Medical Imaging : Image Filtering & Segmentation

Hervé Delingette

Epione Team

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Course teachers

- Hervé Delingette 
- Xavier Pennec 

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Epione Research Team

1. Biomedical Image/Data Analysis, Machine Learning
2. Imaging & Phenomics, Biostatistics
3. Computational Anatomy, Geometric Statistics
4. Computational Physiology & Image-Guided Therapy
5. Computational Cardiology & Image-Based Interventio

Course Schedule

https://www-sop.inria.fr/asclepios/cours/MVA/

Liste of courses, slides, course notes and additional material

- Tuesday Oct 3, 2023, 14:00-17:15 (ENS Saclay, salle 2E30) Introduction to Medical Image Acquisition, Image Filtering [Hervé Delingette]
- Tuesday Oct 10, 2023, 14:00-17:15 (ENS Saclay, salle 3E34) Riemanian Geometry and Statistics [Xavier Pennec]
- Tuesday Oct 17, 2023, 14:00-17:15 (ENS Saclay salle 2E30) Analysis in the space of Covariance Matrices [Xavier Pennec]
- Tuesday Oct 24, 2024: 14:00-17:15 (ENS Saclay, salle 1B18) Basis of Image Segmentation [Hervé Delingette]
- Tuesday Nov 7, 2022: 14:00-17:15 (ENS Saclay, salle 2E30) Image Segmentation based on Clustering and Markov Random Fields [Hervé Delingette]
- Tuesday Nov 14, 2022, 14:00-17:15 (ENS Saclay, salle 3E34) Shape constrained image segmentation and Biophysical Modeling [Hervé Delingette]
- Tuesday Nov 21th : 14:00-17:15 (ENS Saclay, salle 1N82) Image Registration [Xavier Pennec]
- Tuesday Nov 28th : 14:00-17:15 (ENS Saclay, salle 2E30) Diffeomorphic Registration and Computational Anatomy [Xavier Pennec]
- Tuesday Dec 5th, 2023, 14:00-17:15 (Visio) Exam [Hervé Delingette, Xavier Pennec]

Course Exam

- 4 components :
  - Scientific Article Study :
    - 10 min oral presentation
    - 10 min Questions & Answers
    - 5-6 page report presenting the paper and putting it in perspective.
    - Implementation (optional)
    - May be performed in pairs or triplets depending on class size
  - Multiple choice Quizz : 10-15 questions

Medical Imaging Modalities

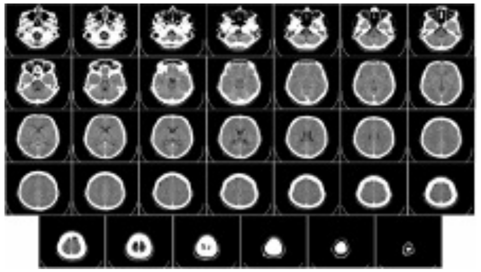
1895

Roentgen

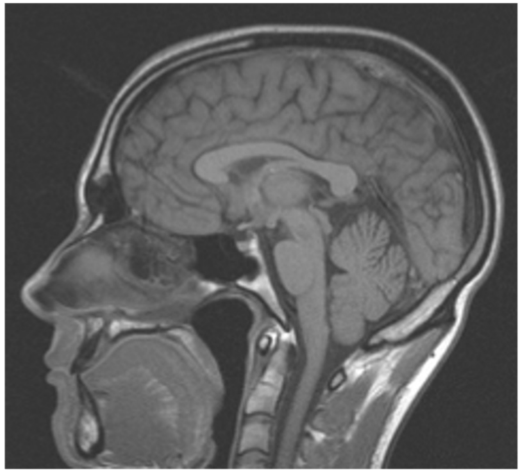
First Nobel prize
in Physics in 1901

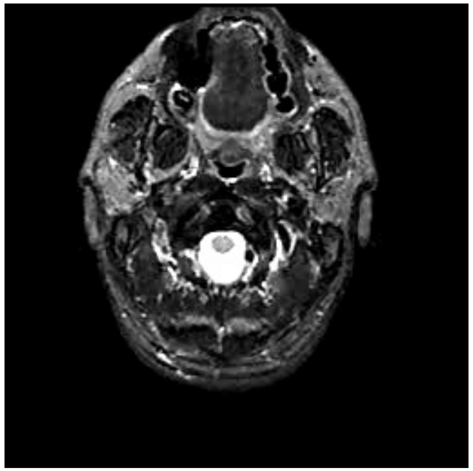
Todays's Medical Imaging modalities

CT Scan

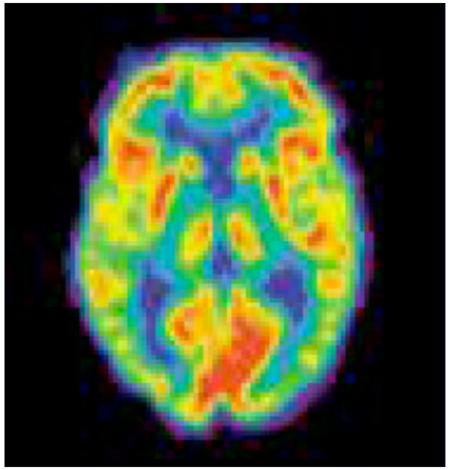


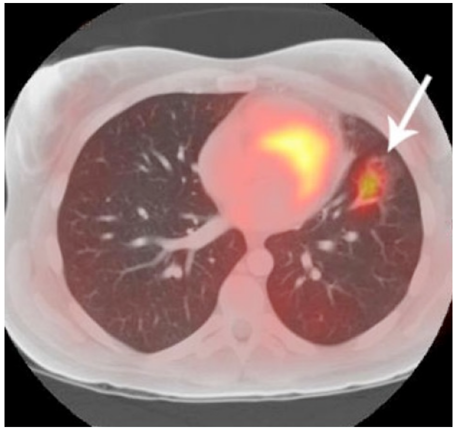
MRI



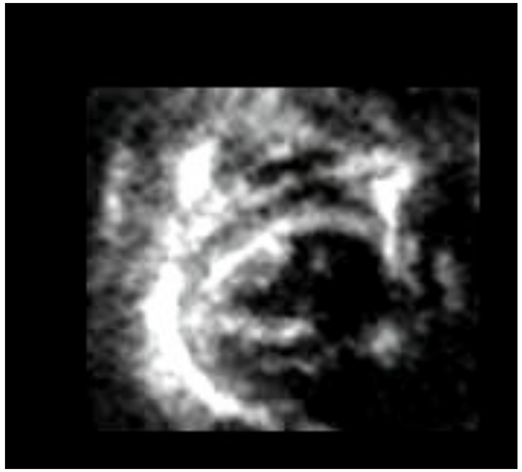


PET





Ultrasound

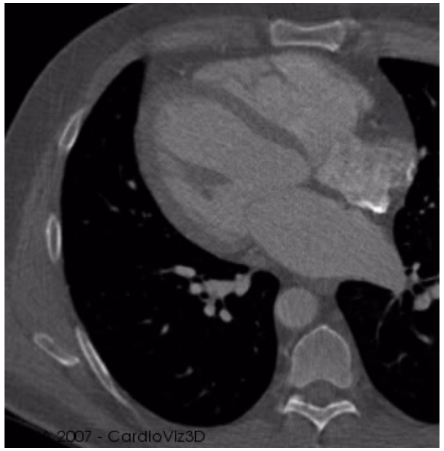


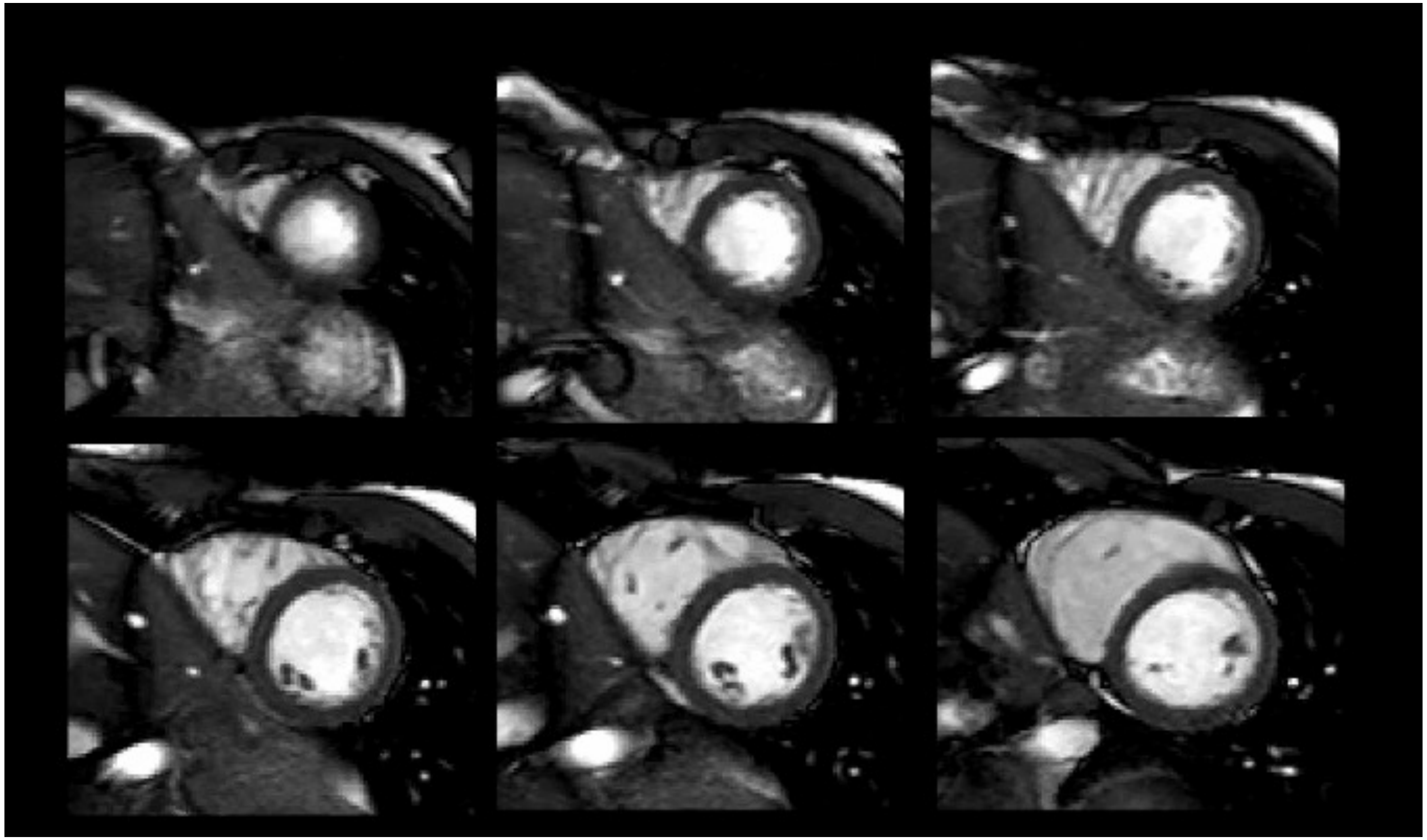
Source :T. Peters

Dynamic Images (4-D)

CT Scan

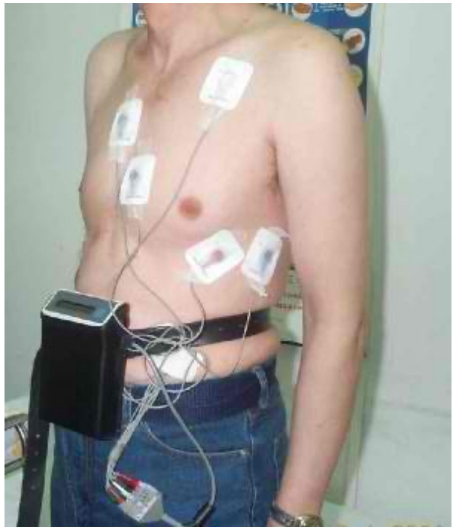
MRI





Bio-signals

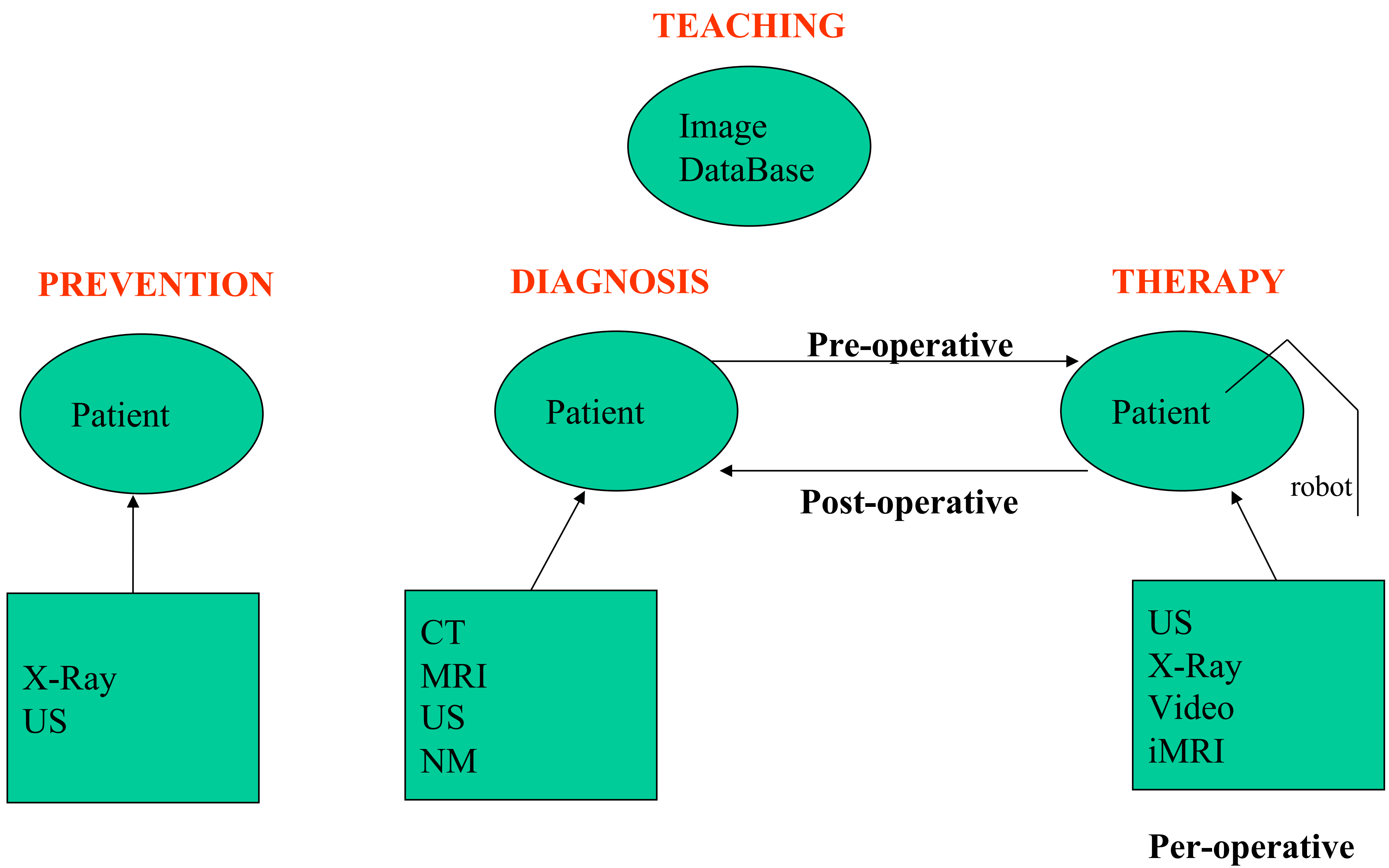
ECG



Pressure Sensor

Temperature

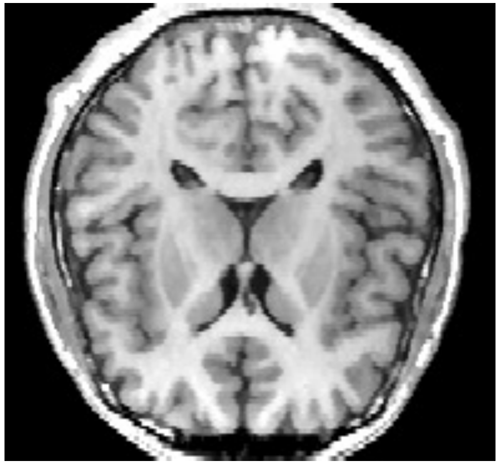
Medical Imaging in clinical practice



Main Medical Image Modalities

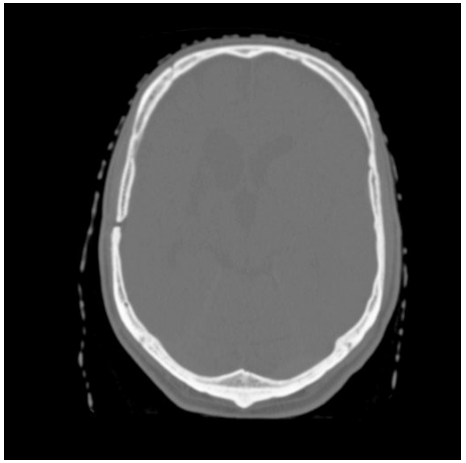
MRI

Density and structure of protons



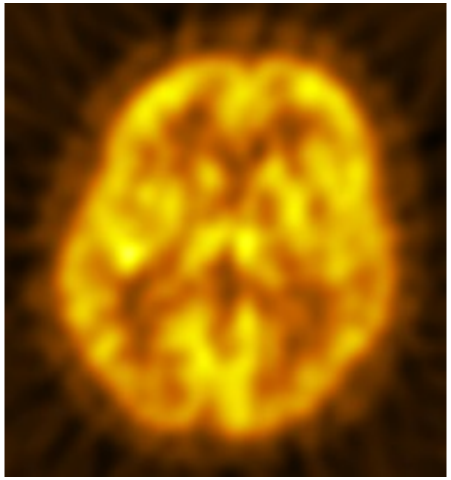
X-Scan

X-ray absorption density



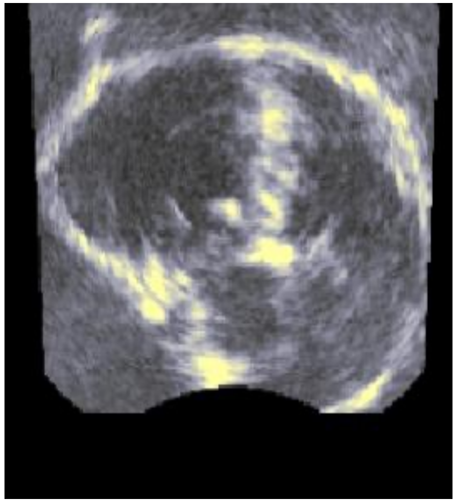
PET / SPECT

Density of Radioactive isotopes



Ultrasound / echography

Variations of acoustic impedance

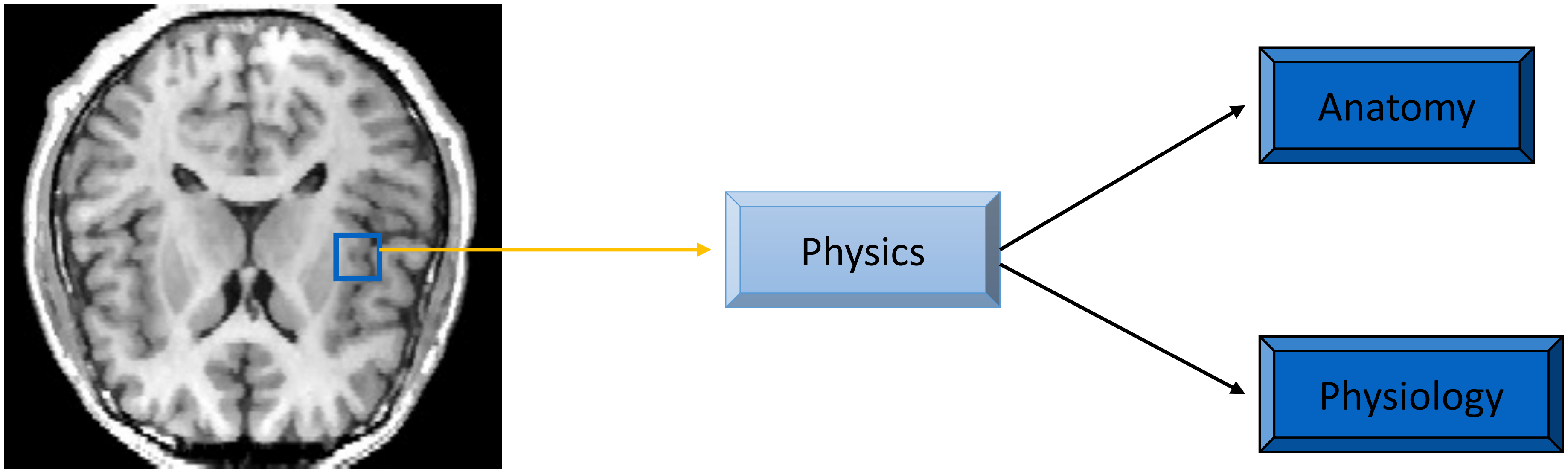


More imaging modalities

- X-ray
- Magnetic resonance imaging
  - anatomic, functional, angiographic, diffusion, spectroscopic, tagged
- Transmission Tomography (X Scan)
- Nuclear Medicine :
  - Positron emission tomography (PET)
  - Single photon emission tomography (SPECT)
- Ultrasonography
- Histological Imaging, confocal in-vivo microscopy, molecular imaging,…

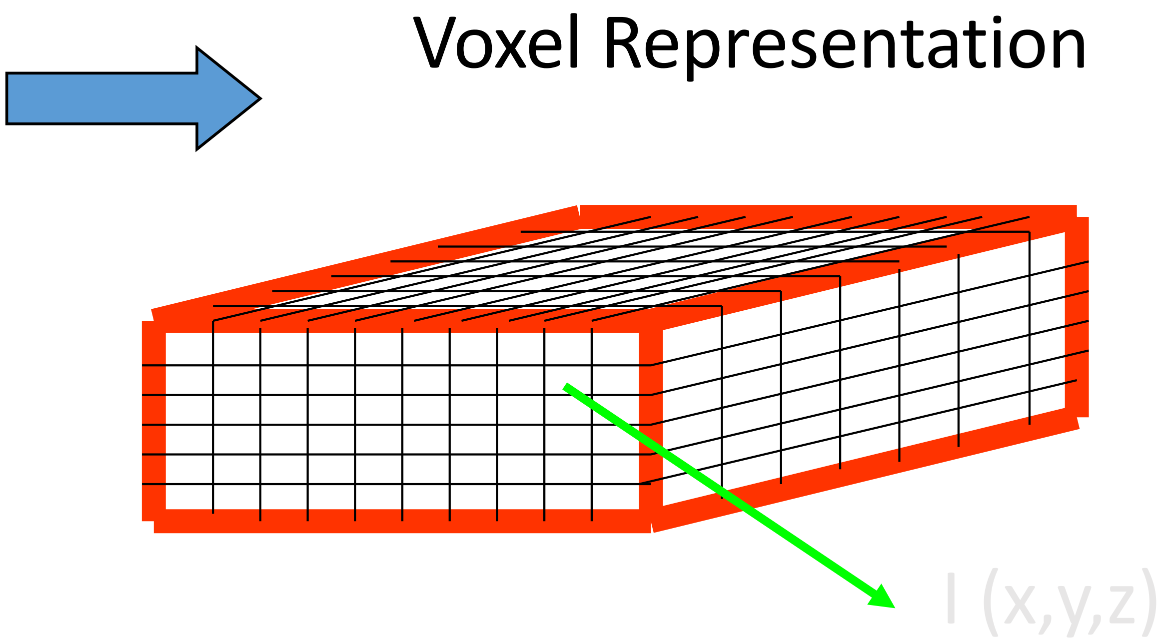
Characteristics of medical images

Intensity values are related to physical tissue characteristics which in turn may relate to a physiological phenomenon

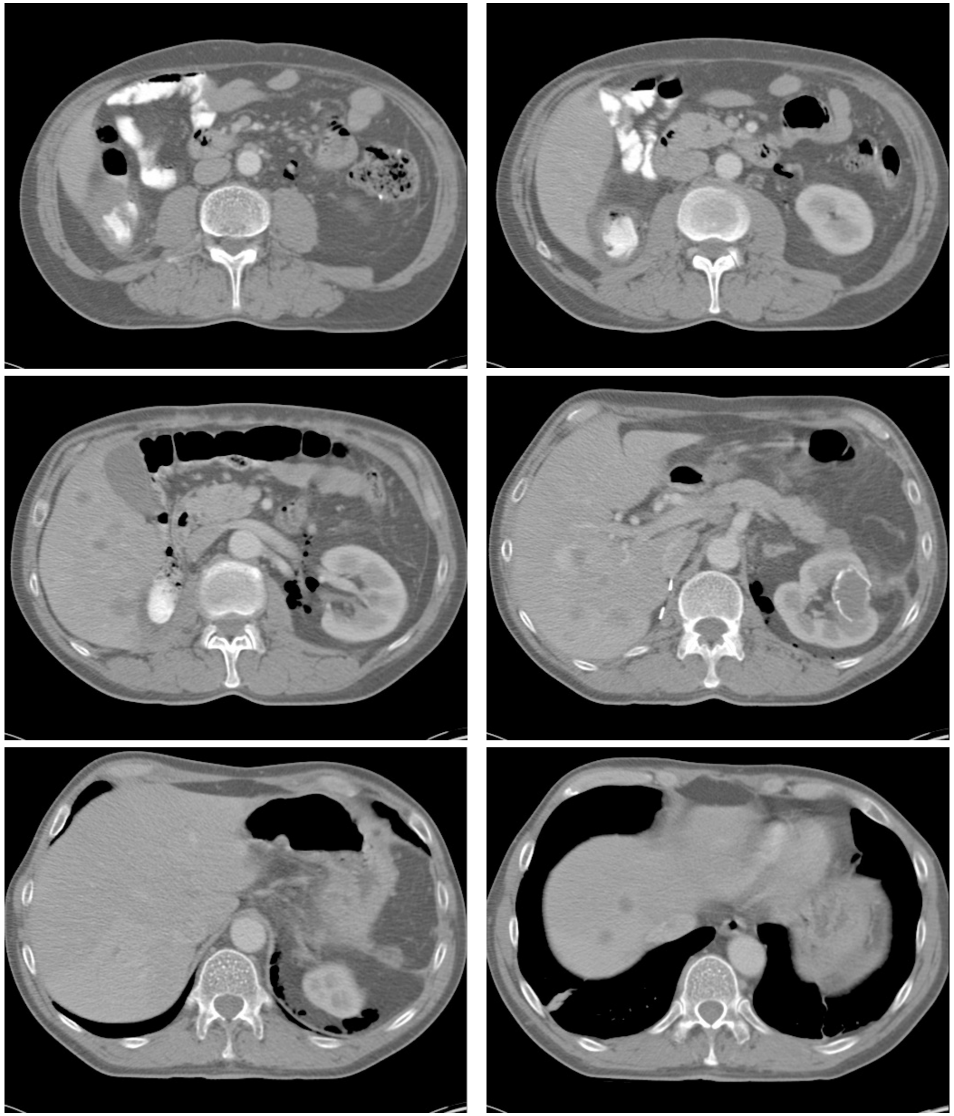


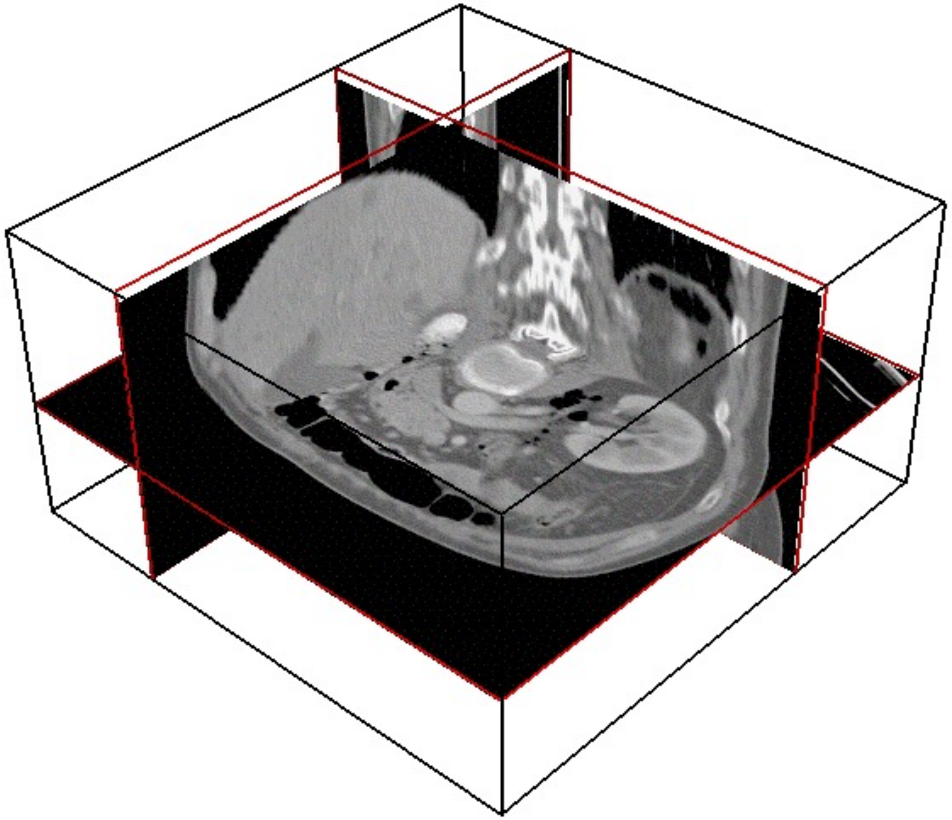
Volumetric medical images

- Very often medical images are volumetric



Example of volumetric images : CT-scan (Scanner)





Size: 512 x 512 x 128
Resolution: 0.5 x 0.5 x 1 mm

Medical Imaging Modalities

0.1Introduction

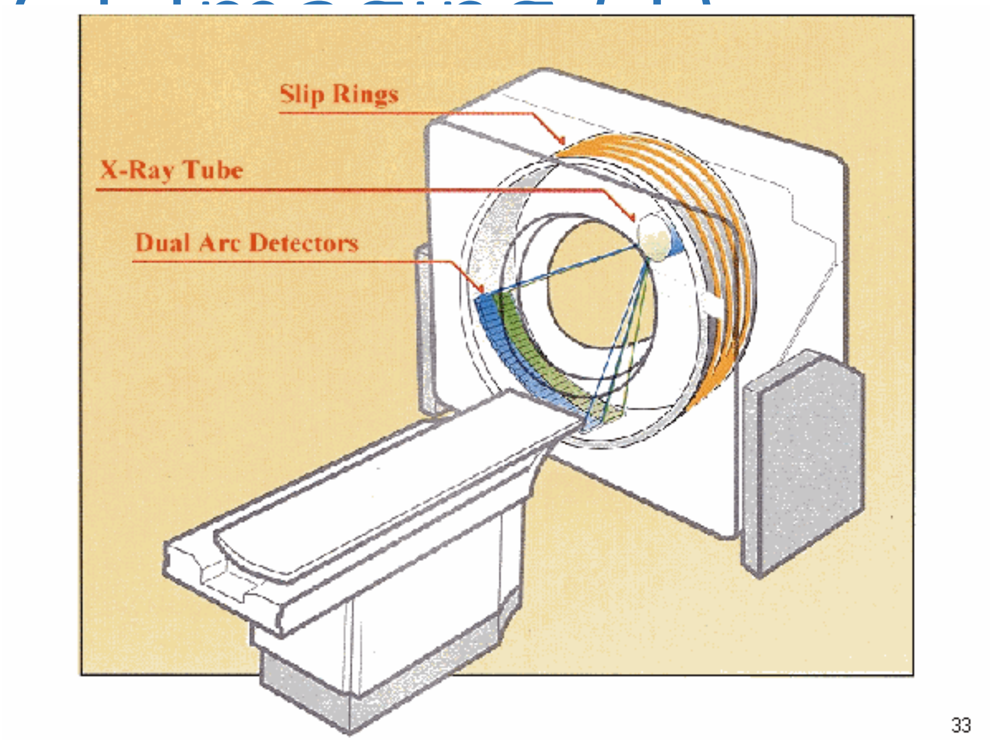
0.2 Tomography

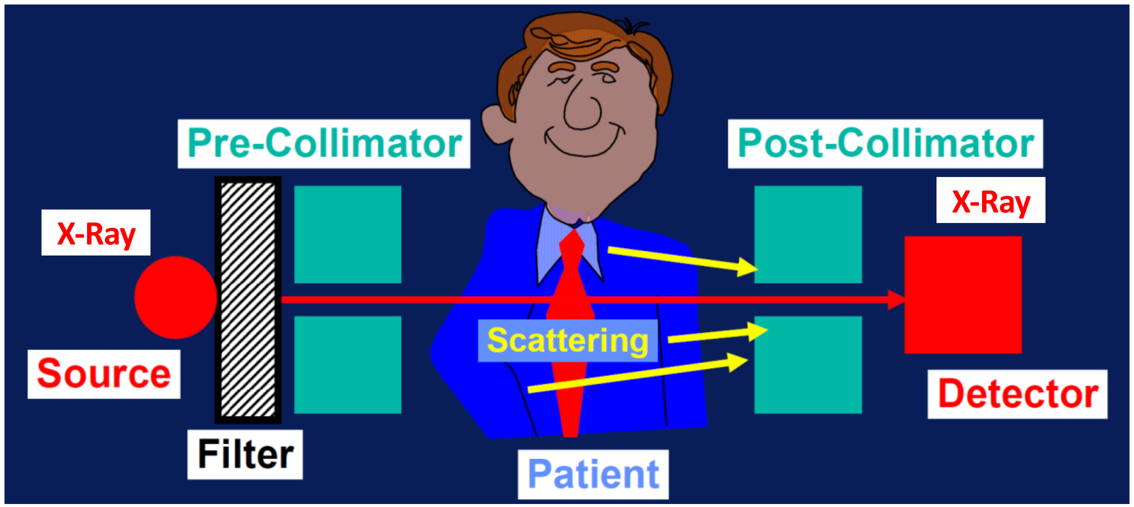
0.3 Nuclear medicine

0.4 MRI

0.5 Echography

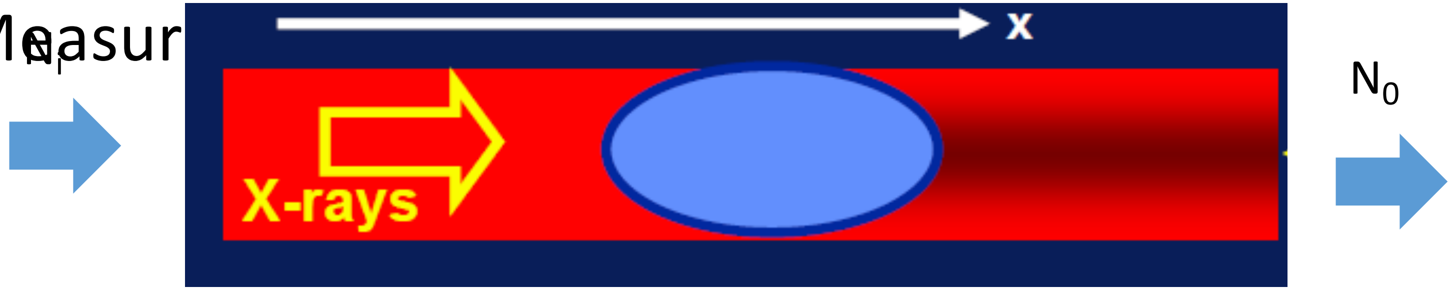
Principle of CT Imaging (1)





Principle of CT Imaging (2)

- Input X-Ray intensity : N_i
- Measur



$$N_o = N_i e^{-\int_{-\infty}^{+\infty} \mu(x) dx}$$

- Exponential attenuation :

- Objective :
  - measure $\mu(x)$ = absorption coefficient of X-ray

Computed Tomography

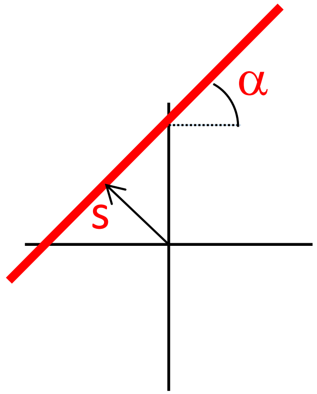
- Principle :
  - Reconstruct n dimensional function (image) from projected data of $(n-1)$ dimension

- Radon Transform (1917)
  - "Two dimension and three dimension object can be reconstructed from the infinite set of projection data".

Radon transform

•Scanner measures 1D projection of X-ray absorption values :

$$-log\left(\frac{N_i}{N_o}\right) = \int_{-\infty}^{+\infty} \mu(x)\,dx$$



• Parameterize line by angle α and offset s

$$R\mu(\alpha, s) = \int_{L(\alpha,s)} \mu(x)dx = \int_{-\infty}^{+\infty} \mu(t\sin\alpha + s\cos\alpha\,, s\sin\alpha - t\cos\alpha)\,dt$$

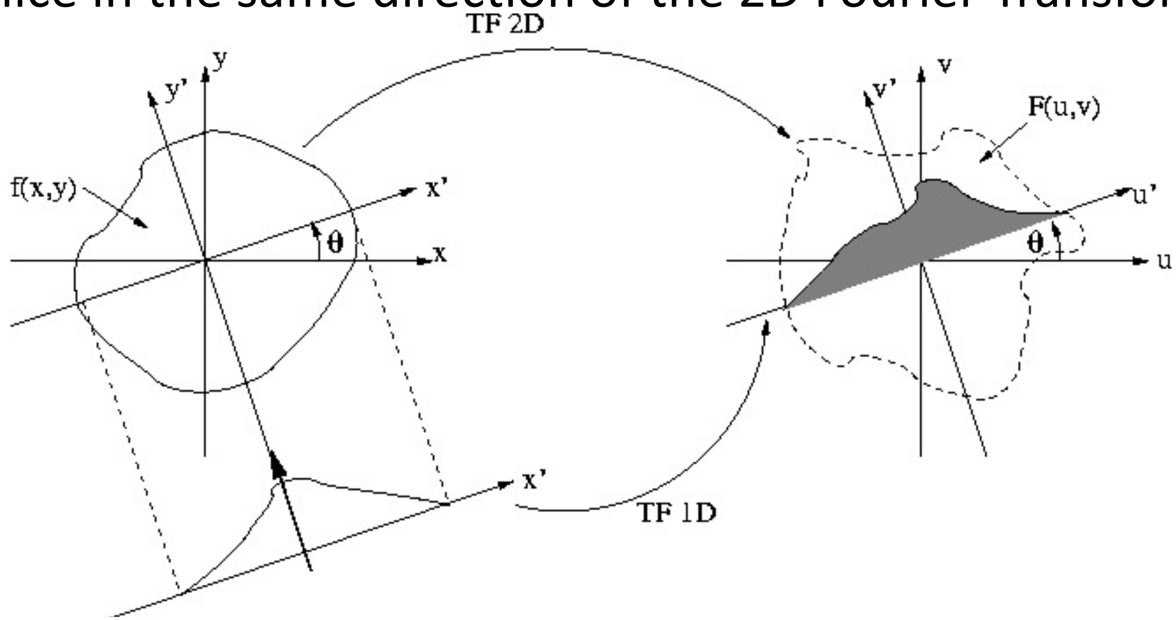
• Radon Transform :

Fourier Slice Theorem

1D Fourier Transform of Projected slice of 2D field $\mu(x,y)$

is equal to

1D slice in the same direction of the 2D Fourier Transform of $\mu(x,y)$

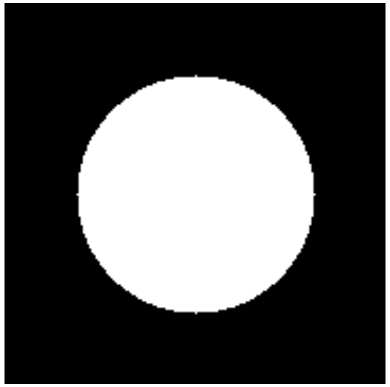


Reconstruction Principle

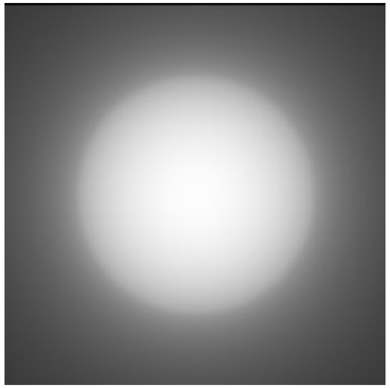
- Backprojection based on inverse Radon Transform

$$n_\alpha = (\cos\alpha, \sin\alpha) \qquad \widetilde{\mu(x)} = \frac{1}{2\pi}\int_{\alpha=0}^{2\pi} R\mu(\alpha, n_\alpha . x)\,d\alpha$$

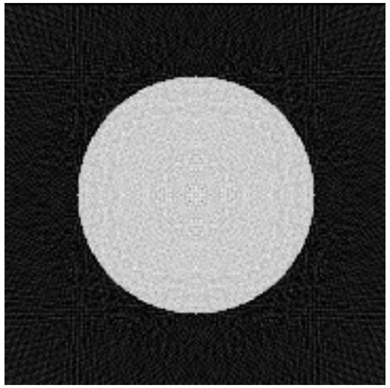
- In practice use filtered back-projection to remove blur



Model Image



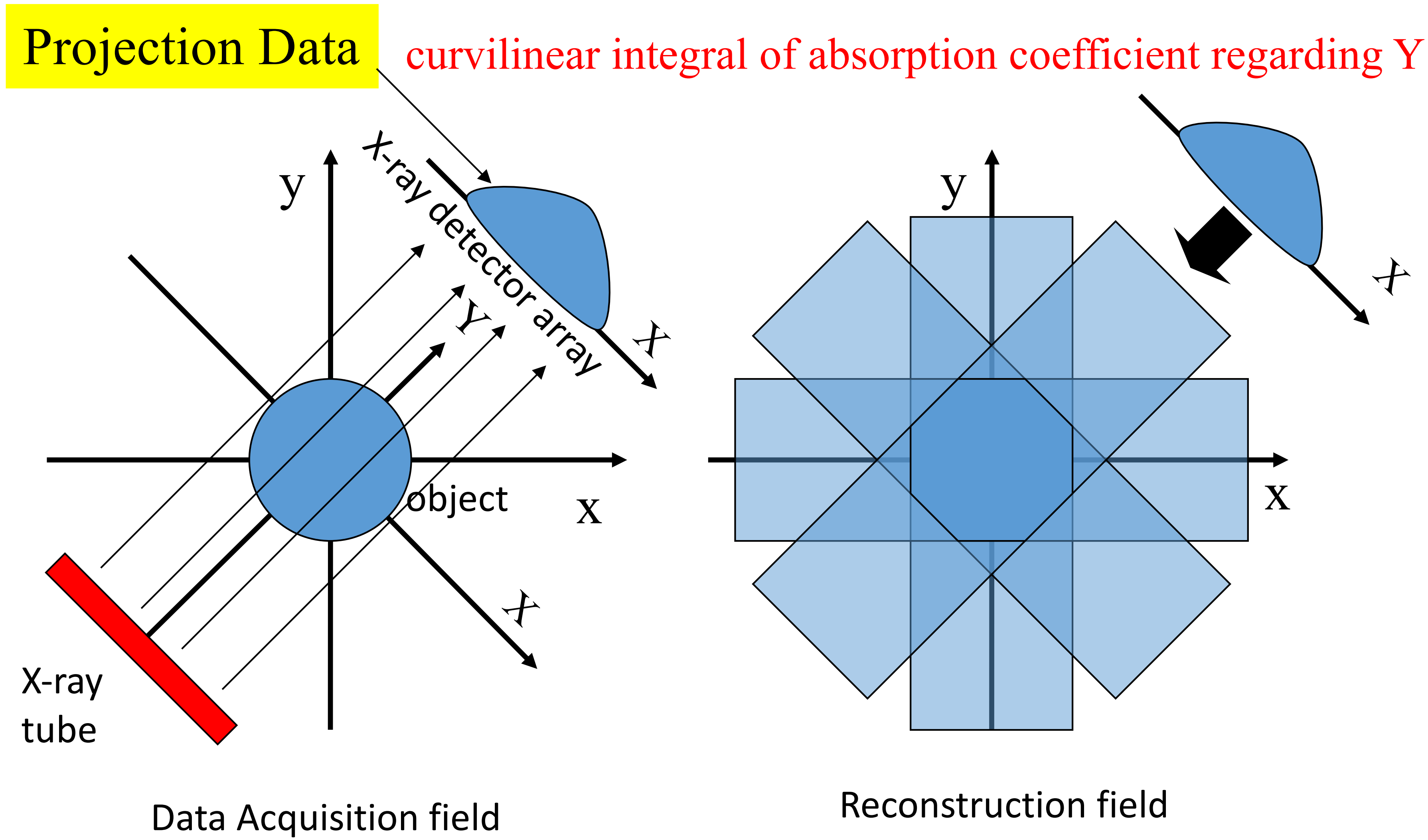
Simple Backprojection



Filtered Backprojection

Basic principle of CT

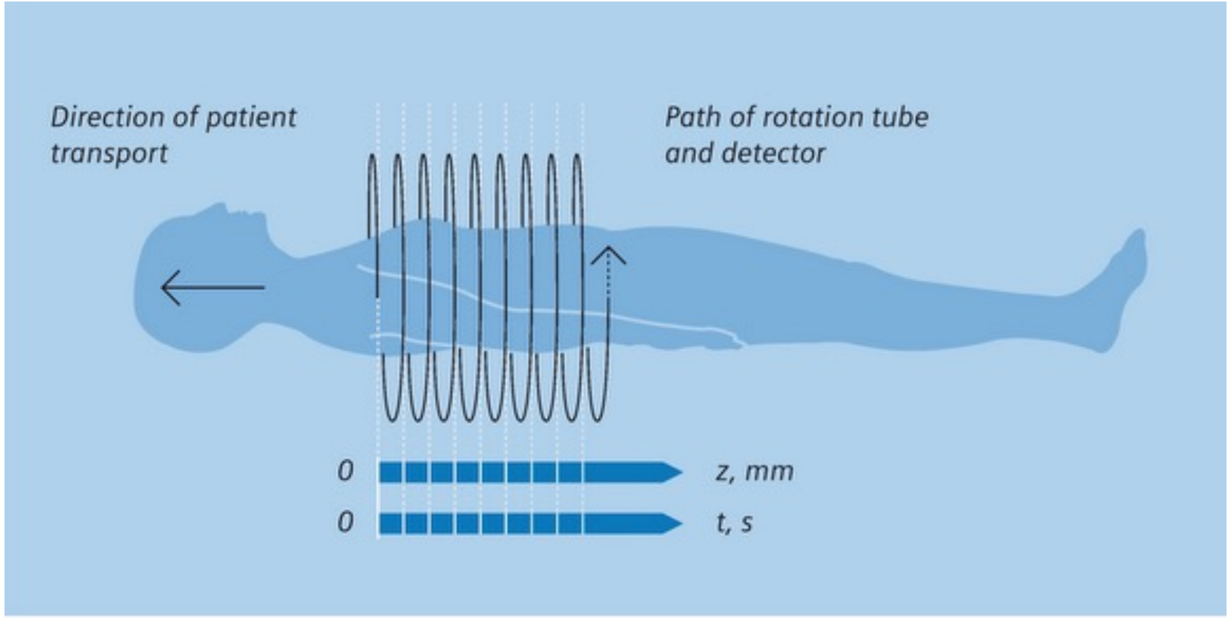
-Reconstruction of 2 dimensional image-



Simple Backprojection

Spiral (3D) CT

- X-ray tube and detectors rotate 360 deg
- Patient table is continuously moving
- Produce an helix of image projections
- 3D reconstruction



Development of Computed Tomography





History

1895
Röntgen

Discovery of X-rays

1917
Radon

Mathematical foundations

1963
Cormack

X-ray tomography idea

1972
Hounsfield

First CT scanning system

1989
Kalender

Introduction of helical CT

1998

First multi-line CT system

2004

Cone beam CT systems

CT Scan Imaging

- Measure absorption coefficient of X-ray rel tissue

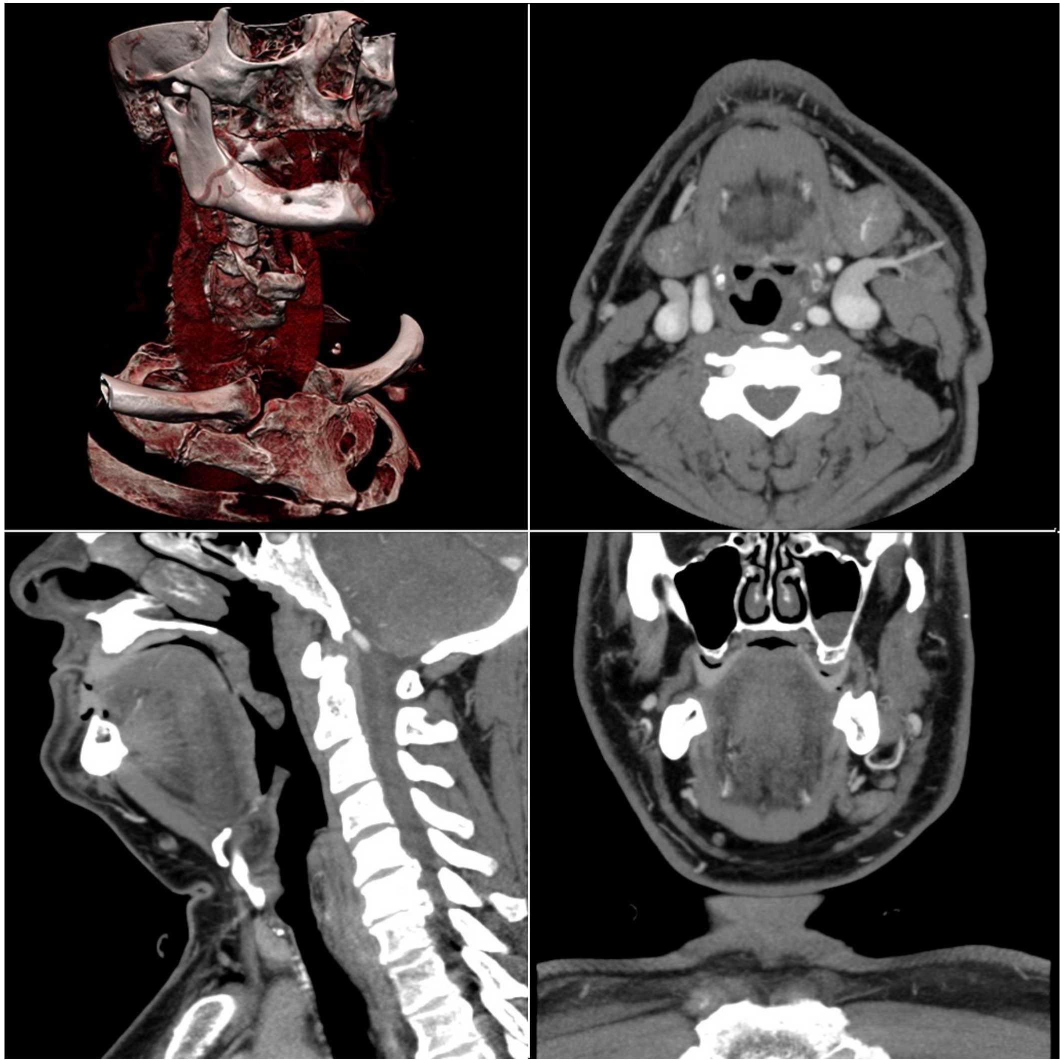
- Invasive image modality (ionizing rays)

- Absolute Hounsfield Unit

  - HU(water)=0, HU(air)= -1024, HU(Bone)=175 to 3000
  - Coded on signed 12 bits

- $$HU(\mu) = 1024 \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}}$$

CT Scan



Medical Imaging Modalities

0.1Introduction

0.2 Tomography

➡ 0.3 Nuclear medicine

0.4 MRI

0.5 Echography

Principle of nuclear imaging

- Introduction into the patient body of a couple

  (vector molecule / radio-isotope)

Vector Molecule	$\Rightarrow$	Targeted organ (drug, protein, blood cells…)
Radio-isotope	$\Rightarrow$	Allow the detection of the molecule

- Emission imaging : the targeted organ emits radioactivity

  $\Rightarrow$ Reflect the metabolic function of the organ
  $\Rightarrow$ *Metabolic* or *functional imaging*
  $\rightarrow$ Local relative concentration (relative)
  $\rightarrow$ Concentration evolves along time

Nuclear Medicine / radioactivity

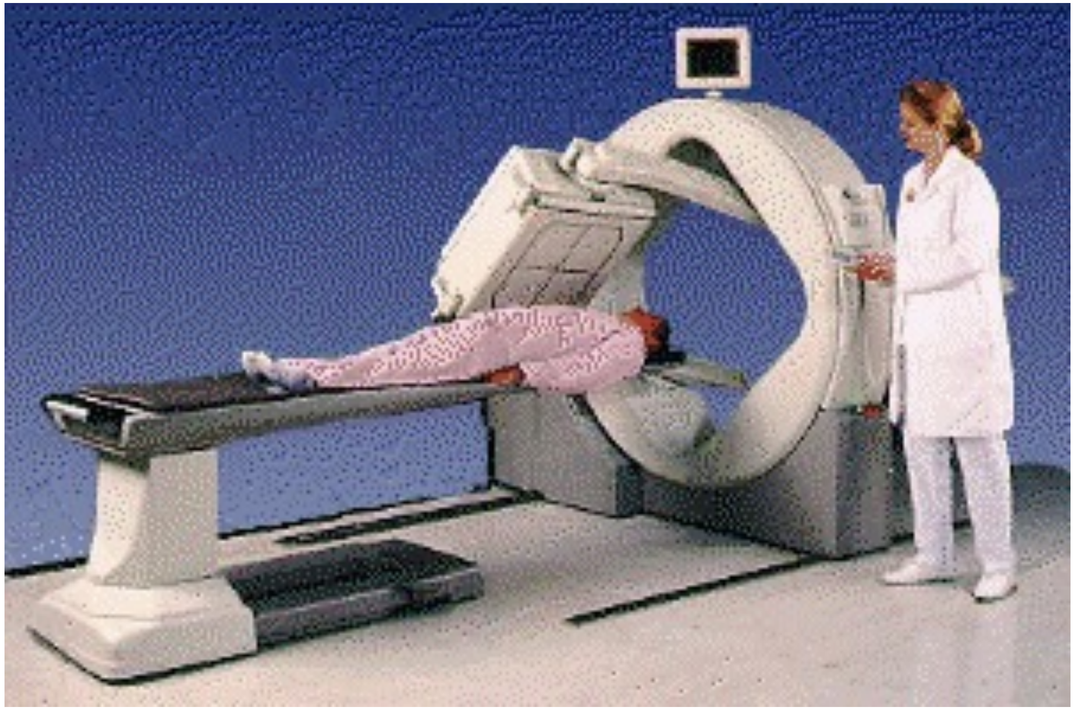
- **Nucleus (Rutherford)** Nucleon = proton or neutron

A= nucleon number	Isobars	For A = constant
Z = proton number	**Isotopes**	For Z = constant
N = neutron number	Isotones	For N = constant

- **Radioactivity (Curie)**

Alpha Particle:	Helium nucleus (2 protons + 2 neutrons)
Beta Particle :	1/ electron β-
	2/ positon β+ $\rightarrow$ 2 photons γ (511 kev)
Gamma Particle:	Photon

Nuclear Medicine



- Density of radioactive tracers

Single photon gamma imaging (SPECT)

- Radio-isotopes (Gamma particles)

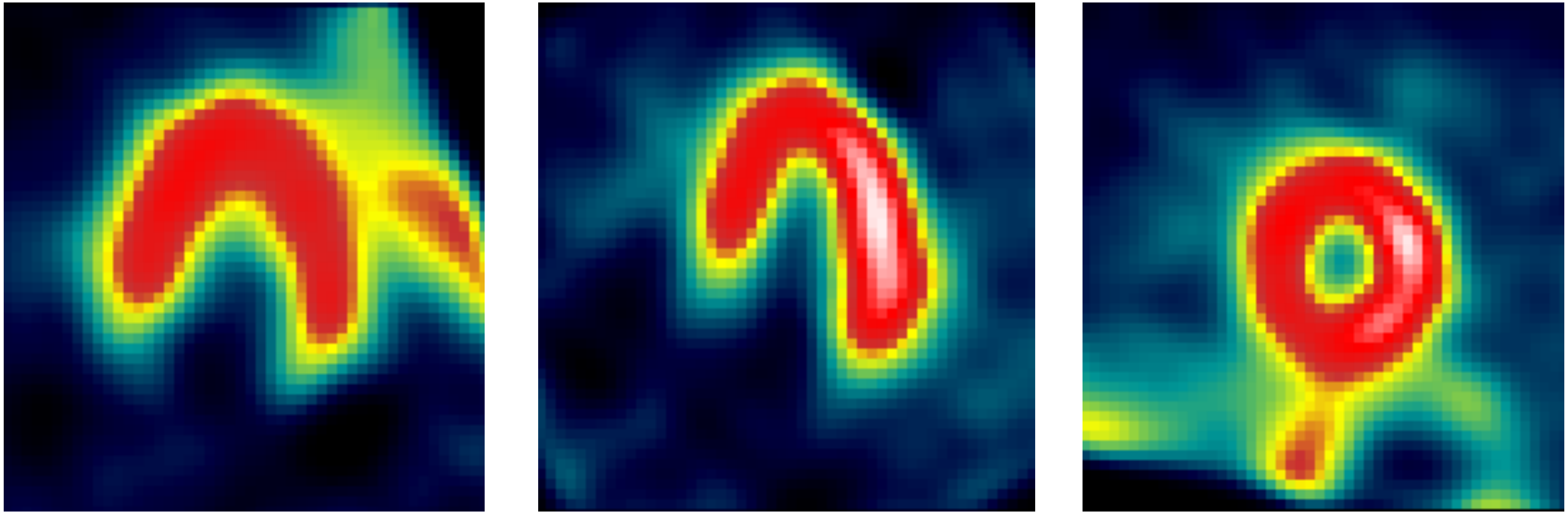
Single photon emitters

Molecule	Half-Life	Energy	Generation
Technetium Tc 99m	6 h	140 kev	Portative generator
Iodine I 131	8 j	360 kev	Reacteur (fission)
Iodine I 123	13 h	159 kev	Cyclotron (industry)
Thallium Tl 201	73 h	80 kev	Cyclotron (industry)

- Krypton (Kr 81 m), Gallium (Ga 67), Indium (In 111), **Xenon (Xe 133, gaz)**

- SPECT = Single Photon Emission Computed Tomography

Single photon gamma imaging



Heart (myocardium perfusion)

- Stress/rest exam

perfusion	/ perfusion	⇒ Healthy area
perfusion	/ (hypo/non-)perfusion	⇒ Zone at risk (ischemia)
(hypo/non-)perfusion	/ (hypo/non-)perfusion	⇒ Infarcted Area

Positon emission tomography (PET)

■ Radio-isotopes

Emission : positron (β+) → Annihilation

→ 2 photons of 511 kev at 180º

Positron emitters

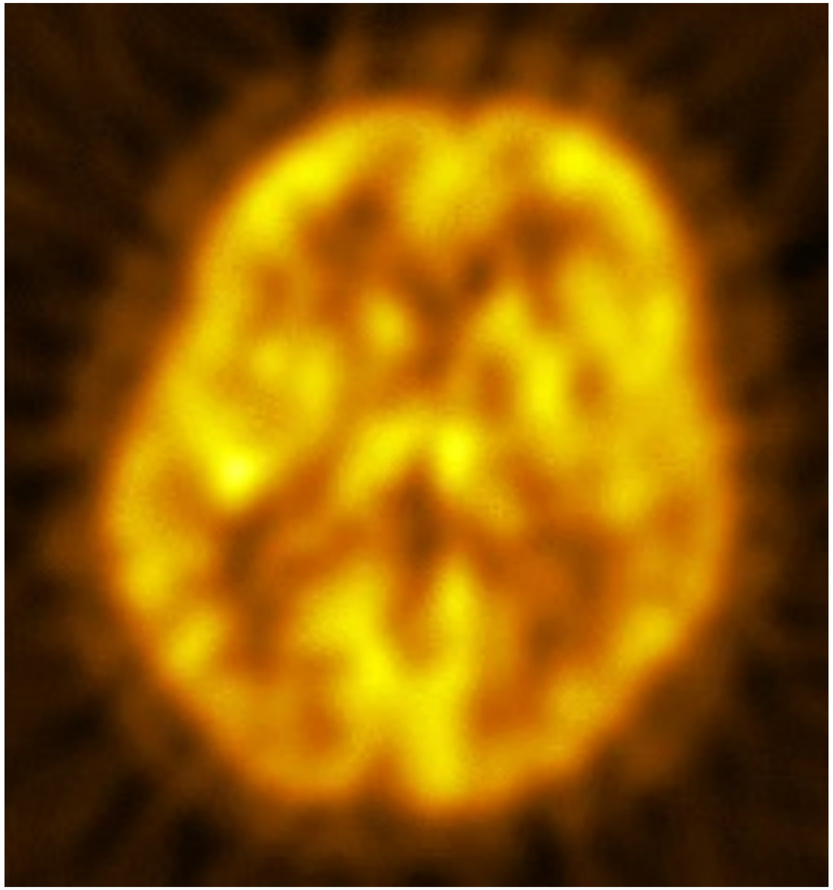
Molecule	Half-life	Generation
Carbon ^{11}C	20 mn	cyclotron (medical)
Nitrogen ^{13}N	10 mn	cyclotron (medical)
Oxygen ^{15}O	2 mn	cyclotron (medical)
Fluor ^{18}F	112 mn	cyclotron (medical)

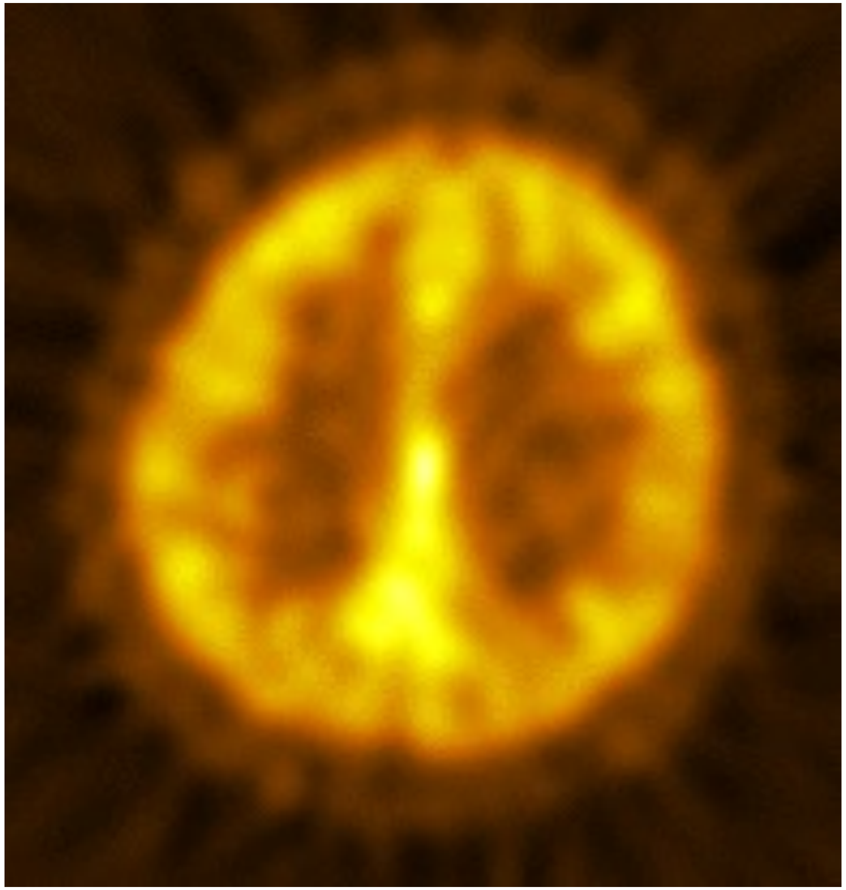
■ Physiological molecules

water → H_2O^{15}

glucose → fluoro-deoxyglucose ($F^{18}DG$)

Positon emission tomography (PET)





PET Scan

https://www.youtube.com/watch?v=GHLBcCv4rqk

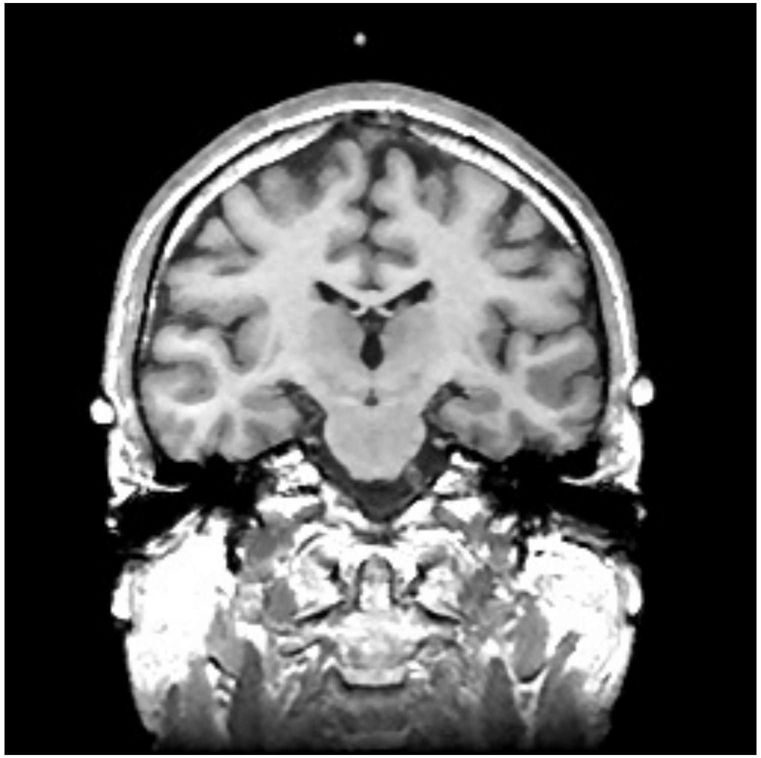
Medical Imaging Modalities

Magnetic resonance imaging

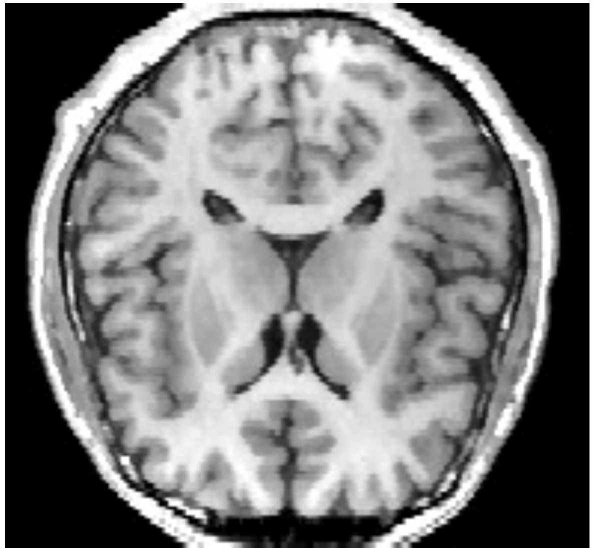
- Density and structure of protons

Magnetic resonance imaging

Sagittal



Coronal or Frontal



Axial or Transverse

dimension: 256 x 256 x 128   résolution: 1x1x1.5 mm

MRI: a few dates

1946: MR phenomenon - Bloch et Purcell
1952: Nobel prize - Bloch et Purcell
1950-1970: development but no imaging
1980: MRI feasibility
1986 - ….: real development

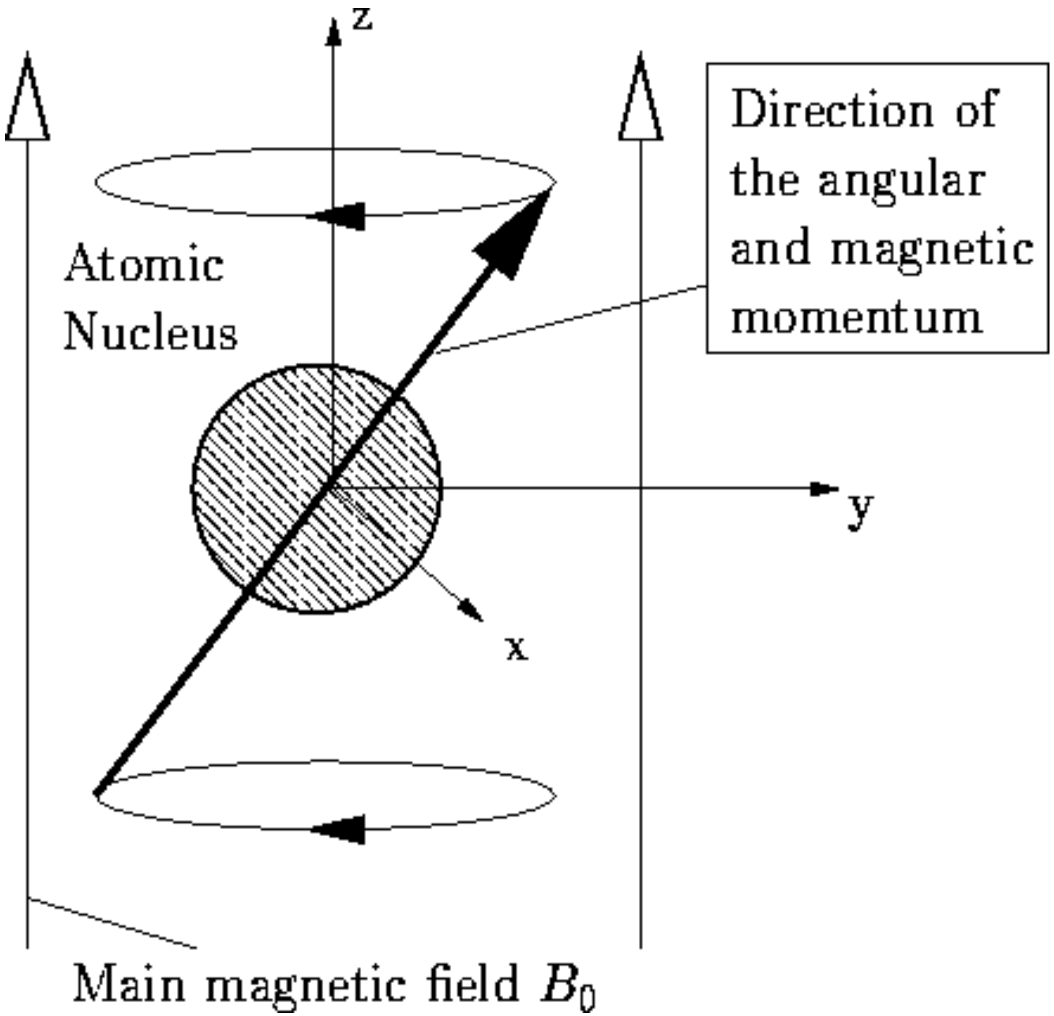
MRI: One modality with multiple sequences

Anatomic MRI: T1, T2, Proton Density weighted images
Angiographic MR
Functional MR: cognitive studies
Diffusion MR: brain connectivity
MR Spectroscopy

No absolute quantification

Magnetism at the molecular level

Electric charges in motion
 magnetic momentum
 Precession motion in a
magnetic field



Bloch's Equations

- **Link between spin and magnetic momentum**

$$\vec{\mu} = \gamma \, \vec{\omega}$$

$\vec{\mu}$ Nuclear magnetic momentum

γ Gyromagnetic ratio

$\vec{\omega}$ Angular momentum(spin)

- Fundamental motion equation

$$I \frac{d\vec{\omega}}{dt} = \vec{m}$$

$\vec{m}$ Total Momentum (mechanics)

- **In a magnetic field** $\vec{m} = \vec{\mu} \times \vec{B}$

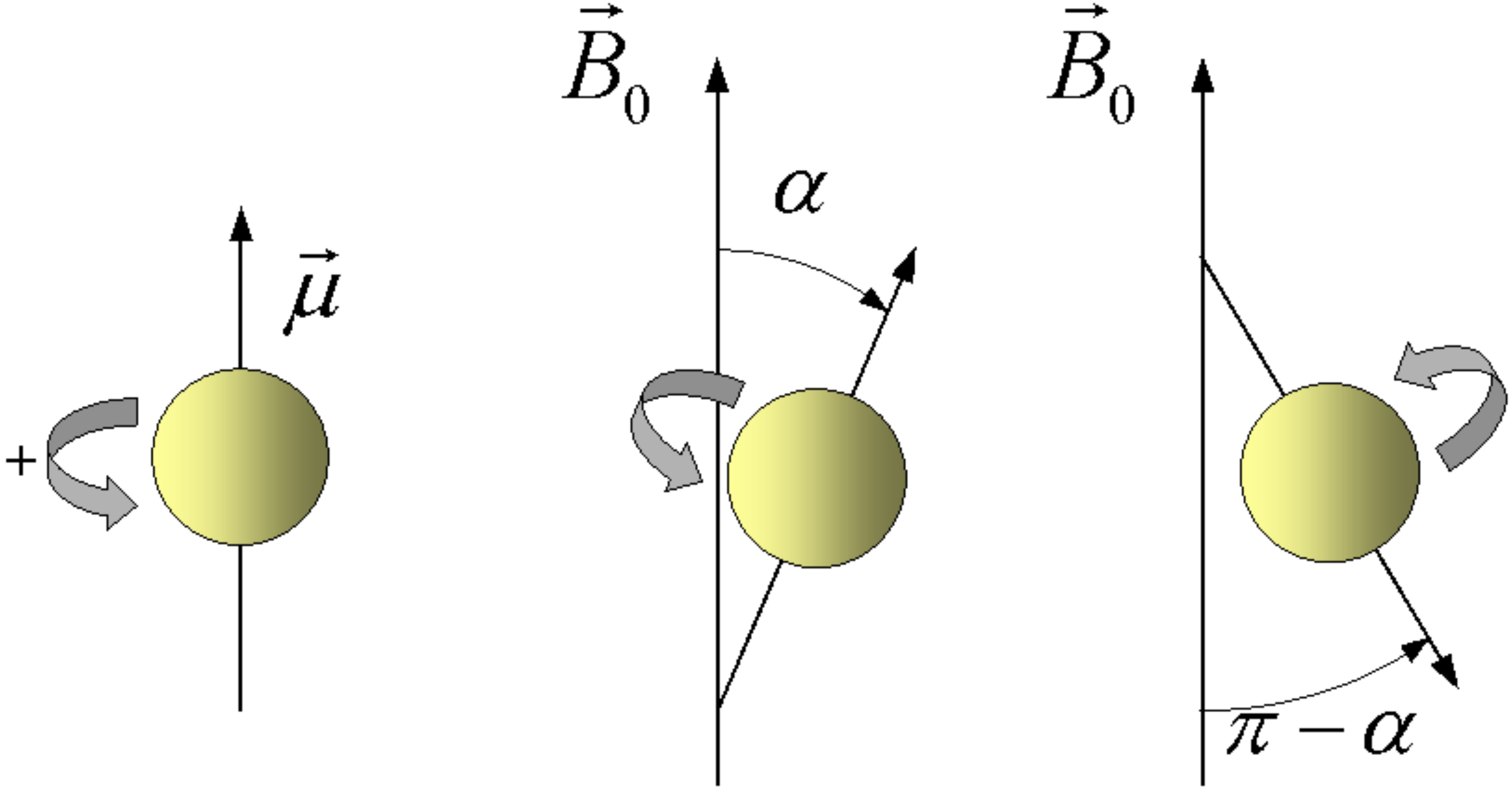
Bloch's Equations

Thus $$\frac{d\vec{\mu}}{dt} = \gamma\left(\vec{\mu} \times \vec{B}\right)$$

$$\vec{B}_0 = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} \Rightarrow \vec{\mu} = \begin{pmatrix} \mu_t \cos\left(\omega_L t + \varphi\right) \\ -\mu_t \sin\left(\omega_L t + \varphi\right) \\ \mu_{z_0} \end{pmatrix}$$

Larmor's frequency $\omega_L = \gamma\, B_0$

Magnetism at the macroscopic level



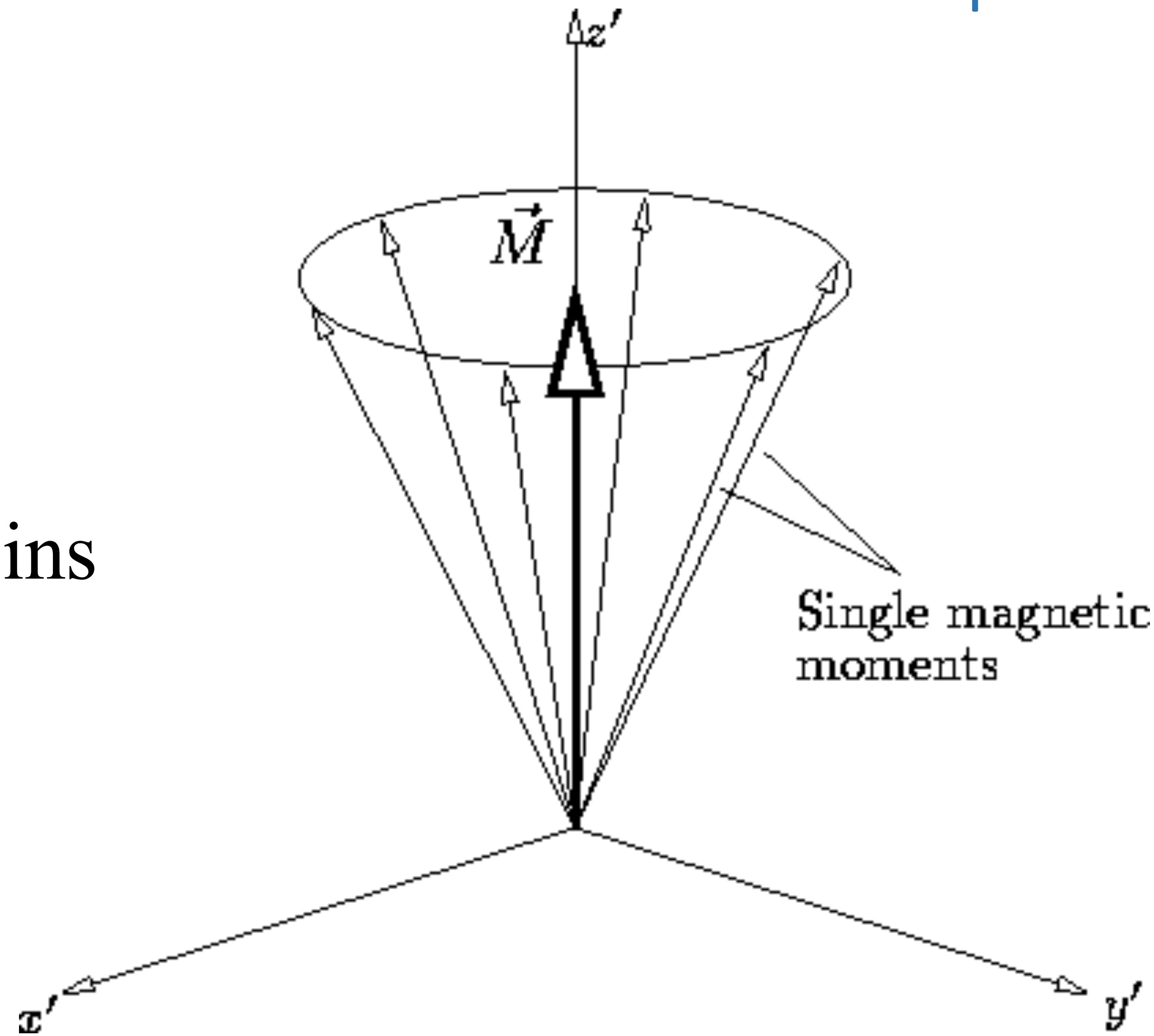
$P_{+1/2}$=0.5000049

B_0=1.5 T

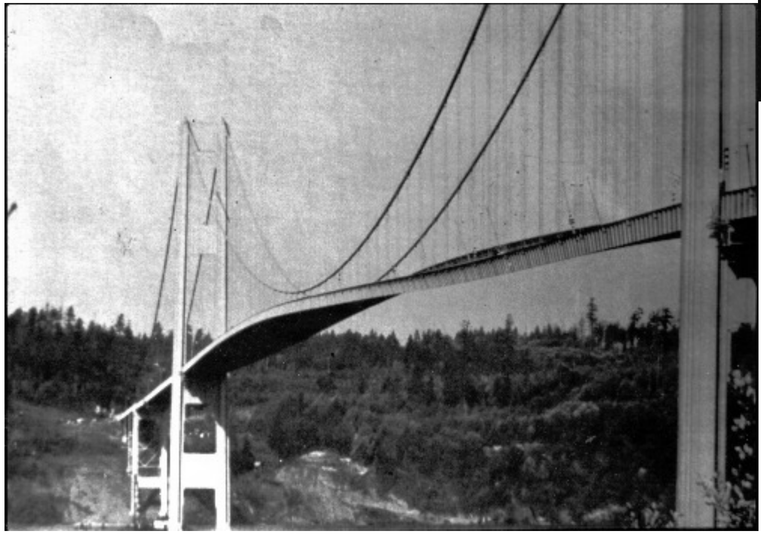
$P_{-1/2}$=0.4999951

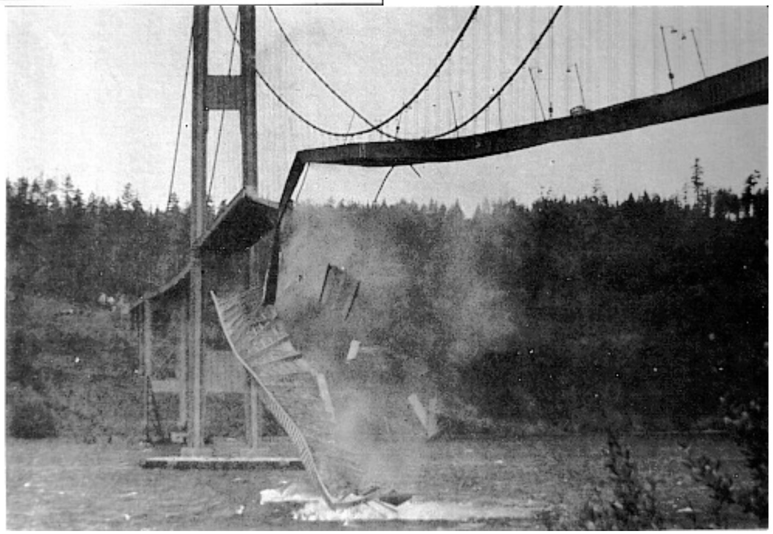
Magnetism at the macroscopic level

10^{23} spins



Resonance





Magnetic Resonance / excitation

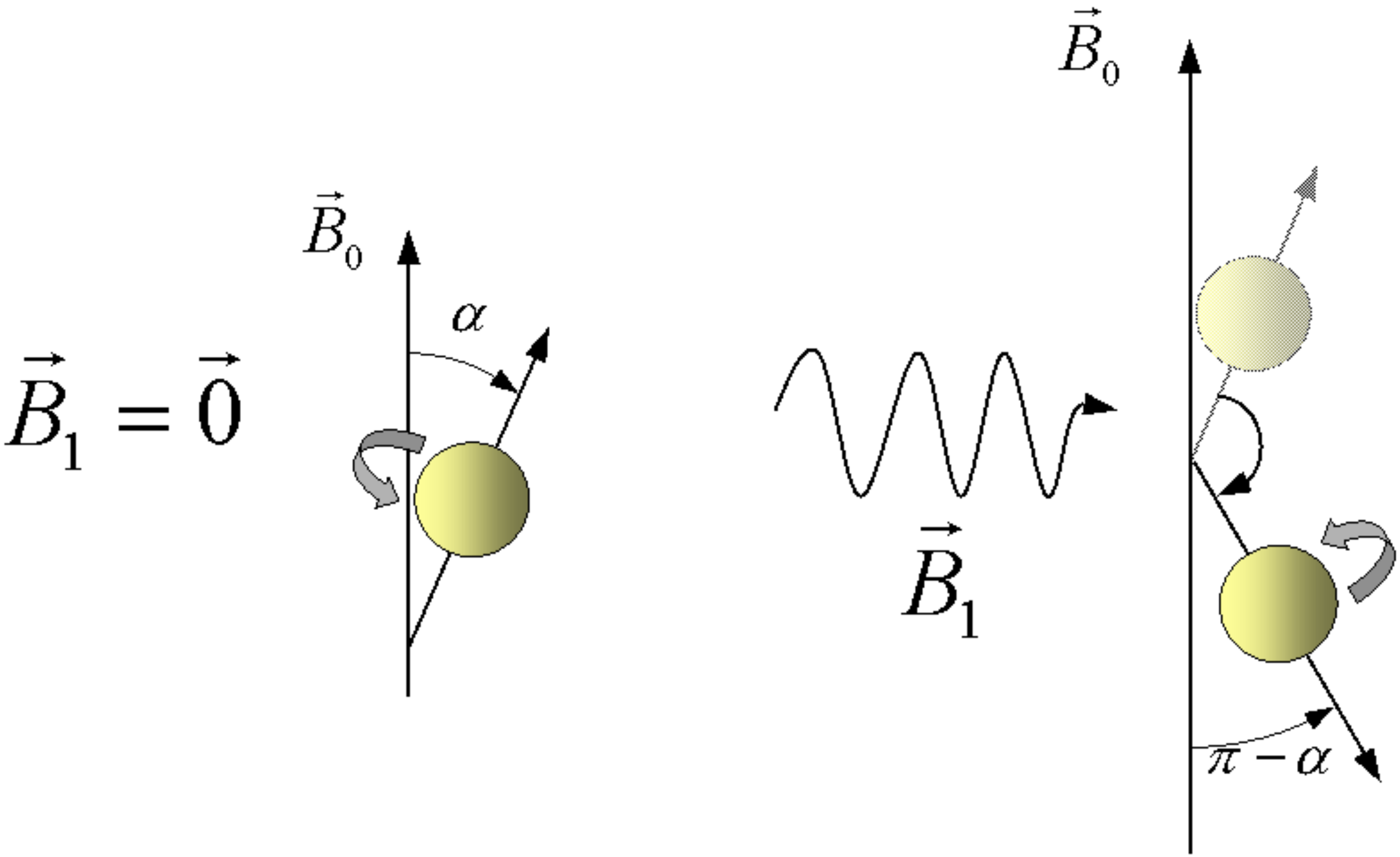
Electro-magnetic field at Larmor's frequency

$$\omega_L = \gamma \, B_0$$

Hydrogen protons enter into resonance

Flip of the macroscopic momentum M

Magnetic Resonance / excitation



Magnetic Resonance / relaxation

Return to equilibrium / B_0: time constant T_1

$$\frac{dM_z}{dt} = \gamma\left(\vec{M} \times \vec{B}\right)_z - \frac{M_z}{T_1}$$

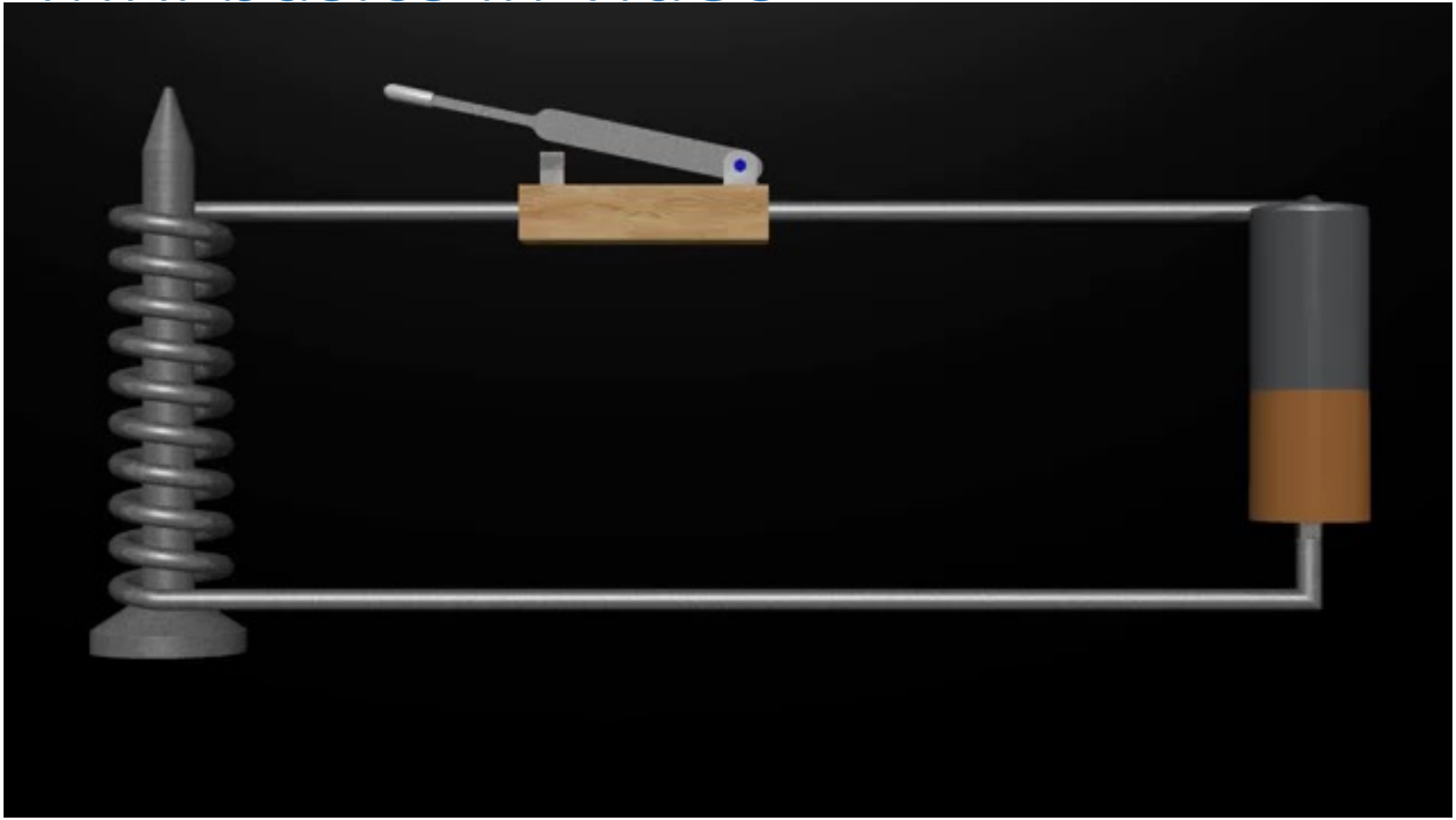
Spin dephasing: Time constant T_2

$$\frac{dM_{x,y}}{dt} = \gamma\left(\vec{M} \times \vec{B}\right)_{x,y} - \frac{M_{x,y}}{T_2}$$

Magnetic Resonance / relaxation

TISSUE	T1 (ms)		T2(ms)
	0.5 T	1.5 T	
Muscle	550	870	45
Heart	580	865	55
Liver	325	490	50
Kidney	495	650	60
Spleen	495	650	58
Fat	215	262	85
Brain, grey matter	655	920	100
Brain, white matter	540	785	90

MRI basics in video

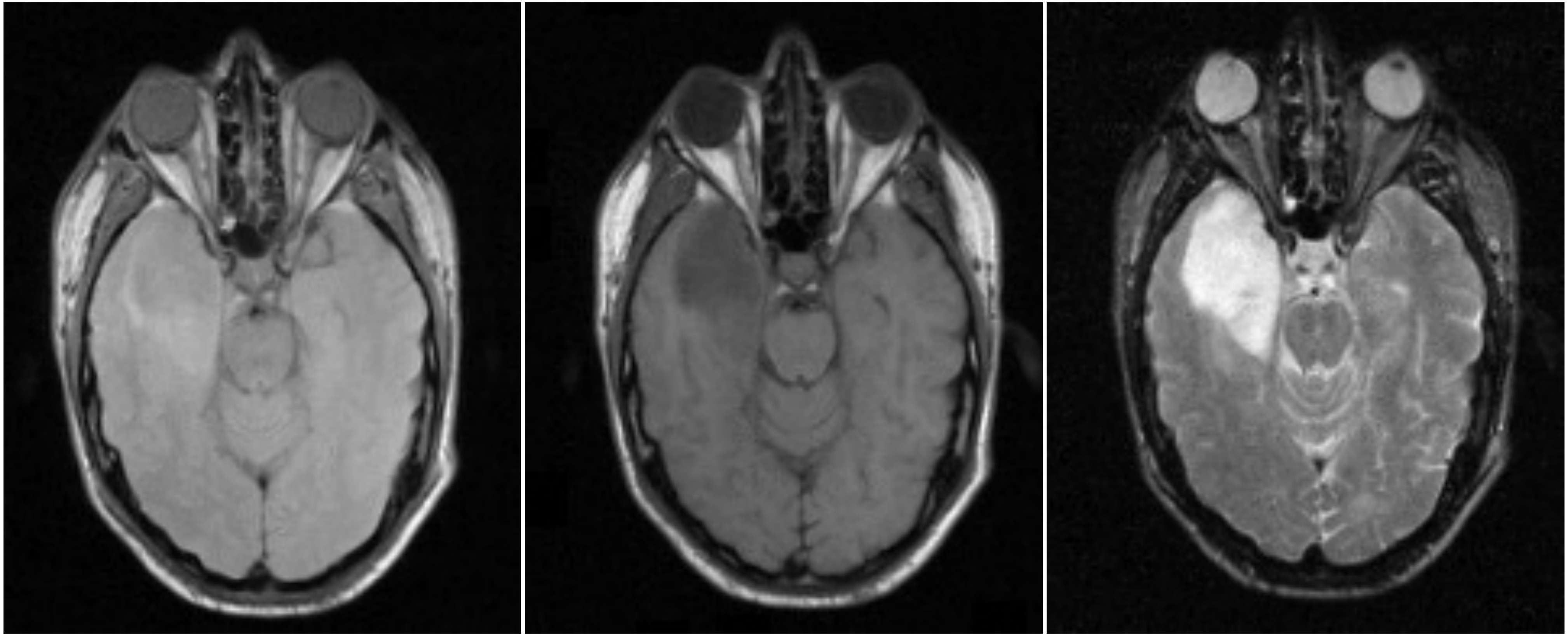


https://www.youtube.com/watch?v=djAxjtN_7VE

MRI / frequency selection

- X encoding by frequency
- Y encoding by phase
- Several measures are necessary

Anatomical MRI



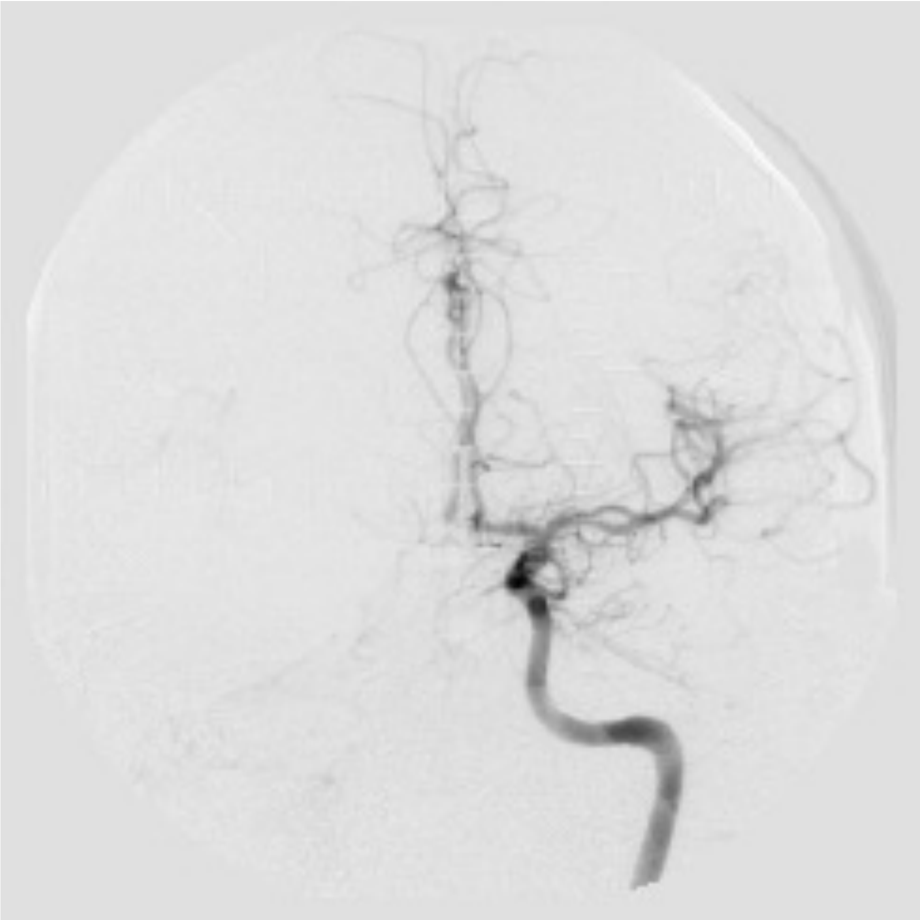
Proton density T_1 T_2

Angiographic MRI

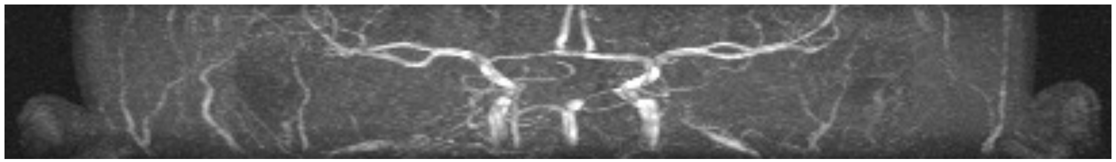
INFLOW
Phases

Maximum intensity projection (MIP)

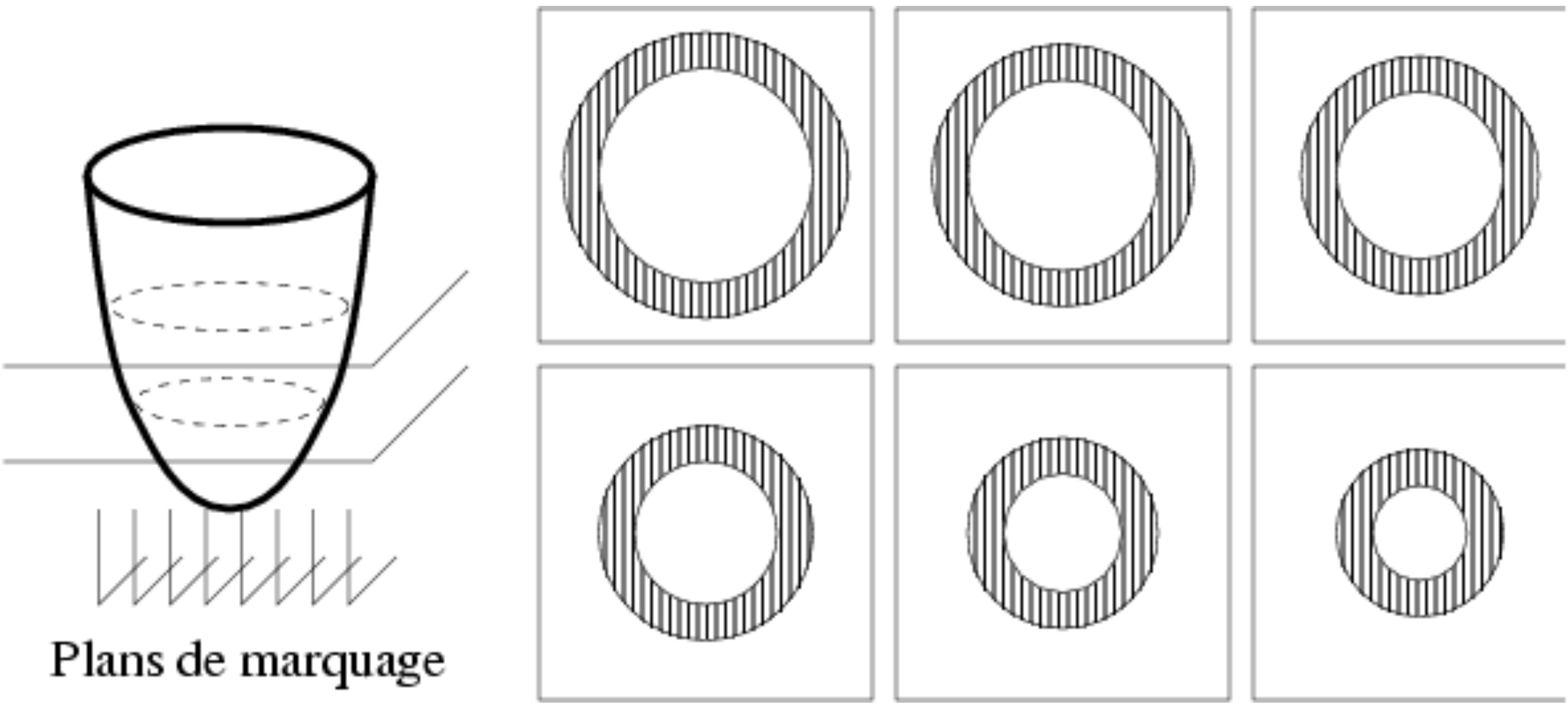
Angiographic MRI



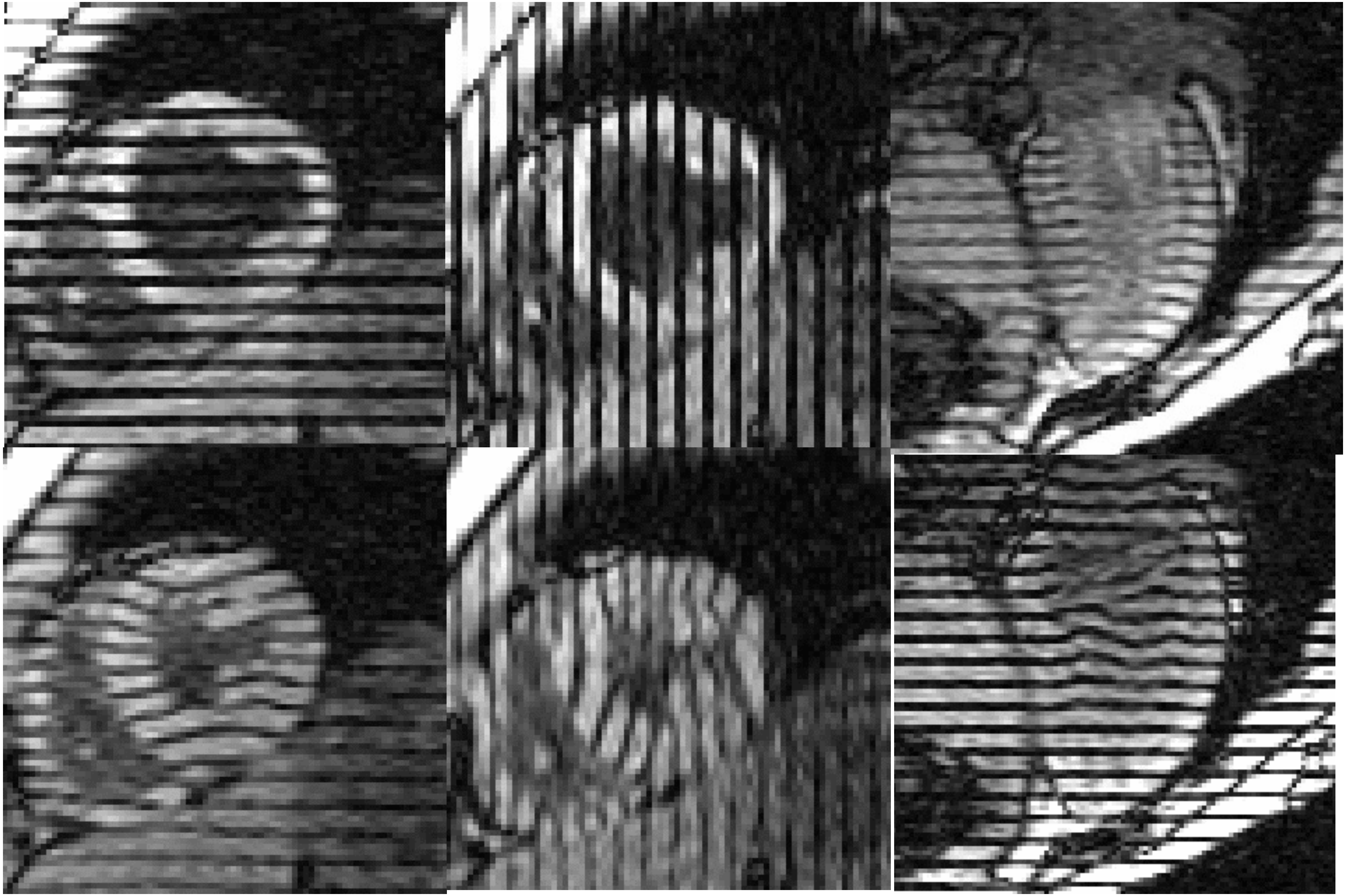
X-Scan / radiology
Selective injection of a contrast agent in one artery



Tagged MRI



Tagged MRI



Avantages of MRI

- Non-Invasive: MRI does not depend on potentially harmful ionizing radiation, as do standard x-ray and CT scans.

- MRI scans are not obstructed by bone, gas, or body waste, which can hinder other imaging techniques

- Can see through bone (the skull) and deliver high quality pictures of the brain's delicate soft tissue structures

- Images of organs and soft tissues

Drawbacks of MRI

- Pacemakers not allowed
- Not suitable for claustrophobic persons
- Tremendous amount of noise during a scan
- MRI scans require patients to hold very still for extended periods of time. MRI exams can range in length from 20 minutes to 90 minutes or more.
- Orthopedic hardware (screws, plates, artificial joints) in the area of a scan can cause severe artifacts
- High cost

Medical Imaging Modalities

0.1Introduction

0.2 Tomography

0.3 Nuclear medicine

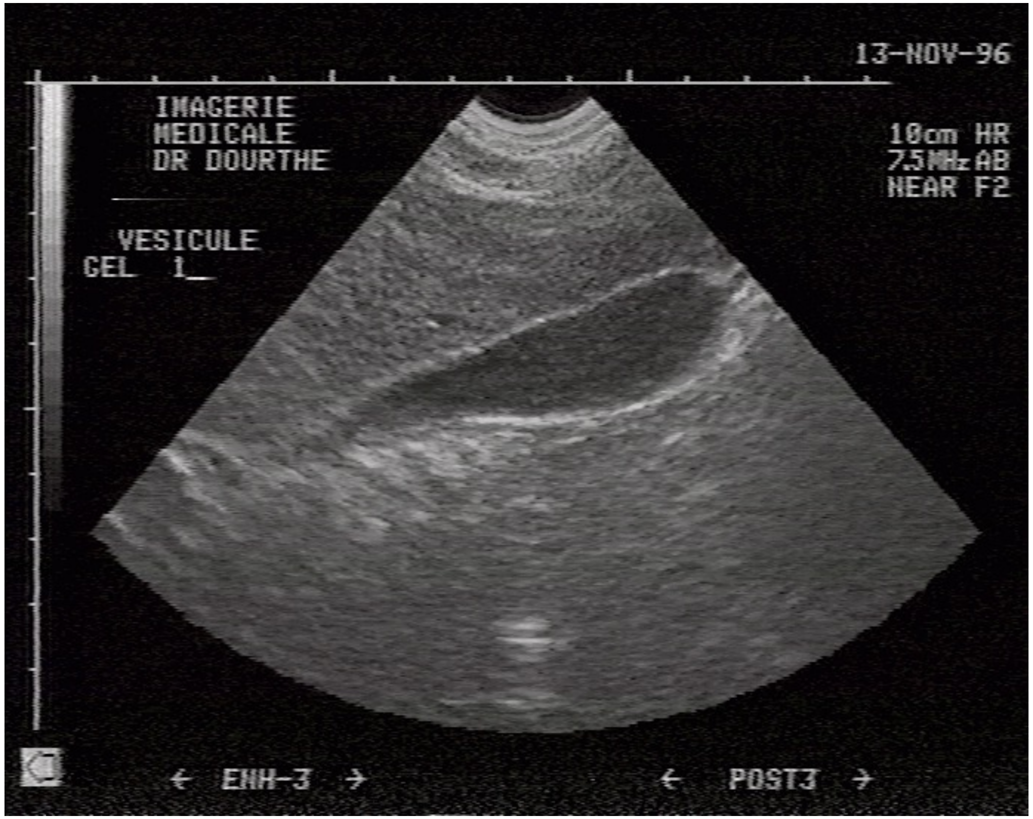
0.4 MRI

➡ 0.5 Echography

Echography

- Local variation of acoustic impedance

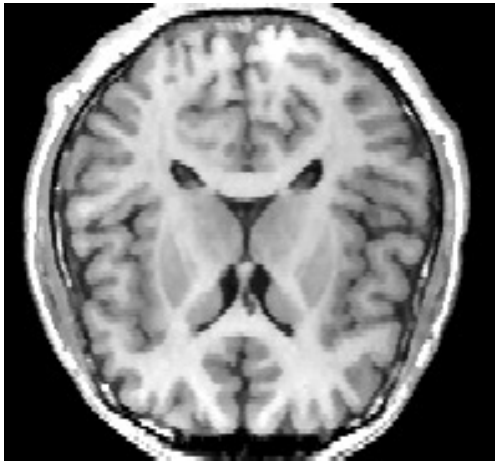
Echography



Gall Blader

Summary of Main Medical Imaging Modalities

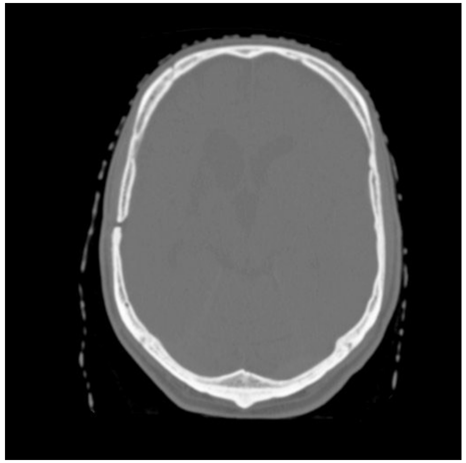
MRI



Measure

Density and structure of Protons

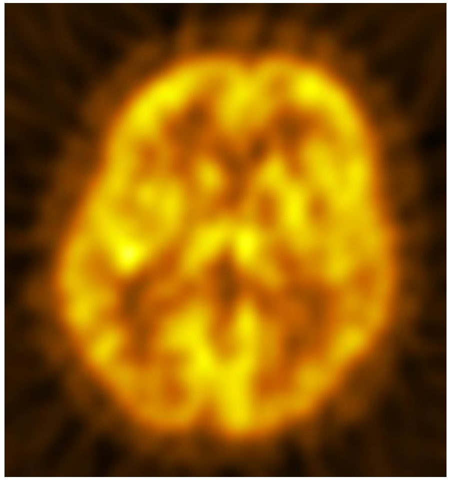
CT-Scanner



Measure

Density of X-Ray absorption

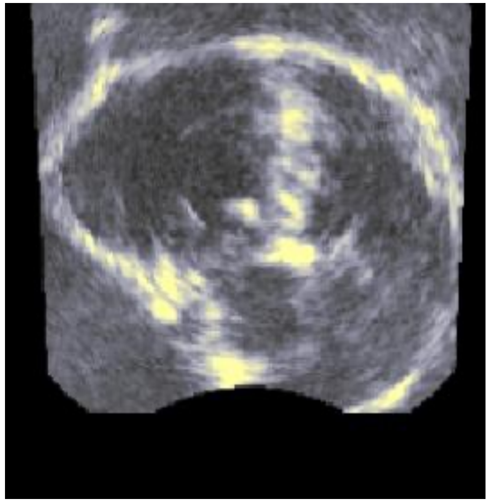
Nuclear Imaging



Measure

Density of injected isotopes

Ultrasound

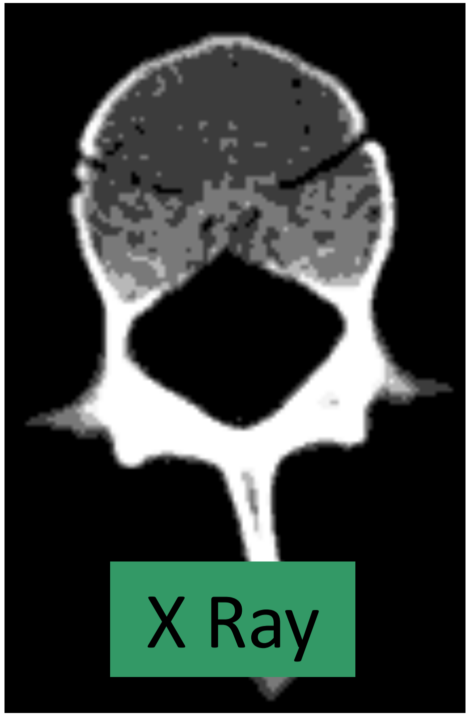


Measure

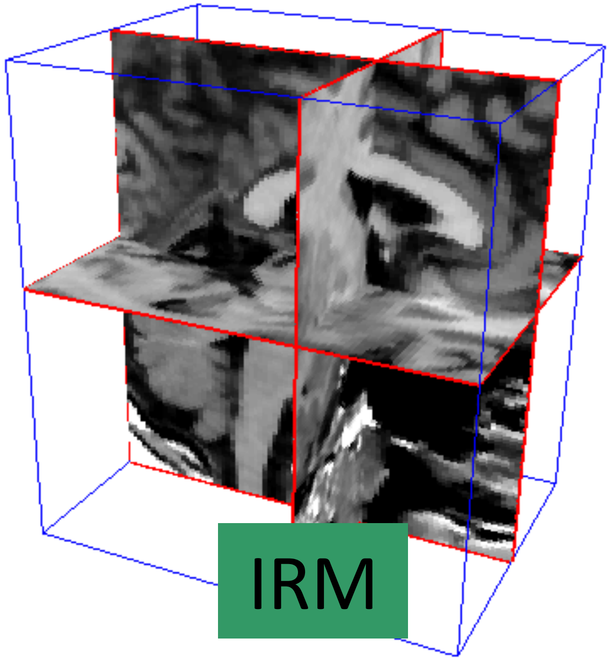
Variations of Acoustic Impedance

Medical Imaging Classification (1)

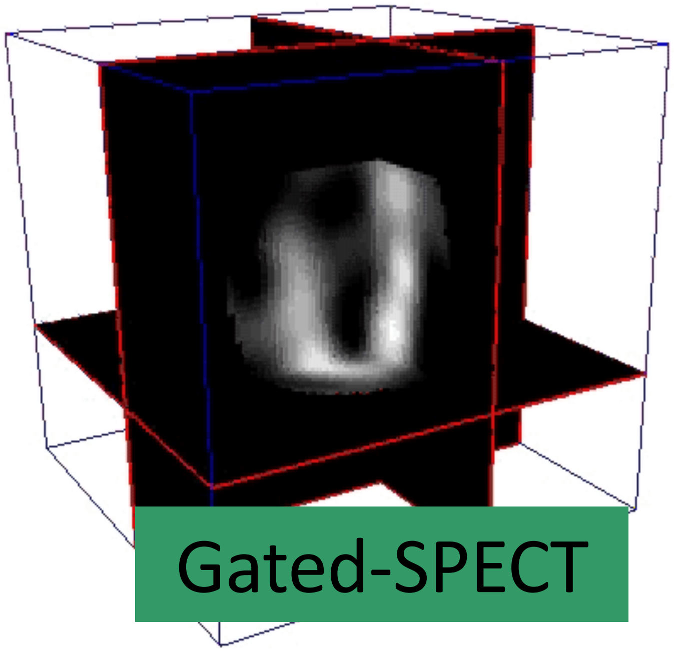
- Dimensionality



2D



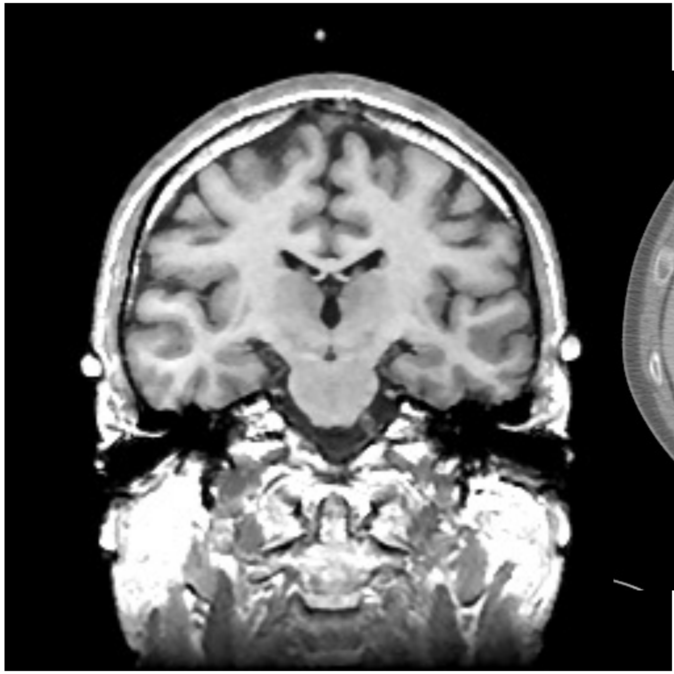
3D



4D (3D+T)

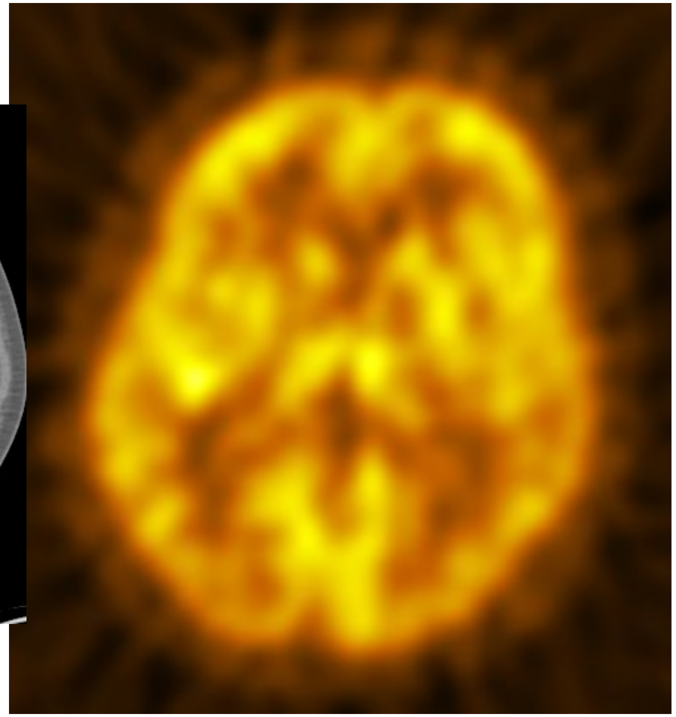
Medical Imaging Classification (2)

- Anatomical vs functional Imagery



MRI

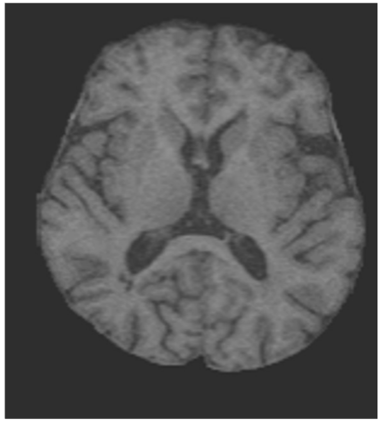
CT with
contrast agent

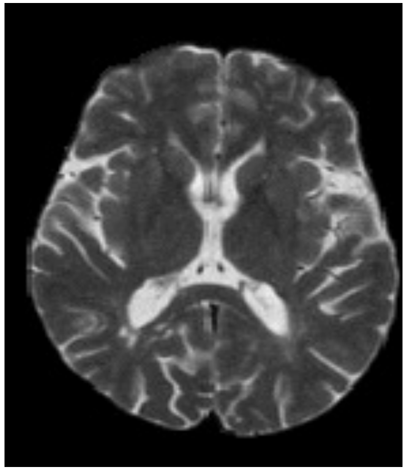


PET scan

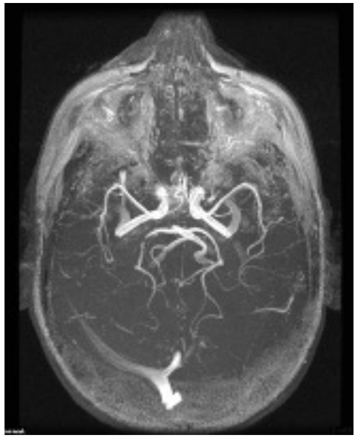
Multiparametric Images

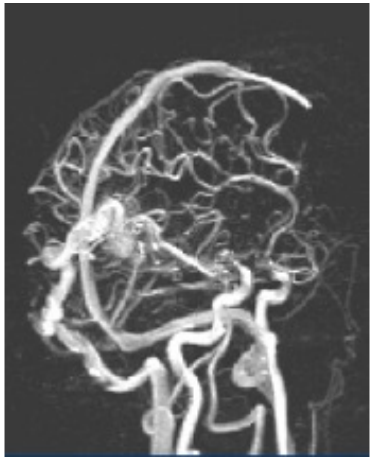
MRI T1, T2



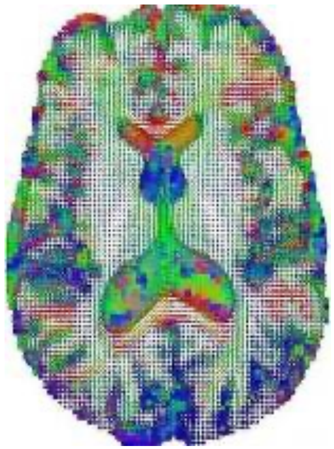


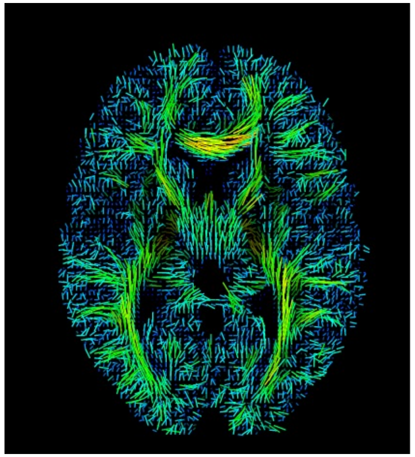
Angio MRI



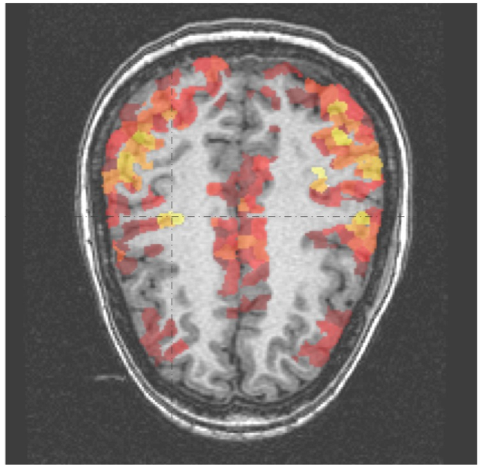


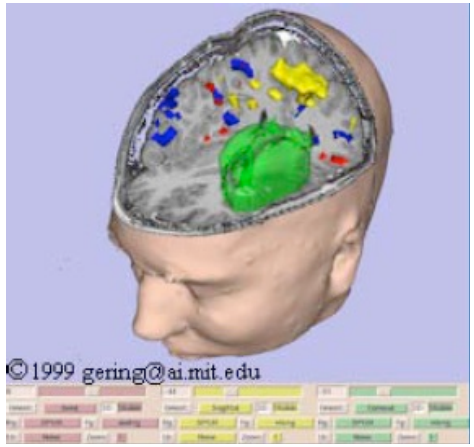
DTI





fMRI





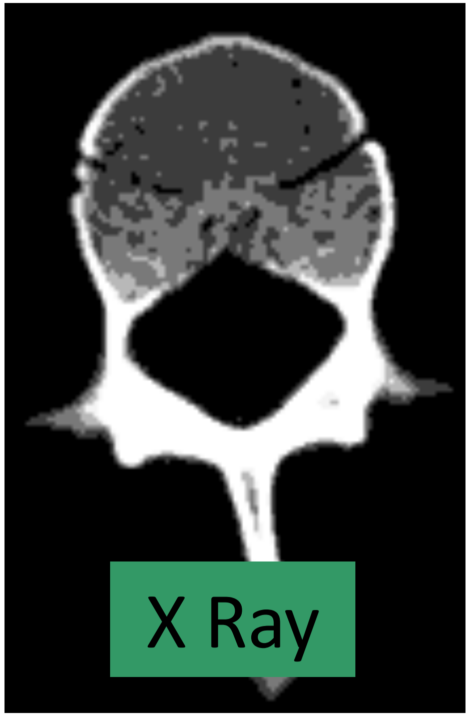
1. Medical Image Representation & Visualization

➡ 1.1 Image representation : discrete or continuous

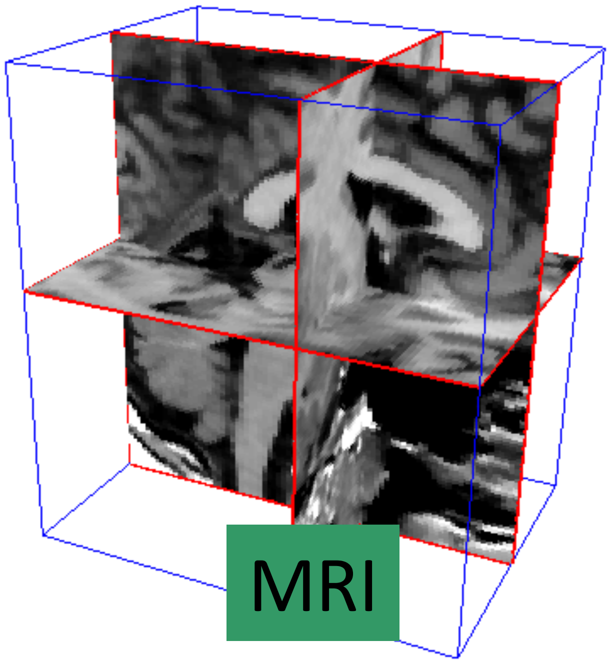
1.2 Image Visualization

Medical Imaging Classification (1)

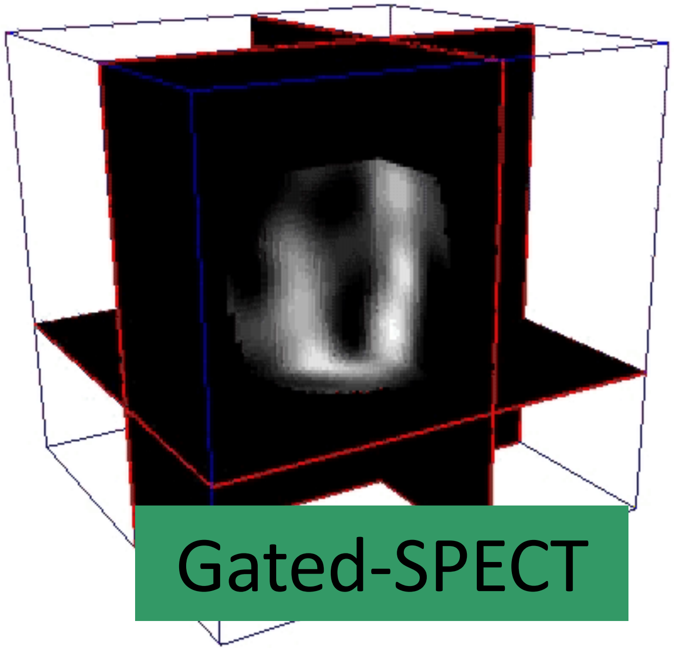
- Dimensionality



2D



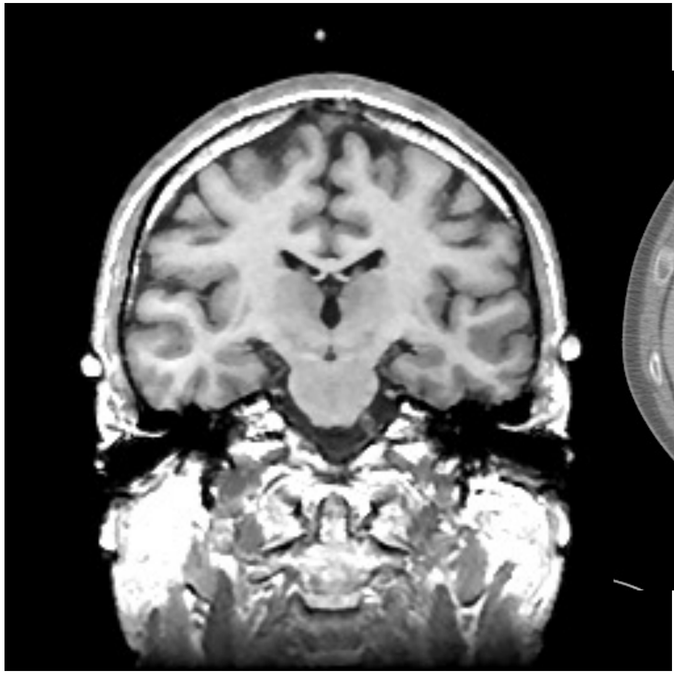
3D



4D (3D+T)

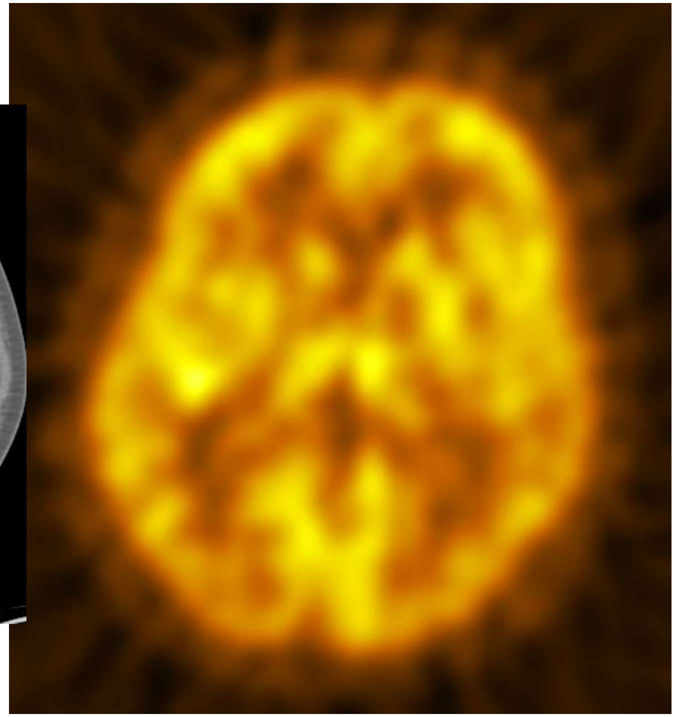
Medical Imaging Classification (2)

- Anatomical vs functional Imagery



MRI

CT with contrast agent



PET scan

Anatomical → Functional

Medical Image Processing
vs
Computer Vision

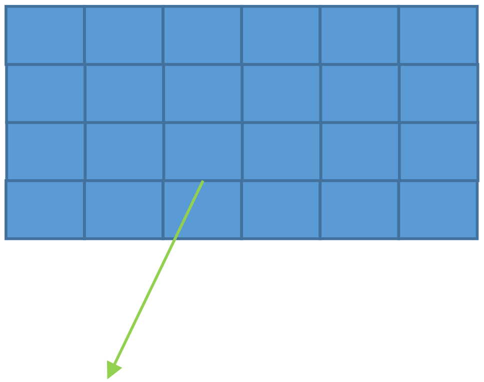
	Computer Vision	Medical Image Processing
	Projective Geometry Occluding Objects Intensity depends on lighting	Complex Image Formation Large Datasets Patient Images
	Easy to acquire Low dimensionality	Cartesian Geometry Statistics Information Intensity links to physics Patient Images

Discrete Image Representation (1)

- Domain is considered as a 2D/3D regular grid

2D Array I

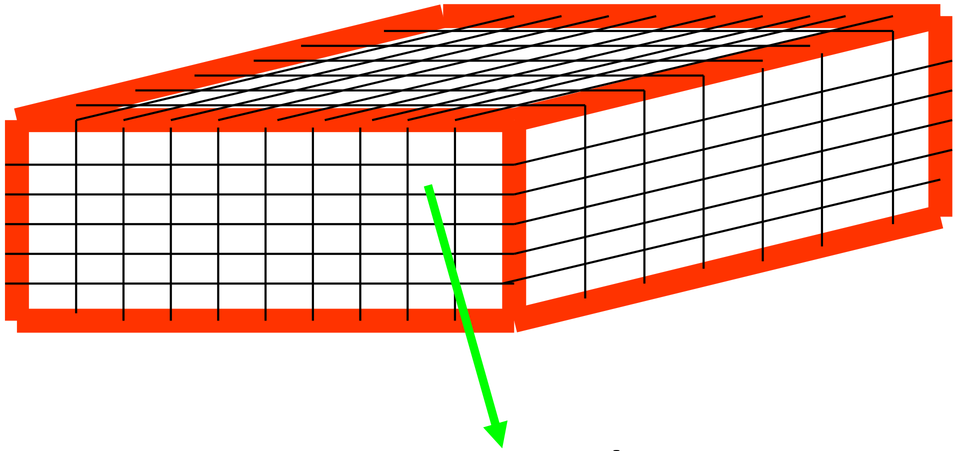
I[col][row]



Pixel=picture element

3D Array I

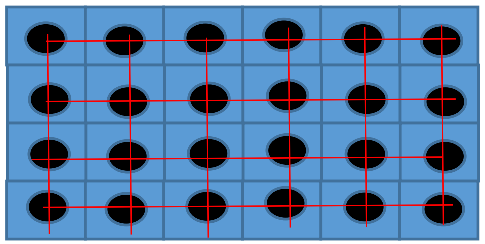
I[plane][col][row]



Voxel=
Volume Element

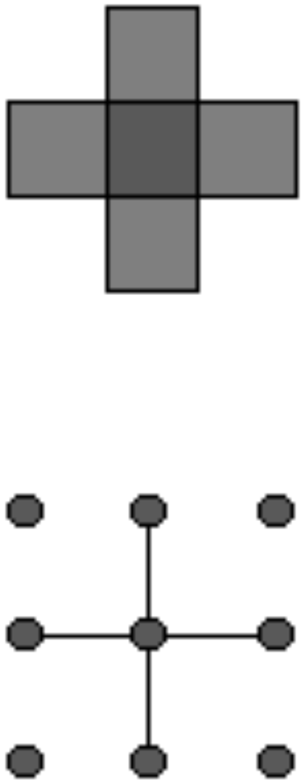
Discrete Image Representation (2)

- Pixel / Voxel values can be :
  - Discrete :
    - Integer : char (MRI), signed short (CT-scan)
    - Labels of structures
  - Continuous :
    - Float / double
- Images can be seen as a graph
  - Nodes are pixel / voxel centers
  - Edges between adjacent elements
  - Grid Duality

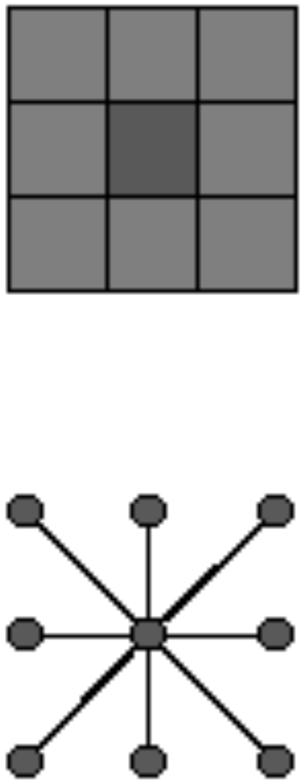


Neighborhood

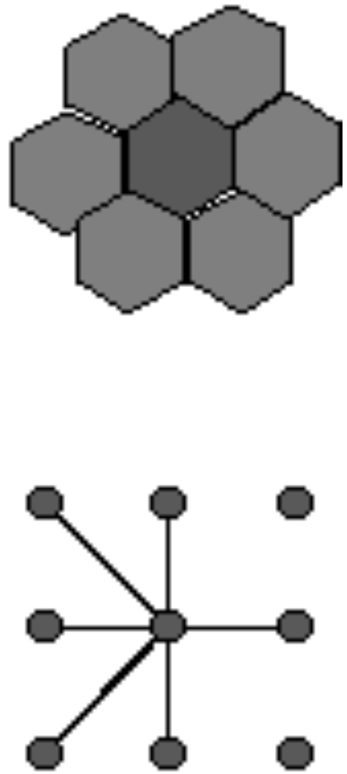
- Different types of neighborhood in 2D



4 -neighborhood



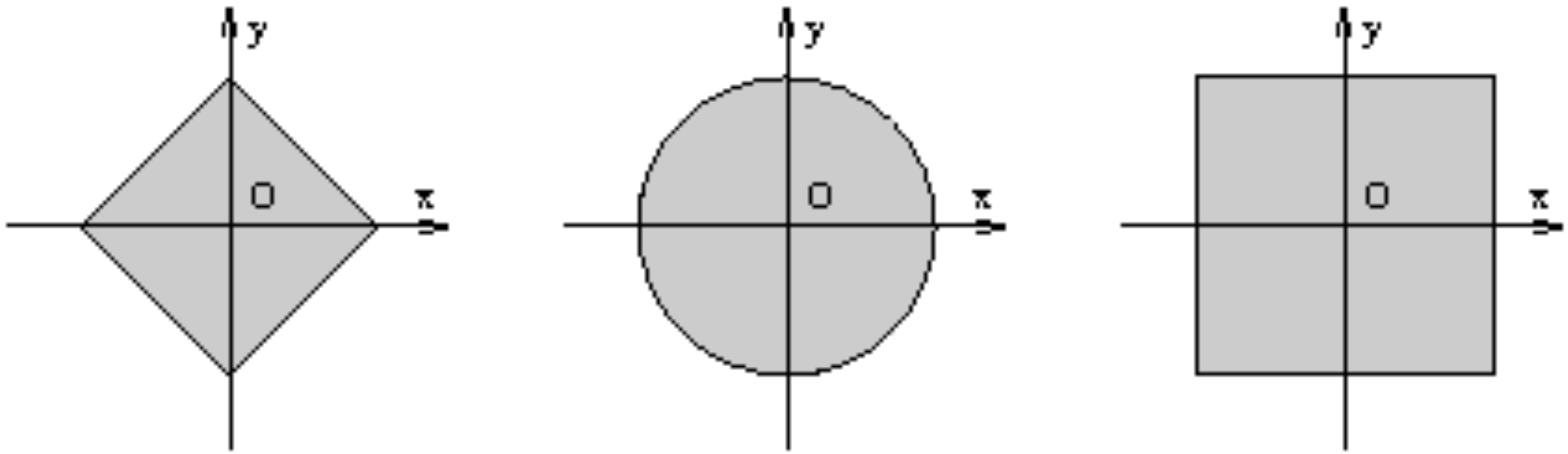
8 -neighborhood



6 -neighborhood

Neighborhood

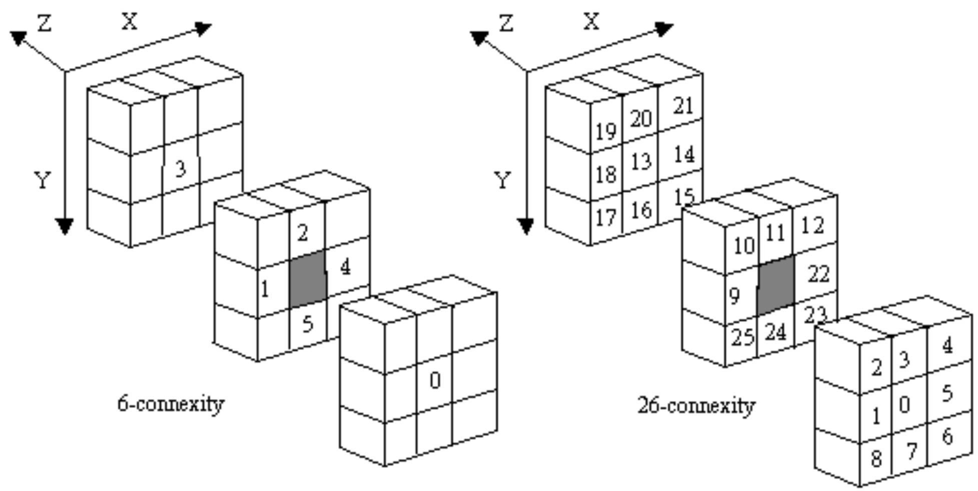
- Some generalizes to higher dimensions
- Corresponds to a choice of metric norm



$$D_1(x,y) = \sum_{i=1}^{n} |y_i - x_i| \qquad D_2(x,y) = \sqrt{\sum_{i=1}^{n} (y_i - x_i)^2} \qquad D_\infty(x,y) = \max_{i=1\ldots n} |y_i - x_i|$$

Neighborhood

- 3 types of neighborhood for a 3D image :
  - 6-neighborhood : adjacency through faces
  - 18-neighborhood : adjacency through faces and edges
  - 26-neighborhood : adjacency through faces and edges and vertices



Continuous Image representation

- Image seen as 2D or 3D Fields :
  $I(x), x \in \mathbb{R}^n, n = 2,3$
- Requires to define interpolation functions

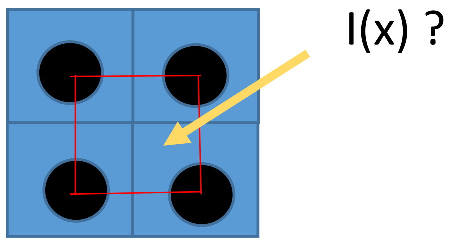
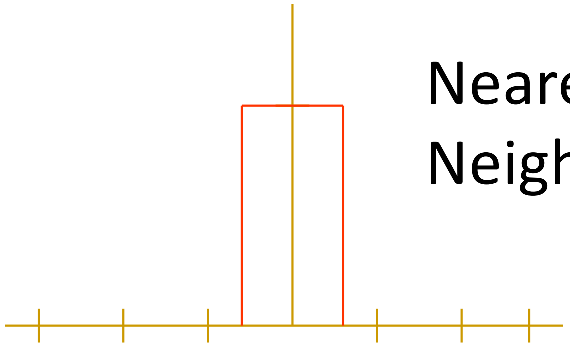


Image Domain / Image Value	**Discrete**	**Continuous**
Discrete	Array of Int	~~Field of Integer~~
Continuous	Array of Float	Field of Float

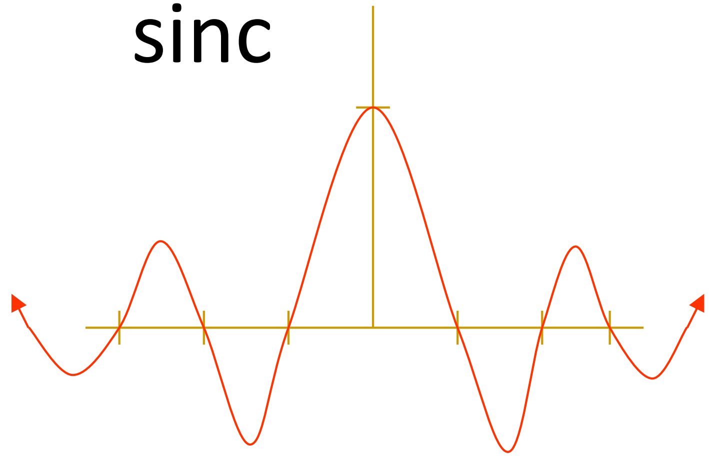
1D Interpolation functions

Nearest Neighbor



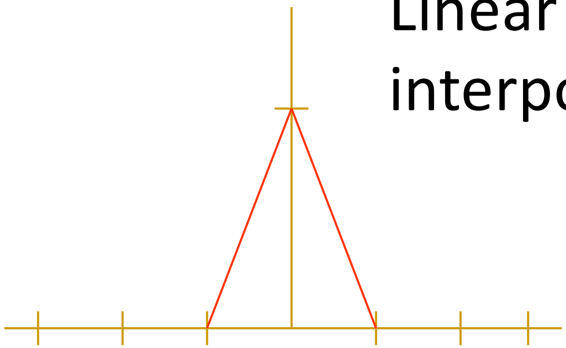
Discontinuous

sinc



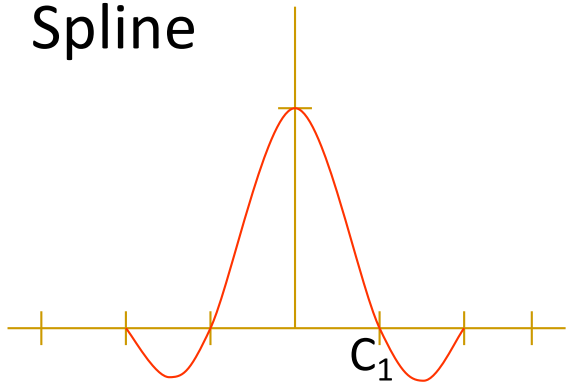
C_{00} continuity

Linear interpolation



C_0 continuity

Spline

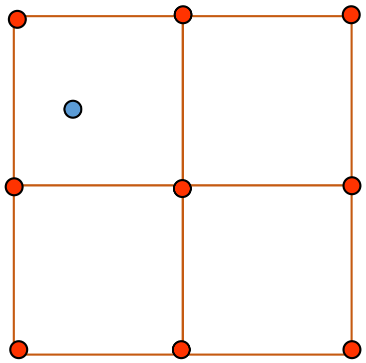


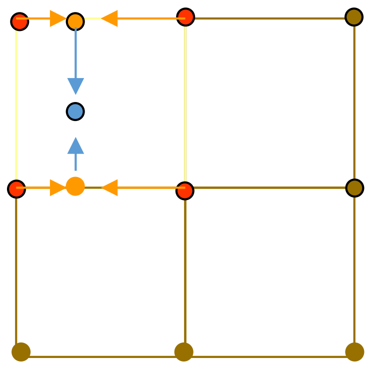
C_1 continuity

Source : Joe Michael Kniss – Direct Volume Rendering

Bilinear Interpolation (2D Field)

- Bilinear Interpolation : 3 linear interpolations



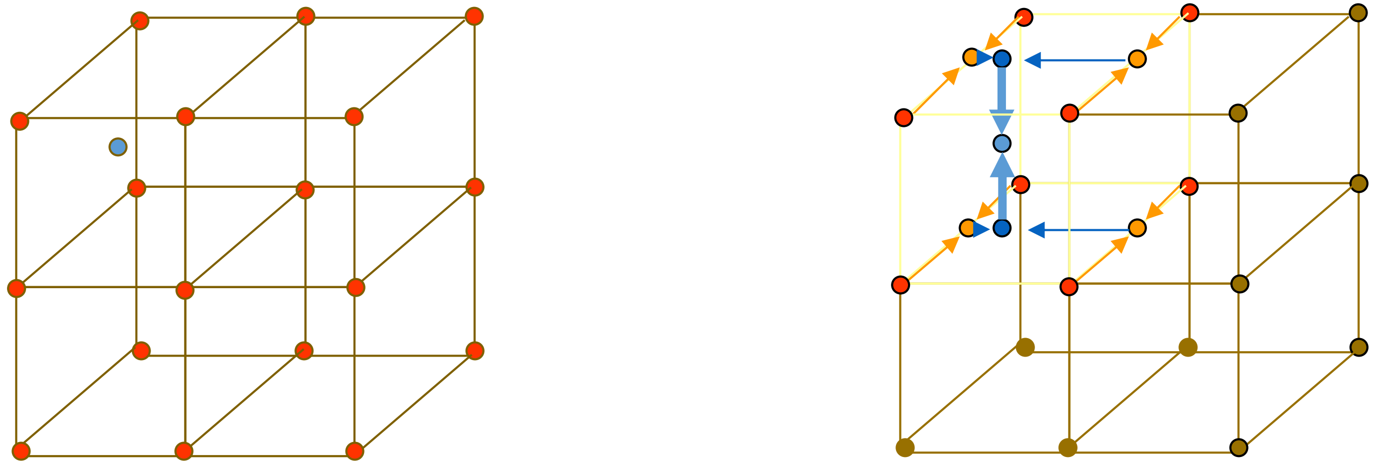


$$I(u,v) = (1-u)(1-v)I_{i,j} + u\,v\,I_{i+1,j+1} + (1-u)v\,I_{i,j+1} + u\,(1-v)I_{i+1,j}$$

Source : Joe Michael Kniss – Direct Volume Rendering

Trilinear Interpolation (3D Field)

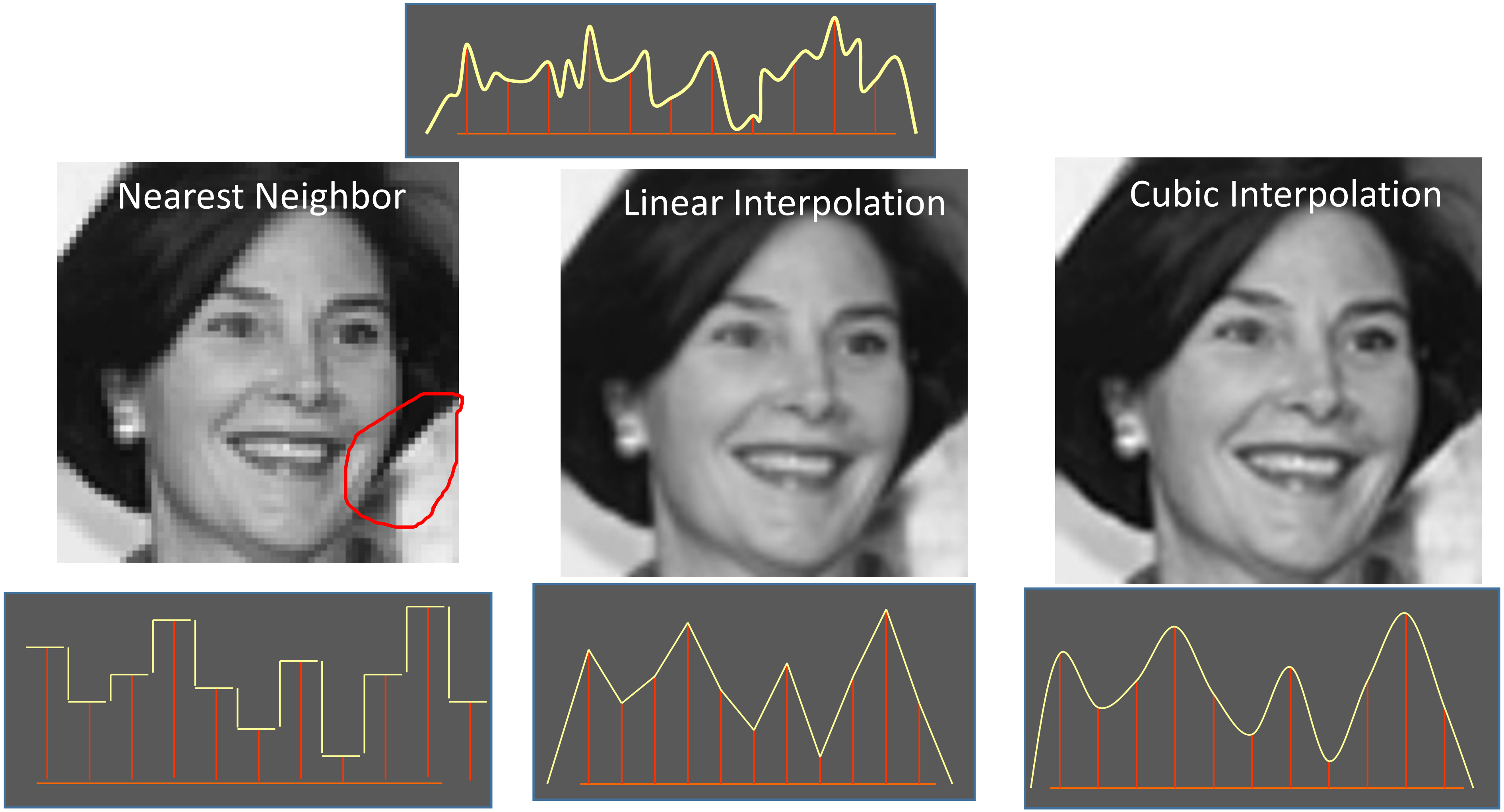
- 7 linear interpolations



$$I(u,v,w) = (1-u)(1-v)(1-w)I_{i,j,k} + u\,v\,w\,I_{i+1,j+1,k+1} +$$
$$(1-u)v\,w\,I_{i,j+1,k+1} + u\,(1-v)w\,I_{i+1,j,k+1} +$$
$$(1-u)v\,(1-w)I_{i,j+1,k} + u\,(1-v)(1-w)I_{i+1,j,k} +$$
$$u\,v\,(1-w)\,I_{i+1,j+1,k} + (1-u)\,(1-v)w\,I_{i,j,k+1}$$

Source : Joe Michael Kniss – Direct Volume Rendering

Image interpolation



Source : Joe Michael Kniss – Direct Volume Rendering

Medical Image Format

- Industrial standard :
  - **DICOM** : Digital Imaging and COmmunications in Medicine
  - More a communication standard for interoperability than an image format
- Academic standard :
  - Must support volumetric images, generic voxel format (short, double, array of double), voxel size, metadata
  - ITK based : MHA, MHD
  - NIFTI : Neuroimaging Informatics Technology Initiative

1. Medical Image Representation & Visualization

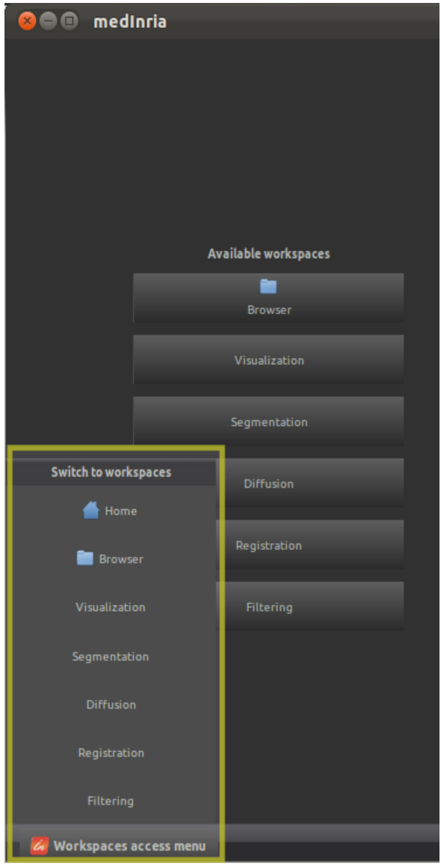
1.1 Image representation : discrete or continuous

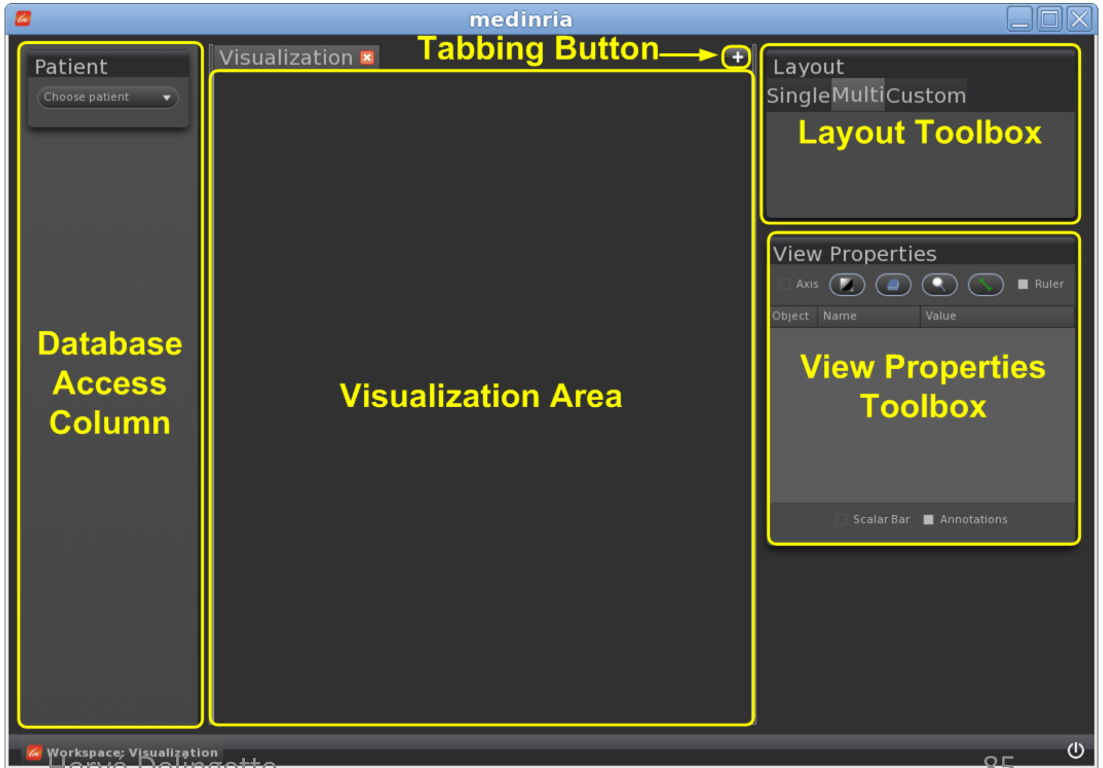
➡ 1.2 Image Visualization

Visualizing Medical Images

- MedInria : https://med.inria.fr
  - Free & Multiplatform, plugin based.

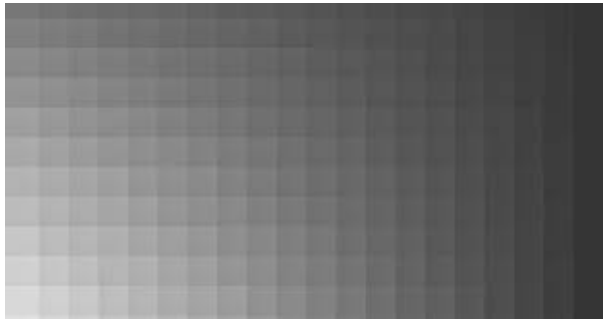
Quick Access Menu



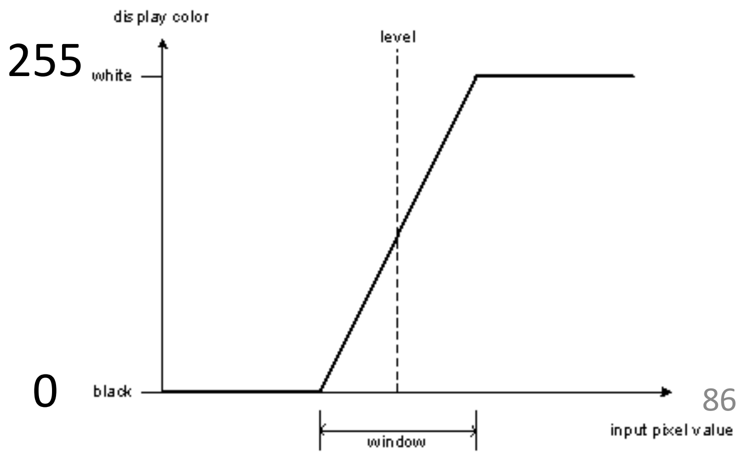


Visualizing Medical Images

- Windowing
  - CT images are coded on 2 bytes (2^{16} values).
  - The human eye can only see a limited (200 ?) number of shades of grey !

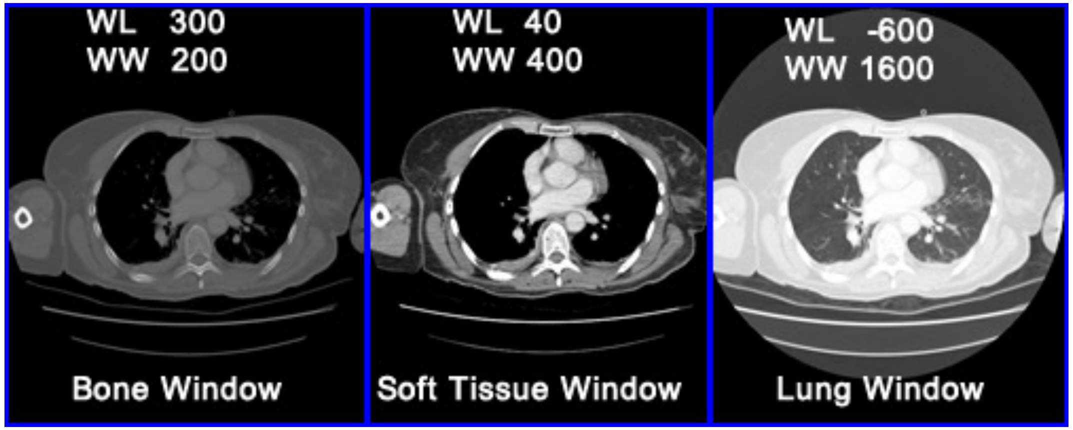


- Need to perform windowing i.e. map a range of intensity values in the [0,255] range

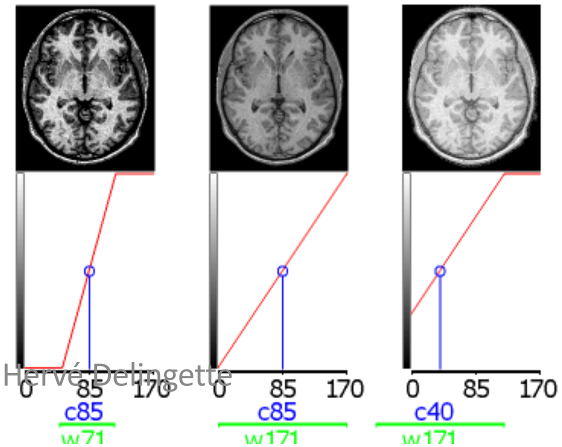


Visualizing Medical Images

- Windowing
  - Predefined windows on CT as Hounsfield units are absolute



Brain MRI Image

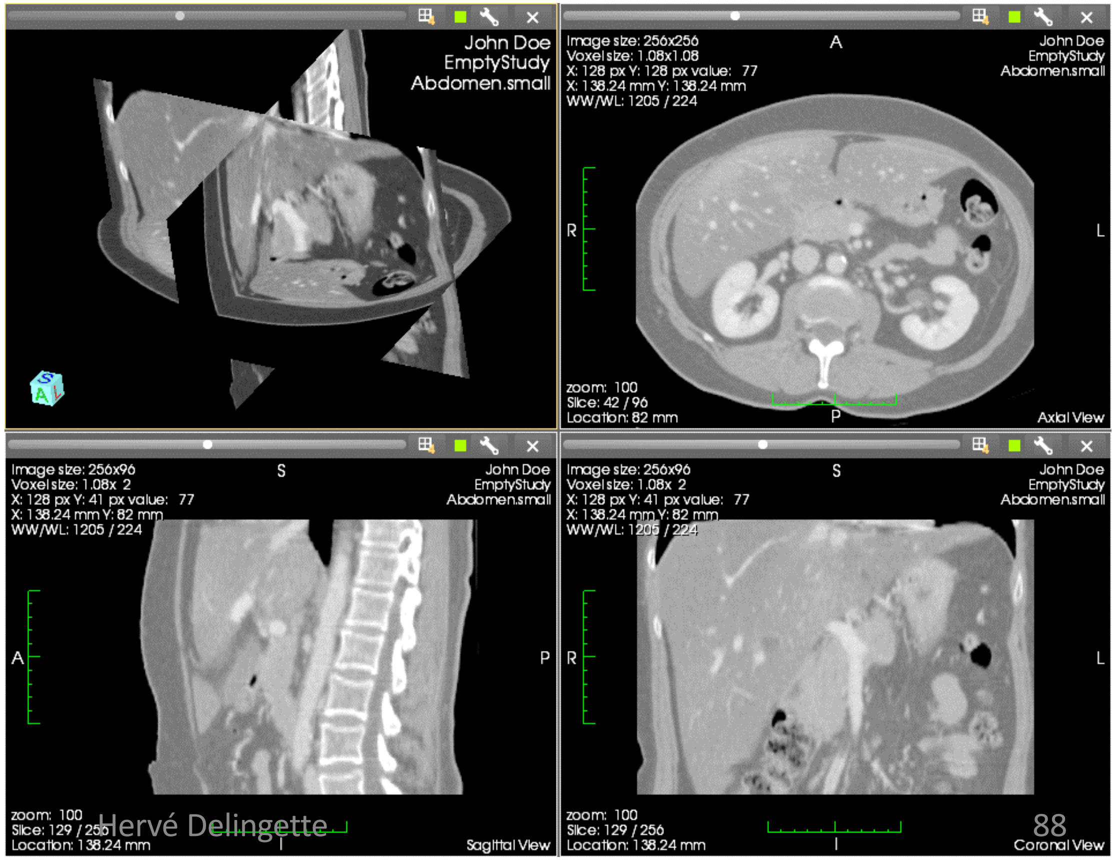


Visualizing Medical Images

- Volumetric Images

How to visualize a 3D image on a 2D screen ?

Multiplanar Reformating



Visualizing Medical Images

- Volumetric Images
  - Radiological Convention to name the 3 orthogonal slices.
  - Axial, coronal and saggital