Acquisition of 3D Data

Tomographic Techniques

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3D Data

- **Animation, film:** a sequence of images with *time* as the third coordinate:

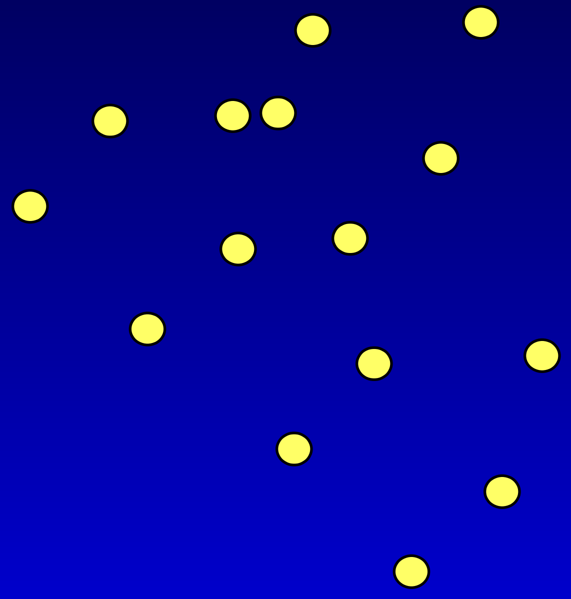
  [x,y,t]

- **Volume data:** a sequence of images with *space* as the third coordinate:

  [x,y,z]

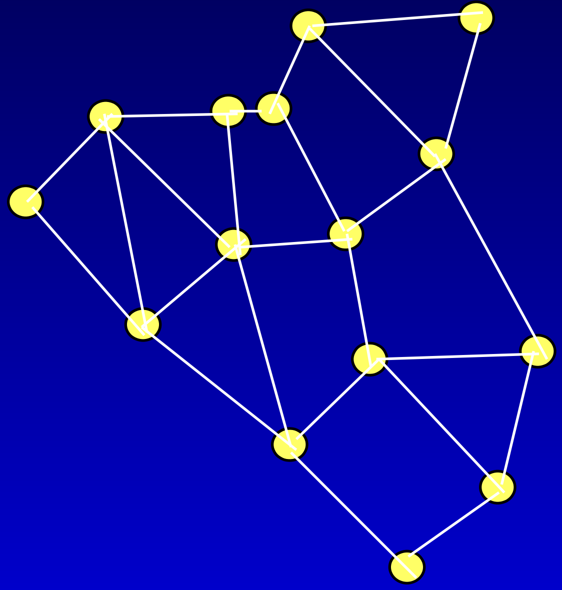
  - Volume data in general: a set of data samples measured on a grid with certain properties

Scattered Points



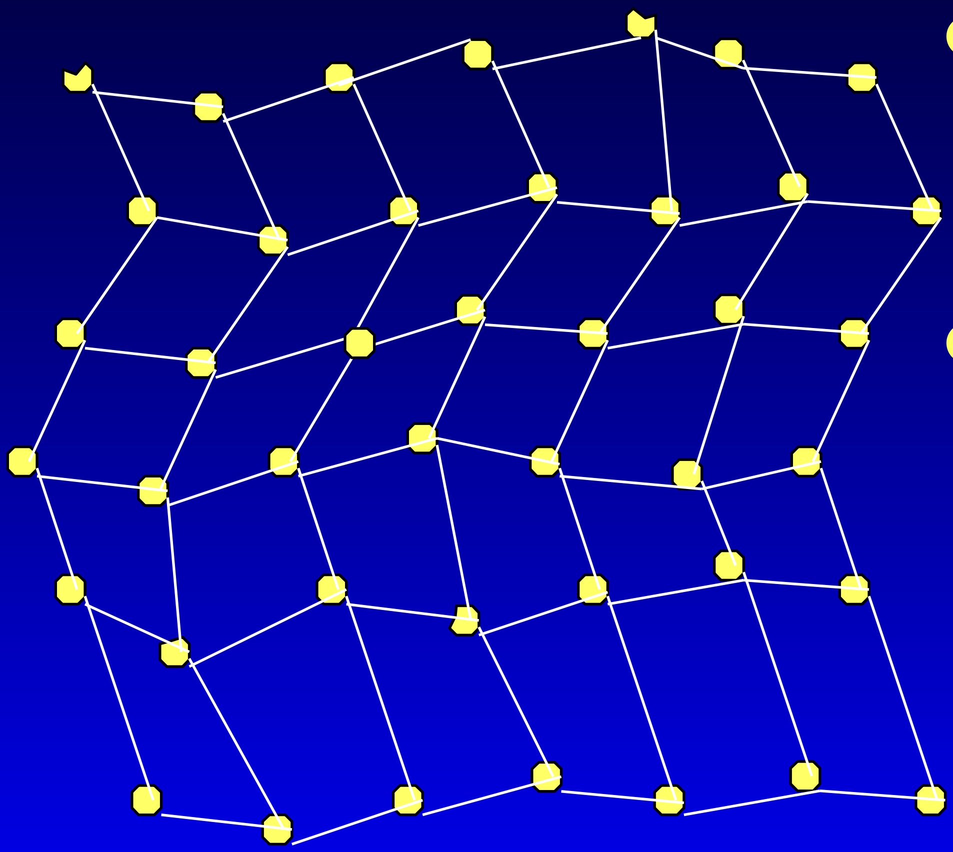
- Sample position
  - $[x_i, y_j, z_k]$
- Neighborhood relation:
  - None

Unstructured Grid



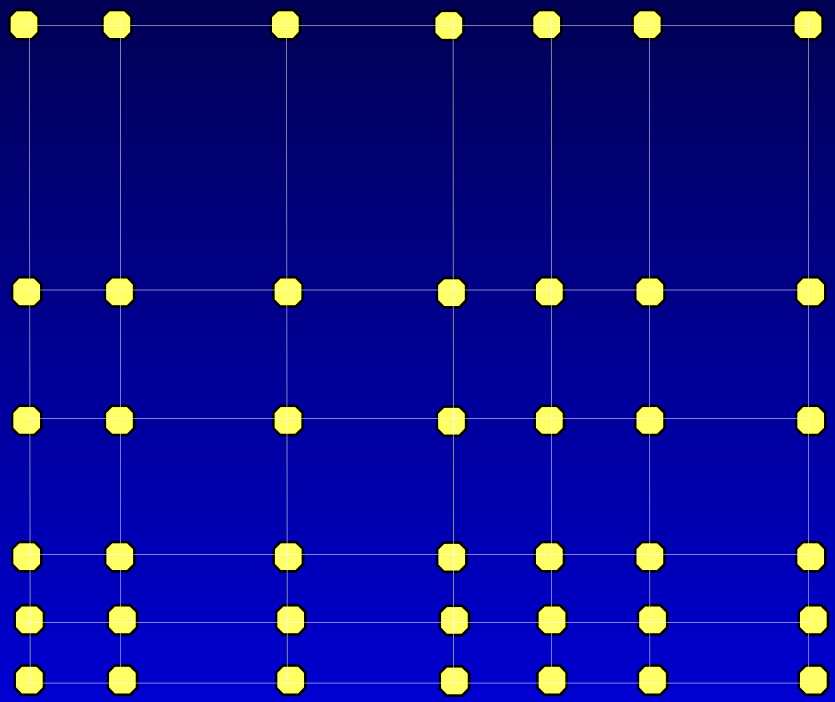
- Sample position
  - *[x_p, y_p, z_p]*
- Neighborhood relation:
  - Explicit *i-k, i-l, ...*

Structured Grid



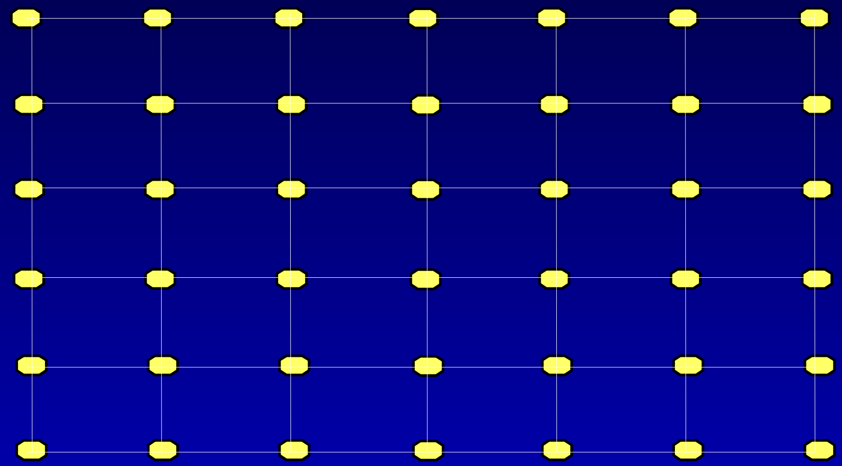
- Sample position:
  - based on coordinates at *[i,j,k]*
- Neighborhood relation:
  - Implicit, neighbors from the grid

Rectilinear Grid



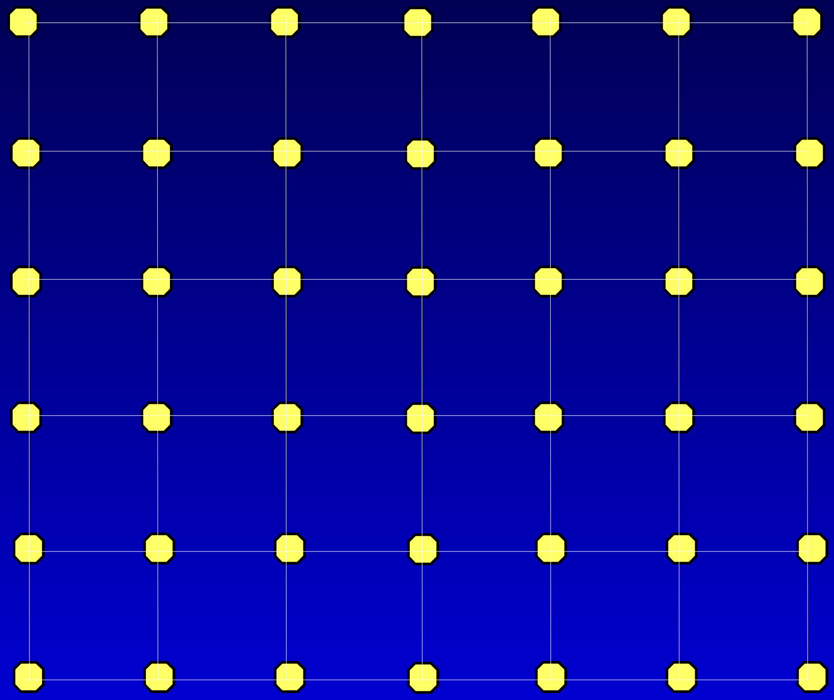
- Sample position:
  - Coordinates *[i,j,k]*
  - Distance between *X,Y* and *Z* planes
- Neighborhood relation:
  - Implicit, neighbors from the grid

Regular Grid



- Sample position:
  - Coordinates *[i,j,k]*
  - Cell size *[X ,Y ,Z]*
- Neighborhood relation:
  - Implicit, neighbors from the grid

Cartesian Grid

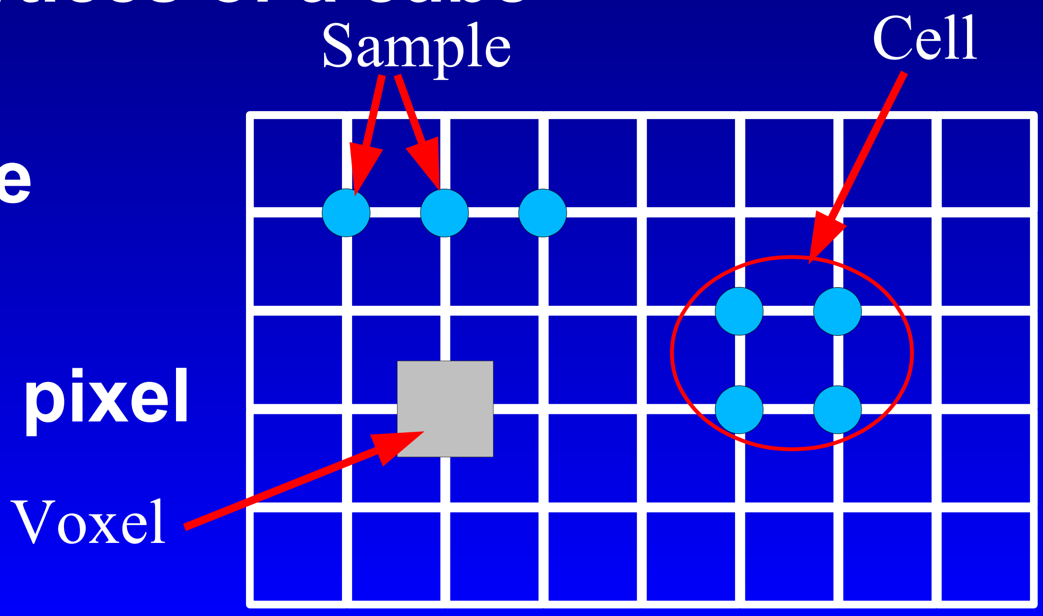


- **Sample position:**
  - **Coordinates *[i,j,k]***
  - **Cell dimension *X***
- **Neighborhood relation:**
  - **Implicit, neighbors from the grid**

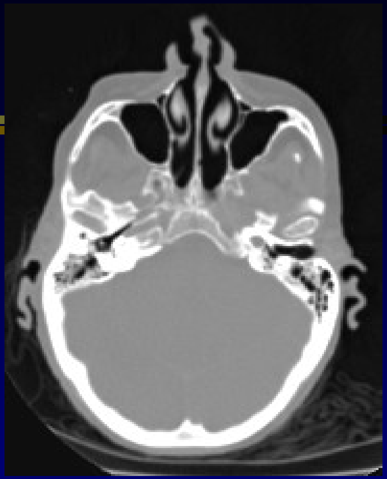
Cartesian Grid and its Elements

Basic elements of volume data

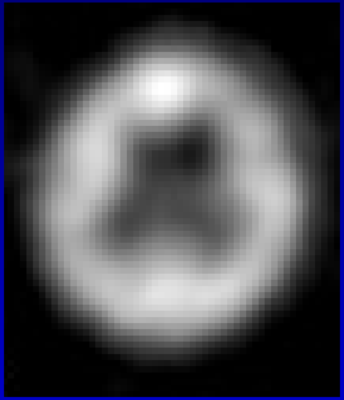
- **Sample:**
  - Dimensionless point with value
- **Cell:**
  - 8 (4) samples in vertices of a cube
- **Voxel**
  - Homogeneous cube centered at sample position
  - Analogue of the 2D pixel



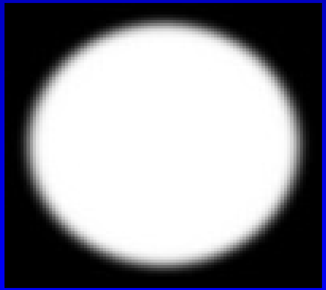
Acquisition of Volumetric Data



- 3D imaging techniques
  - **Anatomically** oriented techniques:
    - Computer tomography-CT, magnetic resonance imaging-MRI, ultrasound imaging-US
  - **Physiologically** oriented techniques :
    - Positron emission tomography-PET, single-photon emission tomography-SPECT, functional MRI



- Synthetic data
  - Voxelization



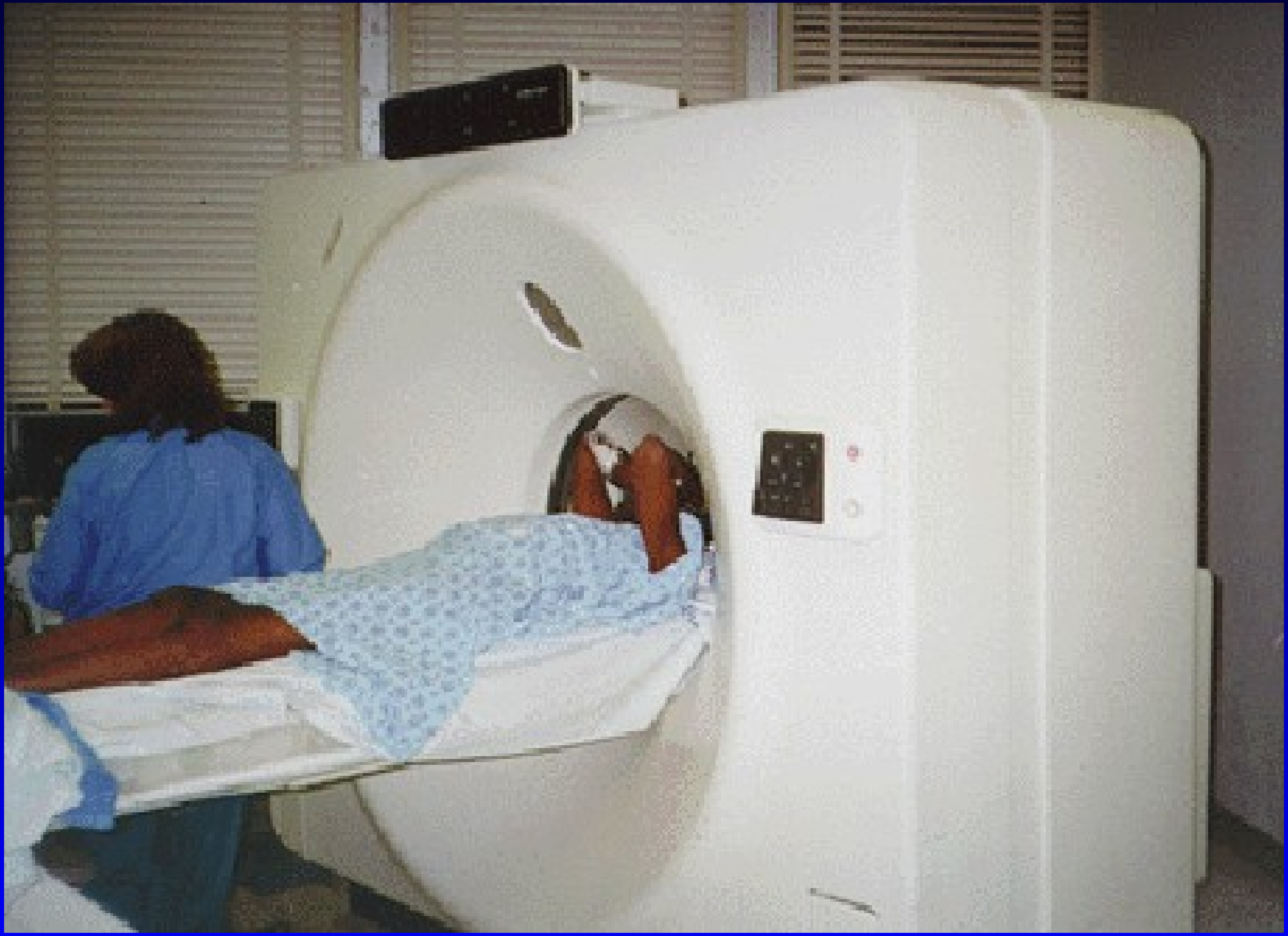
Computed Tomography (CT)

- Also: Computer Aided Tomography (CAT, CAT scan)
- Principle:
  - Measurement of X-ray attenuation along a viewing ray (projections)

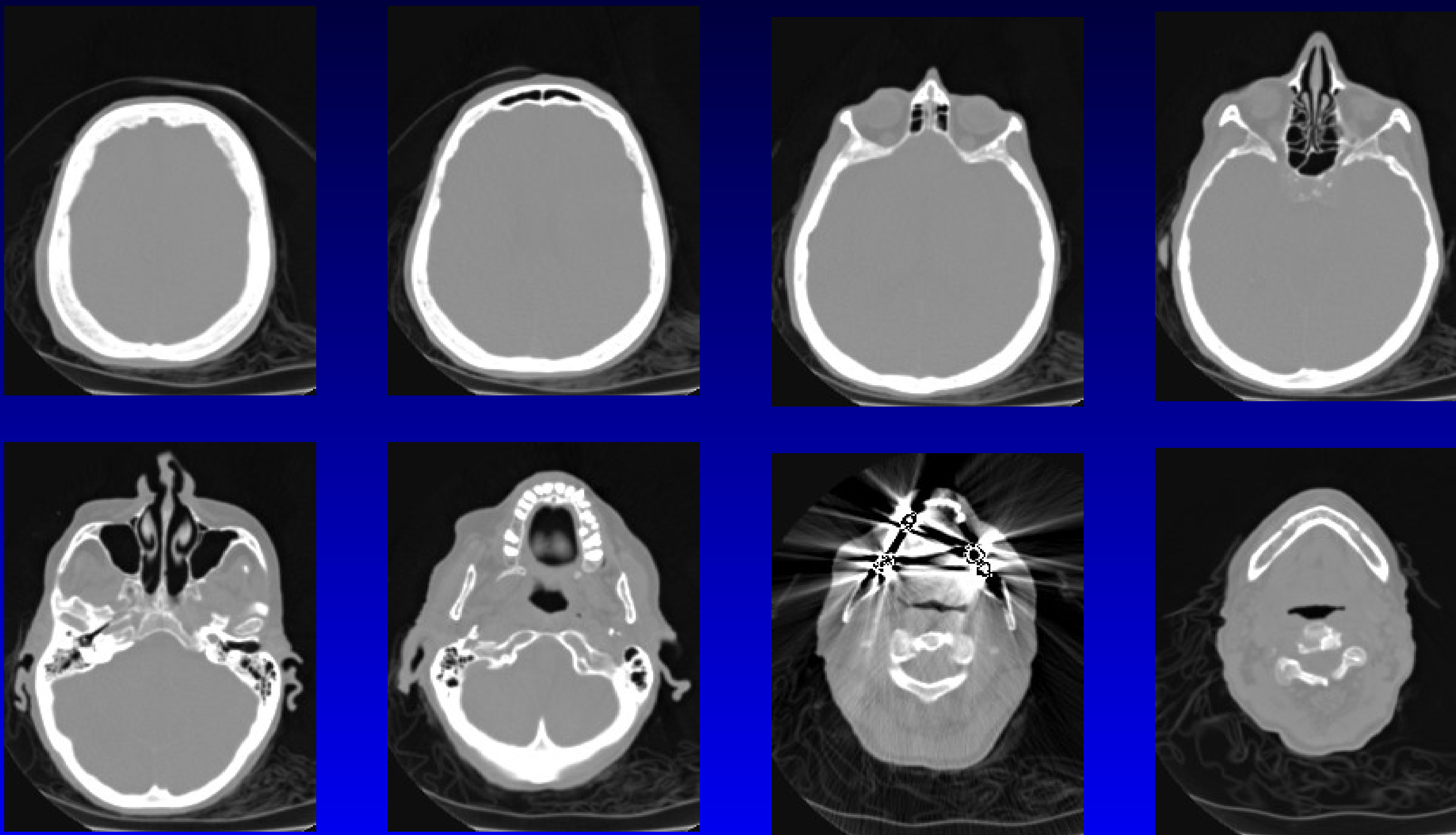
$$S = \int \mu(l)\ dl$$

  - Production of images: reconstruction from projections

A CT Tomograph

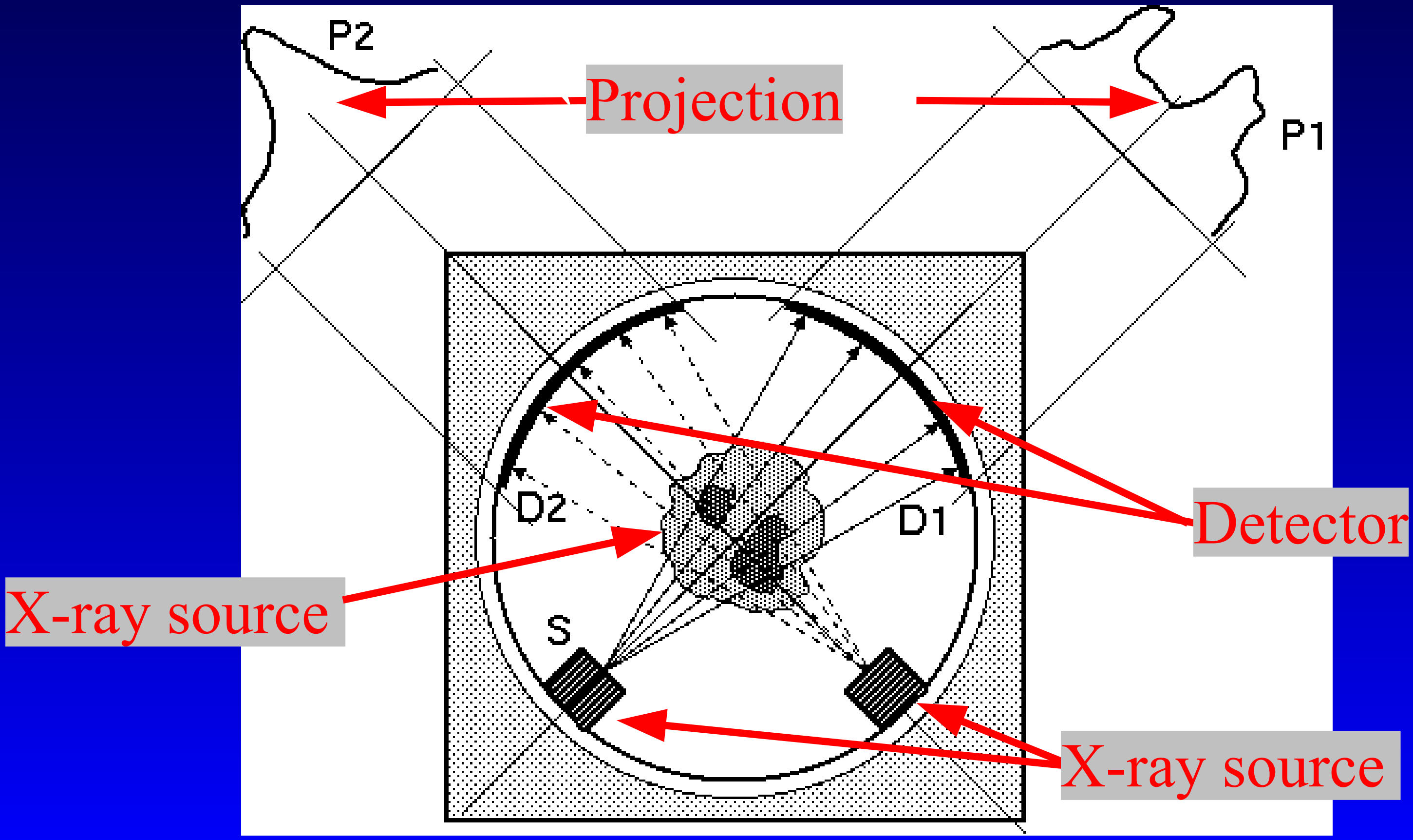


A Sample CT Scan



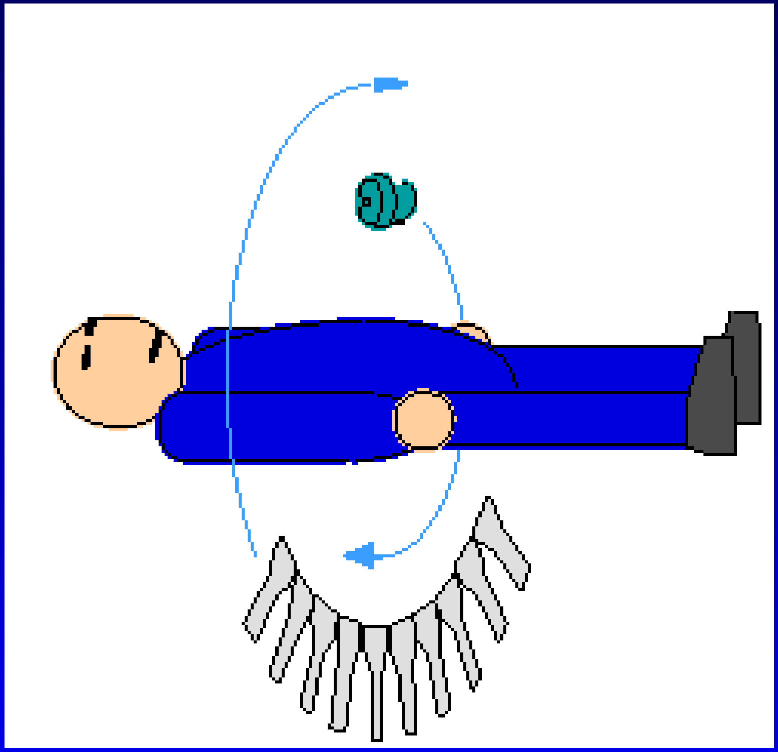
Measurement of Projections

- Standard setup:
  - cca 200 1D projections for one slice

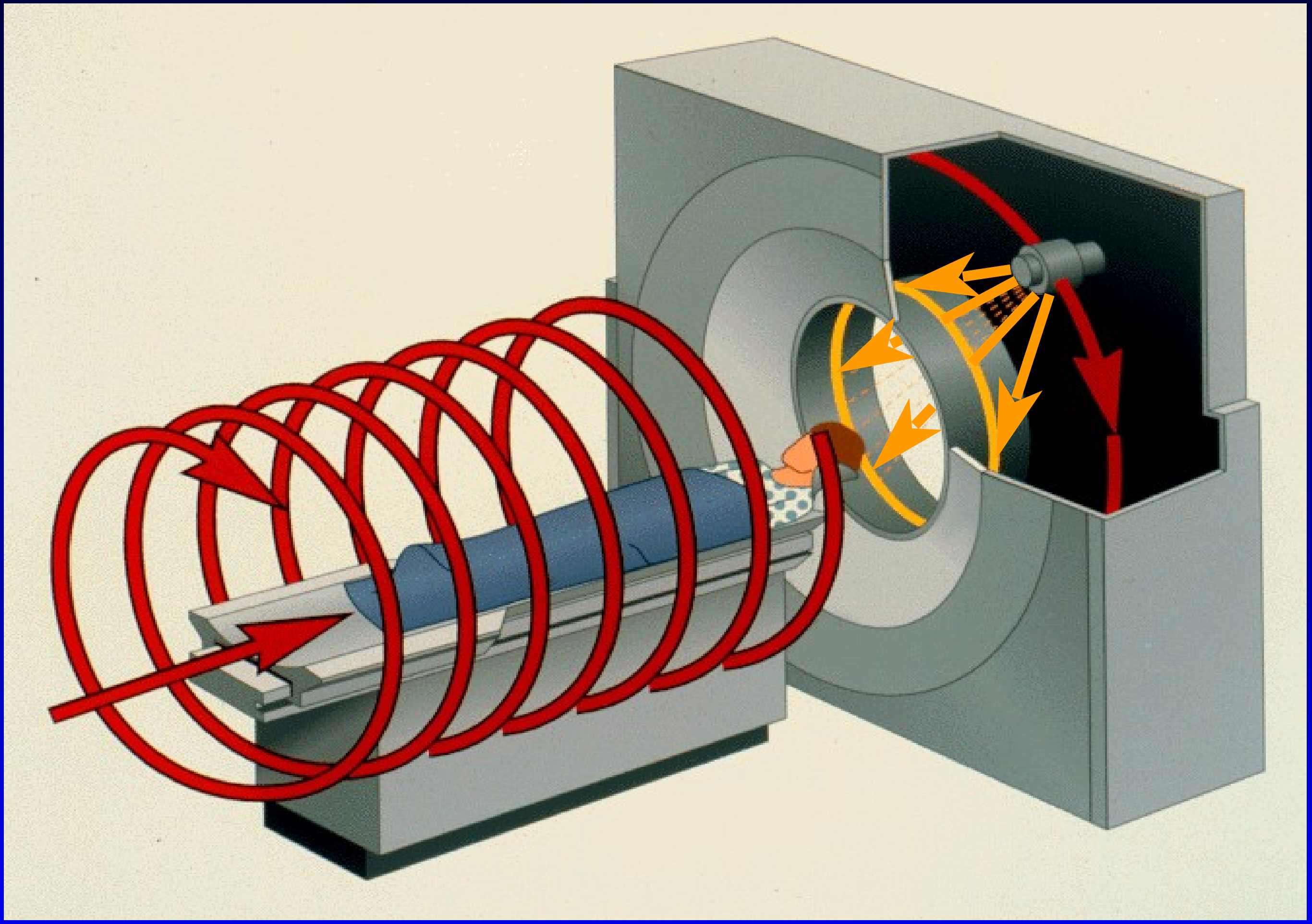


Measurement of Projections

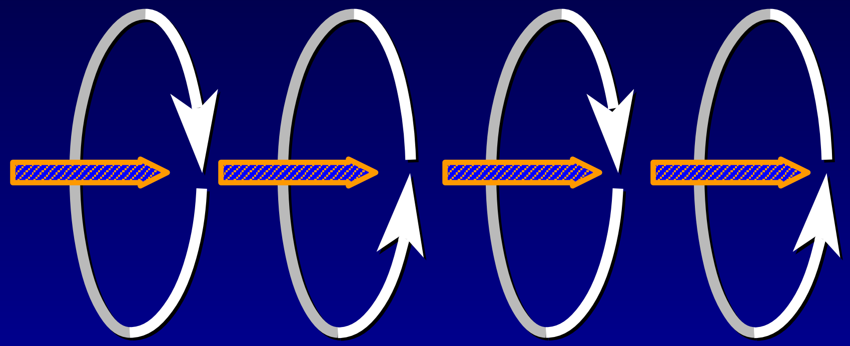
- Spatial configuration of source and detector arrays:
  - Aligned rotation
  - 180 deg



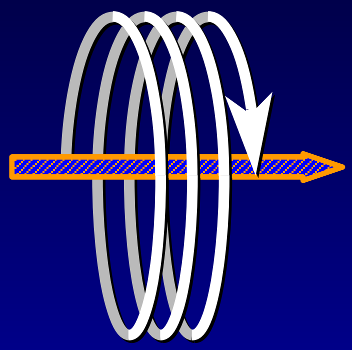
Recent Setup: Fan-Beam Spiral CT



Standard CT vs. Spiral CT



25 Slices in
> 2 Minutes

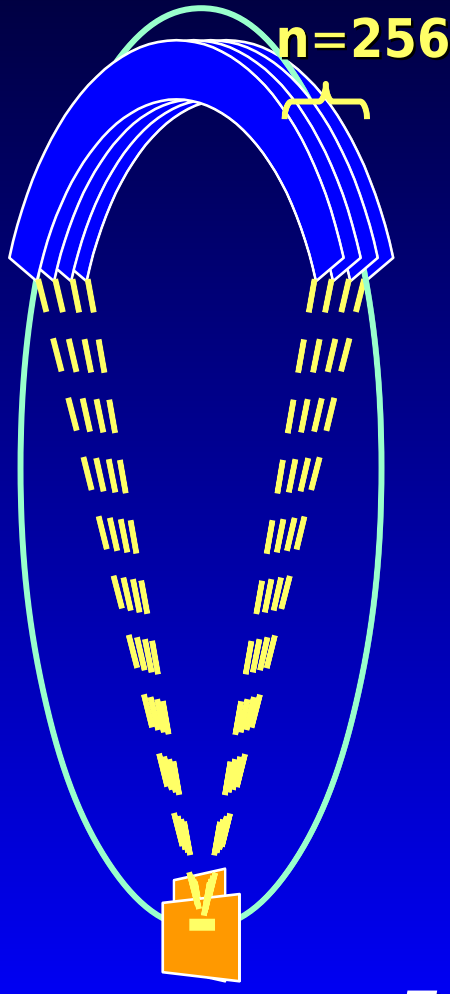


25 Slices in
25 Seconds

Multi-Detector CT Scanner

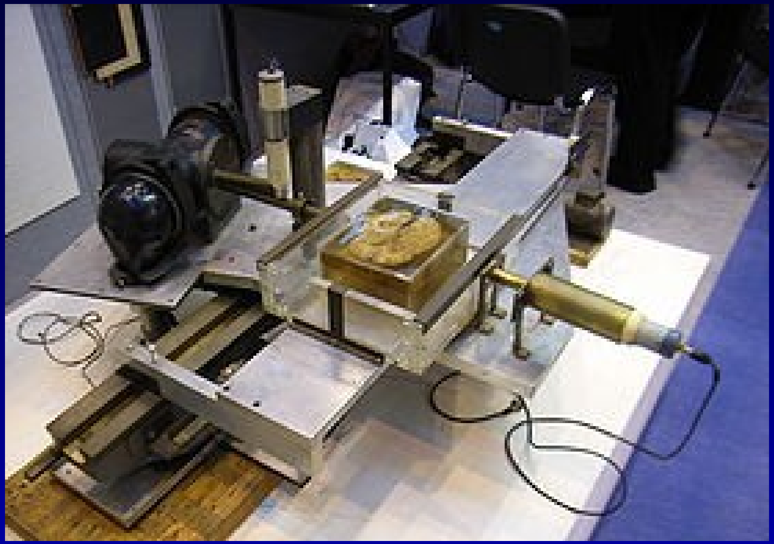
State of the art:

- Detectors
  - Up to 256
  - Spacing < 1mm
- Scanning speed:
  - 1m/30s



Reconstruction from Projections

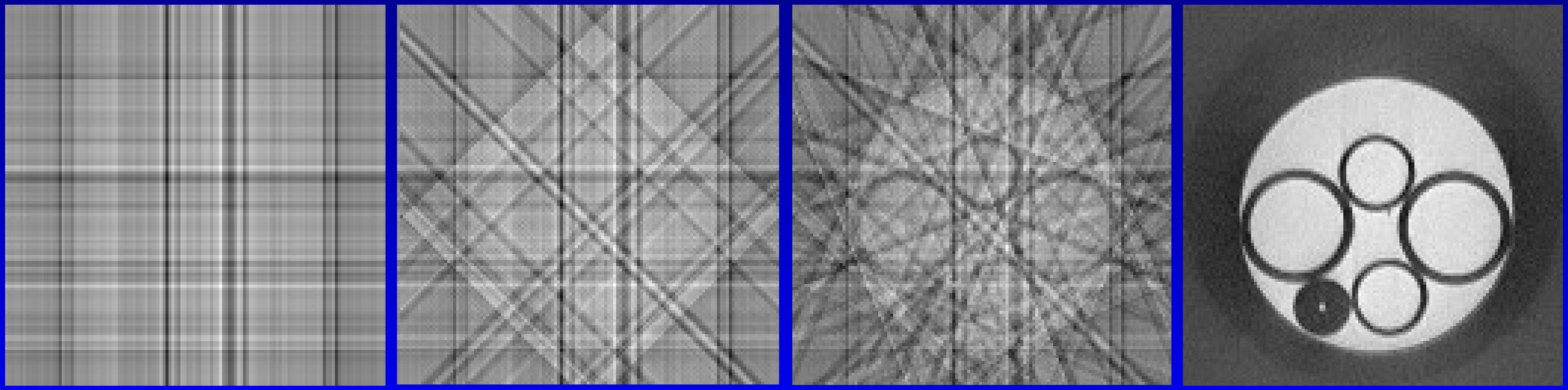
- Theory:
  - Johann Radon
- First Tomograph:
  - Godfrey Hounsfield
  - Nobel prize 1979
- Reconstruction methods:
  - Algebraic methods
  - Filtered backprojection
  - Fourier methods



Source: Wikipedia

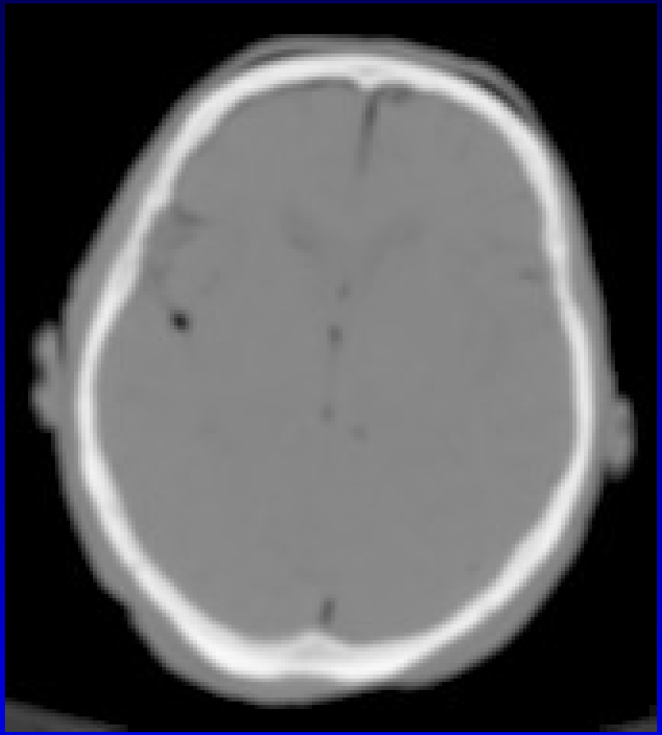
Filtered Backprojection

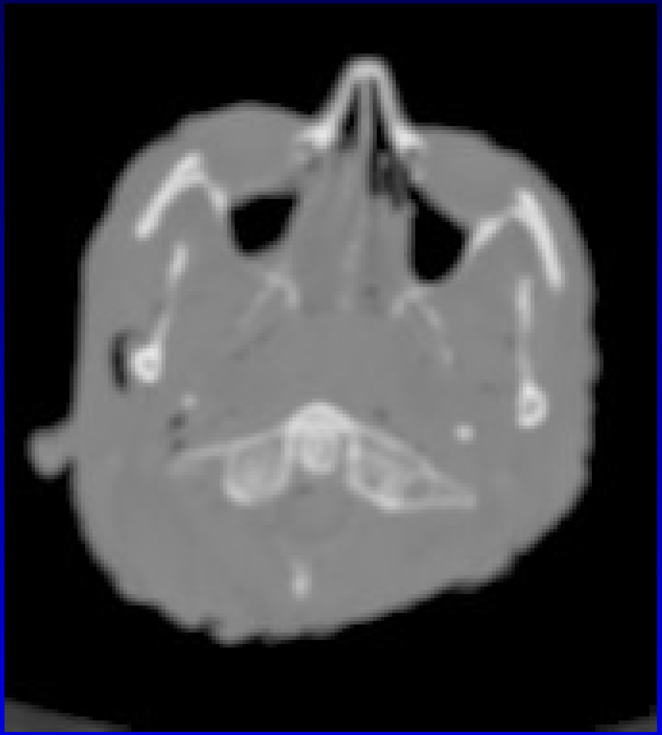
- For all projections:
  - Projection filtration (high pass filter, derivative)
  - Distribution of the filtered projection to the image in the direction of the projection



2 4 8 All

CT Tomogram - an Example



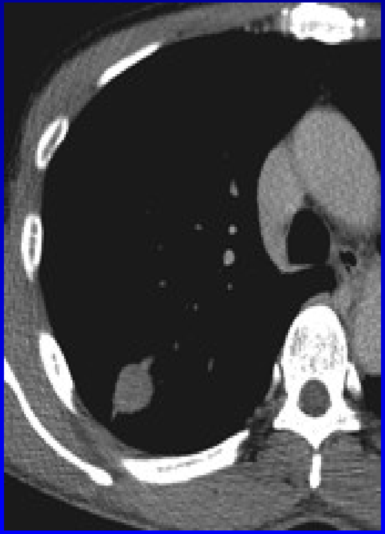


Dual Energy CT

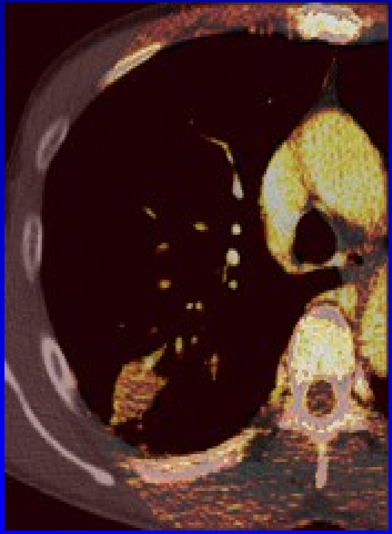
- Attenuation coefficient μ depends on the wavelength
- Scanning with two X-ray lamp voltages (energies)
- Advantage: Discrimination of tissue types

Voltage 80kV

Voltage 120kV



Composited



Hounsfield Unit

- Normalization of measured values to a -1000 – 3095 (12 bit) scale:

Substance	Value [HU]
Air	-1000
Water	0
Fat	70 – 120
Soft tissues	15 – 80
Bone	>1000

- Tissue density is defined by its physical properties

CT Data Properties

- Axial slices 0.5-10 mm thick
- Images 256 x 256 to 512 x 512 pixels of 0.5-2 mm side
- Up to 2000 images per study
- High spatial resolution
- Consistent values (HU scale)
- X-ray irradiation

Application Fields

- Contrast determined by tissue density:
  - Bone imaging
  - Calcifications
  - Inflammations
  - Hematomata
  - Tumors
- Imaging with contract agent:
  - Blood vessels, vessel lumen

Overview

- Computer tomography (CT, CAT)
- Magnetic resonance imaging (MRI)
- fMRI
- SPECT
- PET

Magnetic Resonance Imaging

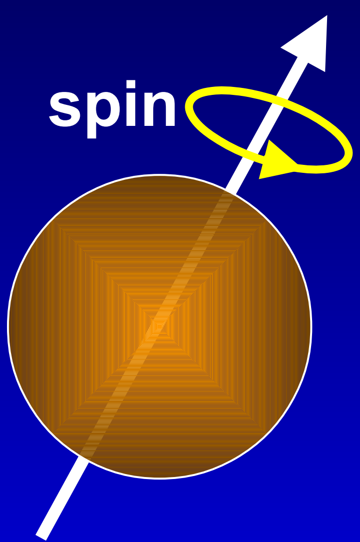
- ~~Nuclear Magnetic Resonance (NMR)~~ Magnetic Resonance Imaging (MRI)
- Physical principle
  - Interaction of atom nuclei with an external magnetic field (resonance)
  - Requirement: Nonzero magnetic or spin moment of the atoms
- Resonance
  - Energy transfer between coupled systems with equal characteristic frequency
  - Example: The Tacoma Narrows bridge

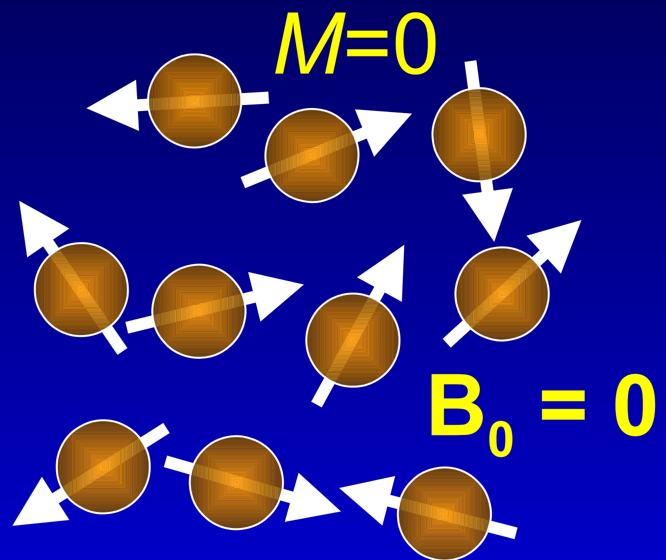
Common NMR Active Nuclei

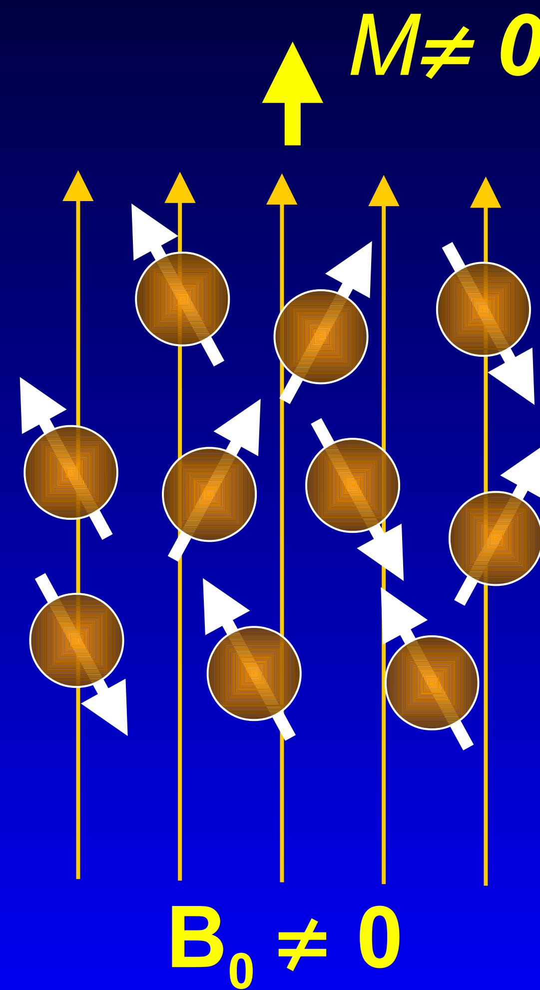
Isotope	Spin *I*	% abundance	γ MHz/T
^{1}H	1/2	99.985	42.575
^{2}H	1	0.015	6.53
^{13}C	1/2	1.108	10.71
^{14}N	1	99.63	3.078
^{15}N	1/2	0.37	4.32
^{17}O	5/2	0.037	5.77
^{19}F	1/2	100	40.08
^{23}Na	3/2	100	11.27
^{31}P	1/2	100	17.25

Spins in a Magnetic Field

Atoms with uncompensated magnetic moment



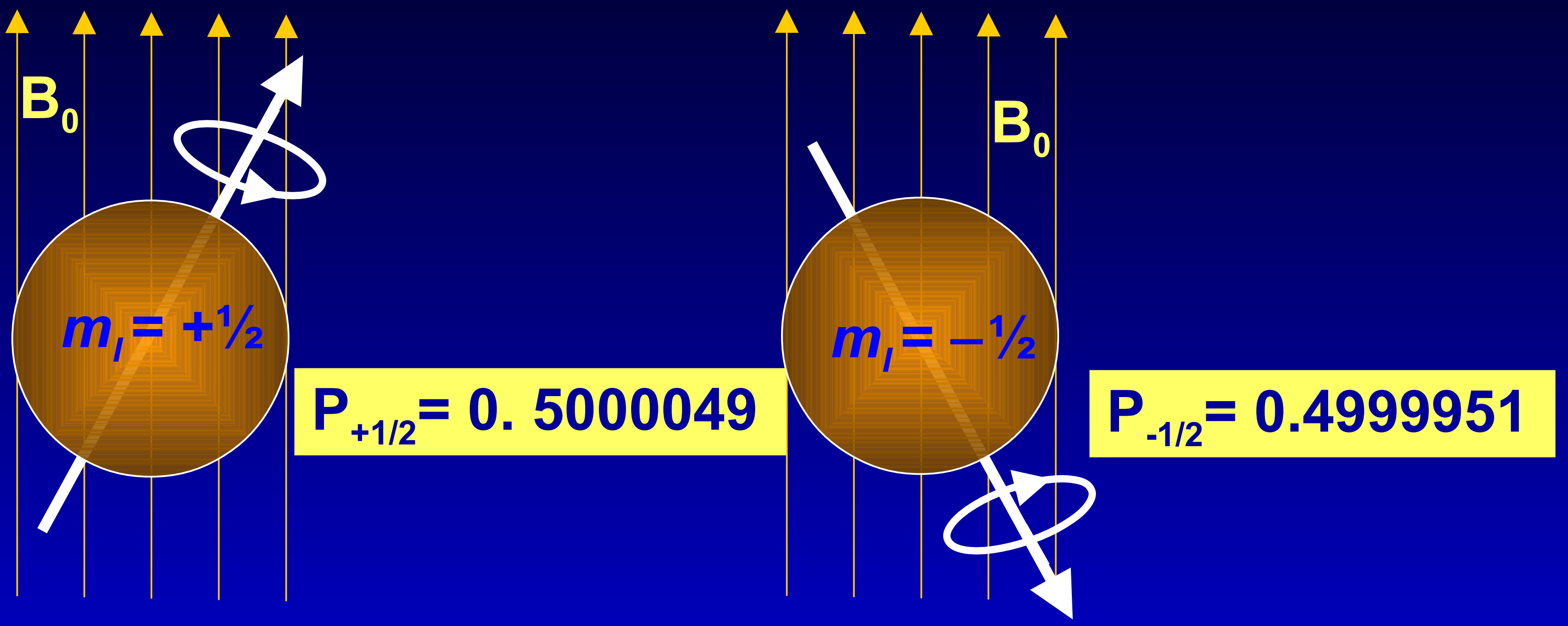




M - Magnetization (material)

B - Induction (field strength)

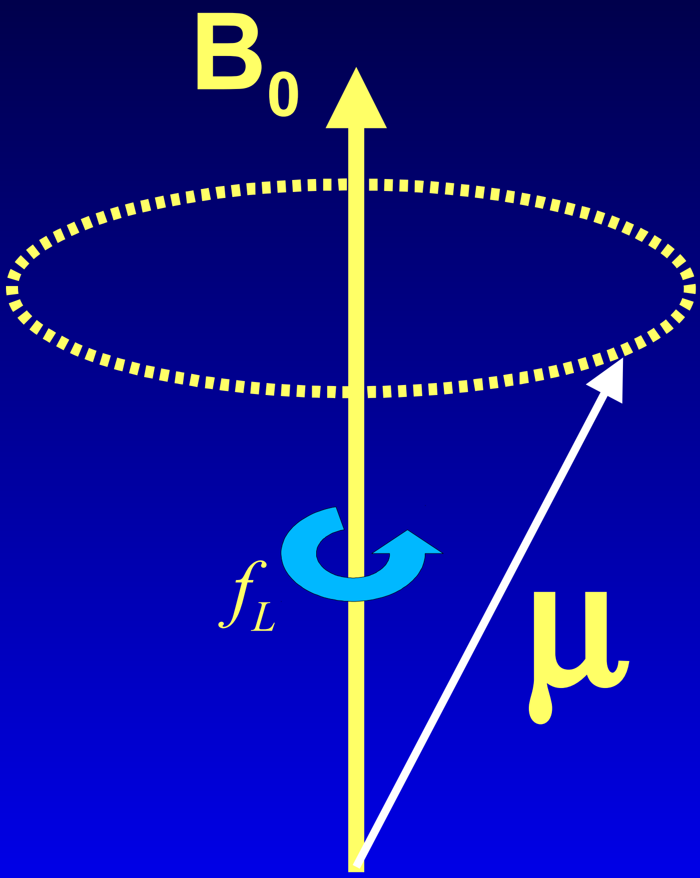
Spin in a Magnetic Field (Zeeman Splitting, Spin ½)



1.5T, T=310K,

⇒ Total magnetization M is parallel to B_0

Spin in a Magnetic Field



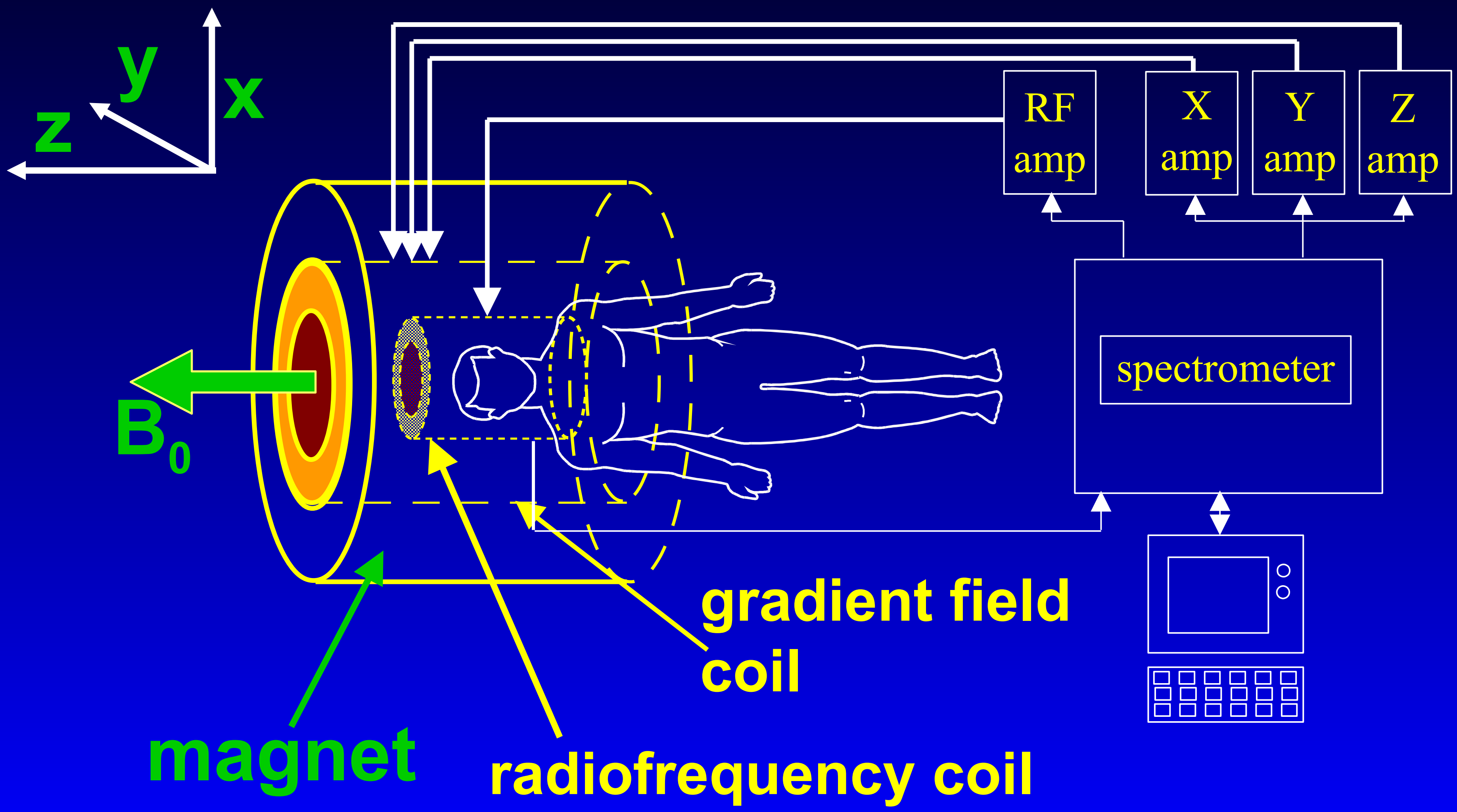
- μ **rotates around** B_0
- B_0 – external mg. field
- **μ** – spin moment
  - rotates around B_0 with Larmor frequency

$$f_L = \gamma B_0$$

- **γ**– gyromagnetic ratio (γ= 42.58 MHz/T for H)
- Total magnetization:

$$M = \sum \mu_i$$

MRI System Block Diagram



Magnetic Field of a Tomograph

- Induced magnetic field:
  - Electromagnets
  - Superconductive electromagnets
  - Permanent magnets
- Field strength
  - 0.5T – 3T, (up to 15T for research)
- Earth’s mg. field : 0.3 - 0.7 x 10^{-5}T

Principle of MR Imaging

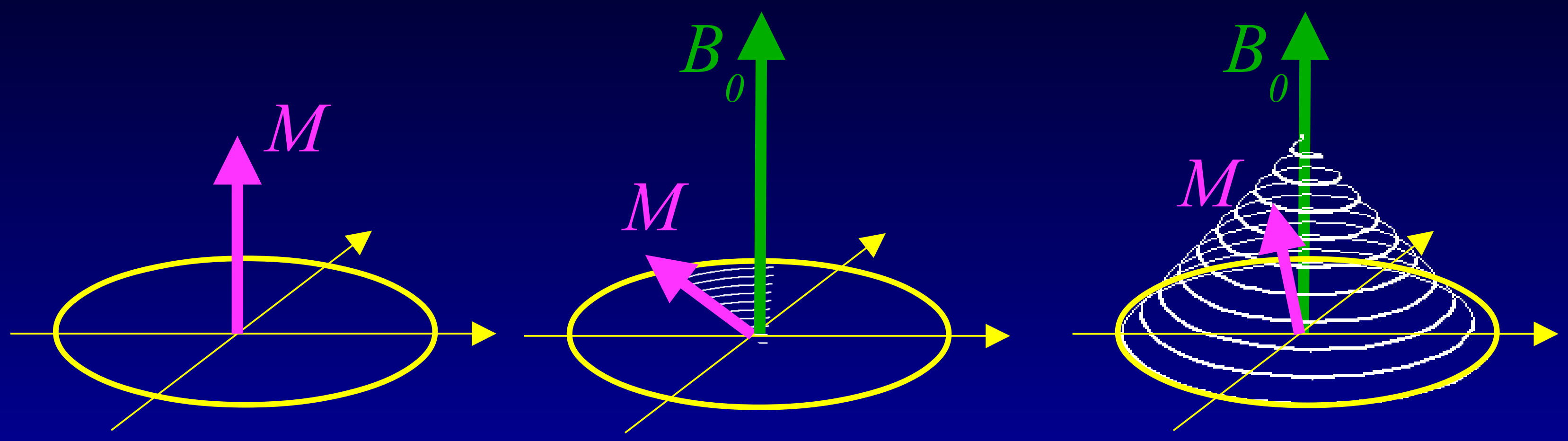
Absorption and emission of energy by spins in external magnetic field (resonance)

- **Equilibrium**: M || B_0: Uncoupled μ_i vectors:

$$M_z = M, \quad M_{xy} = 0$$

- **Absorption of RF (radiofrequency) energy**: excitation($f = f_L$)
  - Transition to higher energy state: $M_z < M$ owing to vector μ_i flipping
  - Coupled rotation of μ_i: $M_{xy} \neq 0$
  - Measurable signal due to M_{xy}
- **Relaxation**: return to equilibrium

Spin Excitation and Relaxation



Equilibrium

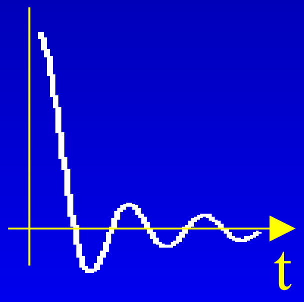
Excitation
by RF
impulse

Relaxation:
Return back to
equilibrium.

Relaxation

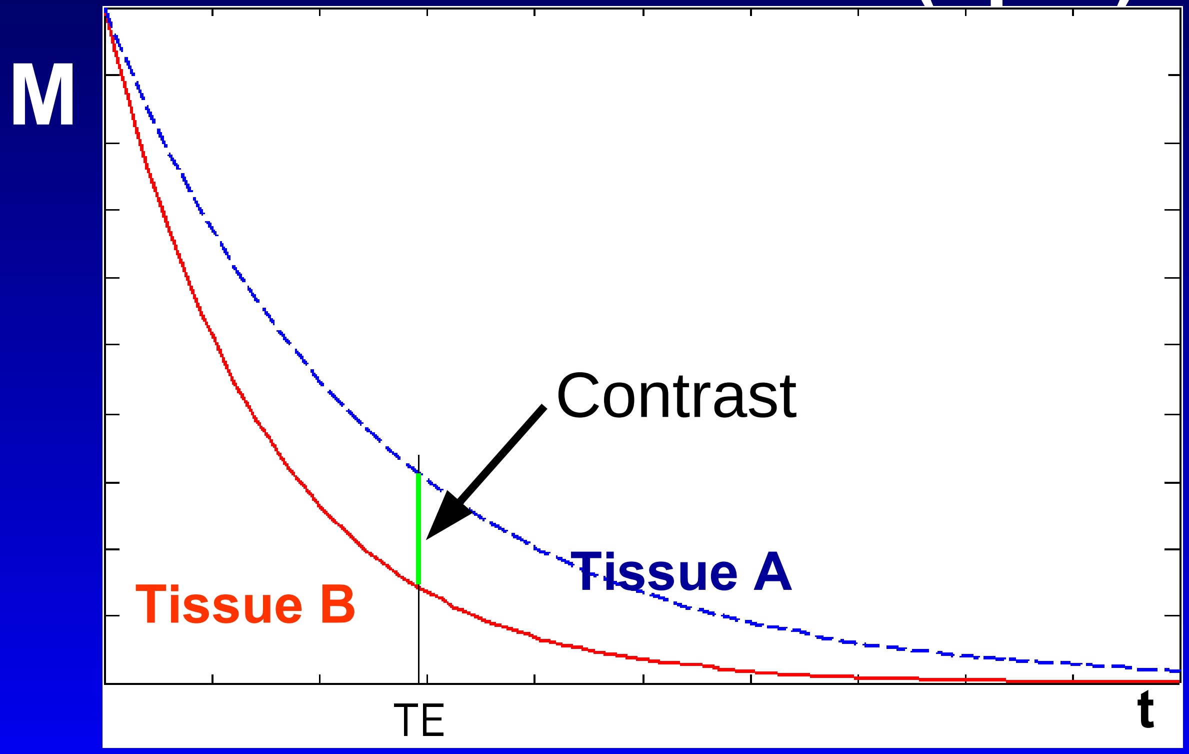
Return to equilibrium state after the RF pulse

- **Longitudinal relaxation (spin-lattice, rate T_1):**
  - **Energy transfer to surrounding tissue**
  - **Flipping of μ_i vectors to original orientation**
- **Transversal relaxation (spin-spin, rate T_2):**
  - **Decoupling of μ_i due to field inhomogeneities and spin-spin interaction**
- **Measured signal during the relaxation**
  - **FID (Free Induction Decay)**



Tissue Contrast

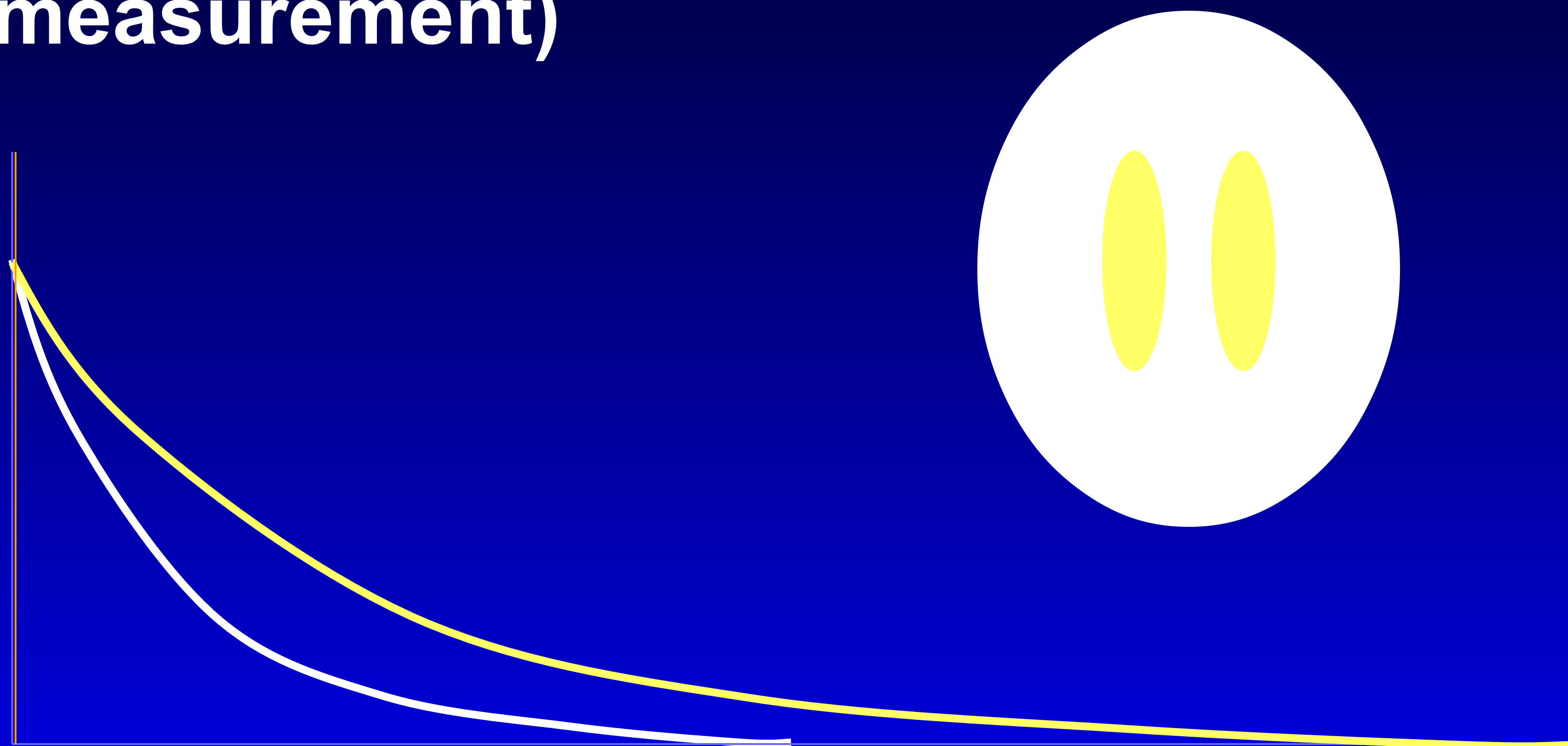
- Both T_1 and T_2 depend on the chemical environment of the nucleus (spin).



TE: time of measurement, echo time

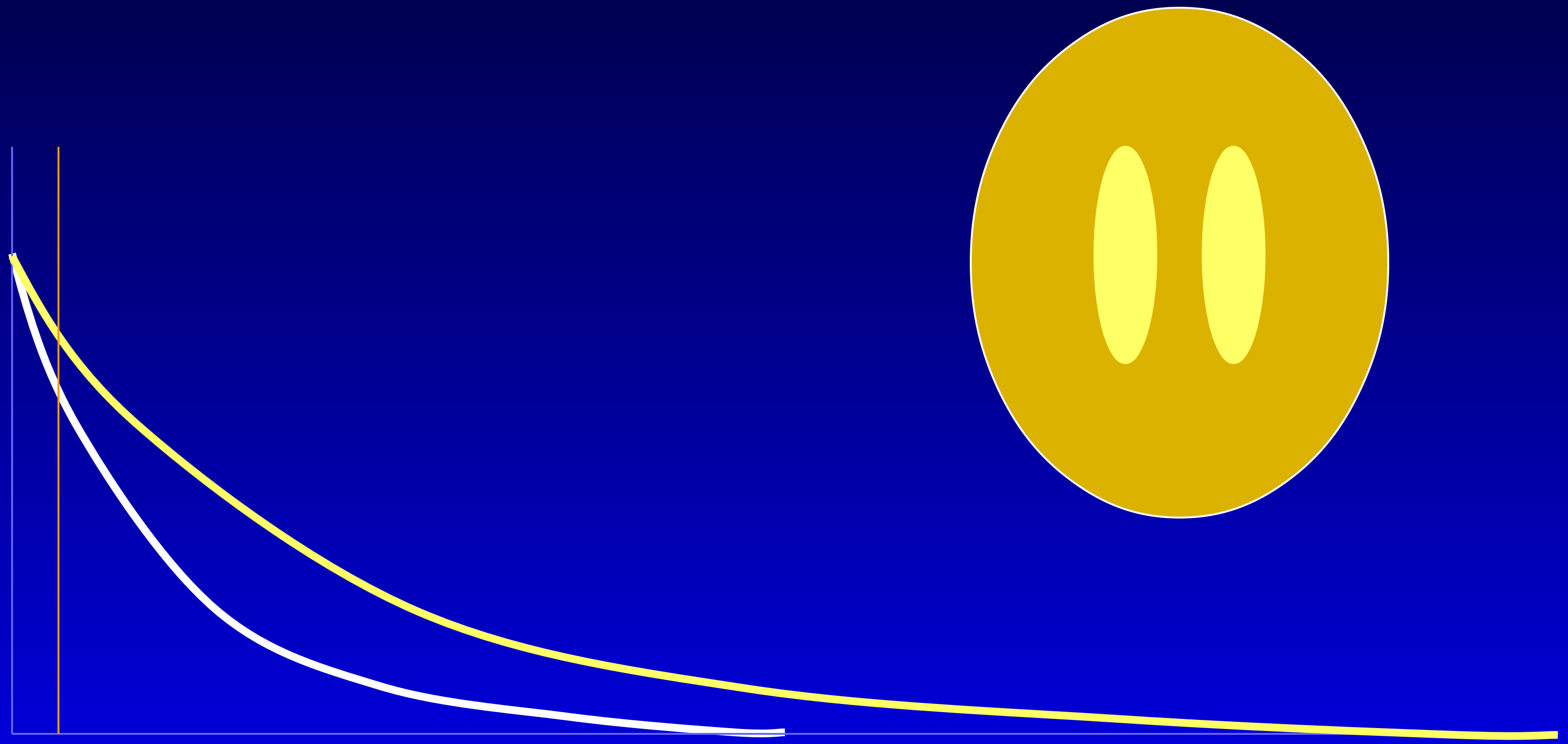
Tissue Contrast

- Effect of TE (echo time, time of measurement)



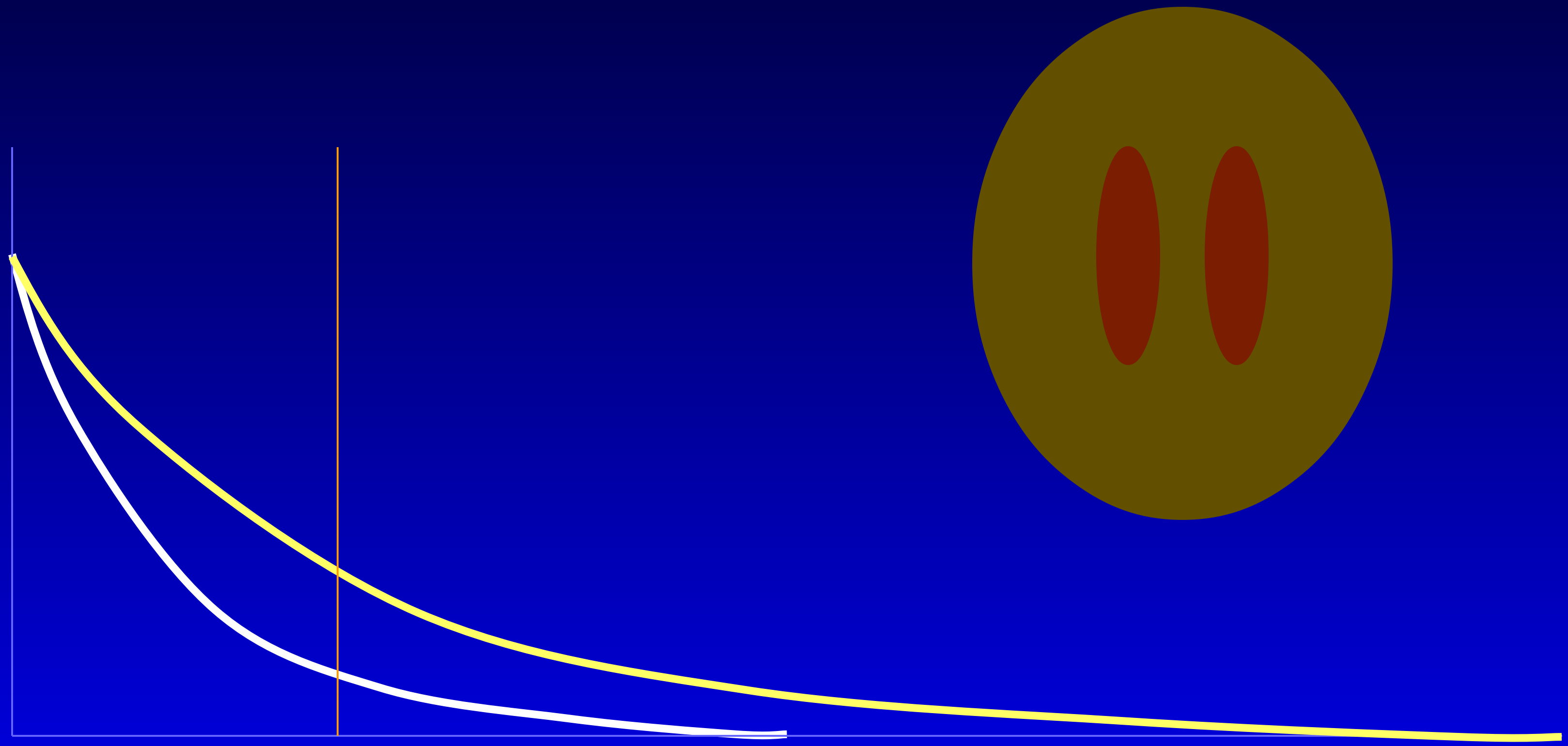
Tissue Contrast

- Effect of echo time



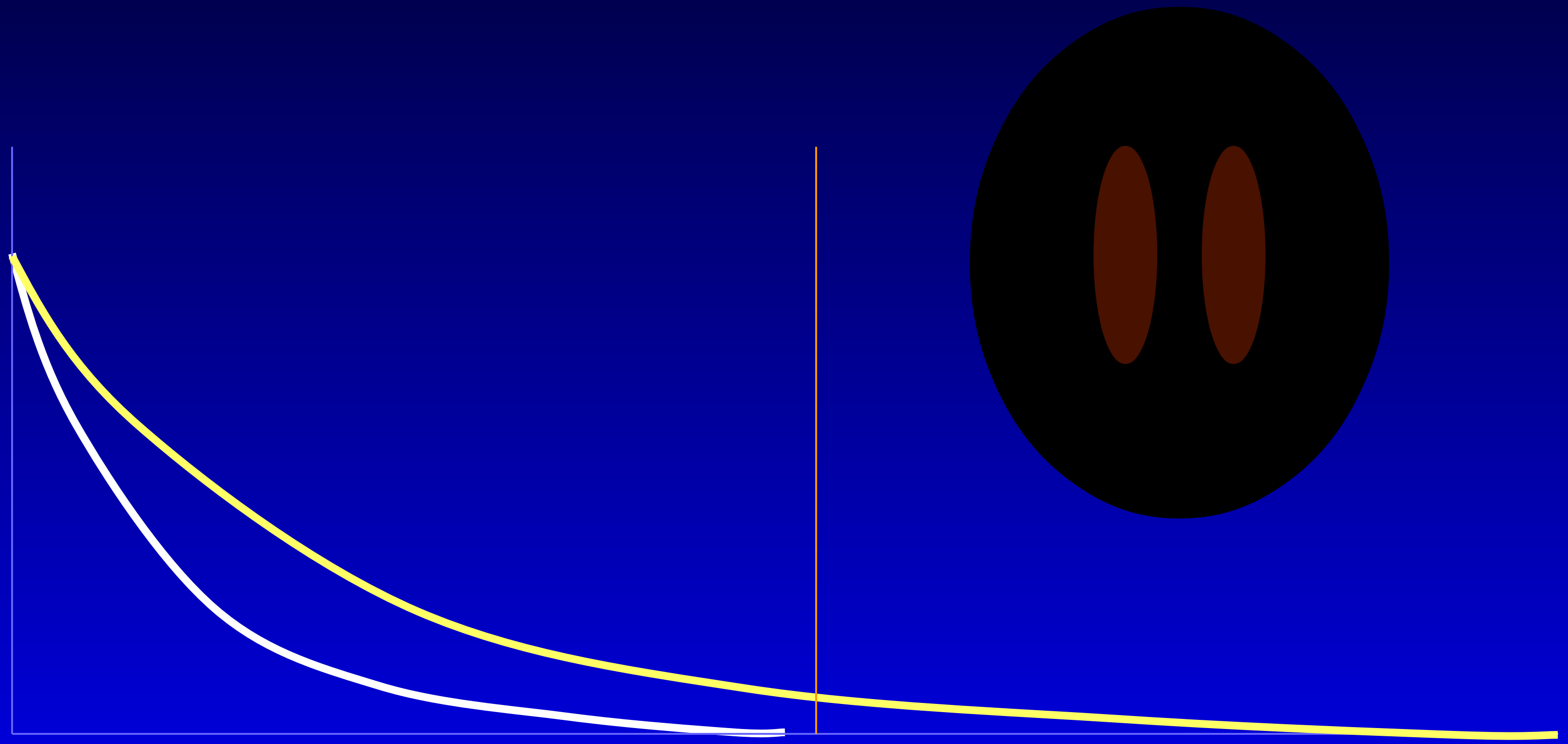
Tissue Contrast

- Effect of echo time

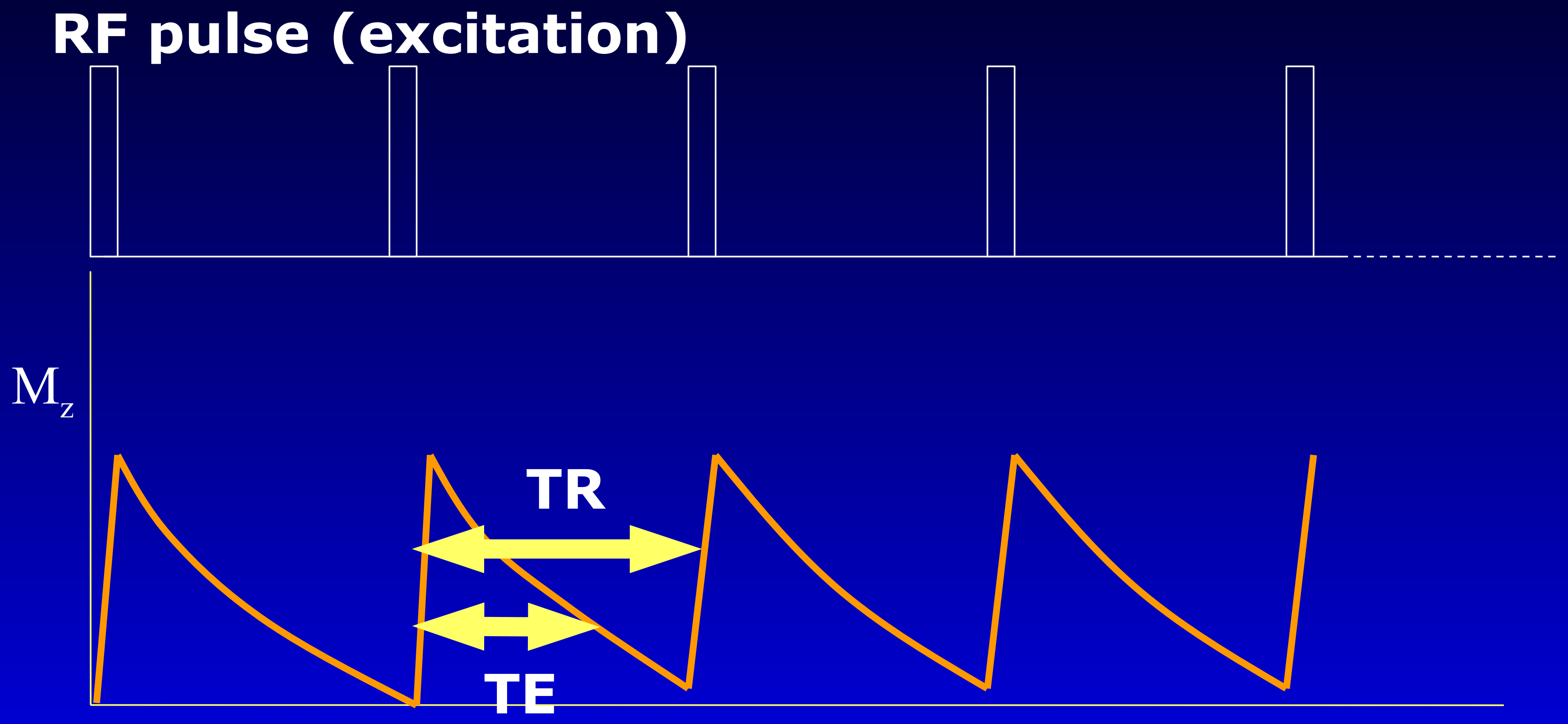


Tissue Contrast

- Effect of echo time



MRI Measurement



- TR: repetition time
- TE: excitation time, moment of measurement

T_1, T_2 and PD Images

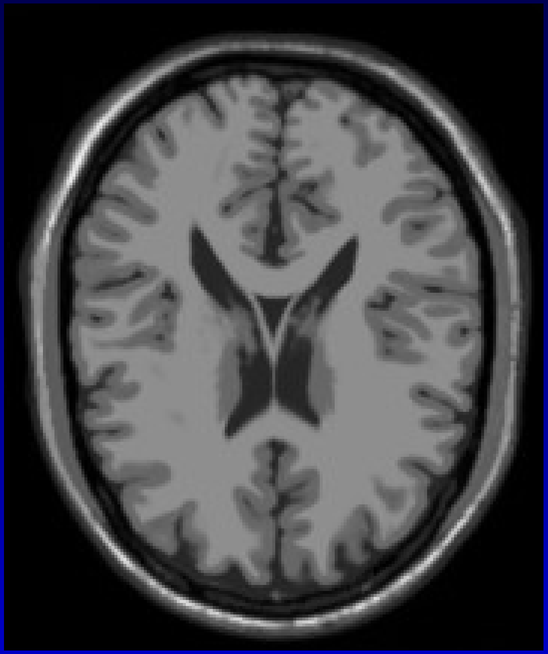
- Different combinations of TR and TE yield different tissue contrast:
  - Long TR (>1500ms)

    Short TE (<25ms) PD (Proton Density) weighting (no T_1 and T_2 influence)

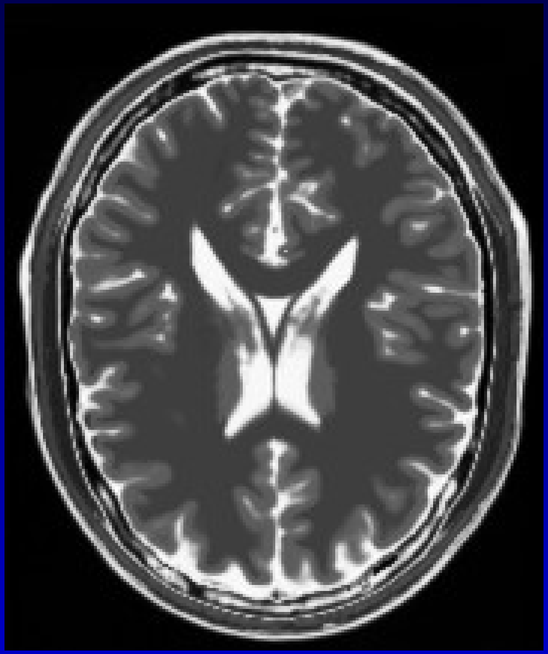
    Long TE (>50ms) T_2 weighting
  - Short TR (<500ms)

    Short TE (<25ms) T_1 weighting

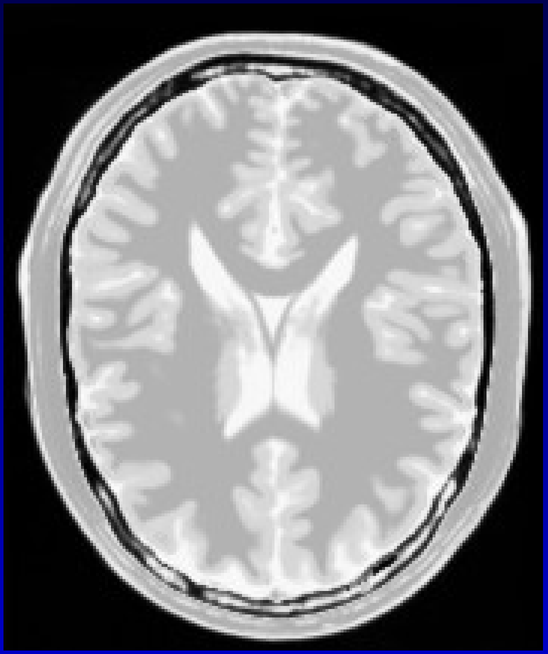
T_1, T_2 and PD Images



T1



T2



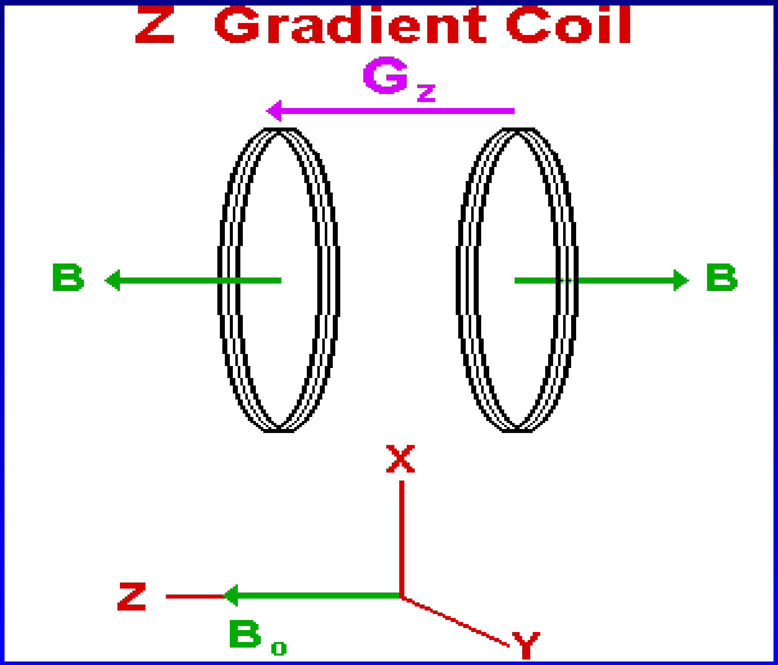
PD

MRI Overview

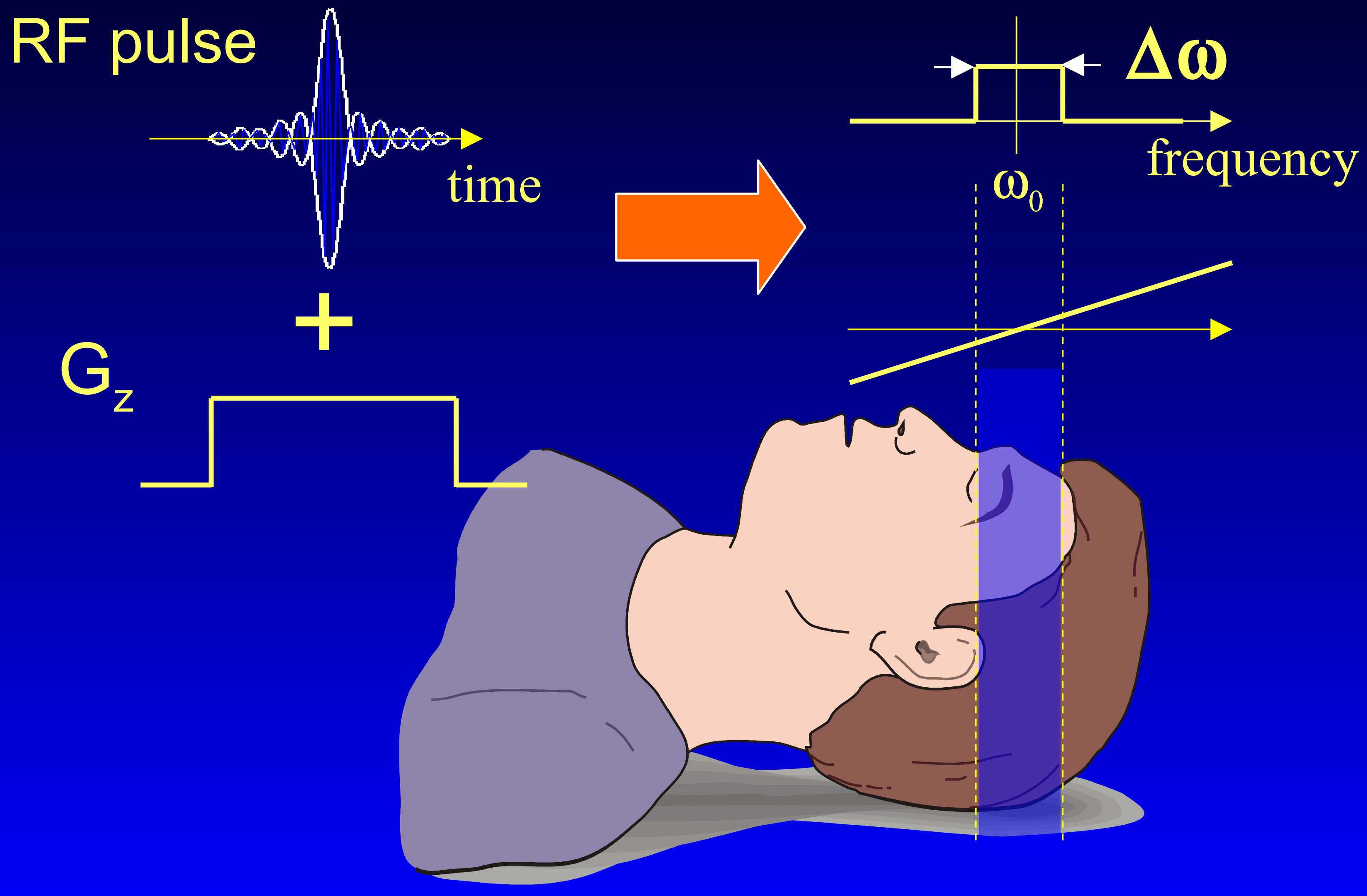
- Physical Background
- Excitation and Relaxation
  - T_1 Relaxation
  - Spin Echo and T_2 Relaxation
- Coding of Spatial Information
  - Slice Selection
  - Read-out Gradient
  - Phase Encoding

Spatial Localization in MRI

- Position encoding by means of gradient fields:
  - Z-gradient: slice selection by changing the Larmor frequency $f_L = \gamma(B_0 + G_z.z)$
  - Z-gradient is applied during the RF pulse

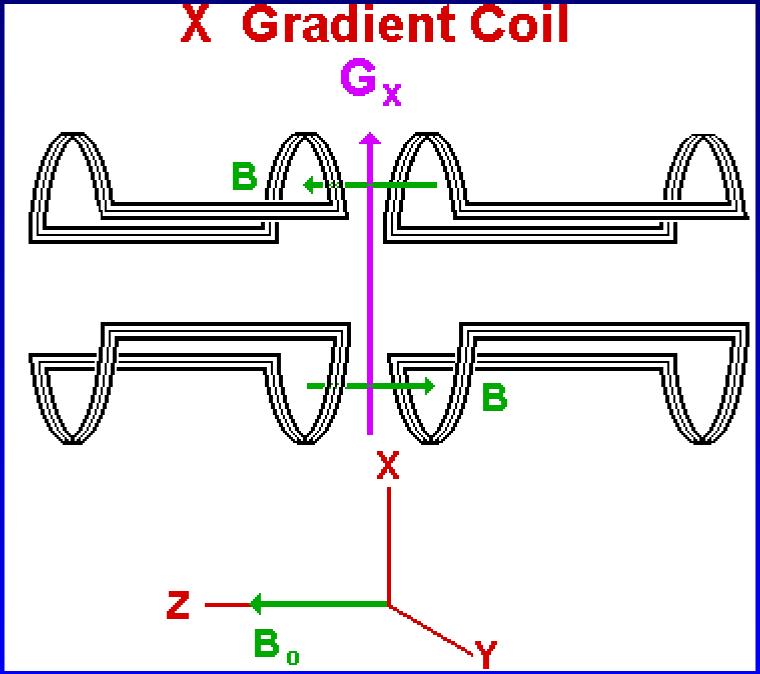


Slice Selection



X, Y encoding

- Similar tricks to encode the **x** and **y** coordinates
  - Only one row measured in one excitation



$$\frac{\partial B_z}{\partial x}$$

Examination Time

- Image is measured row-by-row
- Basic formula: $T = TR \times R \times N$ [ms]
  - TR : repetition time
  - R : number of image rows
  - N : Number of accumulations (noise)

Example: T = 2000 x 256 x 2 = 17 min

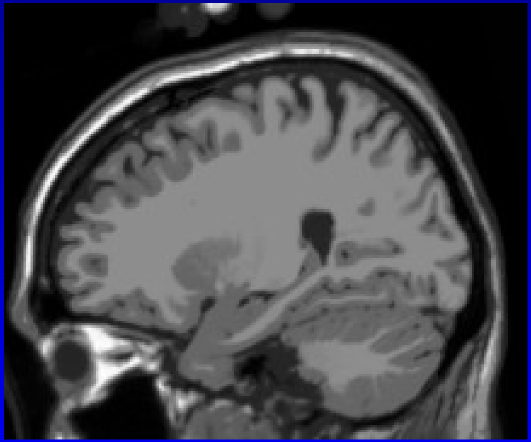
- Speed-up:
  - Low excitation angle ⇒ shorter TR (low energy pulse)
  - Multislice techniques

Multislice Technique

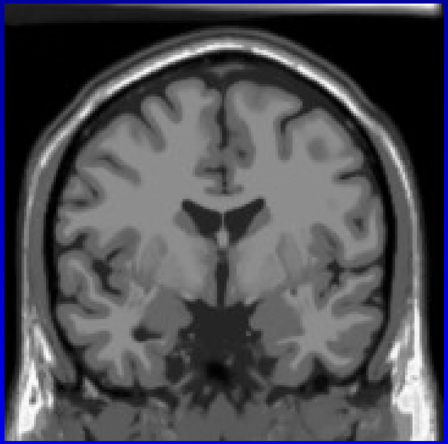
- Interleaved excitation of several (64) slices:

Imaging in Other Planes

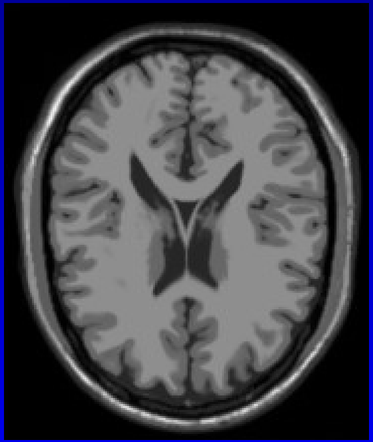
- B_0 always remains in the same direction
- Choice of imaging plane depends on the order of gradients’ application
- Oblique planes: simultaneous application of 2 gradients



Sagittal



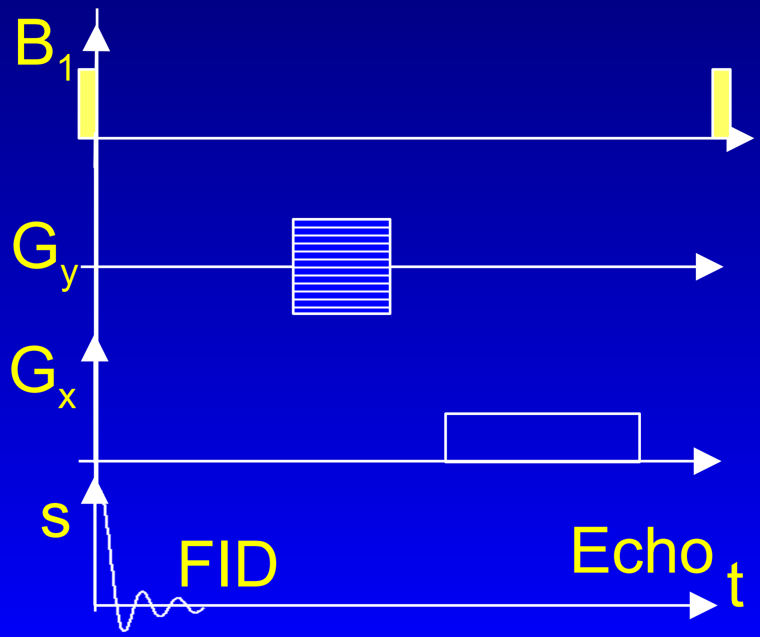
Coronal



Transversal

Scanning Protocols

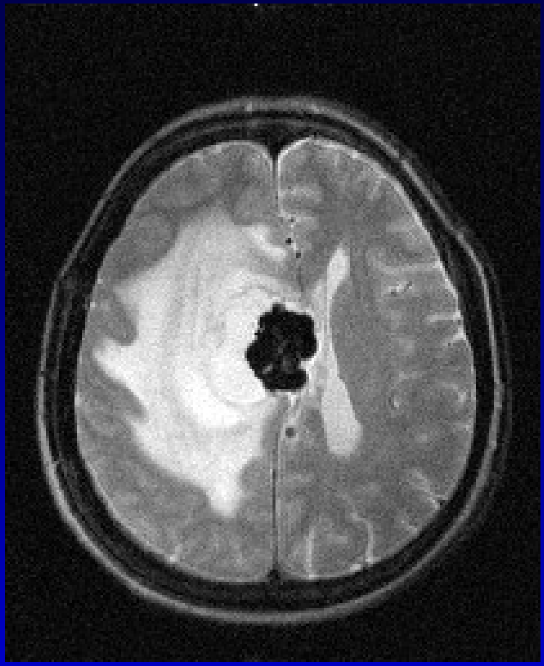
- **Protocol:** a sequence of pulses, gradients and signal measurements
- Protocols influence image properties and examination time
- Patented and sold by scanner vendors
- FISP, FAST, FLASH, STAGE, STERF



Properties of MR data

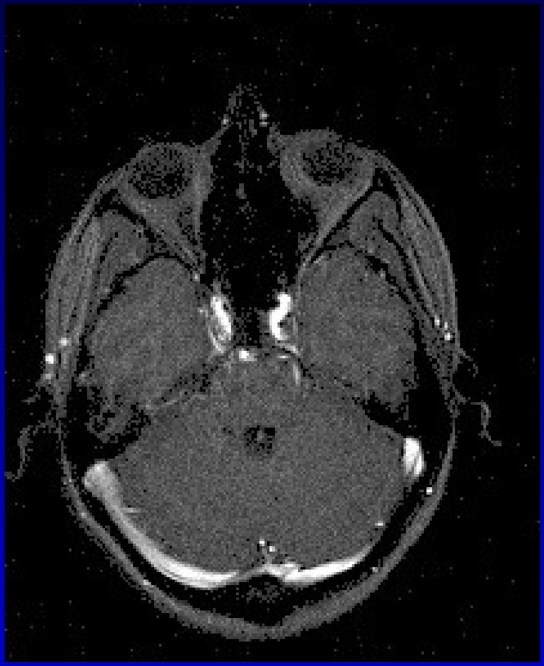
- Measurement in arbitrary planes
- Typically 256x256 (512x512)pixels
- No absolute scale for measured values
- Significant level of noise
- Good soft tissue contrast
- Spatial inhomogeneities - bias
- No irradiation

MR data - examples



T_1

PD



MRA

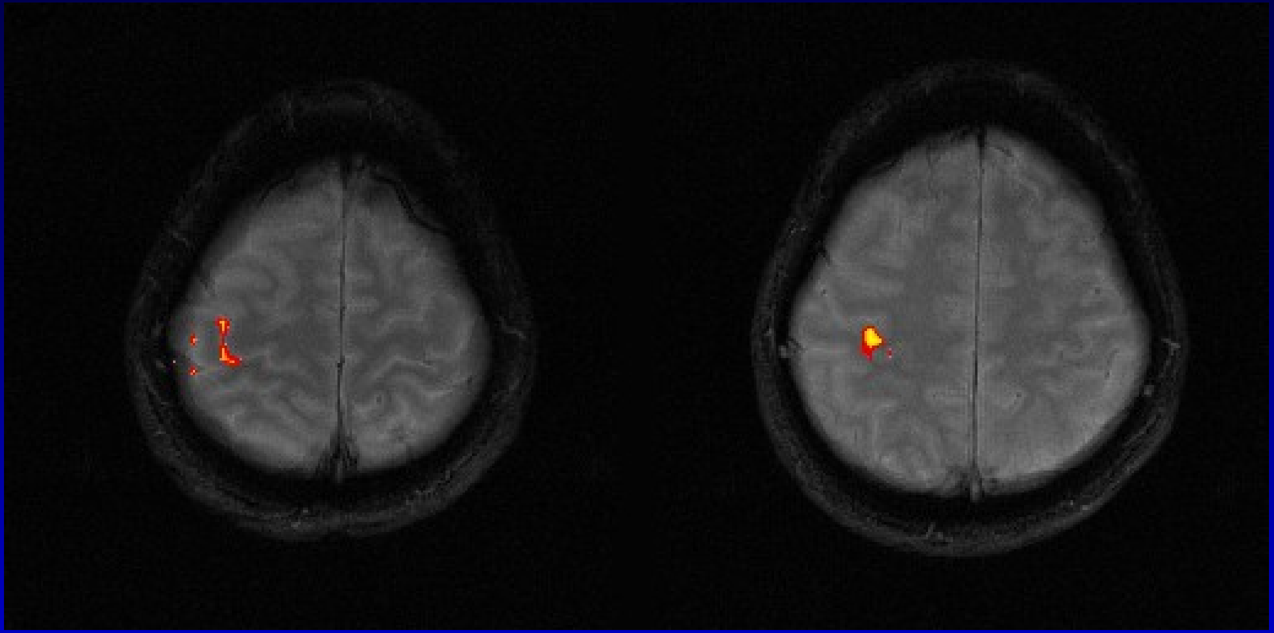
Overview

- Computer tomography (CT, CAT)
- Magnetic resonance imaging (MRI)
- fMRI
- SPECT
- PET

Functional MRI (fMRI)

- Assumption: Active brain area needs more oxygen than inactive ones
- fMRI: statistical detection of areas with oxygenated blood flow
- Visualization by merging with regular MRI data

fMRI Example



Right hand finger tapping at 2Hz

Overview

- Computer tomography (CT, CAT)
- Magnetic resonance imaging (MRI)
- fMRI
- Emission Tomography
  - SPECT
  - PET

Emission Tomography

ECT - Emission computed tomography

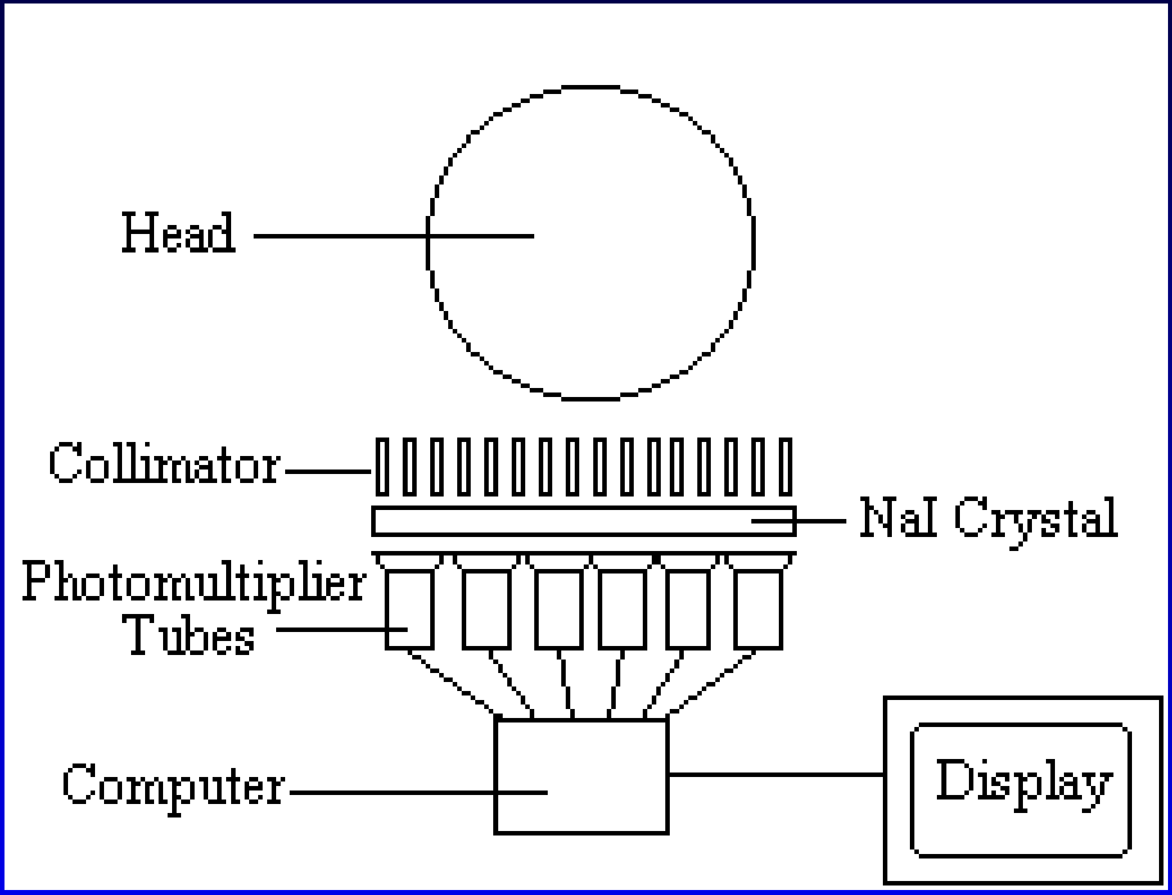
- Introduction of a radioactive agent into the patient’s body (tagged substance)
- Agent’s distribution based on metabolism
- Measurement of its spatial distribution

SPECT

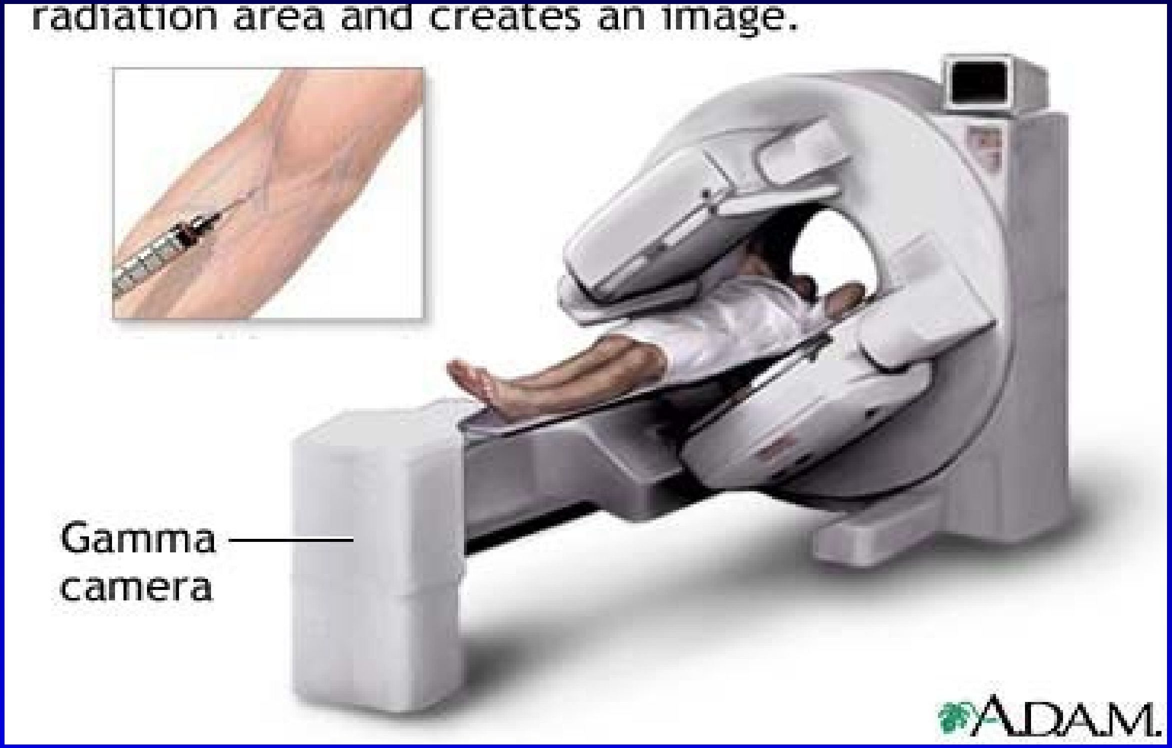
Single-Photon Emission Computed Tomography

- Isotopes emitting γ–photons (Tc-99, I-125, I-131)
- Uniform distribution of photons in all directions
- Scanner - a set of detectors with collimators - gamma camera

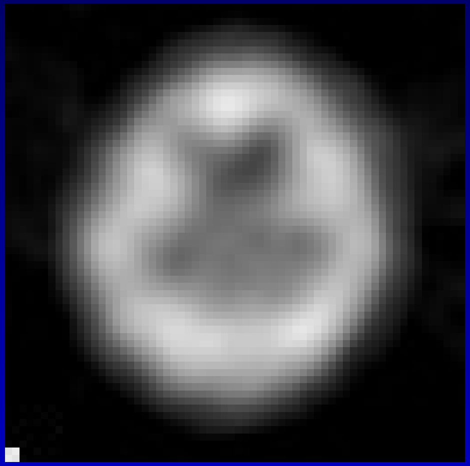
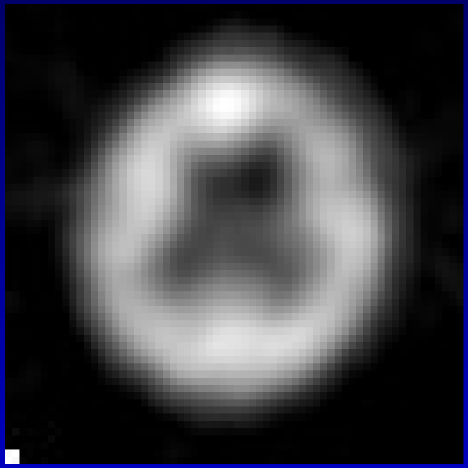
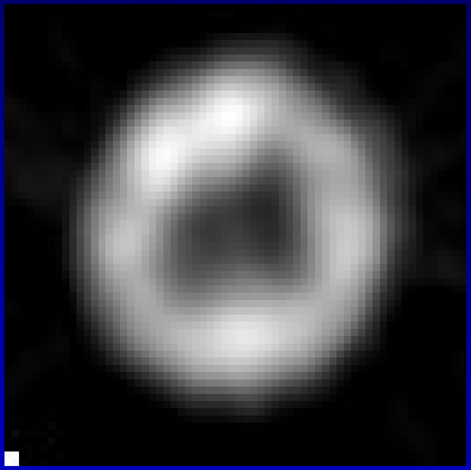
Gamma Camera



Gamma Camera



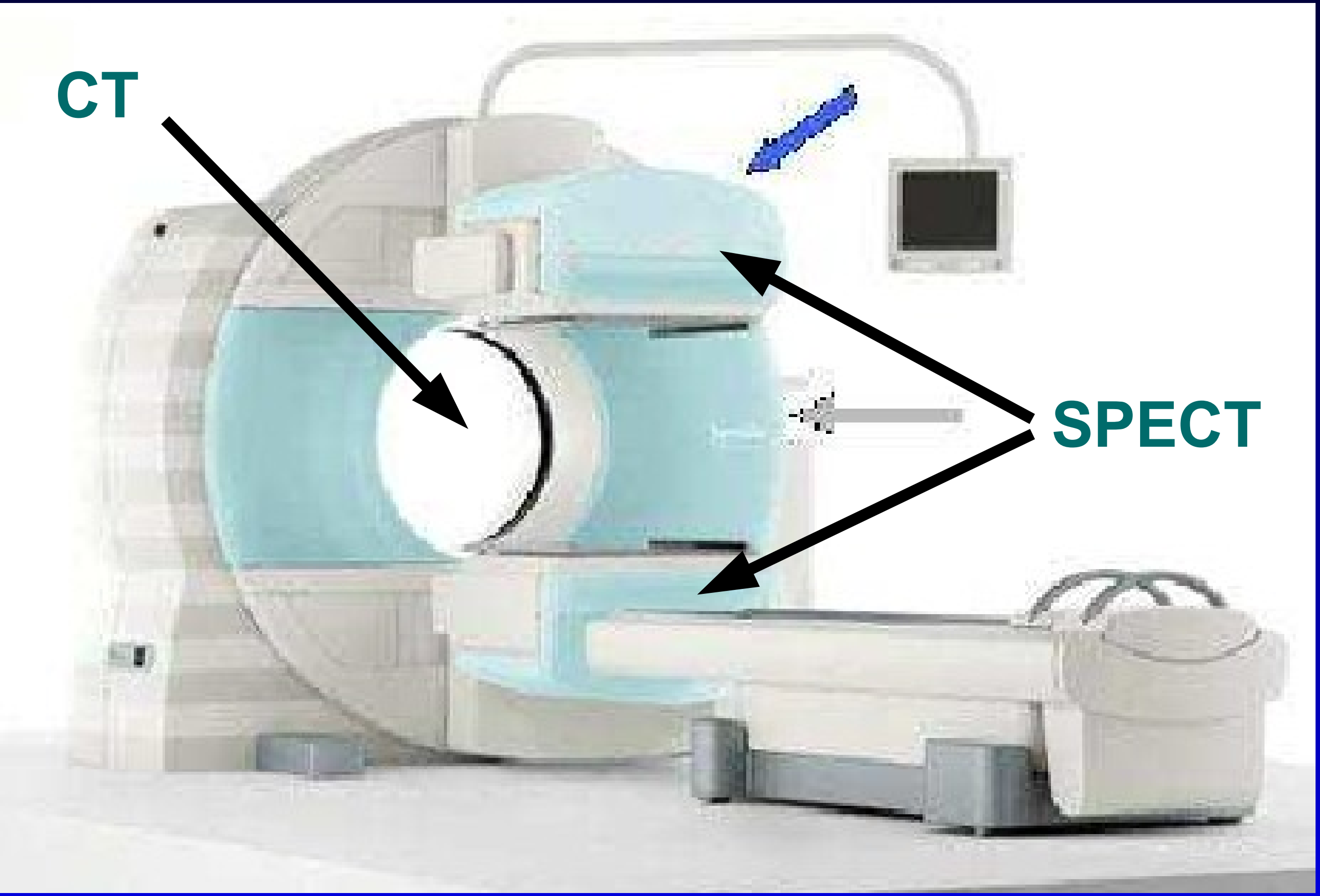
SPECT data

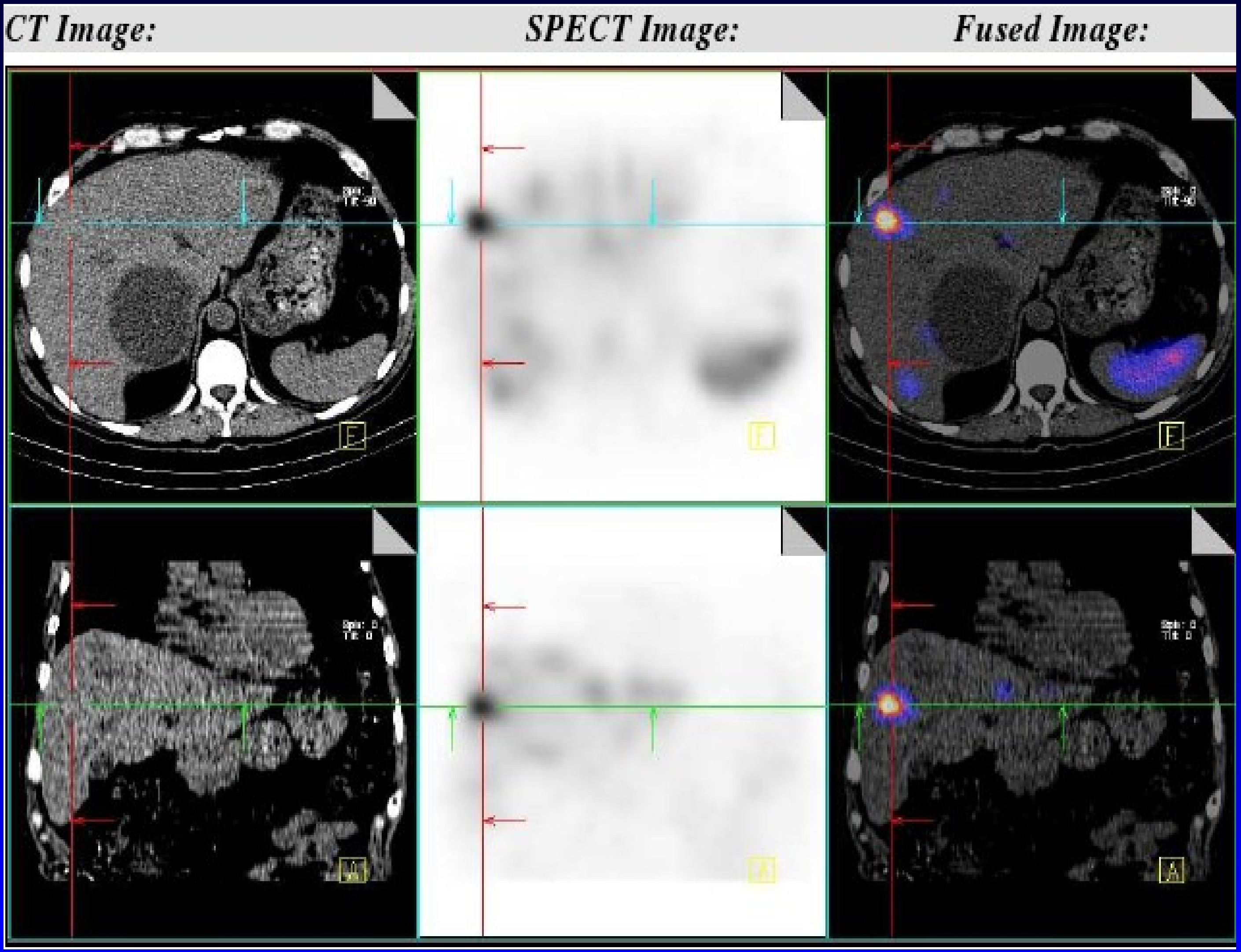
CT-SPECT

- Combination of different techniques – supplementary information
- Registration is required
  - Not a trivial task
  - Solution: CT-SPECT scanner

CT-SPECT (2)



CT-SPECT (3)

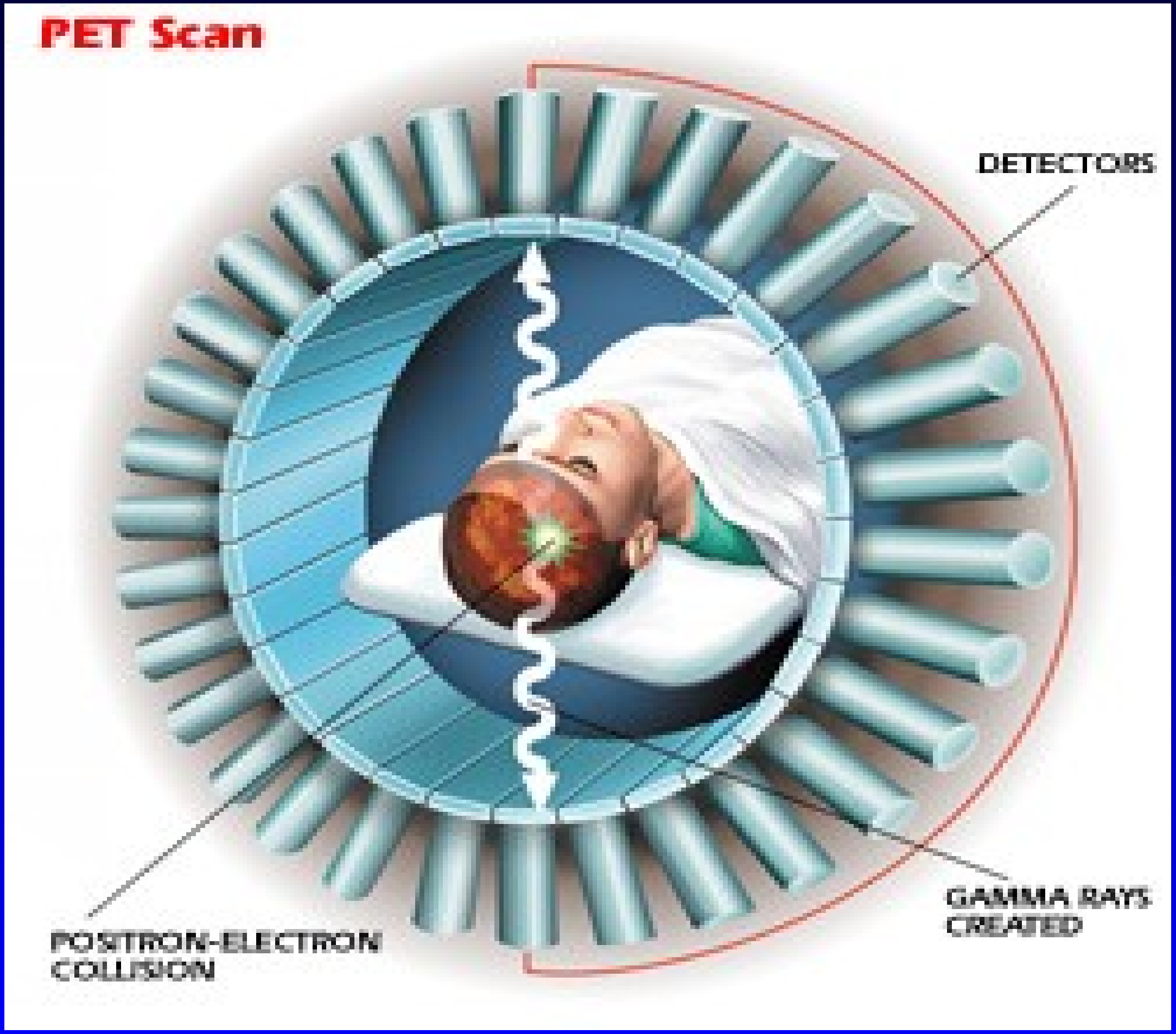


PET

Positron Emission Tomography

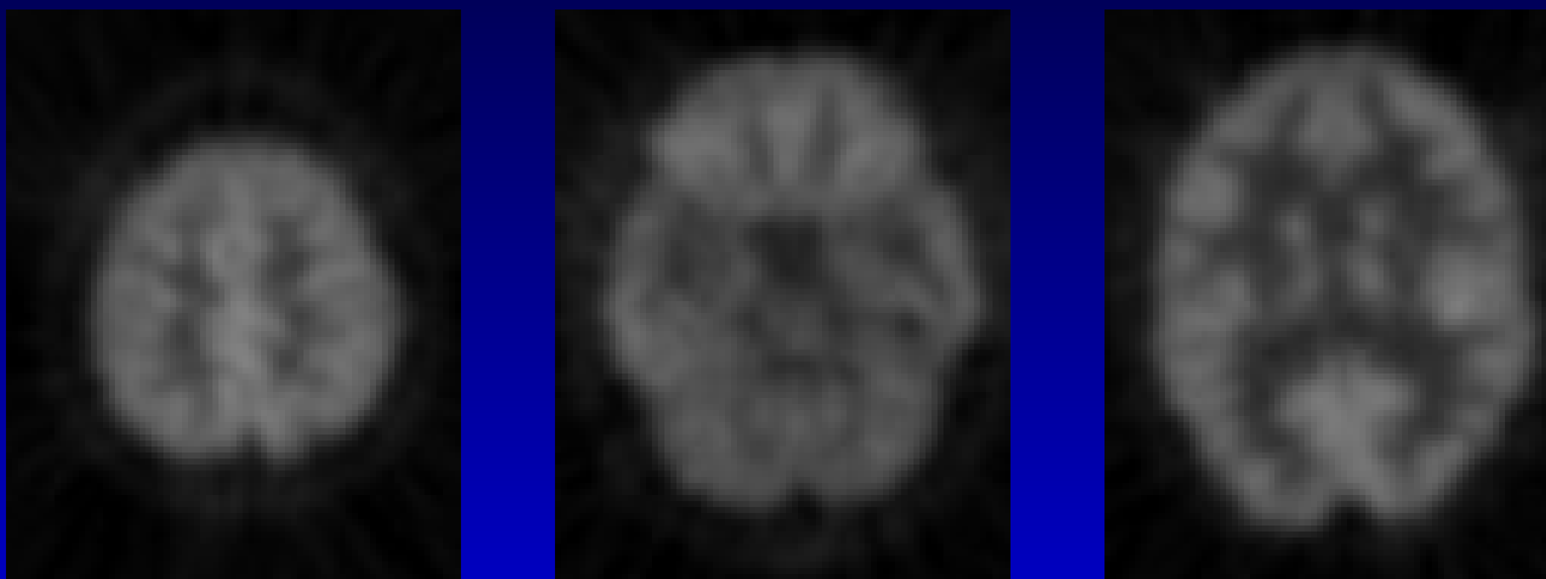
- $\beta+$ decay (positrons)
- Annihilation - a pair of photons with energy 511keV in opposite directions
- Detection without collimators: registration of *concurrent* events in detector pairs
- 3D measurement, statistical reconstruction (MRF)

PET Scanner

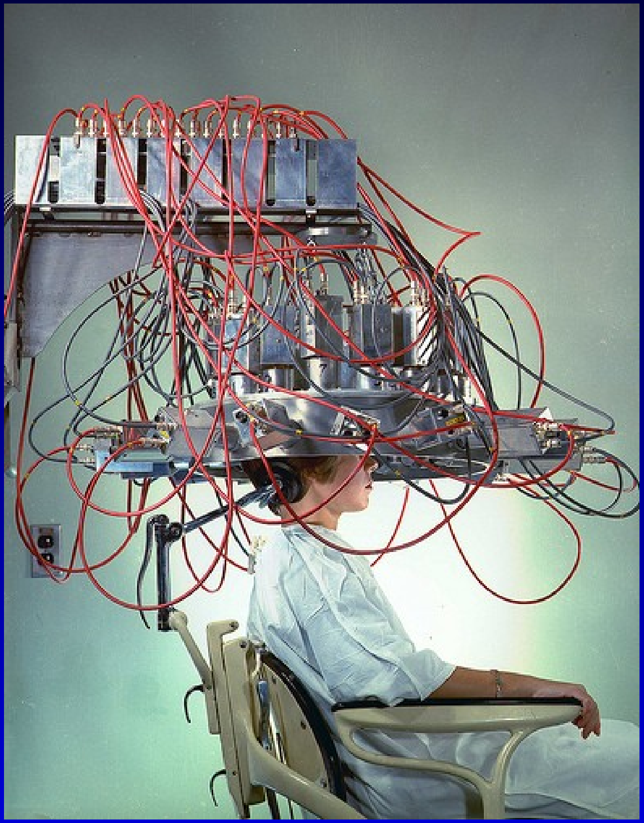


PET Scan
DETECTORS
GAMMA RAYS
CREATED
POSITRON-ELECTRON
COLLISION

PET data



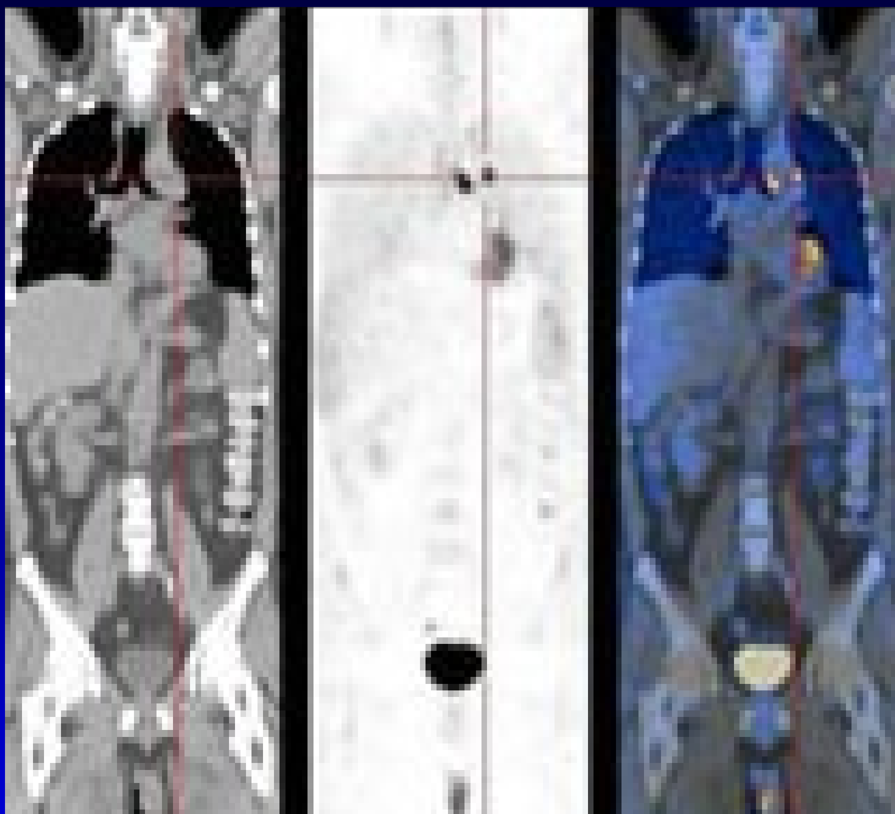
PET Scanners



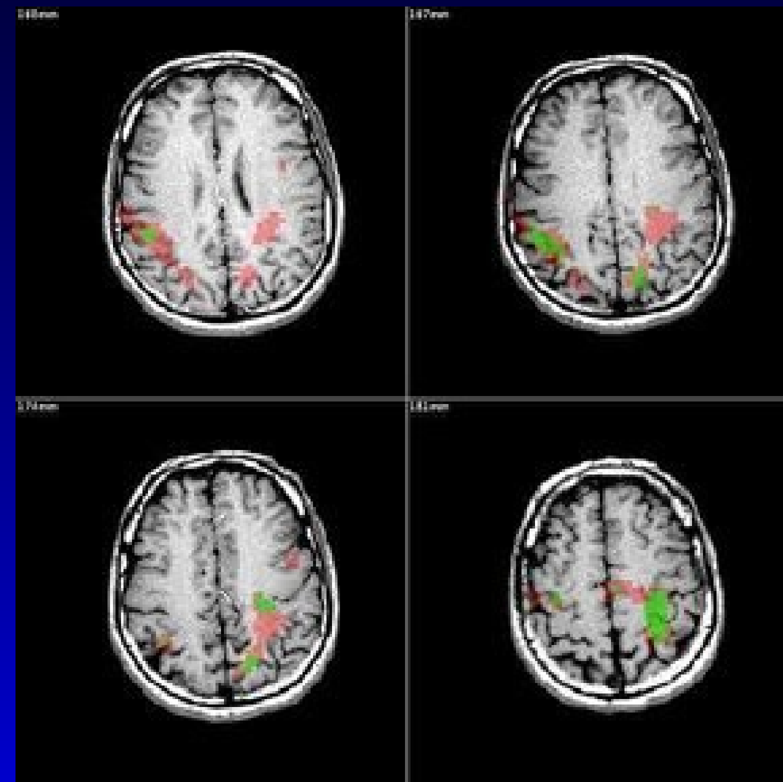
Research prototype
at BNL (1961)

PET today

Combined PET/CT, MRI



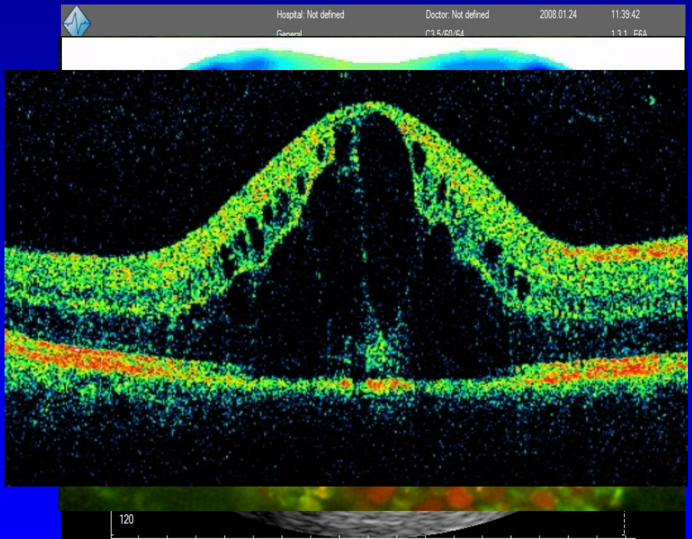
PET / CT



PET / MRI

Other Imaging Modalities

- Ultrasound
- Confocal microscopy
- Electrical impedance tomography
- Optical coherence tomography
- ...



Overview

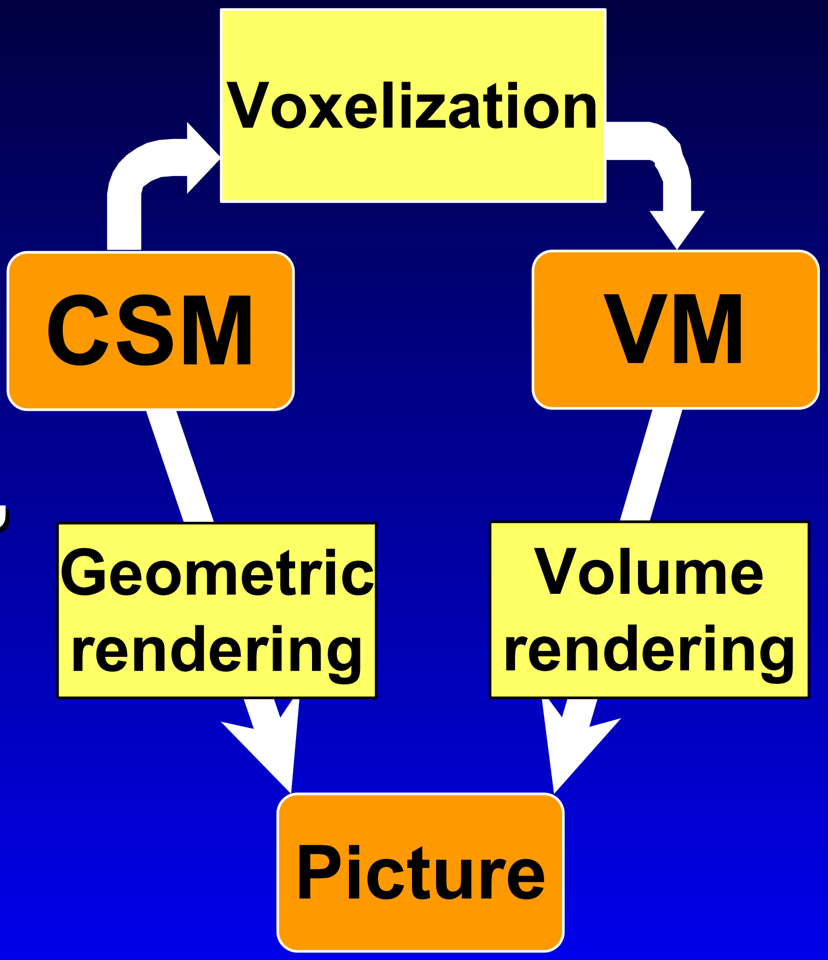
- Computed tomography (CT / CAT)
- Magnetic resonance imaging (MRI)
- fMRI
- SPECT
- PET
- Synthetic Data

Voxelization of Geometric Objects

- Preparation of “synthetic” data
- A CG alternative
- Simultaneous visualization of geometric and volume data
- Modeling of volumetric properties (e.g. weathering)

Surface and Volume Graphics

- **Surface Graphics**: Geometric rendering of Continuous Spatial Models (CSM)
- **Volume Graphics**: Voxelization of a CSM, manipulation, and volume rendering of a Volumetric Model (VM)



Voxelization

- A process of approximating a continuous geometric primitive in the 3D discrete space
- The result of this process

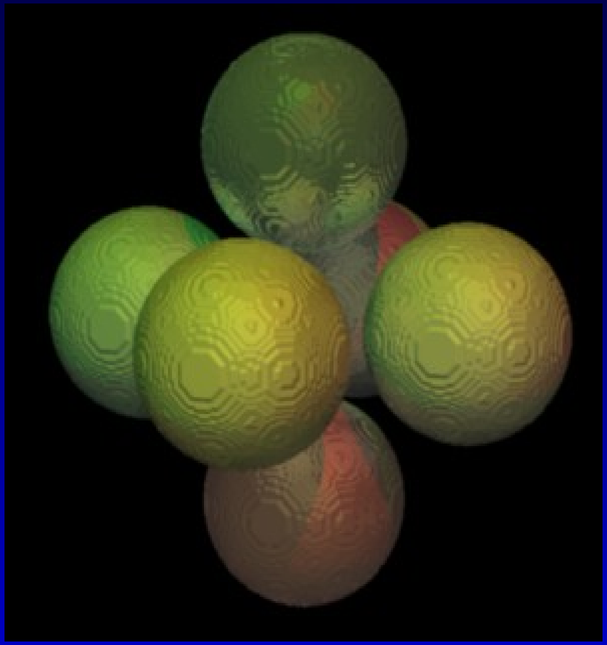
Binary voxelization

Voxels & occupancy O ∈ {0,1} ({Background, Foreground}, {Black, White})

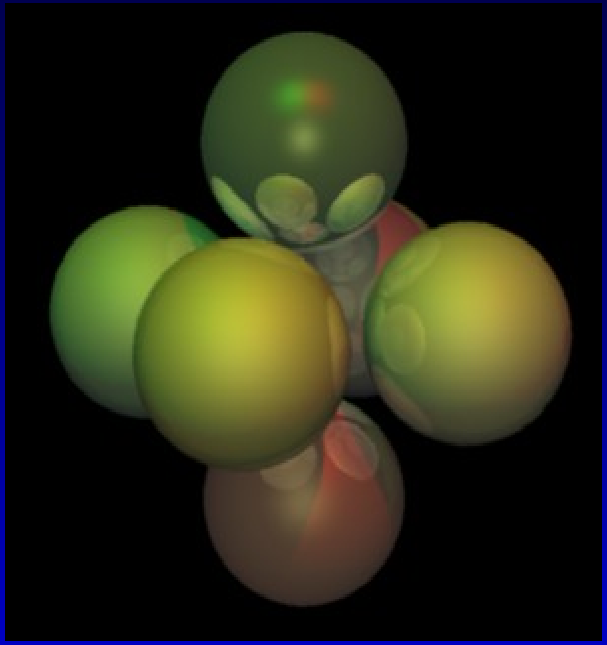
Non-binary voxelization (fuzzy, filtered)

Grid points & densities D ∈ R

Binary vs. nonbinary



Binary

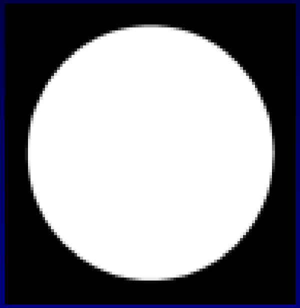


Non binary

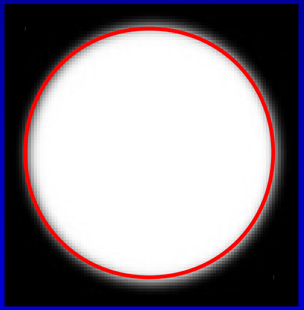
Non-binary Voxelization

Suppression of aliasing in 3D model by smooth density transition in the surface area

- Truncated distance field
- Surface reconstruction
  - Interpolation and thresholding

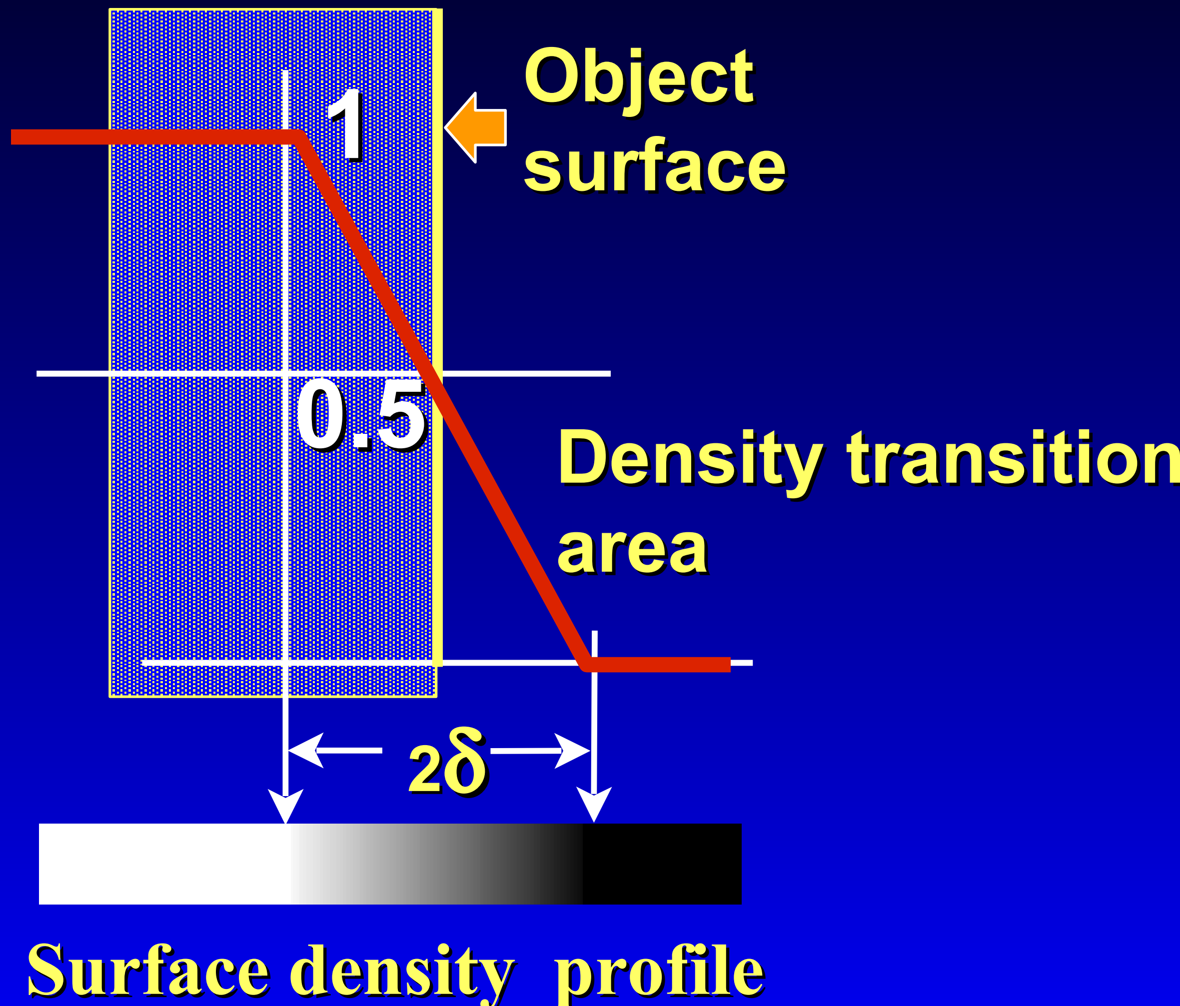


Analytic object



Voxelized object

Solids in Truncated Distance Fields

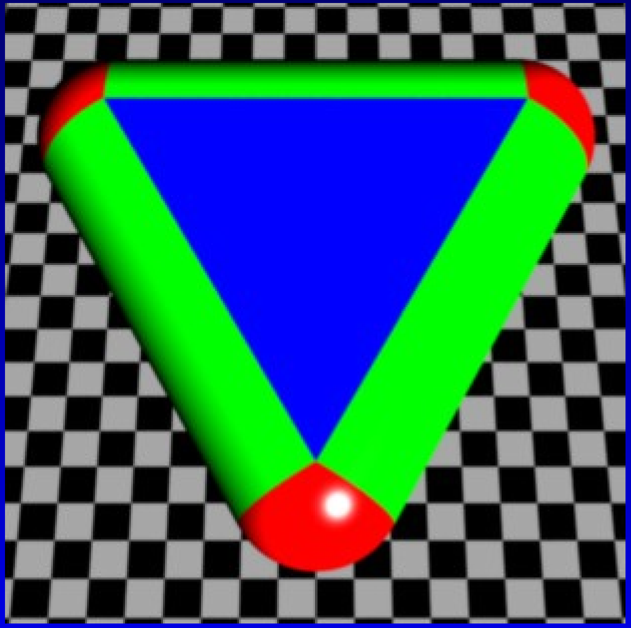


Voxelization by Direct Distance Computation

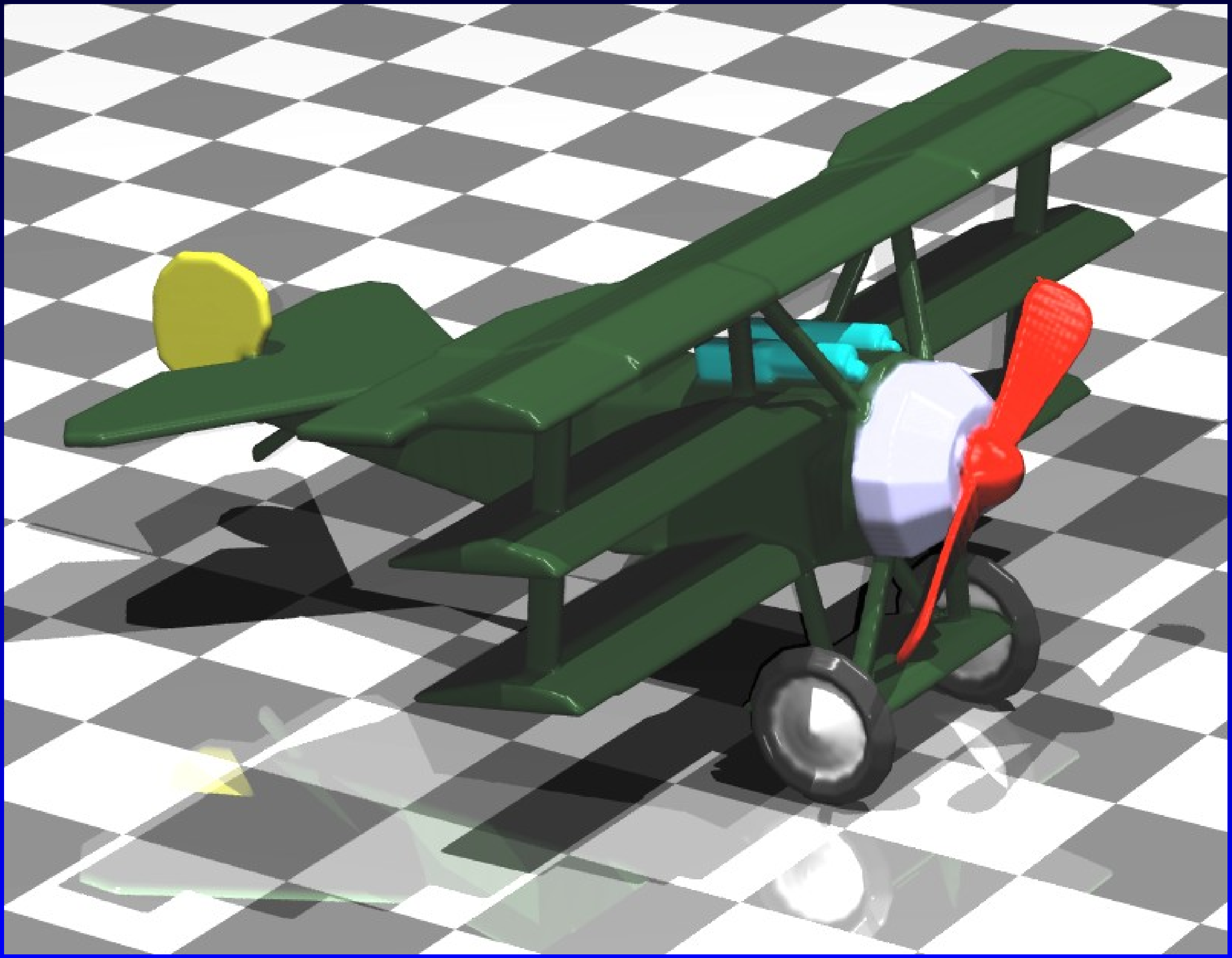
Simple primitives (sphere, torus, polygon)

Example: Voxelization of a triangle:

- Bounding box
- Voxel-by-voxel update of distances to **plane, edges & vertices**
- Density according to the minimal distance



Voxelized Polygonal Model

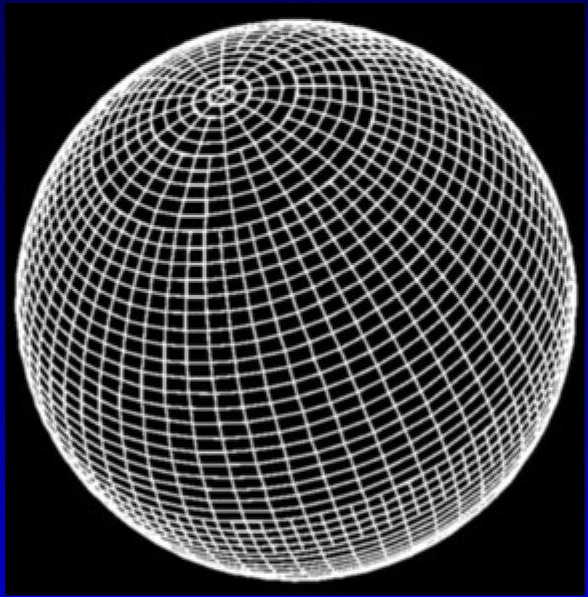


Voxelization of Parametric Surfaces

$$P(u,v) = [\ x(u,v),\ y(u,v),\ z(u,v)\ ]$$

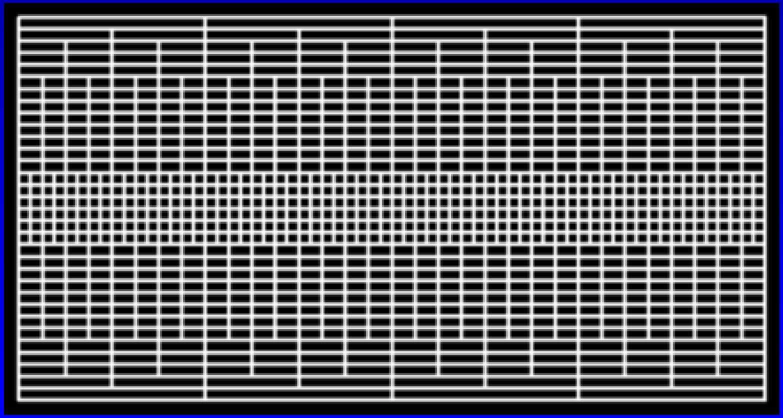
$$[\ u, v\ ] \in (u_0, u_1) \times (v_0, v_1)$$

1. Splatting – adding small voxelized balls
2. Approx uniform sampling by binary domain subdivision

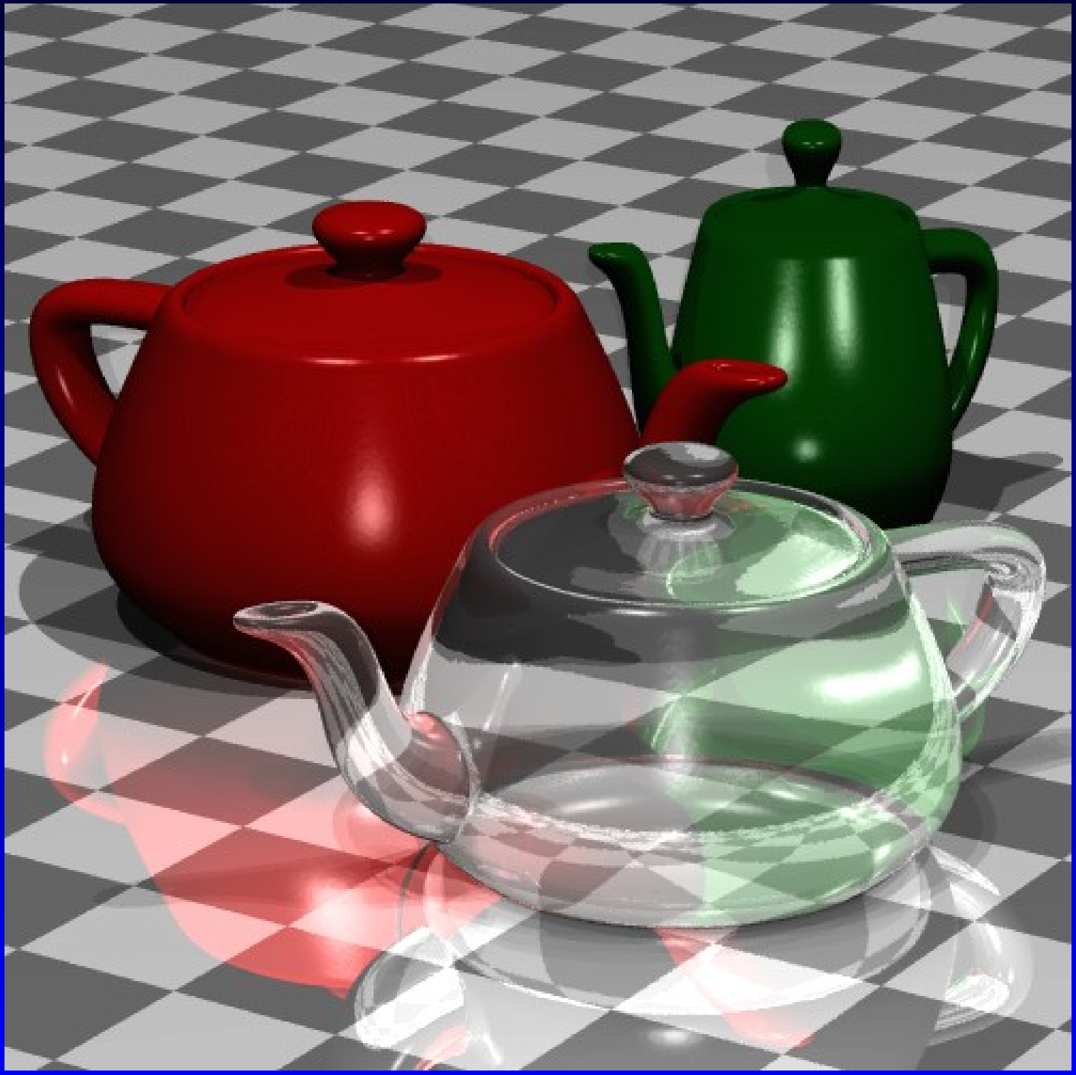


Surface subdivision

Domain subdivis.



Voxelization of Parametric Surfaces



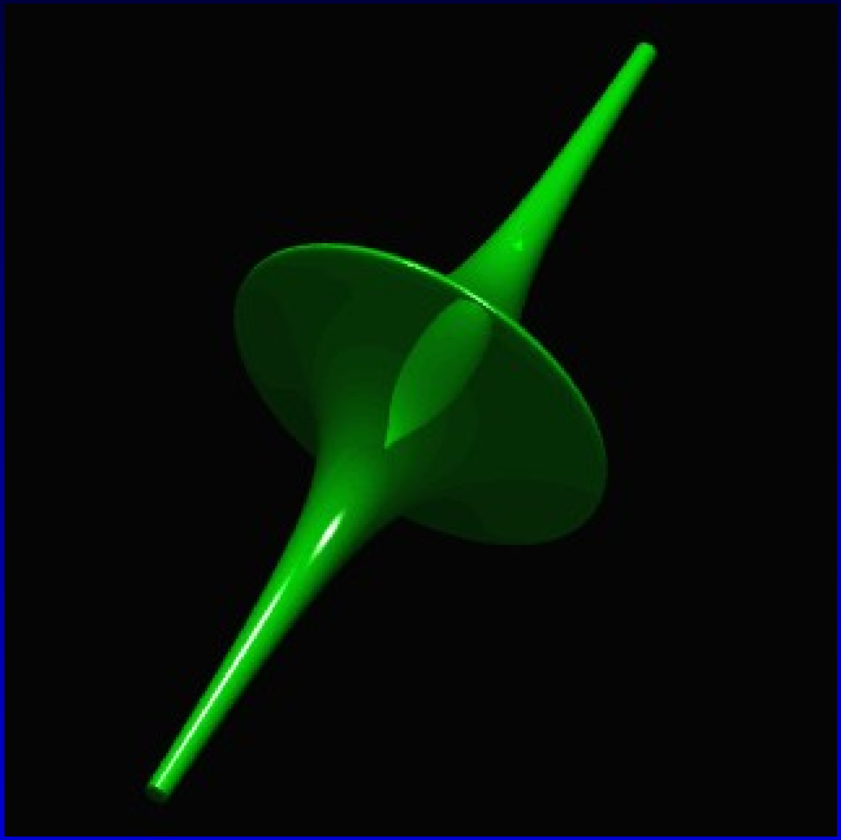
Voxelization of Implicit Solids

$$\{[x,y,z]: f(x, y, z) < 0\}$$

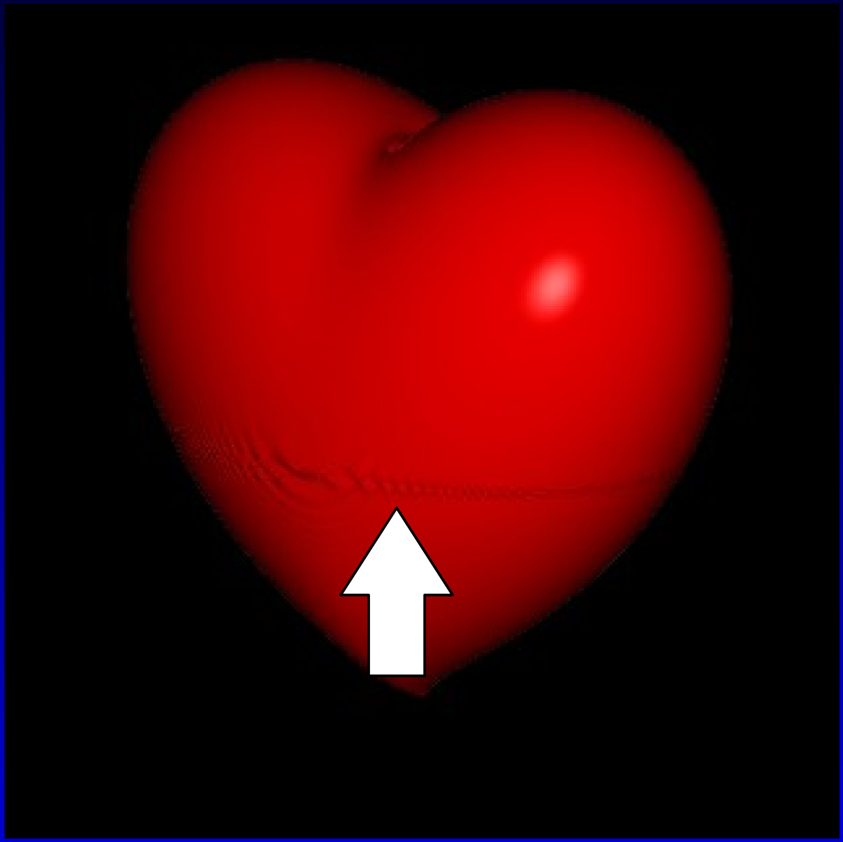
- Distance estimation by linear approximation:

$$d(x,y,z) = \frac{f(x,y,z)}{\|f'(x,y,z)\|}$$

Voxelization of Implicit Solids



$(y^2 + s)(x^2 + z^2) - s$



$(2x^2 + y^2 + z^2)^3 - (x^2/10 + y^2)z^3$

CSG Operations

Operation	Density	Color
Intersection	$d_{A*B} = \mathrm{Min}(d_A, d_B)$	$C_{A*B} = \mathrm{WA}(A,B)$
Union	$d_{A+B} = \mathrm{Max}(d_A, d_B)$	$C_{A+B} = \mathrm{WA}(A,B)$
Difference	$d_{A-B} = \mathrm{Max}(0, d_A - d_B)$	$C_{A-B} = C_A$ if $d_{A-B} > 0$

CSG Operations


a


b


c

a * (b + c)