Tomography

Introduction to Tomography

TEM Tilt-Series Tomography in Life Science

STEM Tomography in Materials Science

Introduction to Tomography

- **Tomography** is imaging by sections or sectioning. A device used in tomography is called a **tomograph**, while the image produced is a **tomogram**.
- The method is used in medicine, archaeology, biology, geophysics, oceanography, materials science, astrophysics and other sciences.
- In most cases it is based on the mathematical procedure called **tomographic reconstruction**.
- The word "tomography" is derived from the Greek *tomos* (slice) and *graphein* (to write).

Wickipedia

Introduction to Tomography

- **Tomography** is a method in which a 3-D structure is reconstructed from a series of 2-D projections (images) acquired at successive tilts (Radon 1917).
- First developed for use in medical imaging (1963, Nobel Prize for Medicine in 1979) using X-rays, ultrasound and magnetic resonance (e.g. 'cat-scans')..
- Found further application in geology, astronomy, materials science, etc…

P. Midgley, tomo workshop in Berlin

Introduction to Tomography

Recording

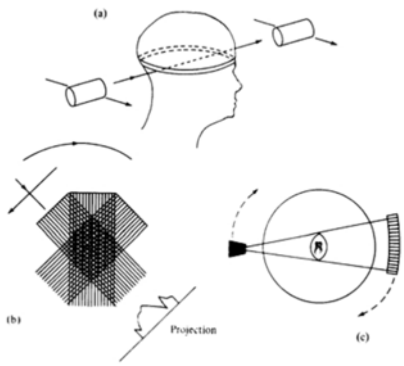
- Series of 2D images
- Destructive: serial sectioning, FIB
- Non-destructive: X-rays, TEM

Reconstruction and « viewing »

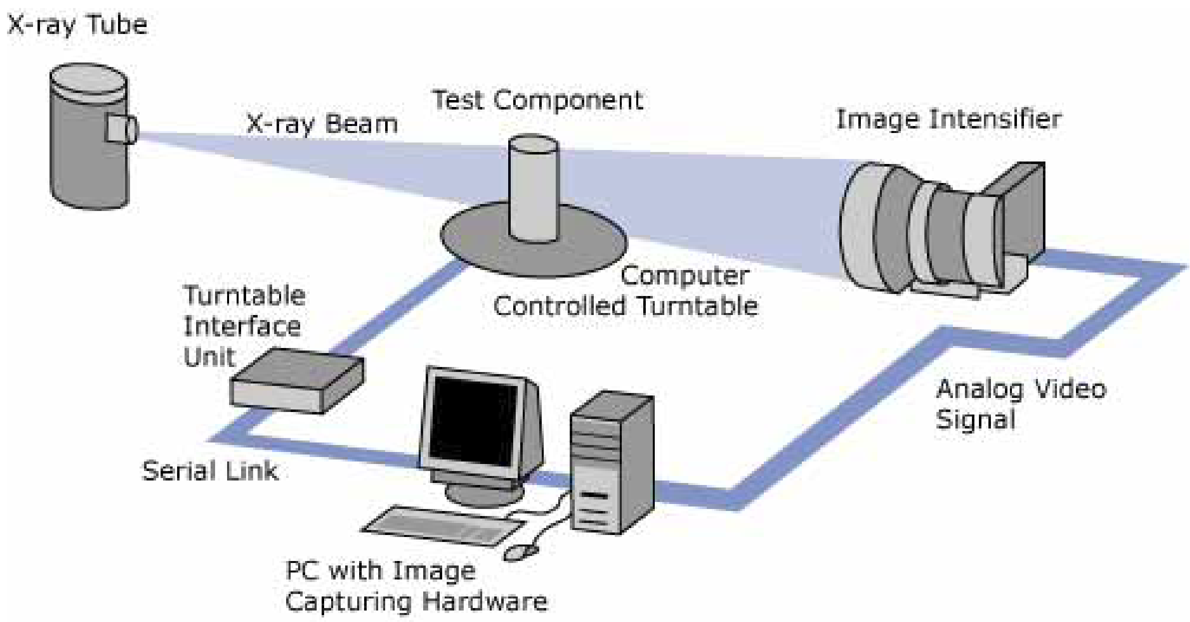
- Registration (alignment of images)
- Back-projection, reconstruct (tilt-series)
- **Tomogram**
- Segmentation (image processing), extraction of the desired information

3D imaging in medicine

- Non-invasive methods are preferred!
- The disadvantage of conventional X-radiographs is its inability to discriminate between organs of close absorptivity or overlapping organs in the viewing direction.
- X-ray computed tomography overcomes that limitation:
- X-radiographs are made in many different directions and combined mathematically to to reconstruct cross-sectional maps.
- reconstruction tomography or computer assisted tomography.



Tomograph



Radon 1917

Über die Bestimmung von Funktionen durch ihre Integralwerte längs gewisser Mannigfaltigkeiten.

Von

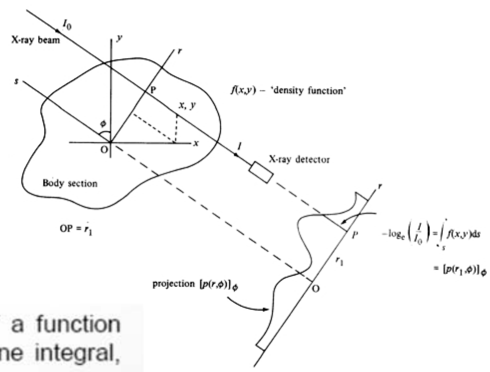
Johann Radon.

Integriert man eine geeigneten Regularitätsbedingungen unterworfene Funktion zweier Veränderlichen x, y — eine *Punktfunktion* $f(P)$ in der Ebene — längs einer beliebigen Geraden g, so erhält man in den Integralwerten $F(g)$ eine *Geradenfunktion*. Das in Abschnitt A vorliegender Abhandlung gelöste Problem ist die Umkehrung dieser linearen Funktionaltransformation, d. h. es werden folgende Fragen beantwortet: kann jede, geeigneten Regularitätsbedingungen genügende Geradenfunktion auf diese Weise entstanden gedacht werden? Wenn ja, ist dann f durch F eindeutig bestimmt und wie kann es ermittelt werden?

Ber. Sächs. Akad. Wiss. Leipzig, Math. Phys. Kl. 69, 262 (1917)

English translation in: Deans, S.R. (1983) The Radon transform and its applications. John Wiley & Sons, NY)

Radon Transform

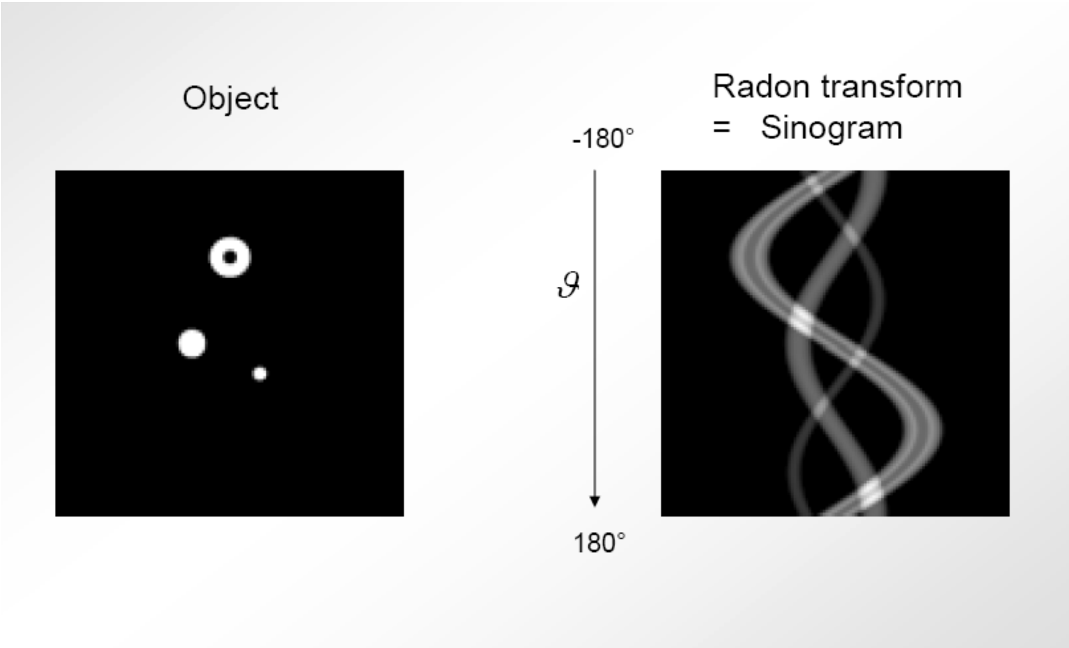


The paper defines the Radon transform R as the mapping of a function $f(x,y)$, describing a real space object D, by the projection, or line integral, through f along all possible lines L:

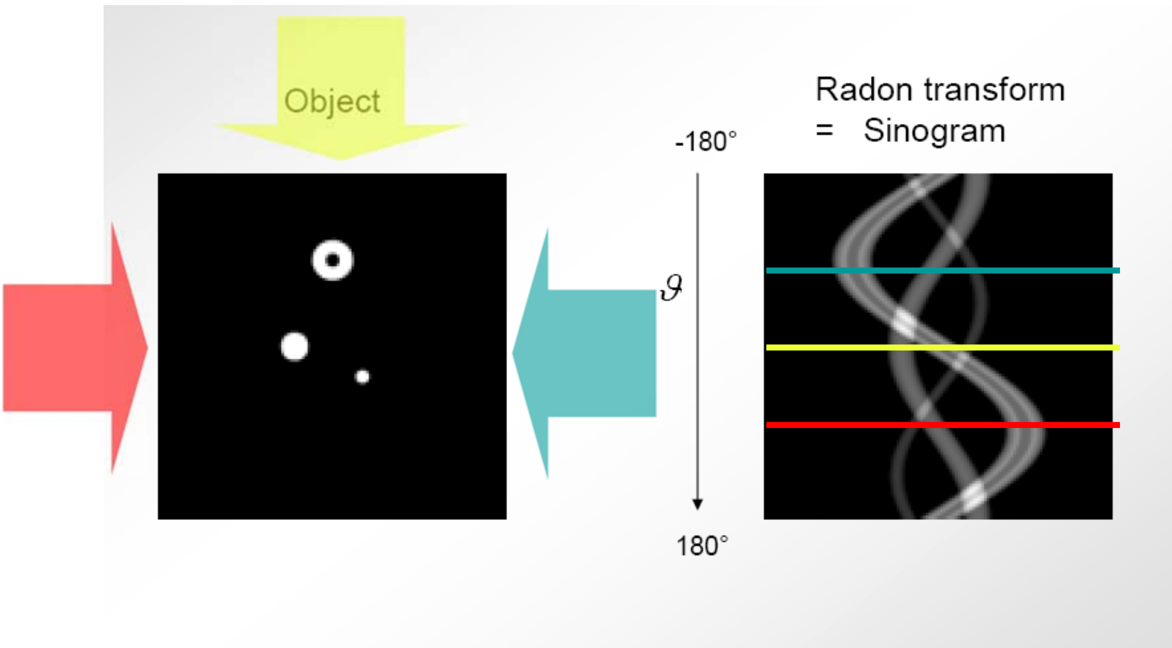
$$Rf = \int_L f(x,y)ds,$$

A discrete sampling of the Radon transform is geometrically equivalent to the sampling of an experimental object by some form of transmitted signal: a projection. ***The consequence of such equivalency is that the reconstruction of an object f(x,y) from projections Rf can be achieved by implementation of the inverse Radon transform***

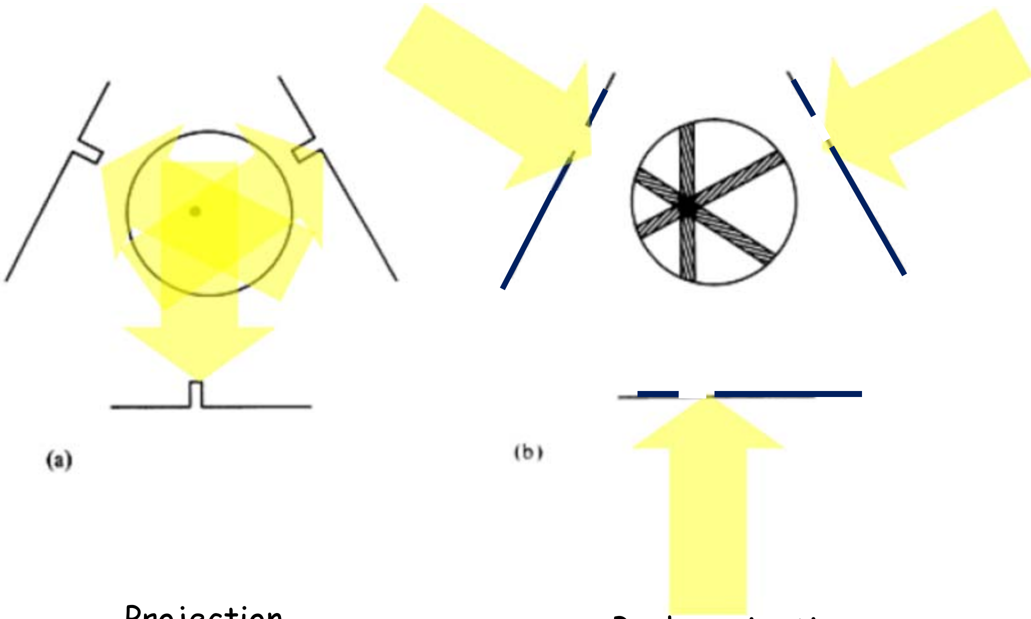
Radon Transform



Radon Transform



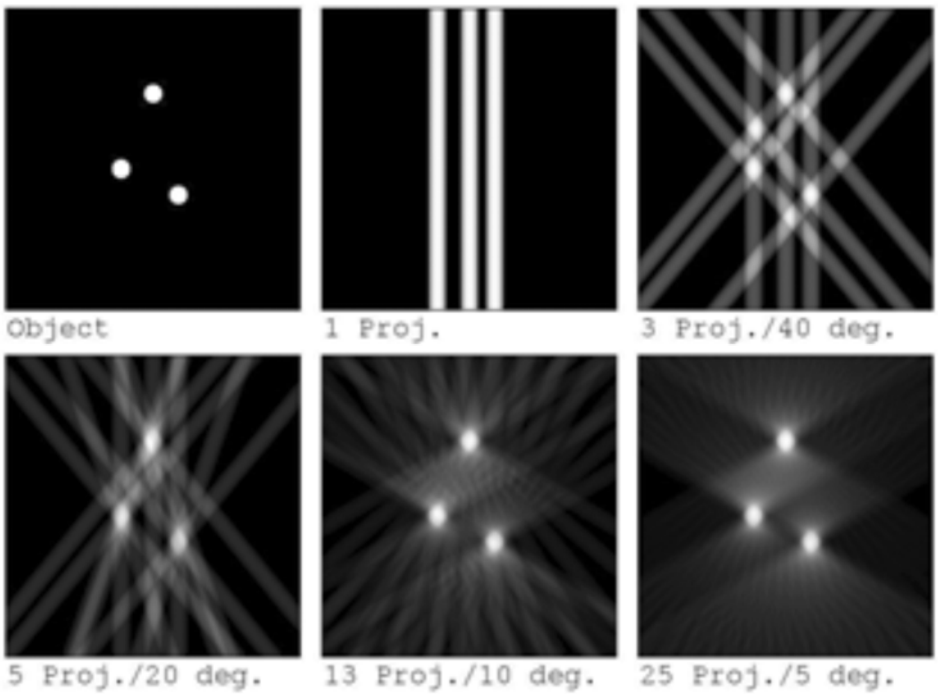
Back projection



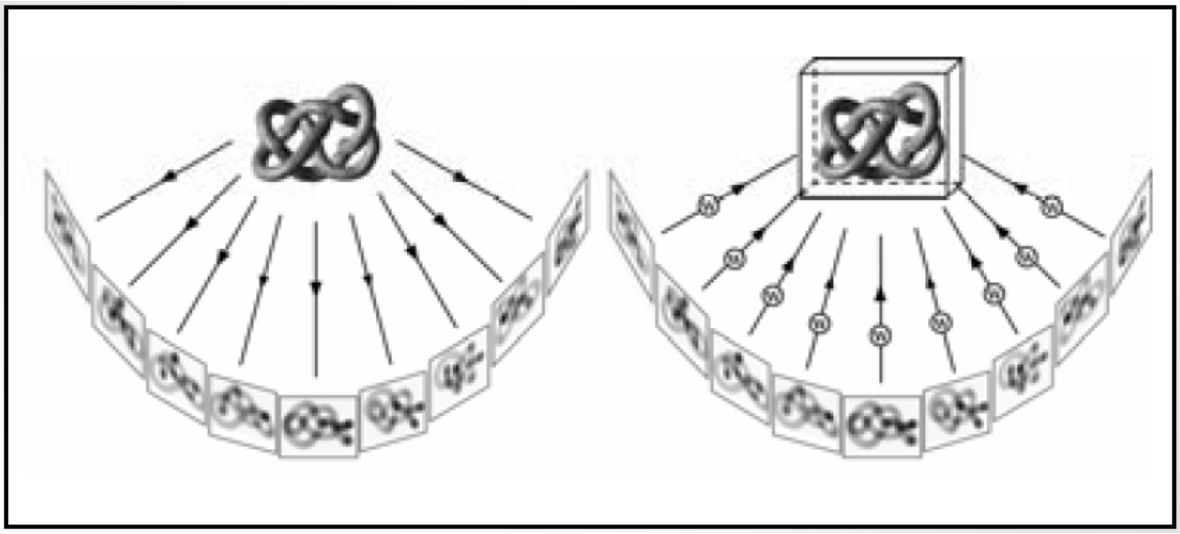
Projection recording

Back projection reconstructing

Back projection



back projection

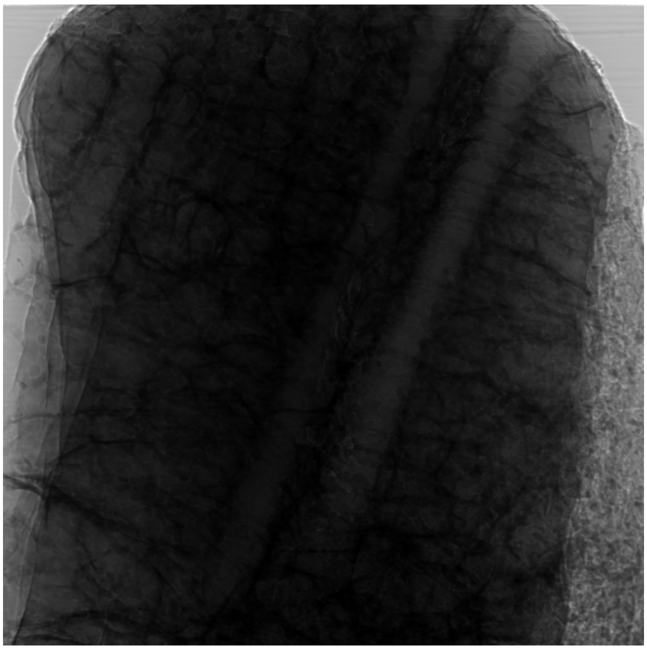


Tomography in medicine

3D imaging in materials science

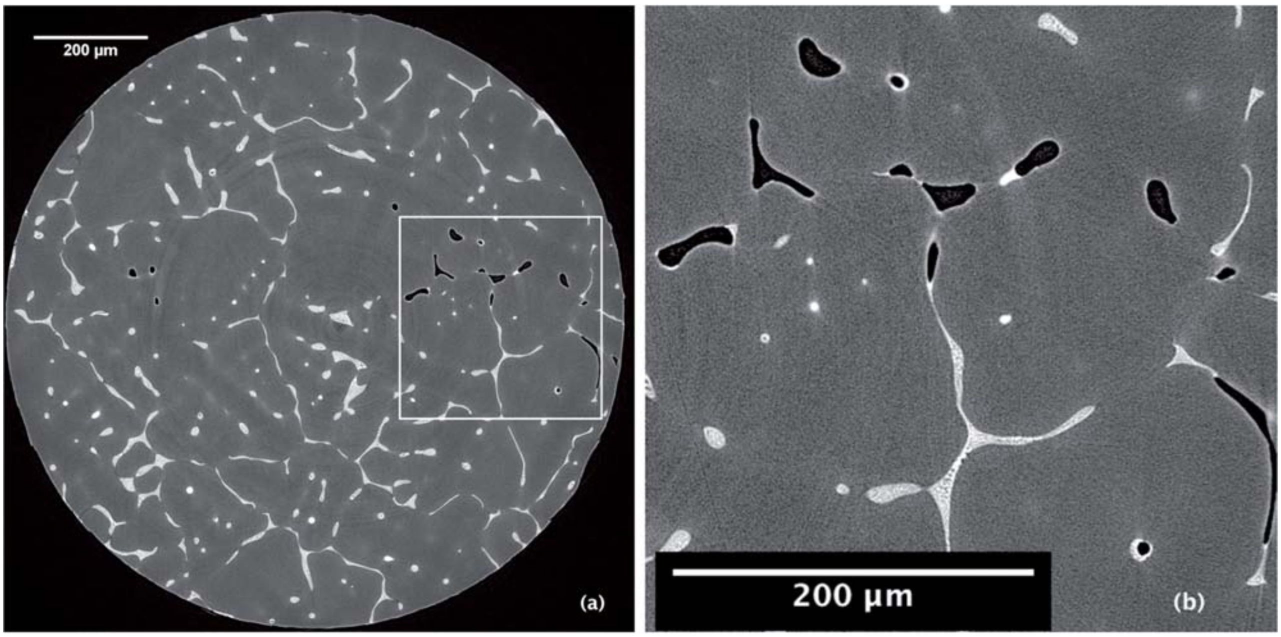
360degree X-ray tomography
Milan Felberbaum
STI-IMX-LSMX

Cylinder of an Al-Cu Alloy



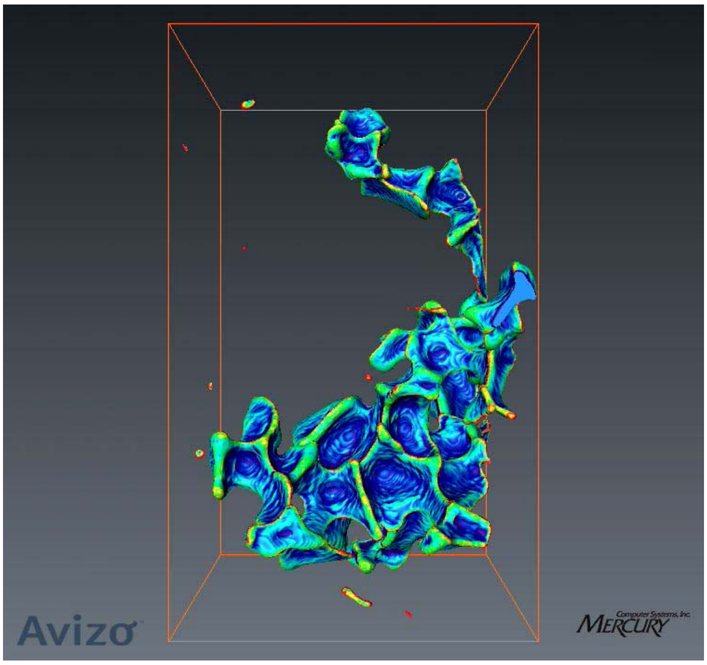
3D imaging in materials science

Tomogram



3D imaging in materials science

Reconstructed pore

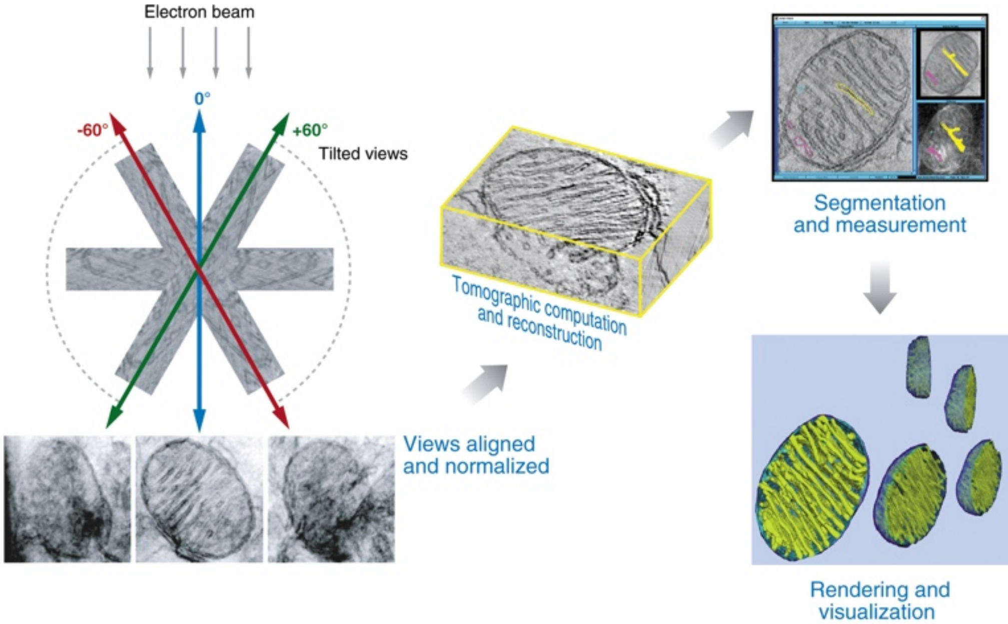


Tomography with electrons

Stopping range for electrons (99% absorbed)

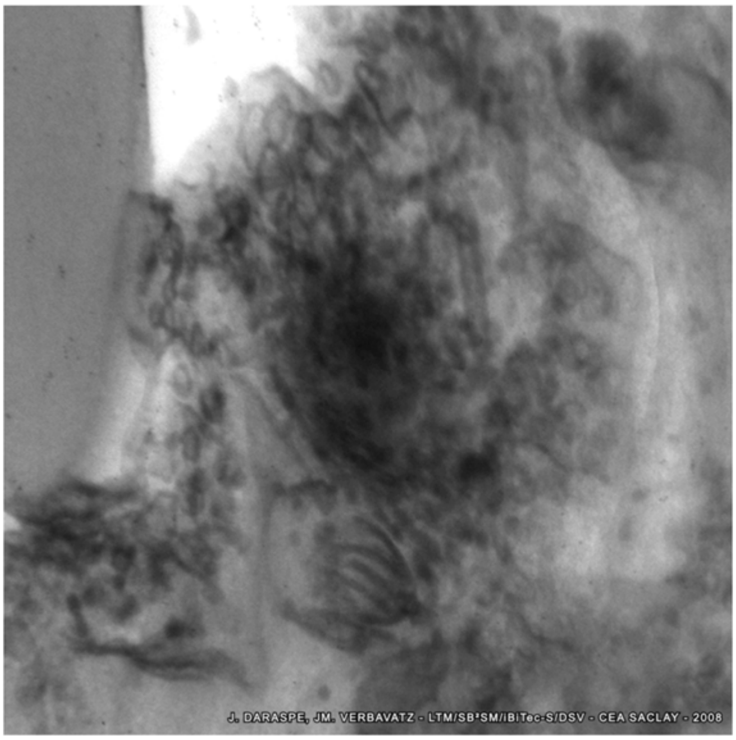
Element (specific weight)	4-Be 1.84 g/cm^3	13-Al 2.7 g/cm^3	29-Cu 8.93 g/cm^3	82-Pb 11.3 g/cm^3
X-rays Cu-Kα λ=1.54 Å Mo-Kα λ=0.71 Å	16 mm 83 mm	0.35 mm 3.3 mm	0.10 mm 0.10 mm	0.017 mm 0.034 mm
Neutrons λ≈1.08 Å	89 m	6 m	0.26 m	14 m
Électrons λ=0.037 Å à 100 kV λ=0.020 Å à 300 kV	39 μm	42 μm ~330 μm	11 μm	0.6 μm

Bio-EM, Tomography



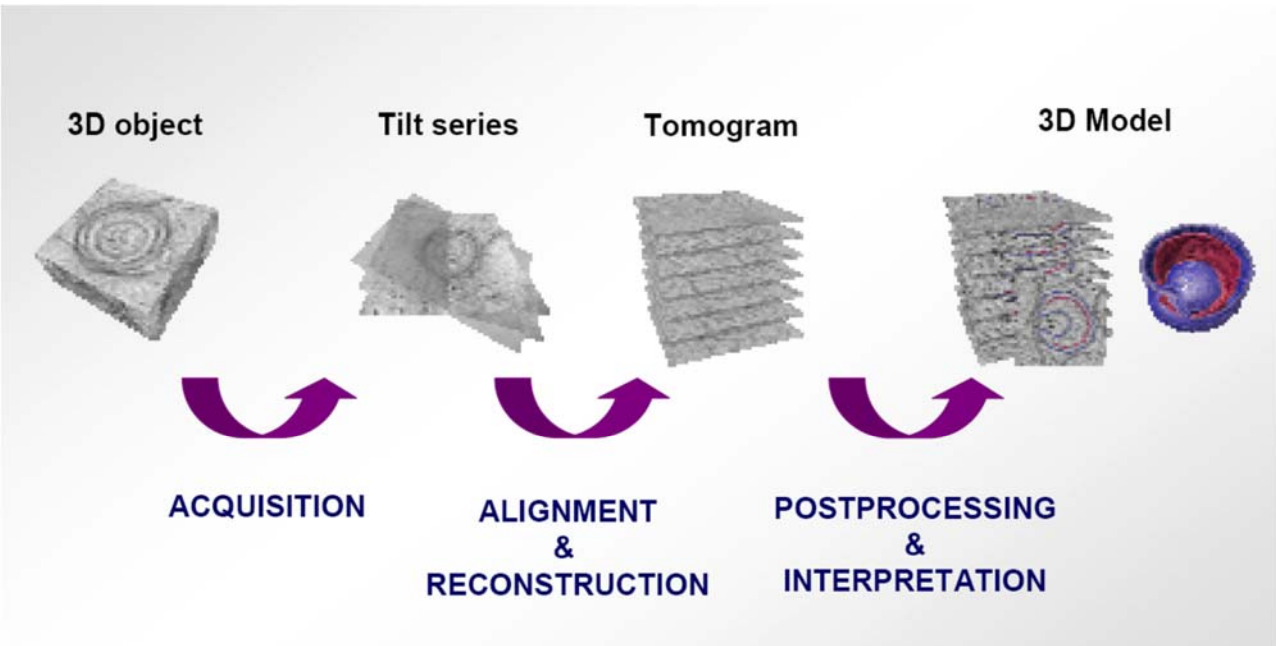
Frey TG, et al. 2006.
Annu. Rev. Biophys. Biomol. Struct. 35:199–224

Tilt series, -60 … +60 degree tilt

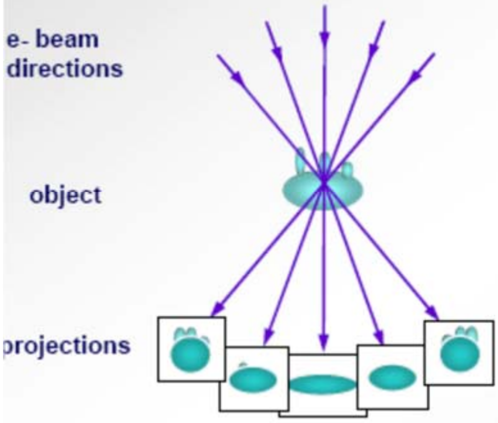


Tomogram

Tomo workflow



resolution



IDEAL SITUATION:

As many images as possible from ALL orientations (-90° to 90°)

RESOLUTION, *d*

Crowther, DeRosier, and Klug, 1970

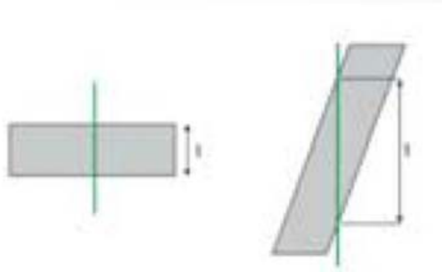
$$d = \pi \frac{D}{N}$$

D, diameter of the object
N, number of projections

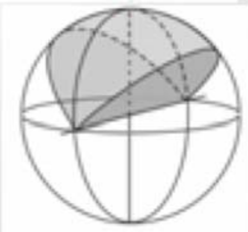
2 nm with 141 images of a 100 nm object

geometrical limit, the missing wedge

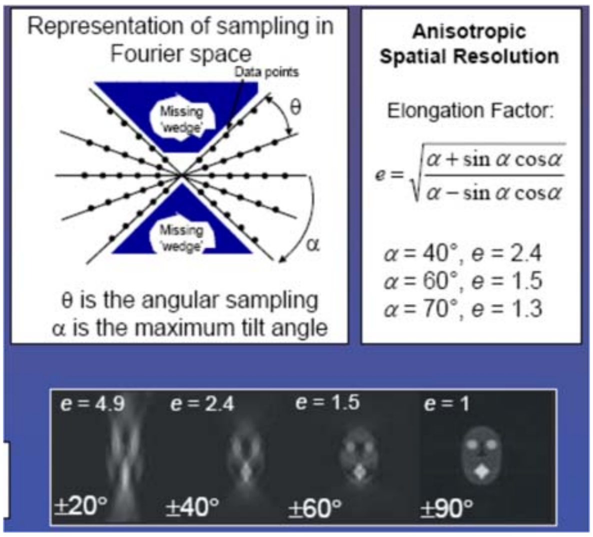
- There is a limit in the tilt angle we can reach (~±70°) due to:
  - Design of the holder
  - Grid bars
  - Increasing thickness of the specimen with high tilt angles

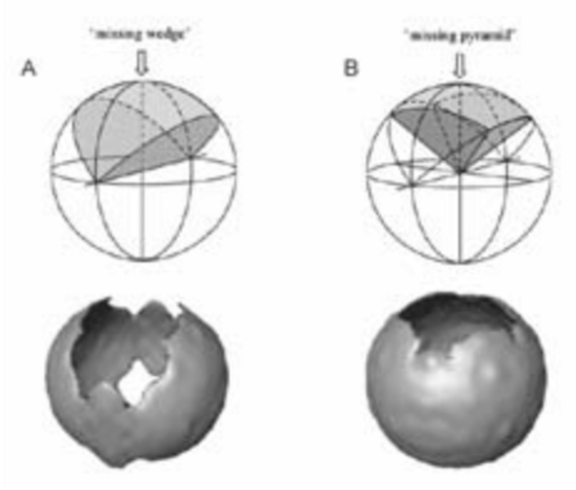


- This is known as the missing wedge problem (missing information, loss of resolution)

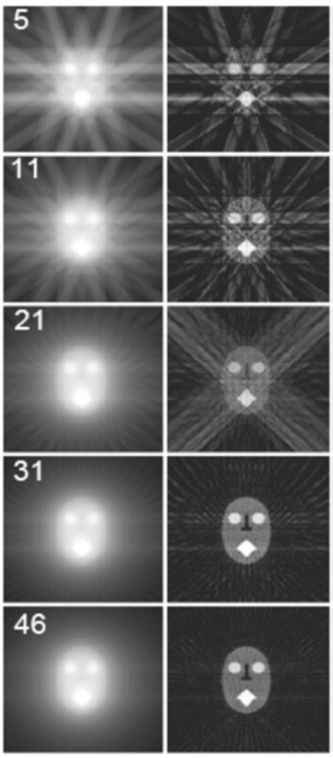


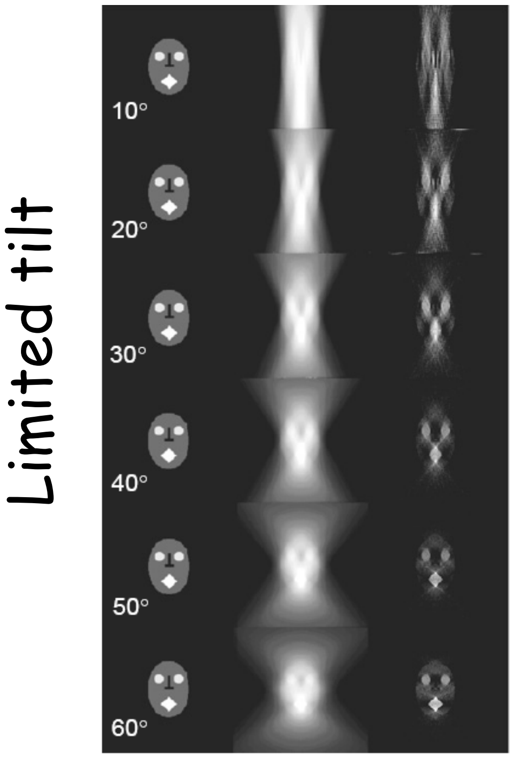
Missing wedge





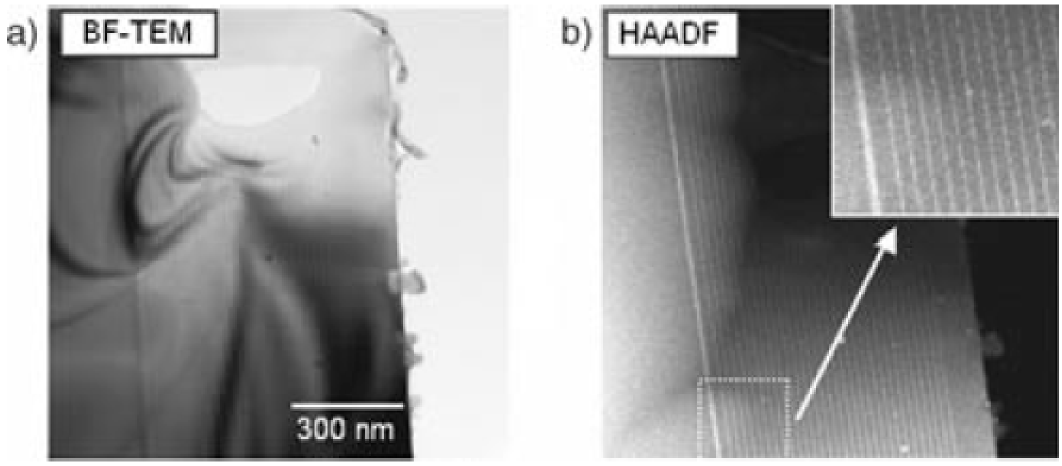
Weighted back projection WBP





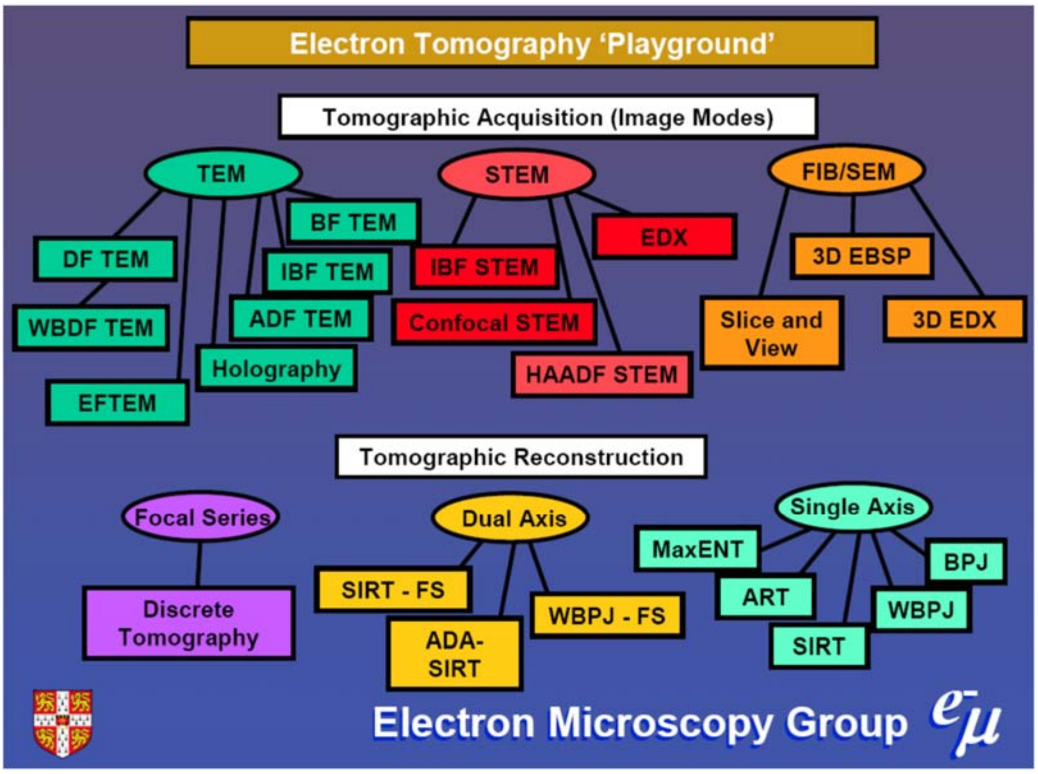
projection requirement

- projection requirement: monotonically varying function of a physical property: mass-thickness dominant in biological samples !



Si-Ge multiple quantum well structure

Tomography in Electron Microscopy

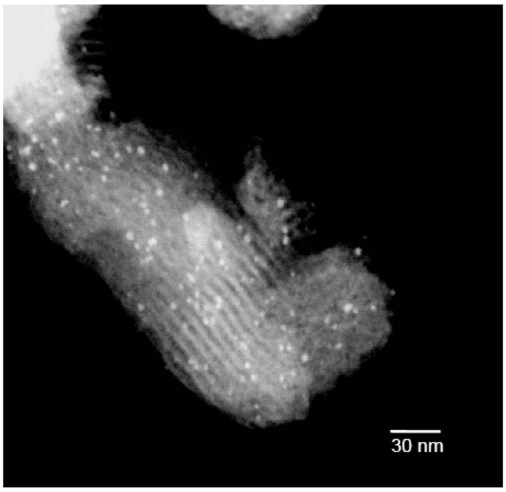


From P. Midgley

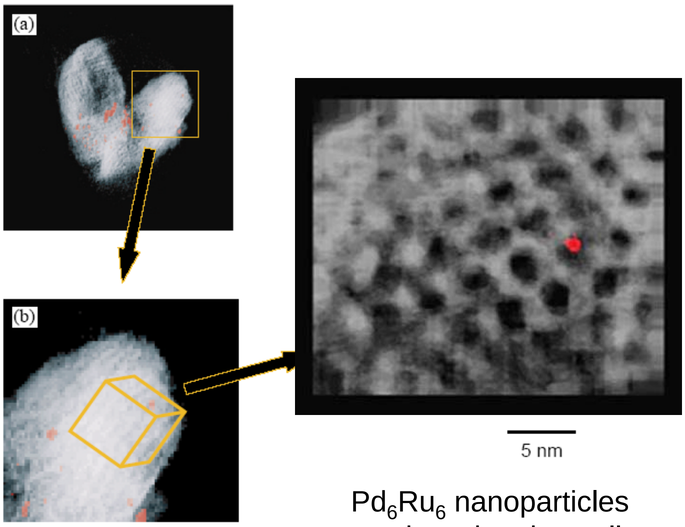
Tomography with HAADF (z-contrast)

nanoparticle bimetallic catalysts supported on mesoporous silica

Dogan Ozkaya, Paul Midgley;
Catalysis Letters 60 (1999) 113–120

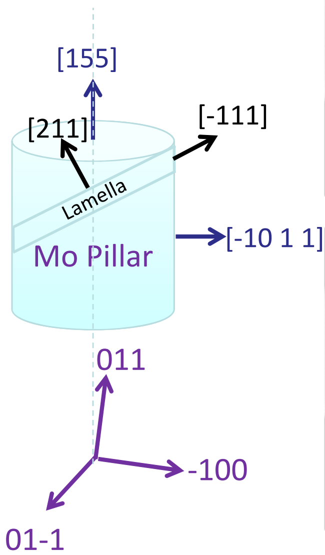


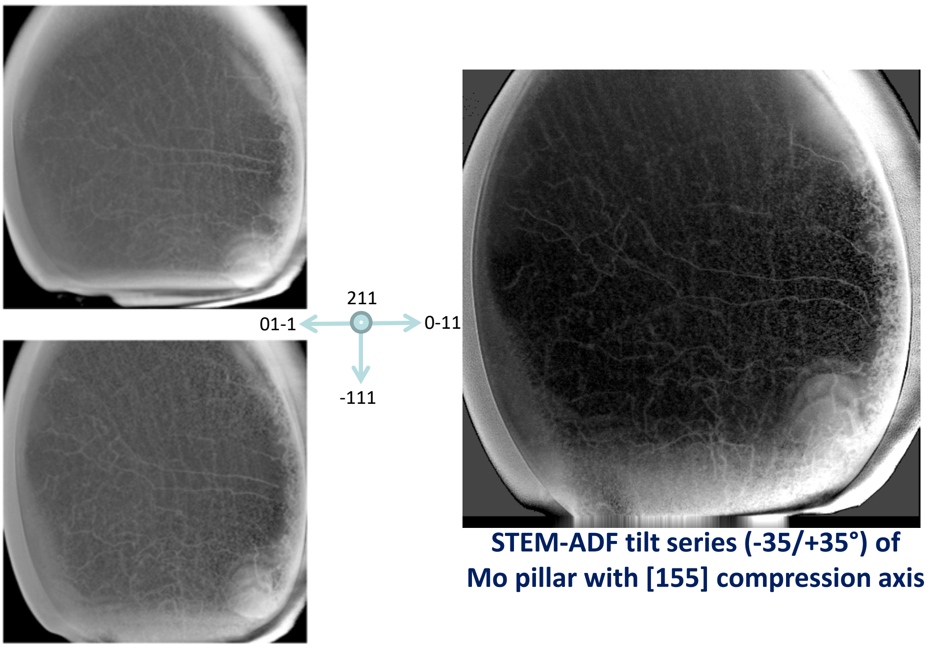
STEM HAADF: heterogeneous catalyst composed of Pd_6Ru_6 nanoparticles (~ 1 nm) on mesoporous silica support with mesopores of ~ 3 nm diameter.



Pd_6Ru_6 nanoparticles anchored to the wall of mesopore

Emad Oveisi (CIME): STEM DF Tomography of Dislocations

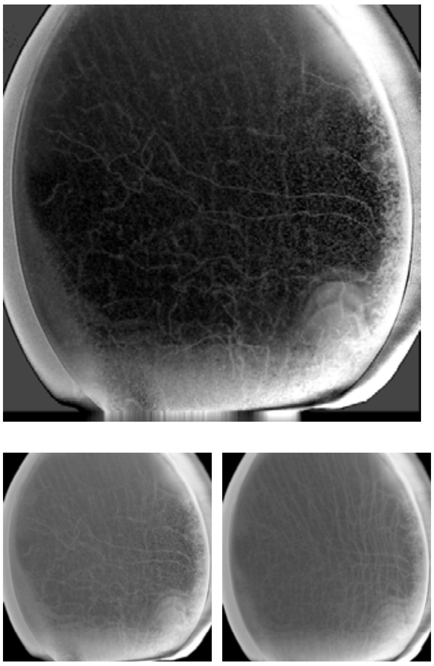




STEM-ADF tilt series (-35/+35°) of Mo pillar with [155] compression axis

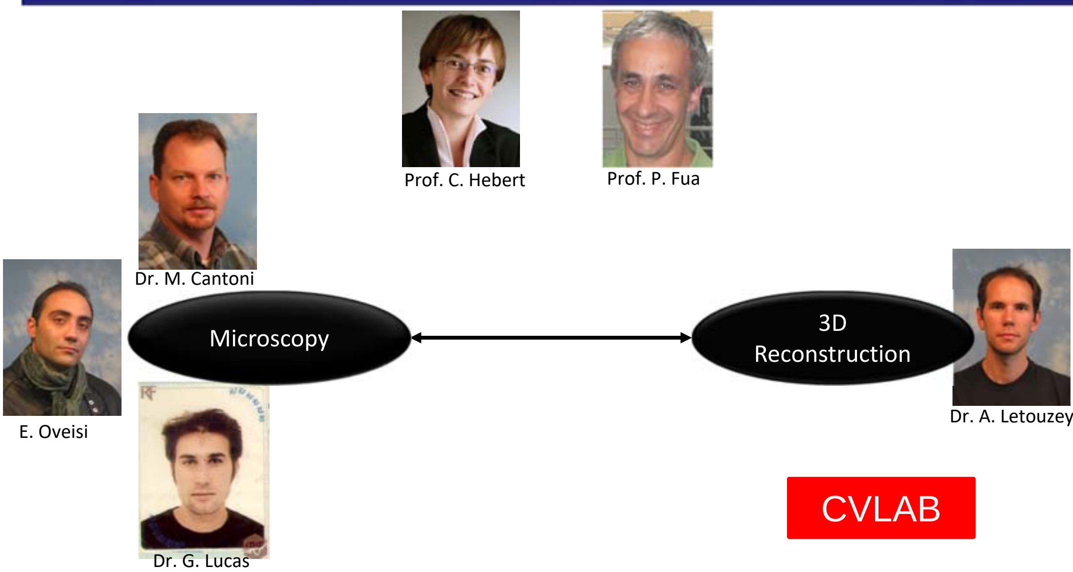
Problems Associated with Tomography

- **High tilt range required to acquire a tilt series (up to +/-70 degree)**
  Increasing the effective thickness with tilt (2 times thicker at 60 degree!)
  No uniform focus: Dynamic focus package is required
- **Misalignment between the tilt axis and diffraction axis;**
  May change the excitation error during tilt series acquisition and results in inconsistent images
- **Changes of diffraction contrast during tilting; e.g. close to zone axes**
- **3D reconstruction is not always straightforward;**
  e.g. missing wedge effect, complications due to surface artifacts, etc.



Algorithm for 3D observation of Dislocations

Developing an algorithm for 3D Reconstruction of Dislocations from TEM images

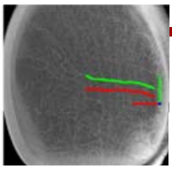


CVLAB

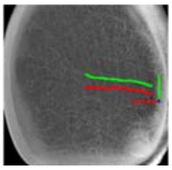
A collaboration with Computer Vision Laboratory at EPFL

Algorithm for 3D observation of Dislocations

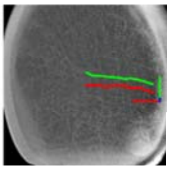
α=8°
ß=1.1°



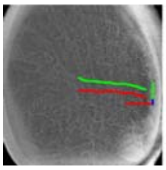
α=9°
ß=1.2°



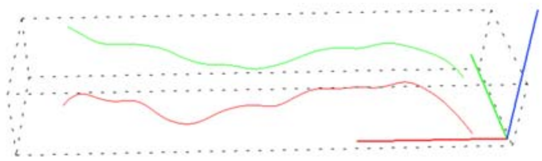
α=10°
ß=1.2°



α=11°
ß=1.3°



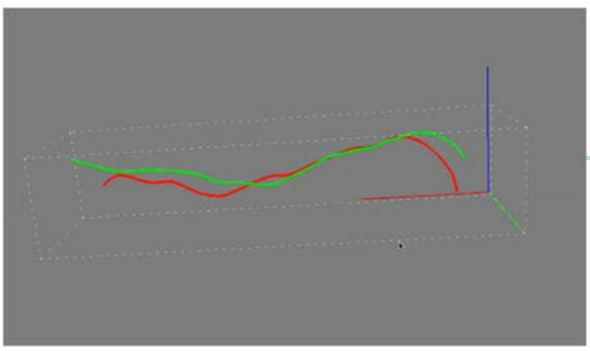
- Using state of the art curvilinear structures detection algorithm, the dislocation segments are extracted semi-automatically in ADF-STEM images.
- These 2D representations of dislocations are then automatically matched between images.
- 3D estimation of the dislocation structure is performed from these segments by taking into account the camera calibration and tilt angle for each image.

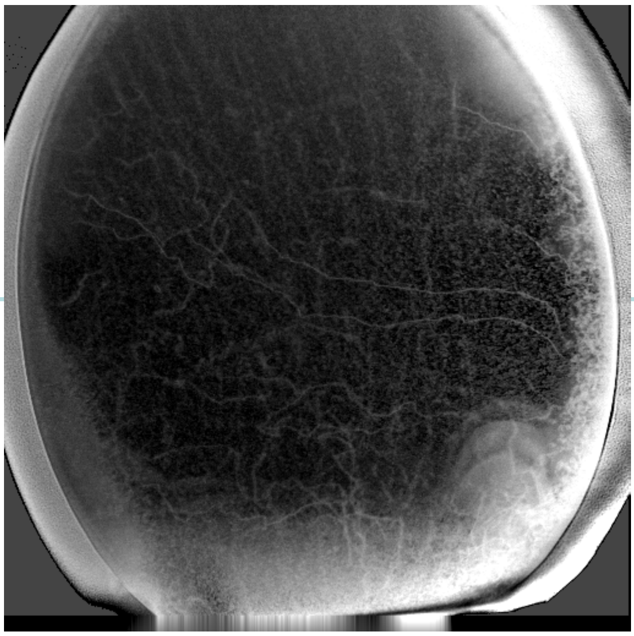


Türetken, E. et al., “Semi-Automated Reconstruction of Curvilinear Structures in Noisy 2D images and 3D image stacks”, EPFL Technical Report (2013).
Benmansour, F. et al., “Tubular Geodesics using Oriented Flux: An ITK Implementation”, Insight Journal (2013).

Algorithm for 3D observation of Dislocations

3D visualization of dislocations





Outlook:
STEM EDX tomography on nanometric devices

Kevin Lepinay[1]*, F. Lorut[1], R. Pantel[1], T. Epicier[2]

[1]STMicroelectronics, Crolles, France
[2]MATEIS Lab, INSA Lyon, France

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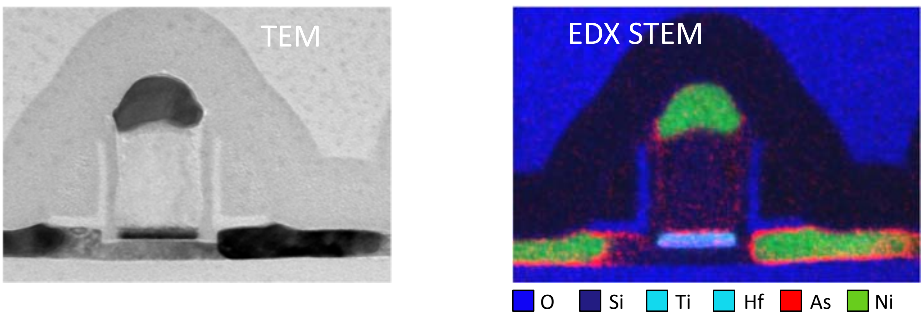
Microscopy needs in semiconductor industry

- Needs in chemical analysis → materials composition, diffusion and dopants → EDX technique (photon detection from electron ionization)

- EDX mappings in ***only a few minutes,*** detecting ***most of elements even dopants*** such as Arsenic.

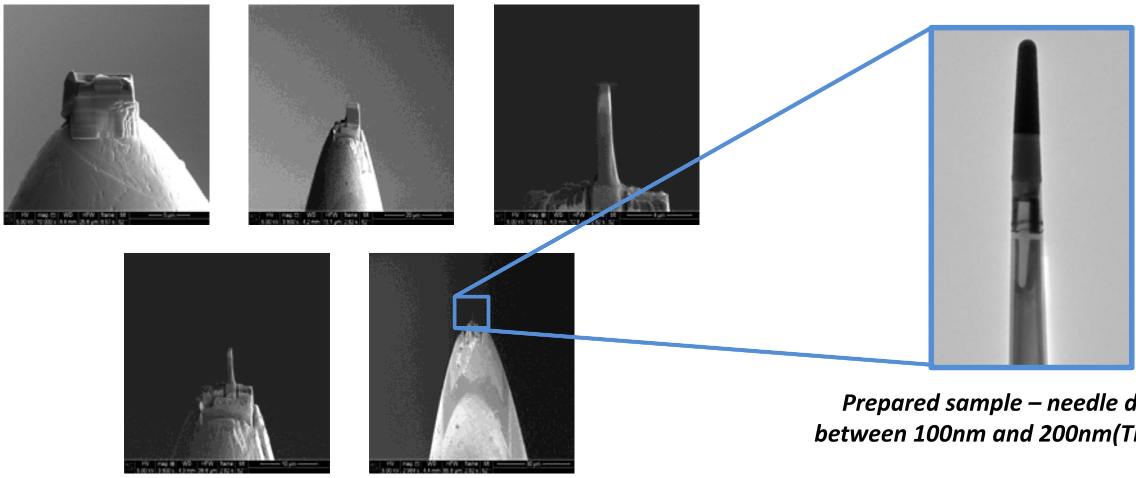


EDX mapping of a 32nm NMOS transistor [R.Pantel] performed on the ***Tecnai OSIRIS***

- The idea is the coupling of these two techniques to obtain a ***nanometric 3D chemical analysis***.

STEM EDX tomography principle

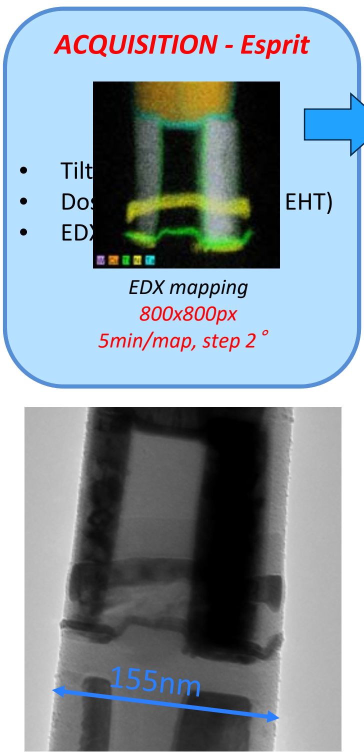
- EDX mapping acquisition ***at each tilt angle***
- Tomography specific FIB sample preparation →***needle shaped***

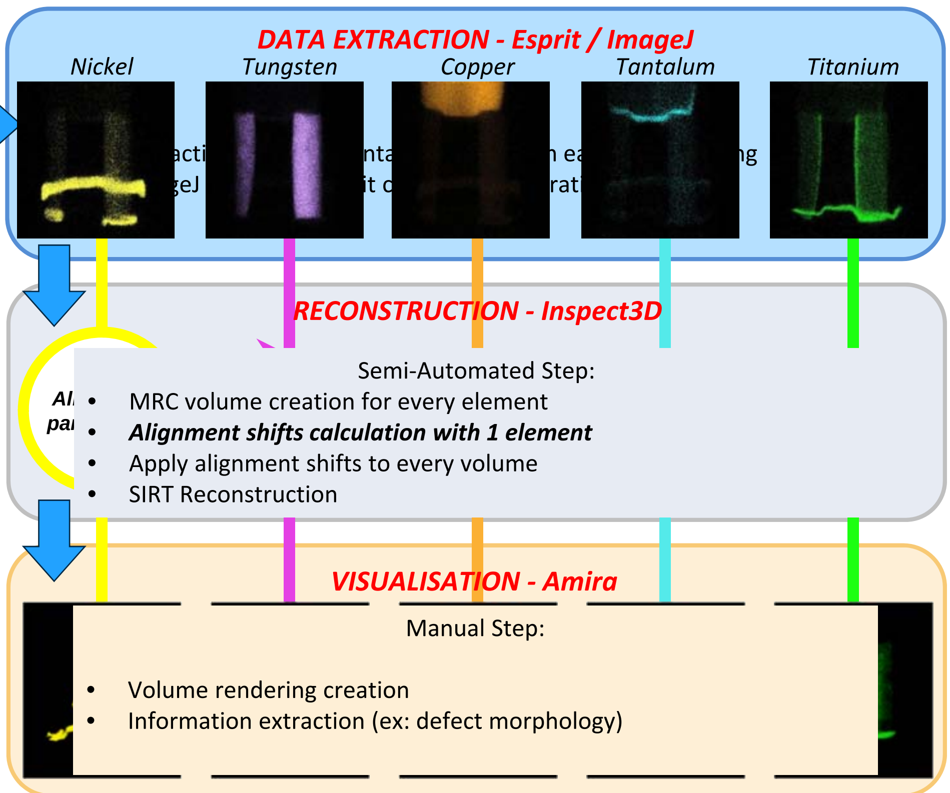


Sample preparation strategy (SEM images)

Prepared sample – needle diameter between 100nm and 200nm(TEM image)

STEM EDX tomography analysis flow

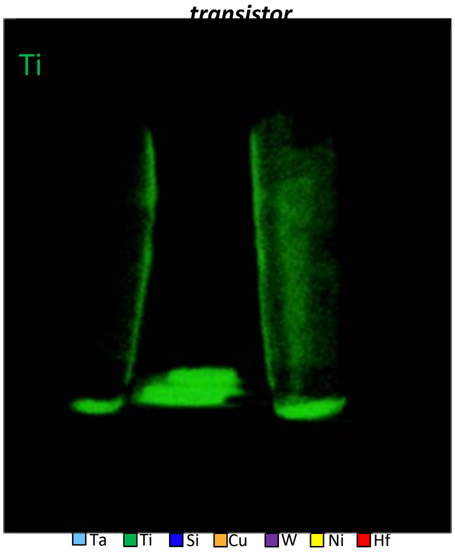




Experimental method and case study

- **Acquisition parameter:**
  - EHT 120keV , probe current : 1nA
  - Tilt range 180°, tilt step 2°
  - Dwell time 500µs, mapping acquisition 5min/map
- **Voxel representation can be obtained**
  - Element per element
  - Combination of elements

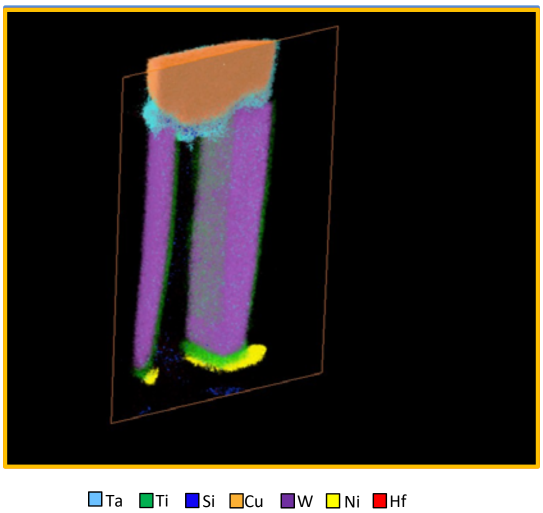
3D chemical rendering of FDSOI transistor

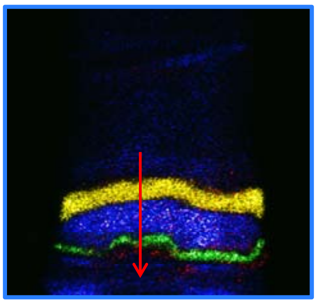


3D chemical representation per element

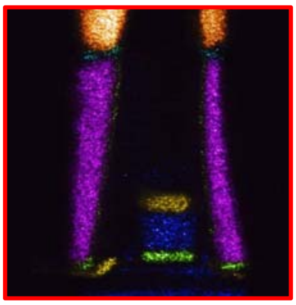
Experimental method and case study

- **Extracted slices in all directions**





Parallel to the gate stack
- *Ni / Si / Ti/ Hf*
- *STI step height*
- *No masking effect*



Perpendicular to the gate
- *Ni / Si / Ti/ Hf*
- *Cu Metal line*
- *TaN Barrier*

In plugs
- *W plugs*
- *TiN Barrier*
- *NiSi siliciuration*