BME I5000: Biomedical Imaging

Lecture 4
Computed Tomography

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some slides inspired by lecture notes of Andreas H. Hilscher at Columbia University.

Blackboard: http://cityonline.ccny.cuny.edu/

Schedule

1. Introduction, Spatial Resolution, Intensity Resolution, Noise
2. X-Ray Imaging, Mammography, Angiography, Fluoroscopy
3. Intensity manipulations: Contrast Enhancement, Histogram Equalization
4. ➡ Computed Tomography
5. Image Reconstruction, Radon Transform, Filtered Back Projection
6. Positron Emission Tomography
7. Maximum Likelihood Reconstruction
8. Magnetic Resonance Imaging
9. Fourier reconstruction, k-space, frequency and phase encoding
10. Optical imaging, Fluorescence, Microscopy, Confocal Imaging
11. Enhancement: Point Spread Function, Filtering, Sharpening, Wiener filter
12. Segmentation: Thresholding, Matched filter, Morphological operations
13. Pattern Recognition: Feature extraction, PCA, Wavelets
14. Pattern Recognition: Bayesian Inference, Linear classification

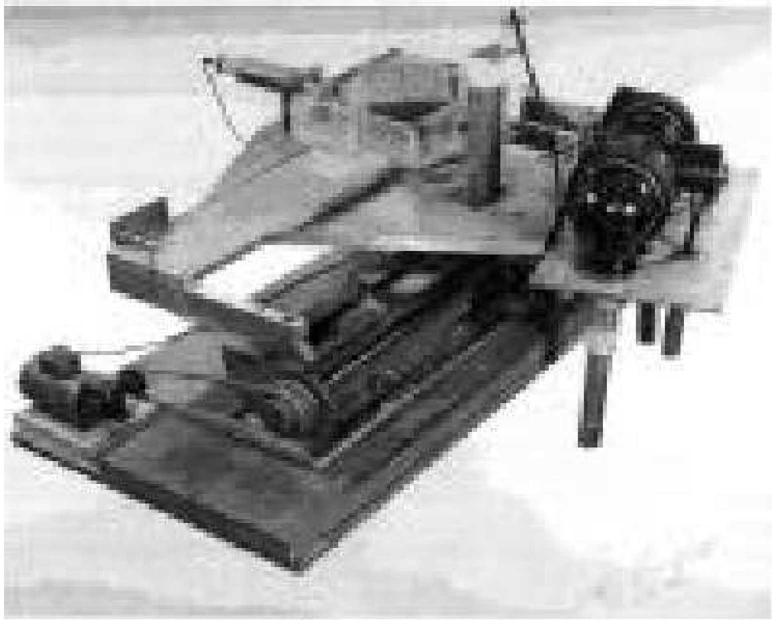
Biomedical Imaging

Imaging Modality	*Year*	*Inventor*	*Wavelength Energy*	*Physical principle*
X-Ray	1895	Röntgen (Nobel 191)	3-100 keV	Measures variable tissue absorption of X-Rays
Single Photon Emission Comp. Tomography (SPECT)	1963	Kuhl, Edwards	150 keV	Radioactive decay. Measures variable concentration of radioactive agent.
Positron Emission Tomography (PET)	1953	Brownell, Sweet	150 keV	SPECT with improved SNR due to increased number of useful events.
Computed Axial Tomography (CAT)	**1972**	**Hounsfield, Cormack (Nobel 1979)**	**keV**	**Multiple axial X-Ray views to obtain 3D volume of absorption.**
Magnetic Resonance Imaging (MRI)	1973	Lauterbur, Mansfield (Nobel 2003)	GHz	Space and tissue dependent resonance frequency of kern spin in variable magnetic field.
Ultrasound	1940-1955	many	MHz	Measures echo of sound at tissue boundaries.

CT: Computed Tomography = CAT: Computed Axial Tomography

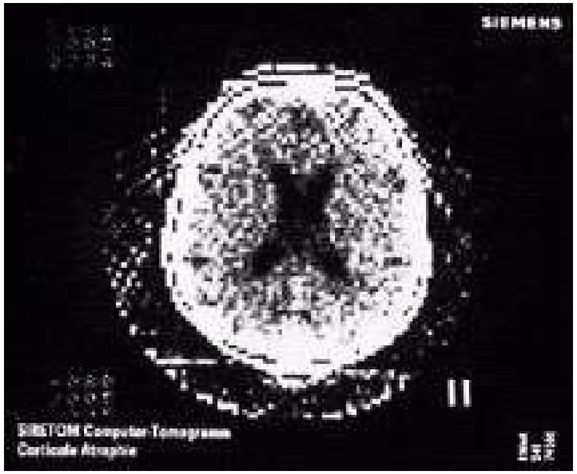
CT - Origine

- Mathematical basis developed by Radon (1917)
- Idea popularized by Cormack (1963)
- First practical x-ray CT scanner by Hounsfield (1971)



CT – then and now

1971



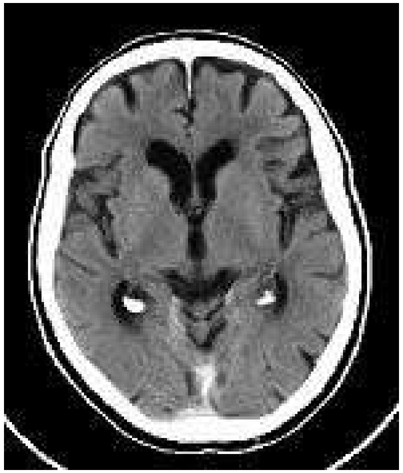
Original axial CT image from the dedicated Siretom CT scanner. Ability to see the soft tissue structures of the brain, including the black ventricles for the first time.

128x128 pixel

1-4 hours acquisition time

1-5 days computation

2000



Axial CT image of a normal brain using a state-of-the-art CT system.

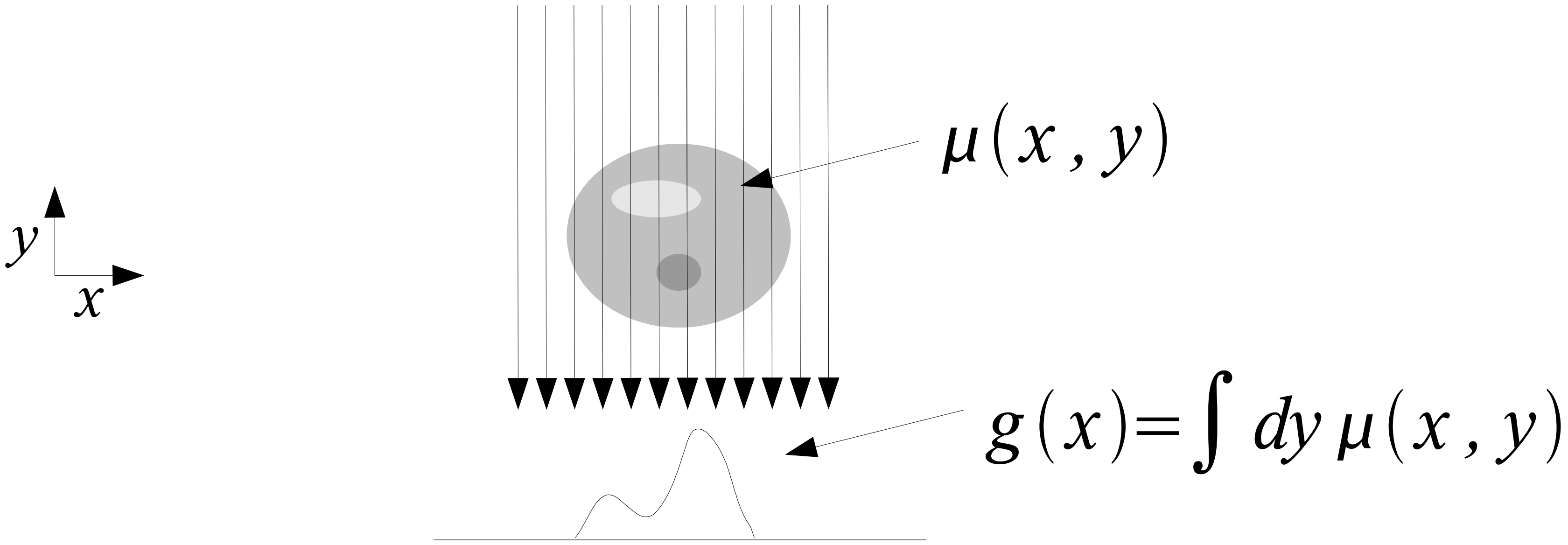
512 x 512 pixel

0.35 sec acquisition time

1 sec computation

CT - Imaging Principle

Computed Axial Tomography: Multiple x-ray projections are acquired around the object and a 2D image is computed from those projections.



$$\mu(x,y)$$

$$g(x)=\int dy\,\mu(x,y)$$

Idea: Reconstruct 2D attenuation distribution $\mu(x,y)$ from multiple 1D x-ray projections $g(\,)$ taken at different angles ϕ .

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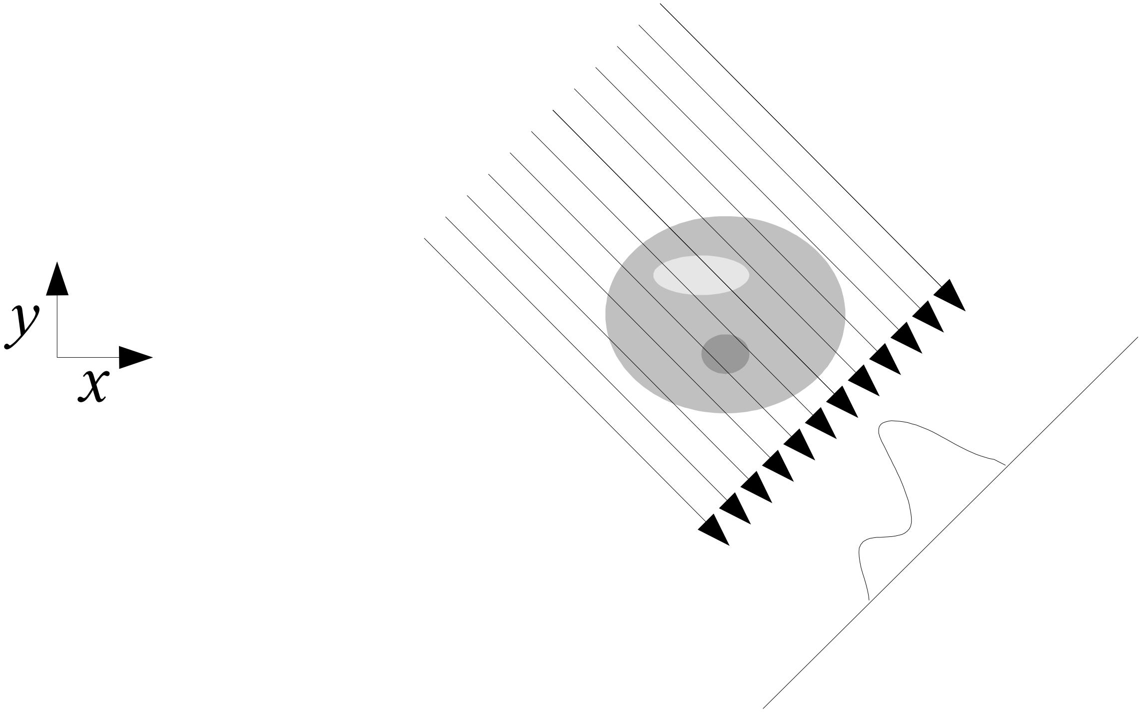

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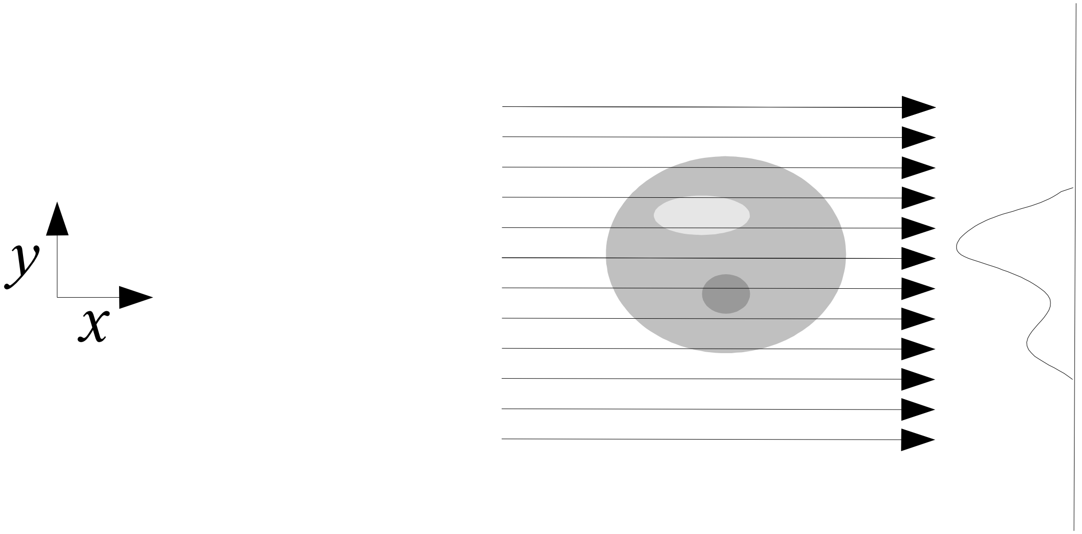

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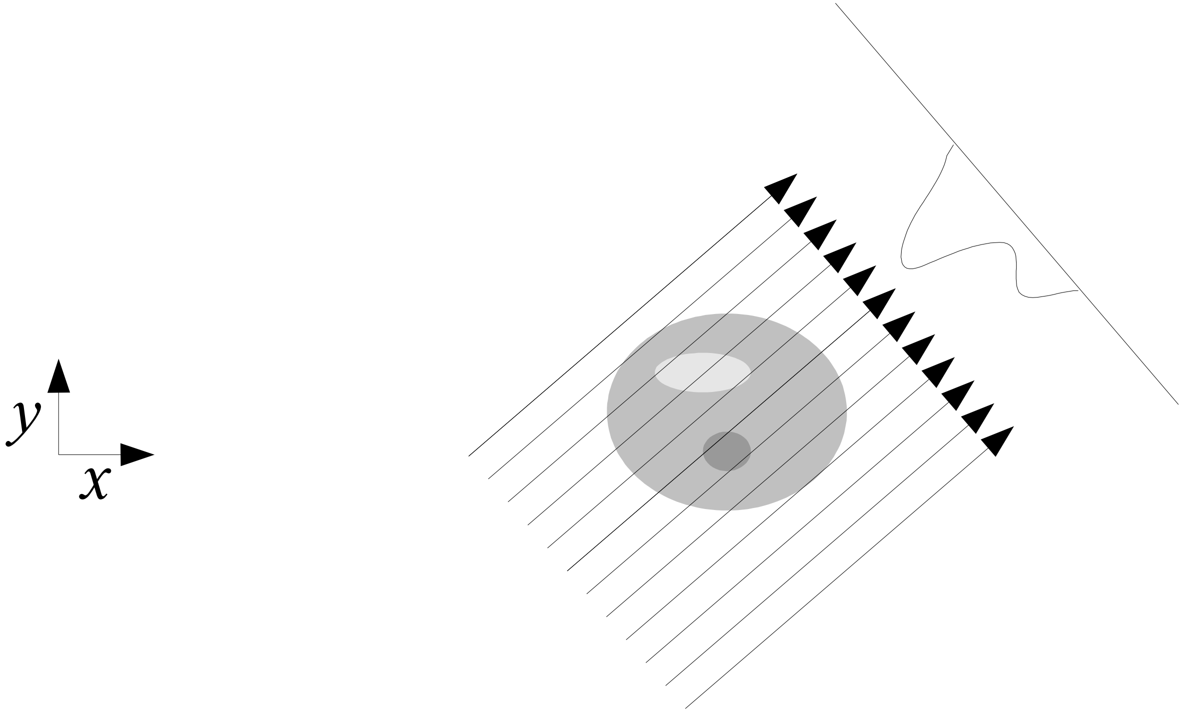

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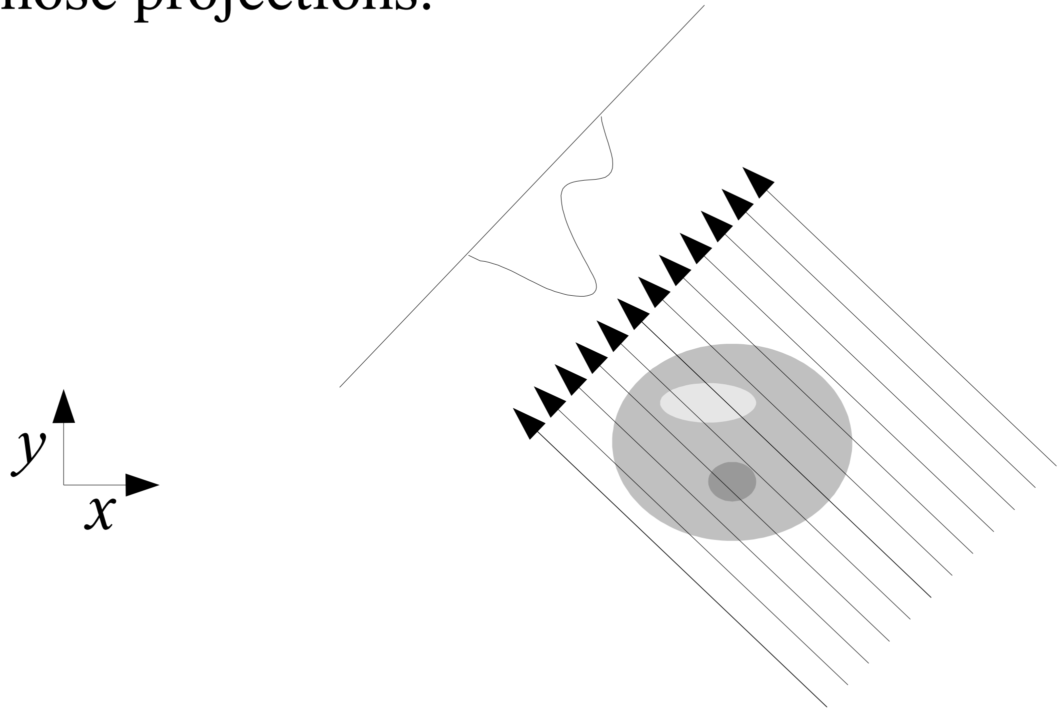

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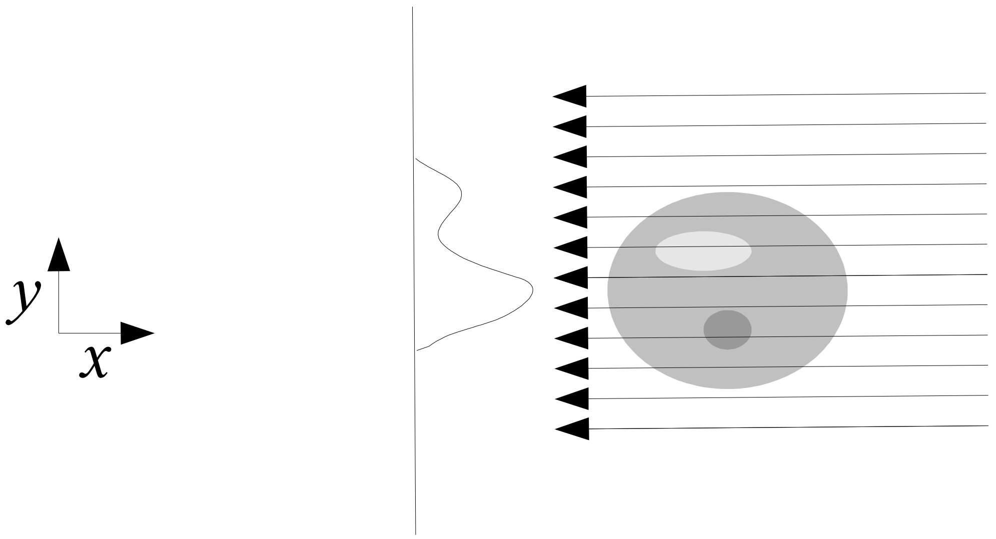

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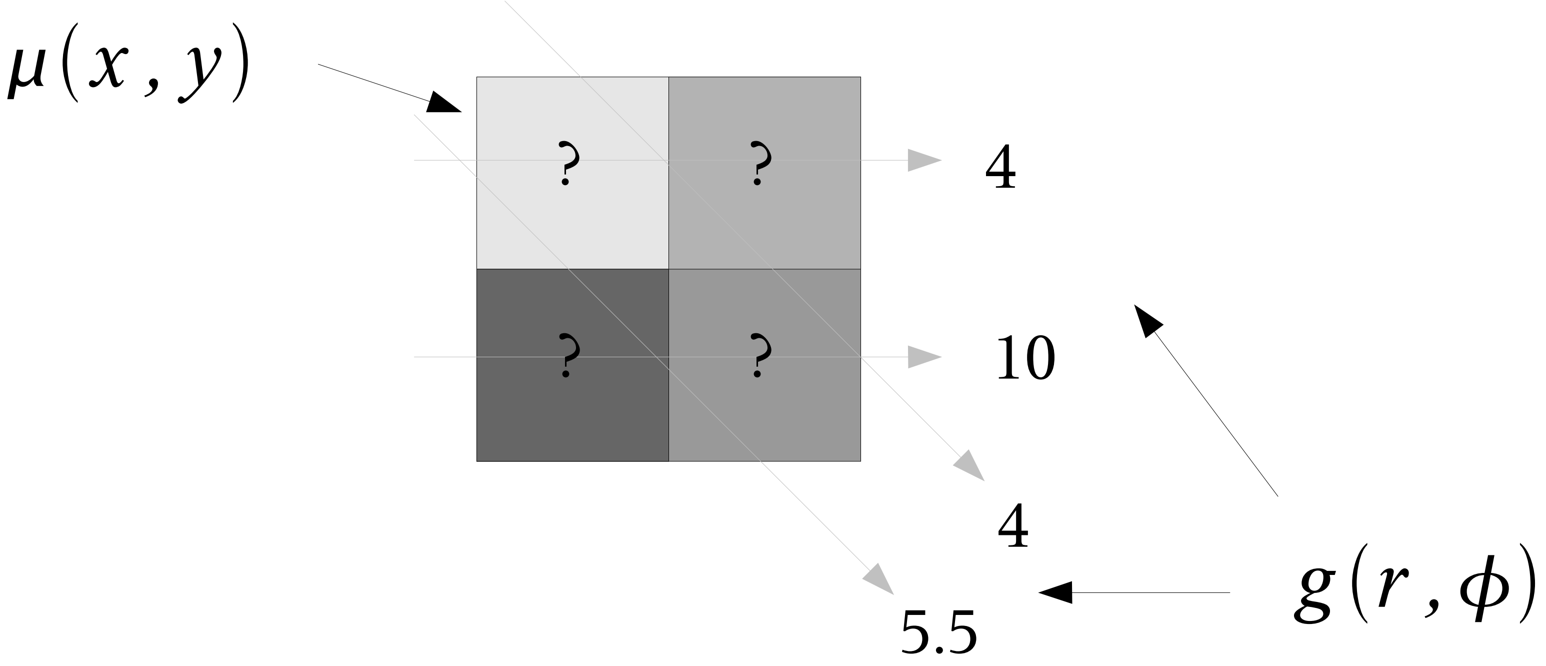
CT – Simple Inversion Example

Given the observed detector values how can one compute the unknown attenuation coefficients?



$g(1,1) = \mu(1,1) + \mu(1,2)$
$g(1,2) = \mu(2,1) + \mu(2,2)$
$g(2,1) = (\mu(1,1) + \mu(1,2) + \mu(2,2))/2$
$g(2,2) = (\mu(1,1) + \mu(2,1) + \mu(2,2))/2$

$$\boldsymbol{g} = M\,\mu$$

$$M = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0.5 & 0.5 & 0 & 0.5 \\ 0.5 & 0 & 0.5 & 0.5 \end{bmatrix}, \quad \mu = \begin{bmatrix} \mu(1,1) \\ \mu(1,2) \\ \mu(2,1) \\ \mu(2,2) \end{bmatrix}, \quad \boldsymbol{g} = \begin{bmatrix} g(1,1) \\ g(1,2) \\ g(2,1) \\ g(2,2) \end{bmatrix}$$

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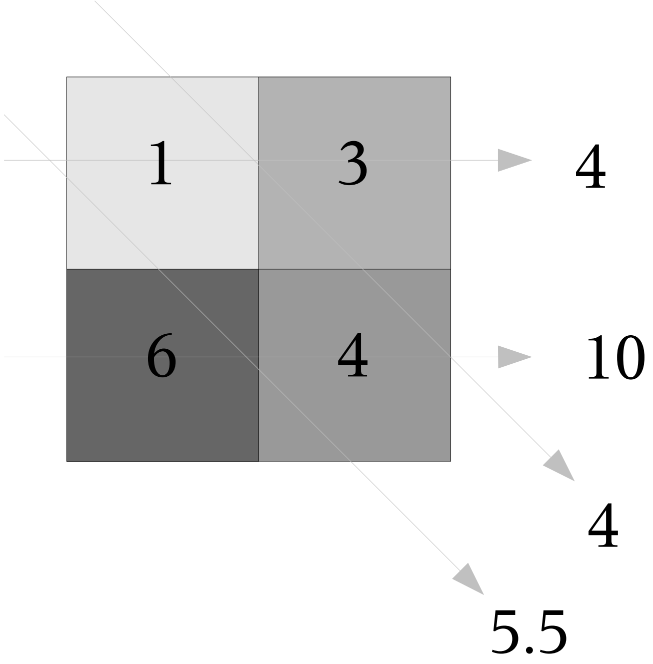


$$\mathbf{g} = M\,\mu$$

Answer: linear inversion!

$$M^{-1} = \begin{bmatrix} 0 & -1 & 0 & 2 \\ 1 & 1 & 0 & -2 \\ 1 & 1 & -2 & 0 \\ -1 & 0 & 2 & 0 \end{bmatrix}, \quad \mu = \begin{bmatrix} 1 \\ 3 \\ 6 \\ 4 \end{bmatrix}, \quad \mathbf{g} = \begin{bmatrix} 4 \\ 10 \\ 4 \\ 5.5 \end{bmatrix}$$

$$\mu = M^{-1}\,\mathbf{g}$$

CT – CT number

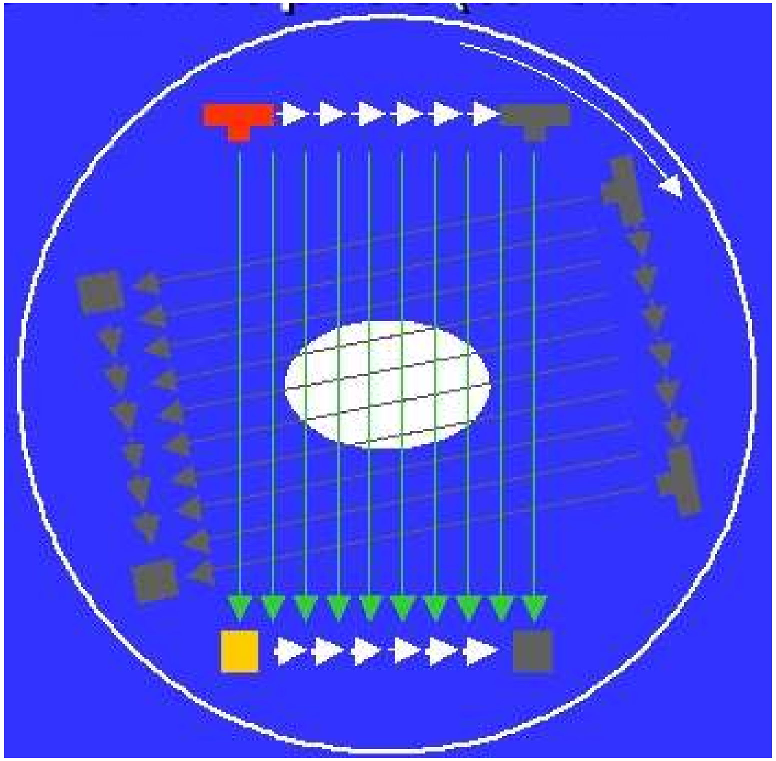
Hounsfield Units or “CT number” are units for attenuation coefficient relative to watter attenuation at μ_{water} at 70keV.

$$HU = 1000 \frac{\mu - \mu_{water}}{\mu_{water}}$$

Tissue	**CT number (HU)**
Bone	1000
Liver	40 ... 60
White matter (brain)	46
Grey matter (brain)	43
Blood	40
Muscle	10 – 40
Kidney	30
Cerebrospinal fluid	15
Water	0
Fat	–50 ... –100
Air	–1000

CT – 1st Generation

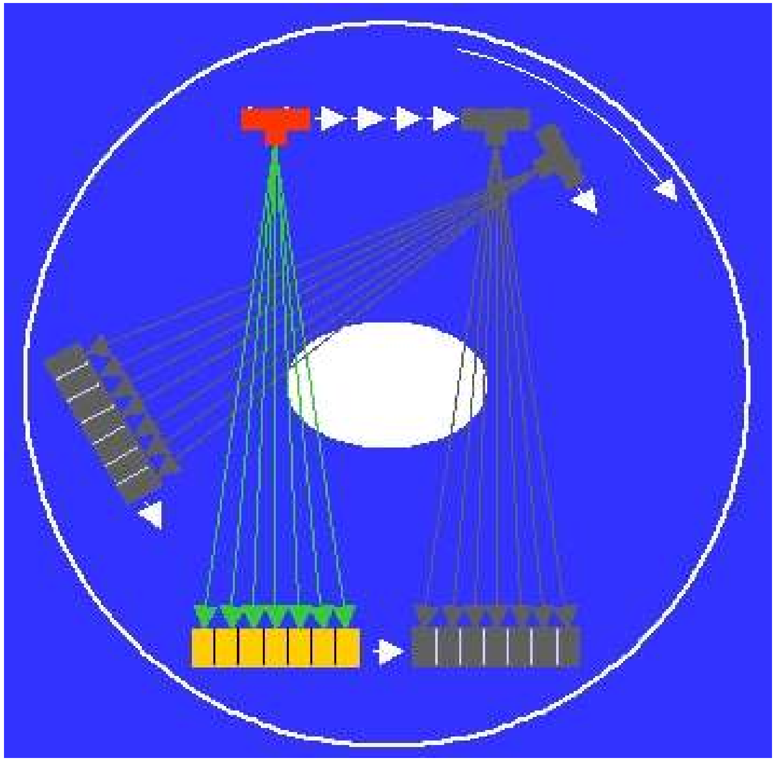
- EMI Mark I (Hounsfield): parallel-beam scanner (highly collimated beam) → excellent scatter rejection, now outdated.
- 180^o-240^o rotation angle in steps of 1^o
- Used for the head
- 5-min scan time, 20 min reconstruction
- Original resolution: 80x80 pixels (ea. 3X3 mm^2), 13 mm slice.



Translation & Rotation

CT – 2nd Generation

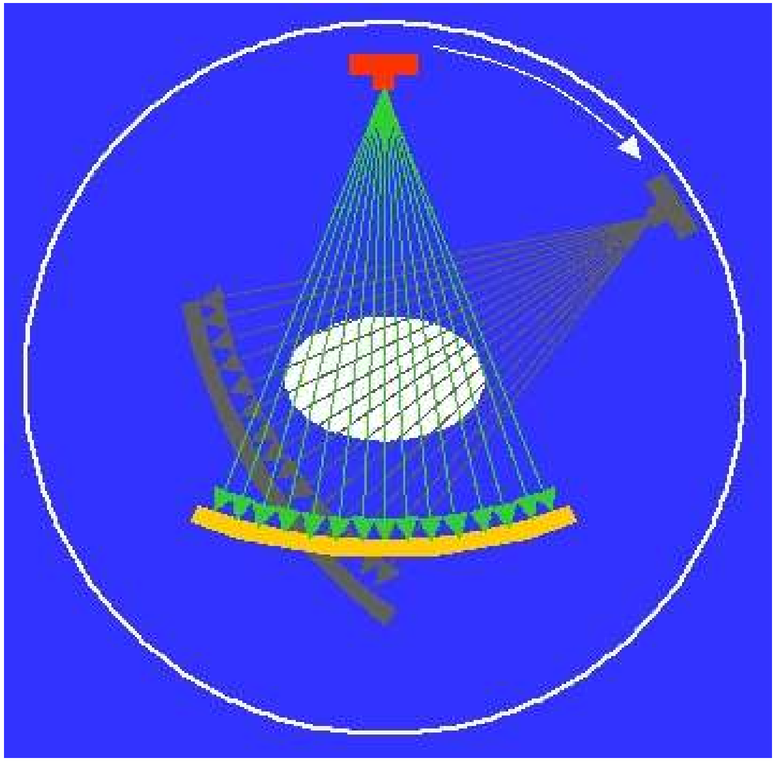
- Hybrid system: Fan beam, linear detector array (~30 detectors)
- Translation and rotation
- Reduced number of view angles → scan time ~ 30 s
- Slightly more complicated reconstruction algorithms because of fan-beam projection
- Non-parallel rays require **rebinning** or fan-beam algorithms



Translation & Rotation

CT – 3rd Generation

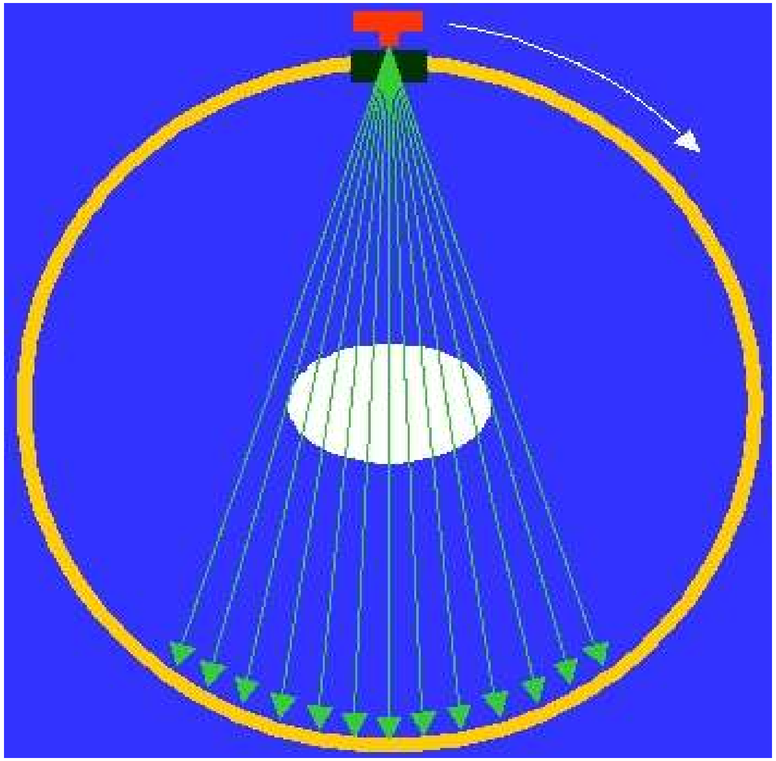
- Wide fan beam covers entire object
- 500-700 detectors (ionization chamber or scintillation detector)
- No translation required → scan time ~ seconds (reduced dose, motion artifacts)
- Reconstruction time ~ seconds



Only Rotation

CT – 4th Generation

- Stationary detector ring (600~4800 scintillation detectors)
- Rotation x-ray tube.
- Scan time, reconstruction time ~ seconds
- Source either inside or outside

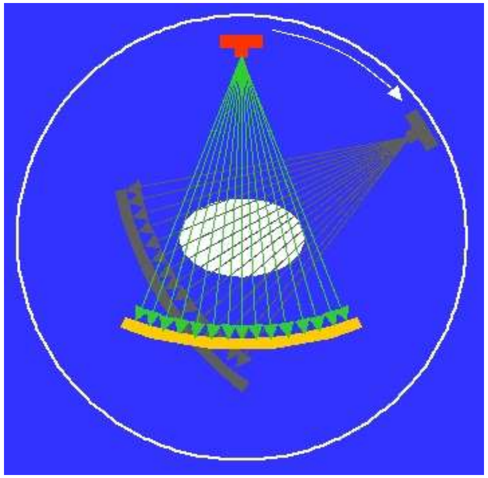


Only Rotation of source

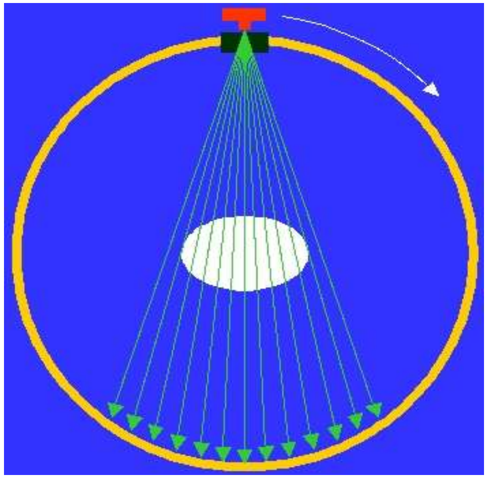
CT – 3rd and 4th Generation comparison

- Both designs currently employed, neither can be considered superior:

- 3rd Generation (GE, Siemens):
  + Fewer detectors (better match, cheaper)
  + Good scatter rejection with focused septa
  - Cumulative detector drift
  - Susceptible to ring artifacts
  (due to detector gain variations)



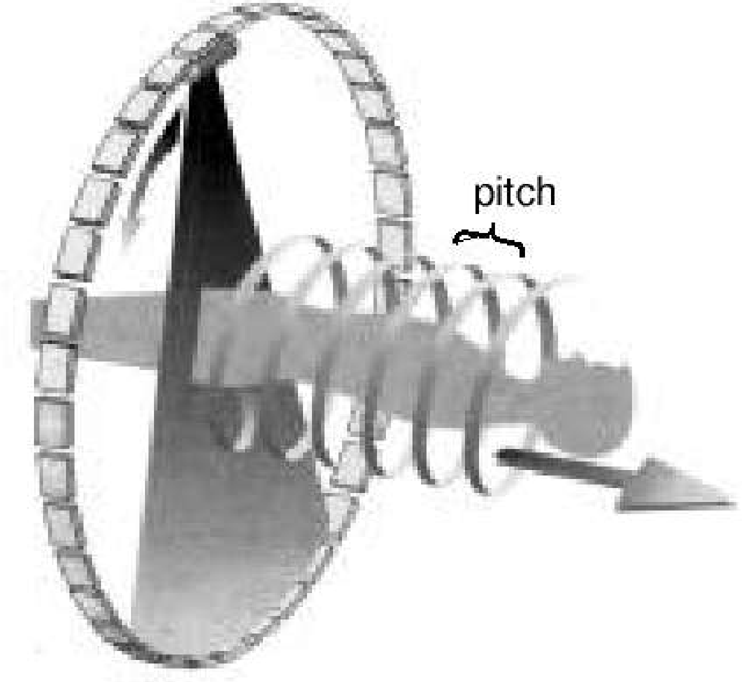
- 4th Generation (Picker, Toshiba):
  + Less moving parts
  + Detector calibrated twice per rotation
  - Wide acceptance angle of detector
  (low scatter rejection)



CT – Spiral

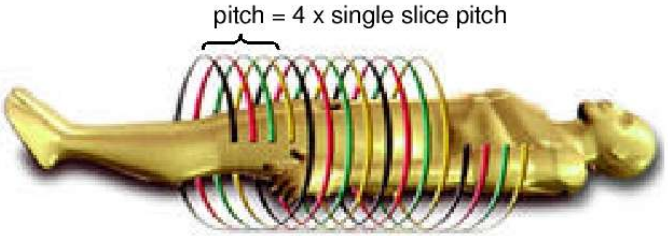
Spiral

- Continuous linear motion of patient table during multiple scans
- Increased coverage volume / rotation
- Pitch: Number of slice thickness the table moves during one rotation (typically ~1-2)



Multi-slice spiral

- Interweaving multiple helices → increased data density
- Allows higher pitch (faster scan speed)



CT – Detectors

Detector Requirements:

- High efficiency to minimize radiation dose (>70%)
- Resolution (< 1mm)
- Linearity
- Wide dynamic range – up to 10^5.
- Stable in time and temperature.
- Uniform gain to avoid ring artifacts.

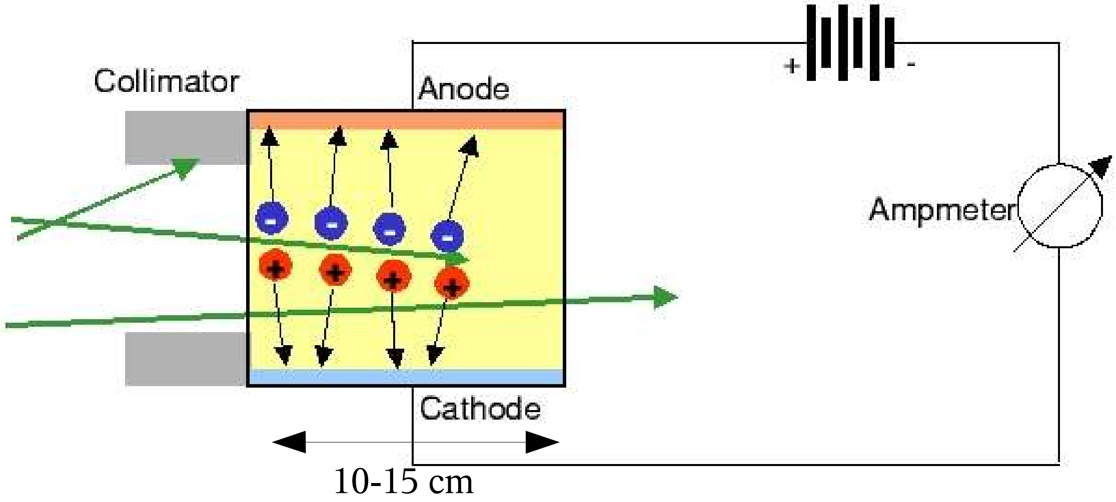
Two basic designs for CT detectors today:

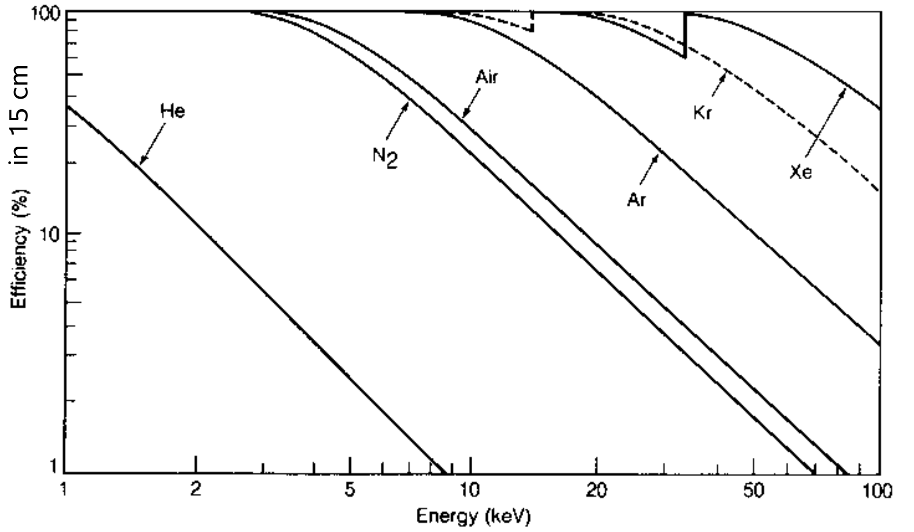
- Ionization chamber
- Scintillation + photodiodes

CT – Detectors

Ion Chamber:

- X-ray ionizes gas, e.g. Xe_2, N_2, Ar_2.
- Electric field attracts electron and ions
- Measured current proportional to x-ray intensity
- High atomic number Z=54 for Xe.
- High pressure to increase absorption (8-20 at).
- Plates act as collimator (3rd generation CT).

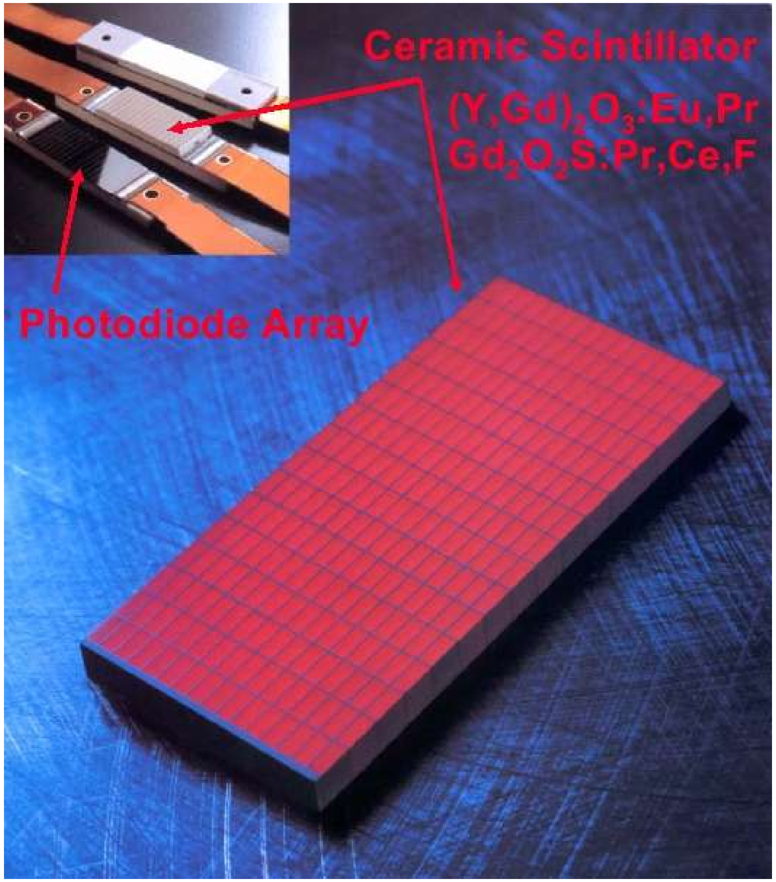




CT – Detectors

Scintillation detector:

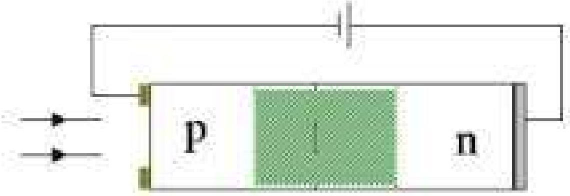
- Scintillation detector converts x-ray into light.
- In CT this light is detected by photo-diodes.
- This arrangement more sensitive than Xe detector.
- Single crystals or ceramic bars.
- Surfaces painted with a metallic paint for light reflection.
- CT detectors do not count individual photons but integrate the energy deposited by many photons.



CT – Detectors

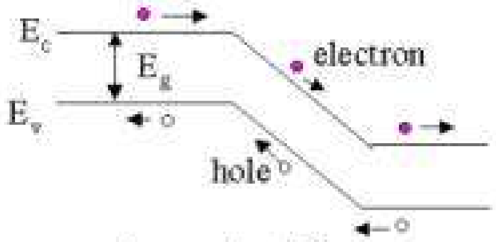
Photodiode:

- P-N junction in semi-conducting crystal (e.g. Si)
- Internal photo-electric effect: Photo generated electron-hole increase the carries density
- Operated in reversed biased (increased depletion zone)



p-n photo diode in reverse bias

Variation of optical power



Energy band diagram