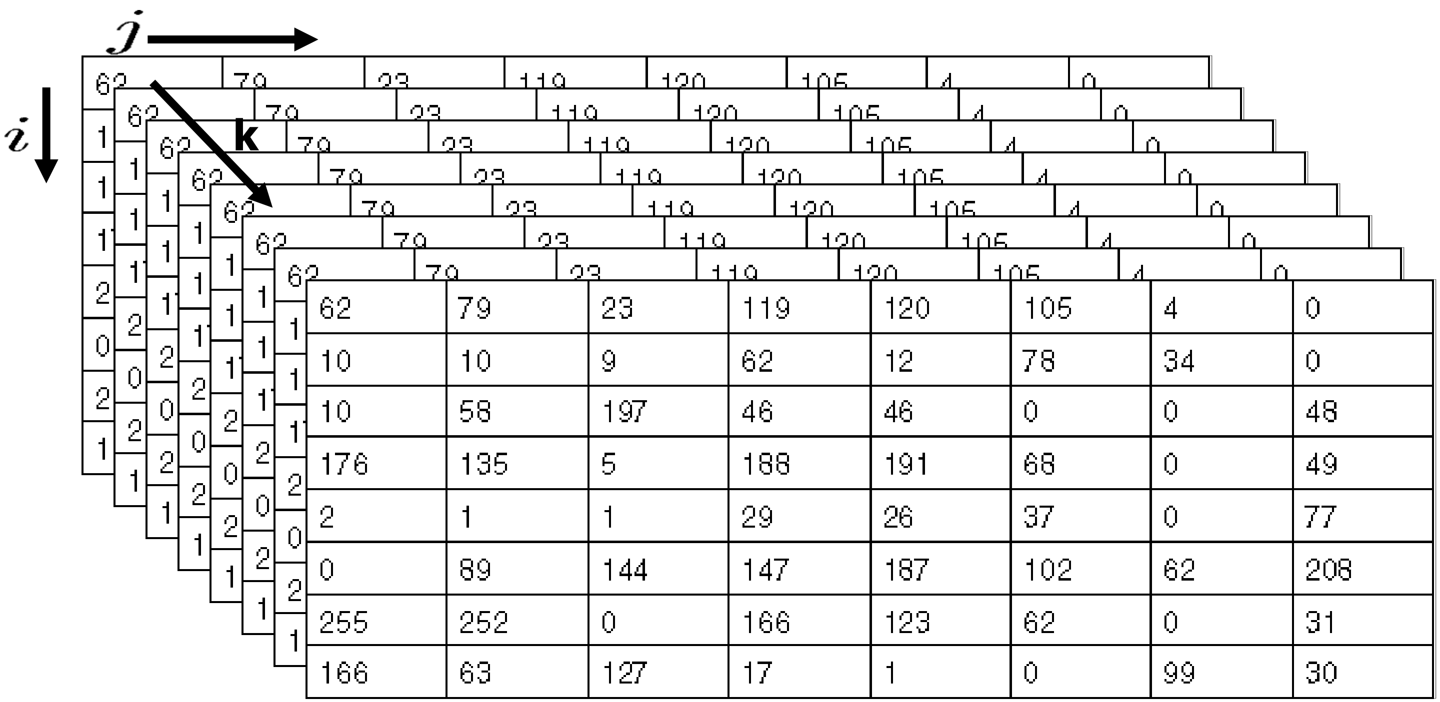
i ↓

RGB

62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
10	58	197	46	46	0	0	48
176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

Image Data "Tensors" (multidimensional arrays)

- Video - 3D = **X*Y*Time**
- Medical volumetric data (MRI, CT) - 3D = **X*Y*Z**



62	79	23	119	120	105	4	0
10	10	9	62	12	78	34	0
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176	135	5	188	191	68	0	49
2	1	1	29	26	37	0	77
0	89	144	147	187	102	62	208
255	252	0	166	123	62	0	31
166	63	127	17	1	0	99	30

Combine multiple images (slices) into a volume

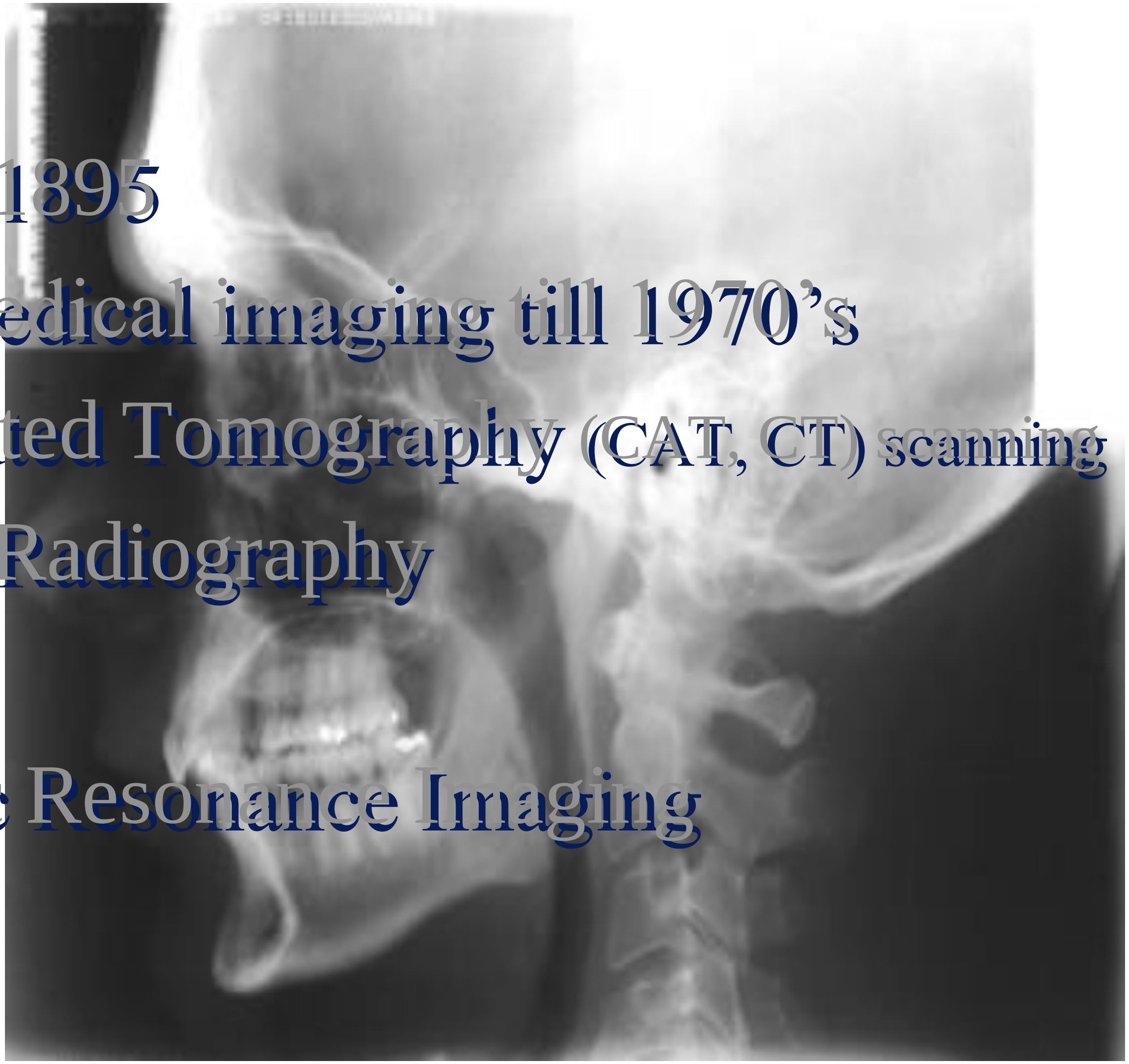
Image Modalities

PART II:
Medical images and volumes

- X-ray
- CT
- MRI
- Ultrasound

Slides from Terry Peters

In the beginning…..X-rays



- Discovered in 1895
- Mainstay of medical imaging till 1970's
- 1971 – Computed Tomography (CAT, CT) scanning
- 1978 - Digital Radiography

  ……….

- 1980 Magnetic Resonance Imaging

X-rays

- Wilhelm Conrad Röntgen (1845-1923)

Nobel Prise in Physics, 1901

- “X” stands for “unknown”
- *X-ray imaging* is also known as
  - radiograph
  - Röntgen imaging

X-rays

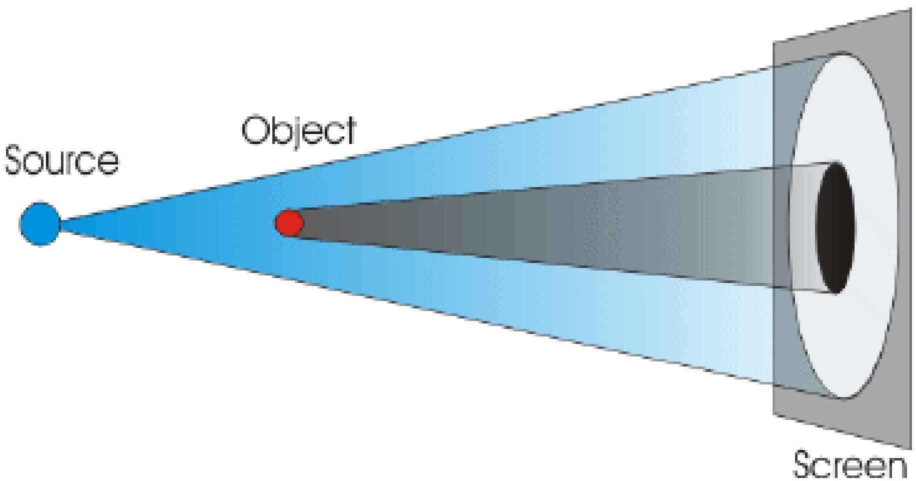
Bertha Röntgen's Hand 8 Nov, 1895

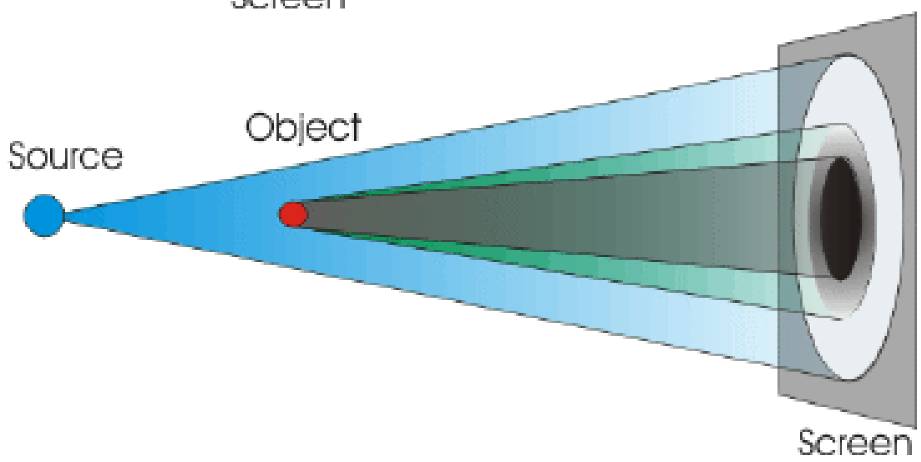
A modern radiograph of a hand

- Calcium in bones absorbs X-rays the most
- Fat and other soft tissues absorb less, and look gray
- Air absorbs the least, so lungs look black on a radiograph

X-rays

2D “**projection**” imaging 1895 - 1970’s





From Projection Imaging Towards True 3D Imaging

X-ray imaging
1895

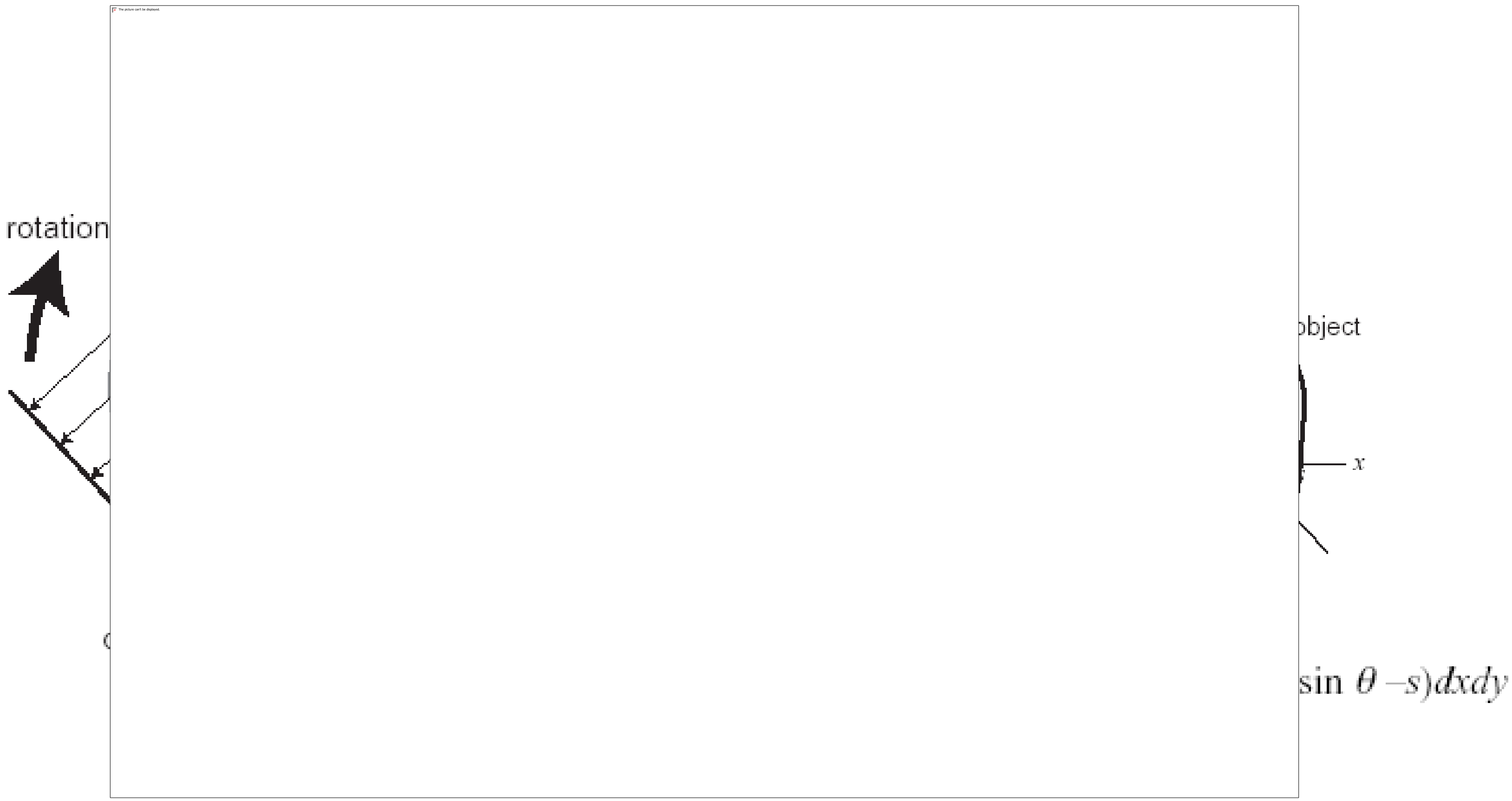
Mathematical results:
Radon transformation
1917

Computers can perform complex mathematics to reconstruct and process images
Late 1960's:

Development of CT
(computed tomography)
1972

- Image reconstruction from projection
- Also known as CAT (Computerized Axial Tomography)
- "tomos" means "slice" (Greek)

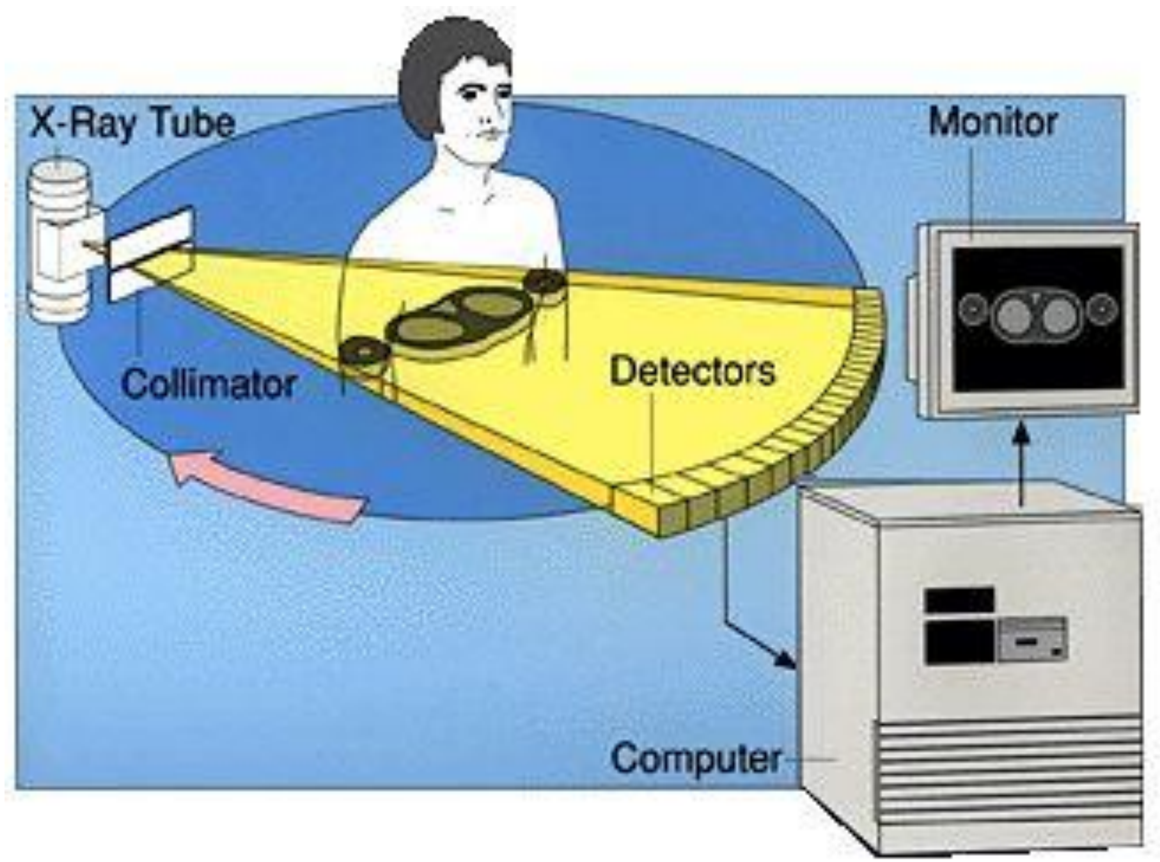
Radon Transformation



- Mathematical transformation (related to Fourier)
- Reconstruction of the shape of object (distribution *f(x,y)*) from the multitude of 2D projections $g(s,\theta)$

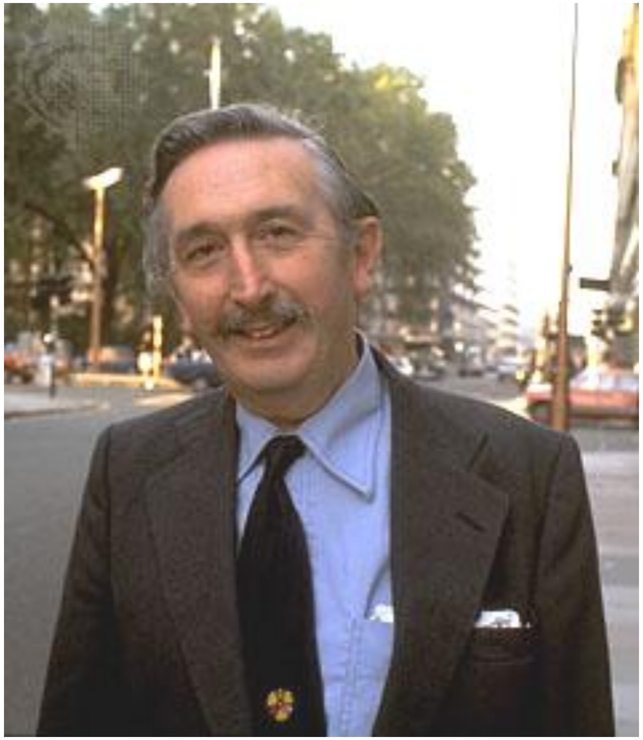
Figure from www.imaginis.com/ct-scan/how_ct.asp

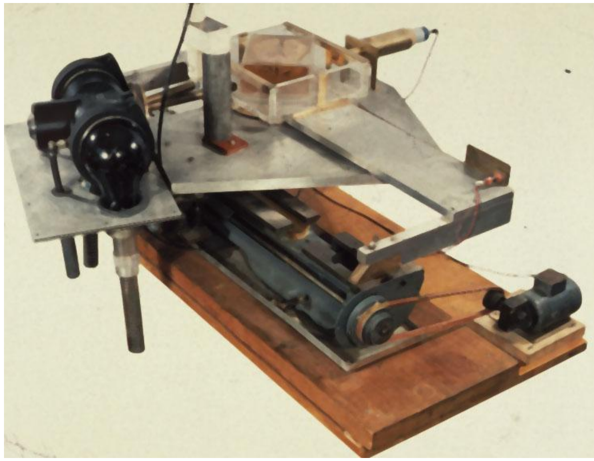
CT imaging



CT imaging, inventing (1972)

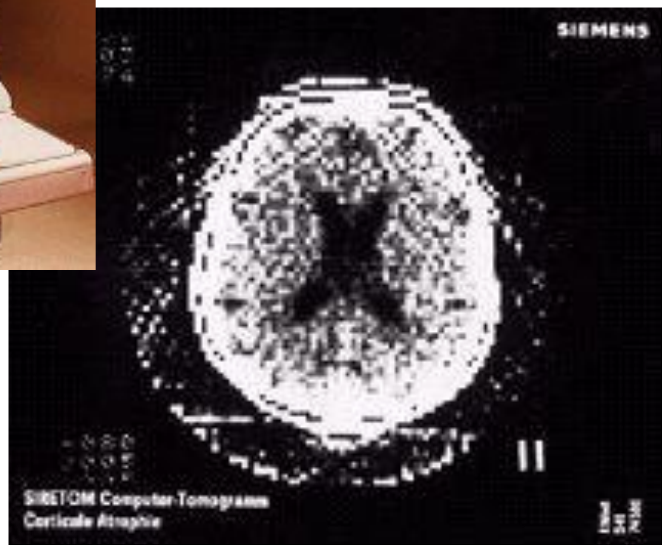
- Sir Godfrey Hounsfield
  Engineer for EMI PLC
  1972
- Nobel Prize 1979 (with Alan Cormack)





CT imaging, availability (since 1975)

1974



Original axial CT image from the dedicated Siretom CT scanner circa 1975. This image is a coarse 128 x 128 matrix; however, in 1975 physicians were fascinated by the ability to see the soft tissue structures of the brain, including the black ventricles for the first time (enlarged in this patient)

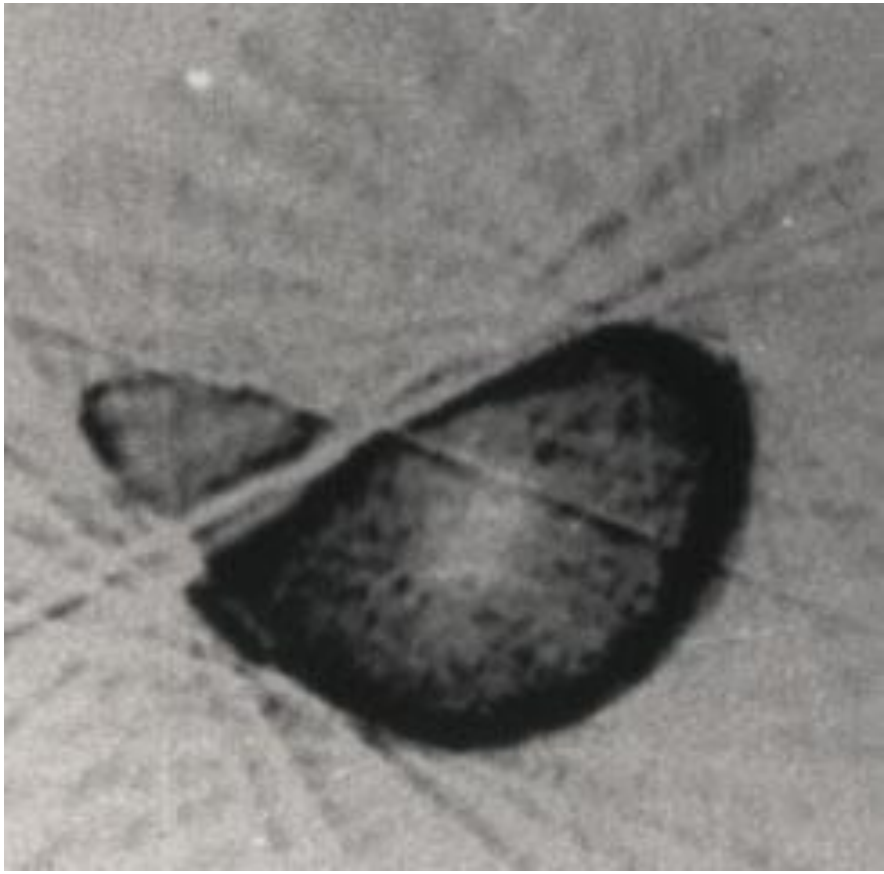
25 years later

Axial CT image of a normal brain using a state-of-the-art CT system and a 512 x 512 matrix image. Note the two black "pea-shaped" ventricles in the middle of the brain and the subtle delineation of gray and white matter (Courtesy: Siemens)

Slides from Terry Peters

Clinical Acceptance of CT!?

- Dr James Ambrose 1972
  - Radiologist, Atkinson - Morley's Hospital London
  - Recognised potential of EMI-scanner
- "Pretty pictures, but they will never replace radiographs" – Neuroradiologist 1972



Slides from Terry Peters

Then ……………….and Now

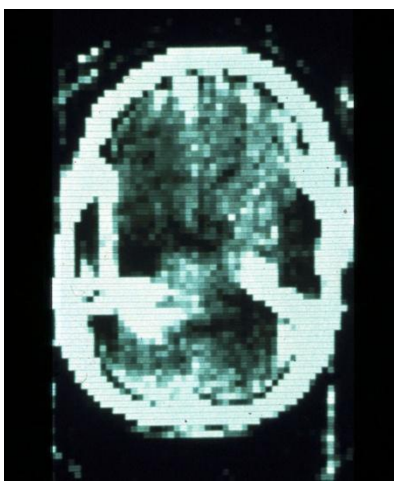
- 80 x 80 image
- 3 mm pixels
- 13 mm thick slices
- Two simultaneous slices!!!
- 80 sec scan time per slice
- 80 sec recon time

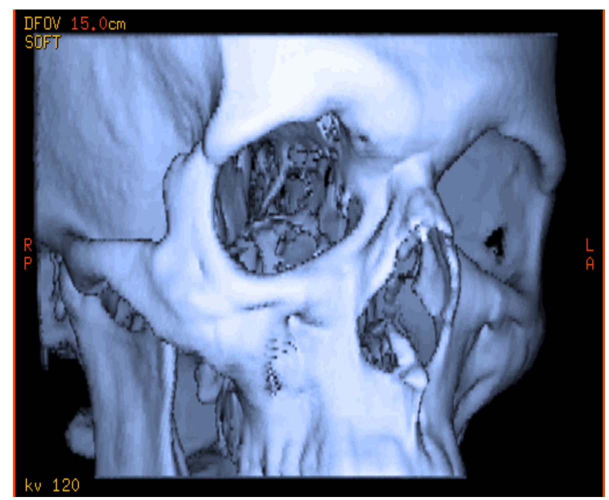
- 512 x 512 image
- <1mm slice thickness
- <0.5mm pixels
- 0.5 sec rotation
- 0.5 sec recon per slice
- Isotropic resolution
- Spiral scanning - up to 16 slices simultaneously

Slides from Terry Peters

30 Years of CT

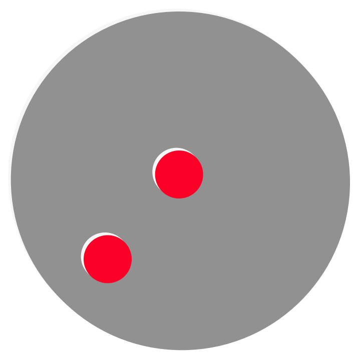


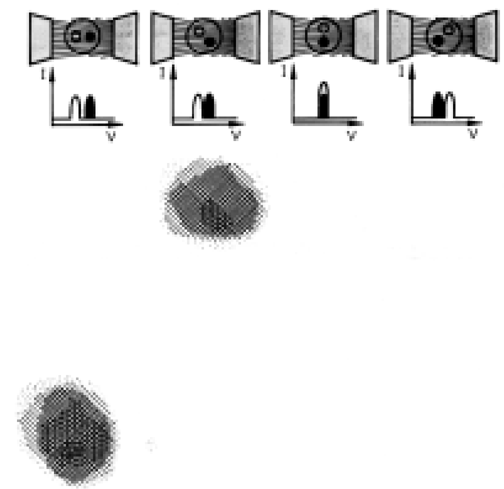


Birth of MRI

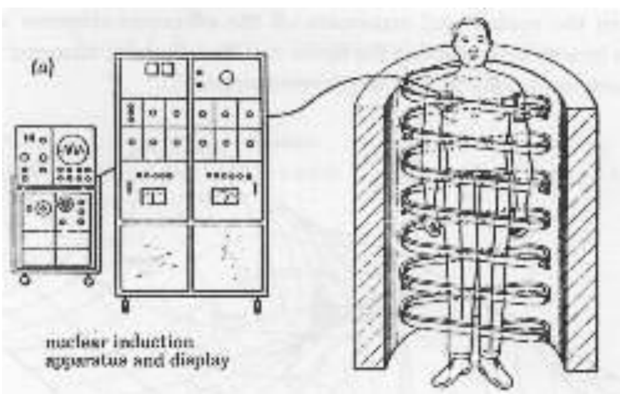
- Paul Lautebur 1975
  - Presented at Stanford CT meeting
  - “Zeugmatography”
- Raymond Damadian 1977 –
- Sir Peter Mansfield early 1980’s

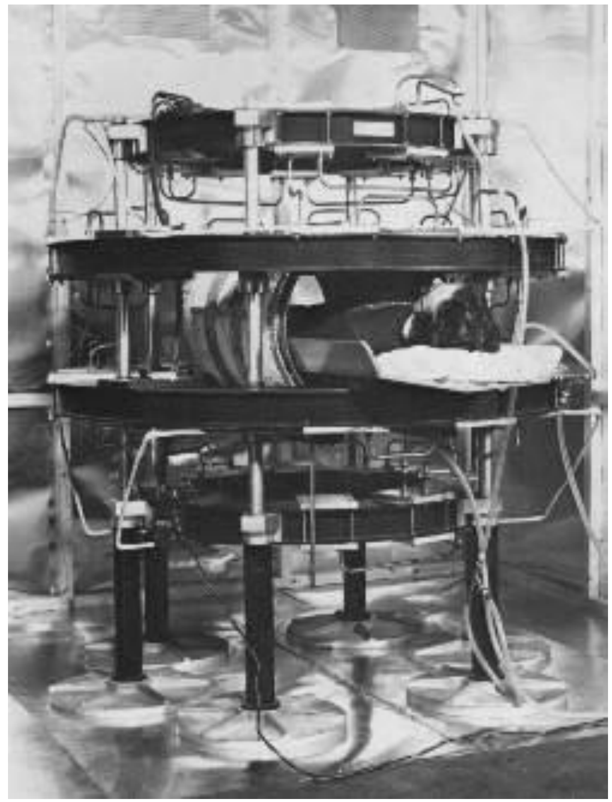




Slides from Terry Peters

Birth of MRI





- Electro Marnetic signal emitted (in harmless radio frequensy) is acquired in the time domain
- image has to be reconstructed (Fourier transform)

Birth of MRI

Lauterbur and the first magnetic resonance images (from *Nature*)

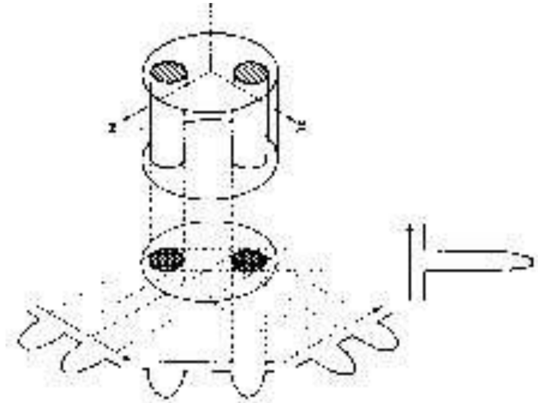


Fig. 1 Relationship between a three-dimensional object, its two-dimensional projection along the Y-axis, and four one-dimensional projections at 45° intervals in the XZ-plane. The arrows indicate the gradient directions.

Fig. 2 Proton nuclear magnetic resonance zeugmatogram of the object described in the text, using four relative orientations of object and gradients as diagrammed in Fig. 1.

In 1978, Mansfield presented his first image through the abdomen.

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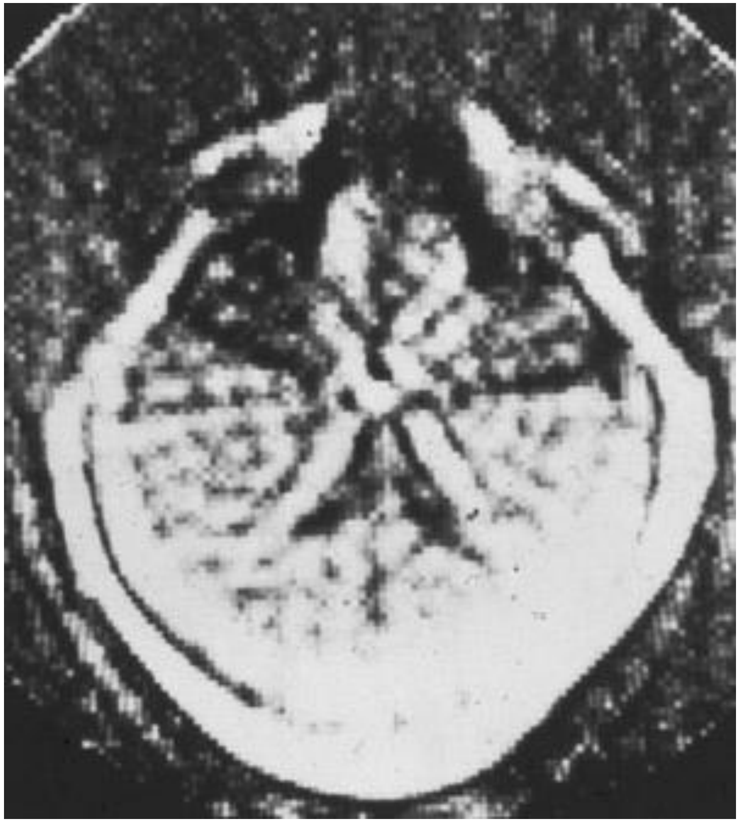
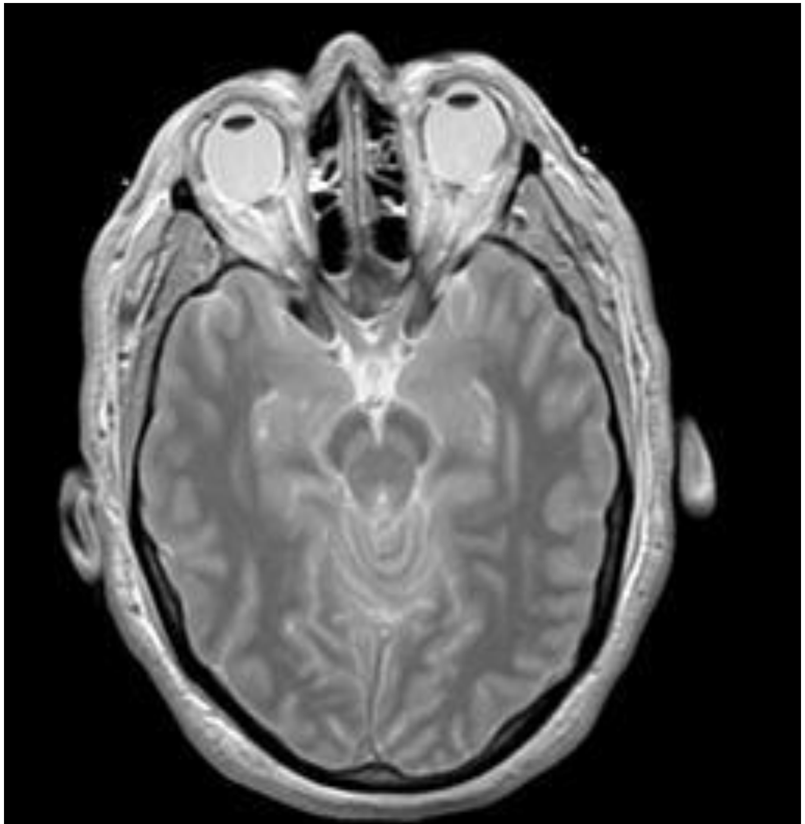
30 Years of MRI



First brain MR image



Typical T2-weighted MR image

MR Imaging

- “Interesting images, but will never be as useful as CT”
  - (A different) neuroradiologist, 1982

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MR Imaging …more than T1 and T2

- MRA - Magnetic resonance angiography
  - images of vessels
- MRS - Magnetic resonance spectroscopy
  - images of chemistry of the brain and muscle metabolism
- fMRI - functional magnetic resonance imaging
  - image of brain function
- PW MRI – Perfusion-weighted imaging
- DW MRI – Diffusion-weighted MRI
  - images of nerve pathways

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Magnetic Resonance Angiography

- MR scanner tuned to measure only moving structures
- "Sees" only blood - no static structure
- Generate 3-D image of vasculature system
- May be enhanced with contrast agent (e.g. Gd-DTPA)

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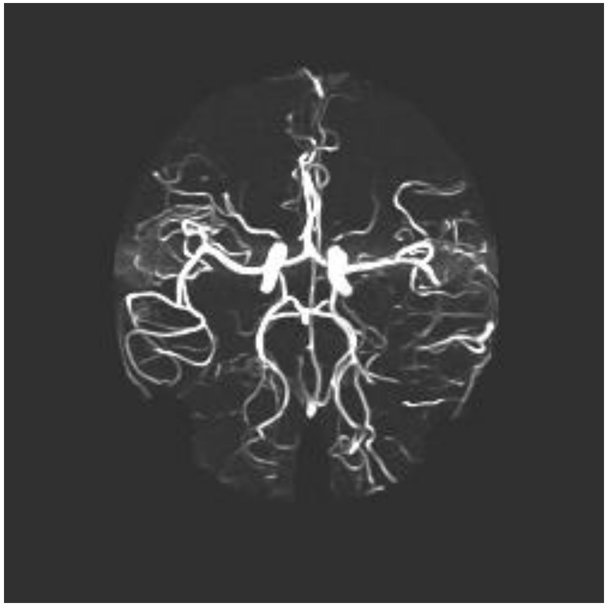
MR Angiography

GD-enhanced

GD-enhanced



Phase-contrast

In-flow

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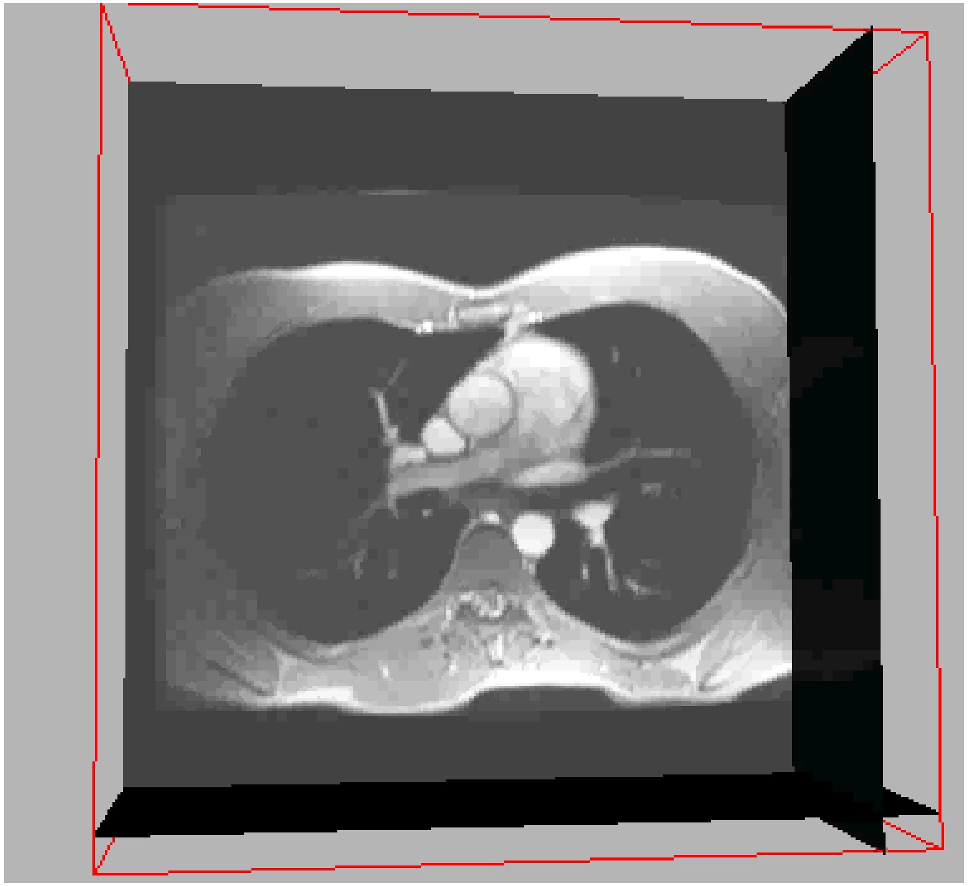
Dynamic 3-D MRI of the thorax



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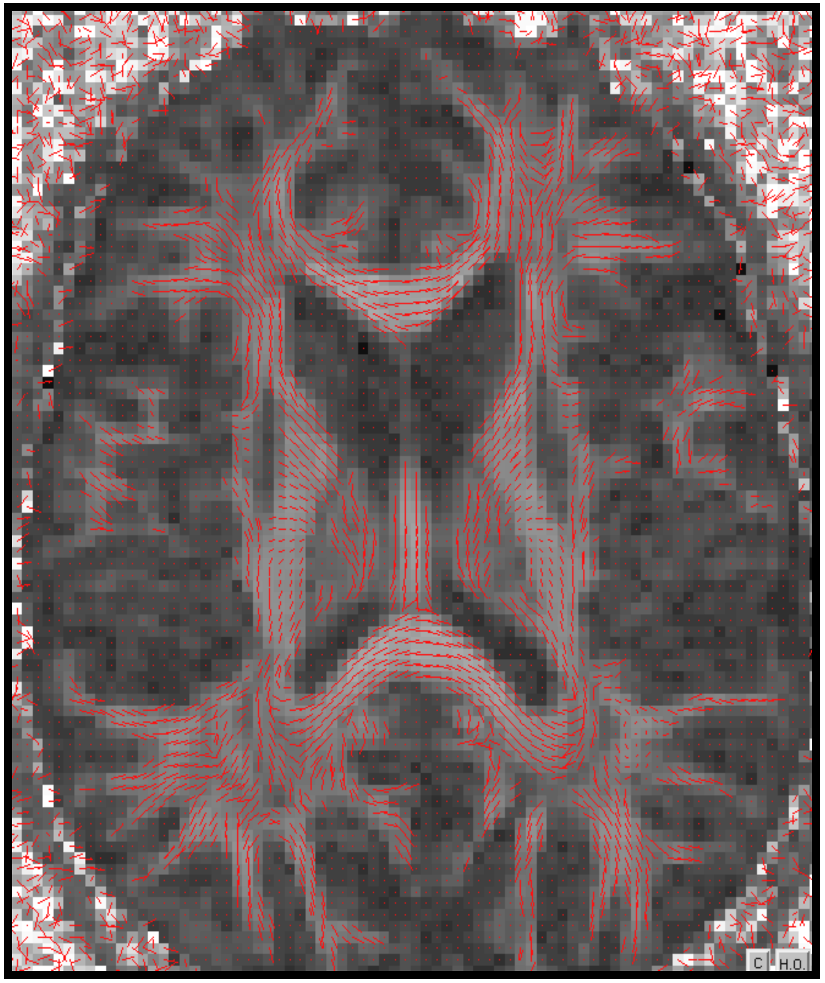
Diffusion-Weighted MRI

- Image diffuse fluid motion in brain
- Construct “Tensor image” – extent of diffusion in each direction in each voxel in image
- Diffusion along nerve sheaths defines nerve tracts.
- Create images of nerve connections/pathways



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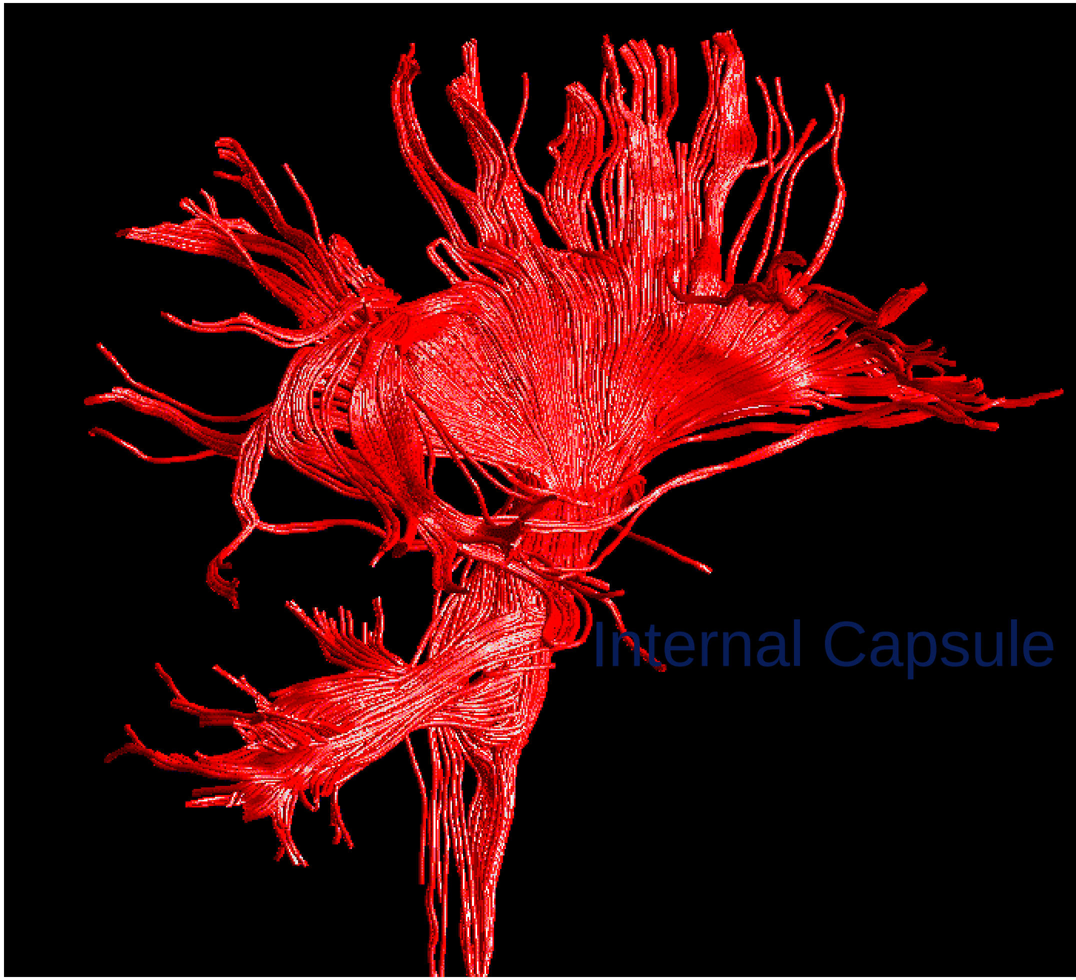
Tractography

- Data analysed after scanning
- Identify “streamlines” of vectors
- Connect to form fibre tracts
- 14 min scan time



- Dr. D Jones, NIH

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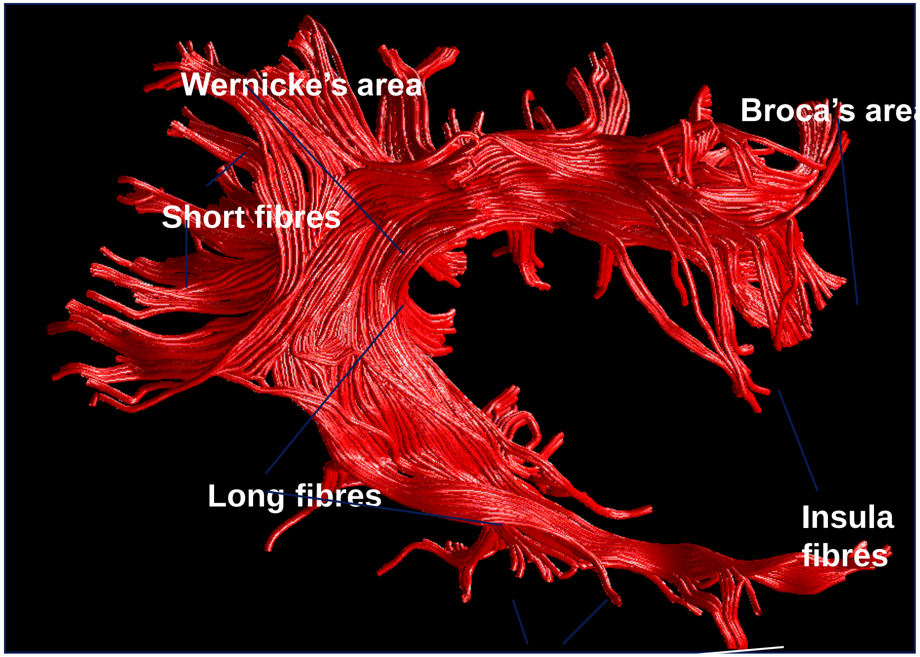
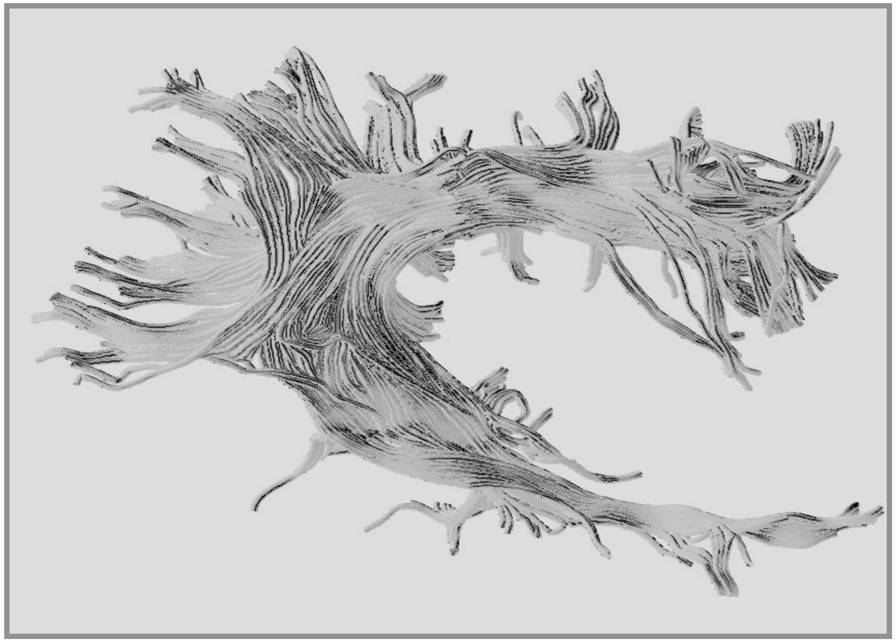
Tractography





Functional MRI (fMRI)

- Active brain regions demand more fuel (oxygen)
- Extra oxygen in blood changes MRI signal
- Activate brain regions with specific tasks
- Oxygenated blood generates small (~1%) signal change
- Correlate signal intensity change with task
- Represent changes on anatomical images

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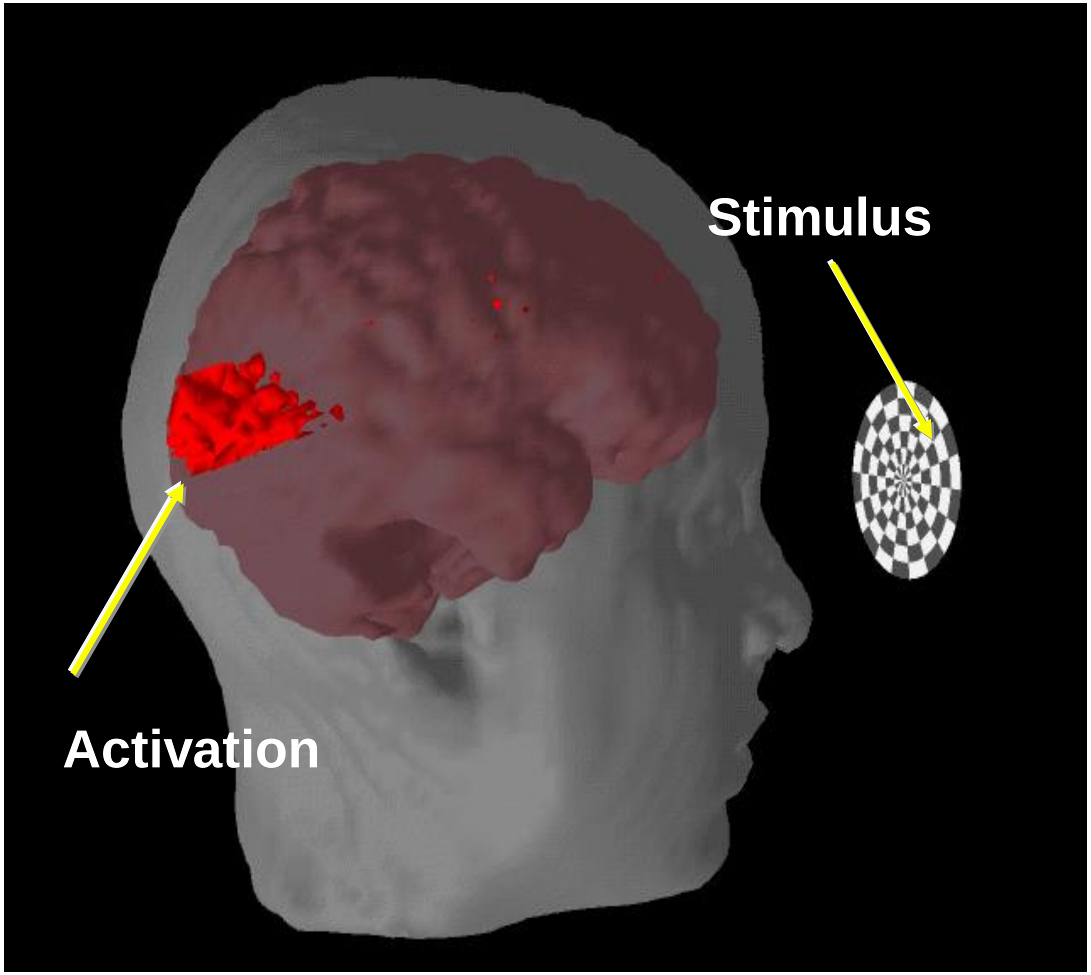
fMRI

Subject looks at flashing disk while being scanned "Activated" sites detected and merged with 3-D MR image



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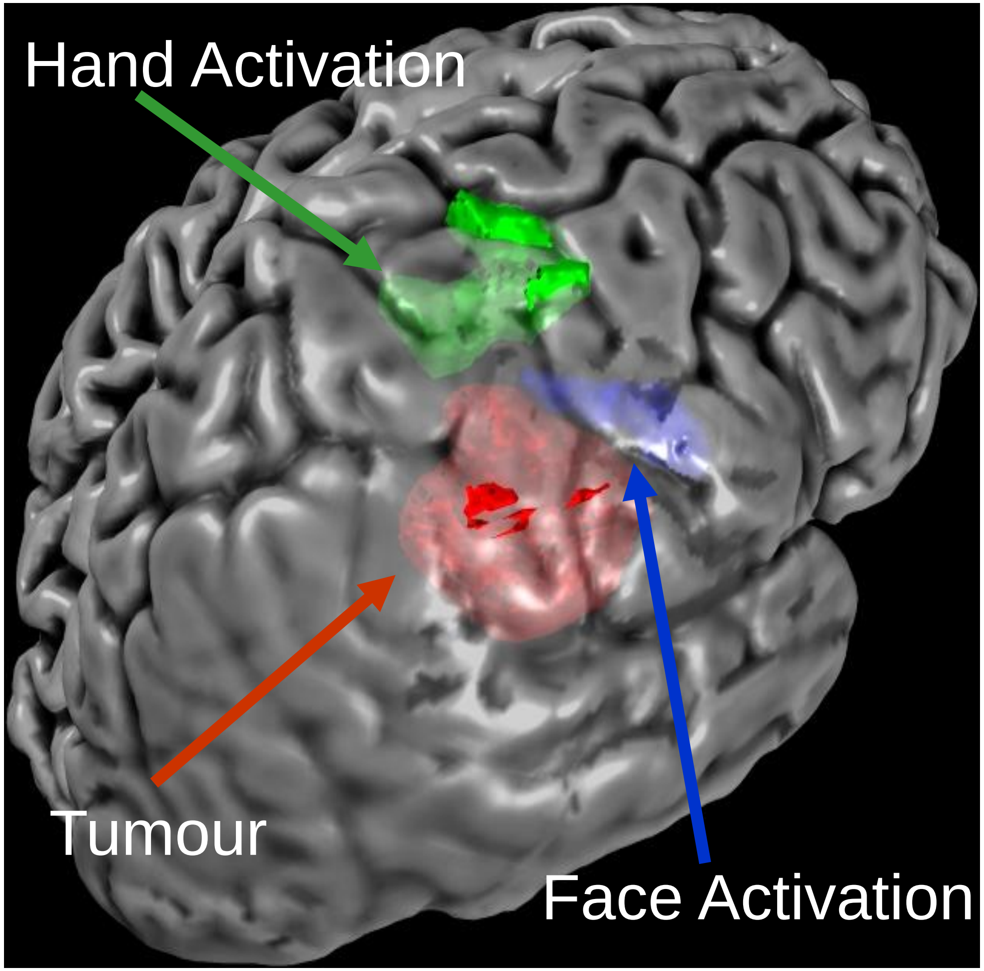
fMRI in Neurosurgery Planning



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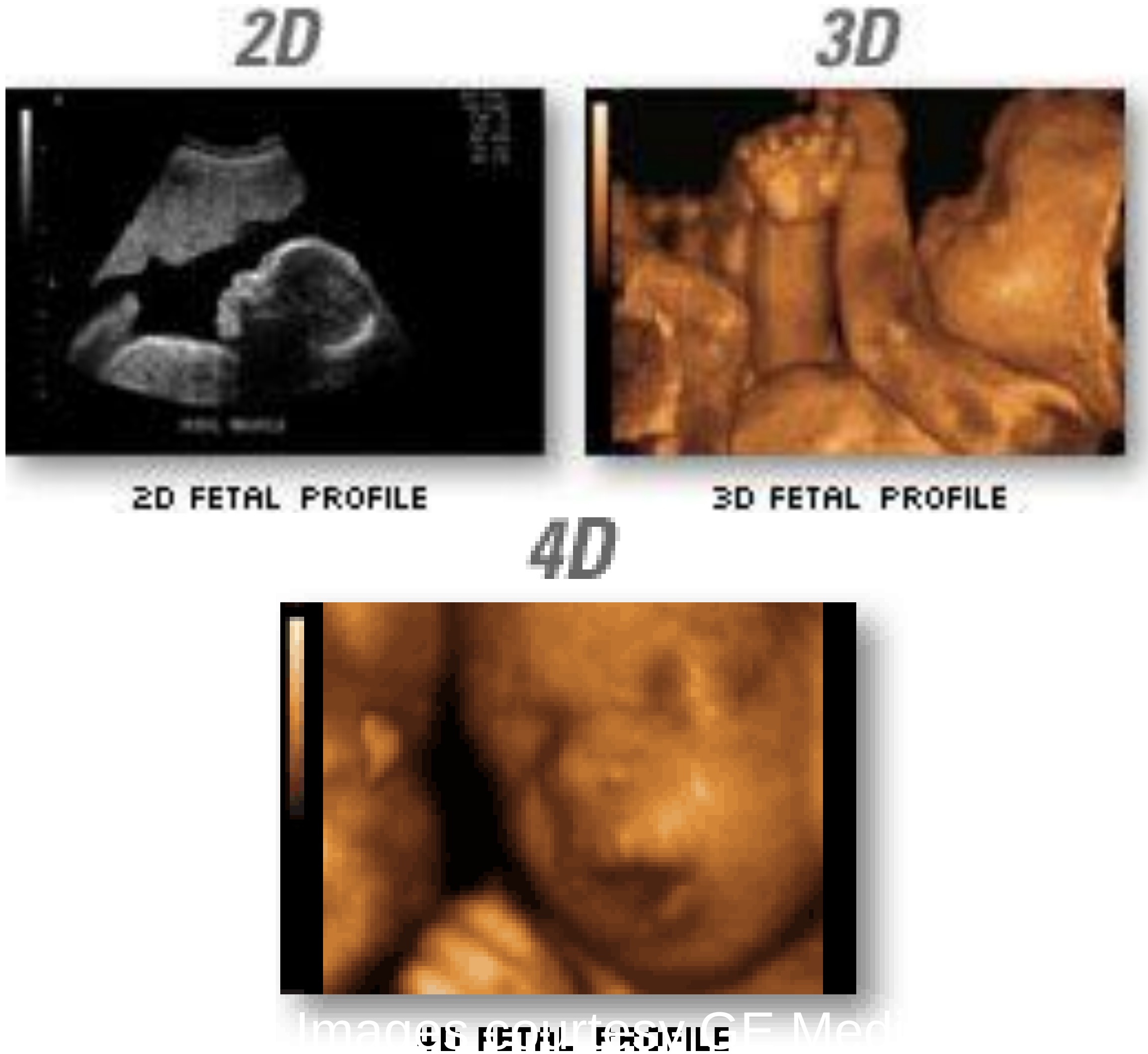
Ultrasound



Images courtesy GE Medi