Lecture 9: Introduction to CT

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- What is CT
- Local contrast in CT images
- Line integral in CT
- Image pre-processing
- Sinogram
- CT Number and Hounsfield unit

- First CT
- CT Generations
- CT Hardware
  - Detectors
  - Gantry
  - Slip Ring
- Spiral CT
- Dual Source CT/Dual Energy CT
- Spectral CT

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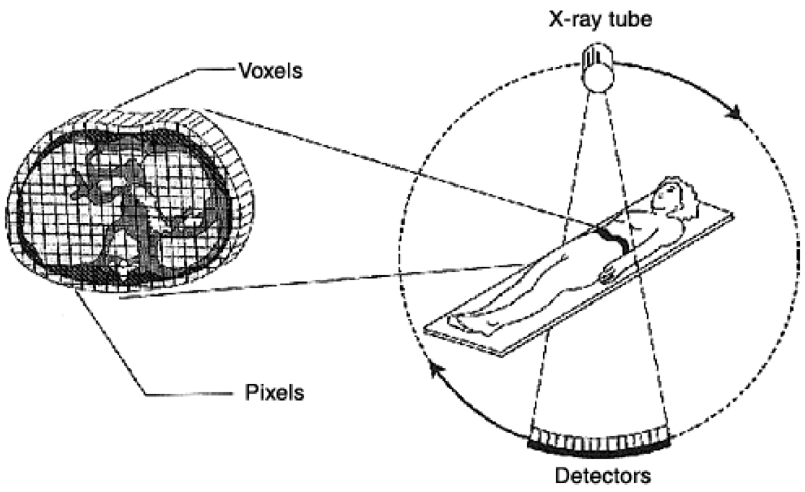
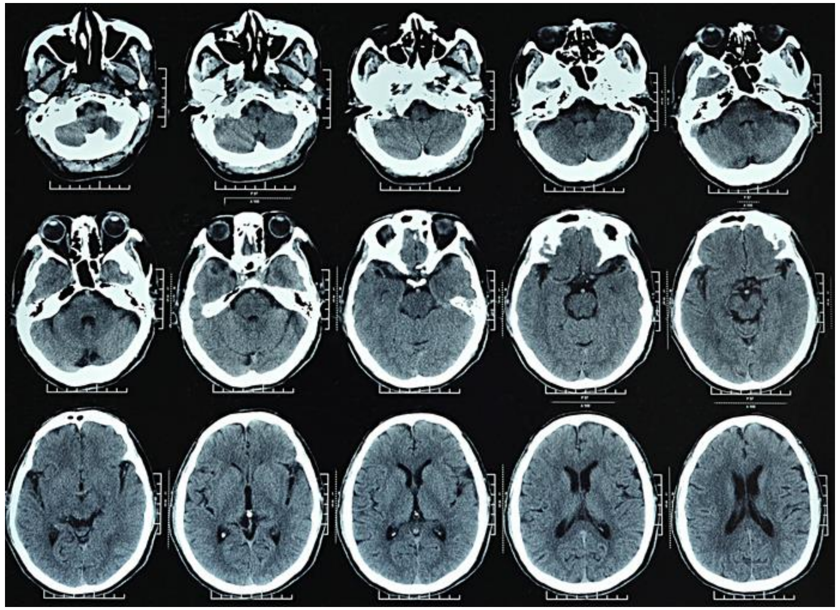
What is X-ray Computed Tomography (CT)?

1. Produce X-rays with X-ray tube
2. X-rays pass through patient
3. X-ray detected on the other side
4. Repeat from all angles surrounding patient
5. Reconstruct cross sectional images
6. Each voxel values represent x-ray attenuation of the tissues at this volume element.

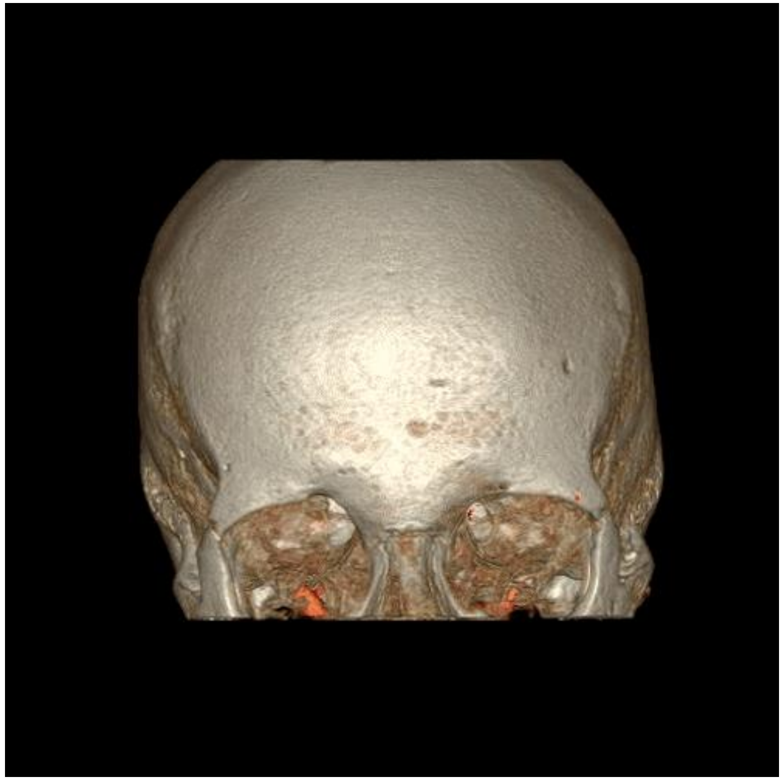


CT example images

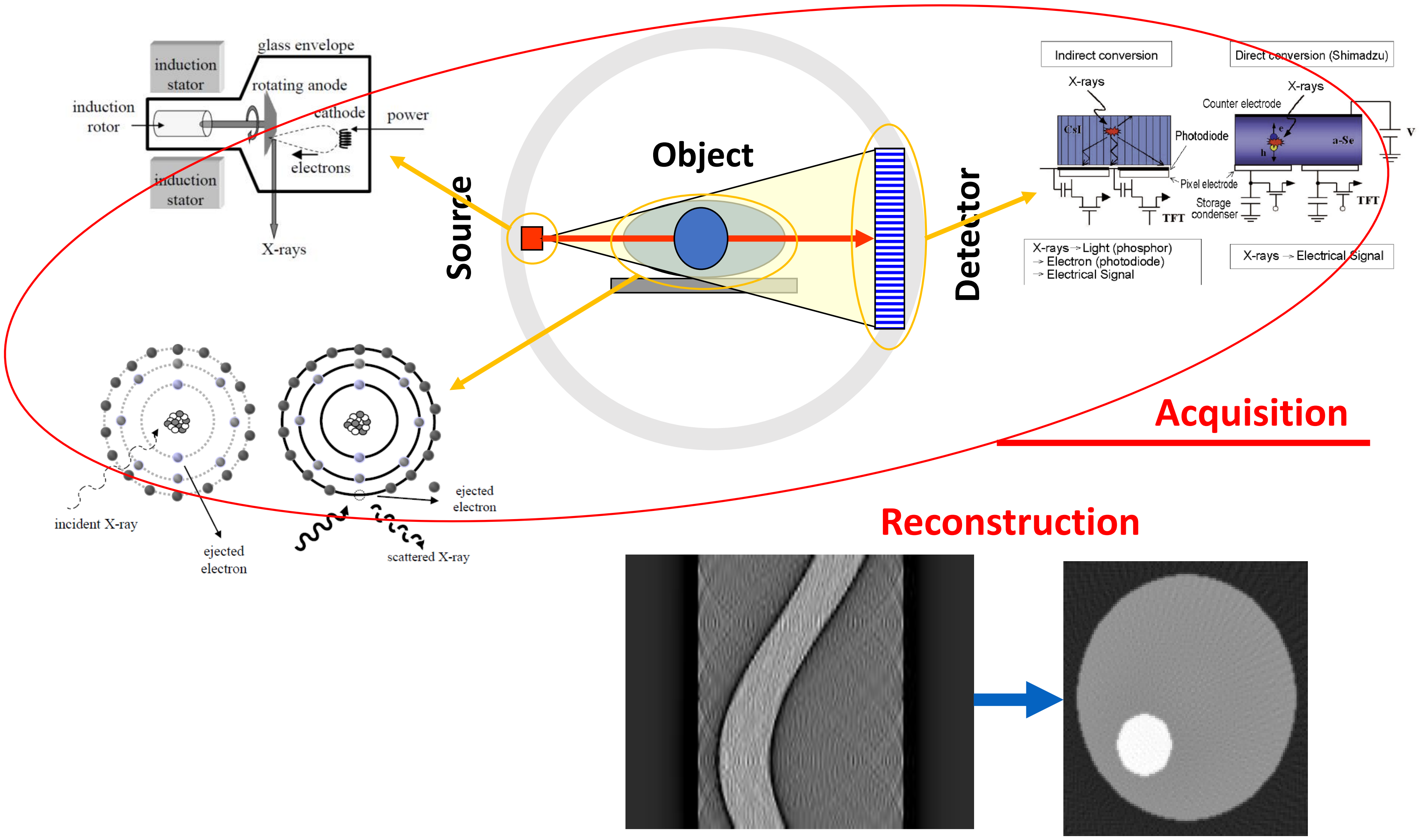
2D slice images



Volume rendered image

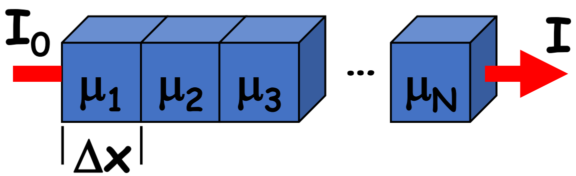


Physics of CT

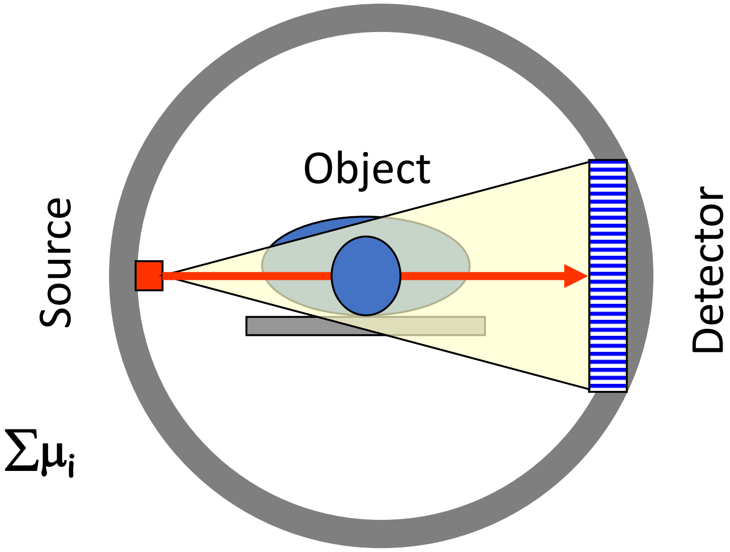


Principles of CT

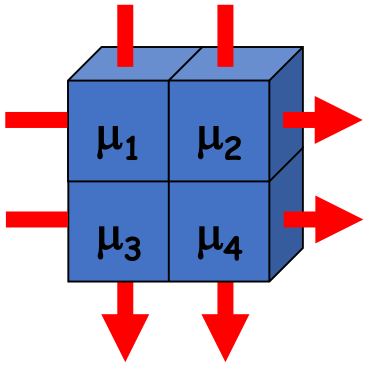
What signals do we measure?



$I = I_0 e^{-\Sigma \mu_i \Delta x} \rightarrow S = 1/\Delta x \log I_0/I = \Sigma \mu_i$



How do we reconstruct CT images?



$S_1 = \mu_1 + \mu_2$

$S_2 = \mu_3 + \mu_4$

$S_4 = \mu_1 + \mu_4$ $S_3 = \mu_2 + \mu_4$

Solve a system of linear equations,

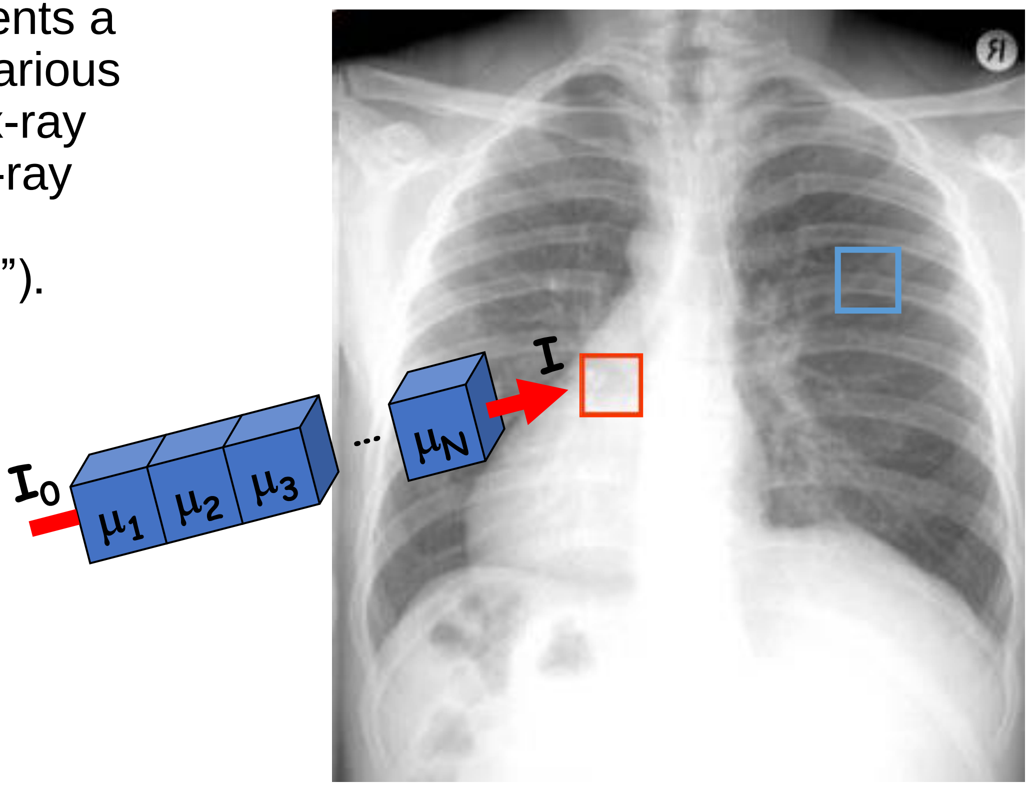
$S_1, S_2, S_3, S_4, \ldots$

to find unknowns,

$\mu_1, \mu_2, \mu_3, \mu_3, \ldots$

Contrast in X-ray projection image

Attenuation signal in radiography represents a summation of individual attenuation by various tissues along the x-ray beam path from x-ray focus to detector. That is, each pixel in x-ray radiographs indicates the integral of the attenuation along a line (i.e. “line integral”).



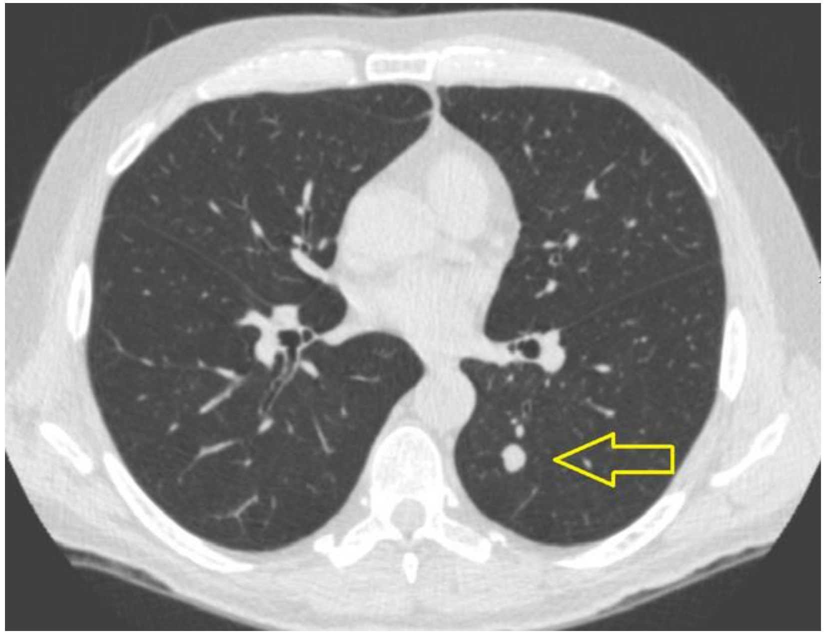
Contrast in x-ray radiographs is dominated by tissues with high attenuation such as bone and contrast media, or by thick objects. Those soft tissues with low attenuation are therefore mostly hidden.

“Local” contrast in CT slice image

In each CT slice image, contrast is given by the **difference in attenuation values of neighboring voxels.**

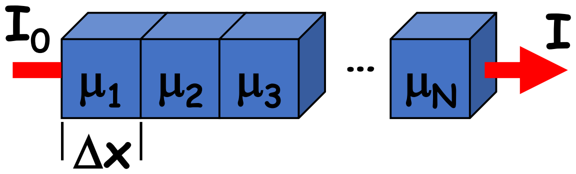
Contrast is determined **locally** by the tissue composition within the volume elements. That is, contrast in CT images is “local”.

This is fundamentally different from radiography!



This lung tumor (arrow indicated) would be difficult to spot from conventional x-ray radiography.

Raw signals in CT imaging



$I = I_0 e^{-\sum \mu_i \Delta x} \rightarrow S = \log I_0/I = \Delta x \sum \mu_i$

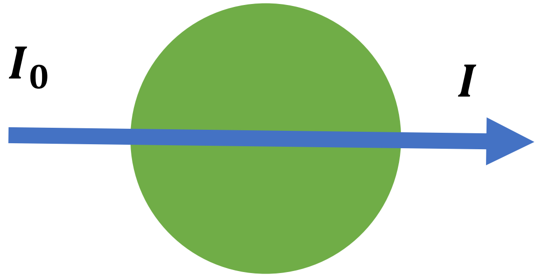
I & I_0 are the raw signals/data measured by the detector.

S is the signal pre-processed from the raw data.
S is **<u>total x-ray attenuation along the beam path</u> (which is a pencil-like line – pencil beam).**

➔ **CT is an x-ray attenuation based imaging modality (just like X-ray radiography).**

The CT signal is called the line integral!

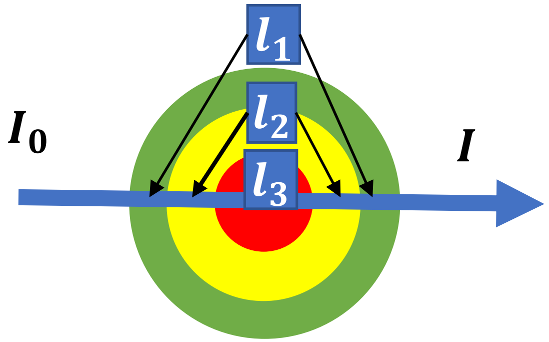
Monochromatic radiation passes through homogeneous object



$$I = I_0 e^{-\mu L}$$

$$S = \ln\left(\frac{I_0}{I}\right) = \mu L$$

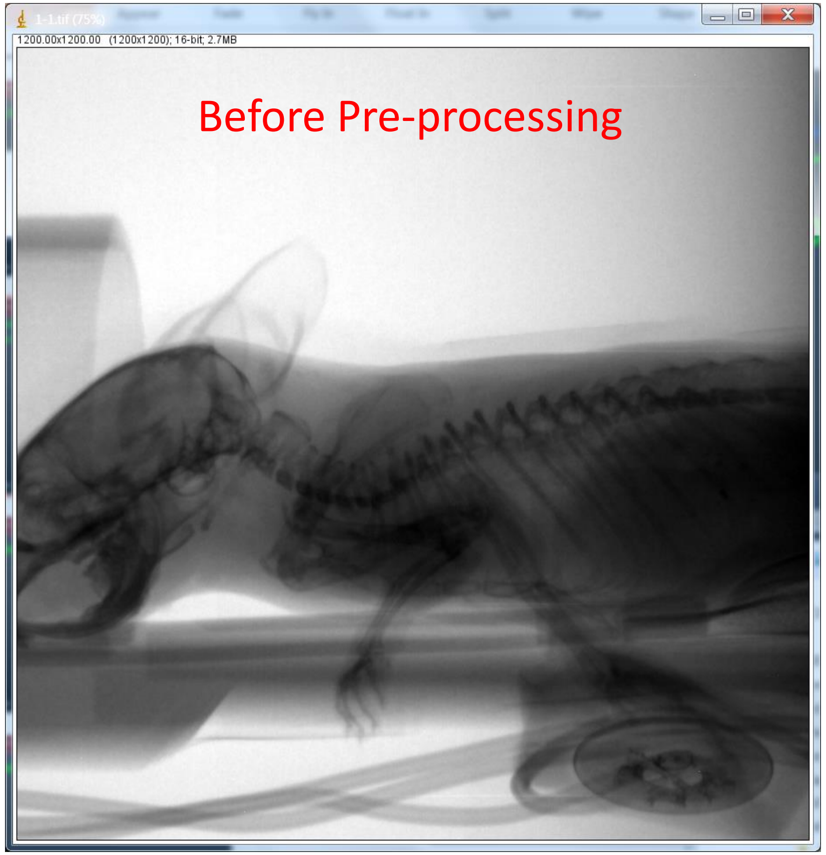
Monochromatic radiation passes through inhomogeneous object

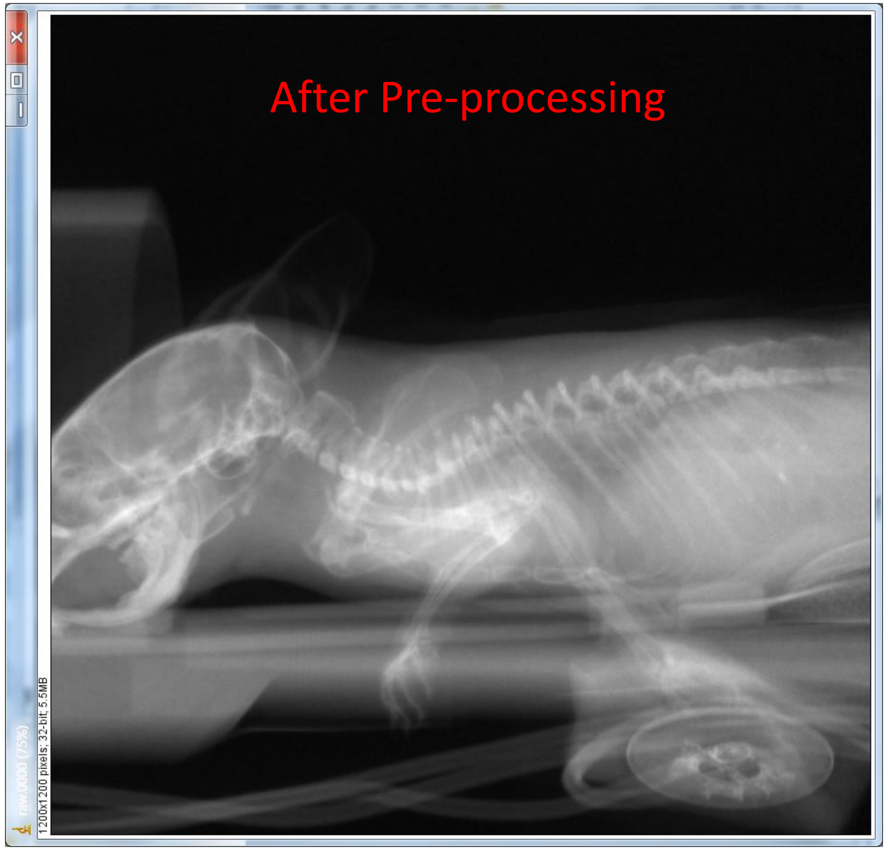


$$I = I_0 e^{-(\mu_1 l_1 + \mu_2 l_2 + \mu_3 l_3)} = I_0 e^{-\sum_{i=1}^{n} \mu_i l_i} = I_0 e^{-\int_0^L \mu dx}$$

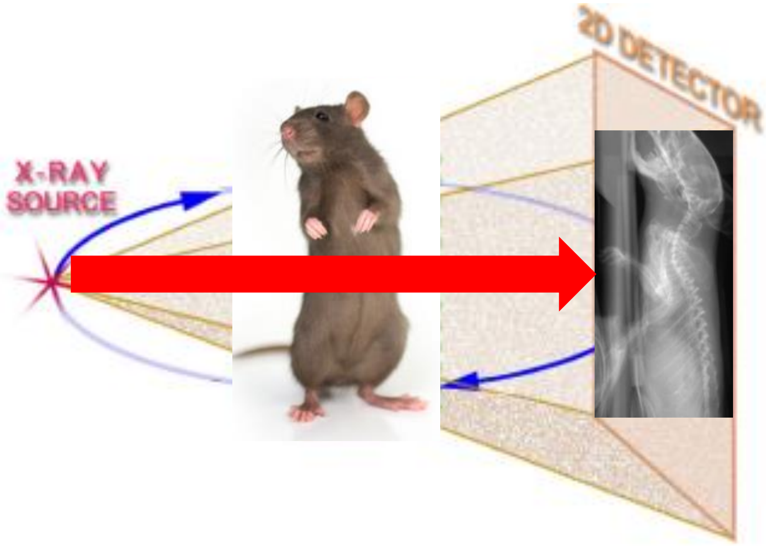
$$S = \ln\left(\frac{I_0}{I}\right) = \sum \mu_i l_i$$

Data Pre-Processing Example



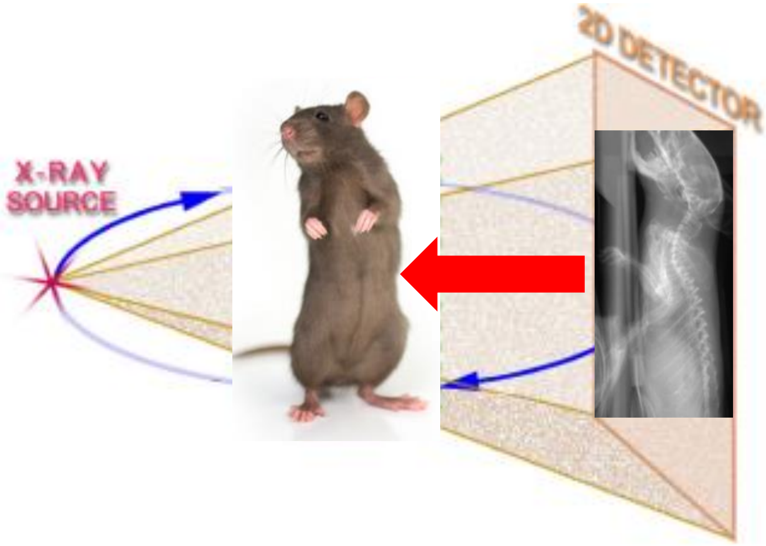


Projection as forward process – Forward Projection



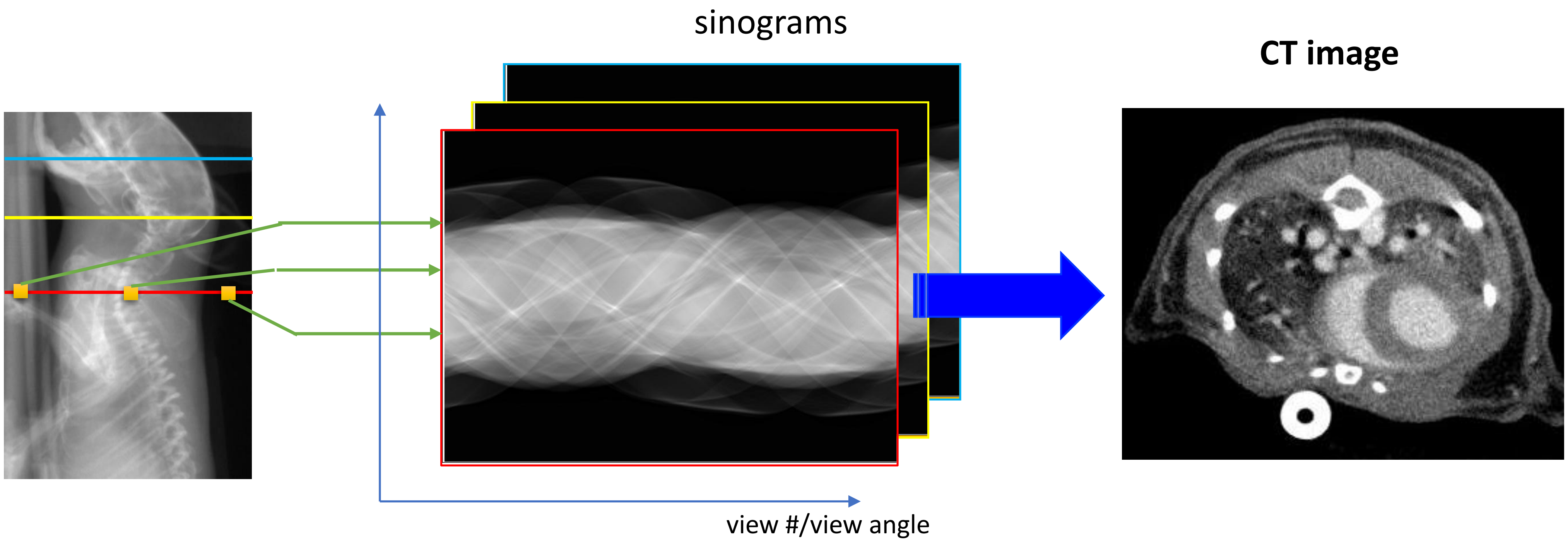
Projection – a forward process, i.e. from object to projections.

Reconstruction as backward process – back-projection is reconstruction



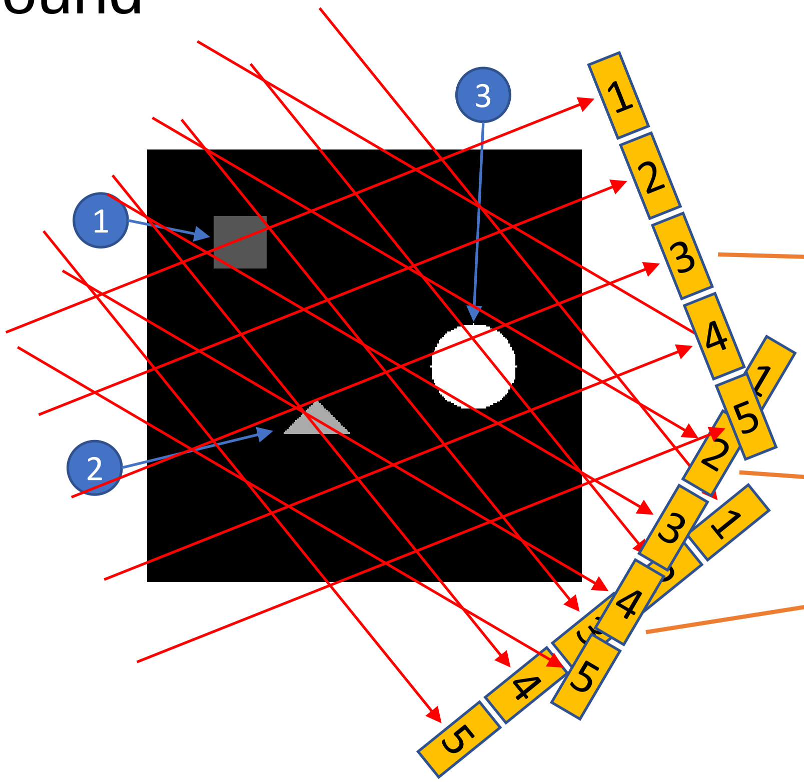
Reconstruction – a backward process that convert the projection images taken at different angles into a volumetric stacks of images (i.e. the object).

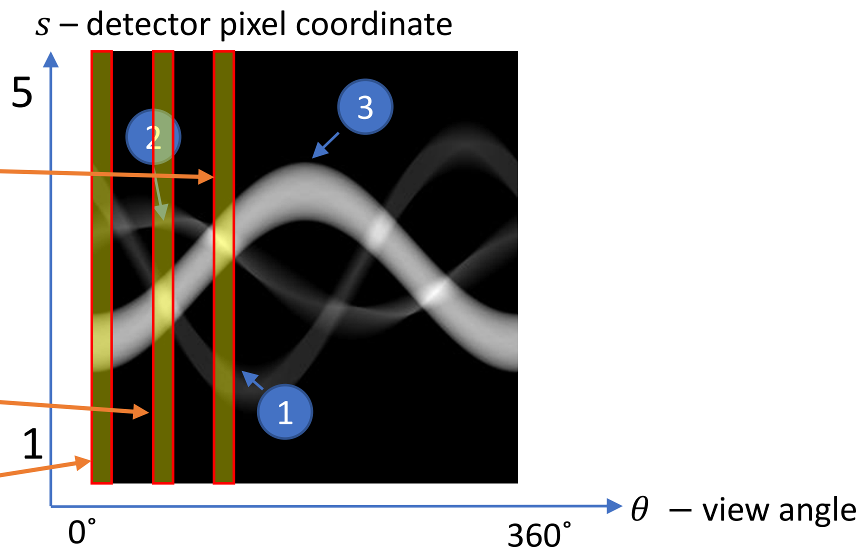
Reconstruction:
Projections → Sinograms → Images



A sinogram example

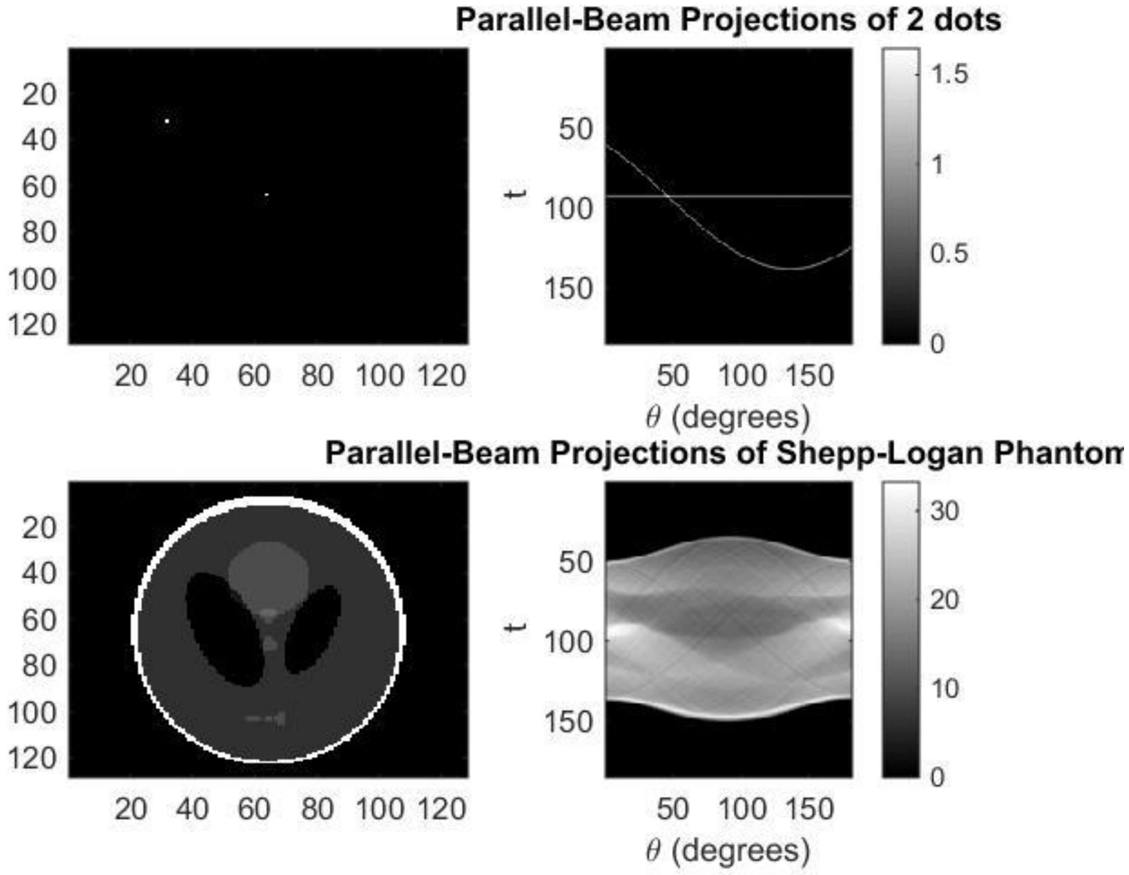
- Object: a (2D) phantom containing a square, a circle, a triangle in a dark background





The sinogram is a **composite** representation of projection data of the entire 2D object.

Sinogram generation using Matlab



Matlab Code for previous slide

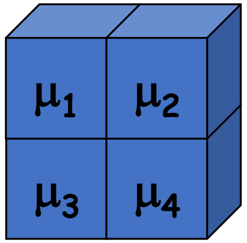
```
figure(33);
ph = zeros(128);
ph(64,64)=1;
ph(32,32)=1;
subplot(2,2,1);
imagesc(ph);

theta = 0:180;
[P,xp] = radon(ph,theta);
subplot(2,2,2);
imagesc(P);
axis normal;
title('Parallel-Beam Projections of 2 dots');
xlabel('\theta (degrees)');
ylabel('t');
colormap(hot);
colorbar;

ph = phantom(128);    /* try P = phantom('Modified Shepp-Logan',256); for practice */
subplot(2,2,3);
imagesc(ph);
subplot(2,2,4);
[P,xp] = radon(ph,theta);
imagesc(P);
axis normal;
title('Parallel-Beam Projections of Shepp-Logan Phantom');
xlabel('\theta (degrees)');
ylabel('t');
colormap(hot);
colorbar;
```

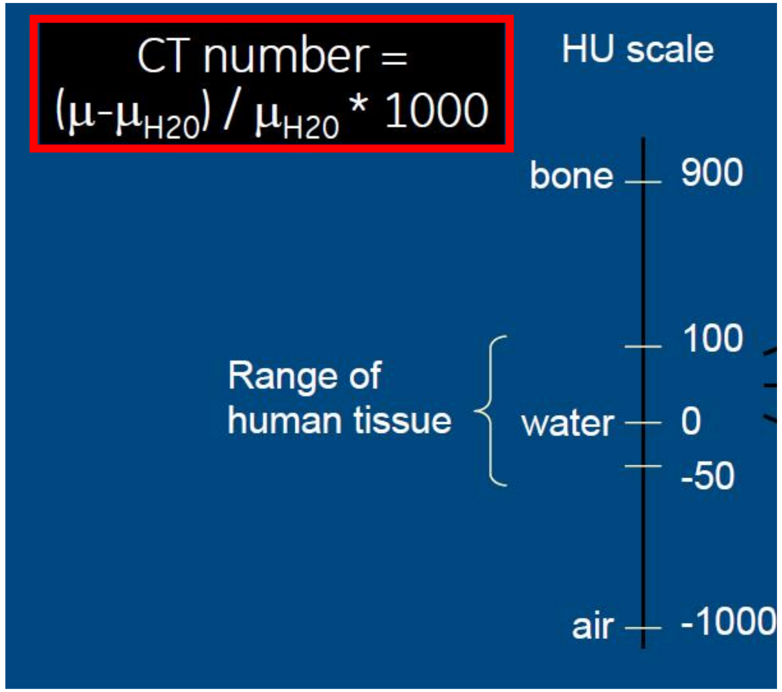
CT Number & Hounsfield Unit

After reconstruction, we got a ‘map’ of attenuation coefficients at each voxel.

The attenuation coefficient at each voxel in CT images, when expressed in a special unit (i.e. **Hounsfield unit**), is called CT number.

In Hounsfield unit (HU), **CT number for water voxel is 0 HU** and **the attenuation for air voxel is -1000 HU**. CT number for all other type of material voxels is calculated as





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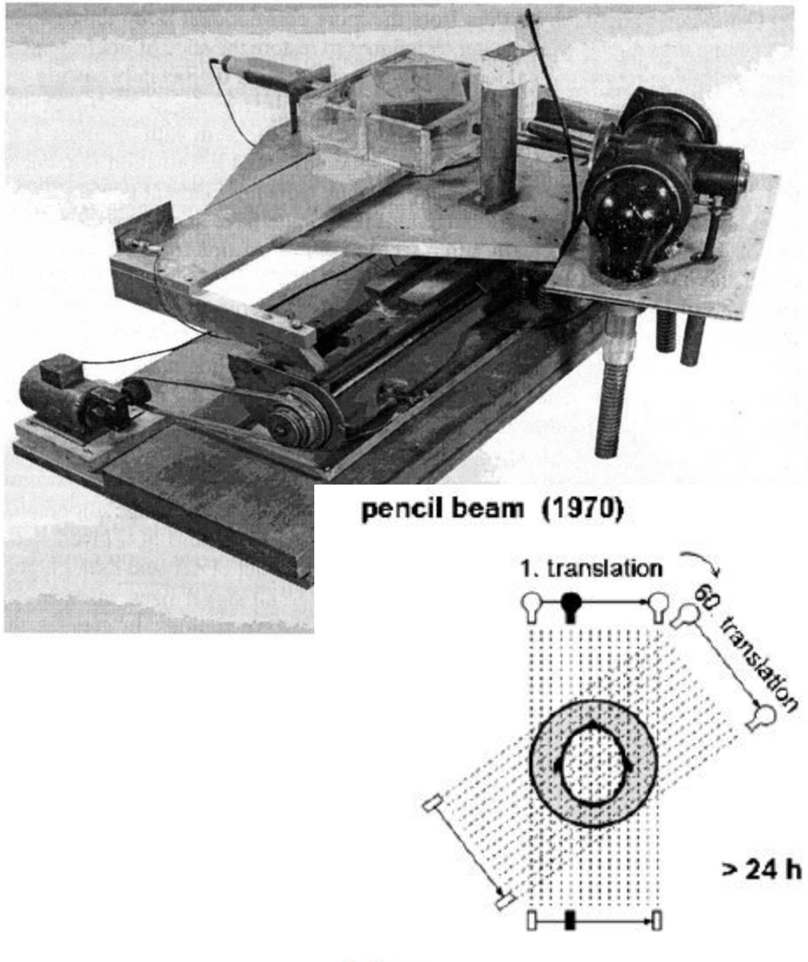
First Generation CT Scanner

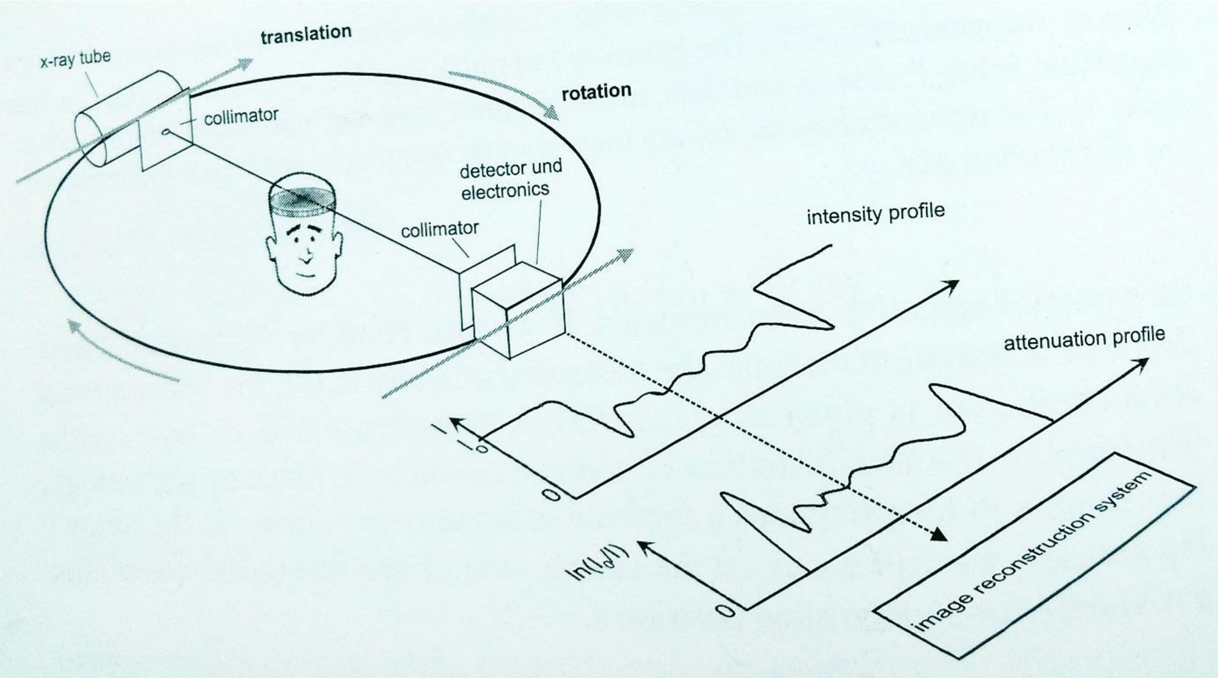


(a) 1st generation: translation/rotation

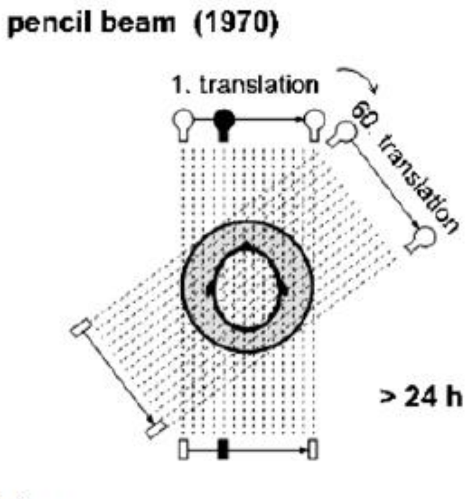
Sir Godfrey Hounsfield

Typical guy engineer!

How does the first CT scanner work?



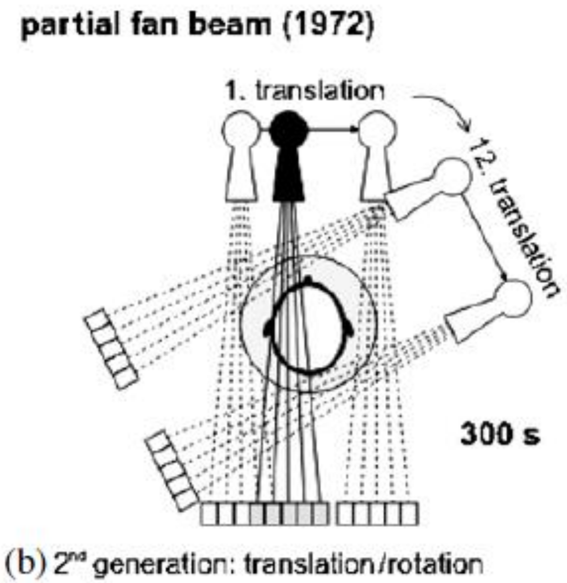
First Generation – **Pencil Beam**

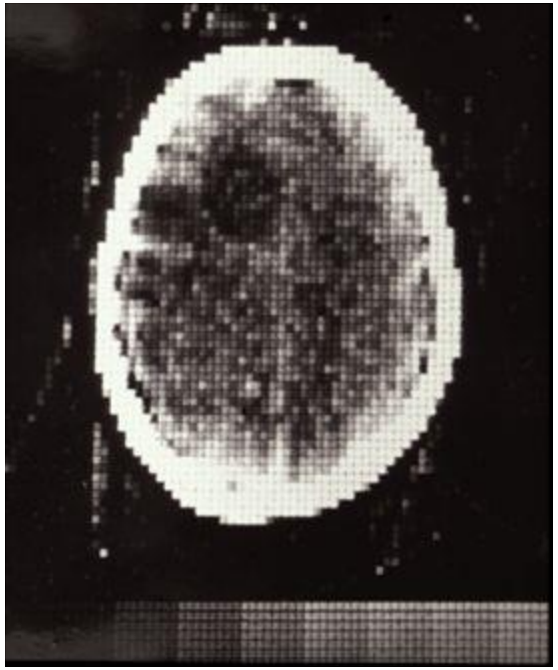


(a) 1st generation: translation/rotation

Second Generation –
First clinical CT scanner

Second Generation –
Partial Fan Beam

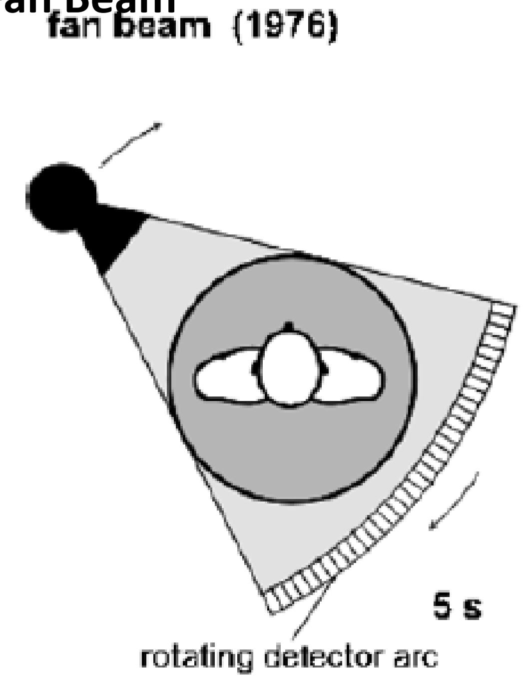




The first clinical CT scan: Atkinson Morley's Hospital, October 1971 England

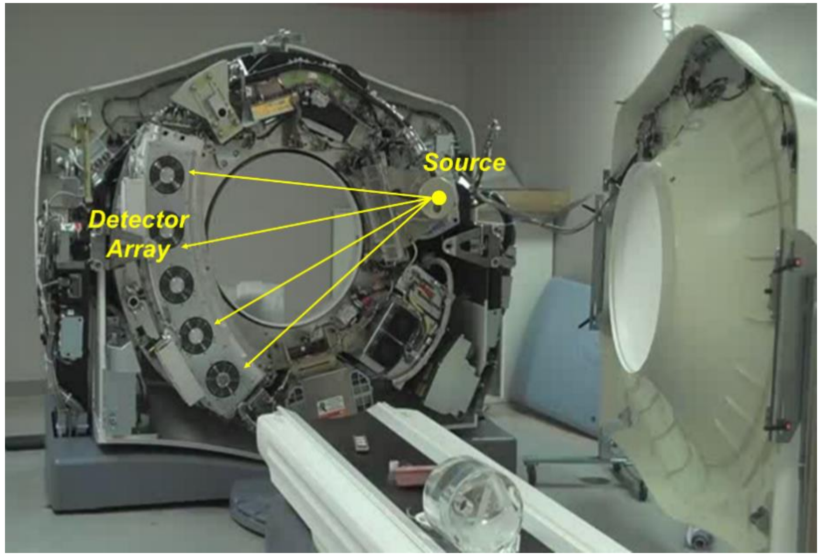
Third-generation CT scanner

Fan Beam



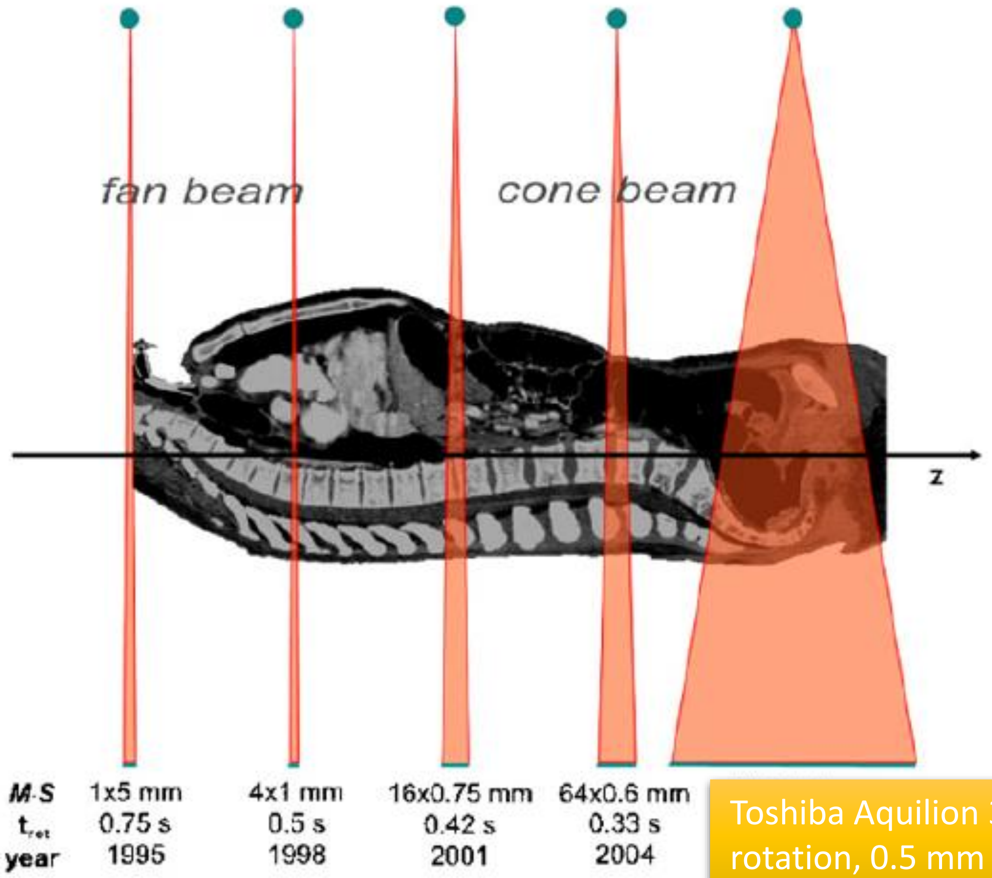
(c) 3rd generation: continuous rotation

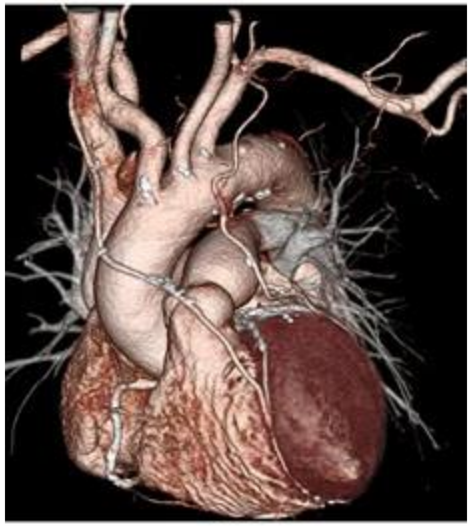
1980



2000

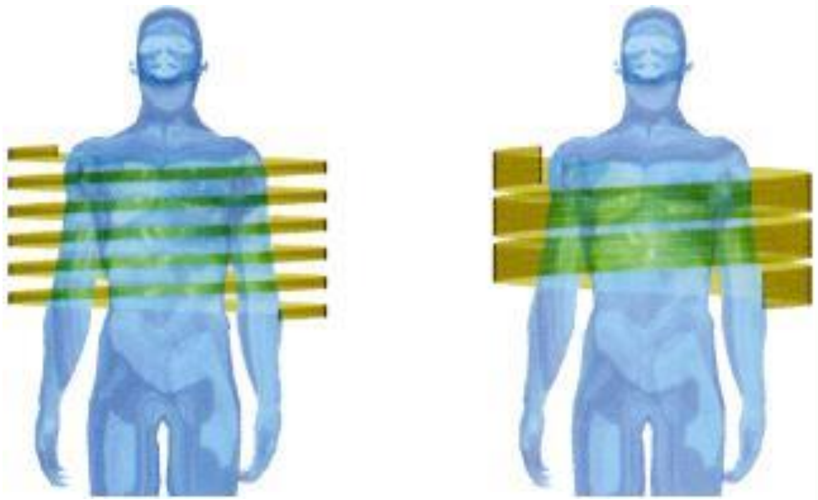
"Slice race" in Multi-Detector row CT (MDCT)

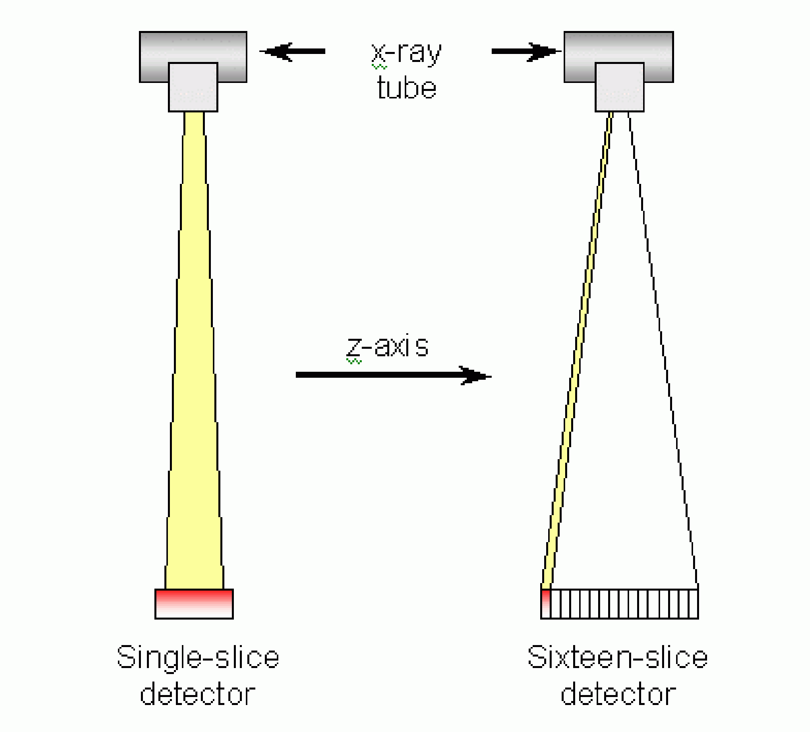




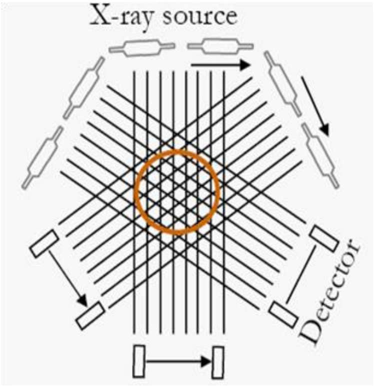
Toshiba Aquilion 320, 320 detector rows, 0.275s rotation, 0.5 mm slice thickness, introduced 2010s

Multi-slice spiral CT

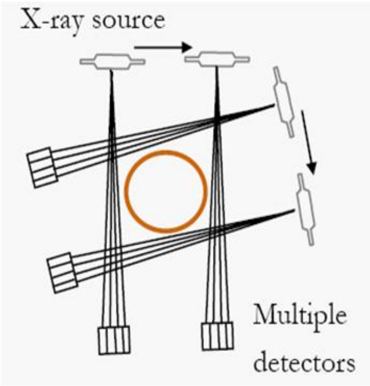




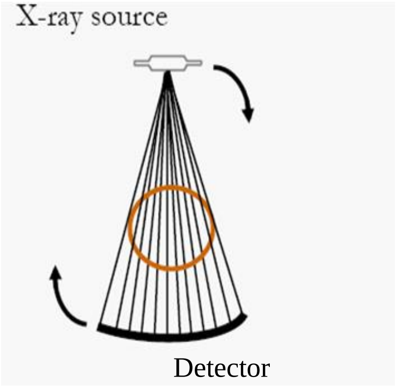
Five Generations of CT



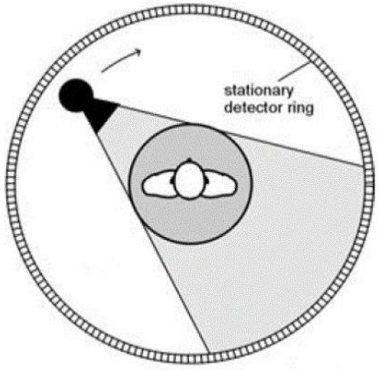
1st Generation



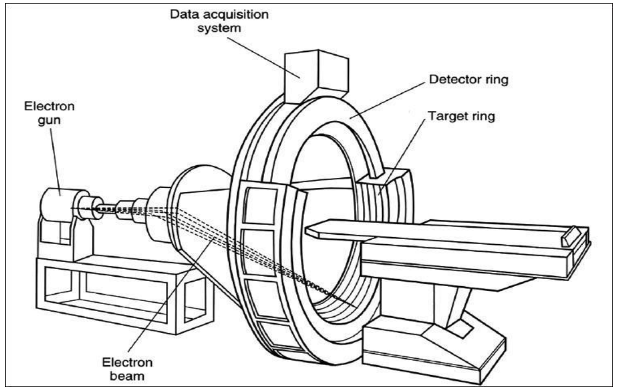
2nd Generation



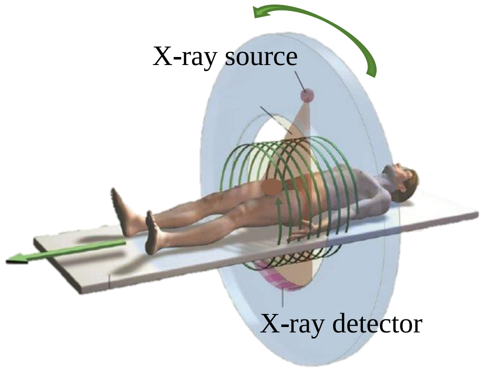
3rd Generation



4th Generation

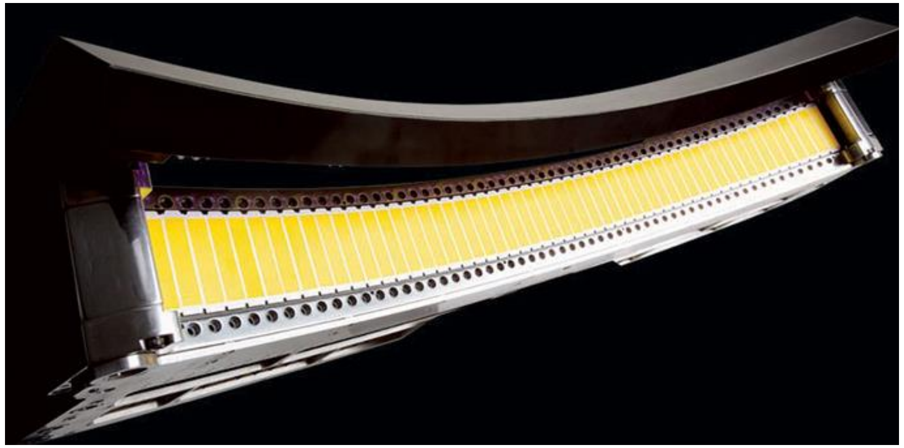


5th Generation

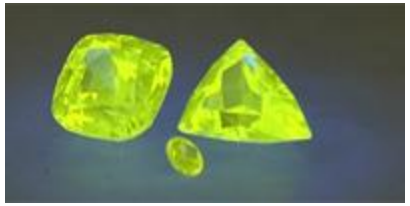


Spiral CT

CT detectors

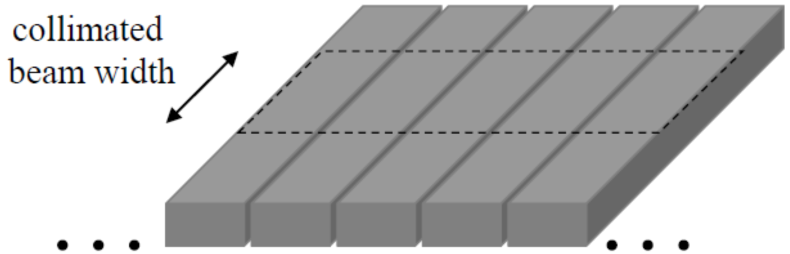


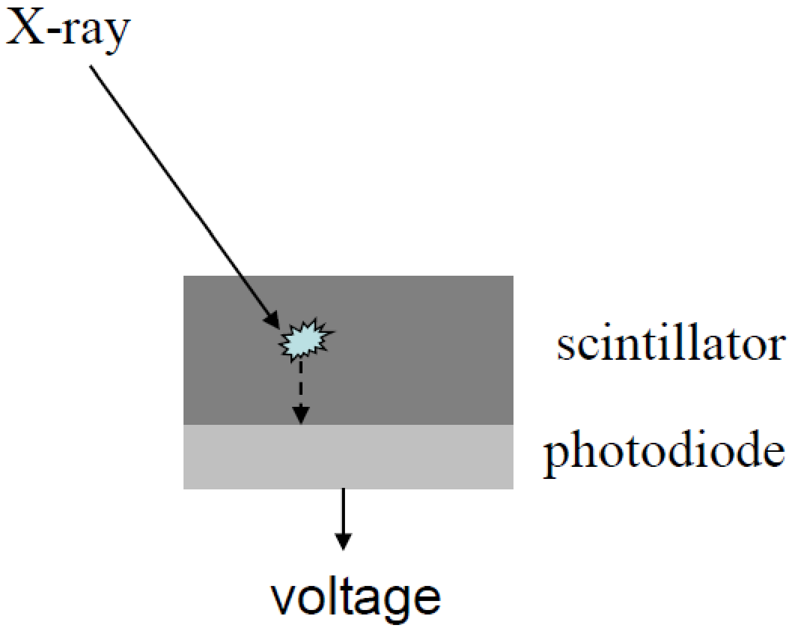
GE's proprietary Gemstone Detector



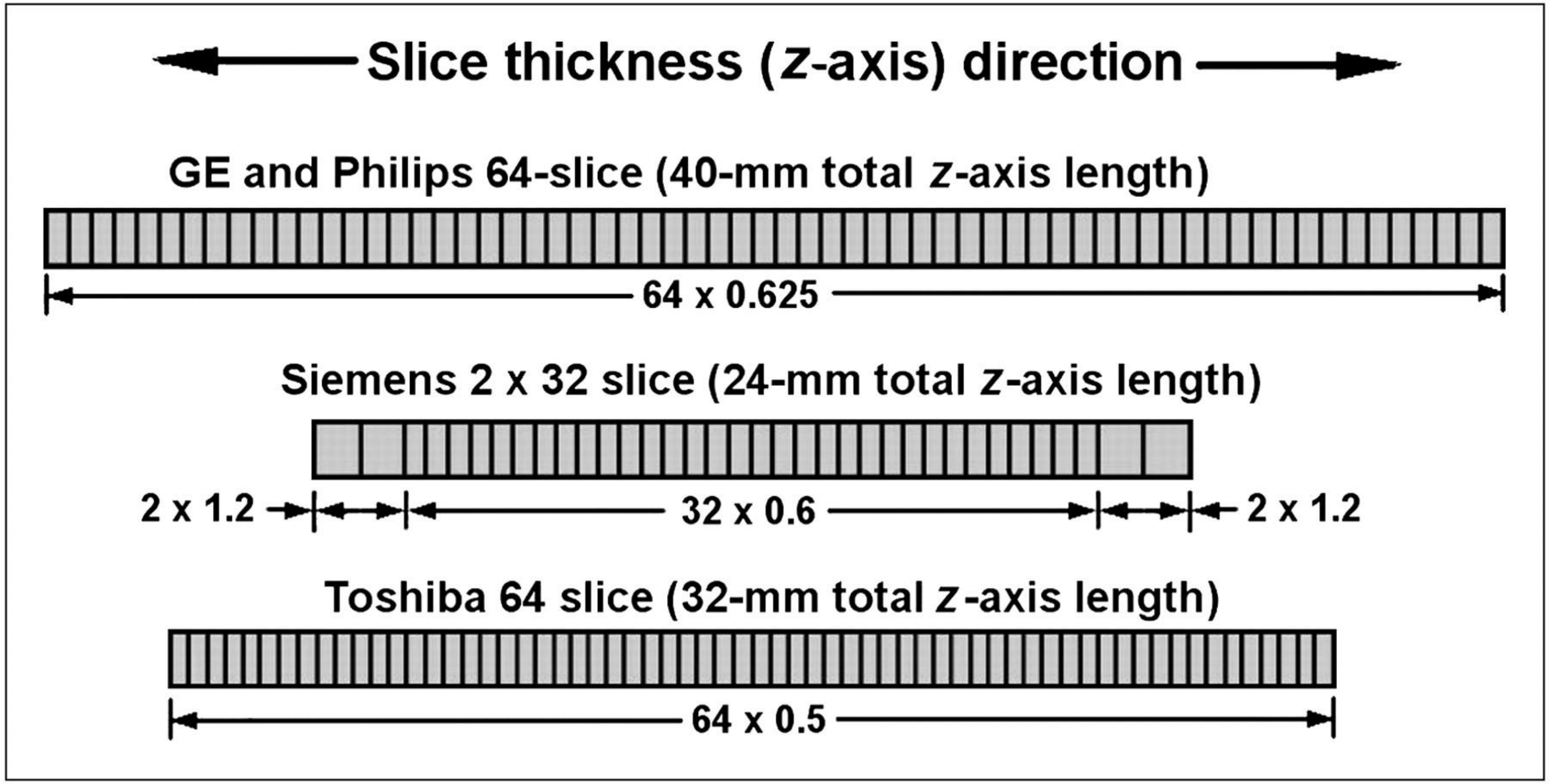
Siemens's proprietary ultra fast ceramics detector

Single row CT detector





64-slice detector designs for multi-slice spiral CT



Diagrams of various 64-slice detector designs (in z-direction). Lee W. Goldman J. Nucl. Med. Technol. 2008;36:57-68

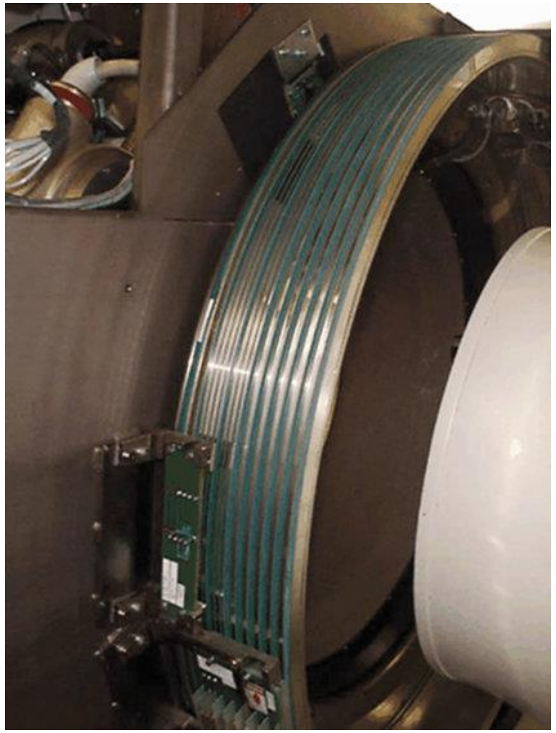
Rotating gantry

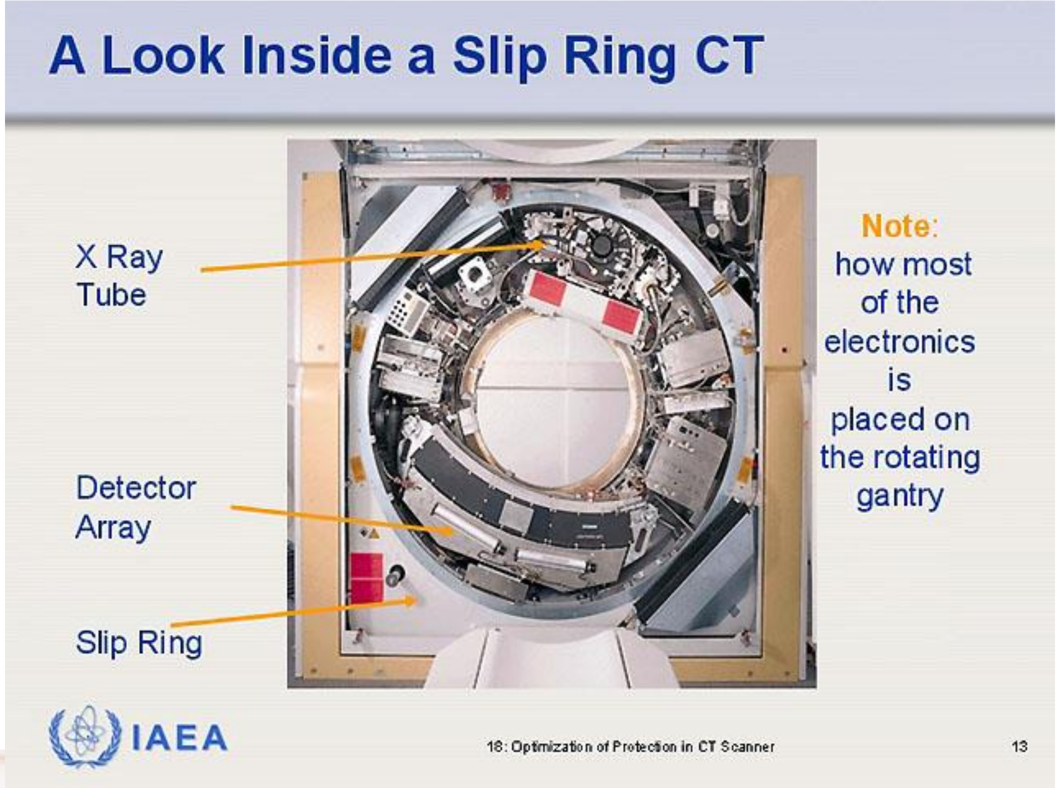
Gantry revolution time	Centrifugal force on tube
1s	3g
0.3s	30g

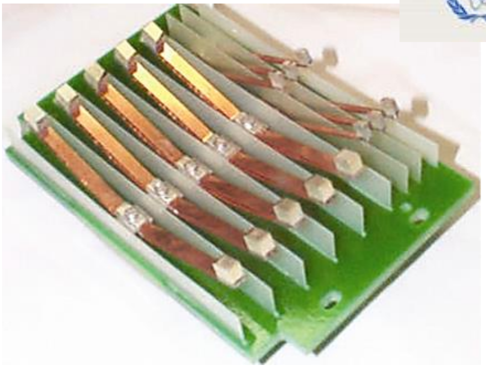
*space shutter liftoff ~ 3g

>3 tons, 0.275s per revolution!

Slip ring




A Look Inside a Slip Ring CT
X Ray Tube
Detector Array
Slip Ring
Note: how most of the electronics is placed on the rotating gantry
IAEA
18: Optimization of Protection in CT Scanner
13



Advances in CT

Table 1. Performance characteristics[a] of CT in a comparison from 1972 to 2005. Significant improvements are given due to technological advances for almost all parameters. Contrast resolution reached a stable level since detector quantum efficiency was close to 100% early on.

	1972	1980	1990	2004	2005 (DSCT)
Rotation time (s)	300	5–10	1–2	0.33–0.5	0.33
Data per 360° scan (MB)	0.058	1	1–2	10–100	20–200
Data per spiral scan (MB)	–	–	24–48	200–4000	200–8000
Image matrix[b]	80 × 80	256 × 256	512 × 512	512 × 512	512 × 512
Power (kW)	2	10	40	60–100	2 × 80
Slice thickness, mm	13	2–10	1–10	0.5–1	0.5–1
Spatial resolution (LP cm^{-1})	3	8–12	10–15	12–25	12–25
Contrast resolution	5 mm/5 HU/ 50 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy	3 mm/3 HU/ 30 mGy

[a] Typical values for high performance scanners.
[b] Values refer to the calculated matrix. Monitor displays often use 1024 × 1024 matrices by means of interpolation.

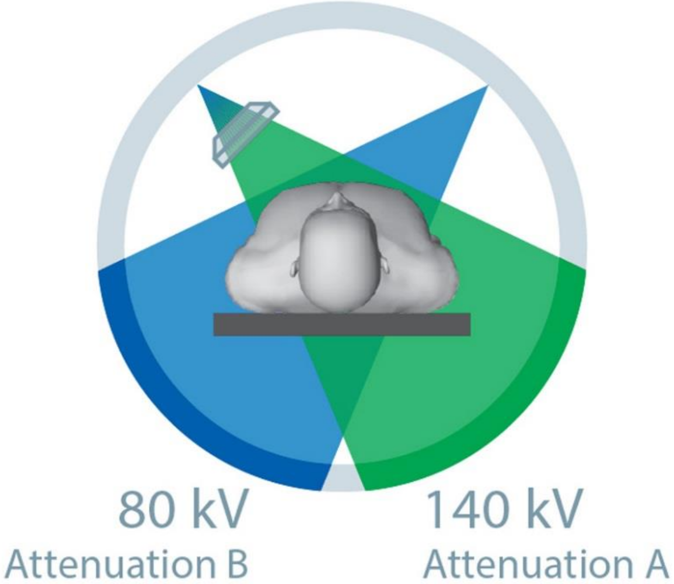
Kalender, W. "X-ray computed tomography", Physics in medicine and biology 51(13) (2006).

Dual source / dual energy CT

Dual energies:

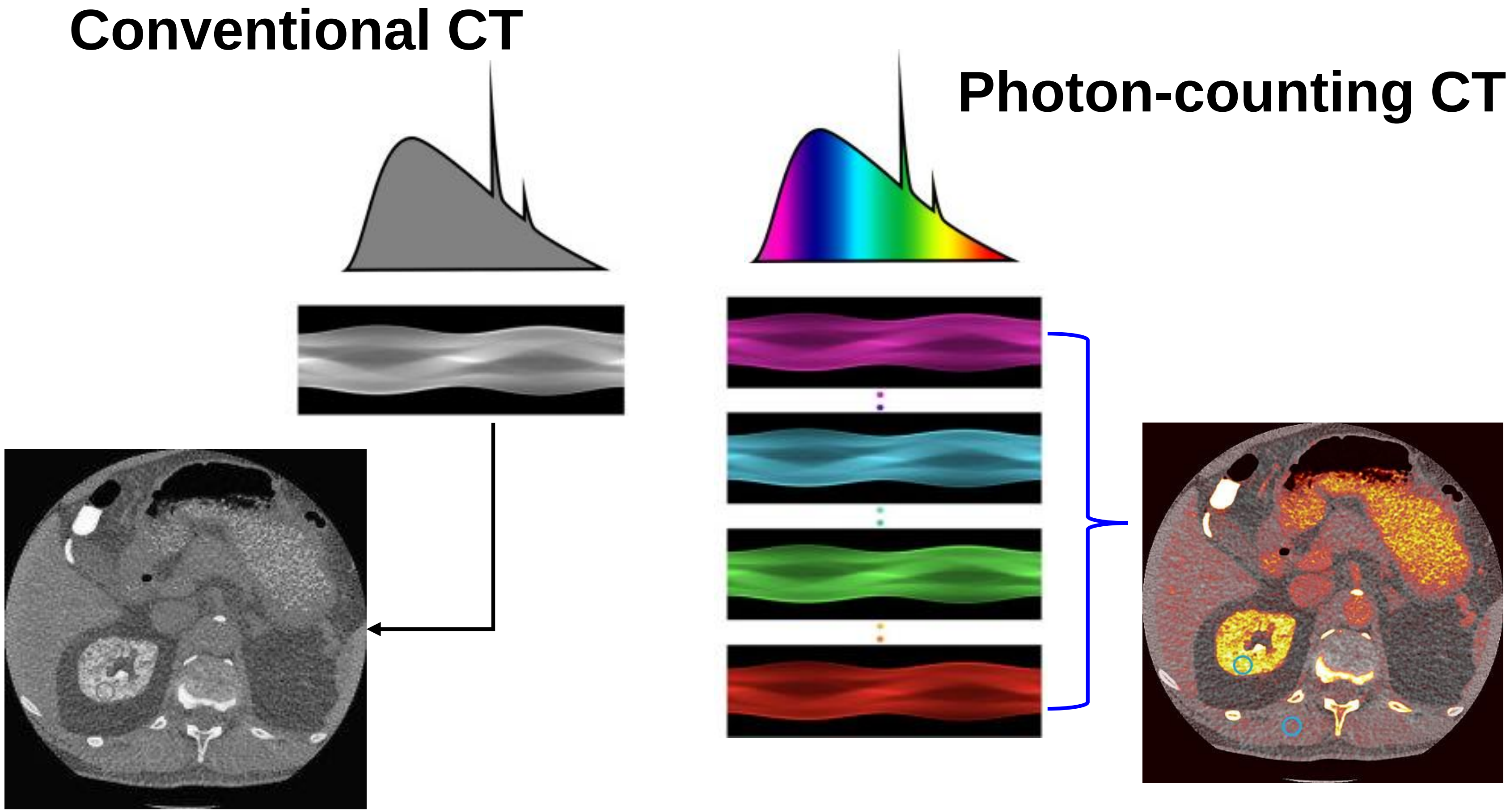
140 kev and 80 kev

Decomposed into iodine, done and tissue

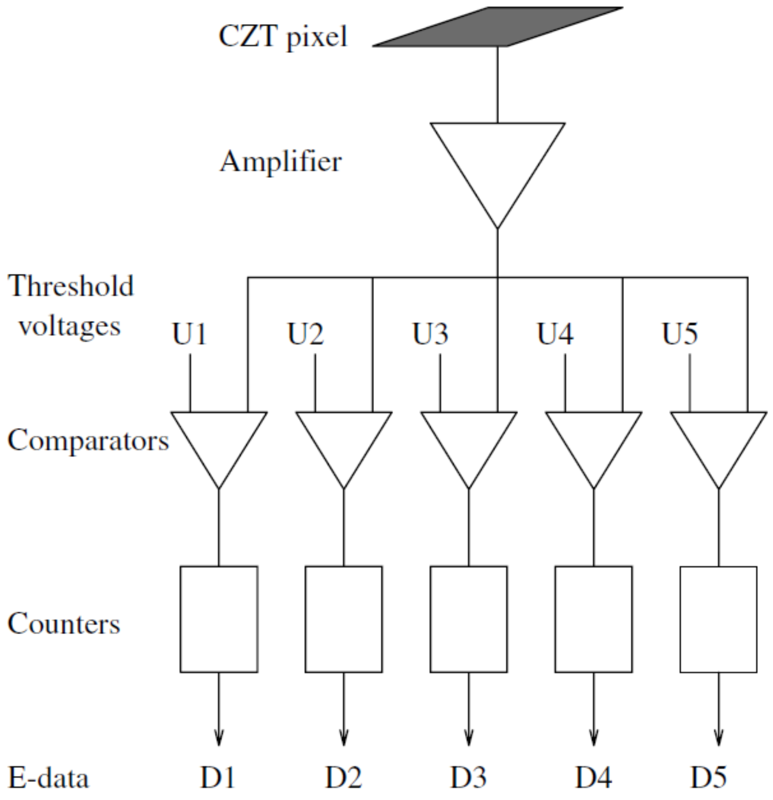


Dual-energy x-rays / CT

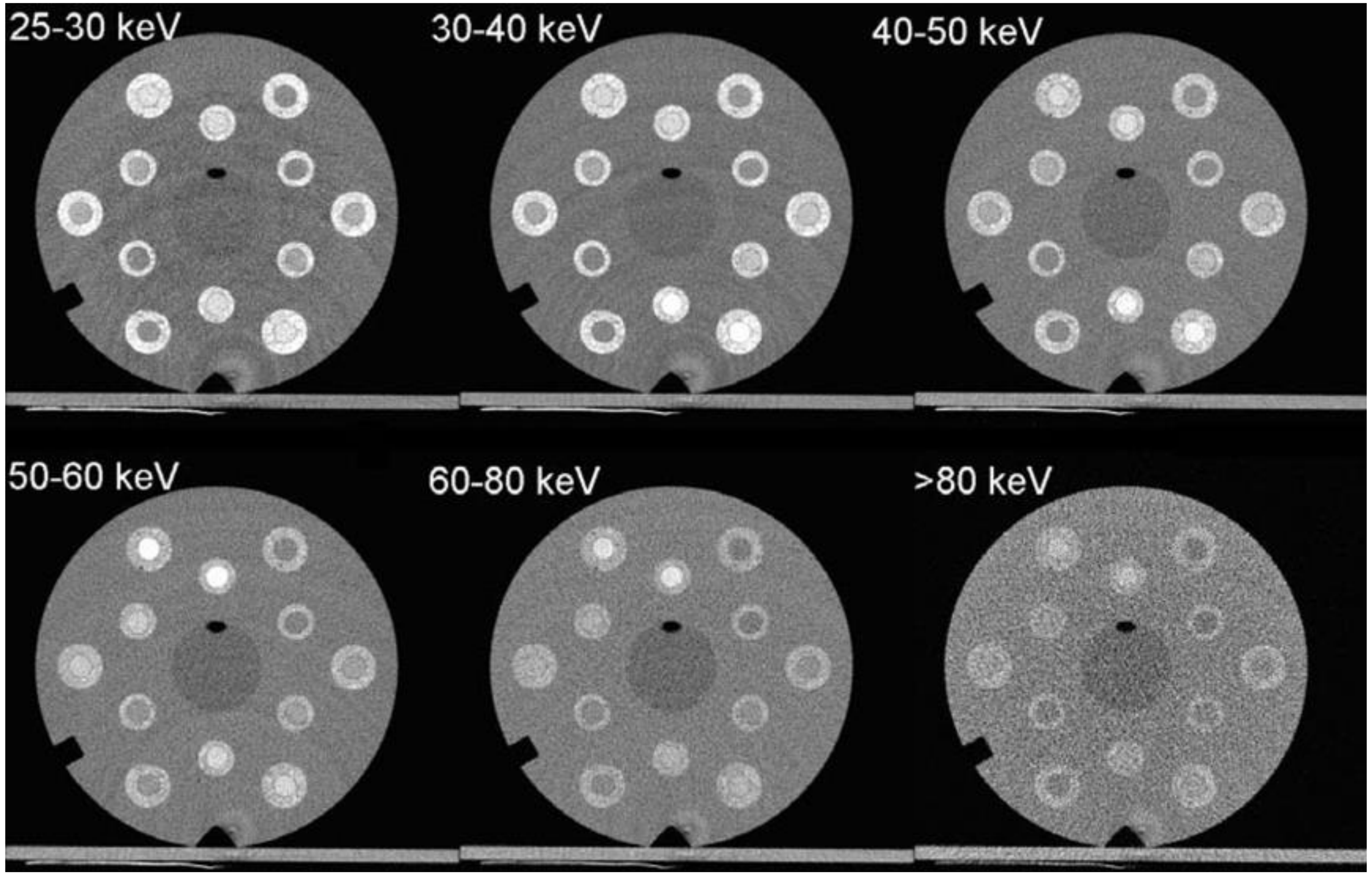
Photon-counting CT



Photon-counting detector for color CT



Spectral CT



J. P. Schlomka, et al, "Experimental feasibility of multi-energy photon-counting K-edge imaging in pre-clinical computed tomography.," *Phys. Med. Biol.*, vol. 53, no. 15, pp. 4031–47, Aug. 2008.