X-ray Computed Tomography

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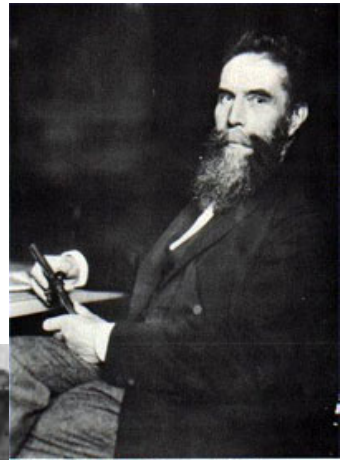
X-ray Computed Tomography (CT)

- **Non-destructive imaging** technique providing a 3D image of the internal structure of the scanned object
- CT is based on X-ray attenuation i.e. removal of photons from a beam of x-rays as it passes through matter

Historical background

- 1895 Roentgen discovers X-rays (1901 Nobel prize)
- 1917 Radon develops the mathematical principle behind CT reconstruction

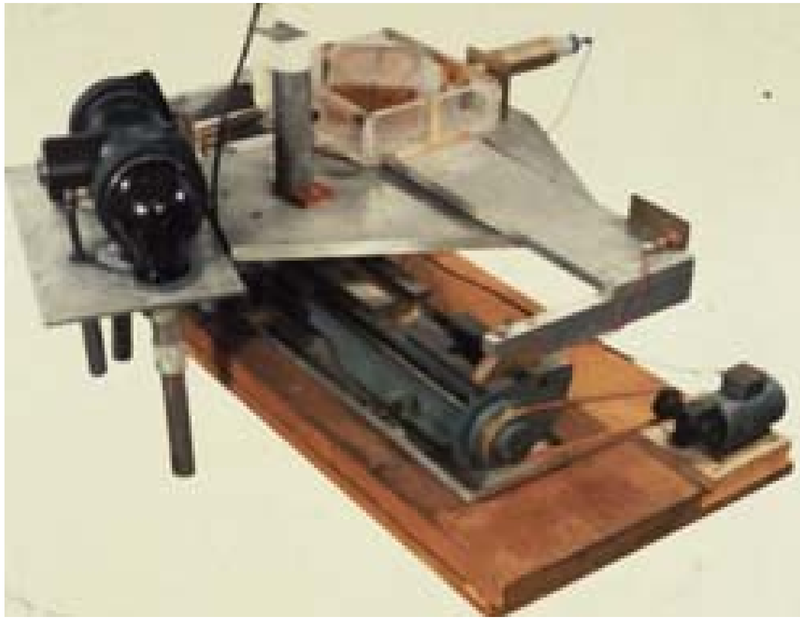
Roentgen 1845- 1923



Radon 1887- 1956

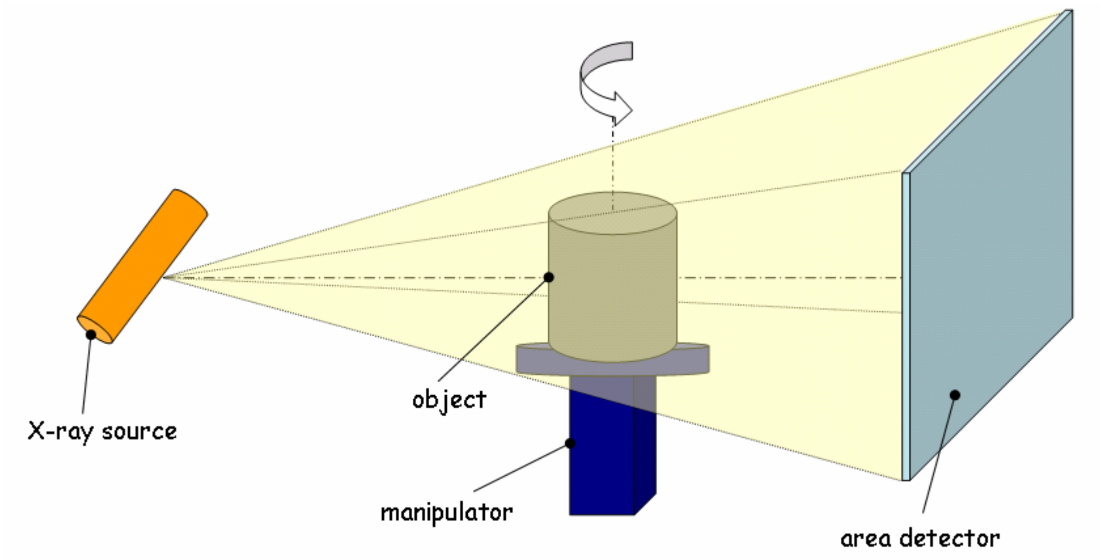
Historical Background

- 1972 Hounsfield builds the first X-ray CT scanner
- 1979 Hounsfield and Cormack receive the Nobel Prize for Medicine
- 1980s CT extended and adapted to a wide variety of non-medical tasks



How a CT system works

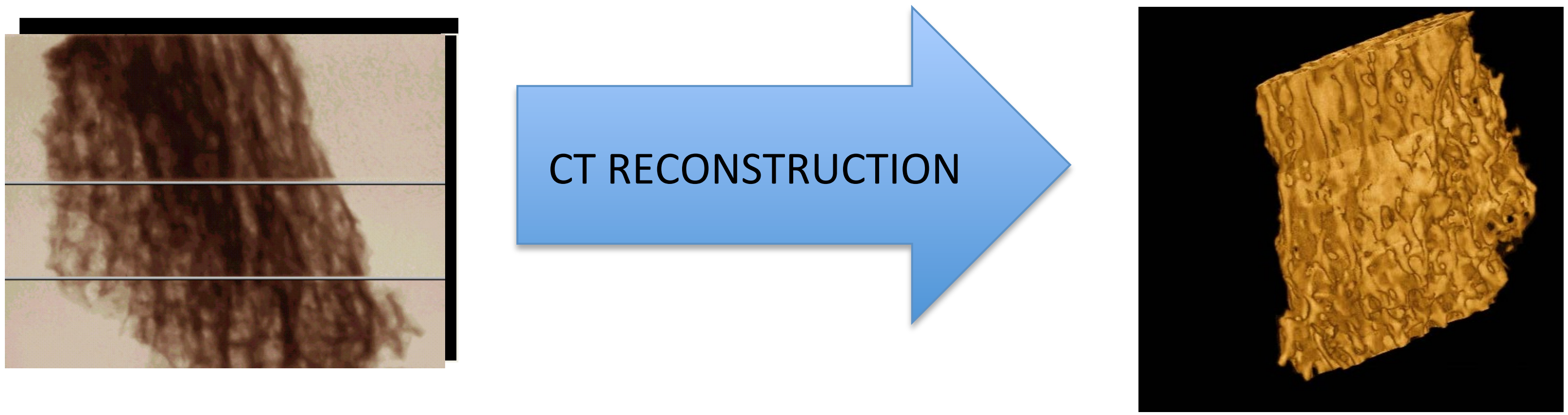
- Sample irradiated by X-ray beam
- Detector measures X-rays transmitted through the sample at one angle → transmitted intensity is a function of X-ray energy, path length, and sample material
- Many different projections (angles) collected by rotating the sample



How a CT system works

- The data are sent to a computer and reconstructed in a 3D image by using a CT reconstruction algorithm

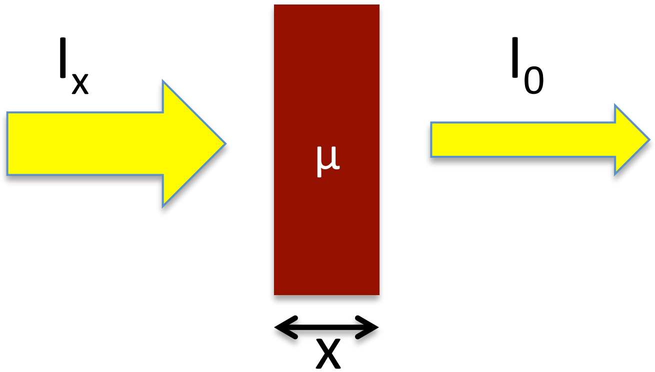
Projections   3D reconstructed volume



Principles of X-ray CT

- Attenuation of a monoenergetic beam through a homogeneous material is Beer's Law:

$$I_x = I_0 \exp(-\mu' \rho x)$$



I_0 = incident beam intensity

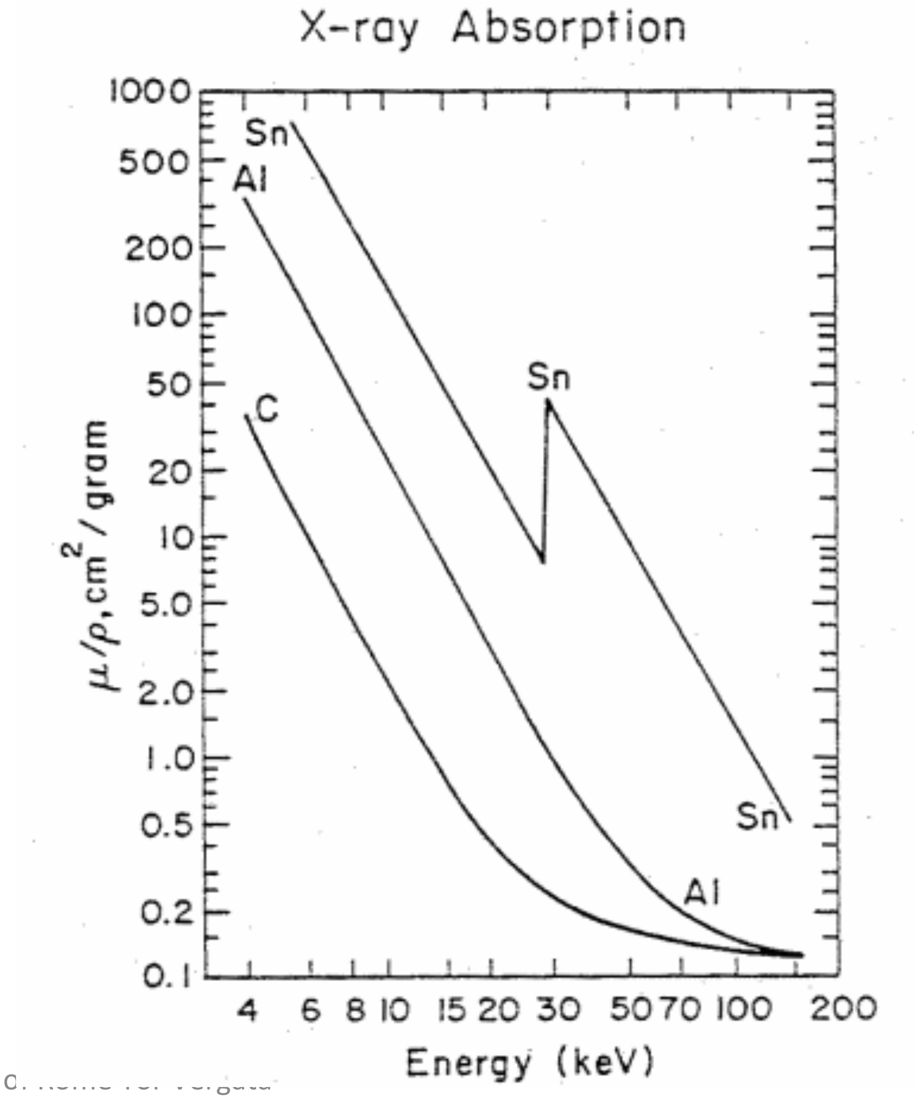
I_x = transmitted beam intensity

x = length of the X-ray path through the material

μ' = mass absorption coefficient for the material being scanned

Mass absorption coefficient

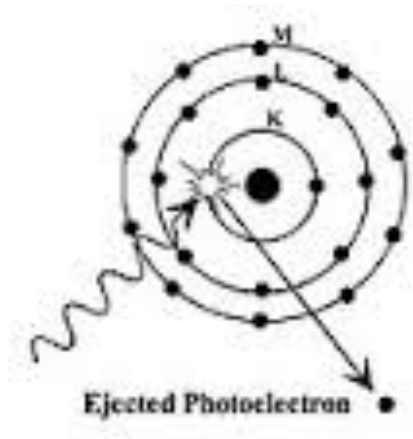
- Mass absorption coefficient is a function of:
  - Photon energy
  - Atomic number of the material being irradiated



Physical processes responsible for X-ray attenuation

- Photoelectric absorption

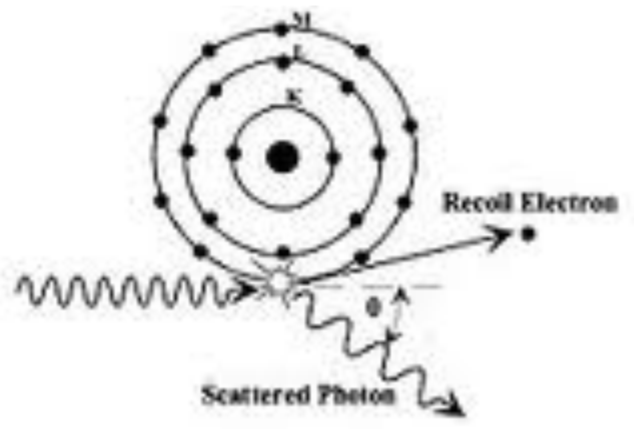
the total energy of an incoming X-ray photon is transferred to an inner electron, causing the electron to be ejected



Physical processes responsible for X-ray attenuation

- Photoelectric absorption
- Compton scattering

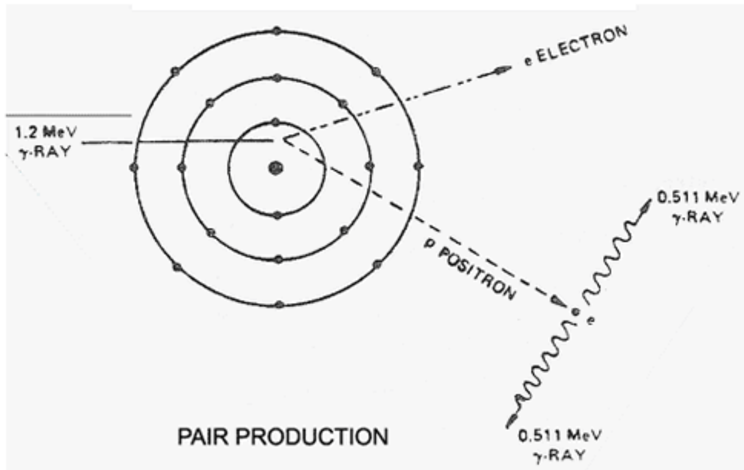
the incoming photon interacts with an outer electron, ejecting the electron and losing only a part of its own energy, after which it is deflected in a different direction.



Physical processes responsible for X-ray attenuation

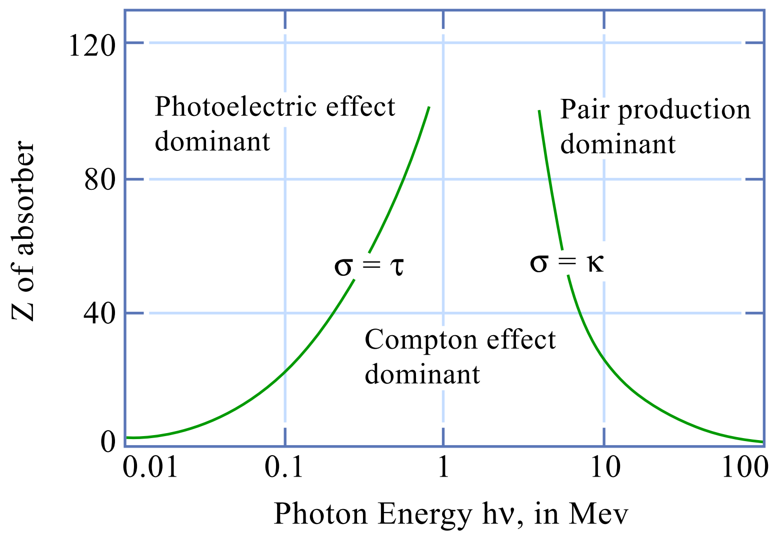
- Photoelectric absorption
- Compton scattering
- Pair production

the photon interacts with a nucleus and is transformed into a positron-electron pair



Physical processes responsible for X-ray attenuation

- The photoelectric effect: low energies (up to ~ 50-100 keV)
- Compton scattering: intermediate energies (up to 5-10 MeV)
- Pair production: high energies (above 5-10 MeV)



In X-ray CT only photoelectric absorption and Compton scattering need to be considered

Physical processes responsible for X-ray attenuation

- Photoelectric absorption α Z^4
- Compton scattering α Z

Z = material atomic number

Low-energy X-rays are more sensitive to differences in composition than higher-energy X-rays

X-ray CT system components

Main components of a X-ray CT system:

- X-ray source to irradiate the sample
- Rotation stage to rotate the sample
- Detector to measure X-ray intensity attenuation

CT scanner configurations

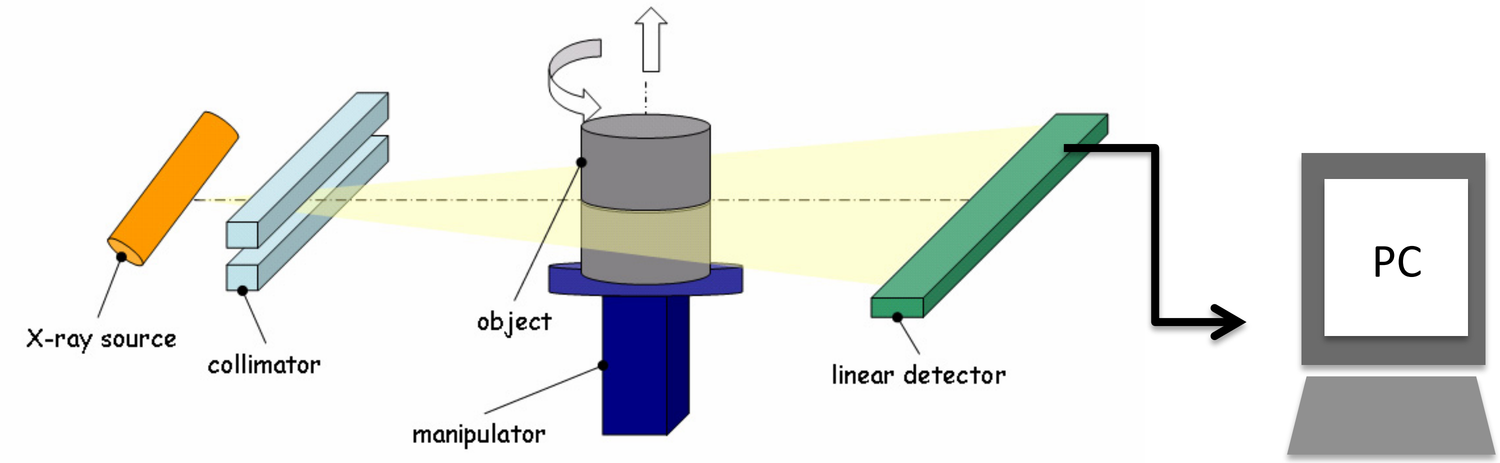
- Fan beam

Fan beam

X-rays are collimated and measured using a linear detector array

+ Scatter-free images

- Only one slice image is acquired → sample translation needed



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CT scanner configurations

- Fan beam
- Cone beam

Cone beam

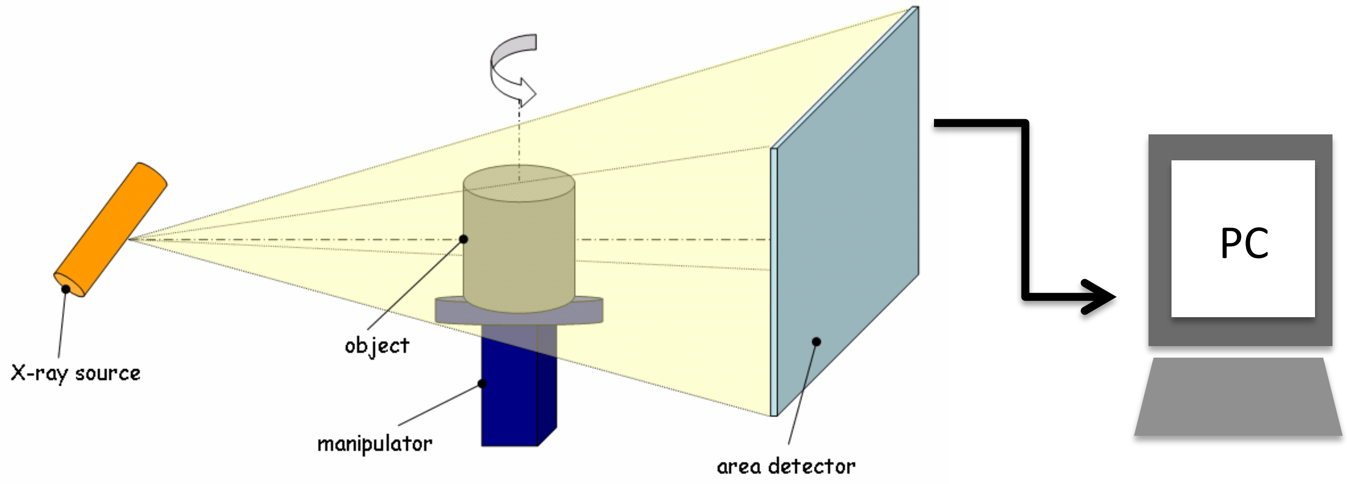
X-ray are measured using an area detector. The beam is no longer collimated

+ Data for an entire object can be acquired in a single rotation: hundreds or thousands of slices at a time

+ More acquisition time can be spent at each angular position→ low noise images

- Data are subject to blurring and distortion the further one goes from the central plane

- Data suffer from scattering → reconstruction artifacts



CT scanner configurations

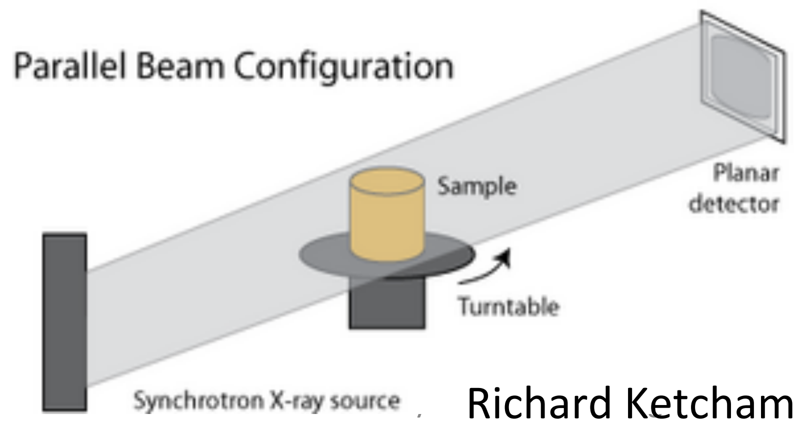
- Fan beam
- Cone beam
- Parallel beam

Parallel beam

Parallel-beam scanning is done using a synchrotron beam line as the radiation source.

- The object size is limited by the width of the X-ray beam → sample translation may be needed

+ Synchrotron radiation has very high intensity → fast data acquisition, low noise images



Richard Ketcham, University of Texas at Austin

Radiation sources

Radiation sources

- Radioisotopes

Radioisotopes

Isotopes used for X-ray imaging:

- Cesium 137 → monochromatic energy of 662 keV
- Americium 241→ monochromatic energy of 60 keV

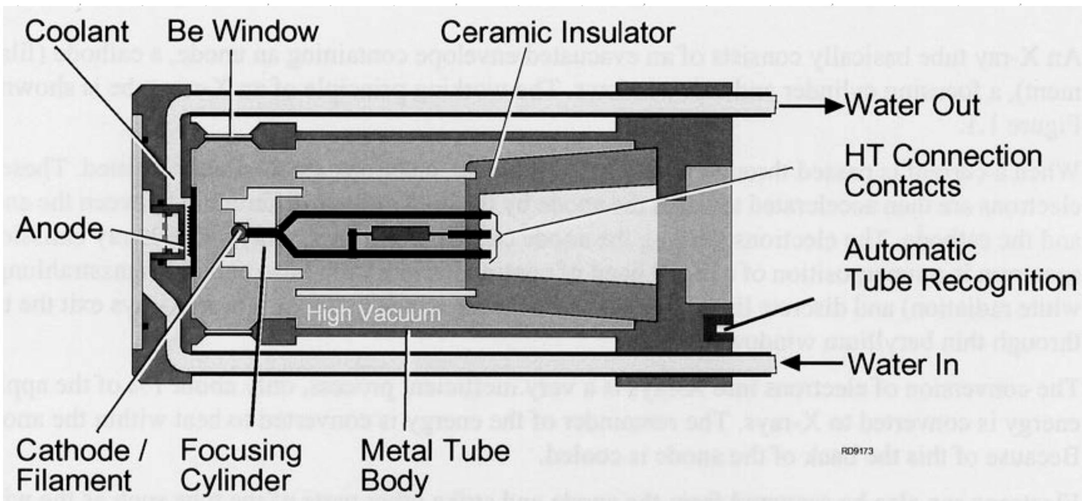
- Pros: Monochromatic source
- Cons:
  - Transportation (they can not be switched off)
  - Low flux → Long exposition time needed

Radiation sources

- Radioisotopes
- X-ray tubes

X-ray tubes

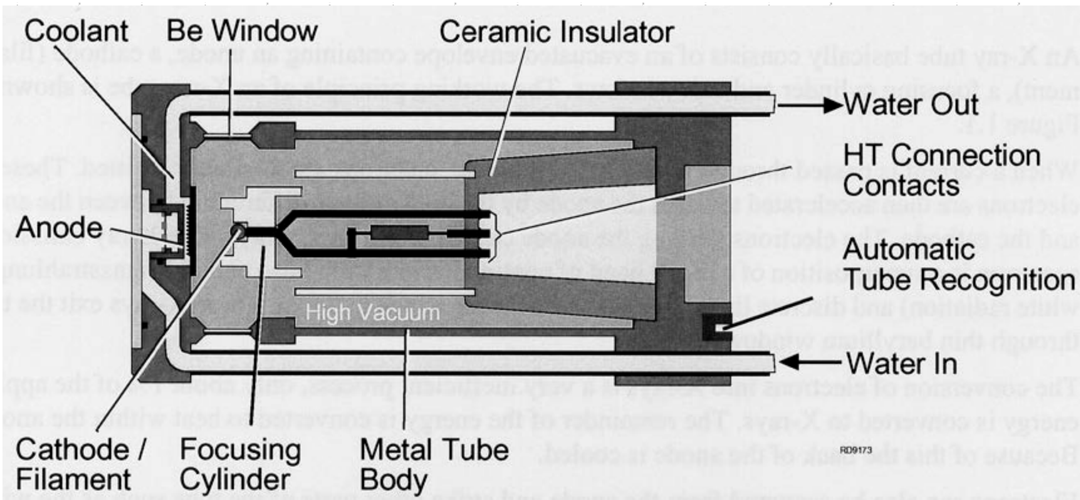
- Most used radiation source in X-ray imaging
- Main components of X-ray tubes:
  - source of electrons
  - high accelerating voltage
  - metal target (tungsten)



Arturas Vailionis, Stanford University

X-ray tubes

- Electrons are emitted from the hot filament surface (thermionic emission)
- Electrons are accelerated towards the positively charged anode by an applied electric field
- X-rays are produced when accelerated electrons collide with the anode



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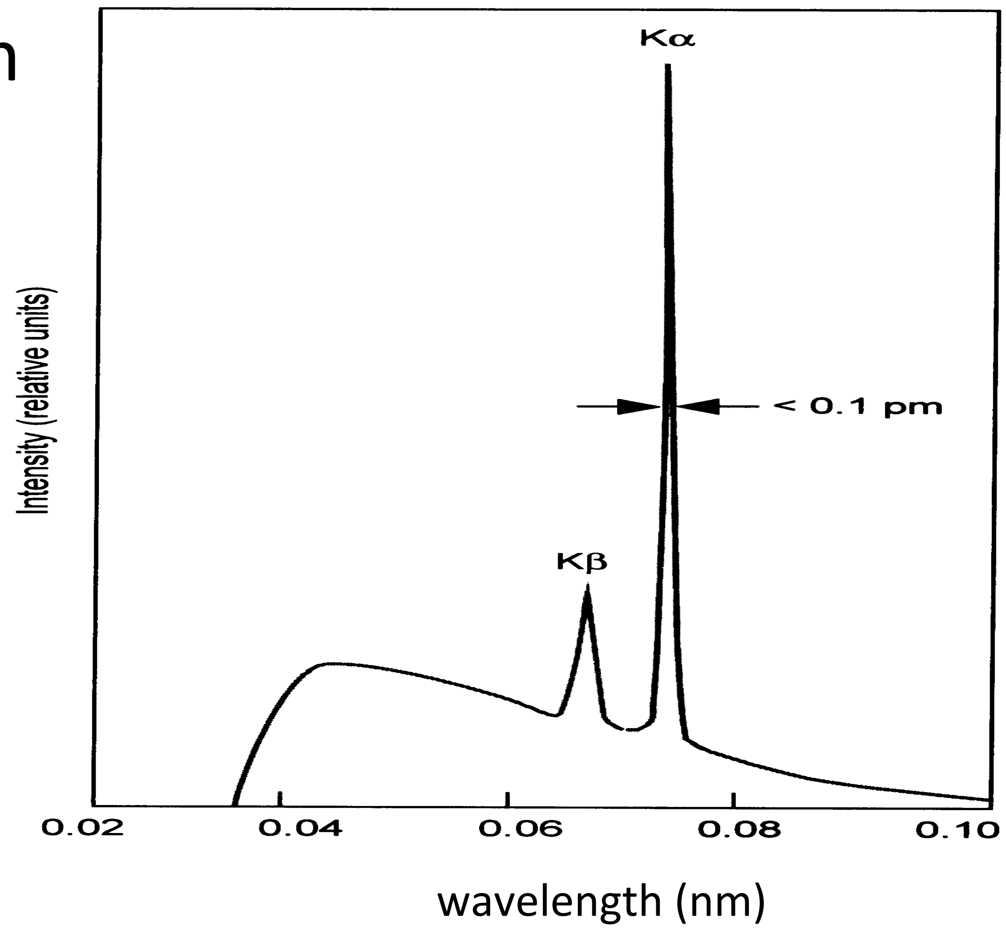
X-ray tube spectrum

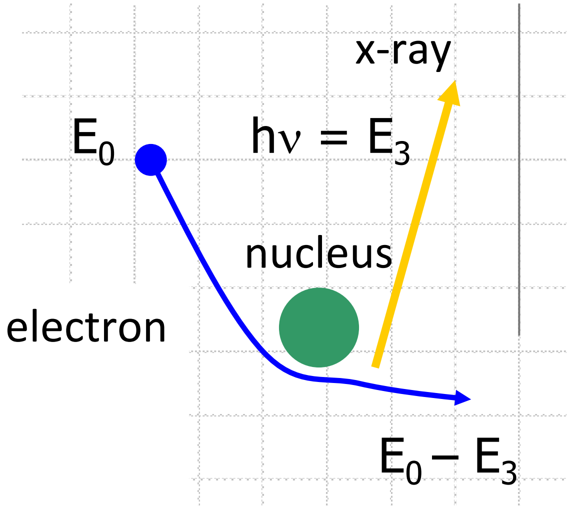
- Continuous spectrum
- Characteristic peaks



Arturas Vailionis, Stanford University

Continuous spectrum

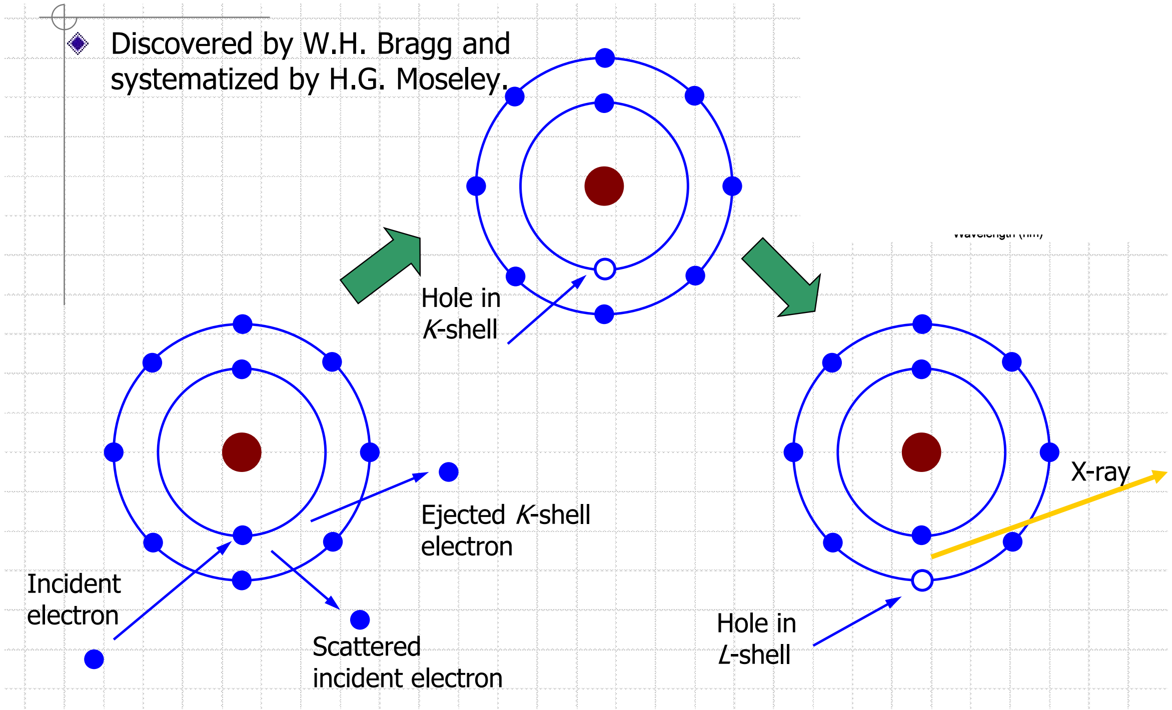
- Continuous spectrum arises due to the deceleration of the electrons hitting the target
- The electron slows down and changes direction as it speeds past the atom emitting a X-ray photon
- This type of radiation is know as bremsstrahlung



Stanford lecture - Arturas Vailionis, Stanford University

Characteristic spectrum

- The characteristic peak is created when a hole in the inner shell, created by a collision event, is filled by an electron from higher energy shell
- Characteristic lines are very narrow



Arturas Vailionis, Stanford University

Radiation sources

- Radioisotopes
- X-ray tubes
- Synchrotons

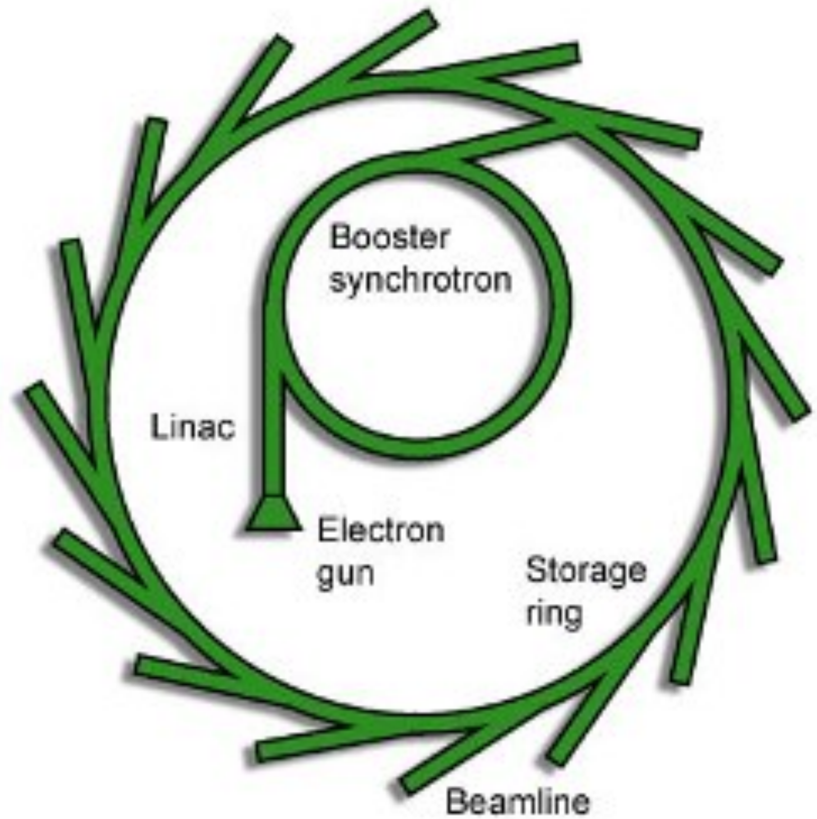
Synchrotron radiation

- Synchrotron radiation ~10^{10} brighter than X-ray tubes
- Broad continuum energy spectrum: infrared – X-rays

ELETTRA, Trieste

Synchrotron radiation

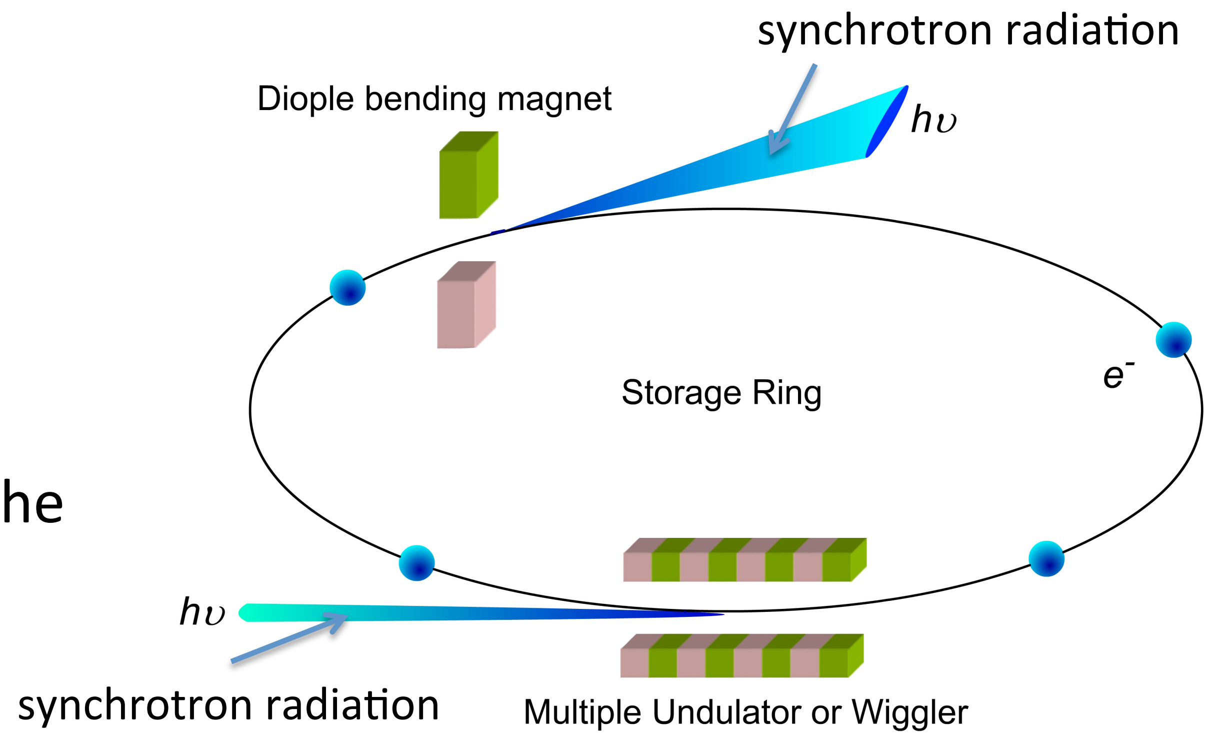
- Electron gun produces a stream of low energy electrons
- Linear accelerator increases their energy
- Booster synchrotron further accelerates the electrons to their final energy (GeV)
- Storage ring maintains the energy and confines the electron beam



 Diamond light source

Synchrotron radiation

- Synchrotron radiation is generated by high-energy electrons accelerated in the magnetic fields of the storage ring



Chung-Li Dong 15 August 2007, SPIE Newsroom

Synchrotron radiation

Synchrotron	Energy	Location
ESRF	6 GeV	France
ALS	1.9 GeV	USA
APS	7 GeV	USA
BESSY II	1.7 GeV	Germany
ELETTRA	2.0 GeV	Italy
SPring-8	8 GeV	Japan
MAX II	1.5 GeV	Sweden
SLS	2.4 GeV	Switzerland
PLS	2 GeV	Korea
SRRC	1.4 GeV	Taiwan
SSRL	3 GeV	USA
CLS	2.9 GeV	Canada
Soleil	2.5 GeV	France
Diamond	3 GeV	UK

Synchrotron radiation

- Pros:
  - Monochromatic
  - High flux
  - Coherent
  - Parallel beam

- High spatial resolution
- Good signal to noise ratio
- Fast data acquisition
- Image quality superior to X-ray tubes

Synchrotron radiation

- Cons:
  - Non easily accessible: large scale facilities
  - Sample must be transported to the facility

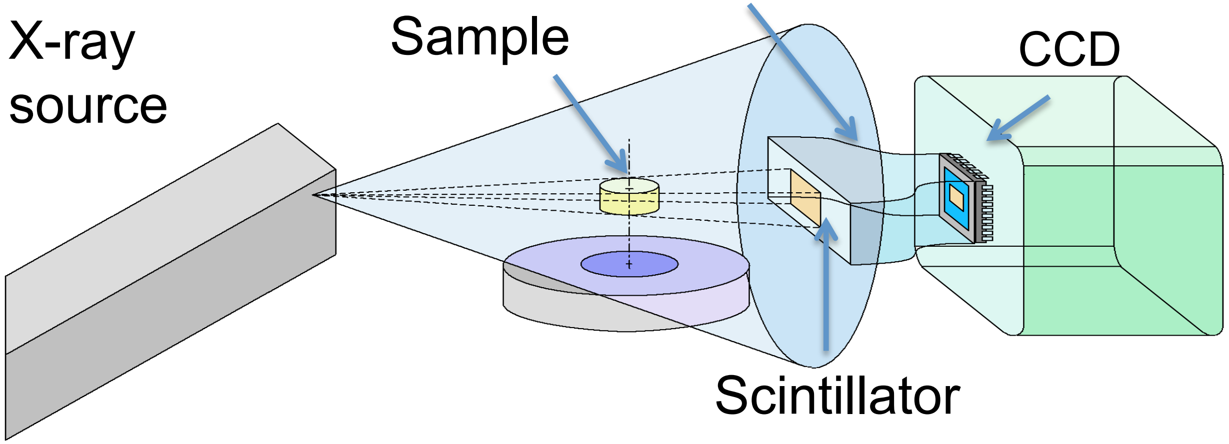
Detection System

Detection System

Most X-ray CT systems use scintillator detectors.

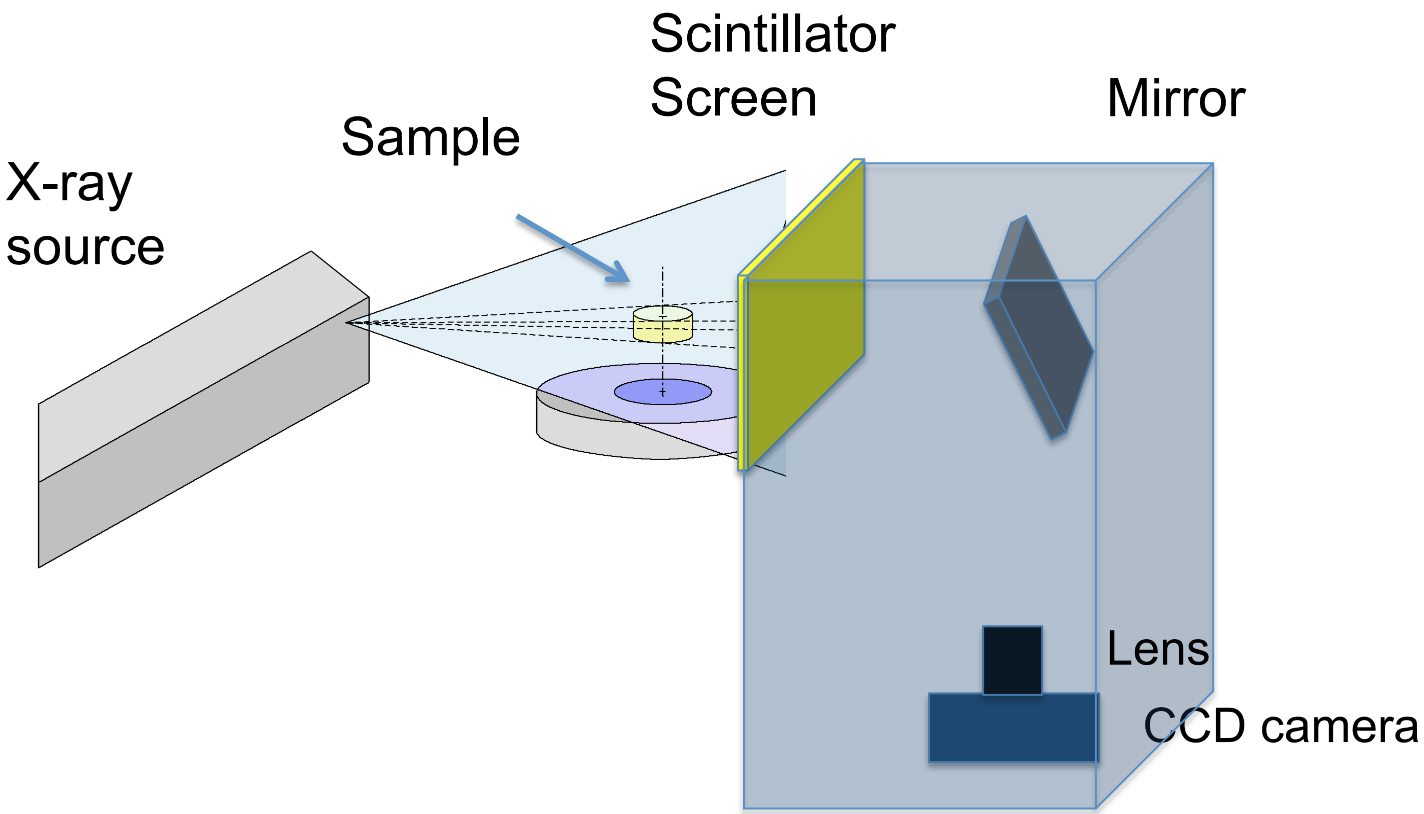
- Scintillator: converts energy deposited by x-ray photons into visible light
- Light guide/mirror: guides scintillation light to photosensor
- Photosensor: converts light into a detectable electronic signal

Light guide based CT system



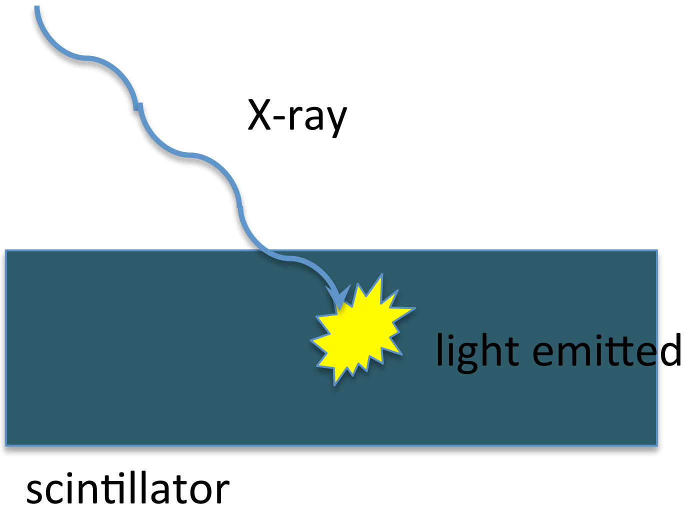
Bettuzzi, University of Bologna

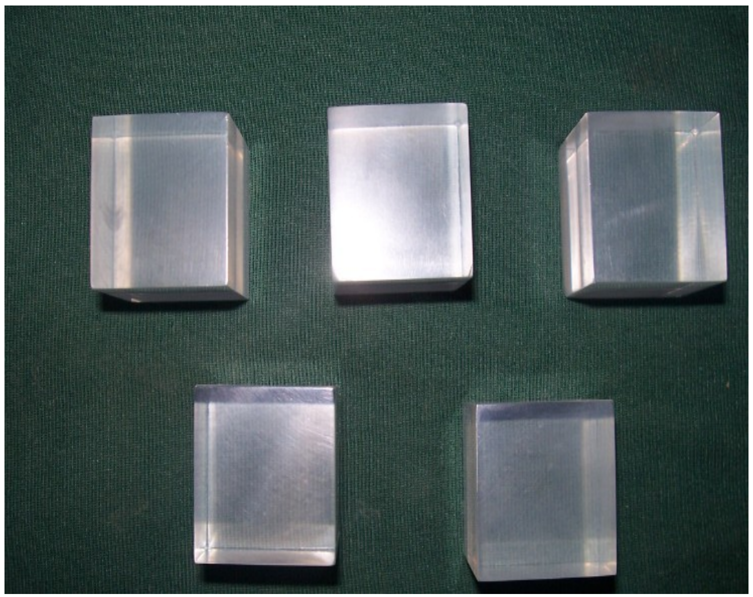
Mirror based CT system



Scintillators

- Absorb and re-emit energy as visible light
- Incoming X-rays produce flashes of light





Scintillators

Requirements:

- High density and Z-value → High detection efficiency
- High light yield (light output per MeV of deposited energy) → Large, easily detectable signal
- Transparency to its fluorescent radiation to allow transmission of light
- Emission of light in a spectral range detectable for photosensors
- Short scintillation decay time → Fast response

Scintillators

Common scintillation materials:

– Thallium doped Cesium Iodine CsI(Tl)

– Bismuth Germanate BGO

– Terbium activated Gadolinium Oxysulfide GOS (Gd_2O_2S:Tb)

Scintillator	Density (g/cm^3)	Light Yield (photons/keV)	Scintillation Decay Time (ns)
CsI (Tl)	4.5	54	1.0 µs
BGO	7.1	8	0.3 µs
GOS	7.3	30	> 1 ms

Scintillators

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Low detection efficiency → Density of CsI (Tl) (4.5)

Bright scintillator → Light Yield of CsI (Tl) (54)

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High detection efficiency

Yields small amount of light

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Short decay time

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High detection efficiency

Slow scintillator

Image Reconstruction

Reconstruction methods

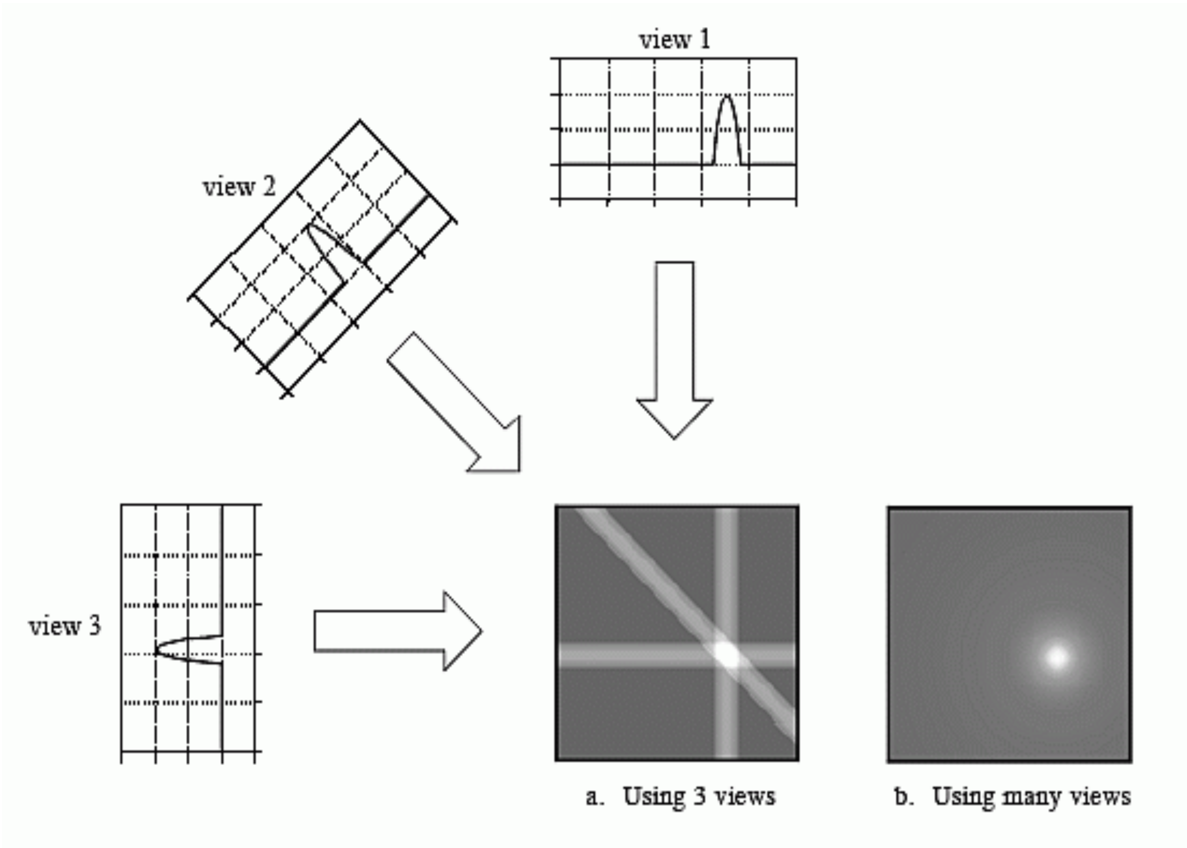
- Reconstruction of a 3D image from measured projection data
- Most used reconstruction method: filtered back projection
- Iterative reconstruction method

  - CT Large dataset → Computationally very intense

  + Works well with truncated or low count data

Back Projection

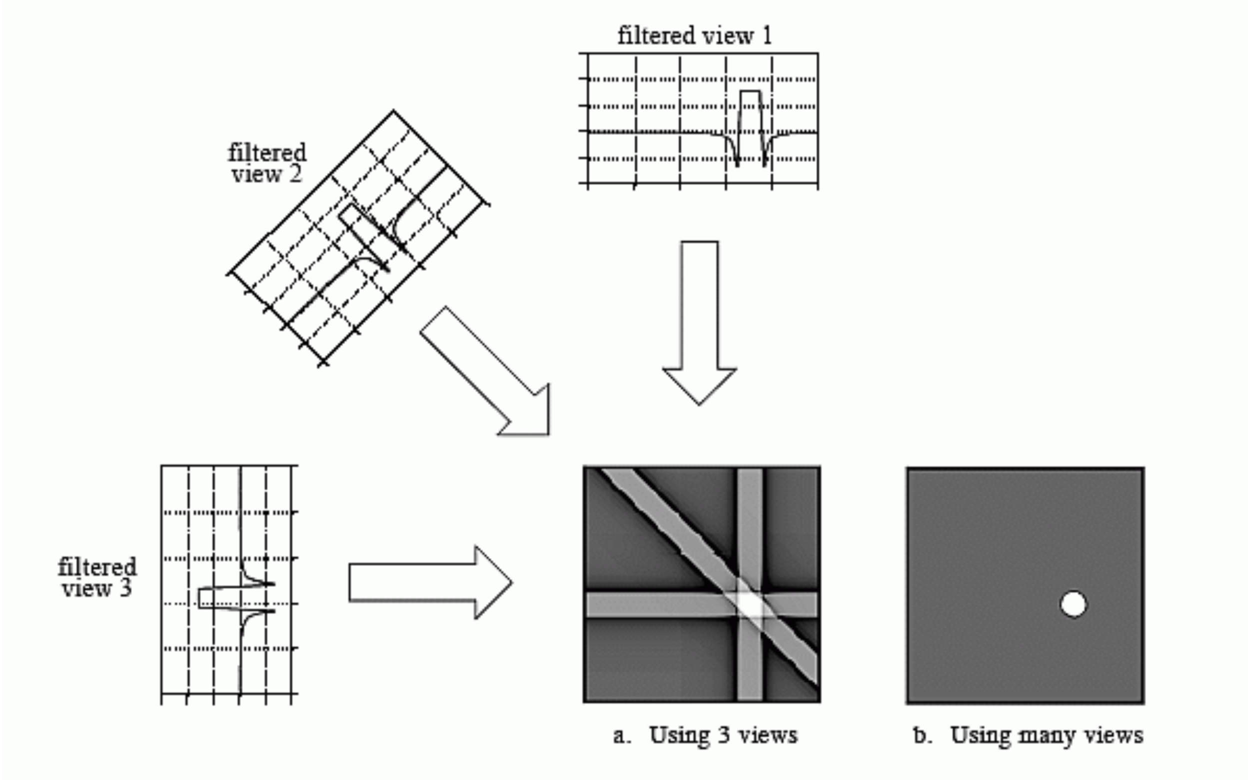
- An individual sample is back projected by setting all the image pixels along the ray pointing to the sample to the same value
- The final back projected image is the sum of all the back projected views



Taken from Digital Signal Processing, S.W. Smith

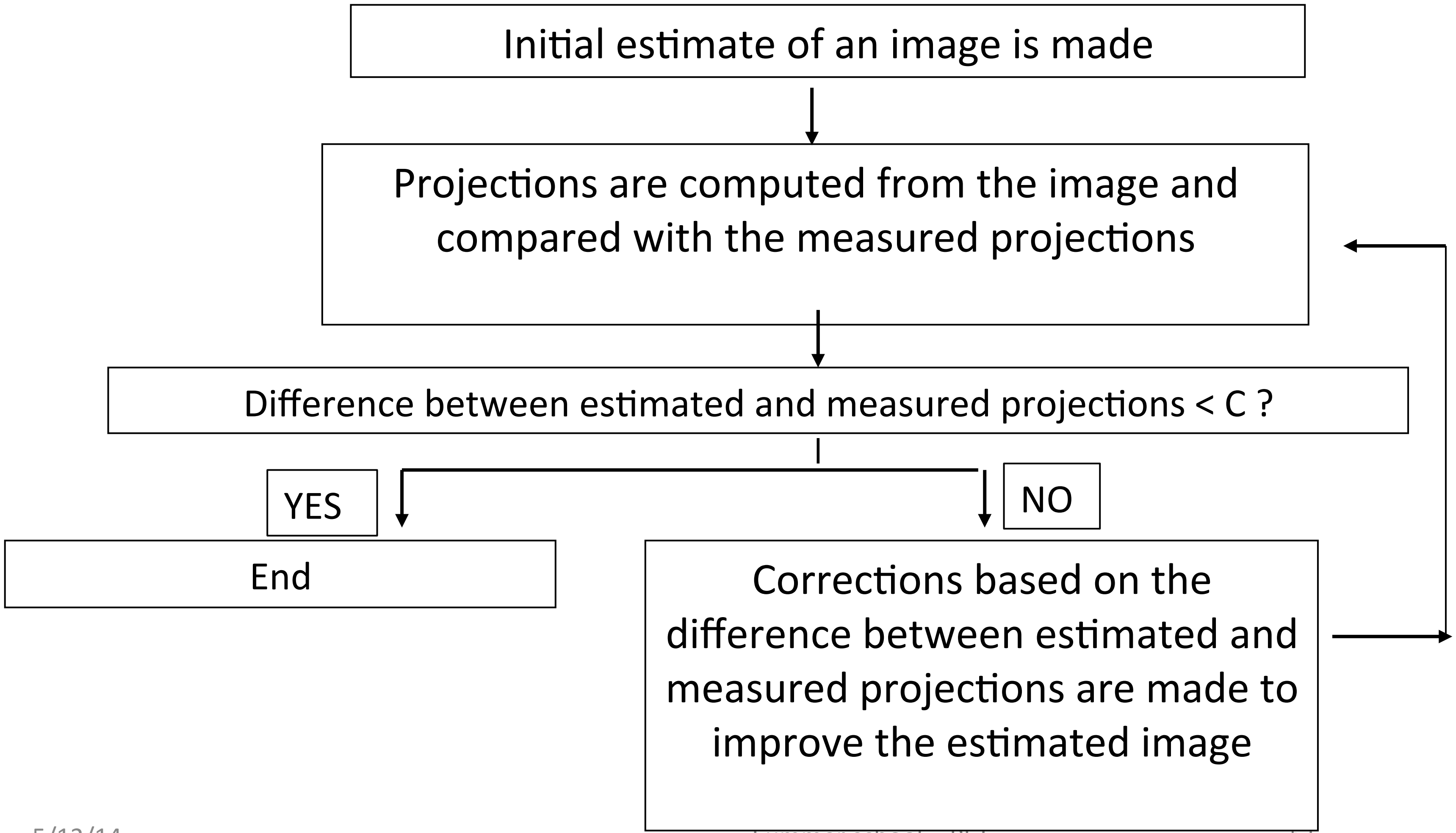
Filtered Back Projection

- Each projection is filtered before back projection
- Removes the blurring present in the back projection algorithm



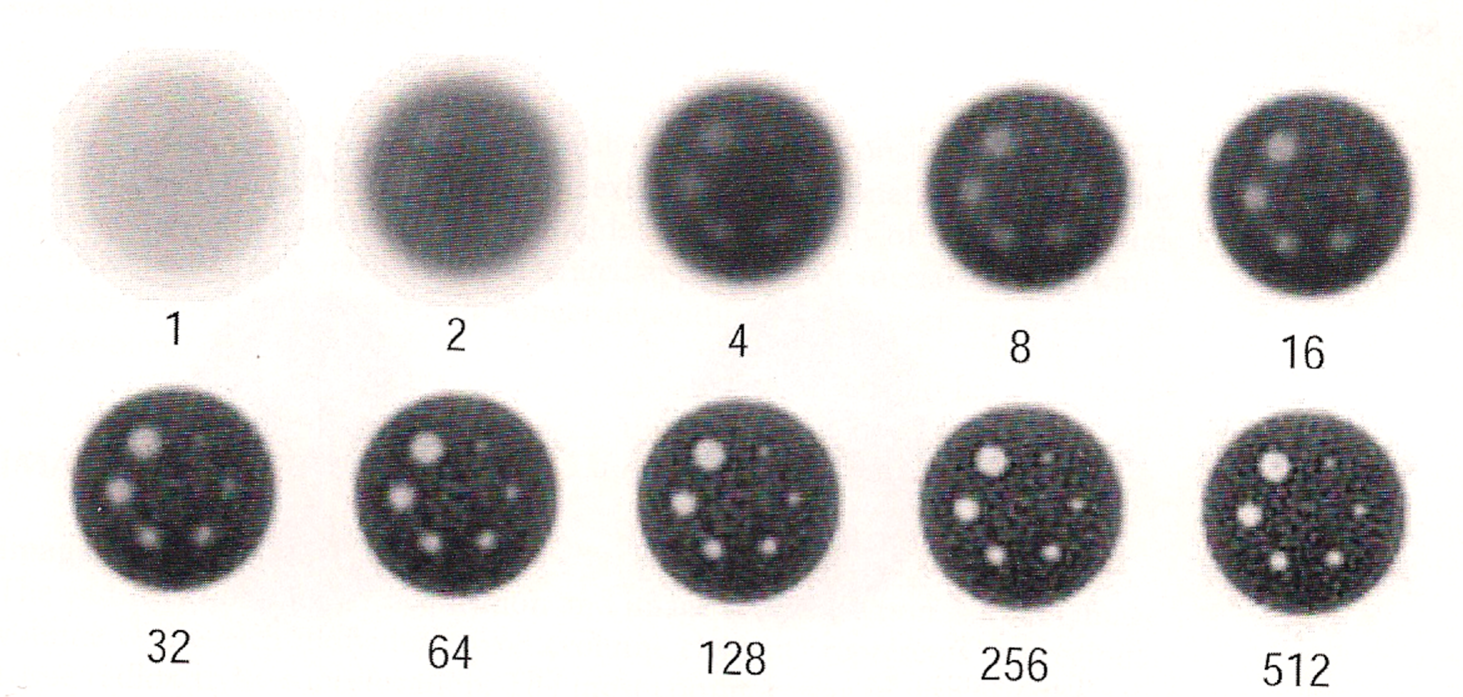
Taken from Digital Signal Processing, S.W. Smith

Iterative method



Iterative method

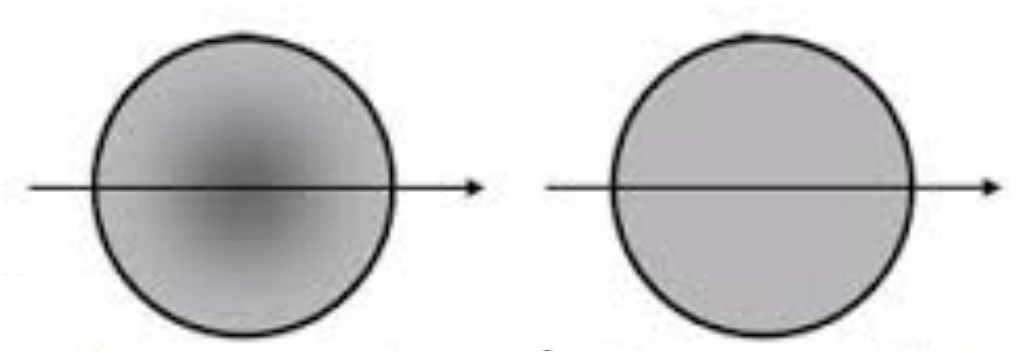
- After N iterations the image converges to the solution



Reconstruction Artifacts

Beam Hardening

- Polychromatic beams only
- Cause: the increase in mean energy or “hardening” of the X-ray beam as it passed through the sample
- Cupping artifact: the edges of an object appear brighter than the center

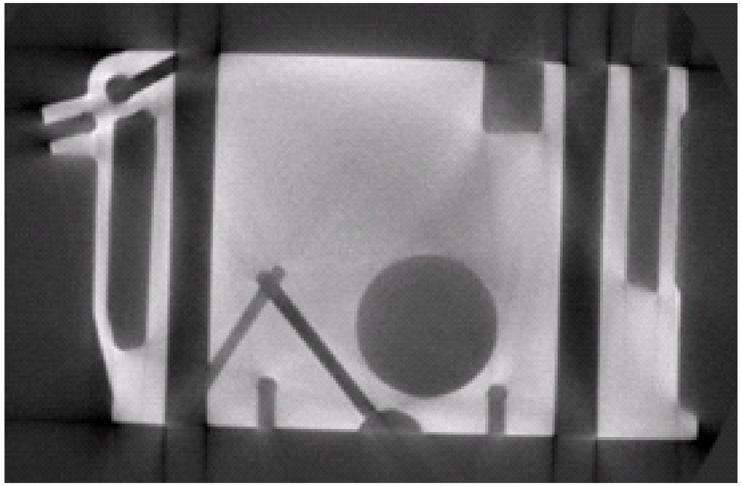


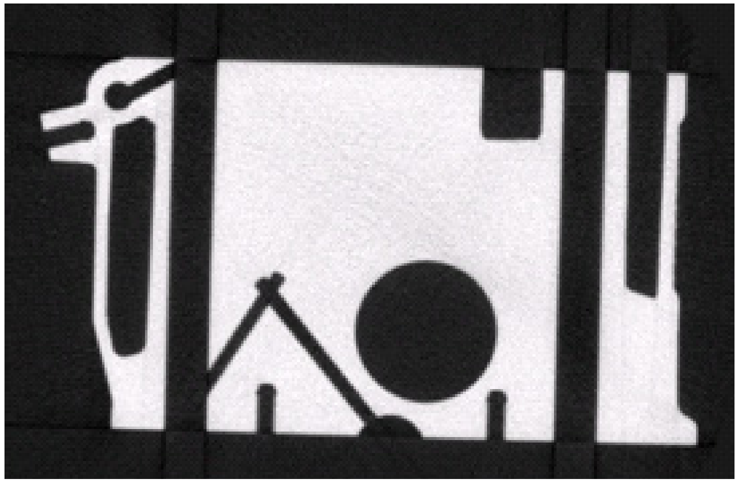
Reconstructed slice:
beam hardening artifact

Reconstructed slice:
monochromatic beam

Scattering radiation

- Cause: X-rays scattered by the sample and detected → wrong counts in the detector → the object appears to be less attenuating than in reality
- Underestimation of attenuation
- Image blurring
- Cupping and streak artifacts





Scatter-free image

X-ray CT - Pros

- Entirely non-destructive 3D imaging
- No sample preparation required
- Easily accessible (X-ray tubes/radioisotopes)
- Fast acquisition
- High spatial resolution ~ micrometer

X-ray CT - Cons

- Thick dense samples cannot be penetrated by X-rays, reducing resolving capability
- Not all features have sufficiently large attenuation contrasts for useful imaging (i.e. carbonate fossils in carbonate matrix)

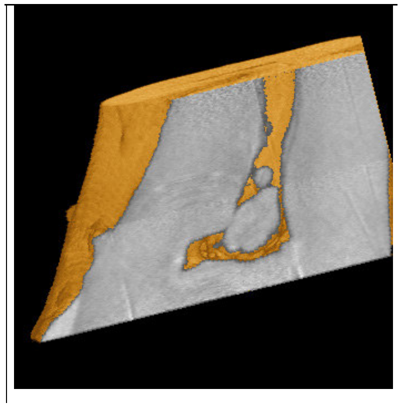
Applications

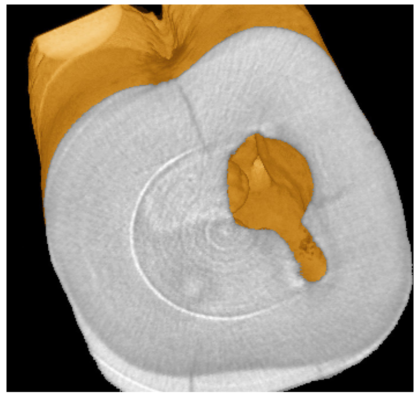
- Cultural Heritage
  - Study internal structure of artifacts
- Bio-medicine
  - characterization of the internal structure of trabecular bone
- Materials science
  - characterization of the internal structure of metal foams
- Engineering
  - determination of size and shape of cracks inside turbine blades
- Environmental science
- Nanotechnology

Applications to CH

Prehistoric tooth

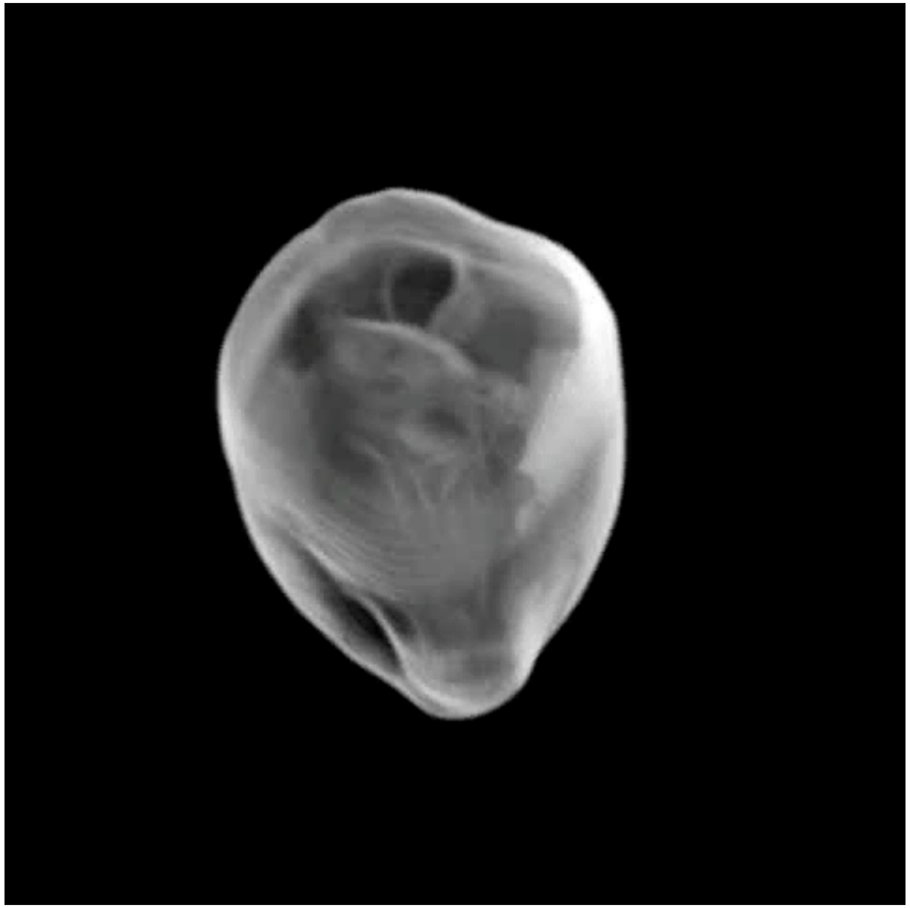
- Site: “Isola Sacra” necropolis





Depart. of Physics, University of Bologna (Prof. Casali) and Paleo-anthropological Museum “Pigorini”- Rome, Italy

Prehistoric tooth – 3D Reconstruction



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Danti's Globe

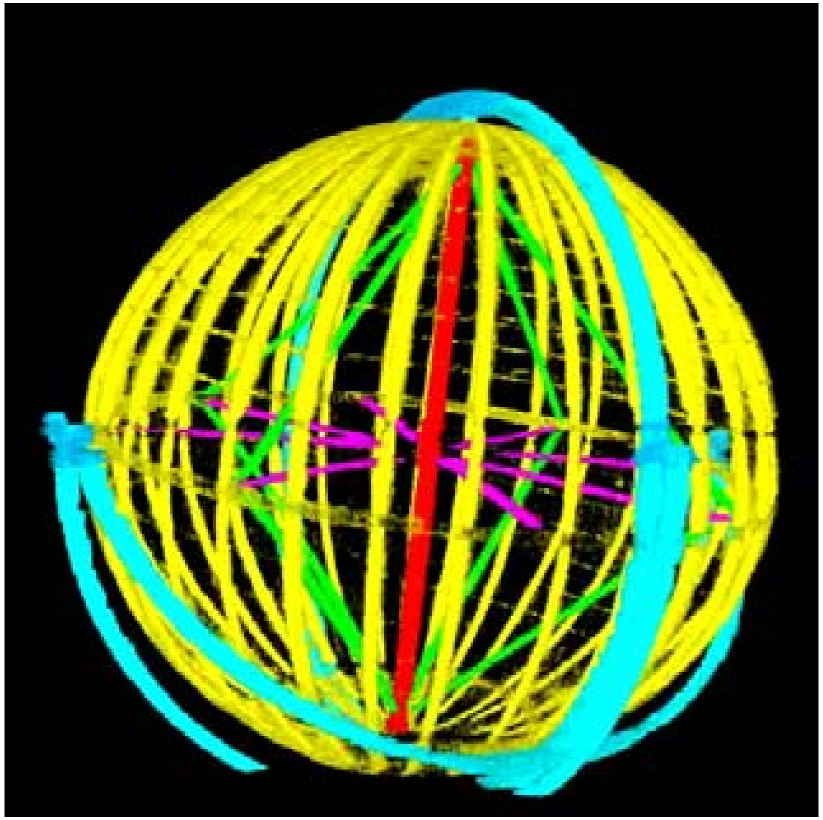
- Globe of Ignazio Danti (Uffizi, Florence)
- Goal: find the best conservation and restoration procedures

Danti's globe (1567), Florence

M.P. Morigi, F. Casali, R. Brancaccio, M. Bettuzzi, ***Department of Physics – University of Bologna***

Danti's Globe – 3D Reconstruction

- 3D reconstruction of the iron inner structure



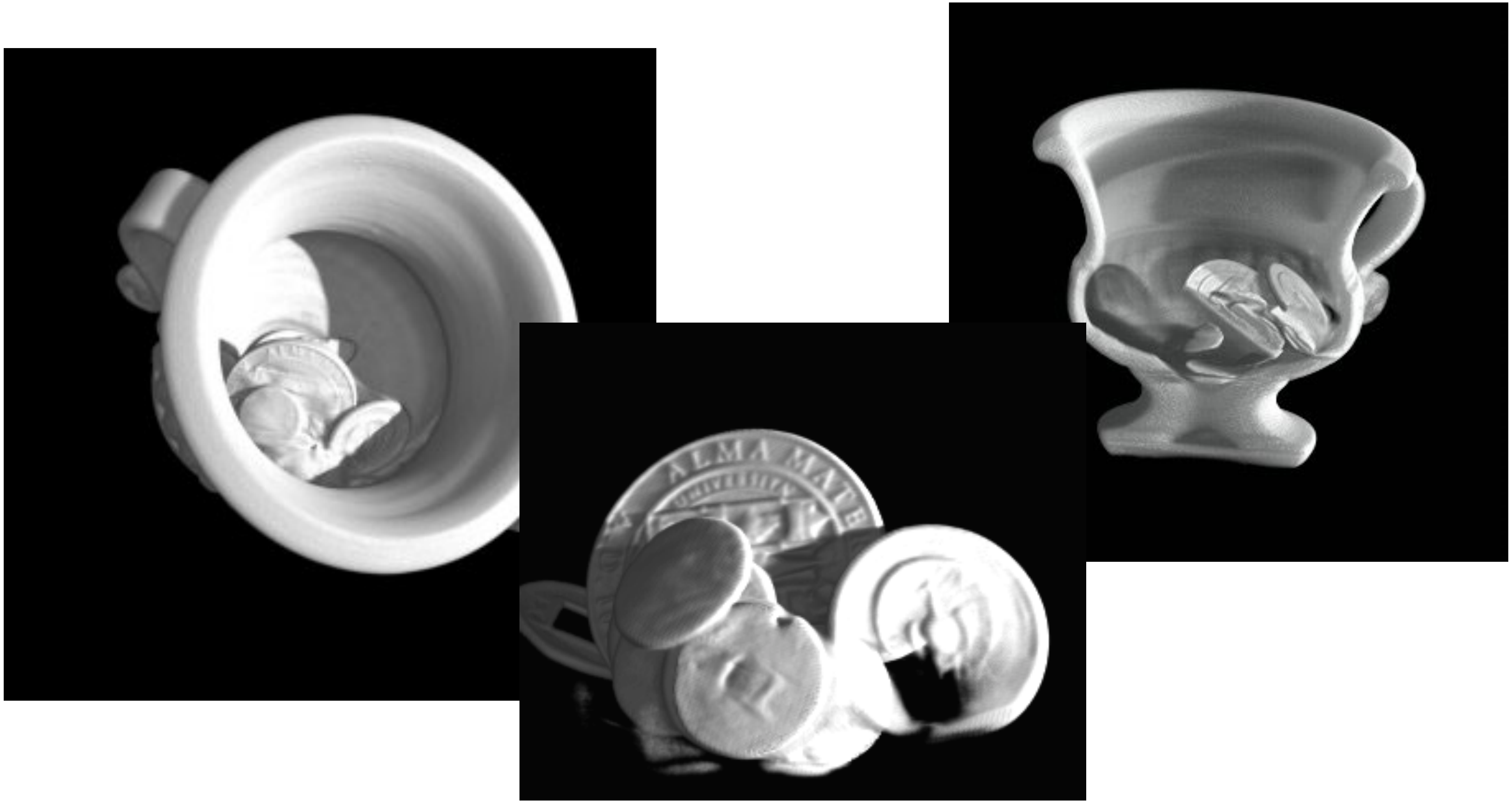
M.P. Morigi, F. Casali, R. Brancaccio, M. Bettuzzi, ***Department of Physics – University of Bologna***

Ancient coins

- Dummy sample: pot with ancient coins

M.P. Morigi, F. Casali, R. Brancaccio, M. Bettuzzi, ***Department of Physics – University of Bologna*** and ***EMPA, Duebendorf (Switzerland)***

Ancient coins – 3 D Reconstruction



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Thank you