

Medical Imaging : Image Filtering & Segmentation

Hervé Delingette

Epione Team

Herve.Delingette@inria.fr



Course teachers

- Hervé Delingette



- Xavier Pennec



Inria Research Centers



Inria



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 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

- 0.1 Introduction
- 0.2 Tomography
- 0.3 Nuclear medicine
- 0.4 MRI
- 0.5 Echography

1895



Roentgen

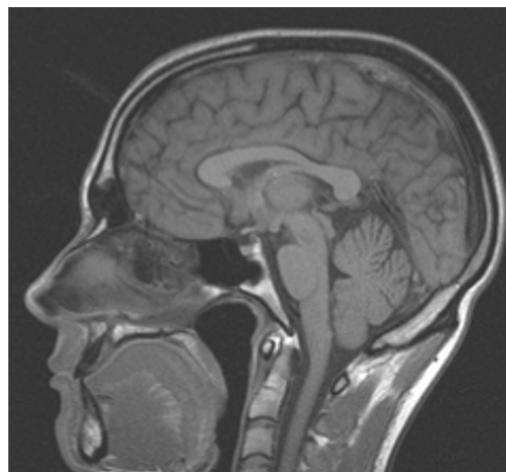
First Nobel prize
in Physics in 1901

Todays's Medical Imaging modalities

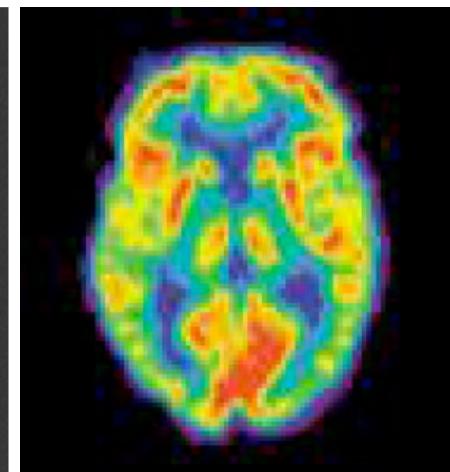
CT Scan



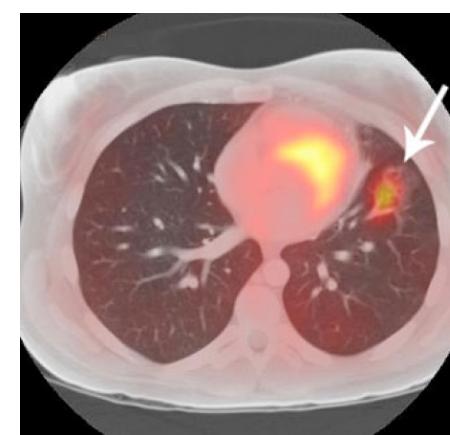
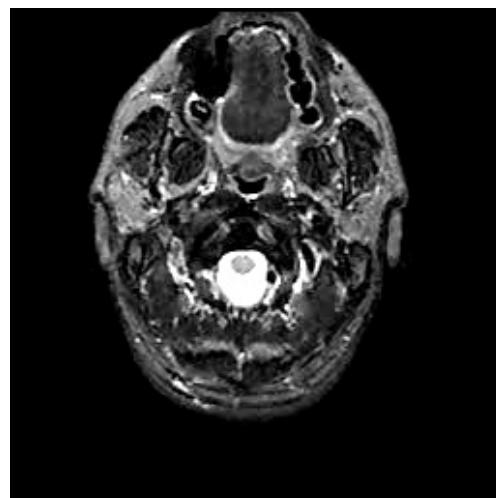
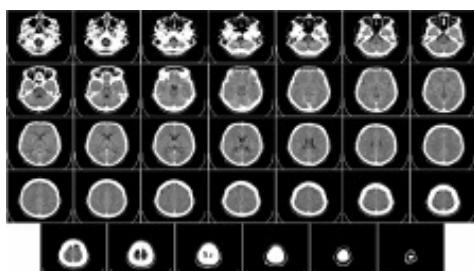
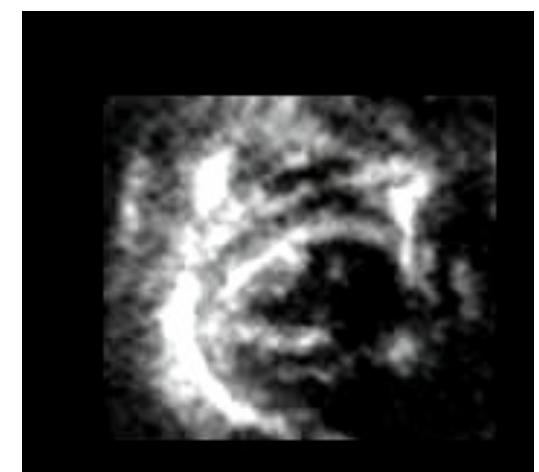
MRI



PET



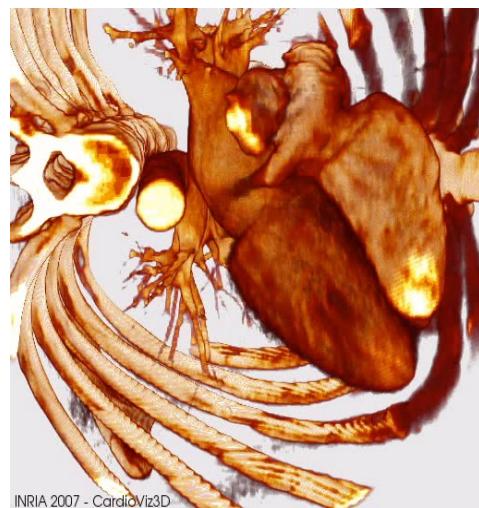
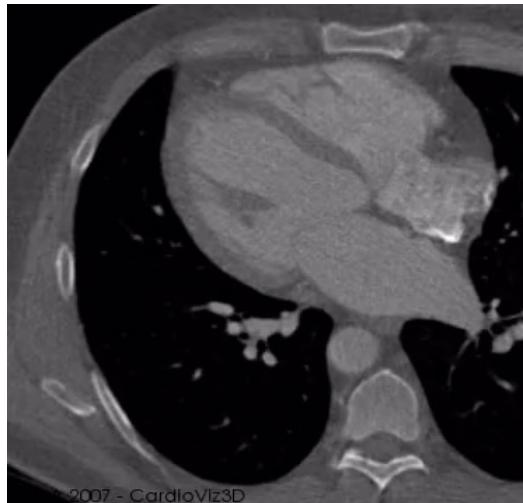
Ultrasound



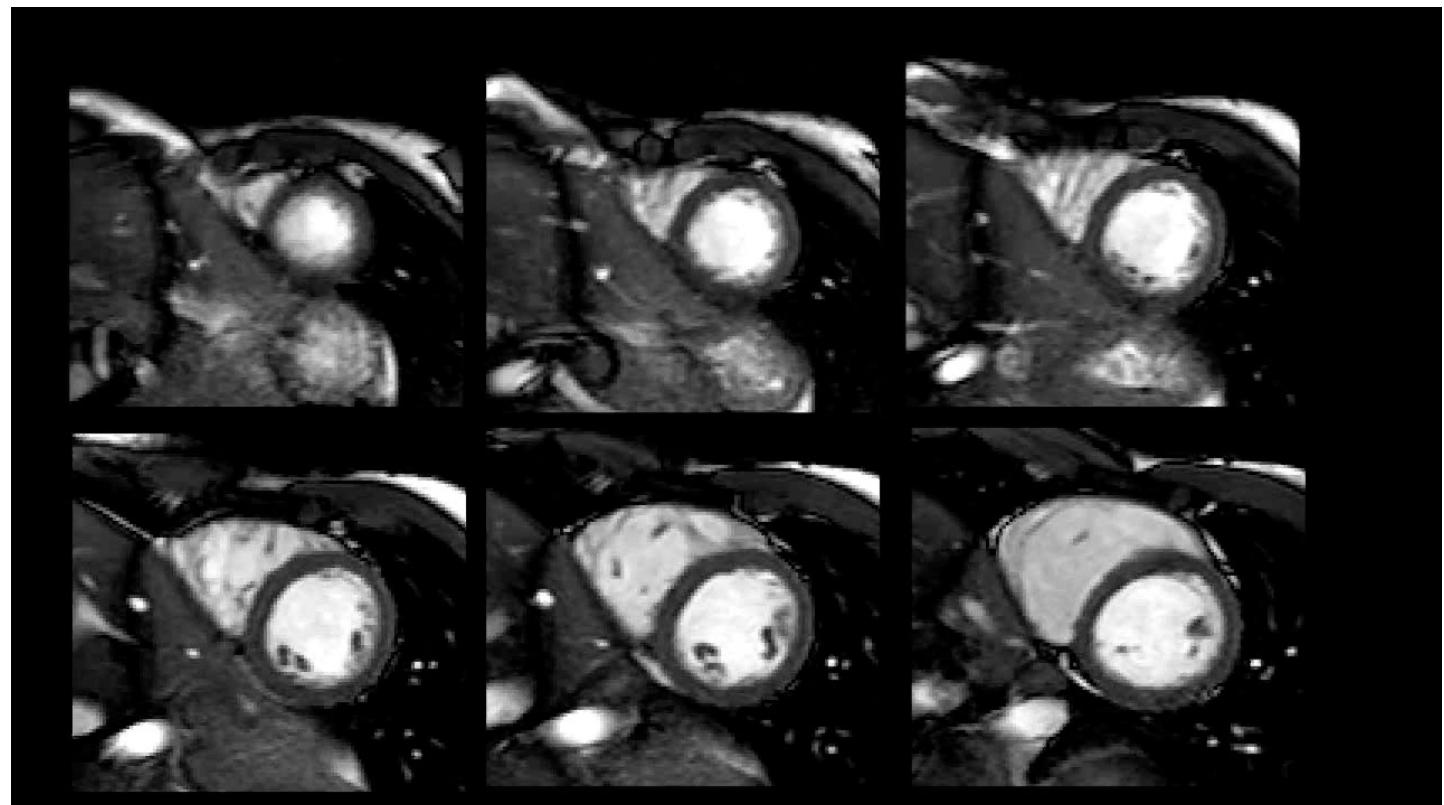
Source :T. Peters

Dynamic Images (4-D)

CT Scan

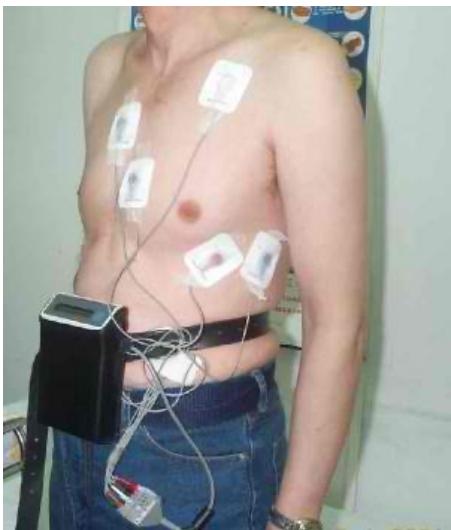


MRI



Bio-signals

ECG



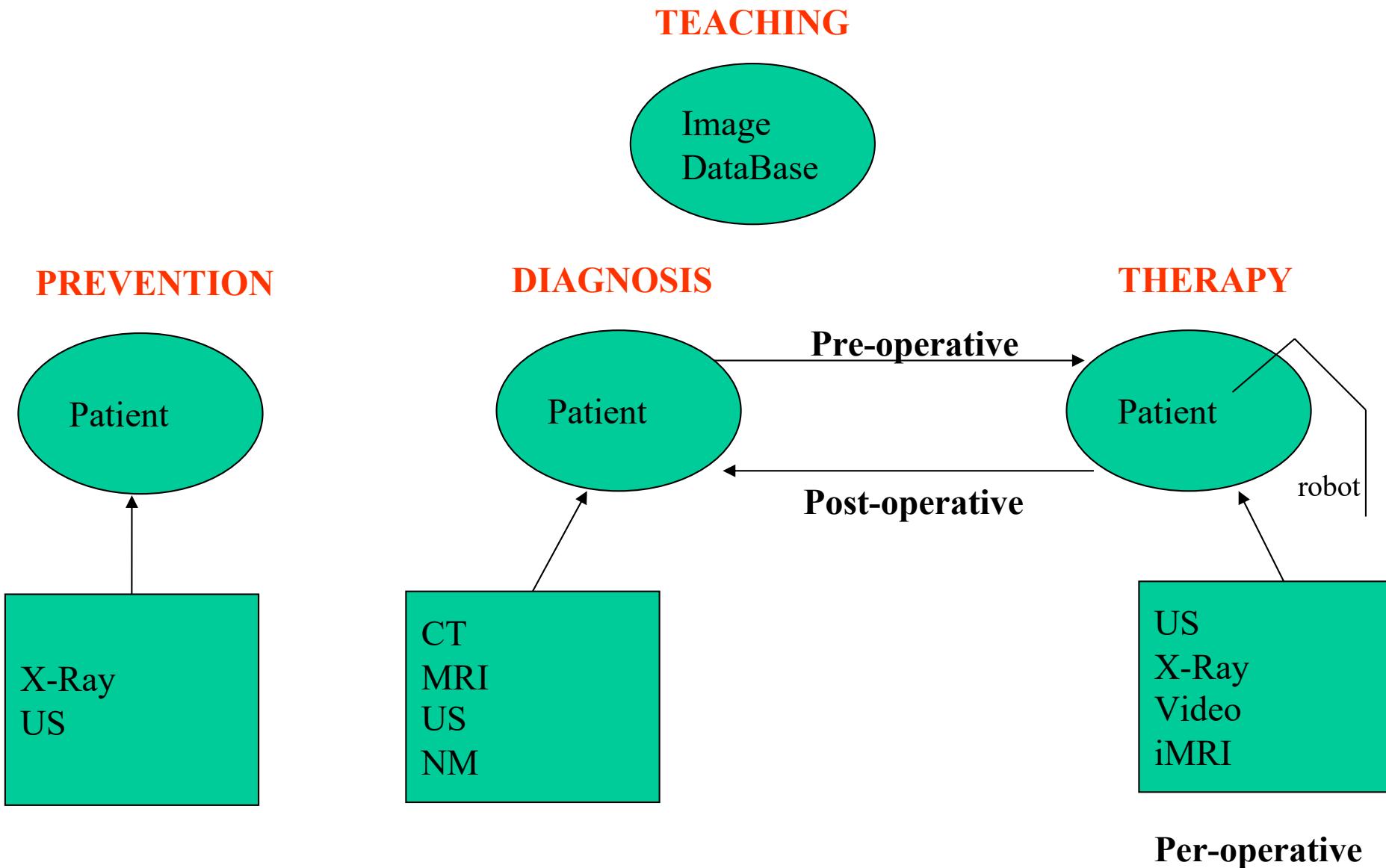
Pressure Sensor



Temperature



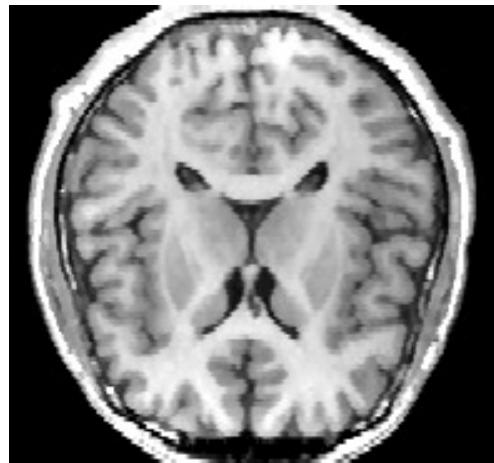
Medical Imaging in clinical practice



Main Medical Image Modalities

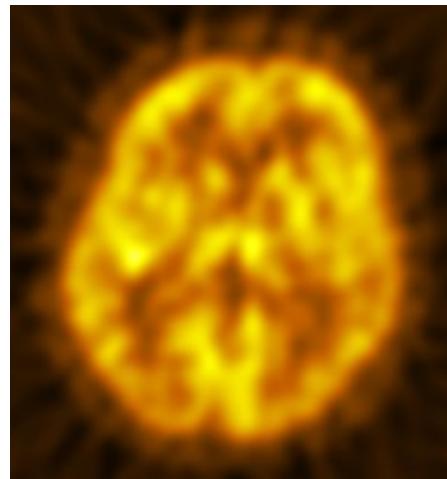
Density and
structure of
protons

MRI



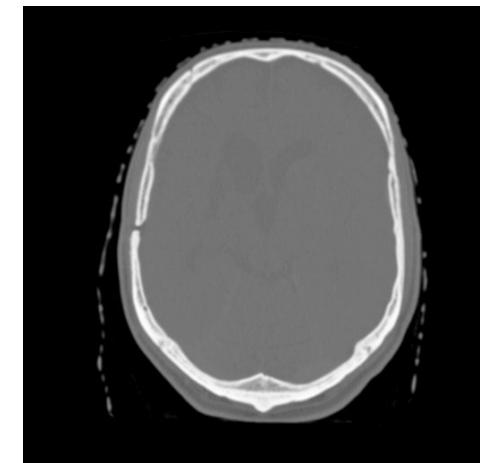
Density of
Radioactive
isotopes

PET / SPECT



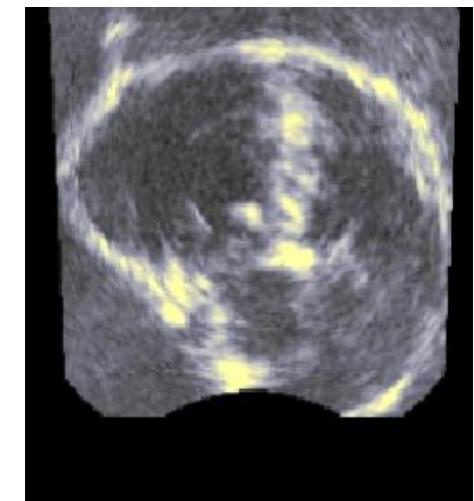
X-ray
absorption
density

X-Scan



Variations of
acoustic
impedance

Ultrasound / echography

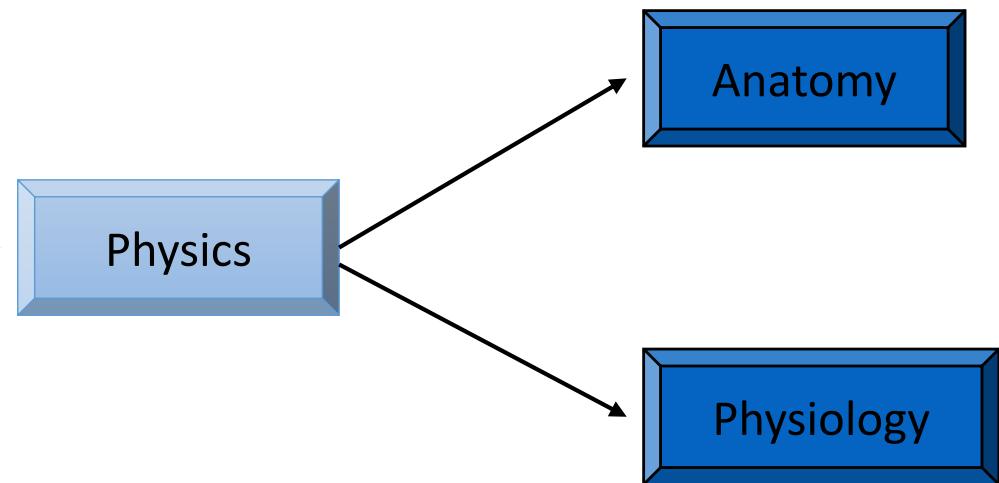
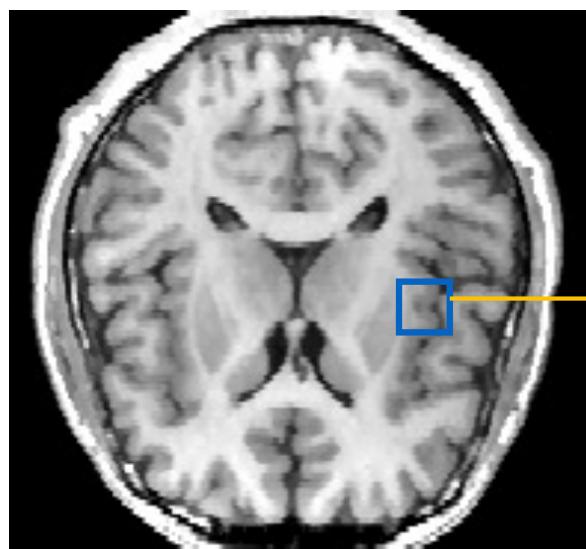


More imaging modalities

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

Characteristics of medical images

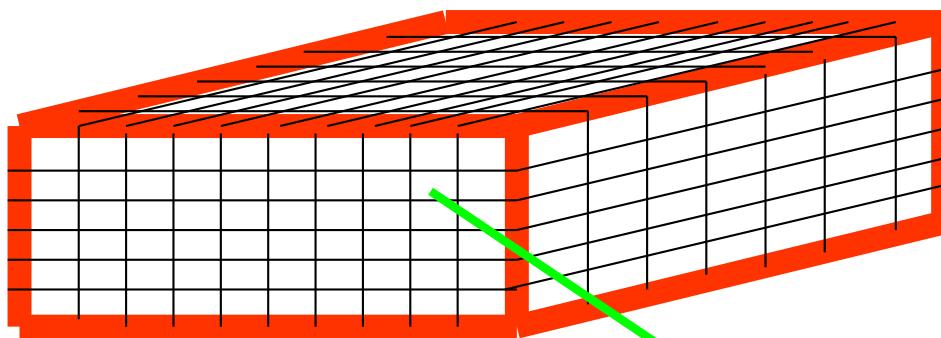
Intensity values are related to physical tissue characteristics which in turn may relate to a physiological phenomenon



Volumetric medical images

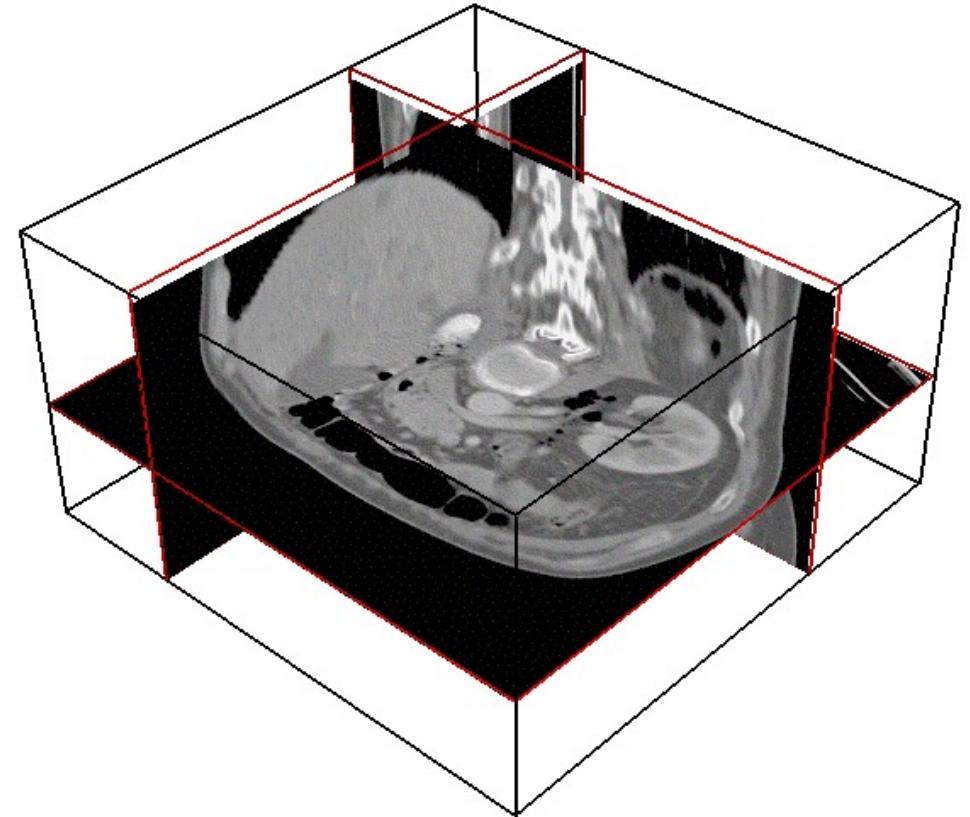
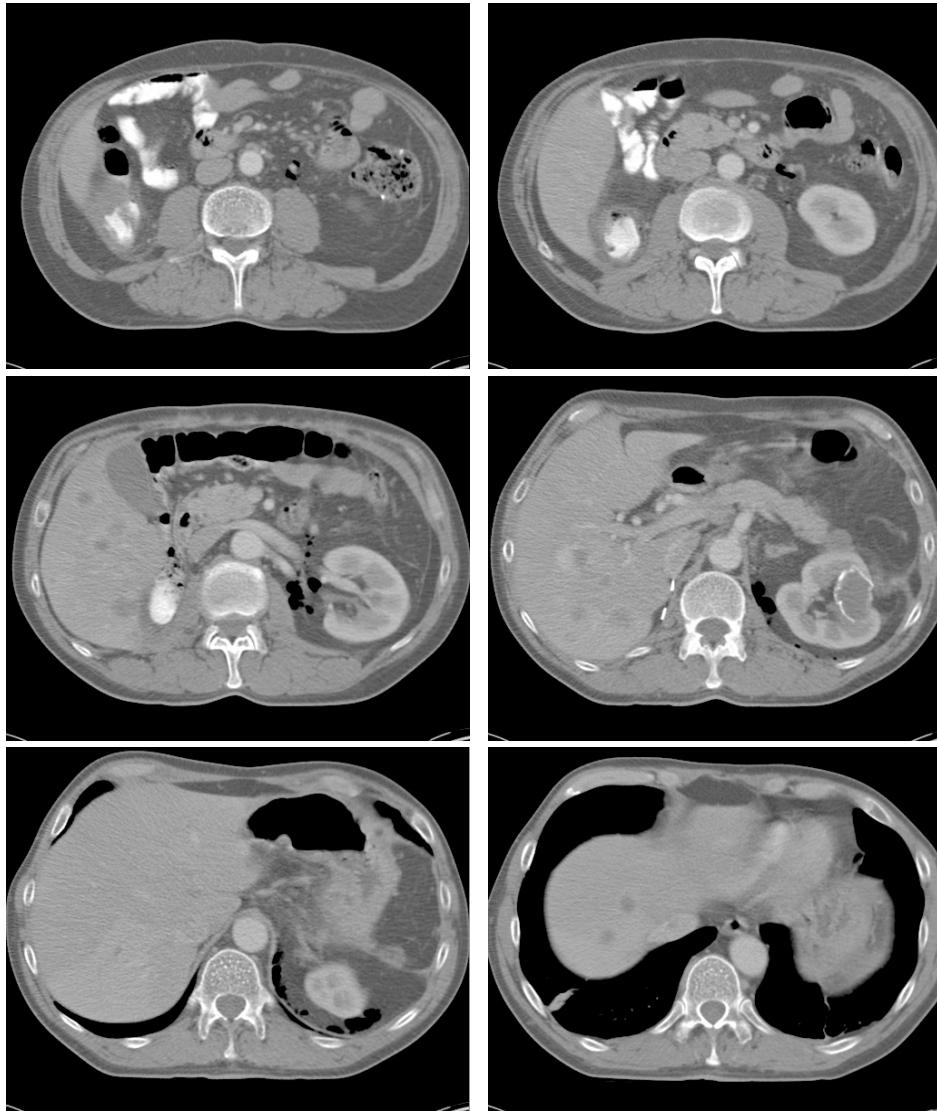
- Very often medical images are volumetric

Voxel Representation



$I(x,y,z)$

Example of volumetric images : CT-scan (Scanner)



Size: 512 x 512 x 128

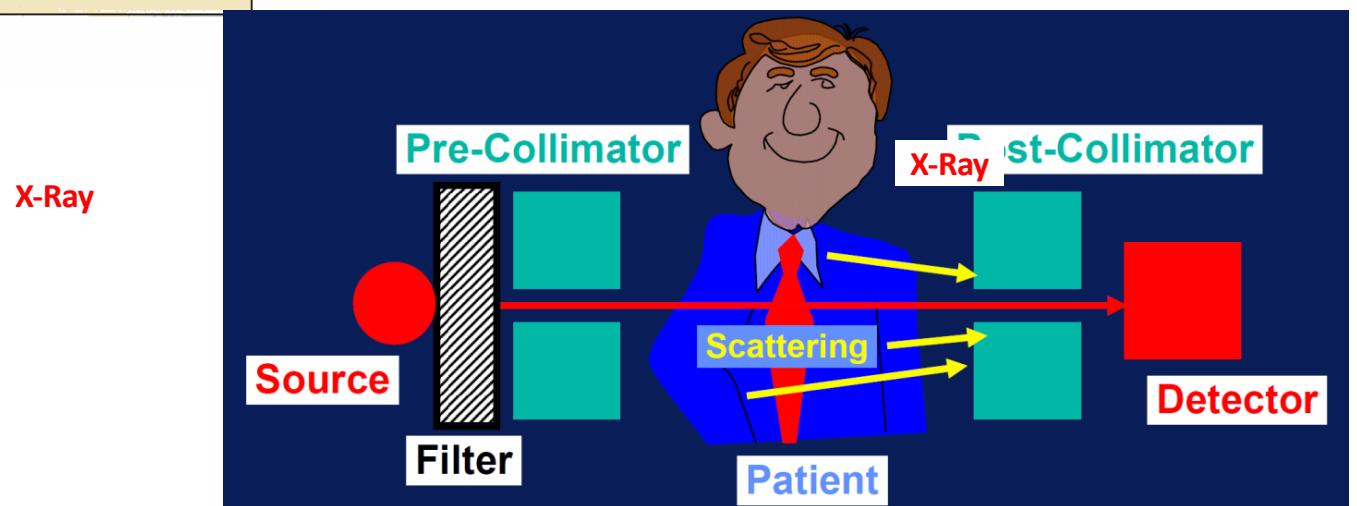
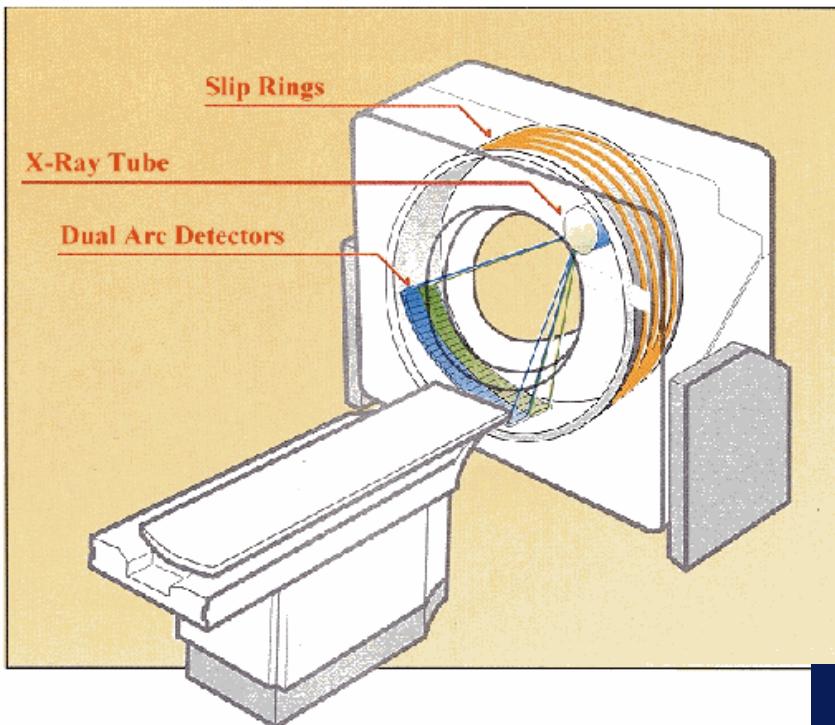
Resolution: 0.5 x 0.5 x 1 mm



Medical Imaging Modalities

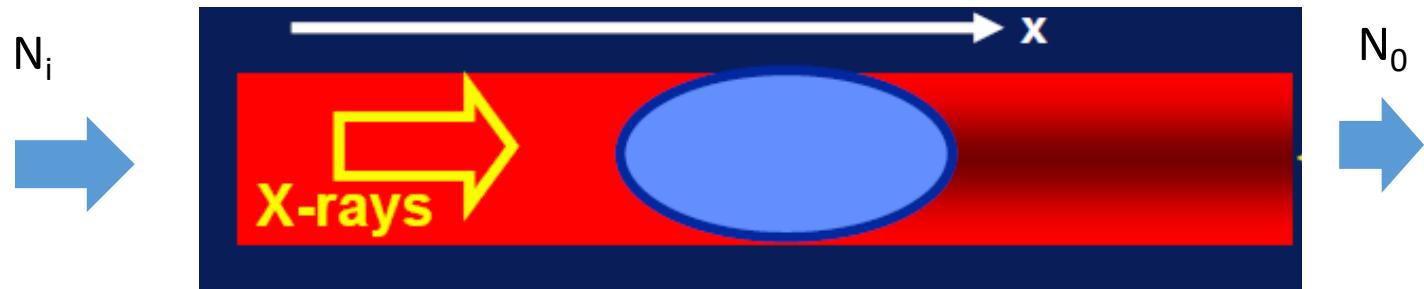
- 0.1 Introduction
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Principle of CT Imaging (1)



Principle of CT Imaging (2)

- Input X-Ray intensity : N_i
- Measured Output X-Ray intensity : N_o



- Exponential attenuation :

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

- Objective :

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

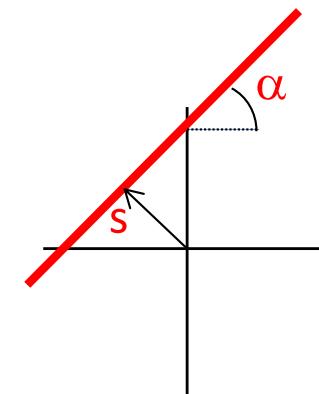
Computed Tomography

- 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

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

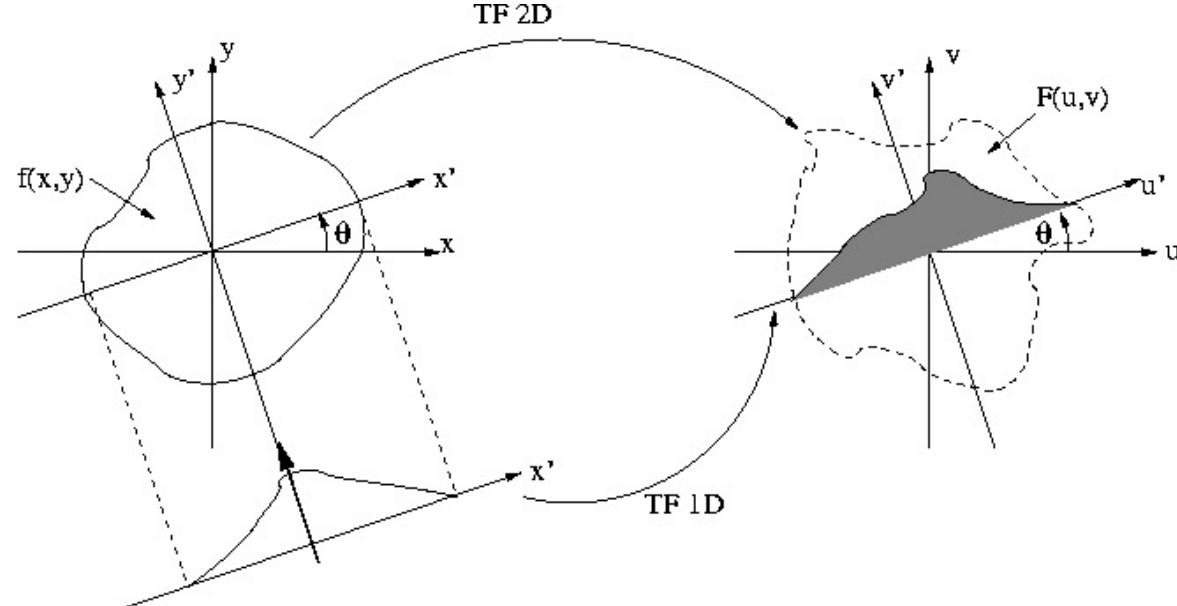
- Radon Transform :

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 $\mu(x,y)$



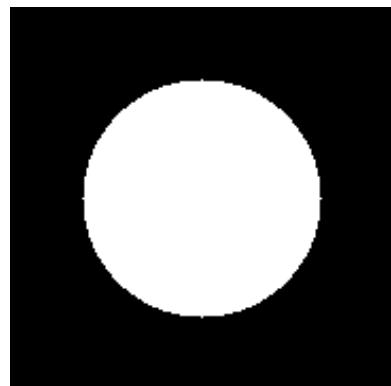
Reconstruction Principle

- Backprojection based on inverse Radon Transform

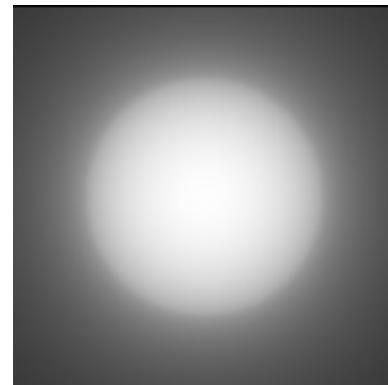
$$n_\alpha = (\cos \alpha, \sin \alpha)$$

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

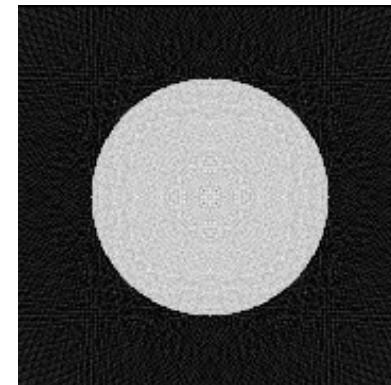
- In practice use filtered back-projection to remove blur



Model Image



Simple
Backprojection



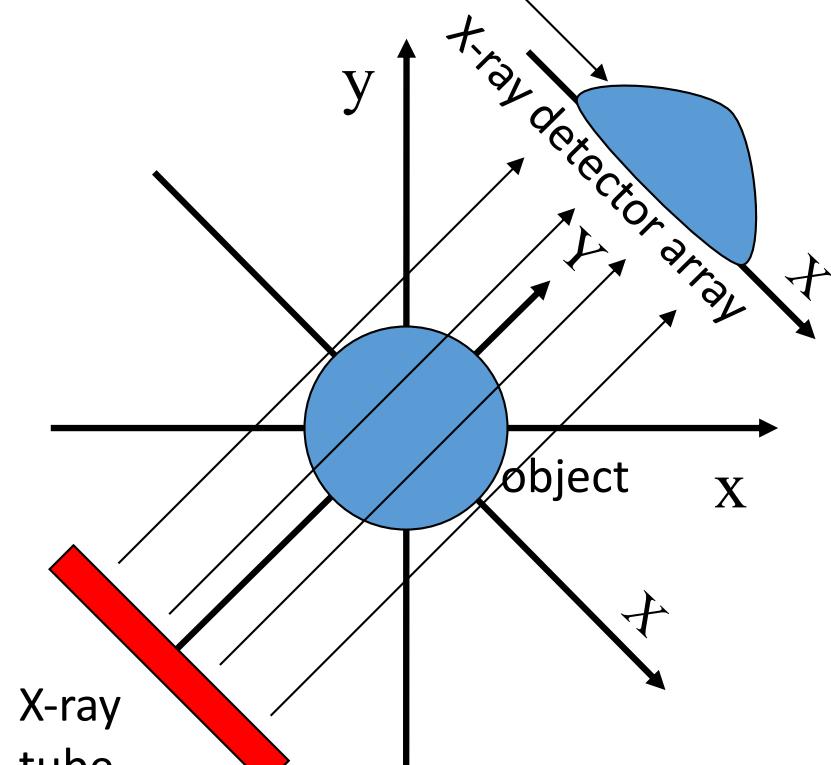
Filtered
Backprojection

Basic principle of CT

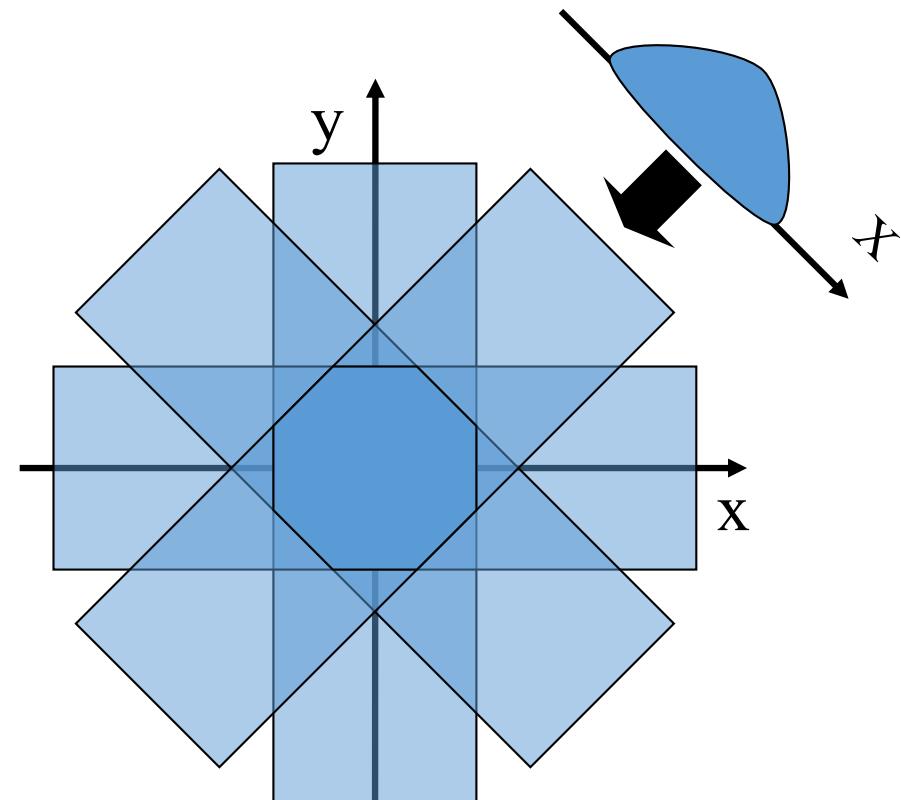
-Reconstruction of 2 dimensional image-

Projection Data

curvilinear integral of absorption coefficient regarding Y



Data Acquisition field

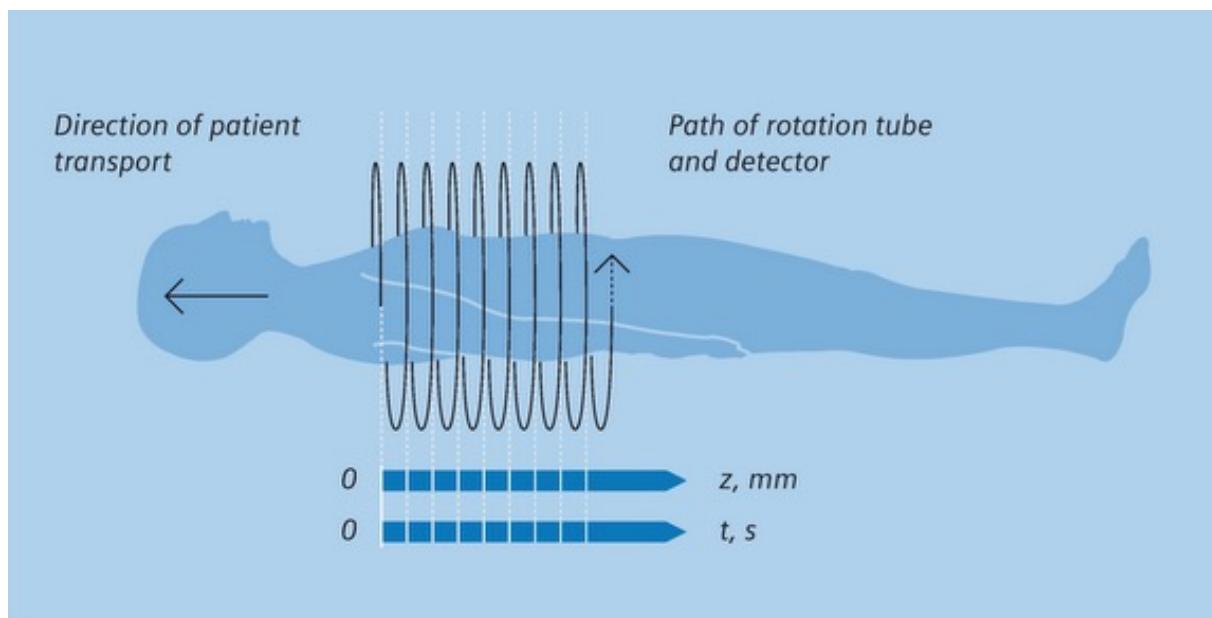


Reconstruction field

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

1963
Cormack
X-ray
tomography
idea

1989
Kalender
Introduction
of helical CT

2004
Cone beam
CT systems

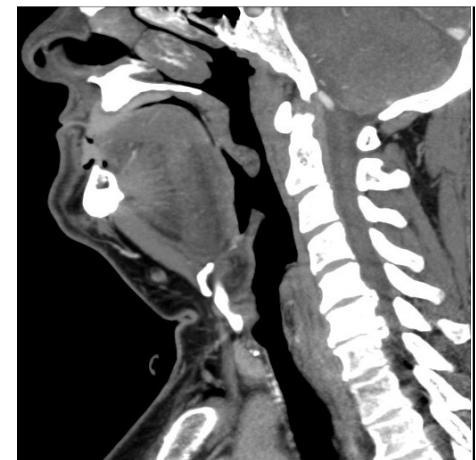
1917
Radon
Mathematical
foundations

1972
Hounsfield
First CT
scanning
system

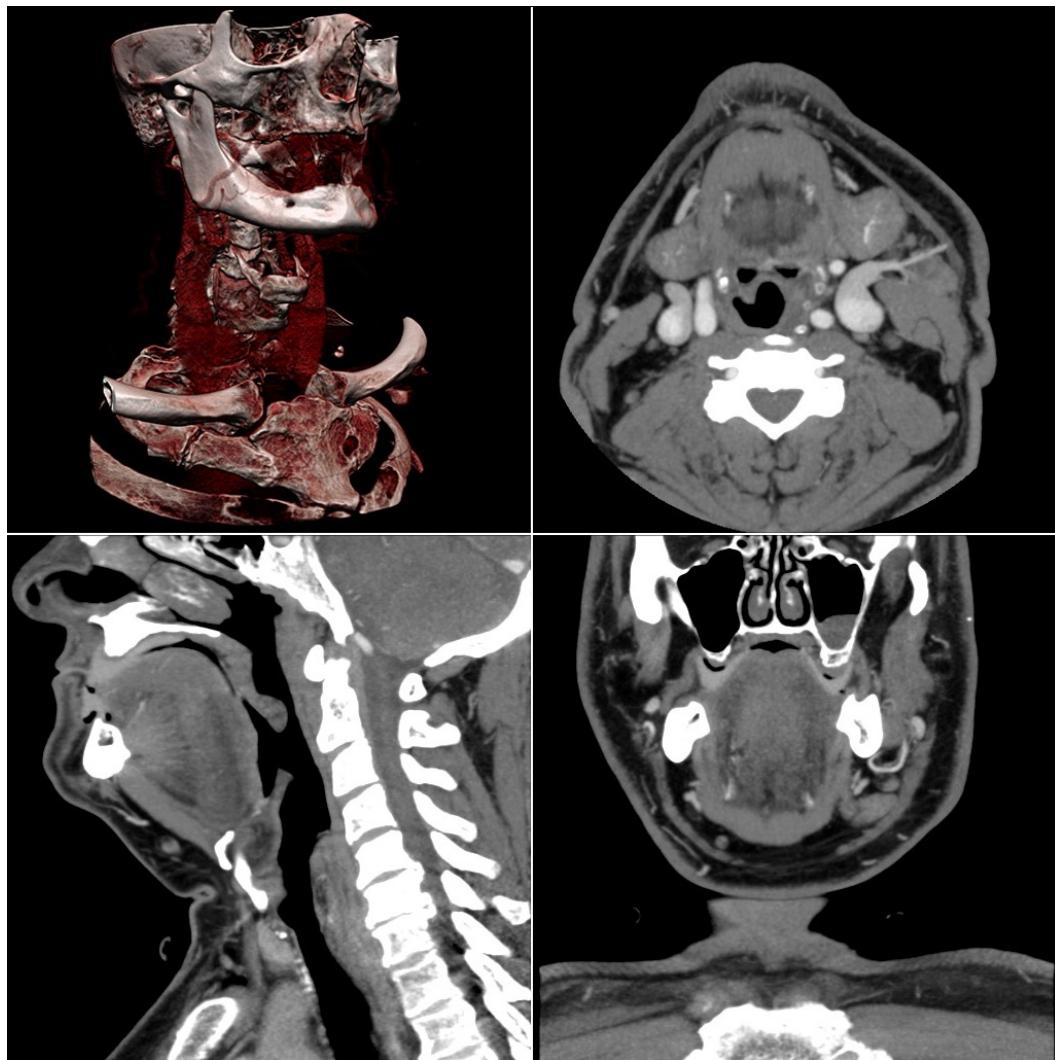
1998
First
multi-line
CT system

CT Scan Imaging

- Measure absorption coefficient of X-ray related to density of tissue
- Invasive image modality (ionizing rays)
- Absolute Hounsfield Unit
 - $HU(\mu) = 1024 \frac{\mu - \mu_{water}}{\mu_{water}}$



CT Scan



Medical Imaging Modalities

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Principle of nuclear imaging

■ Introduction into the patient body of a couple (vector molecule / radio-isotope)

Vector Molecule	⇒	Targeted organ (drug, protein, blood cells...)
Radio-isotope	⇒	Allow the detection of the molecule

■ Emission imaging : the targeted organ emits radioactivity

- ⇒ Reflect the metabolic function of the organ
- ⇒ *Metabolic or functional imaging*
- Local relative concentration (relative)
- 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)

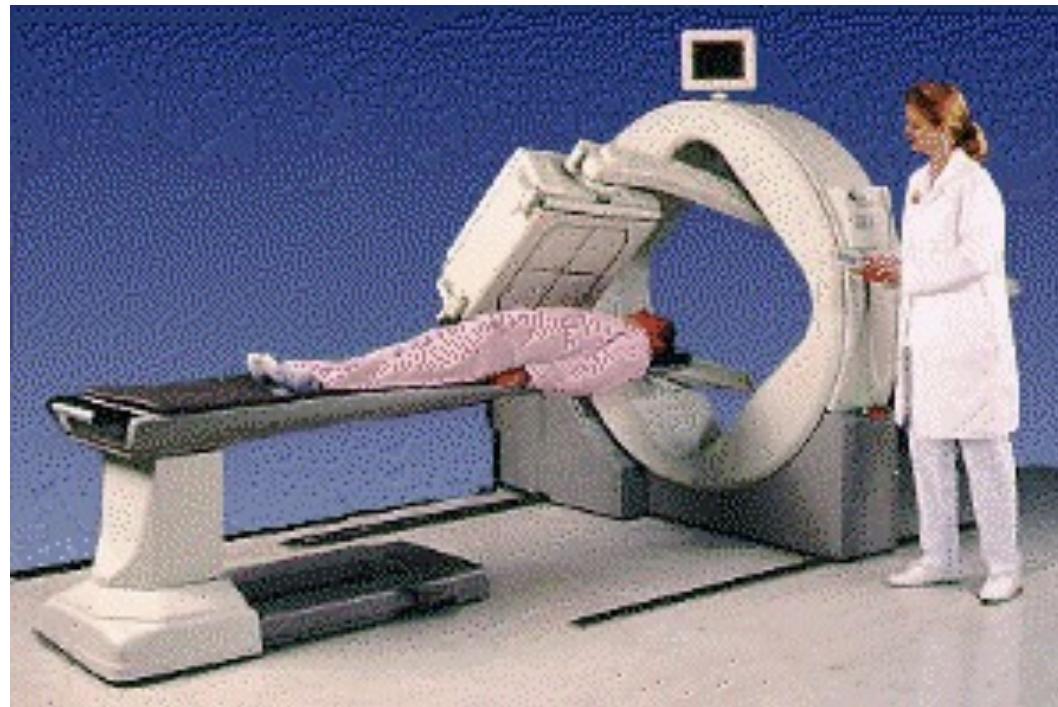
Alpha Particle: Helium nucleus (2 protons + 2 neutrons)

Beta Particle : 1/ electron β^-

2/ **positon** $\beta^+ \rightarrow 2$ photons γ (511 kev)

Gamma Particle: **Photon**

Nuclear Medicine



- Density of radioactive tracers

Single photon gamma imaging (SPECT)

■ Radio-isotopes (Gamma particles)

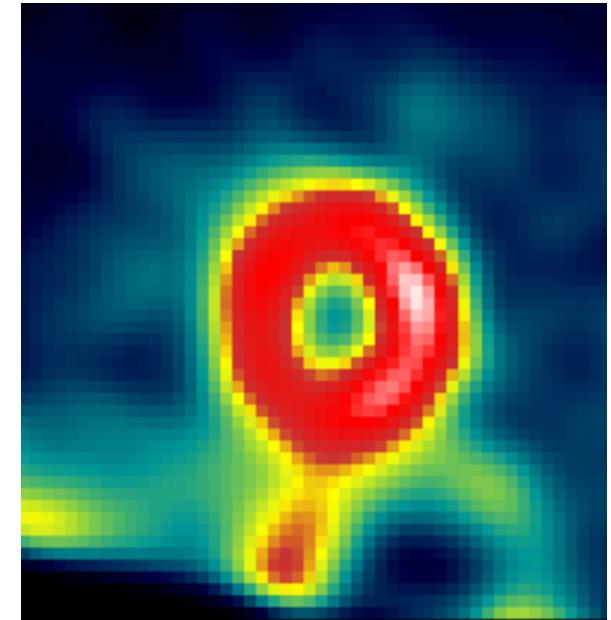
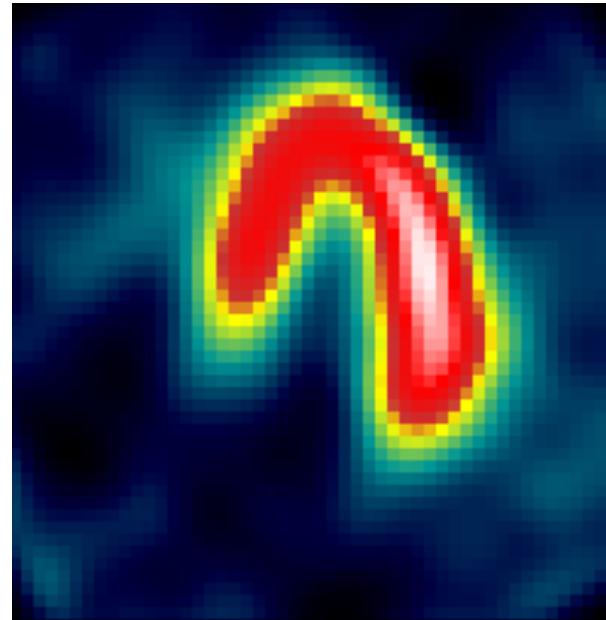
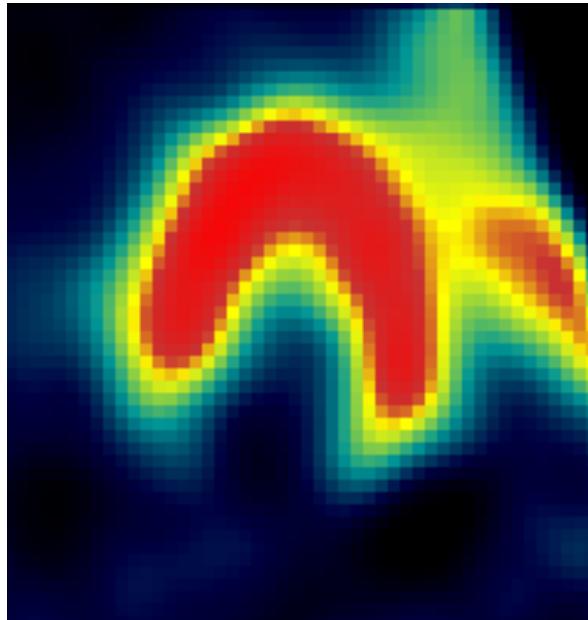
Single photon emitters

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



■ Stress/rest exam **Heart (myocardium perfusion)**

perfusion / perfusion \Rightarrow Healthy area

perfusion / (hypo/non-)perfusion \Rightarrow Zone at risk (ischemia)

(hypo/non-)perfusion / (hypo/non-)perfusion \Rightarrow Infarcted Area

Positon emission tomography (PET)

■ Radio-isotopes

Emission : positron (β^+) → Annihilation
 → 2 photons of 511 kev at 180°

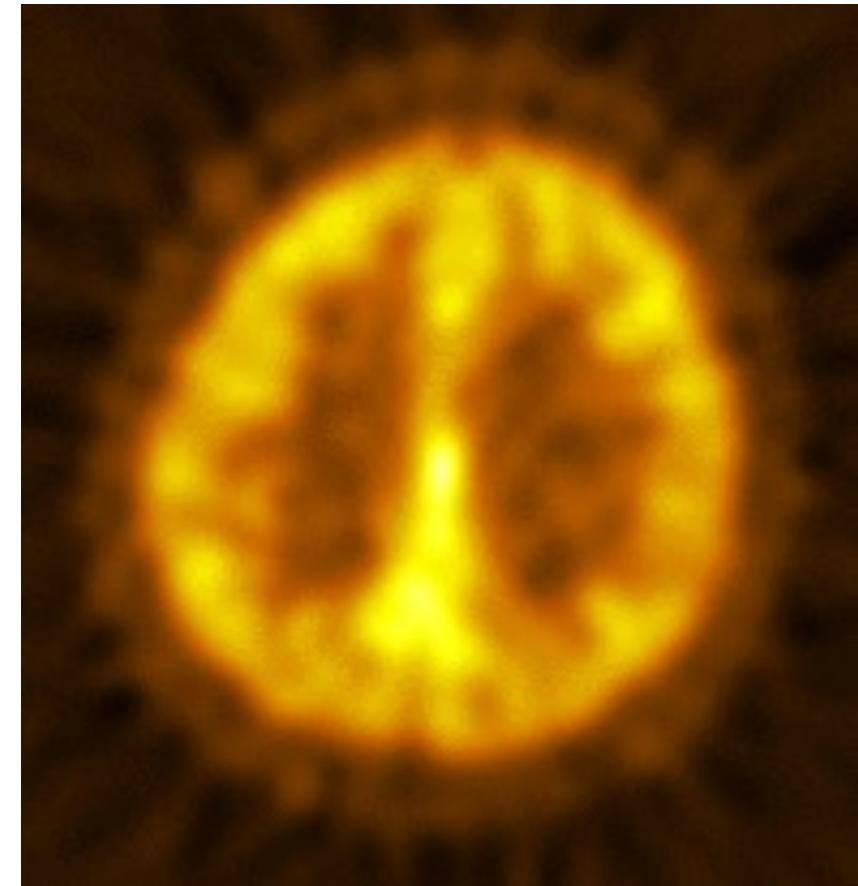
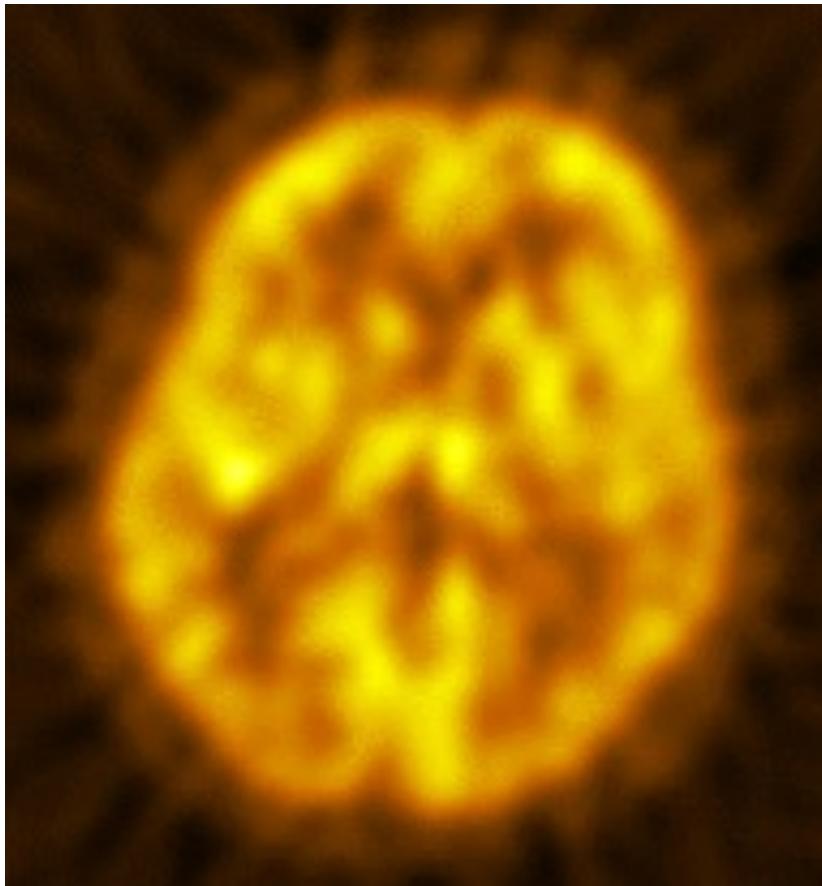
Positron emitters

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)

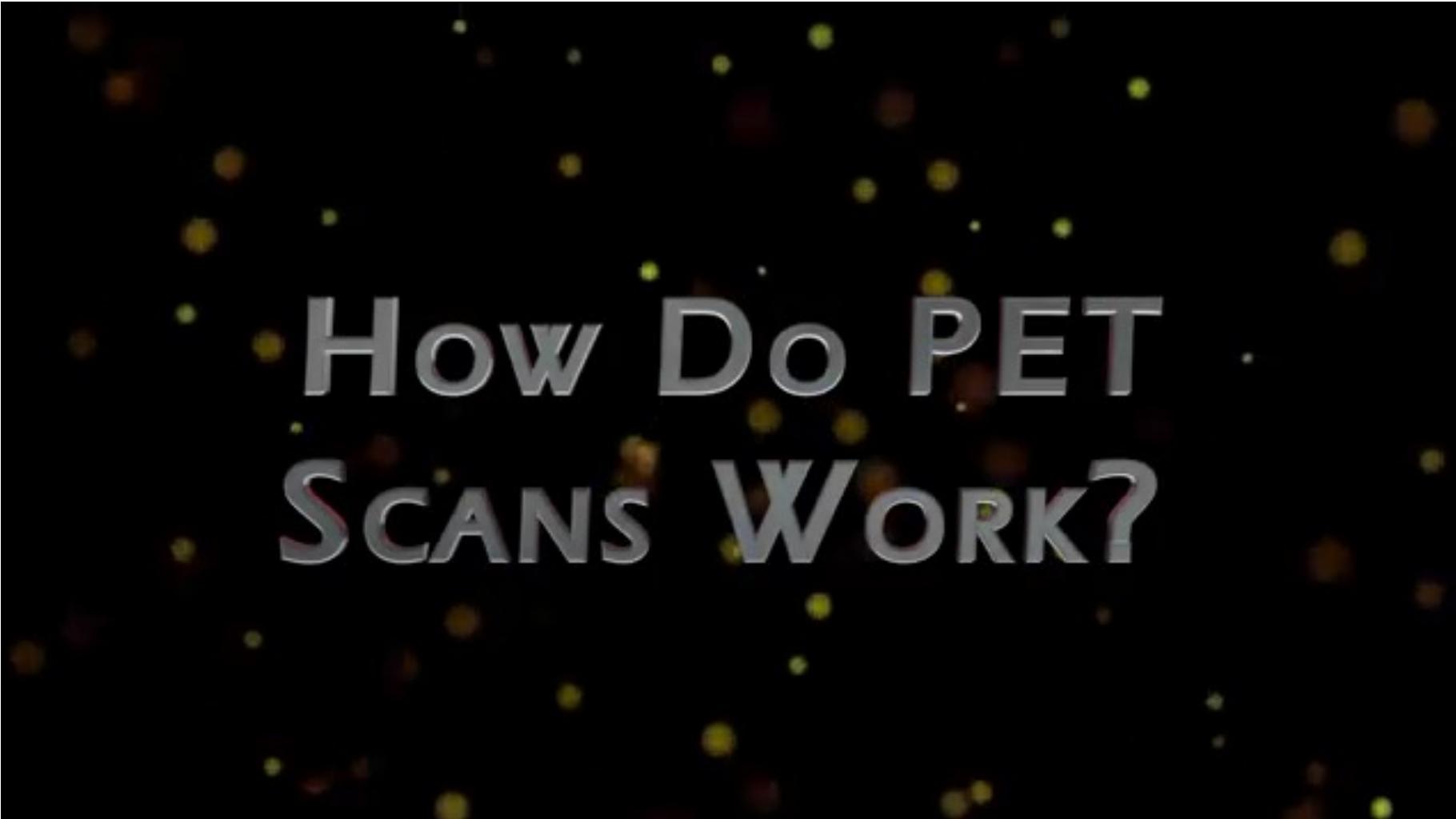
■ Physiological molecules



Positon emission tomography (PET)



PET Scan



How Do PET
SCANS WORK?

<https://www.youtube.com/watch?v=GHLBcCv4rpk>

Medical Imaging Modalities

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Magnetic resonance imaging

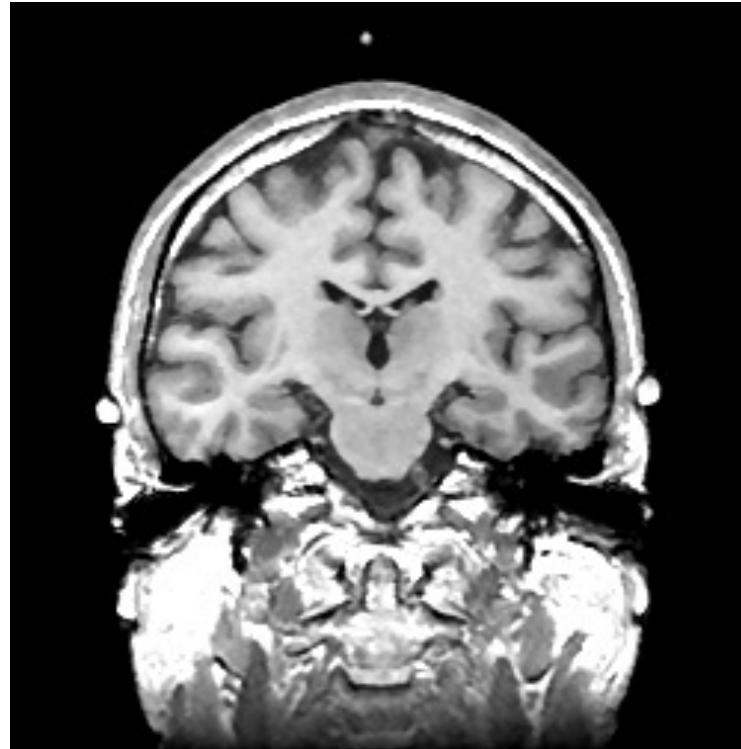


- Density and structure of protons

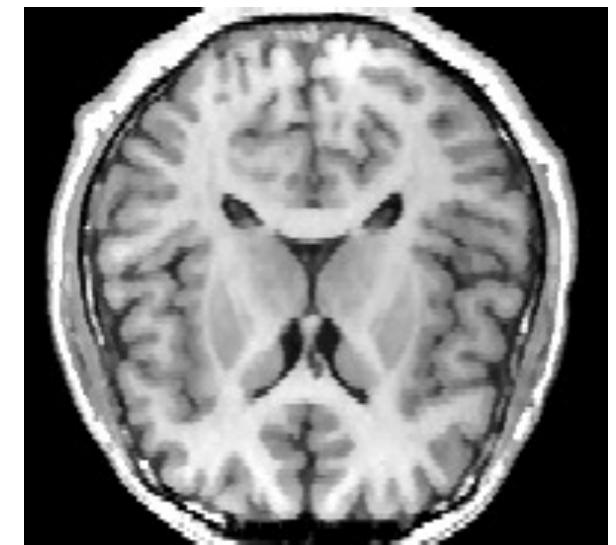
Magnetic resonance imaging



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

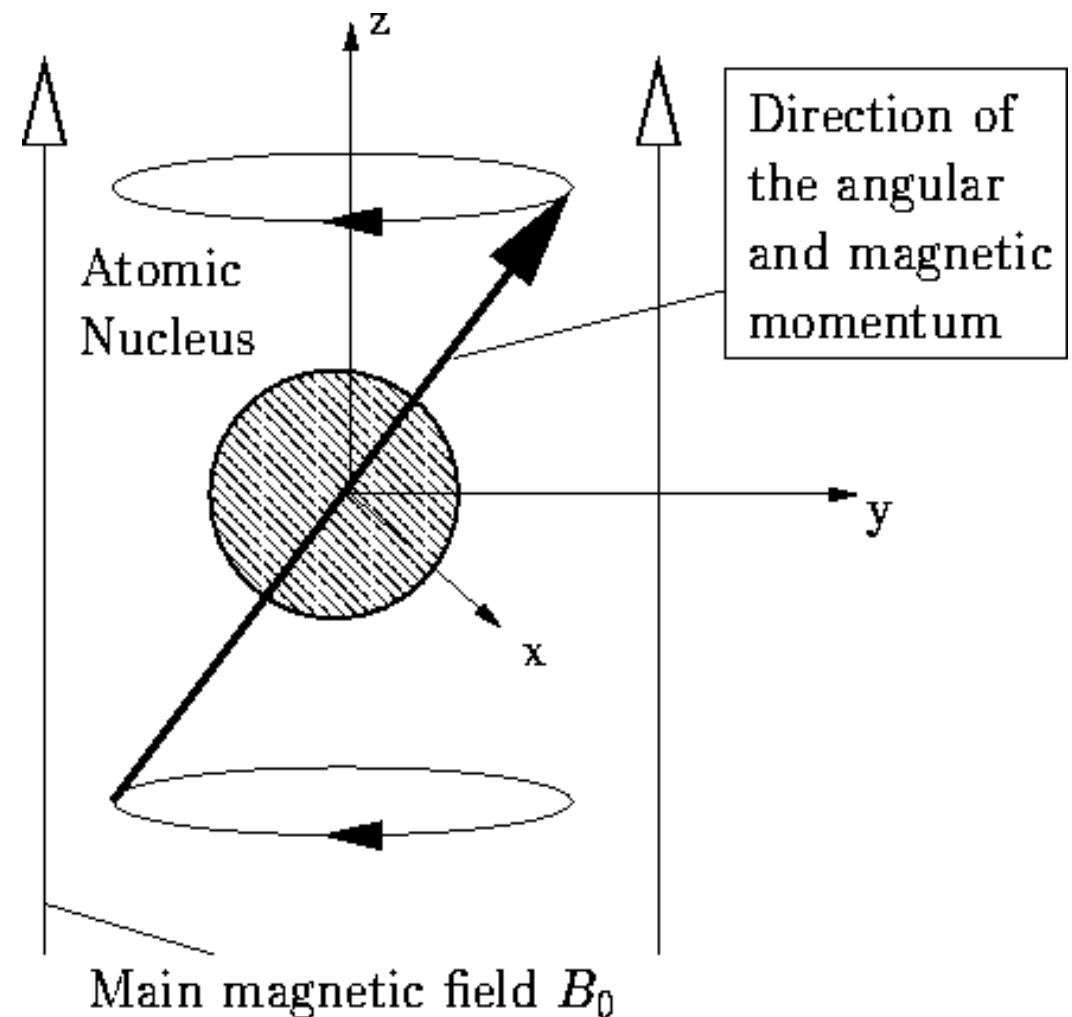
Diffusion MR: brain connectivity

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

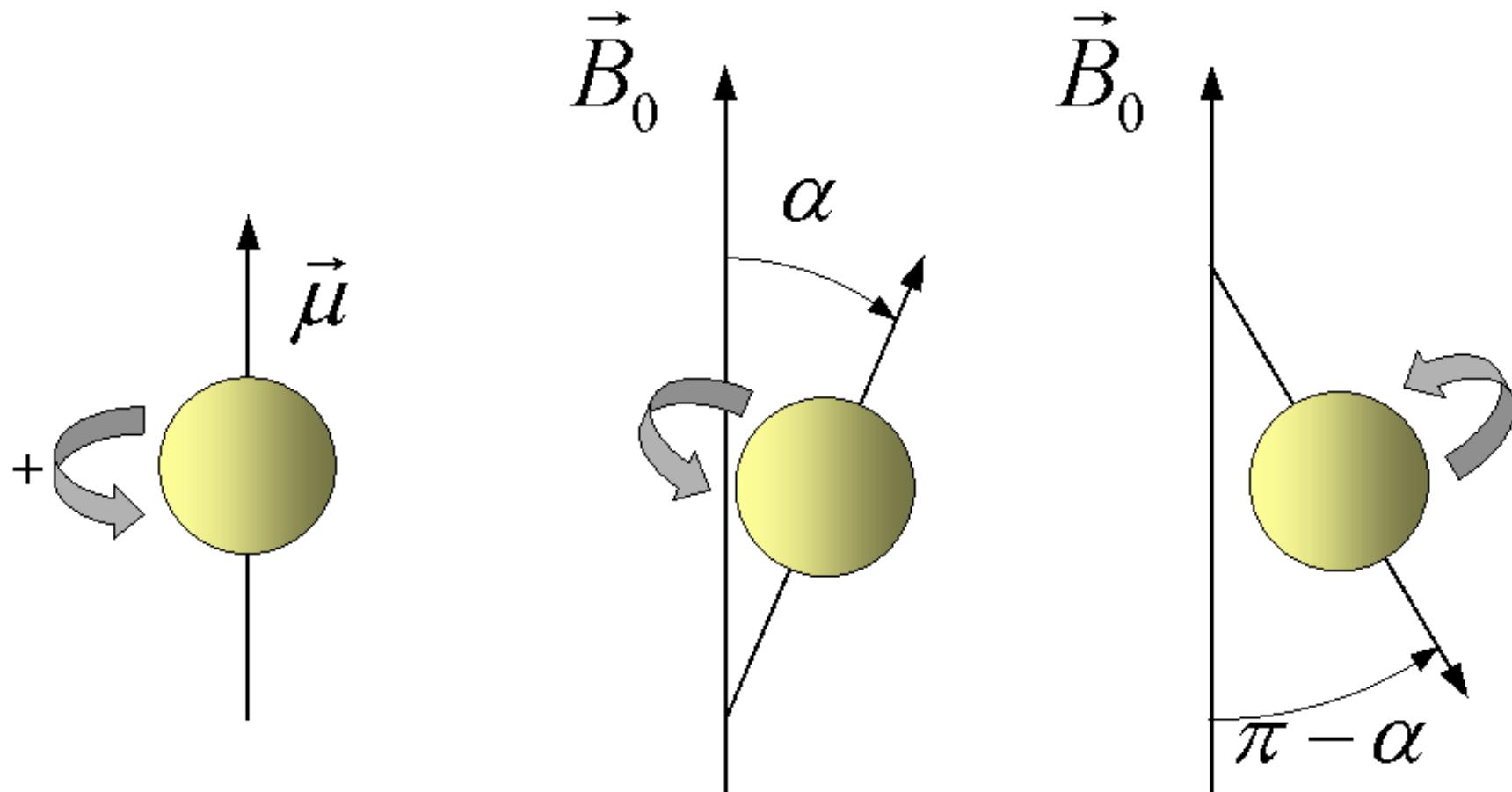
Thus $\frac{d\vec{\mu}}{dt} = \gamma(\vec{\mu} \times \vec{B})$

$$\vec{B}_0 = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} \xrightarrow{\text{red arrow}} \vec{\mu} = \begin{pmatrix} \mu_t \cos(\omega_L t + \varphi) \\ -\mu_t \sin(\omega_L t + \varphi) \\ \mu_{z_0} \end{pmatrix}$$

Larmor's frequency

$$\omega_L = \gamma B_0$$

Magnetism at the macroscopic level



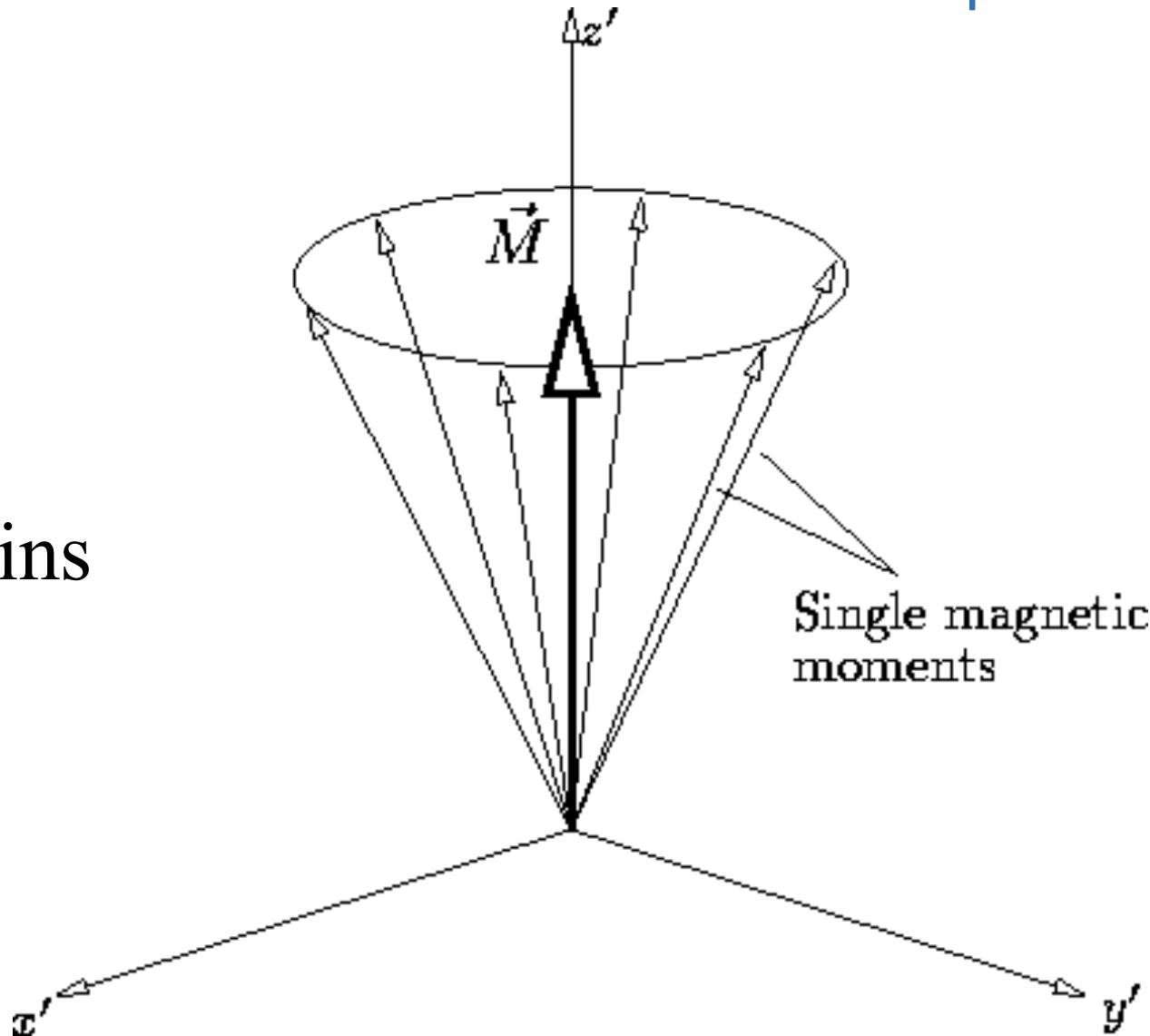
$$P_{+1/2} = 0.5000049$$

$$B_0 = 1.5 \text{ T}$$

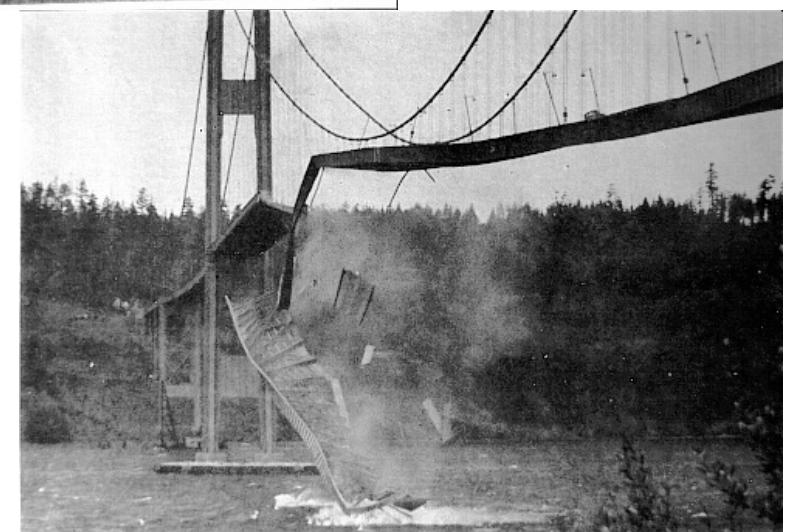
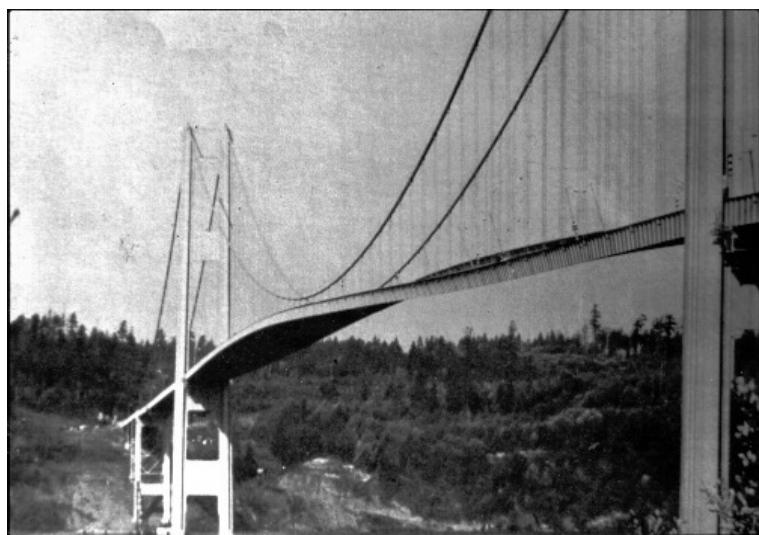
$$P_{-1/2} = 0.4999951$$

Magnetism at the macroscopic level

10^{23} spins



Resonance



Magnetic Resonance / excitation

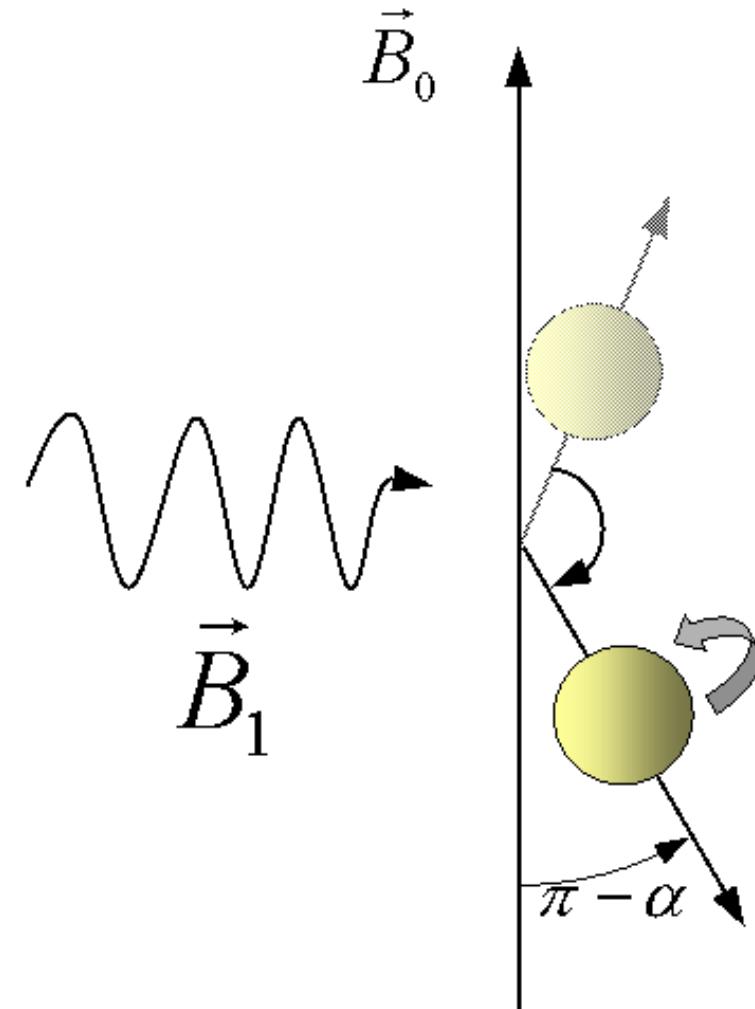
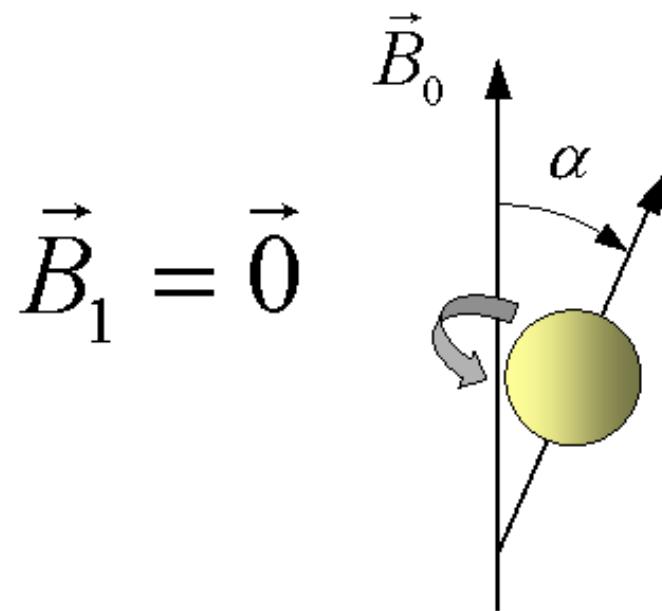
Electro-magnetic field at Larmor's frequency

$$\omega_L = \gamma B_0$$

Hydrogen protons enter into resonance

Flip of the macroscopic momentum \mathbf{M}

Magnetic Resonance / excitation



Magnetic Resonance / relaxation

Return to equilibrium / B_0 : time constant T_1

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

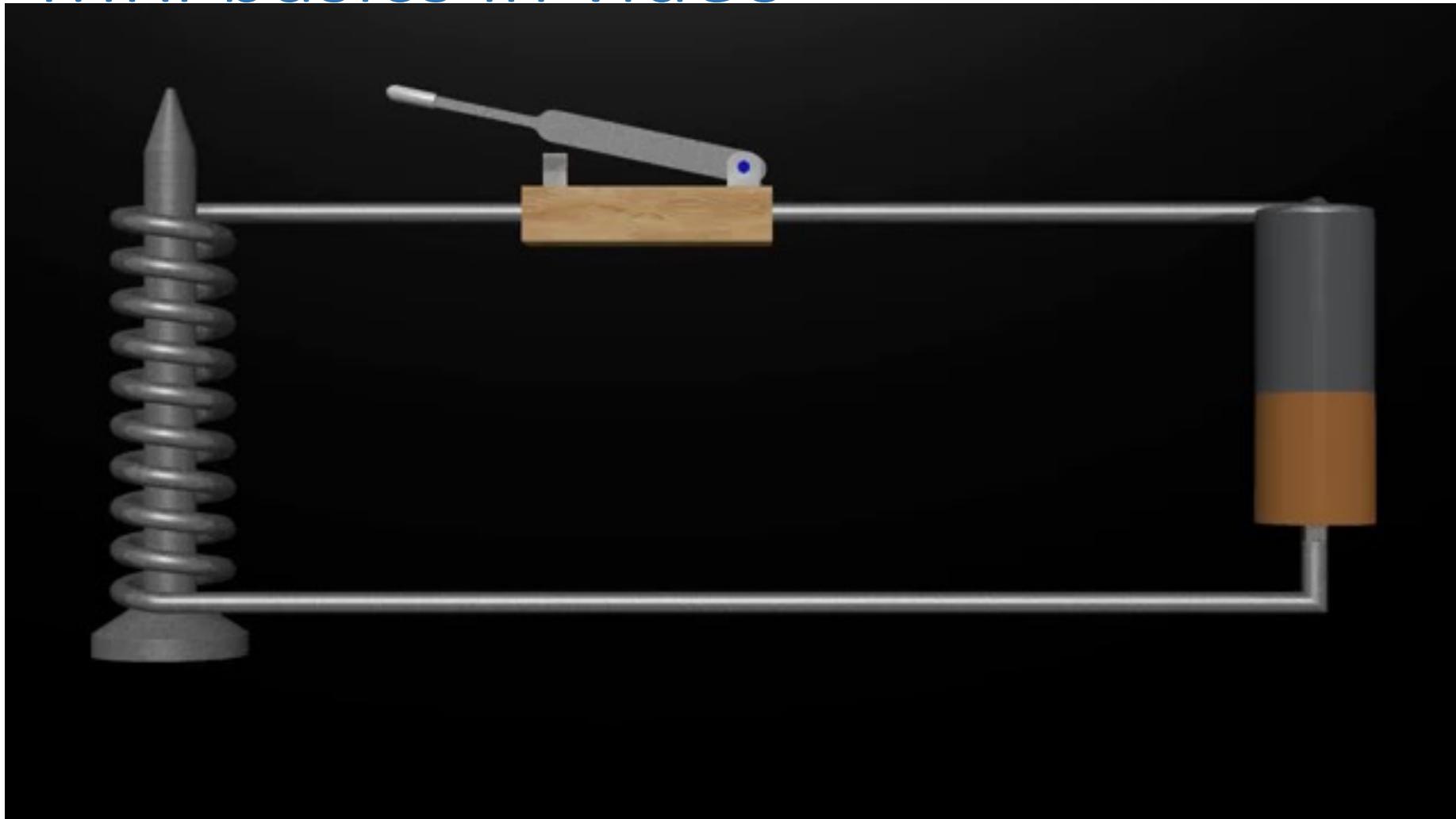
Spin dephasing: Time constant T_2

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

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

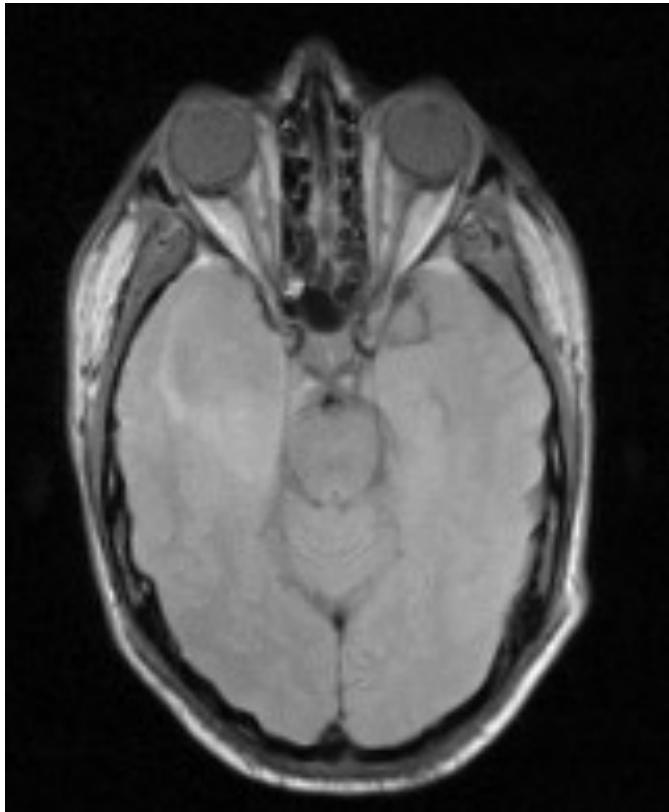


https://www.youtube.com/watch?v=djAxjtN_7VE

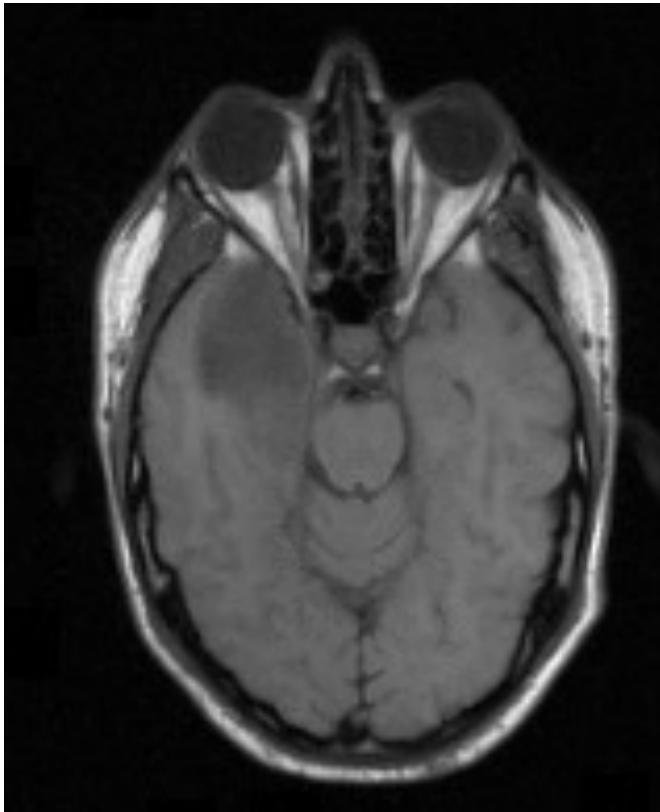
MRI / frequency selection

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

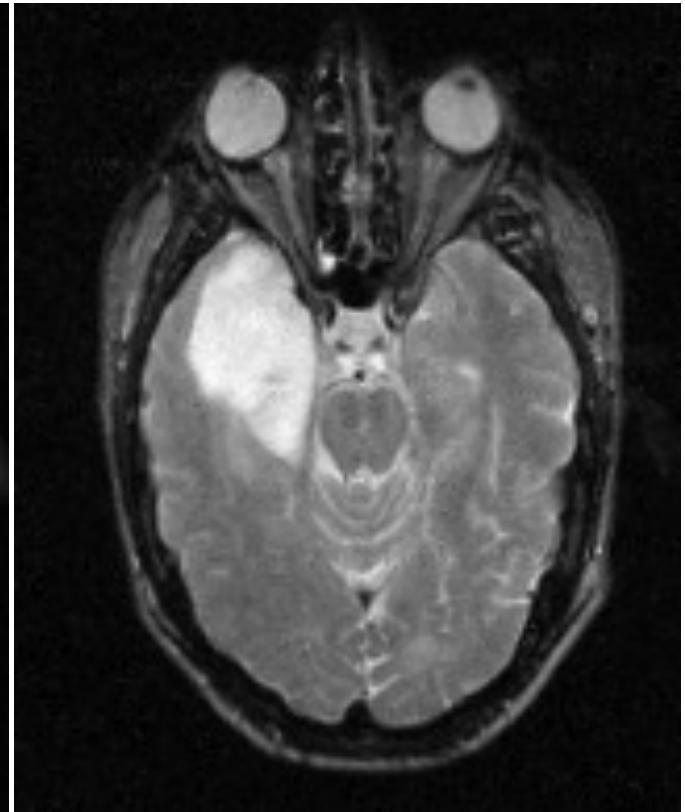
Anatomical MRI



Proton density



T_1



T_2

Angiographic MRI

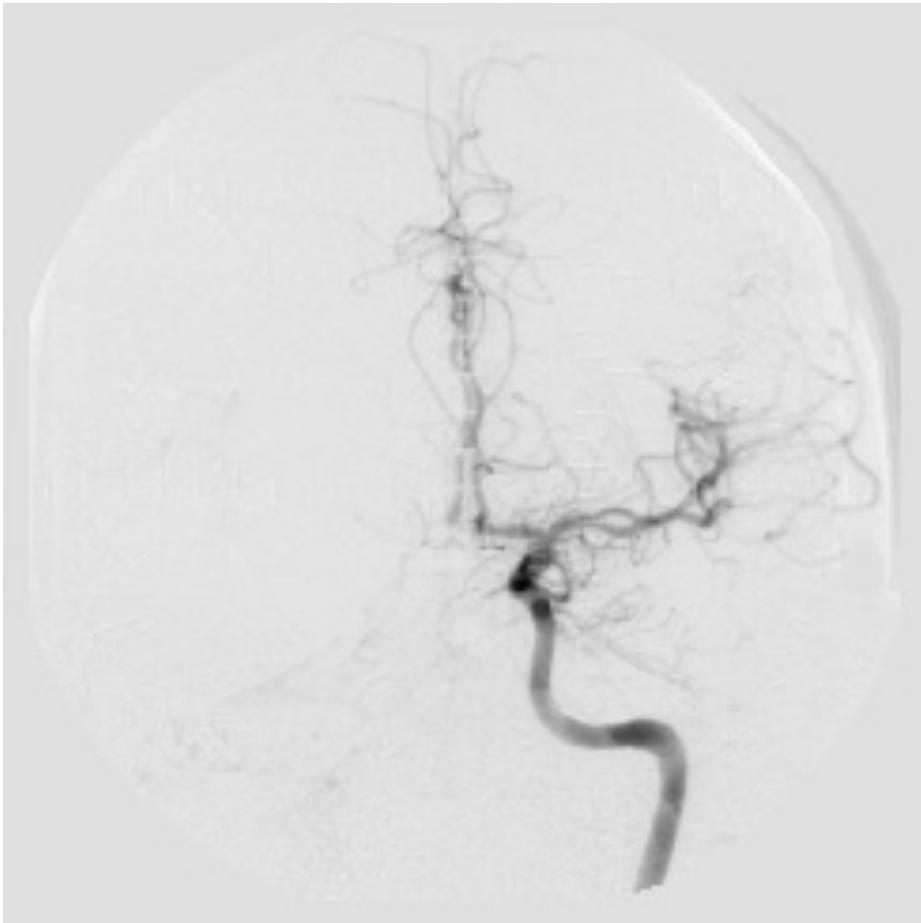


**INFLOW
Phases**

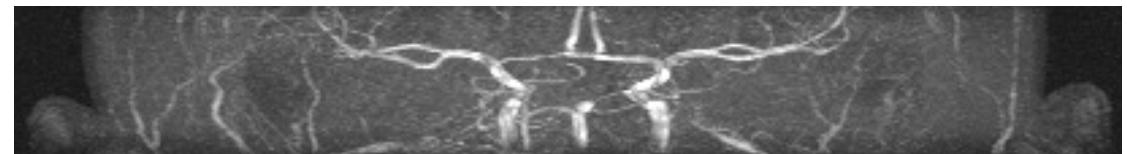
**Maximum intensity
projection (MIP)**



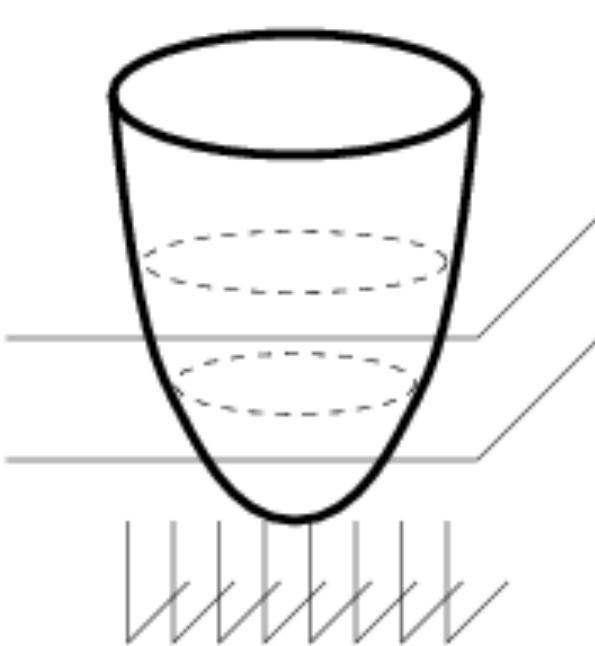
Angiographic MRI



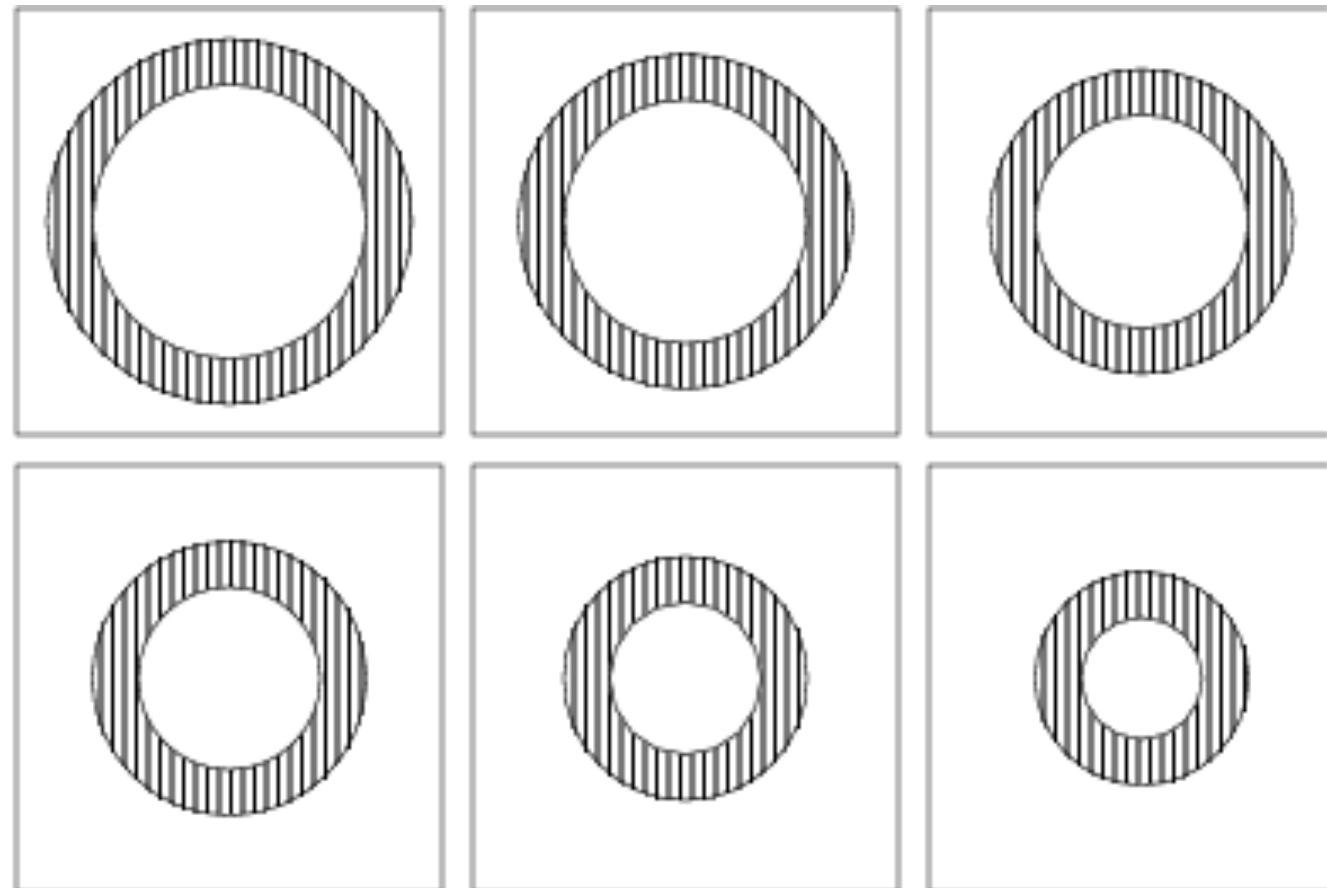
X-Scan / radiology
Selective injection of
a contrast agent in
one artery



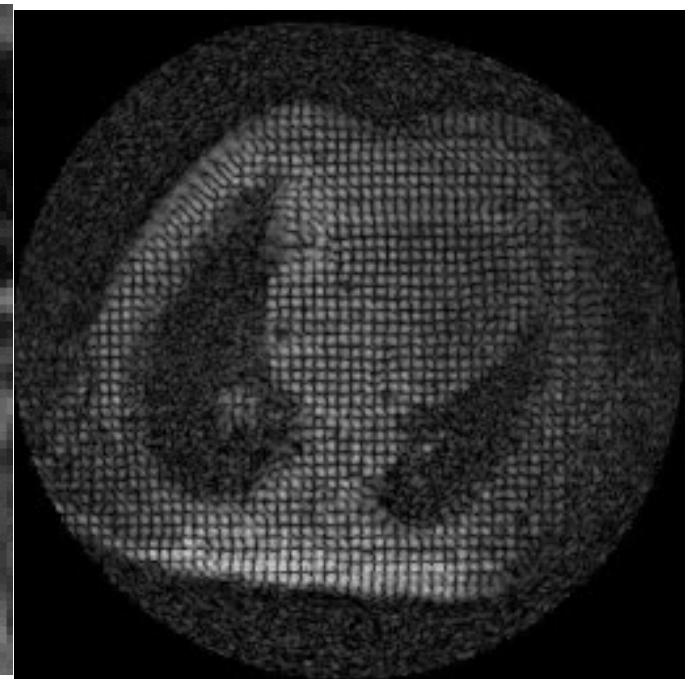
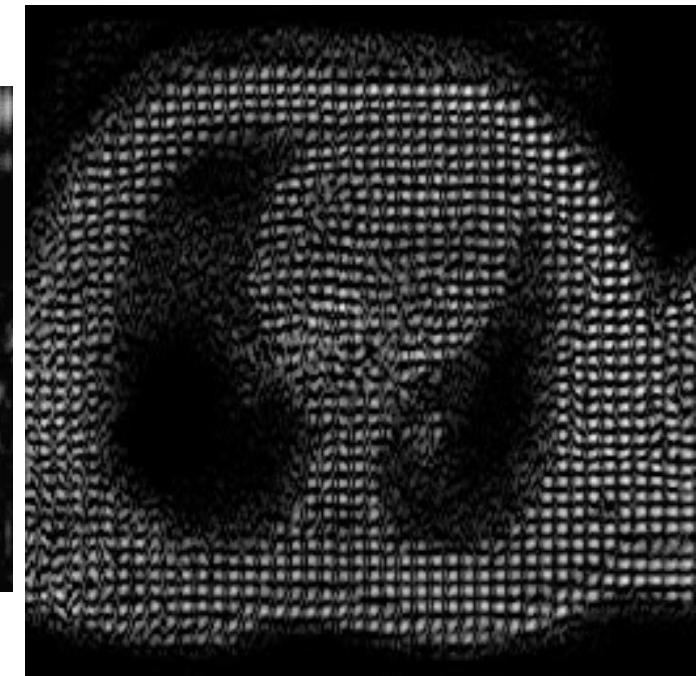
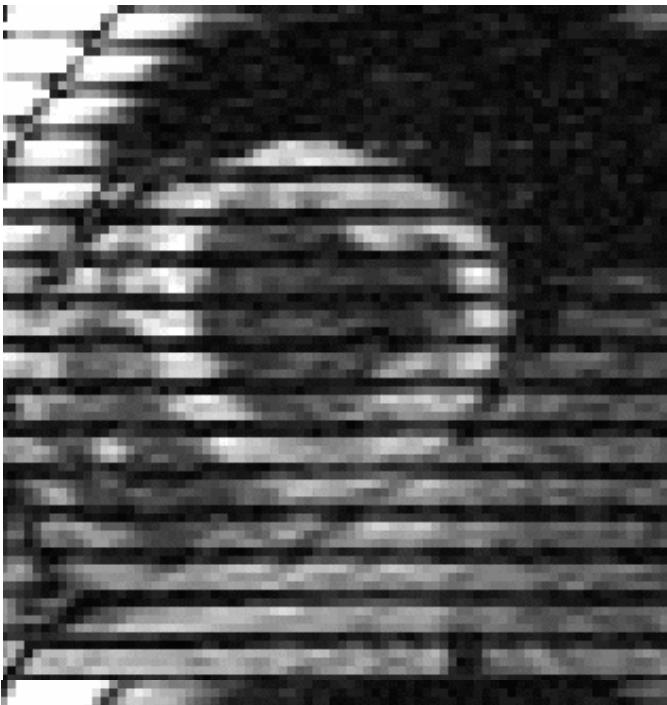
Tagged MRI



Plans de marquage



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

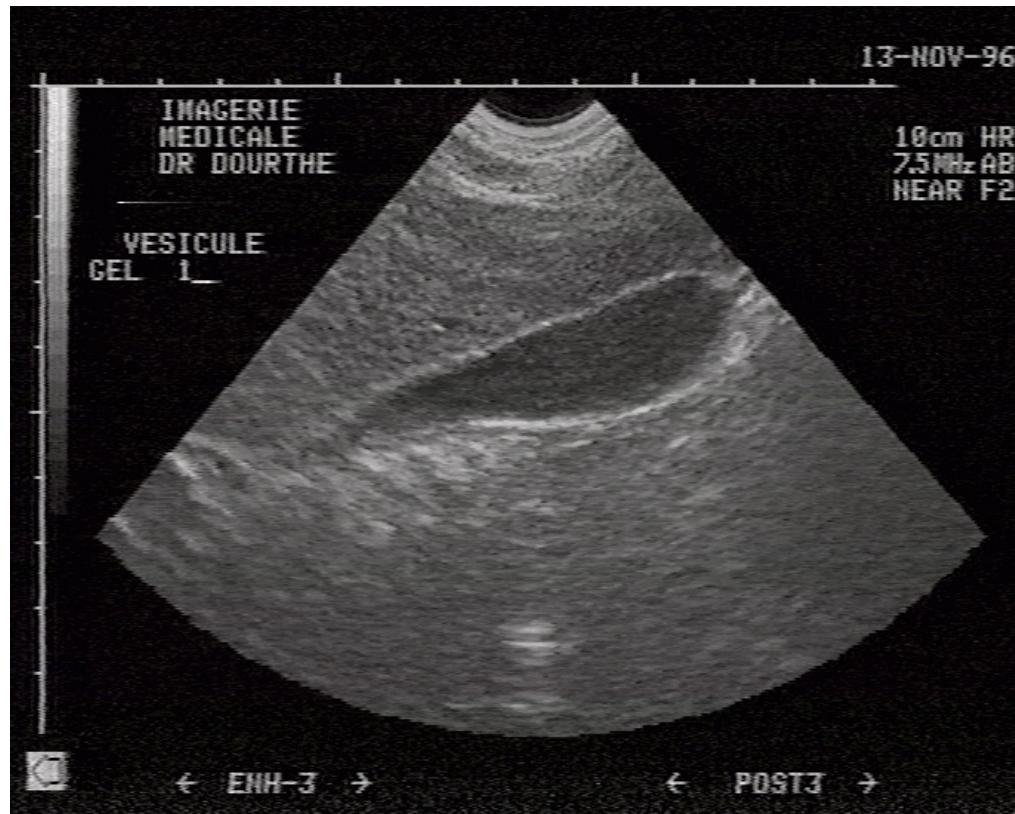
- 0.1 Introduction
- 0.2 Tomography
- 0.3 Nuclear medicine
- 0.4 MRI
-  0.5 Echography

Echography



- Local variation of acoustic impedance

Echography



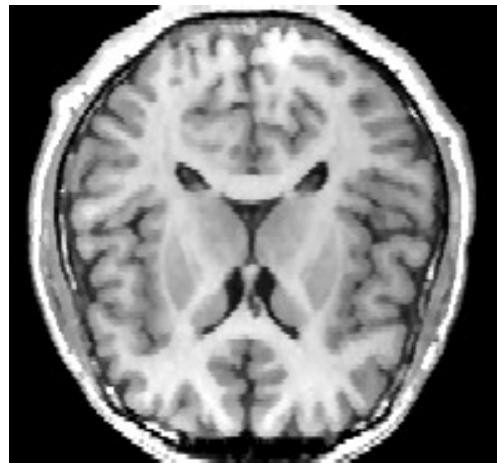
Gall Blader

Summary of Main Medical Imaging Modalities

MRI

Measure

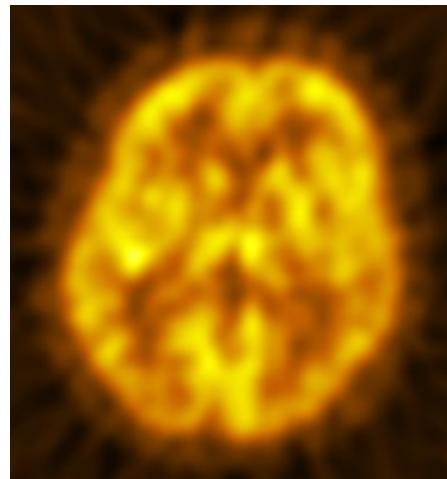
Density and
structure of
Protons



Nuclear Imaging

Measure

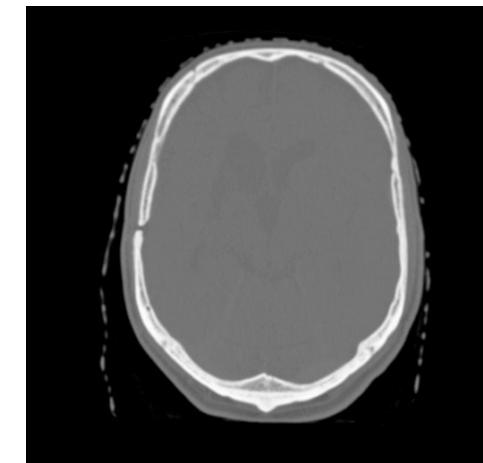
Density of
injected
isotopes



CT-Scanner

Measure

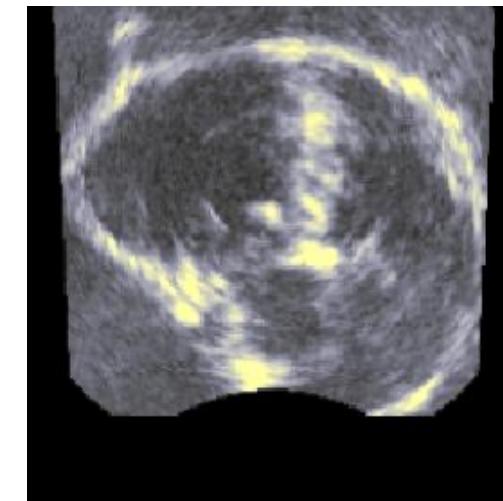
Density of
X-Ray
absorption



Ultrasound

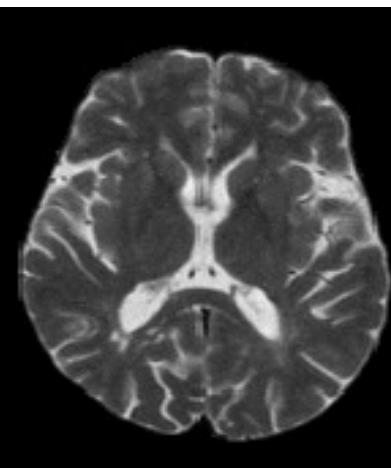
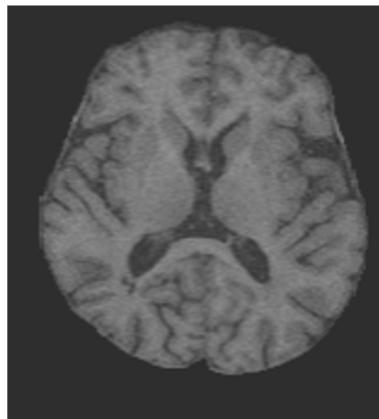
Measure

Variations of
Acoustic
Impedance

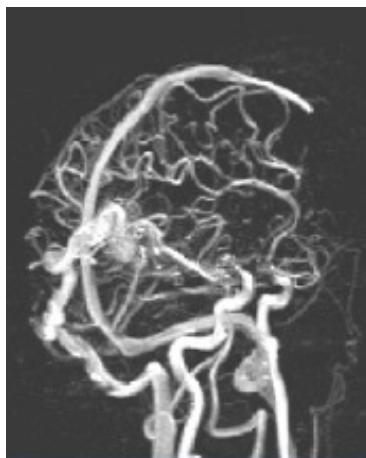
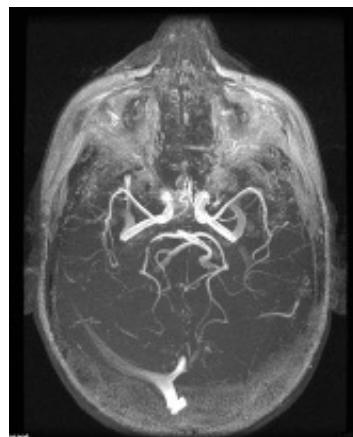


Multiparametric Images

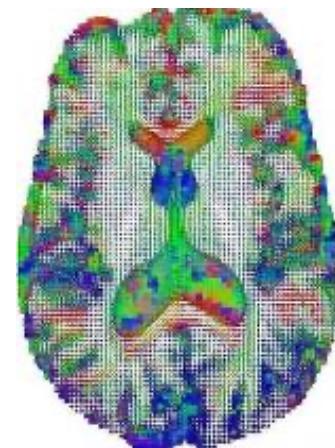
MRI T1, T2



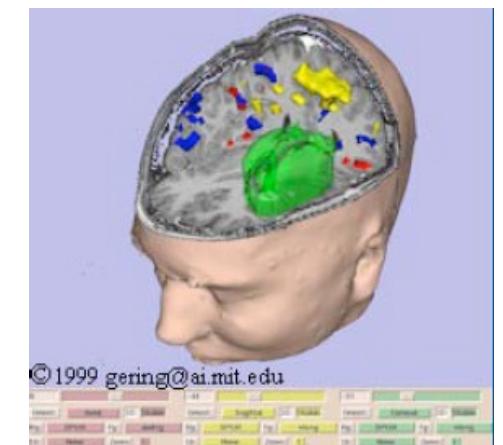
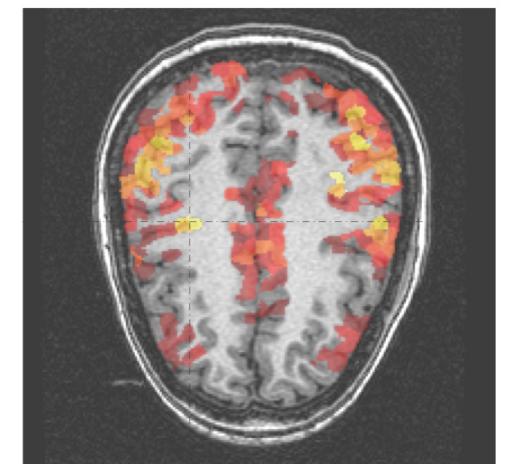
Angio MRI



DTI



fMRI

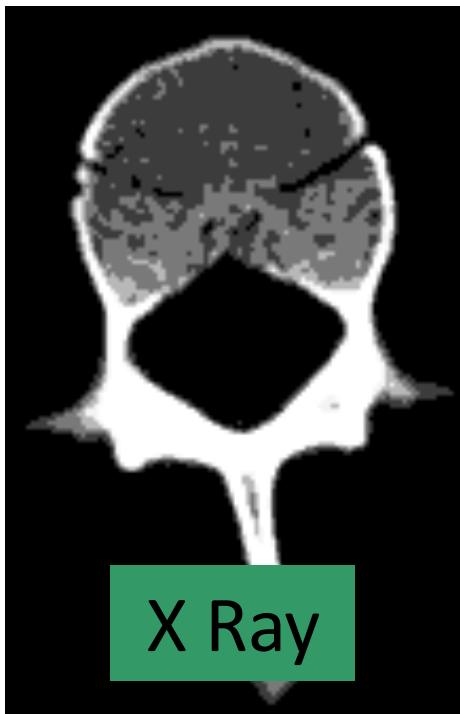


1. Medical Image Representation & Visualization

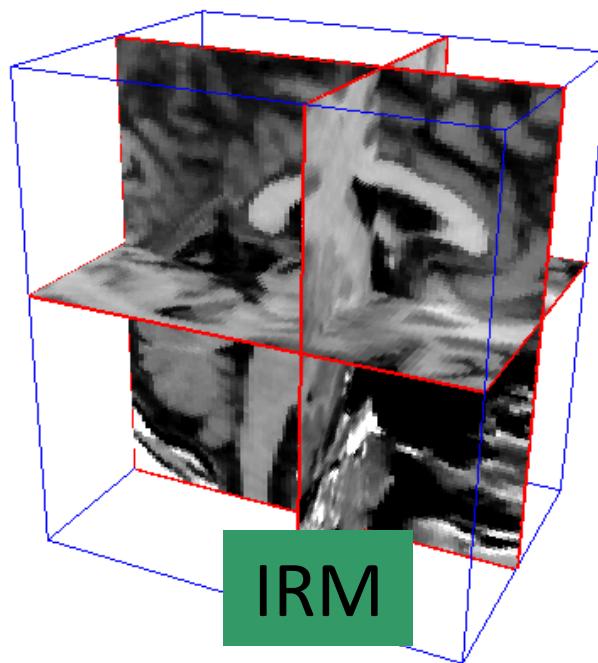
- 1.1 Image representation : discrete or continuous
- 1.2 Image Visualization

Medical Imaging Classification (1)

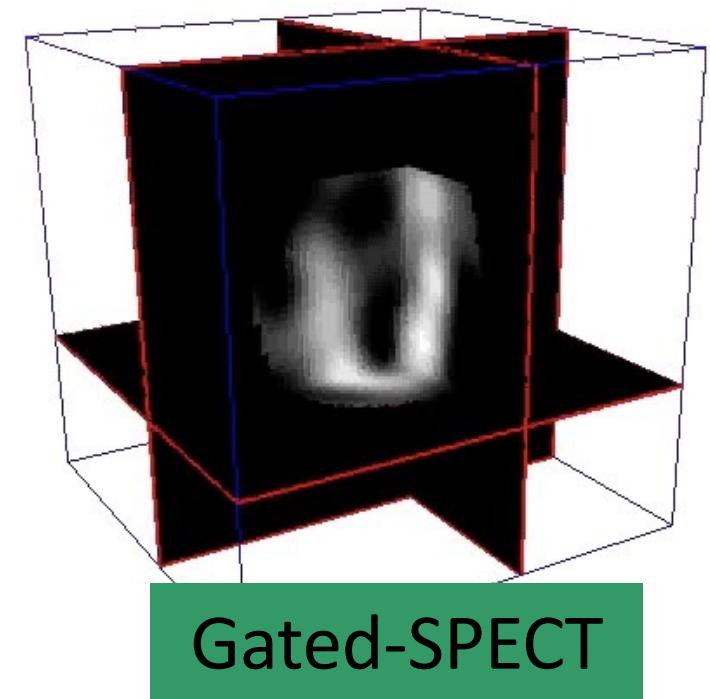
- Dimensionality



2D



3D



4D (3D+T)

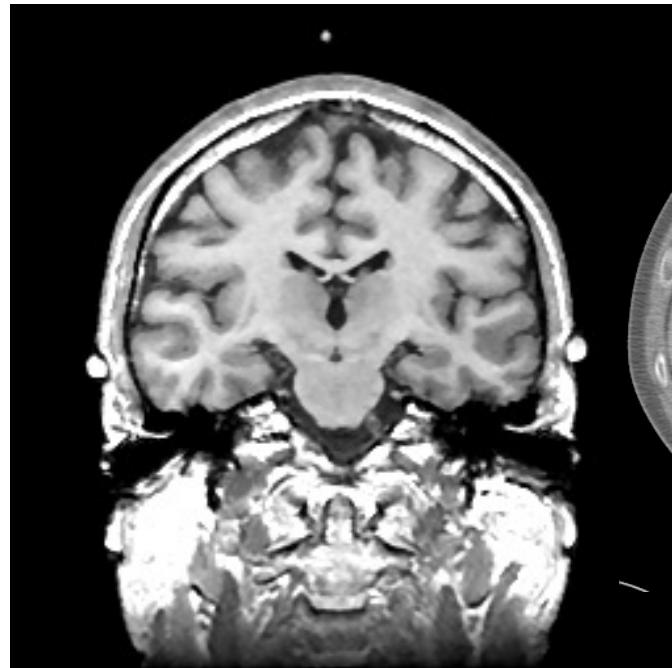


Medical Image Processing vs Computer Vision

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

Medical Imaging Classification (2)

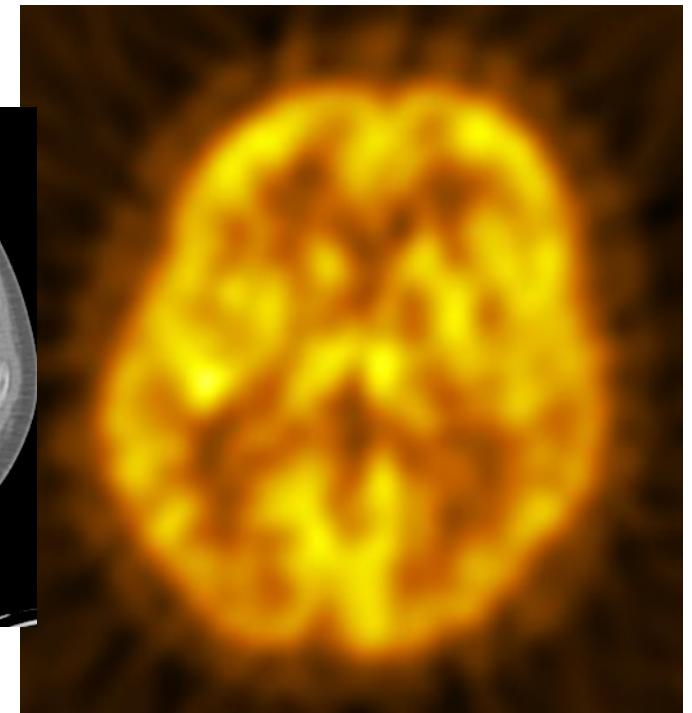
- Anatomical vs functional Imagery



MRI
Anatomical



CT with
contrast agent



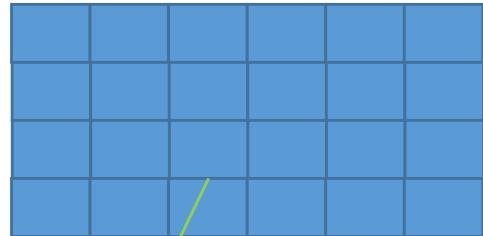
PET scan
Functional

Discrete Image Representation (1)

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

2D Array I

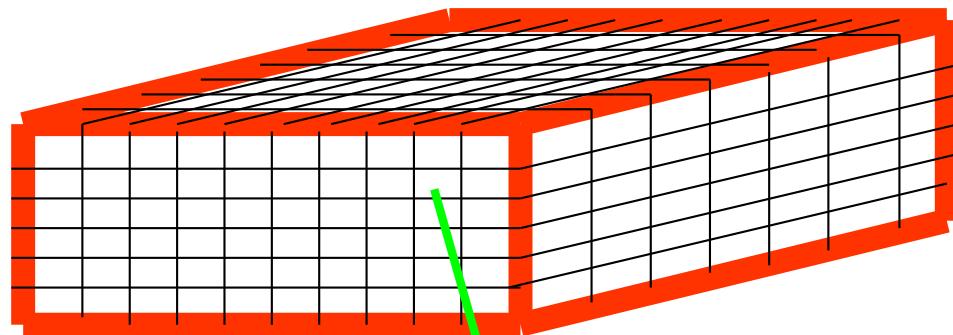
$I[\text{col}][\text{row}]$



Pixel=picture element

3D Array I

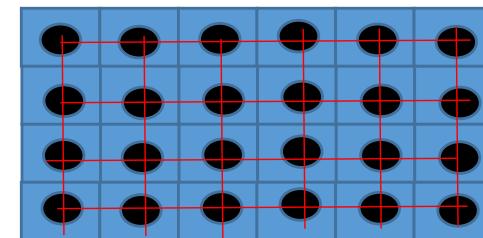
$I[\text{plane}][\text{col}][\text{row}]$



Voxel=
Volume Element

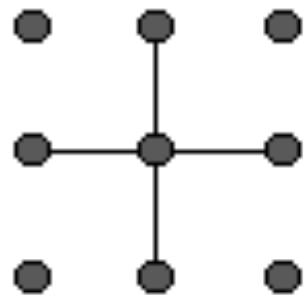
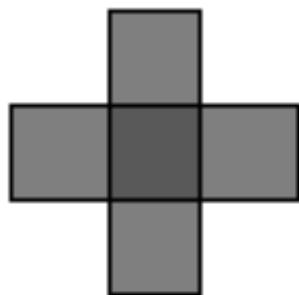
Discrete Image Representation (2)

- 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

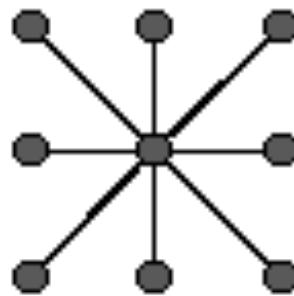


Neighborhood

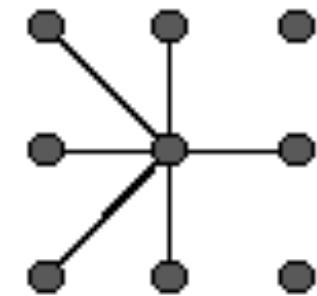
- Different types of neighborhood in 2D



4 -neighborhood



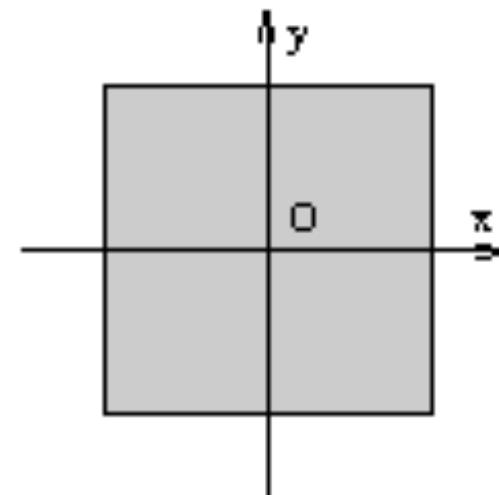
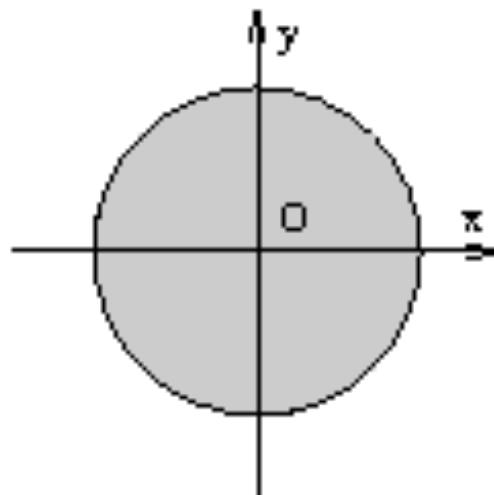
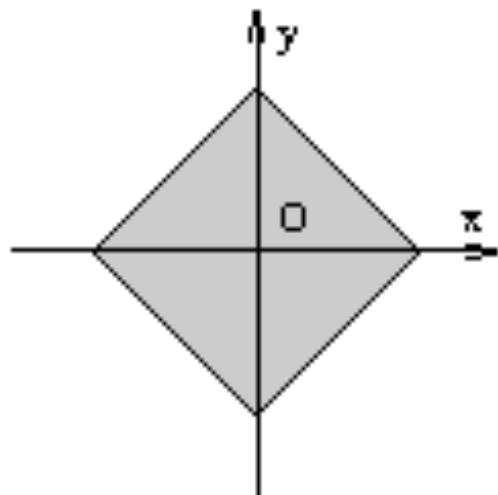
8 -neighborhood



6 -neighborhood

Neighborhood

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



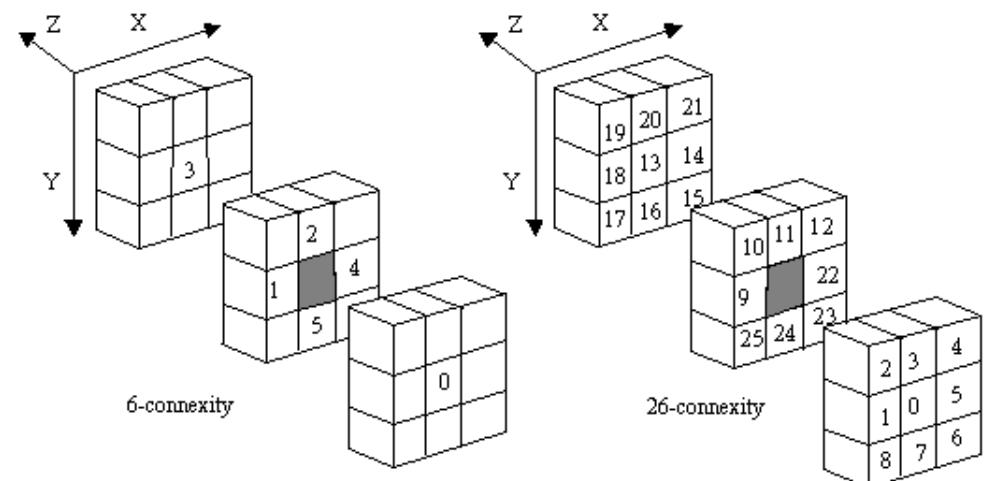
$$D_1(x, y) = \sum_{i=1}^n |y_i - x_i|$$

$$D_2(x, y) = \sqrt{\sum_{i=1}^n (y_i - x_i)^2}$$

$$D_\infty(x, y) = \max_{i=1 \dots n} |y_i - x_i|$$

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

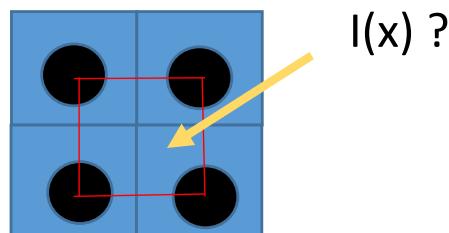
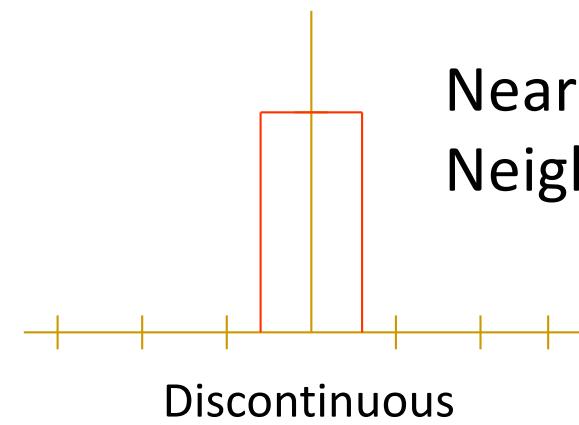
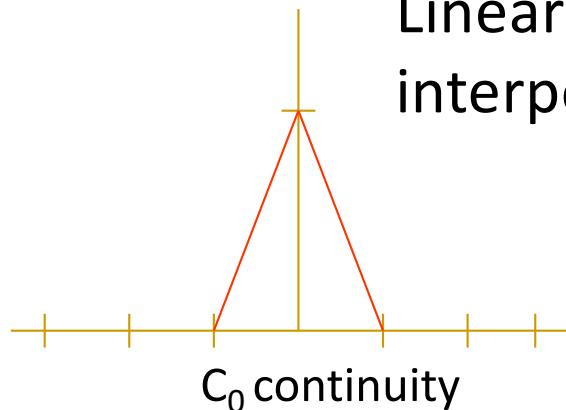


Image Domain \ Image Value	Discrete	Continuous
Discrete	Array of Int	Field of Integer
Continuous	Array of Float	Field of Float

1D Interpolation functions



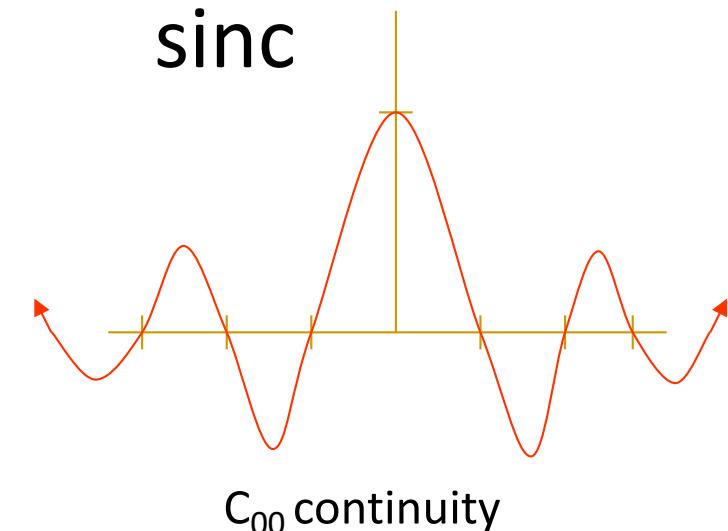
Nearest
Neighbor



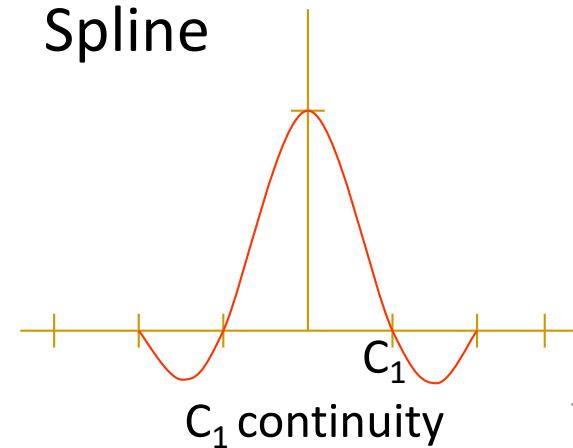
Linear
interpolation

Source : Joe Michael Kniss – Direct Volume Rendering

Hervé Delingette



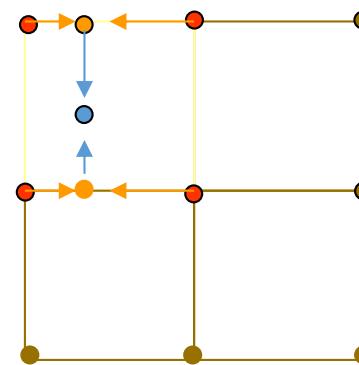
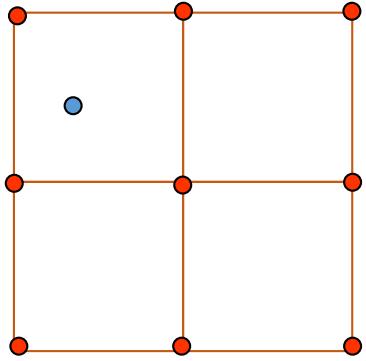
C_{00} continuity



C_1 continuity

Bilinear Interpolation (2D Field)

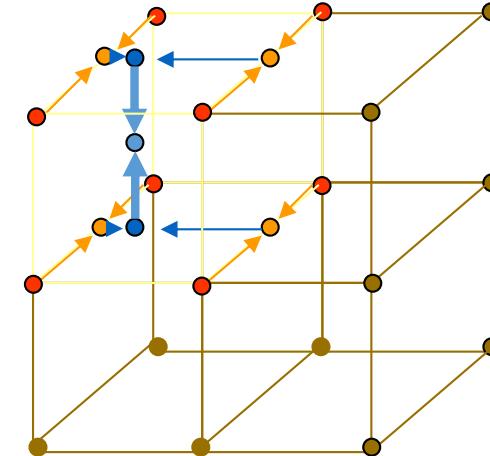
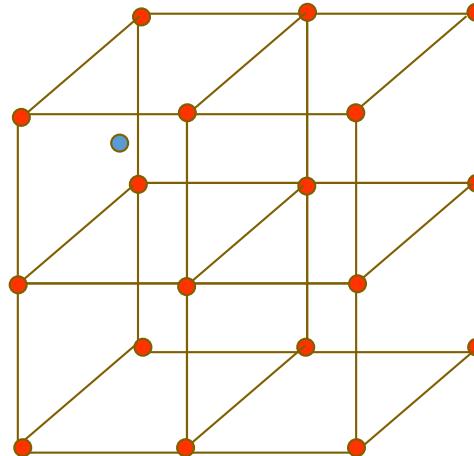
- Bilinear Interpolation : 3 linear interpolations



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

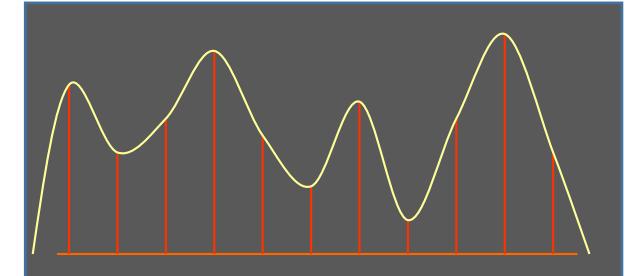
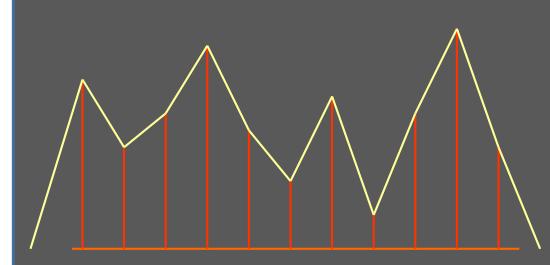
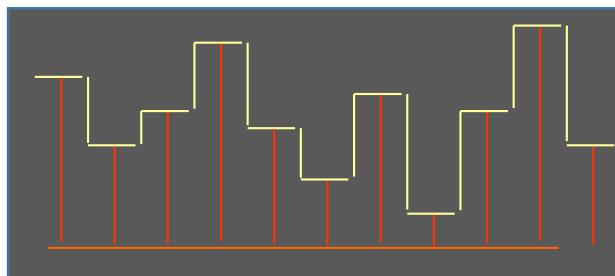
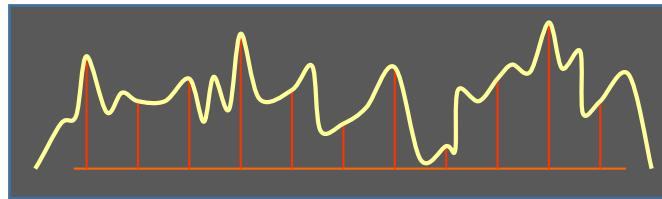
Trilinear Interpolation (3D Field)

- 7 linear interpolations



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

Image interpolation



Hervé Delingette