MOUNT SINAI SCHOOL OF MEDICINE
NEW YORK

Hydrogen-the most responsible element for MRI imaging

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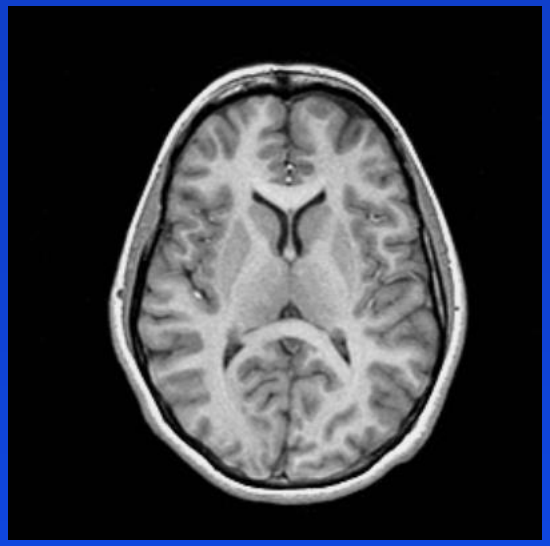
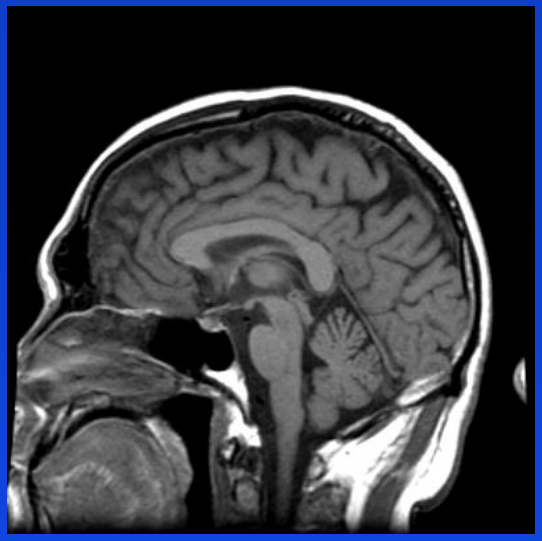
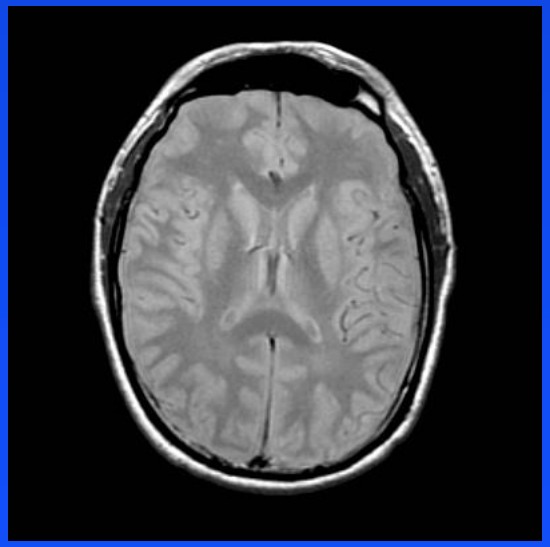
U S A

Anatomy

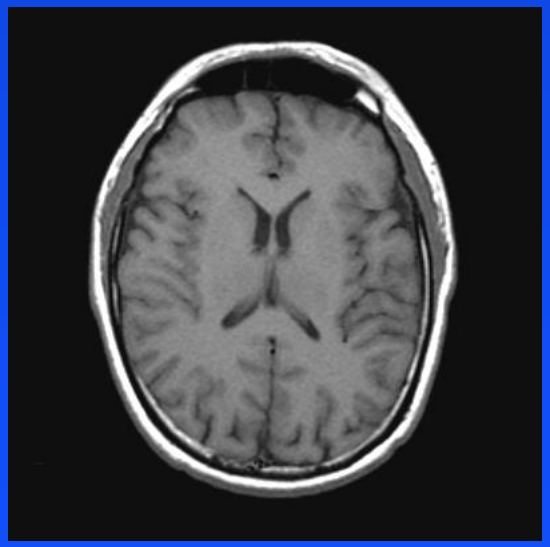




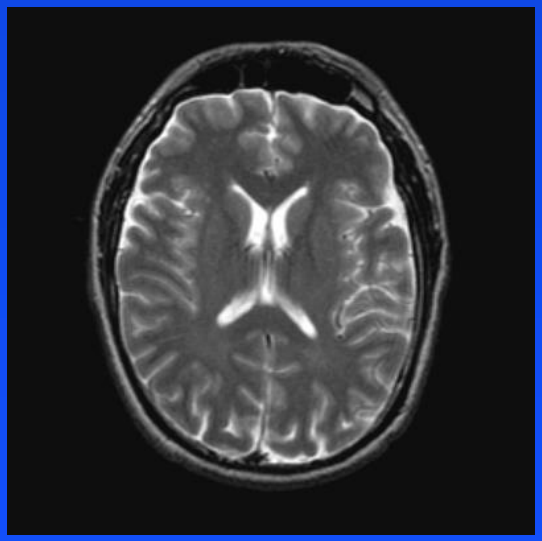
Pathology



PD

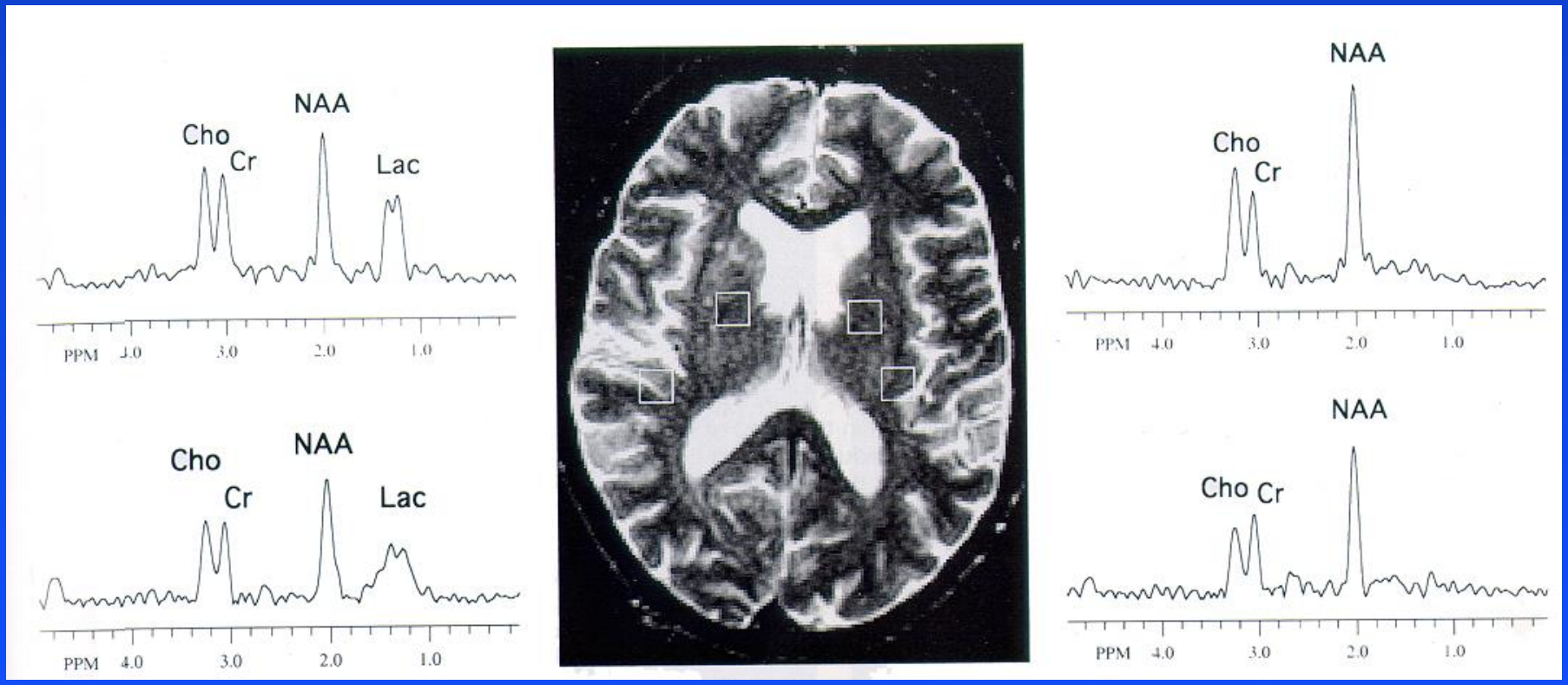


T1



T2

MR Spectroscopy



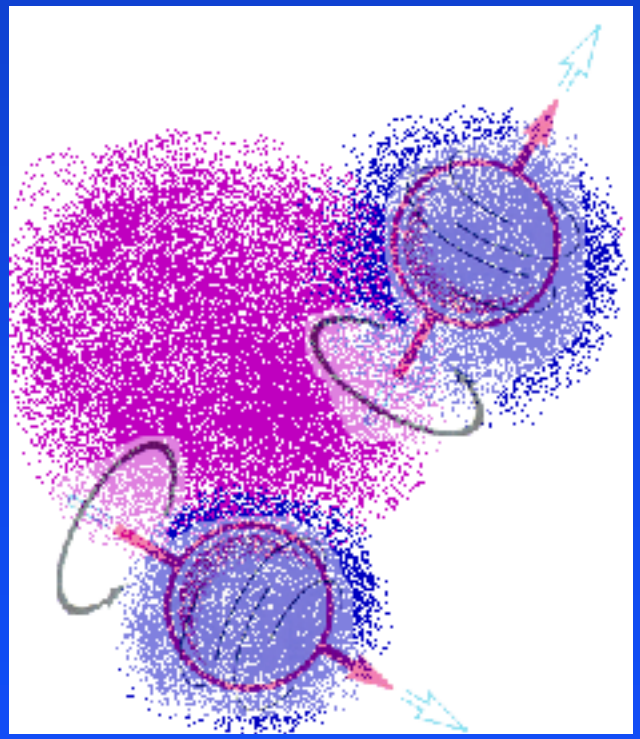
2003 Nobel Prize in Physiology or Medicine

Paul Lauterbur and Sir Peter Mansfield were awarded the for their "discoveries concerning magnetic resonance imaging

Element	**Biological Abundance**
Hydrogen (H)	0.63
Sodium (Na)	0.00041
Phosphorus (P)	0.0024
Carbon (C)	0.094
Oxygen (O)	0.26
Calcium (Ca)	0.0022
Nitrogen (N)	0.015

MRI
Physical Principles

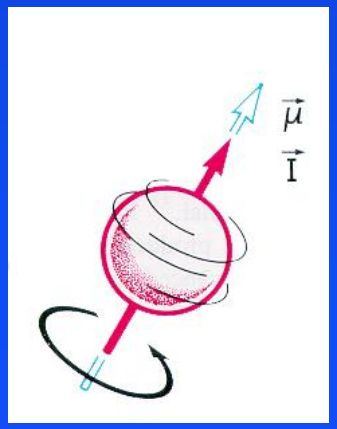
- **Signal sources are the protons (H) of free water**



Water: H_2O

Properties of Protons

- **Mass** = $1.67 \times 10^{-27}\,kg$
- **Charge** = $1.60 \times 10^{-19}\,C$
- **Spin** = $\frac{1}{2}$



Mass

Spin

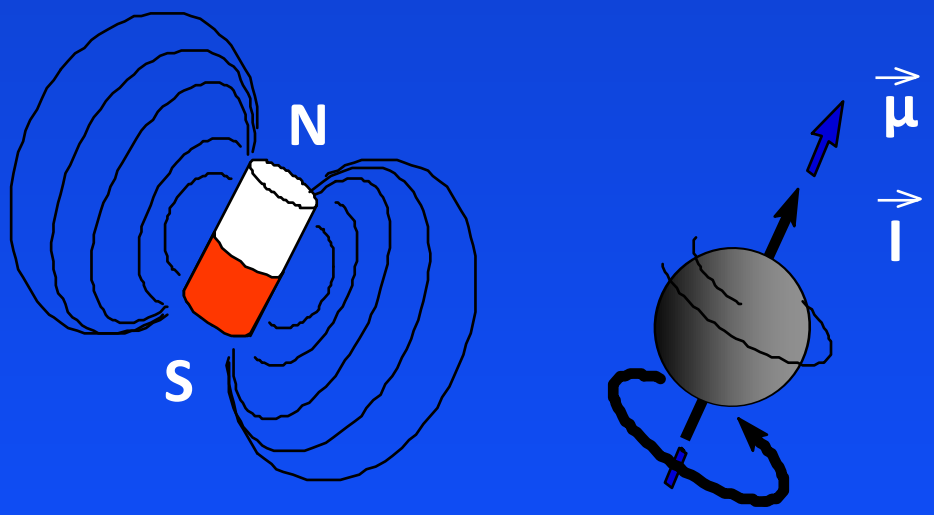
Charge

Angular Momentum

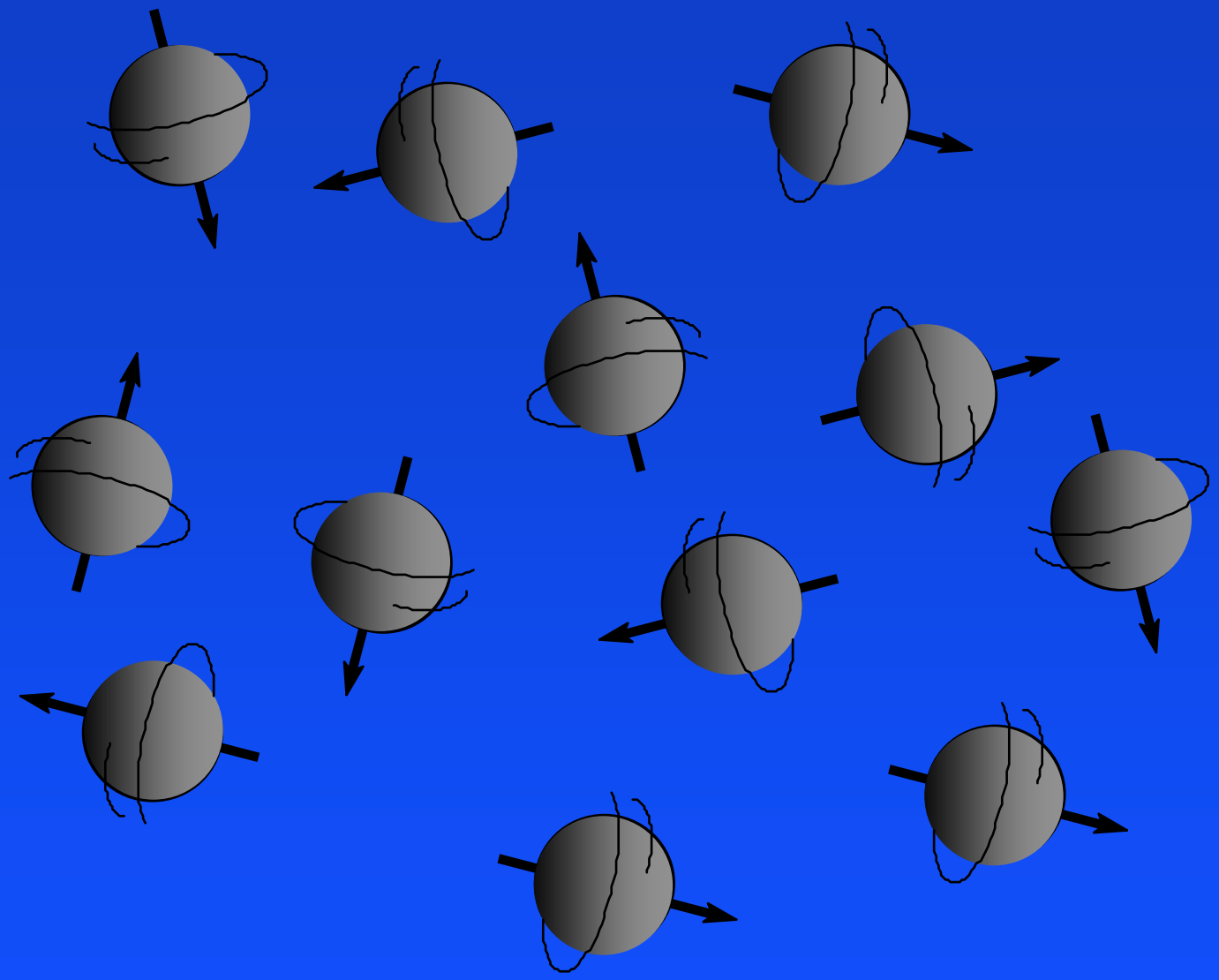
Magnetic Dipole Moment

Magnetic Resonance Imaging

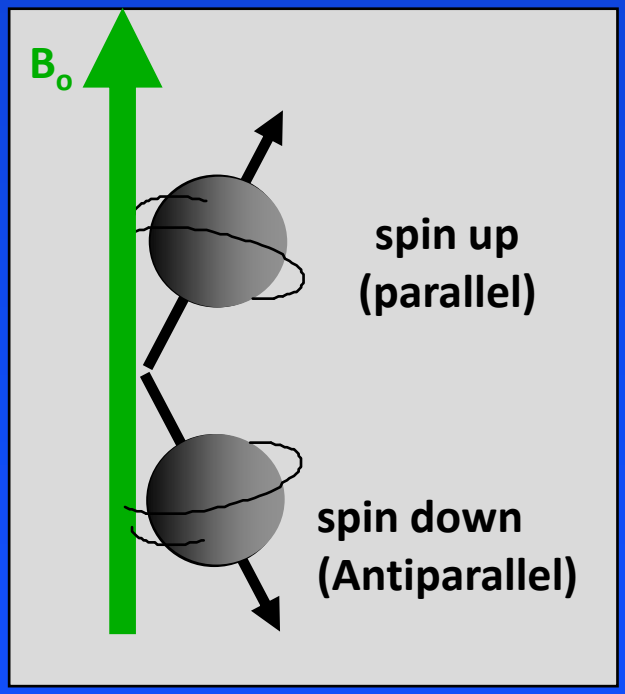
Proton has a magnetic moment



Magnetic nuclei behave like microscopic bar magnet



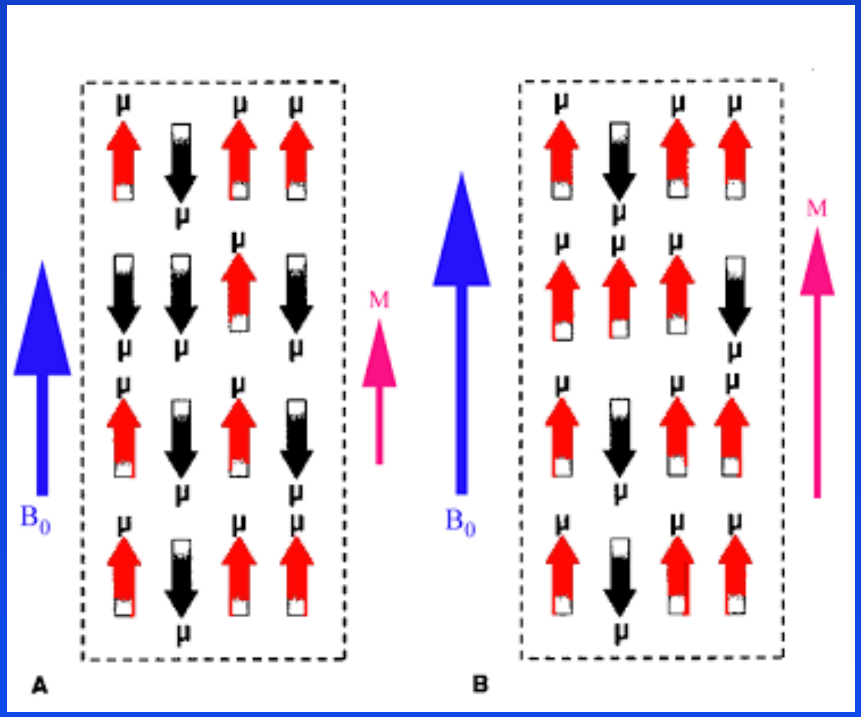
In absence of magnetic field, spins are randomly oriented.



In a magnetic field the magnetic moments become oriented

Boltzmann Distribution

Low B field



High B field

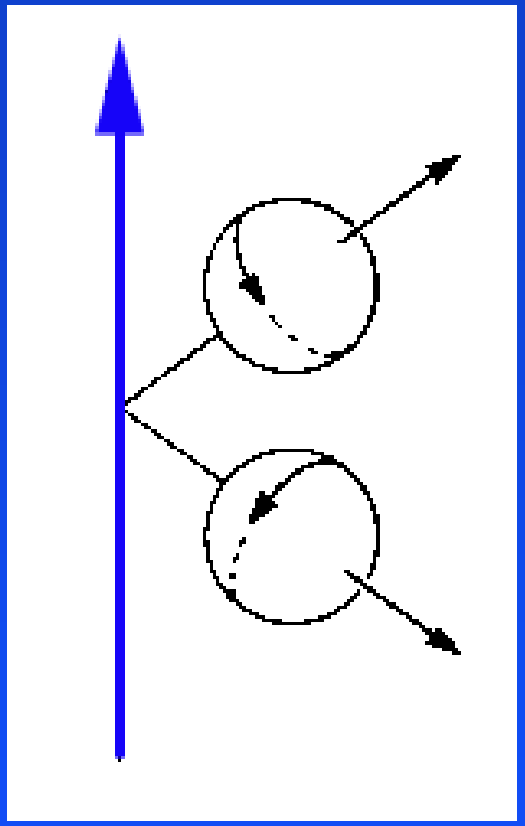
M depends on:

- Main field Bo
- Temperature
- Nucleus type

$$\frac{n_{up}}{n_{down}} = e^{\frac{-2\mu_m B_0}{k_b T}}$$

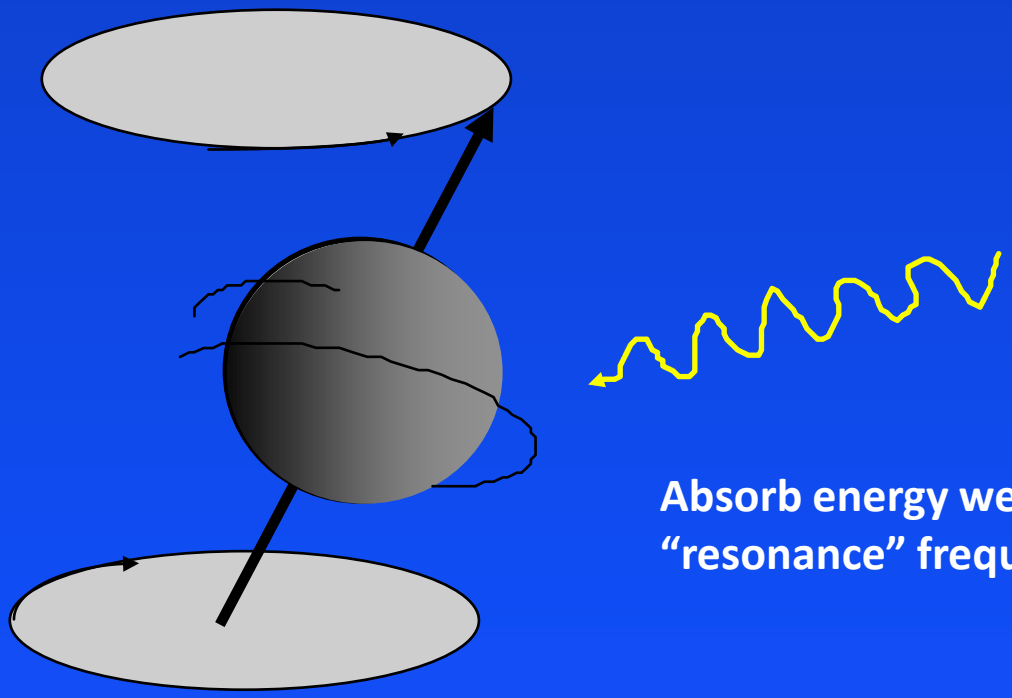
Energy Splitting in the presence of a Magnetic Field

Splitting of energy levels
for spin 1/2 particles (Protons)



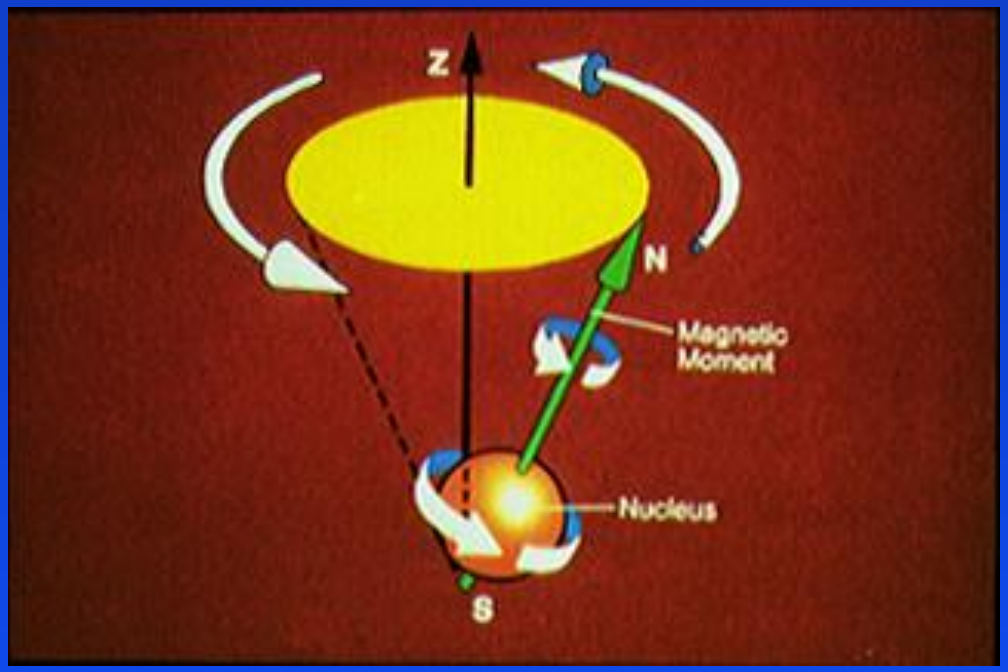
The magnetic moments also precess at a well-defined (radio) frequency

(42.6 MHz at 1.0 T)



Absorb energy well at this "resonance" frequency

Larmor Frequency

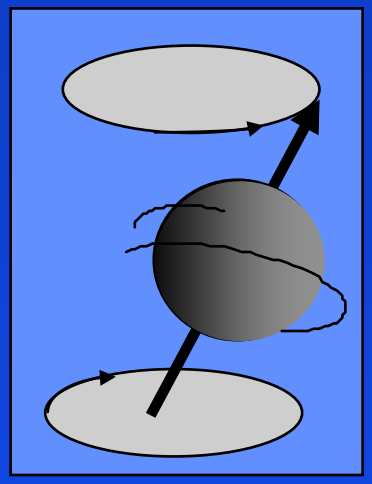


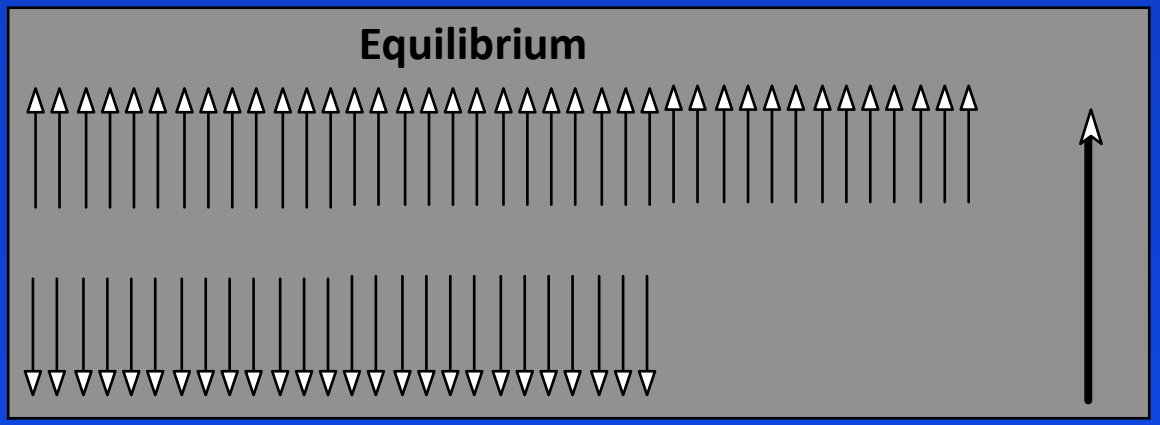
$$\Delta E = h\nu = \gamma \frac{h}{2\pi} B_0$$

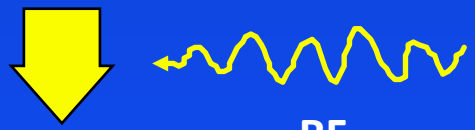
$$2\pi\nu = \omega = \gamma B_0$$

Nucleus type	Mag. Dipole moment, μ_m	Nuclear Spin Number, I	Gyromagnetic Ratio, γ	Larmor Frequency, (MHz/tesla)
^{1}H	2.79	½	2.7×10^{8}	42.6
^{2}H	0.85	1	4.1×10^{7}	6.5
^{13}C	0.7	½	6.7×10^{7}	10.7
^{14}N	0.4	1	1.9×10^{7}	3.1
^{23}Na	2.21	3/2	7.1×10^{7}	11.7
^{31}P	1.13	½	1.1×10^{8}	17.2

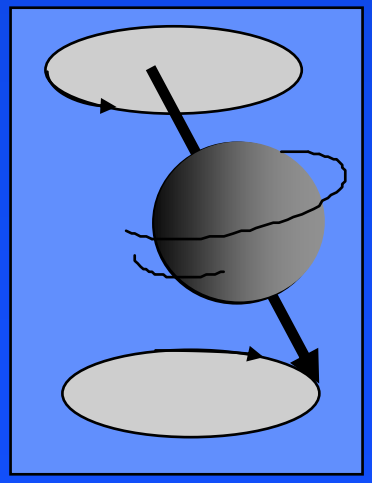
RF at the resonance frequency causes spin flip

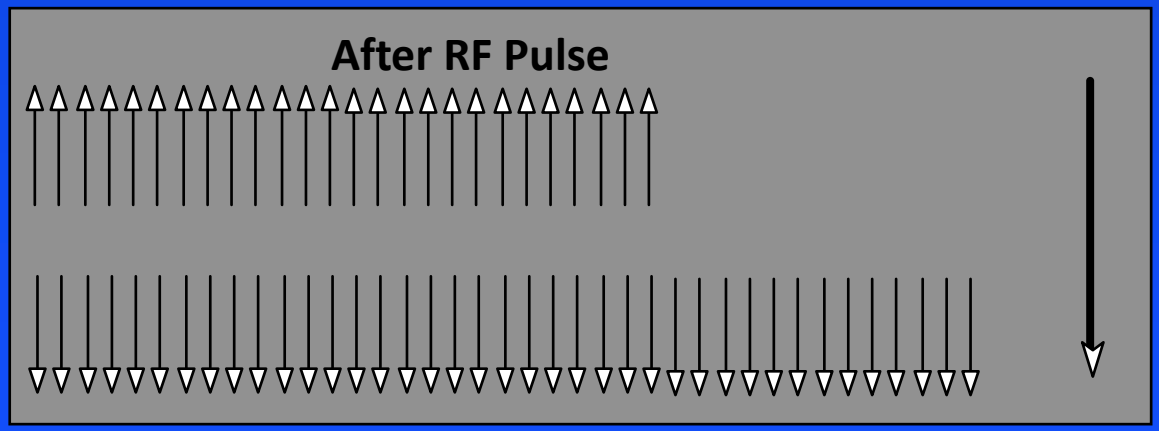




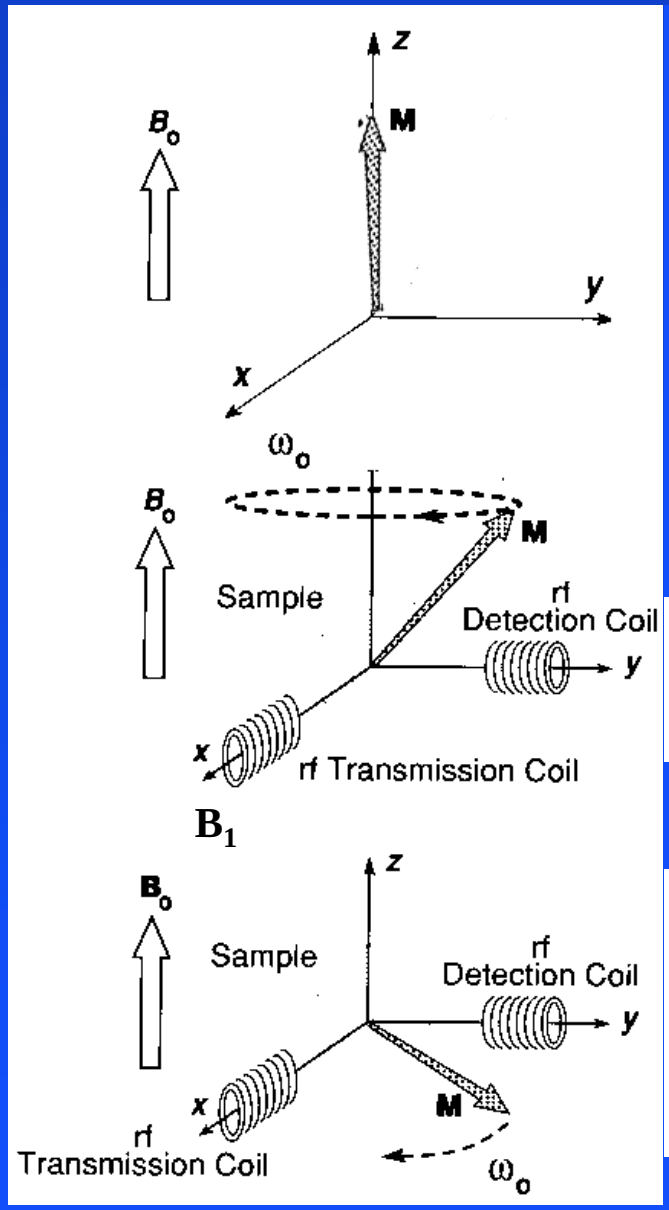


RF

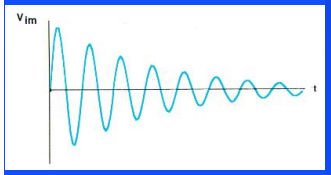


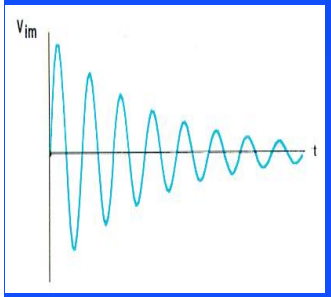


Signal Detection



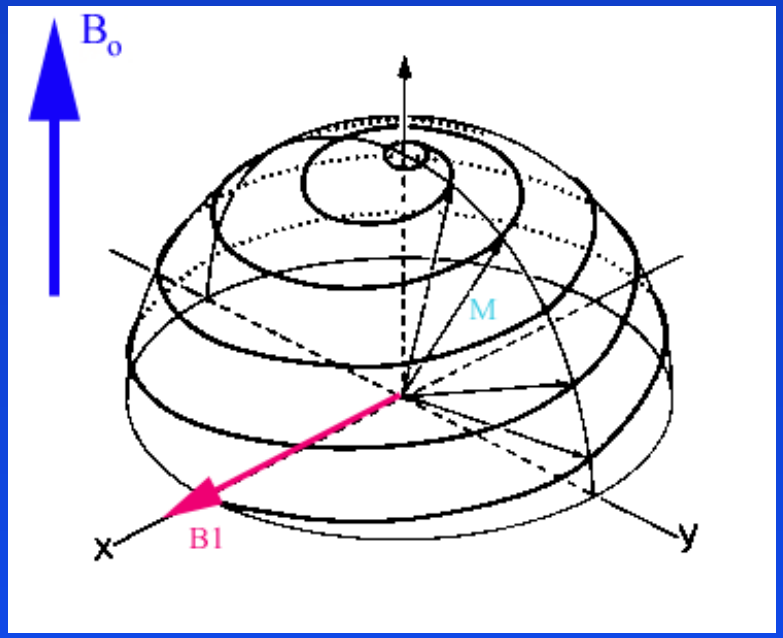
free induction decay (FID)



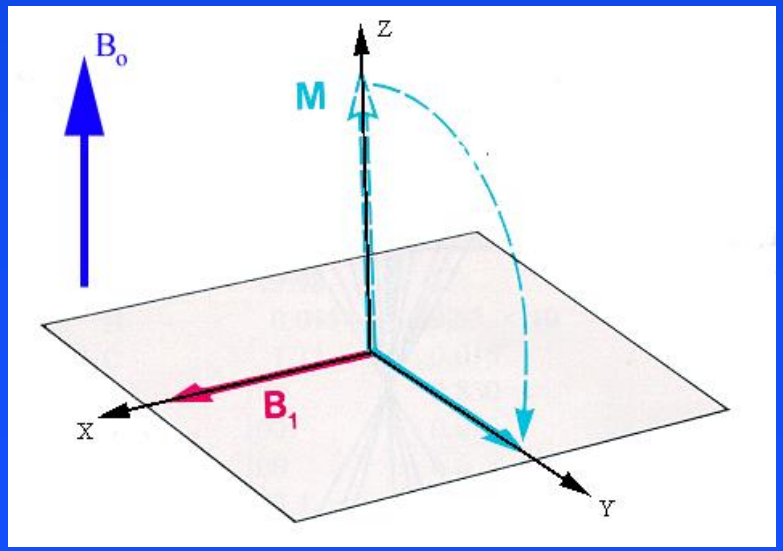


Radio-frequency field: B1

Laboratory Frame

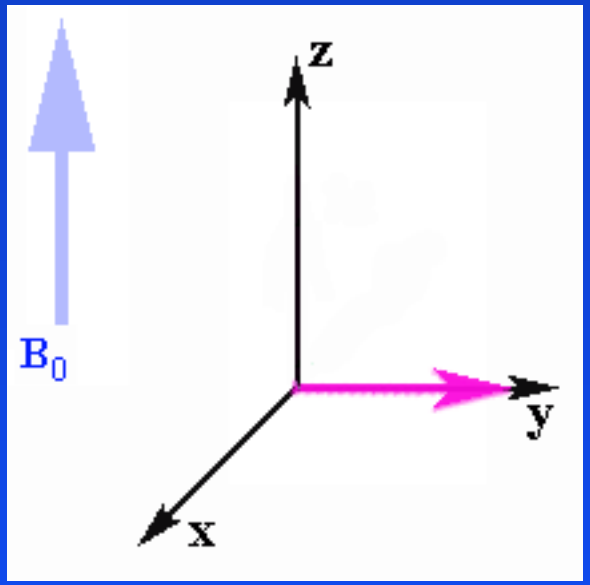


Rotating Frame

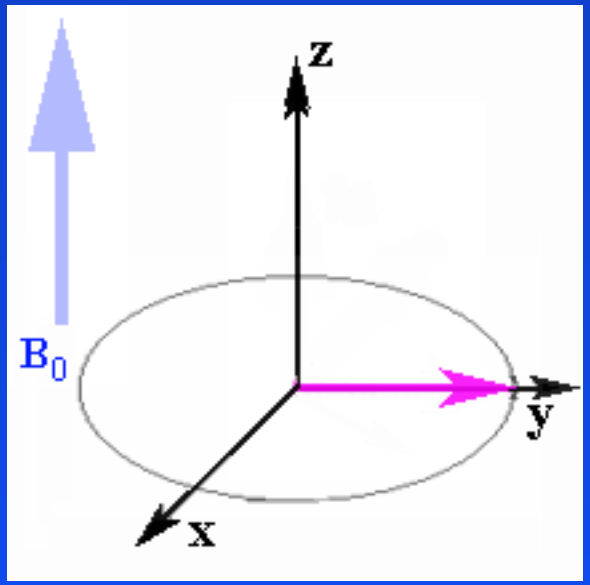


B_1, FID

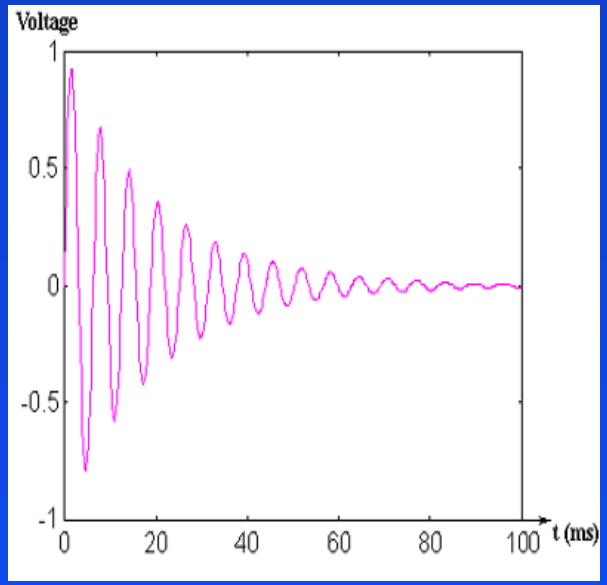
RF excitation



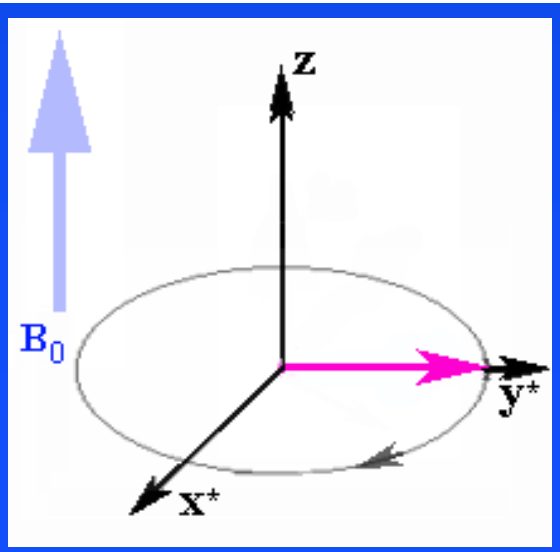
Precession



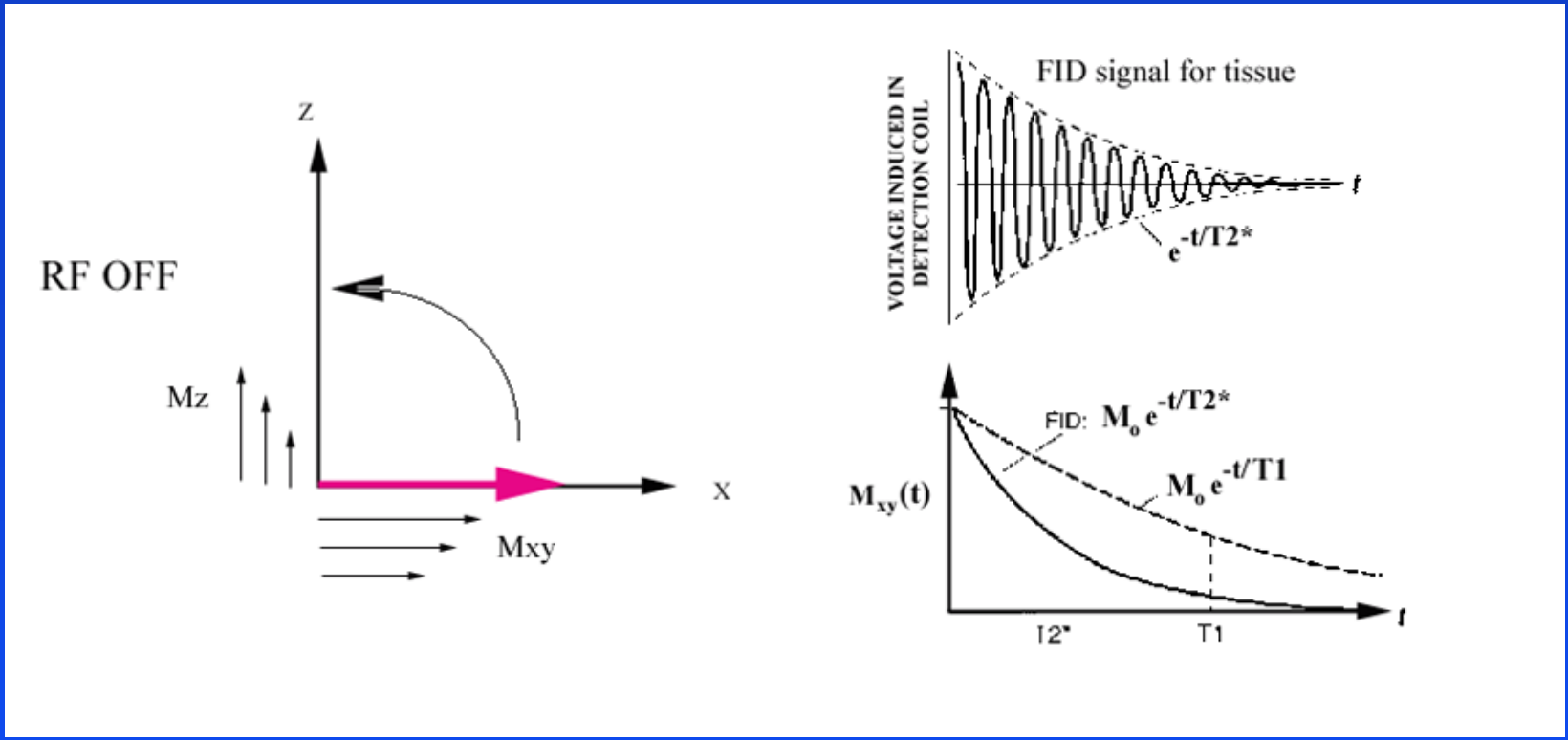
FID
Free Induction Decay



Rotating Frame



RELAXATION: T1, T2, T2*



T1: Spin lattice relaxation

T2: Spin-Spin relaxation

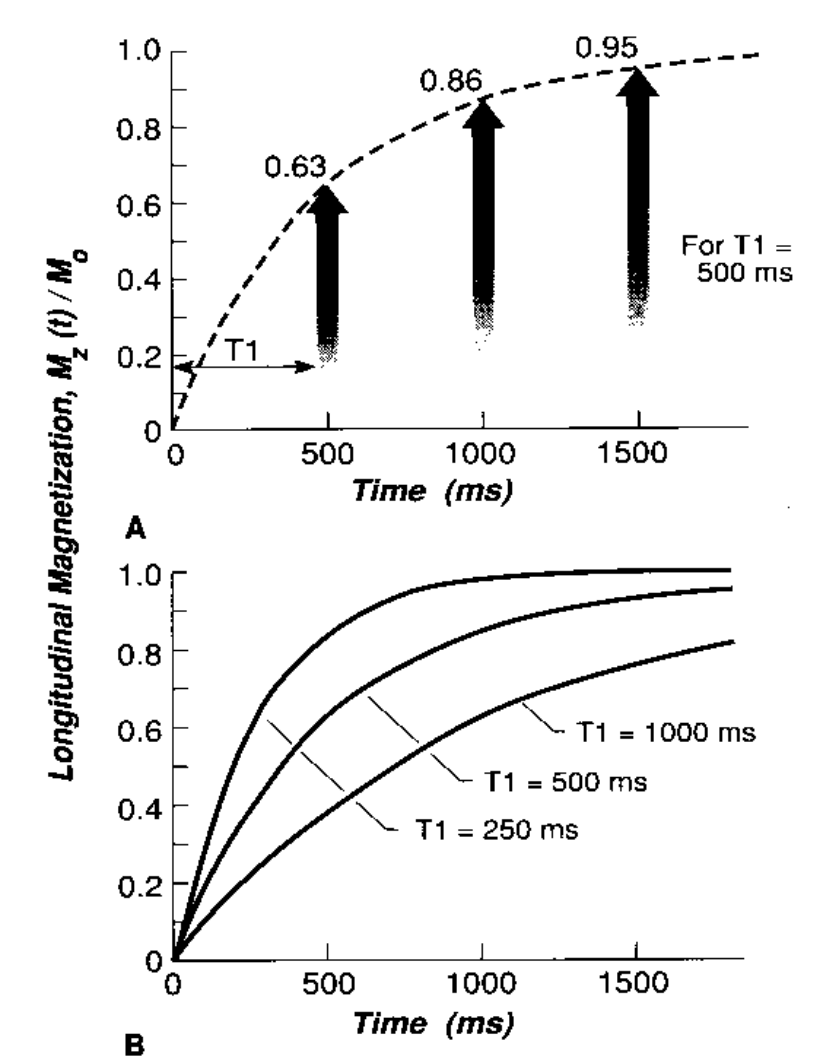
T2*: inhomogeneity, susceptibility...

free induction decay (FID)

RELAXATION: T1, T2, T2*

- The recovery of longitudinal magnetization is called longitudinal or ***T*1** relaxation.
- The loss of phase coherence in the transverse plane is called transverse or ***T*2** relaxation.
- The time constant for the observed decay of the FID is called the ***T*2 *** relaxation time, and is always shorter than *T*2.

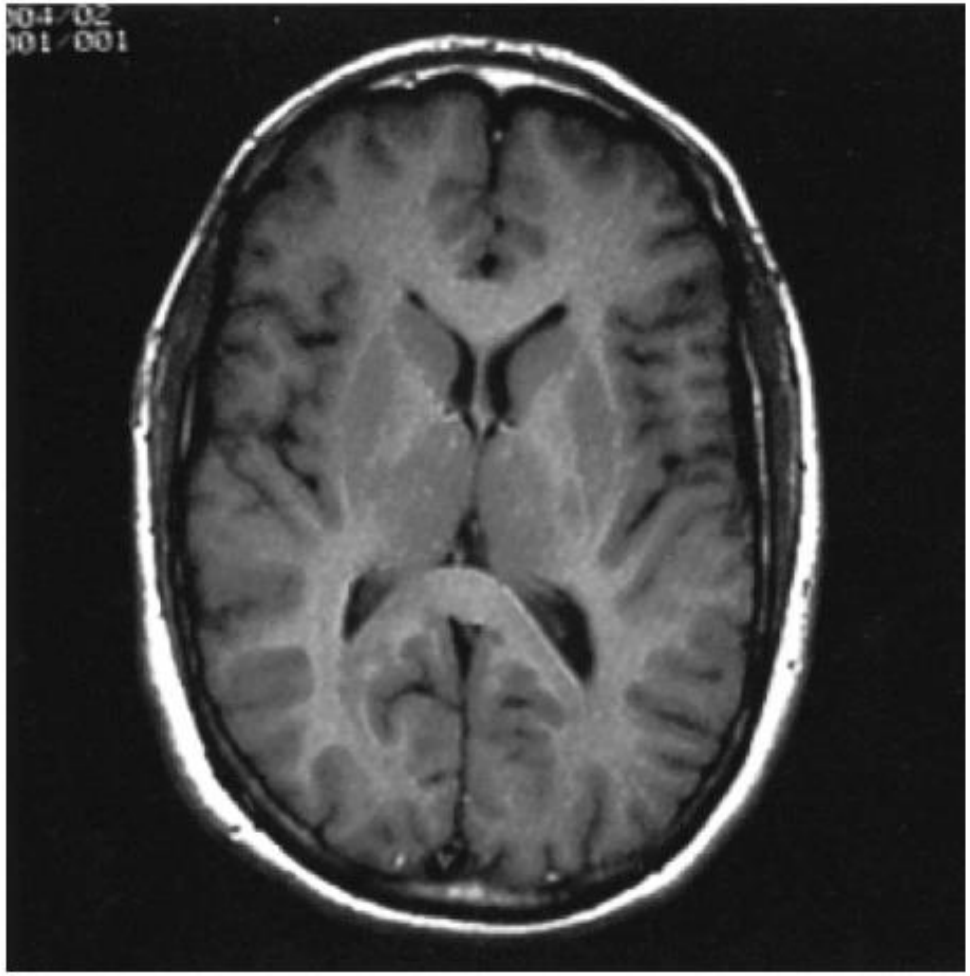
T1 Recovery

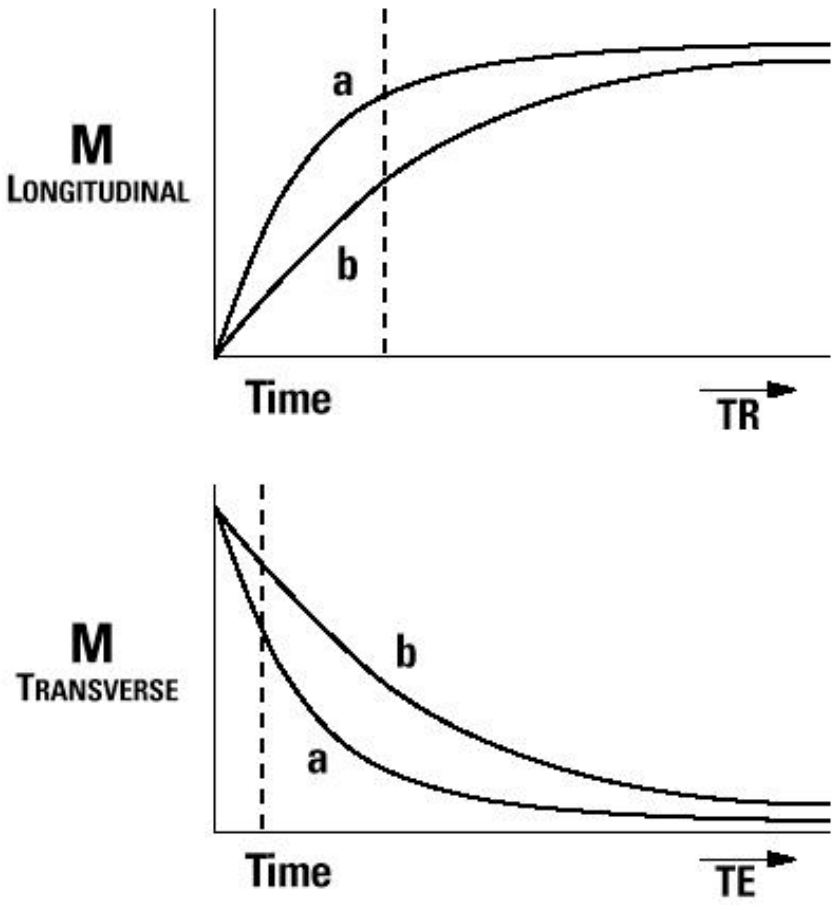


$$M_0(1-e^{-t/T1})$$

Organ	T_1(ms)
Putamen	747+/-33
Caudate	822+/-16
CSF	1900+/-353
Cortical gray	871+/-73
Corpus Callosum	509+/-39

T1 Weighted

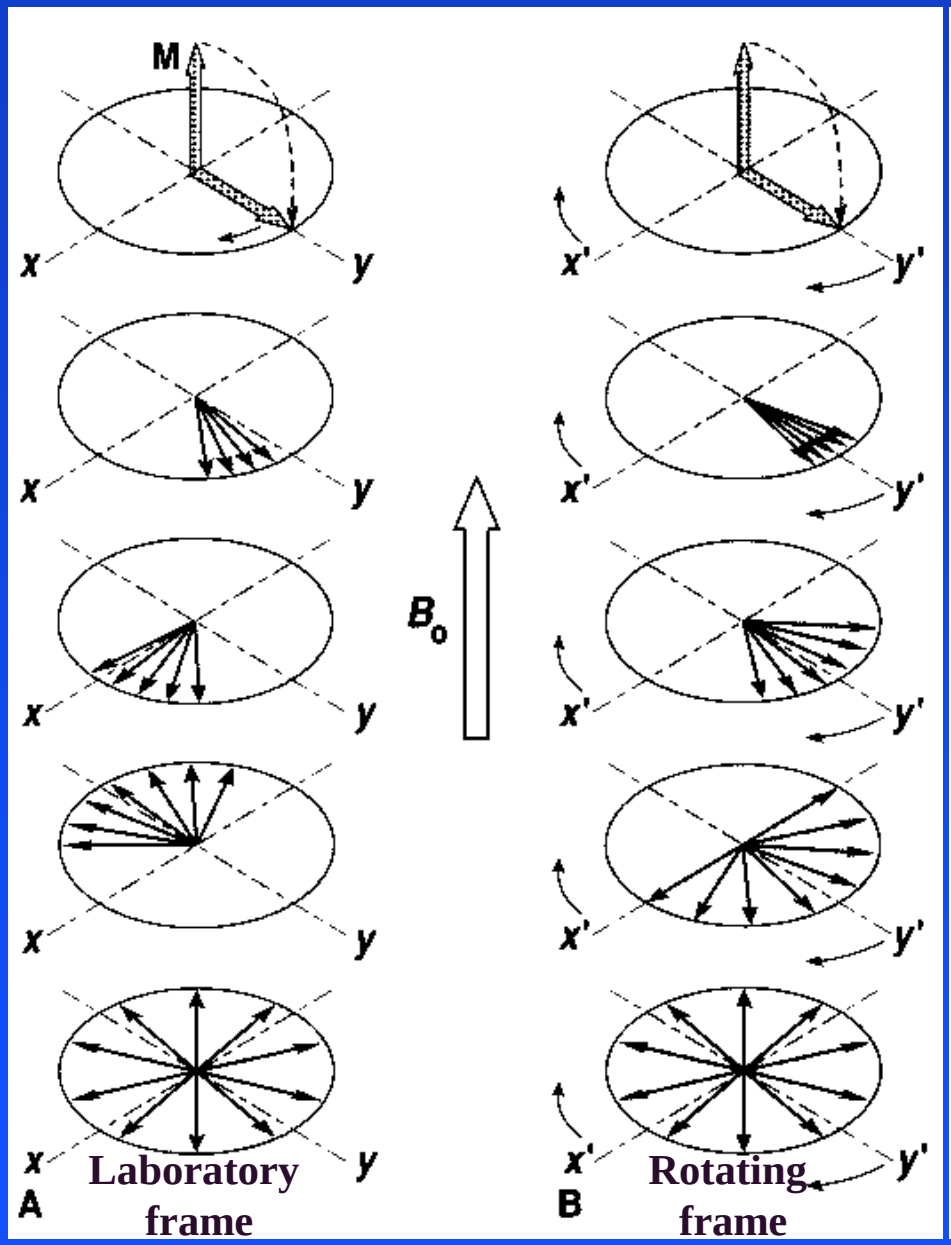


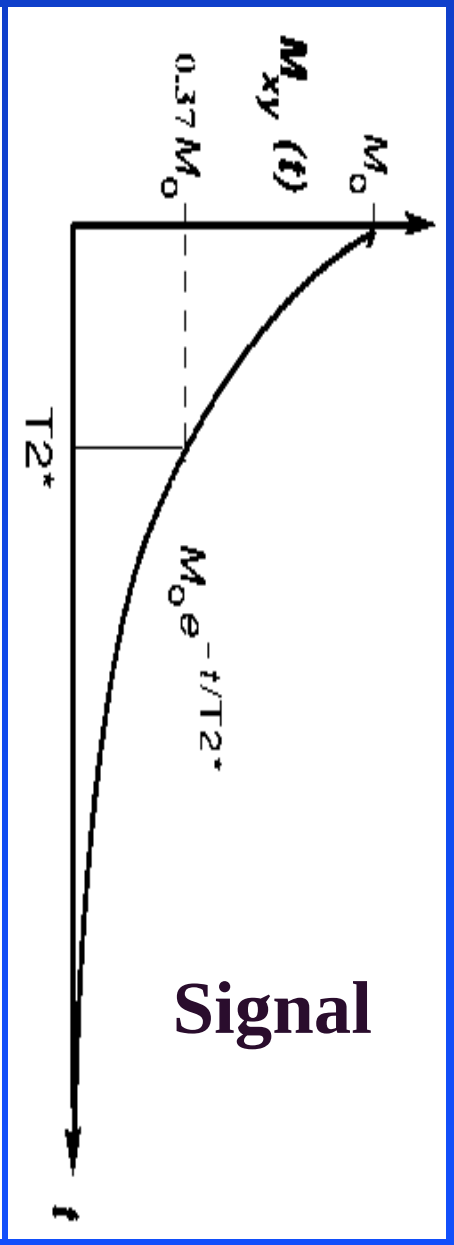


T2,T2* dephasing

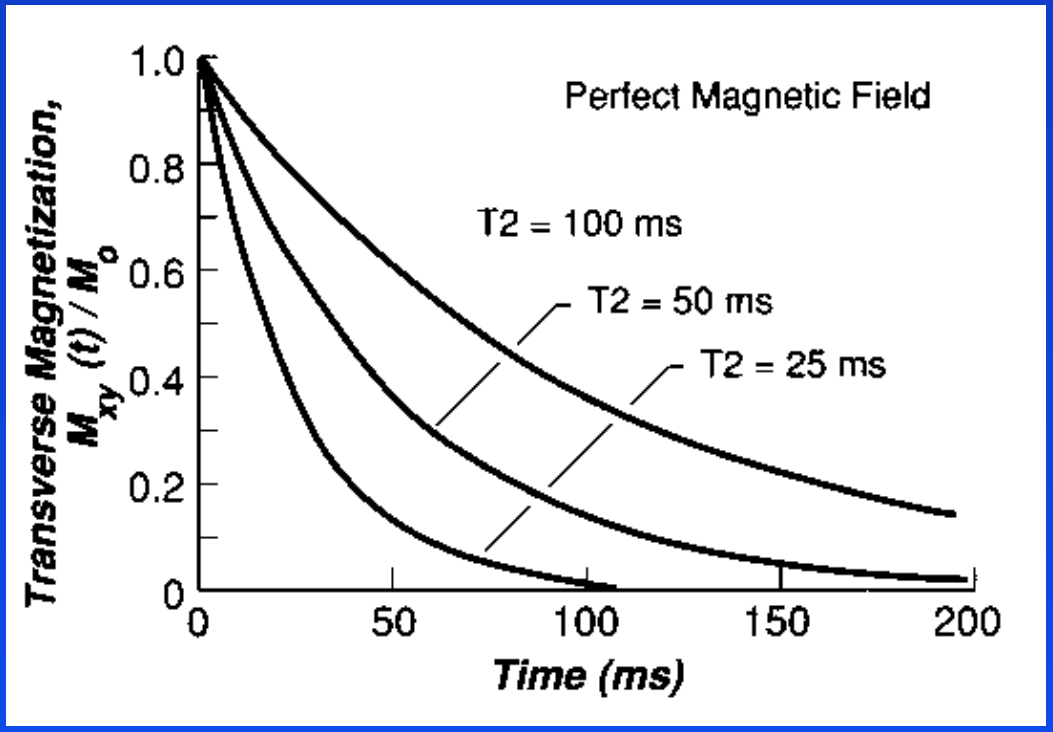
As time goes spin coherence is lost

t





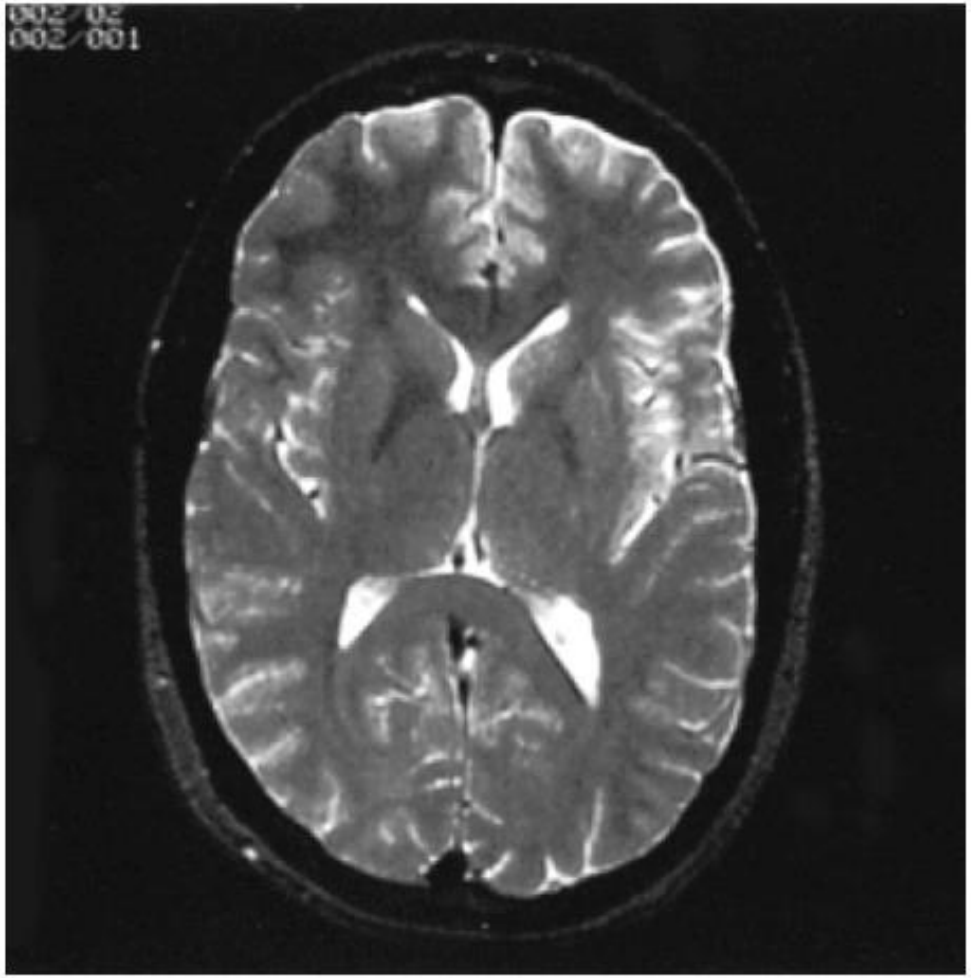
T2 Decay

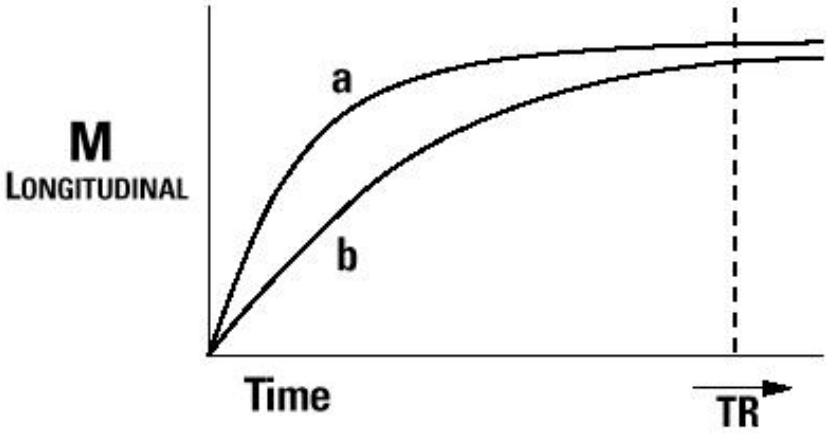


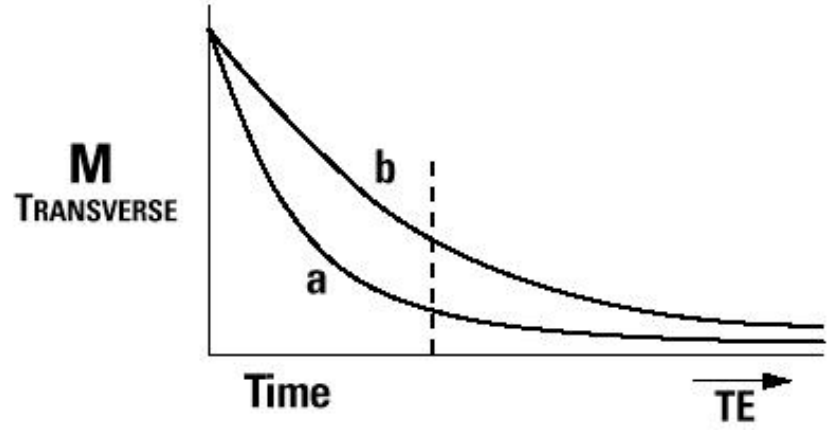
$$M_{xy}(t) = M_0 e^{-t/T_2}$$

Organ	T_2(ms)
Putamen	71+/-4
Caudate	76+/-4
CSF	250+/-3
Cortical gray	87+/-2
Corpus Callosum	69+/-8

T2 Weighted

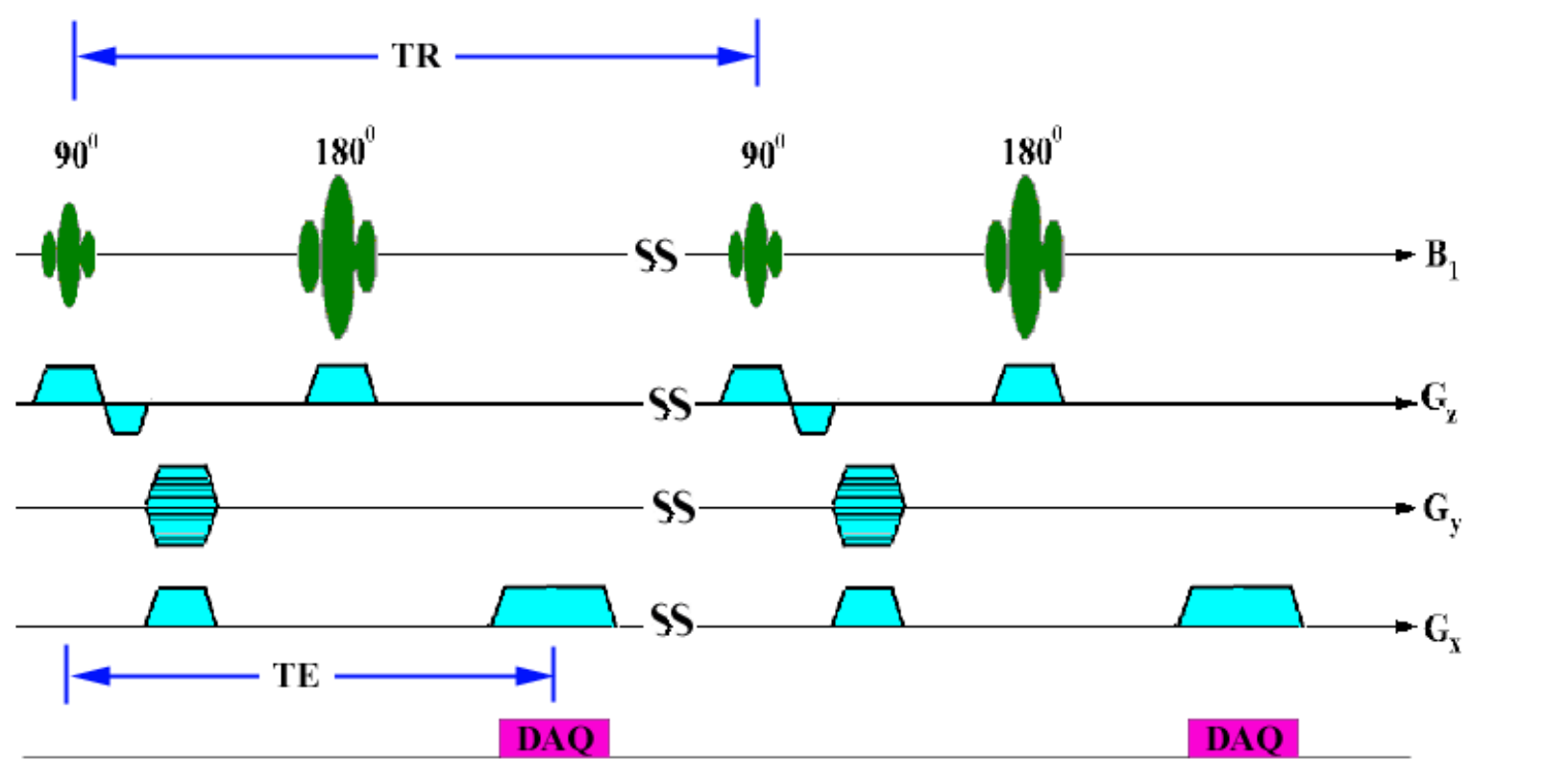


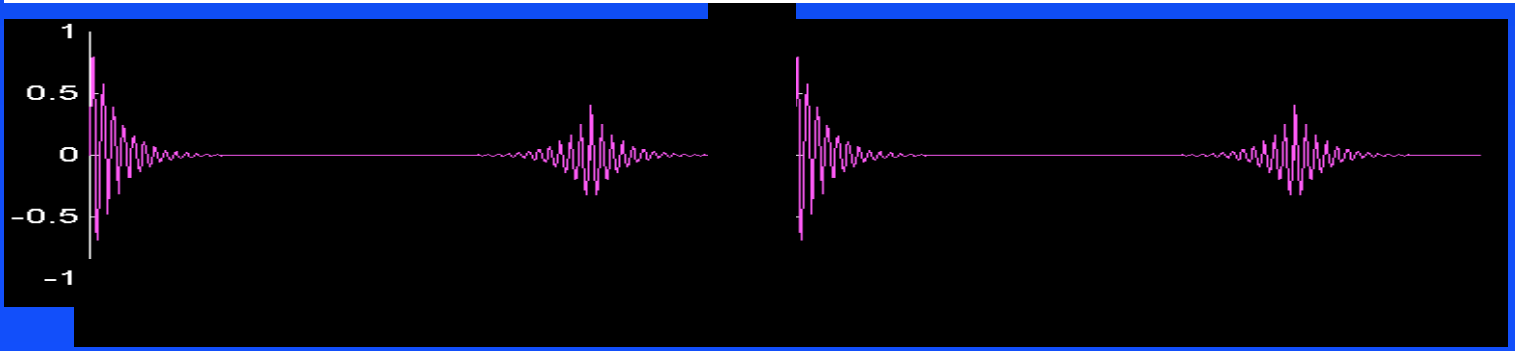




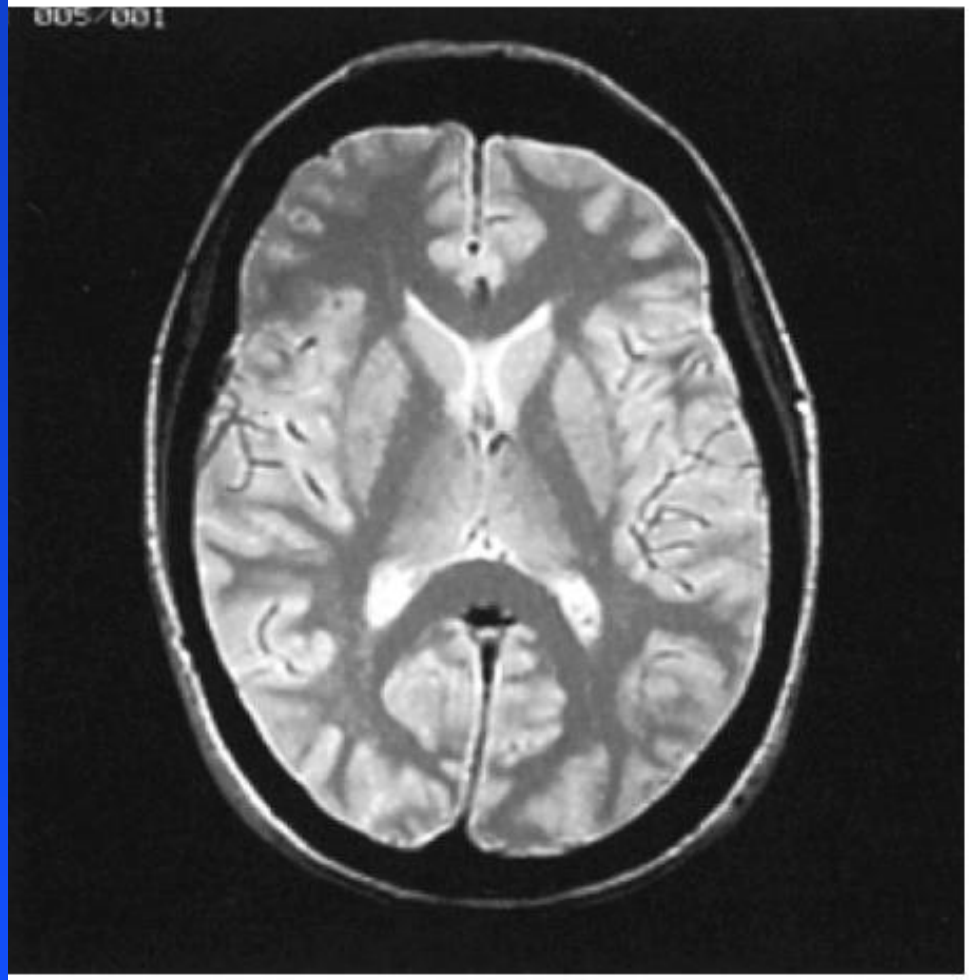
Spin-echo imaging

Pulse Diagram





Proton Density Weighted



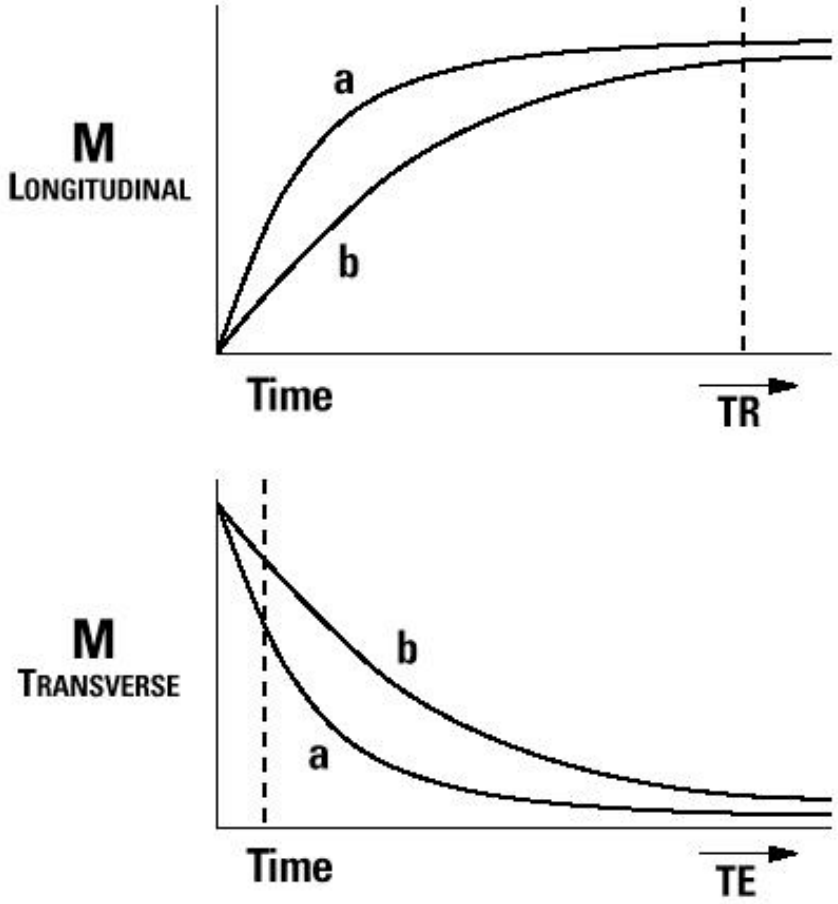
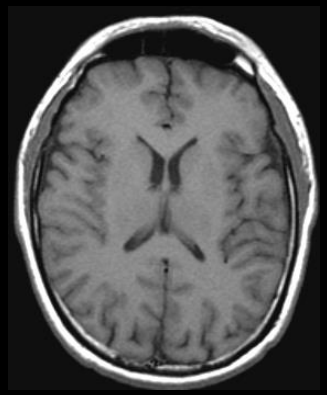
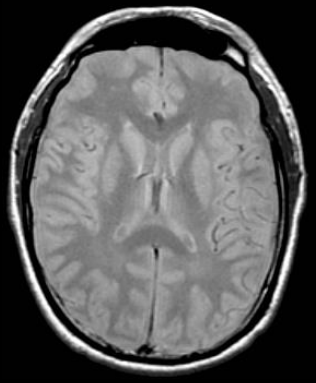
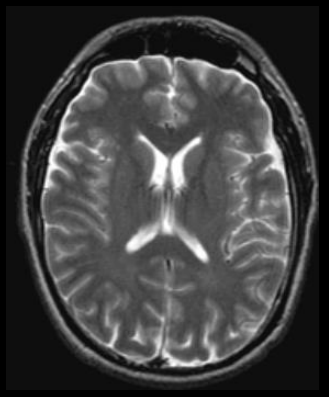
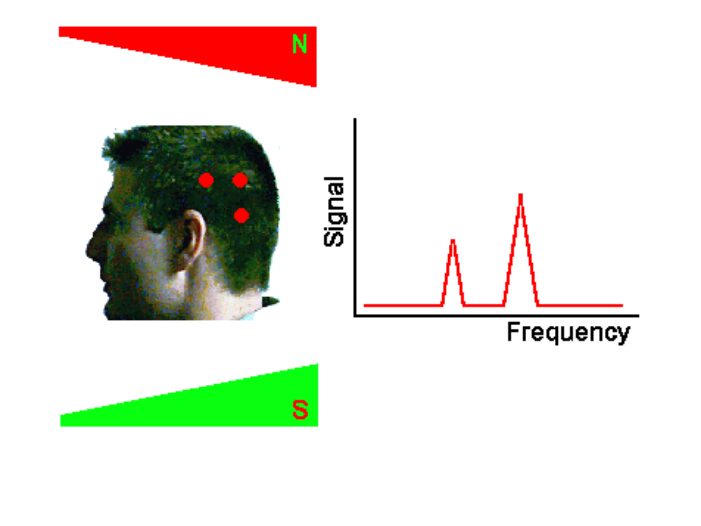
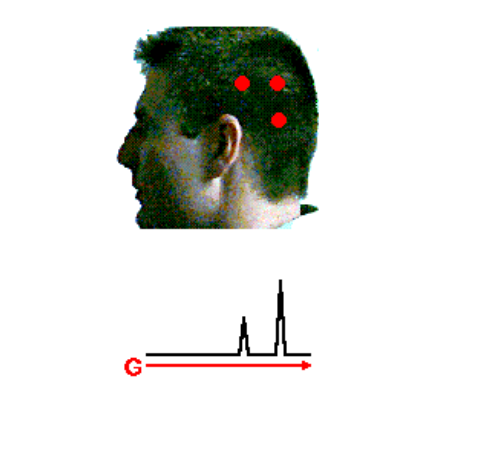


Image Contrast

TR \ TE	Short TE 10-30ms	Long TE 70-150ms
Short TR 400-600ms	T1 Weighted 	Mixed
Long TR 1500-2500ms	Proton Density Weighted PDW 	T2 Weighted 

Gradient

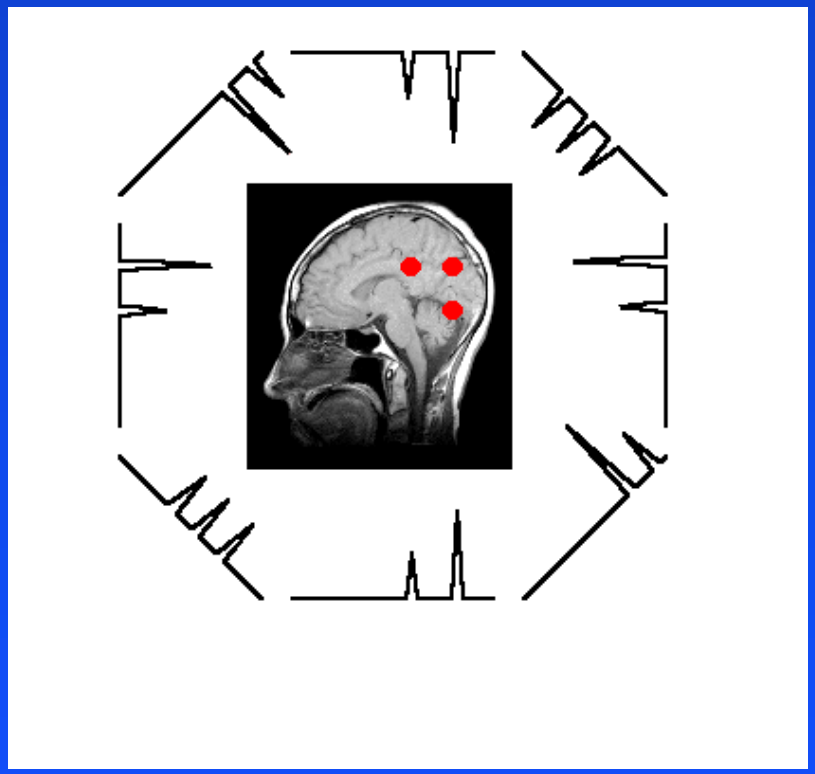


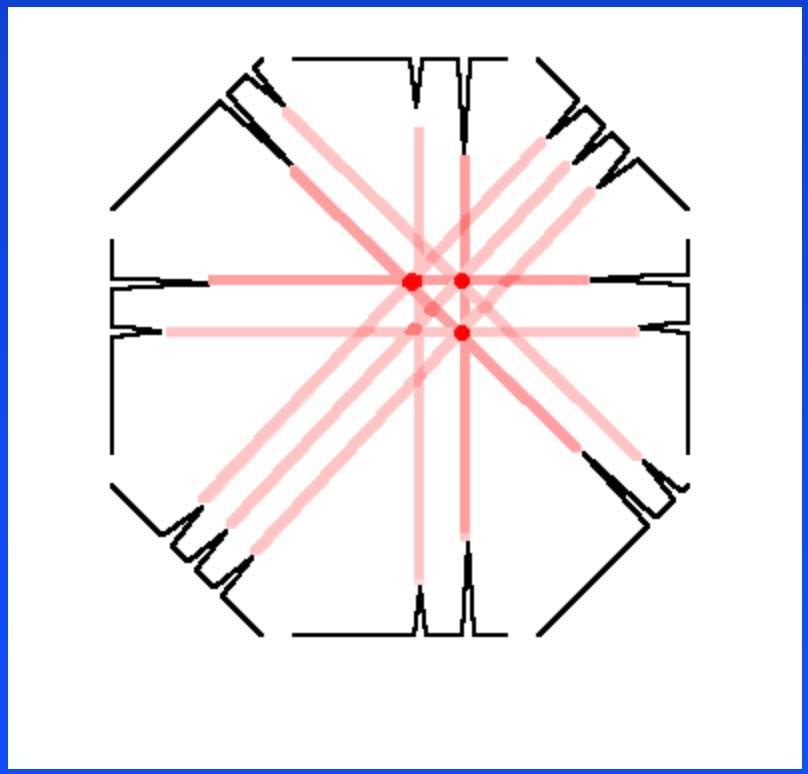


$$\nu = \gamma (B_0 + x G_x) = \nu_0 + \gamma x G_x$$

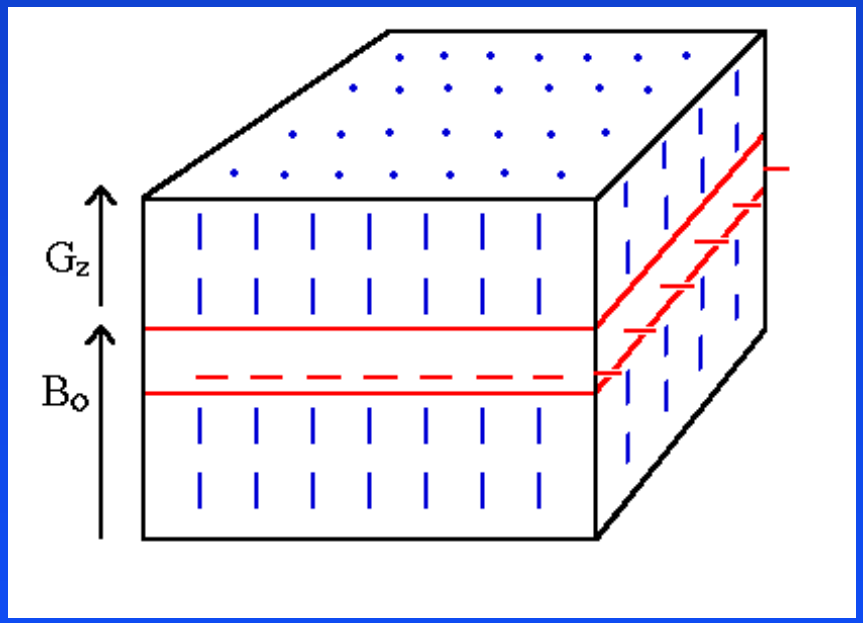
$$x = (\nu - \nu_0) / (\gamma G_x)$$

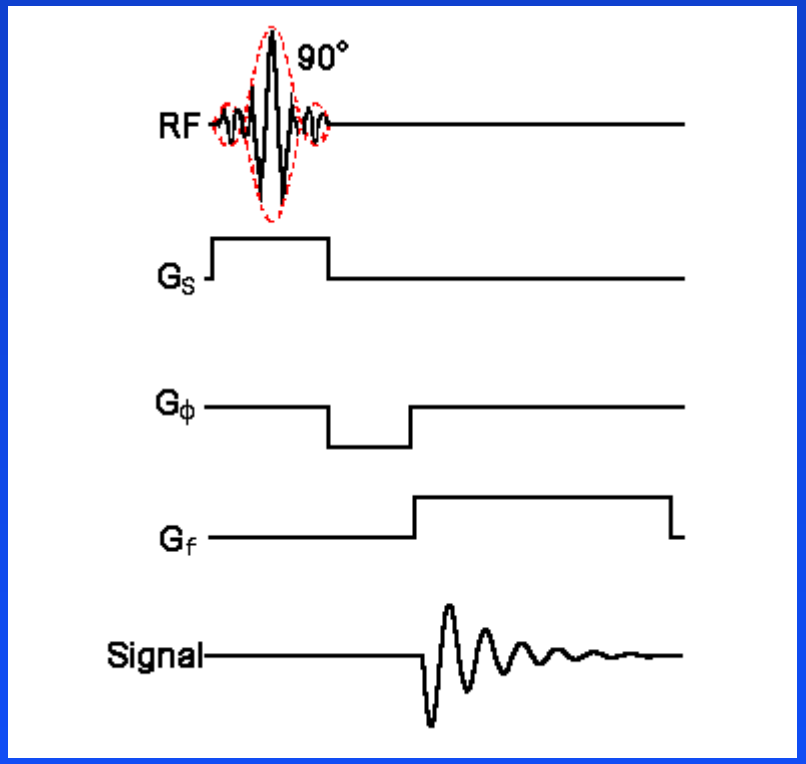
Reconstruction





Slice selection

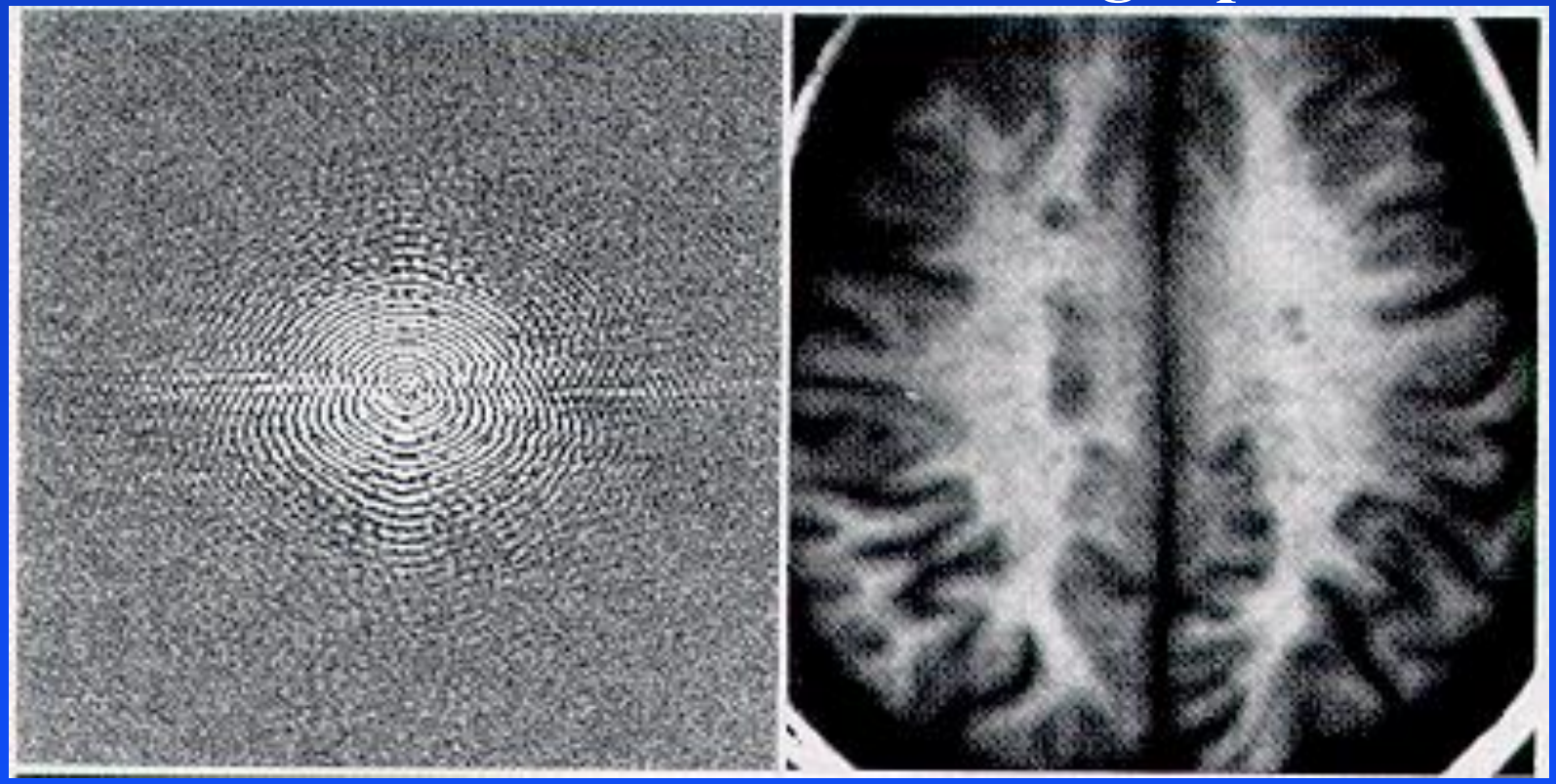




2D Imaging

***k*-space**

image space



phase encoding

y

frequency encoding

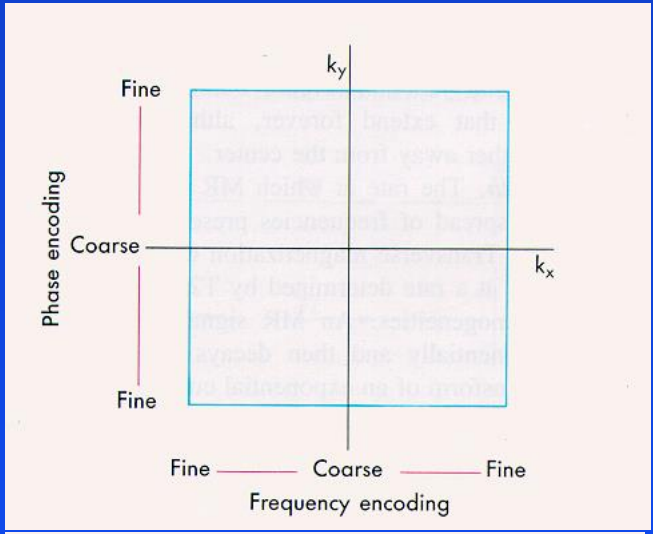
x

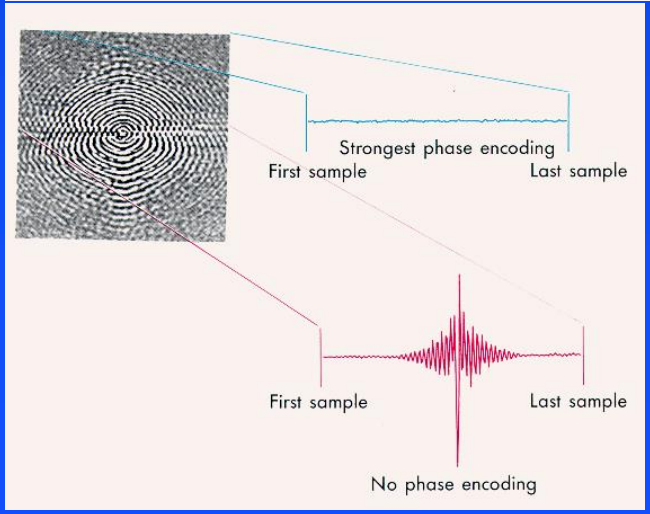
Encode with
magnetic-field gradients

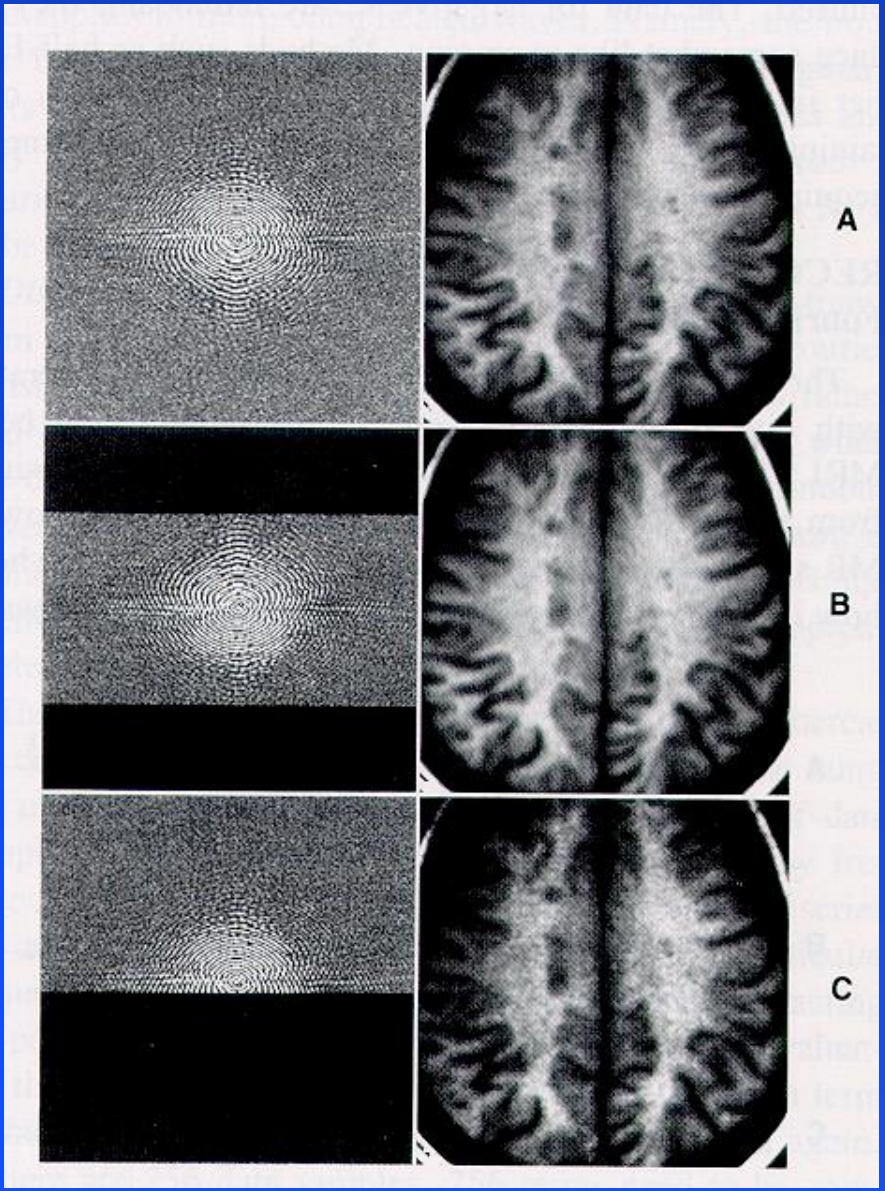
Decode with
Fourier transform

K-Space

Sampling of K-space







Factors Influencing Image Intensity

- **Relaxation Times (T1, T2)**
- **Proton Distribution**
- **Flow and Motion**

Pulse Sequence

A Combination of RF and Gradient Pulses that Control Image Parameters and Must be Repeated Several Times to Complete Image Data Set

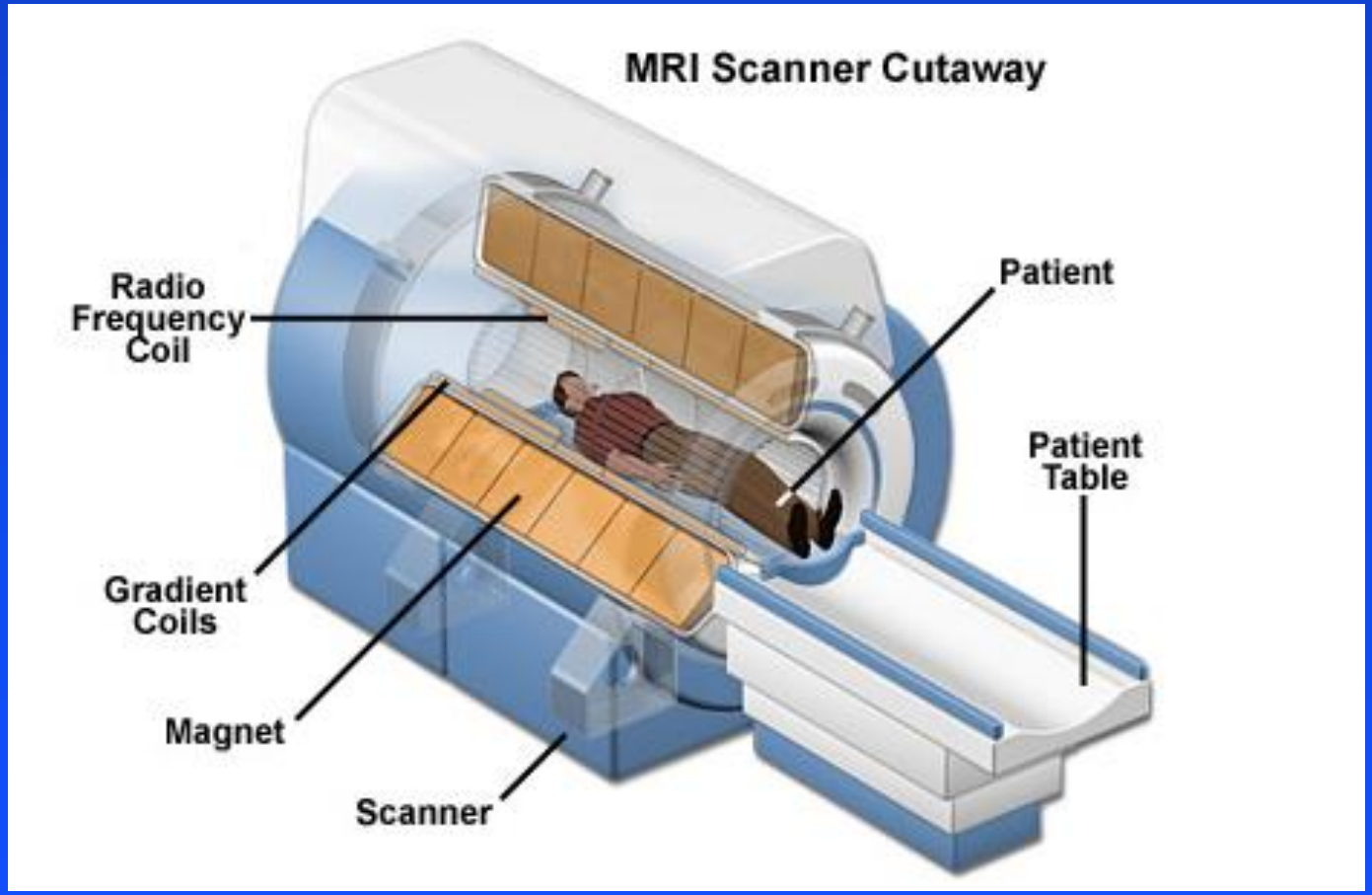
A Pulse Sequence Controls

- **Slice Location & Orientation**
- **Slice Thickness**
- **Tissue Contrast**

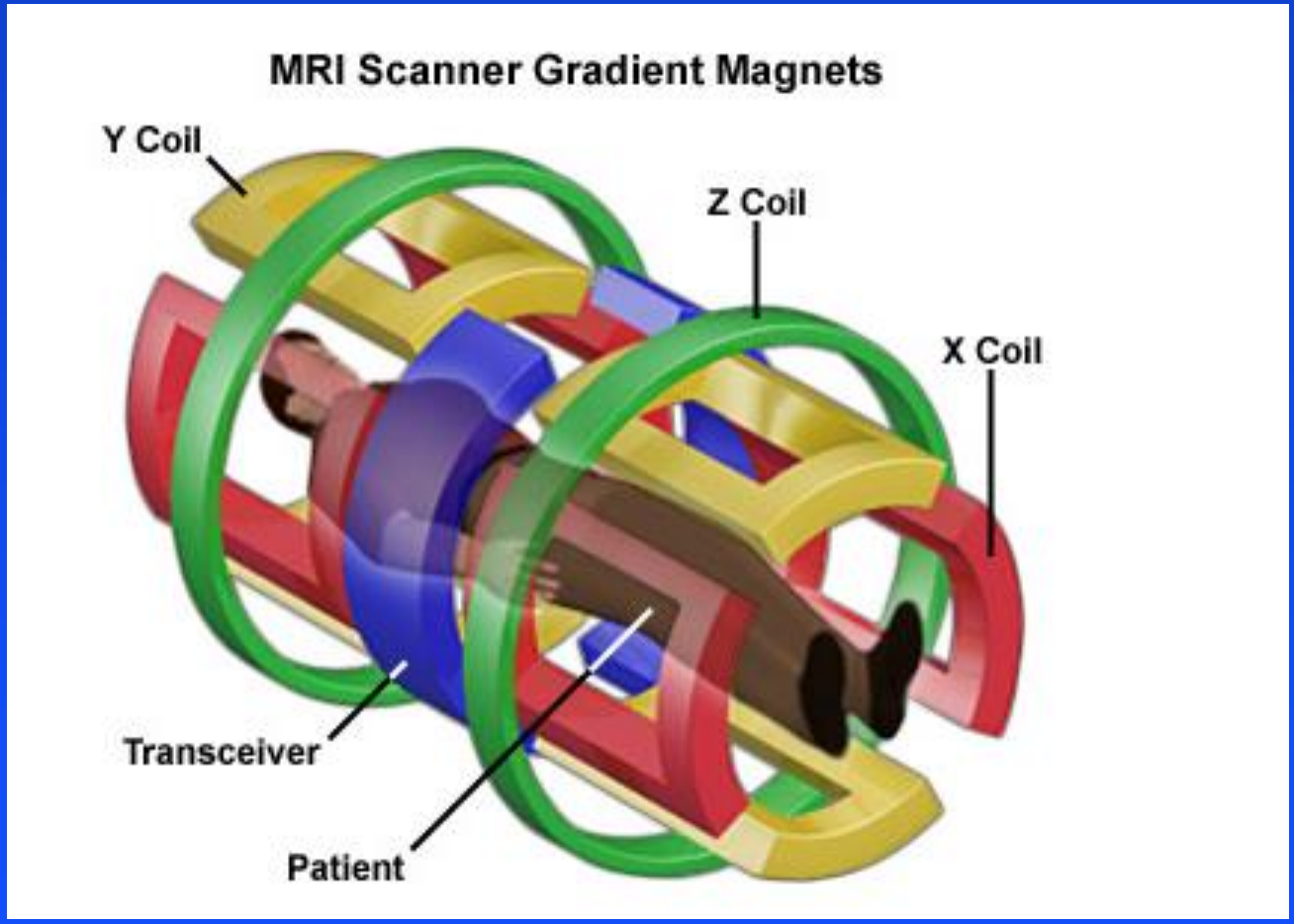
Spin Echo Sequence

- **T1, T2 or PDW Contrast Possible**
- **Adjust TR & TE to Change Contrast**
- **Acquisition Time Several Minutes**

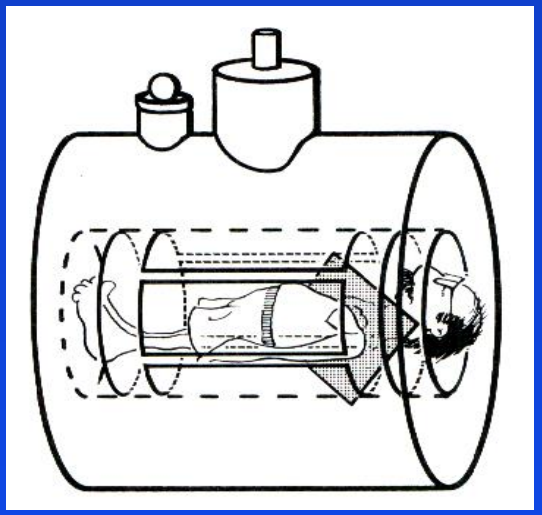
MRI scanner

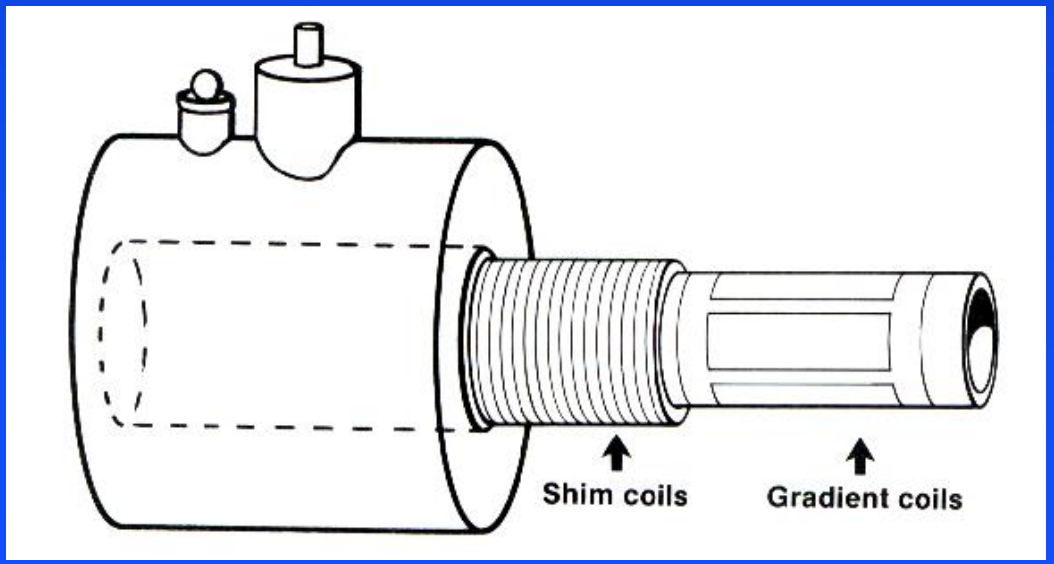

MRI Scanner Cutaway
Radio Frequency Coil
Patient
Patient Table
Gradient Coils
Magnet
Scanner

MRI Gradient Magnets



Hardware





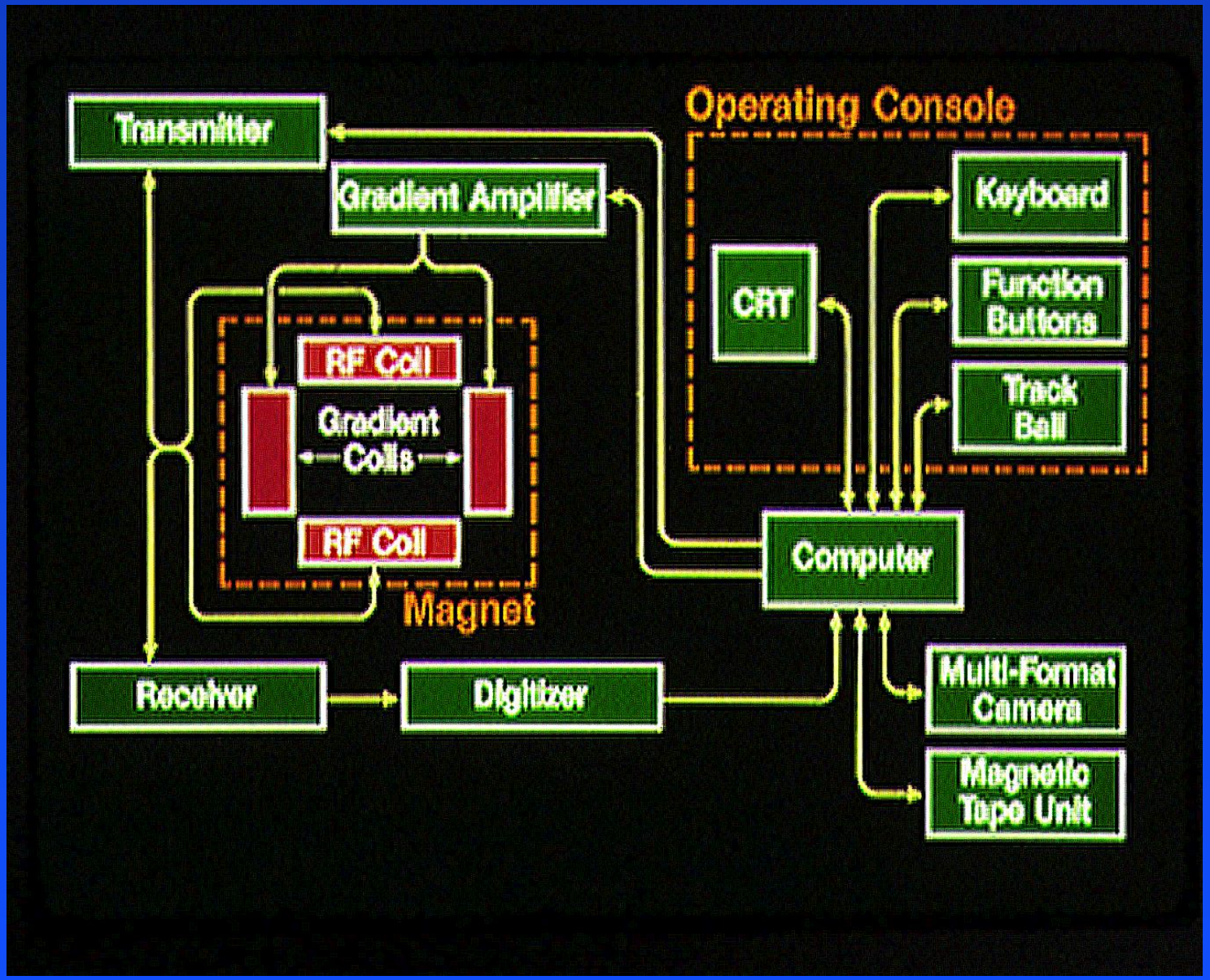
RF (B1) Coils

Shoulder
Surface Coil

Knee
Quad Coil

Body
Phased Array

Head
Quad Coil


Transmitter
Gradient Amplifier
Operating Console
Keyboard
CRT
Function Buttons
Track Ball
RF Coil
Gradient Coils
RF Coil
Magnet
Computer
Receiver
Digitizer
Multi-Format Camera
Magnetic Tape Unit

Conclusions

- **MRI: non-invasive and flexible**
- **Several natural contrast mechanisms**
- **Imaging: magnetic field creates resonance condition, which can be made spatially-variant**

Conclusions

- **MRI: not a magic bullet**
- **Still lacks a good contrast**
- **Relatively slow in comparison with CT**

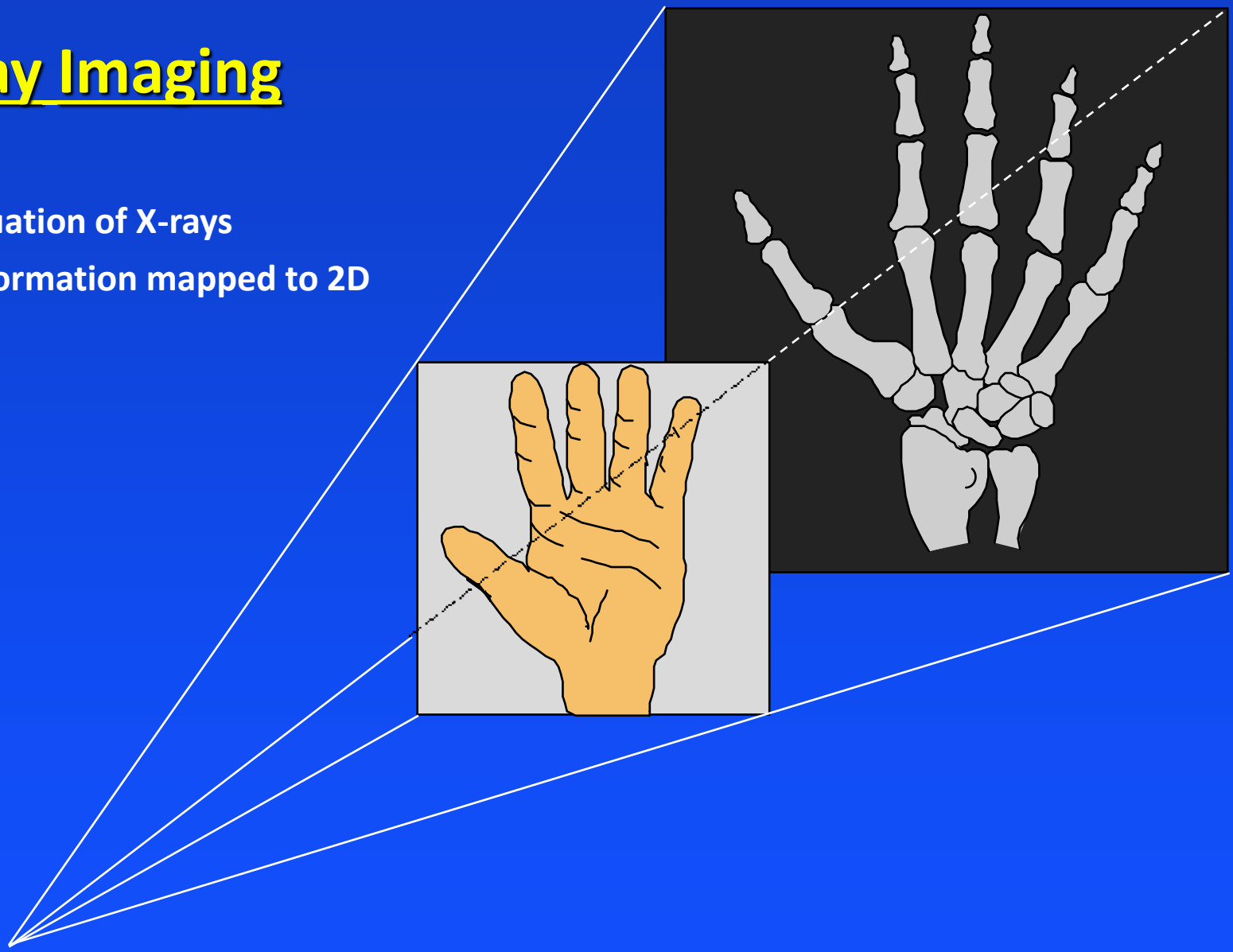
Other medical imaging modalities

- X-ray imaging and CT
- Nuclear Medicine
  - Single photon emission tomography (SPECT)
  - Positron emission tomography (PET)

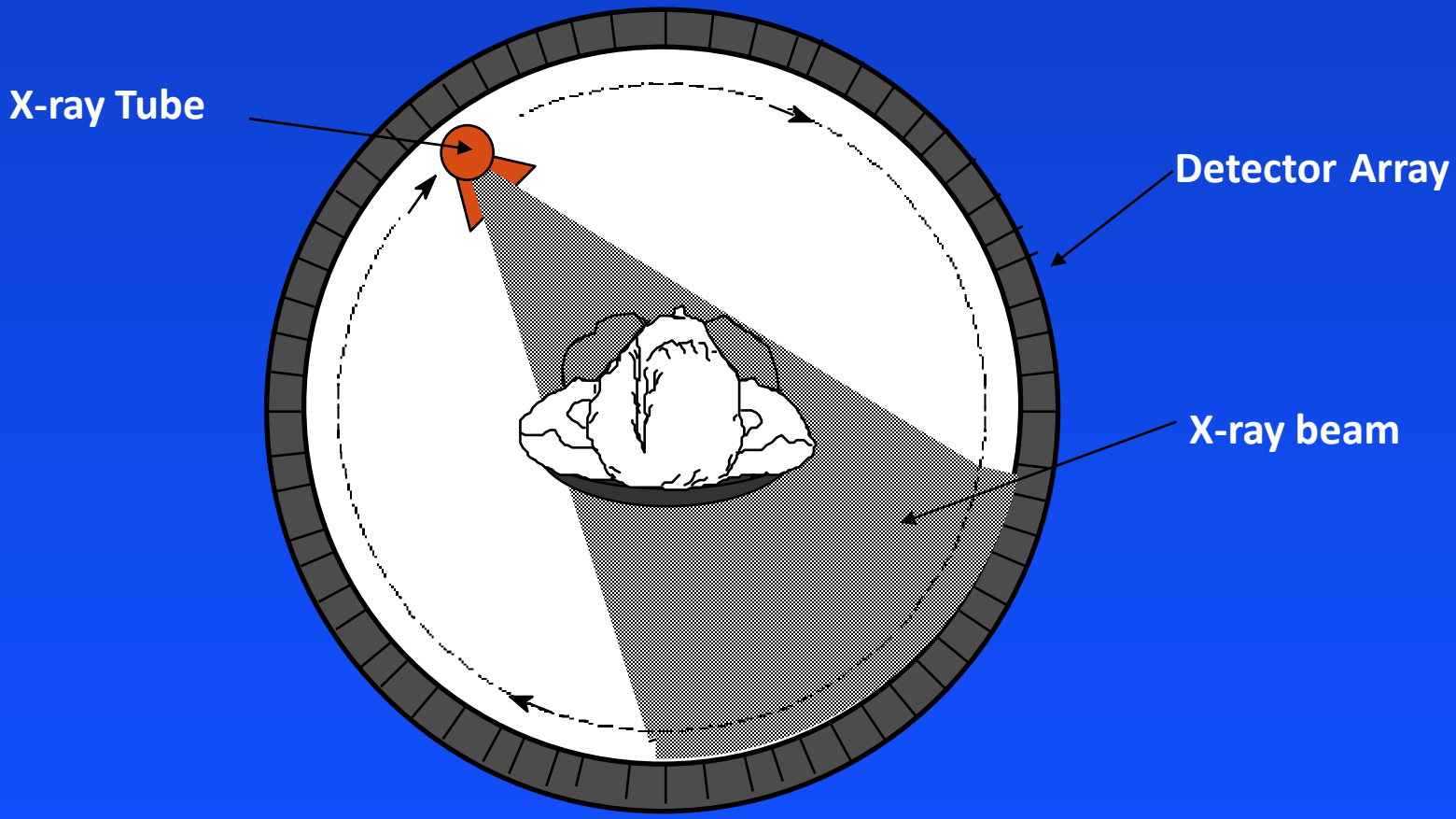
X-ray Imaging

Attenuation of X-rays

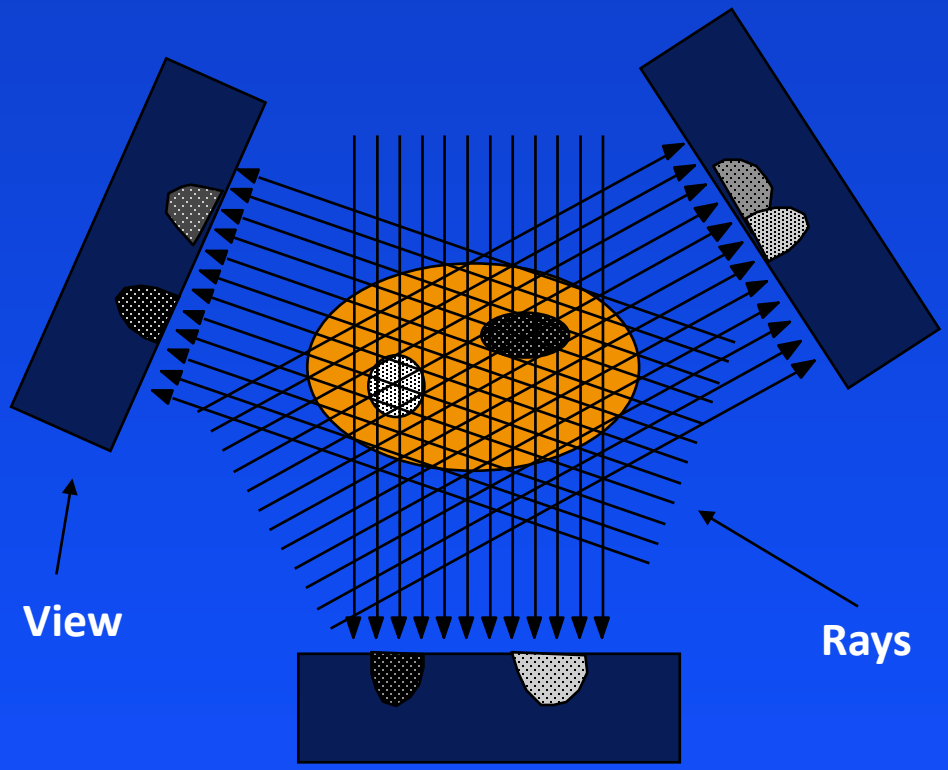
3D information mapped to 2D



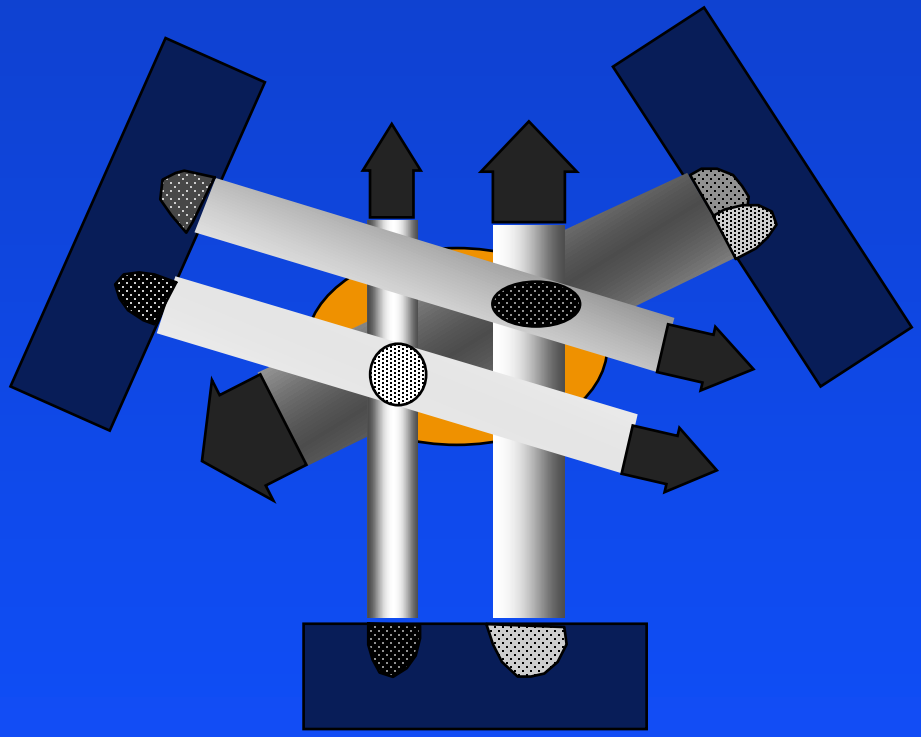
CT
Computed Tomography
(Transmission Computed Tomography - TCT)



CT Acquisition



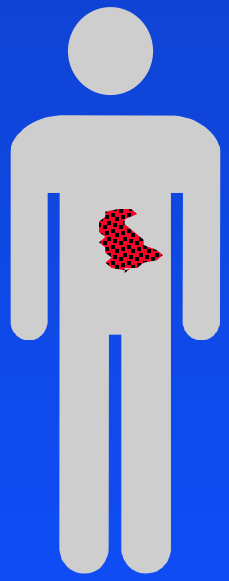
CT Reconstruction



Filtered Backprojection

Nuclear Medicine

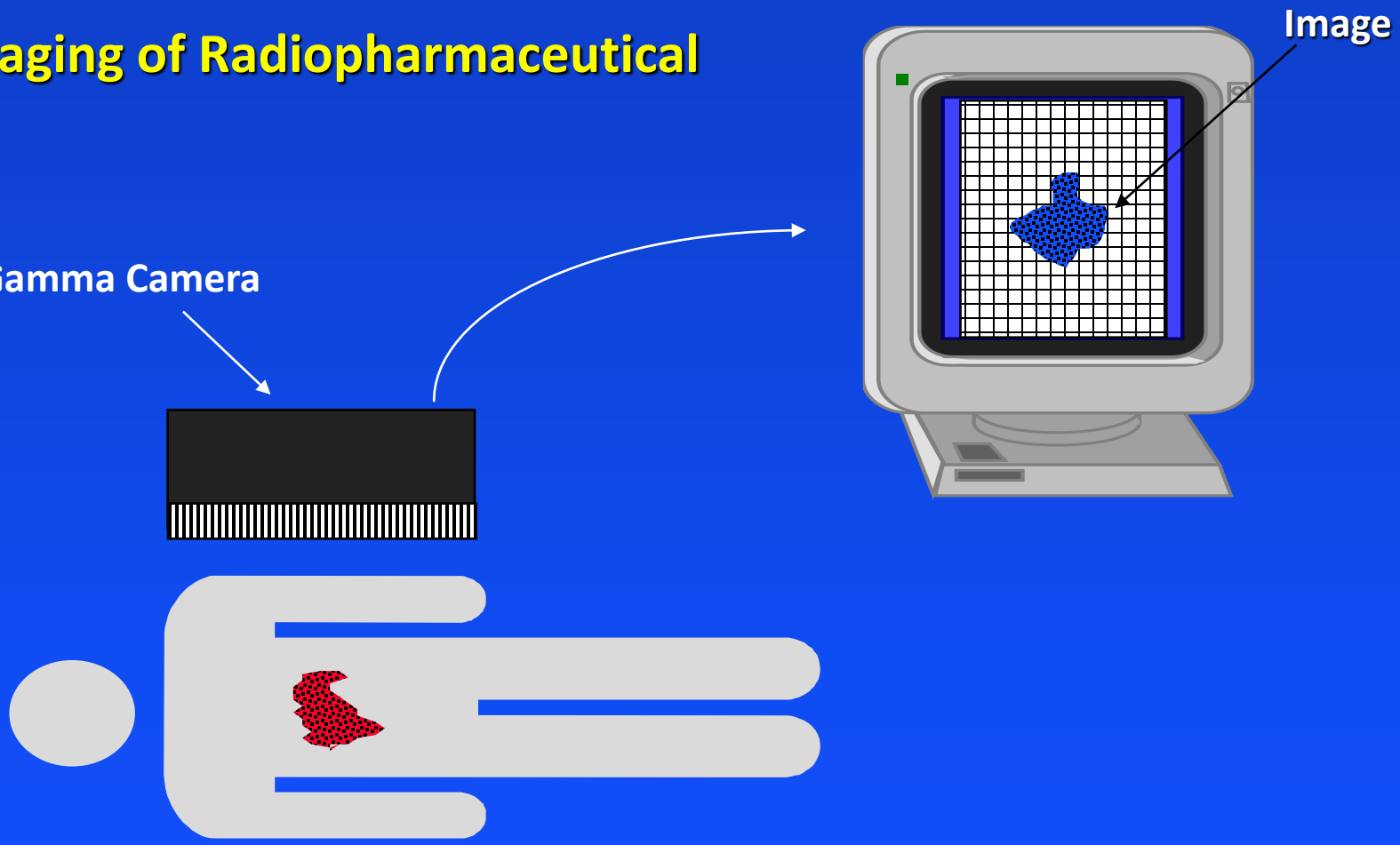
Injection of
Radiopharmaceutical



Redistribution of
Radiopharmaceutical

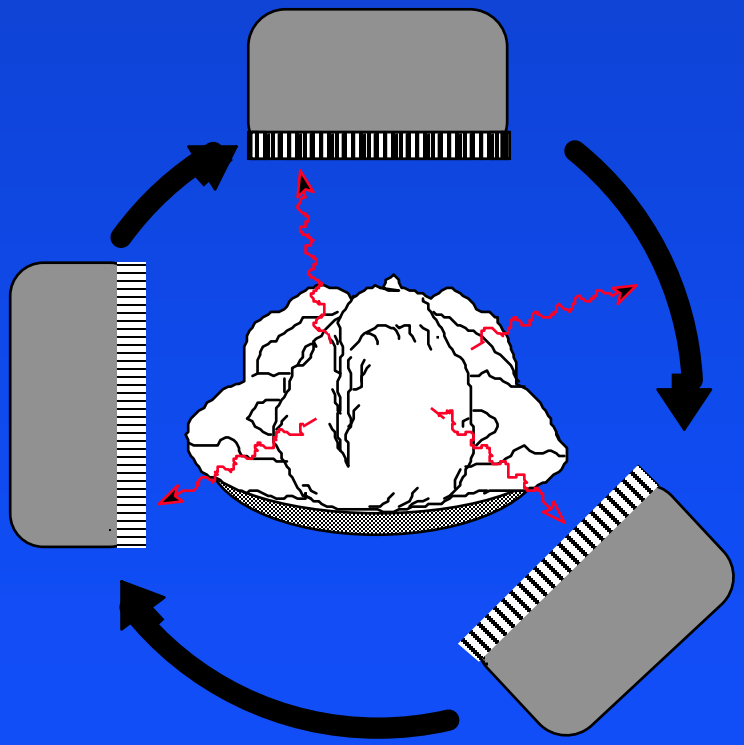
Nuclear Medicine

Imaging of Radiopharmaceutical

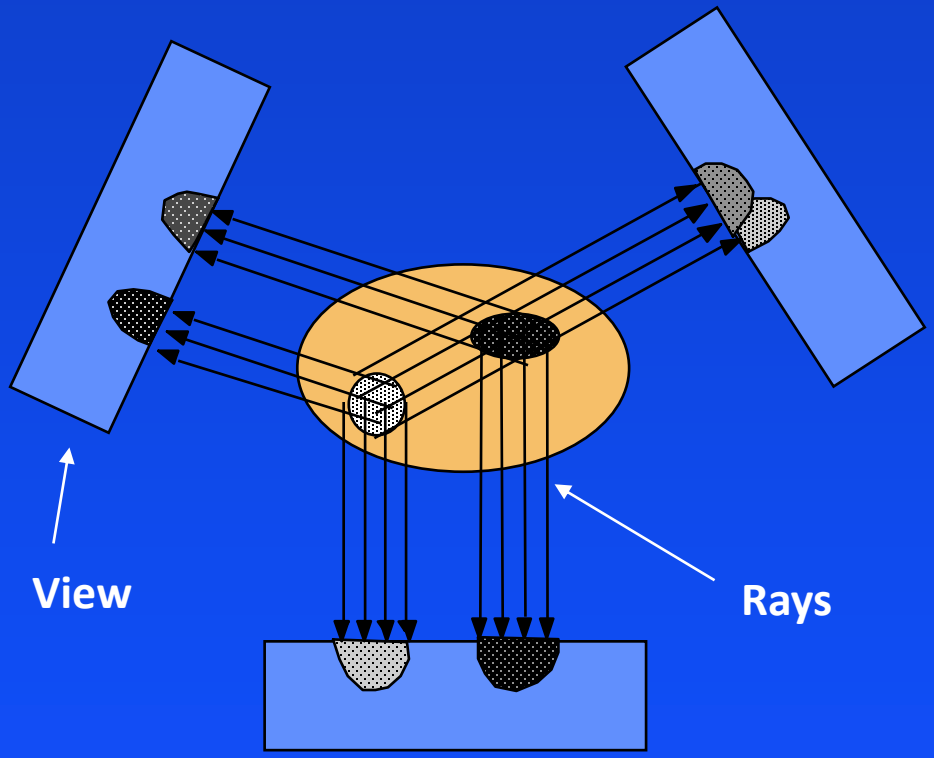


SPECT

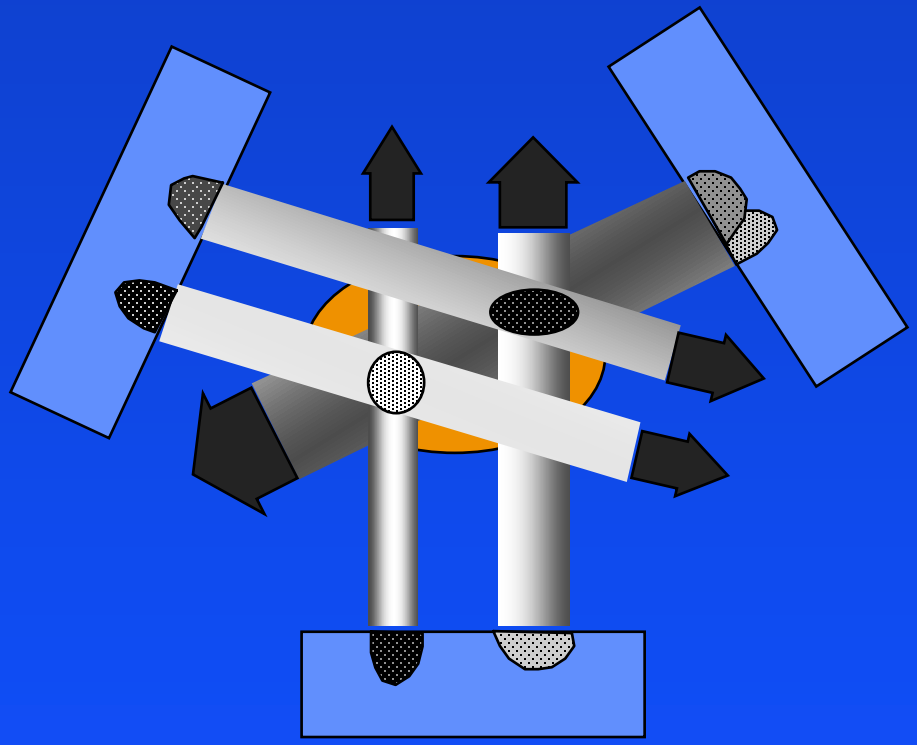
Single Photon Emission Computed Tomography



SPECT Acquisition

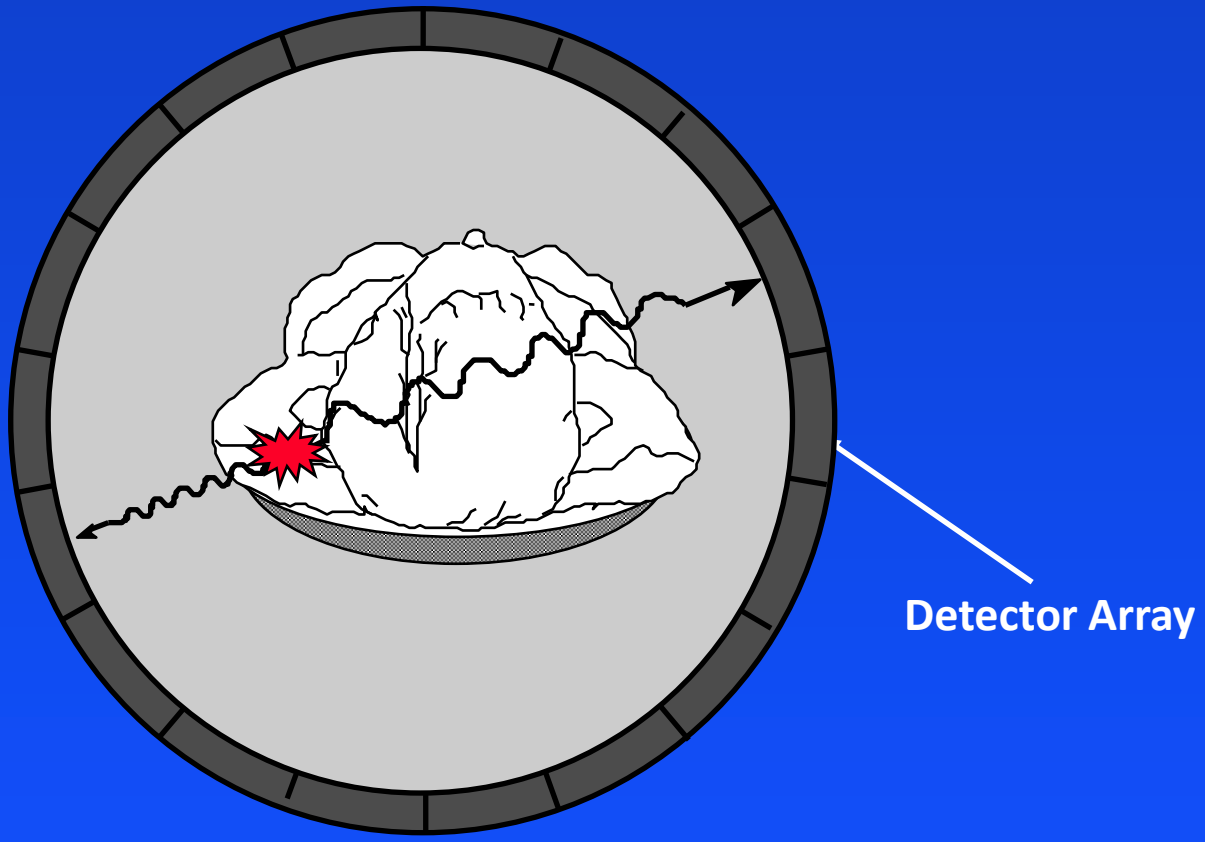


SPECT Reconstruction



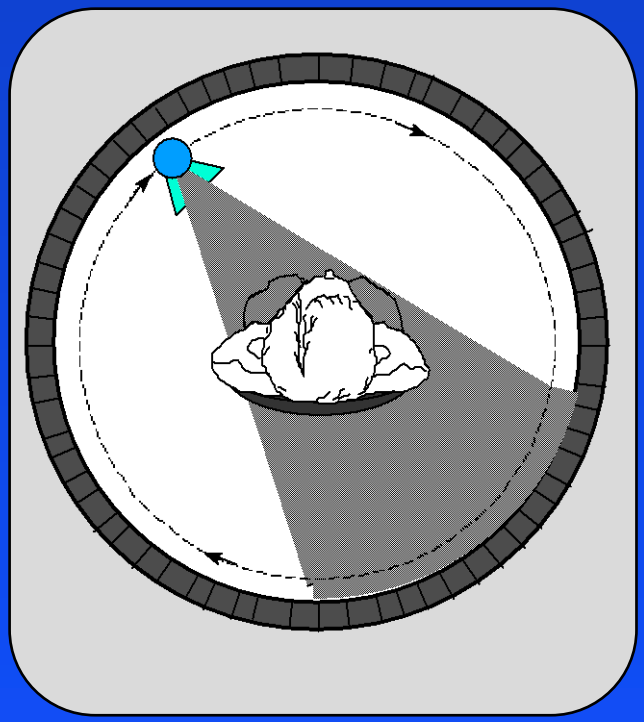
Filtered Backprojection

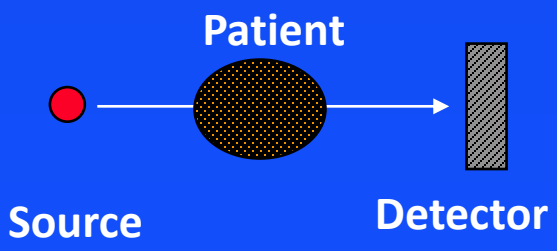
PET
Positron Emission Tomography



Computed Tomography

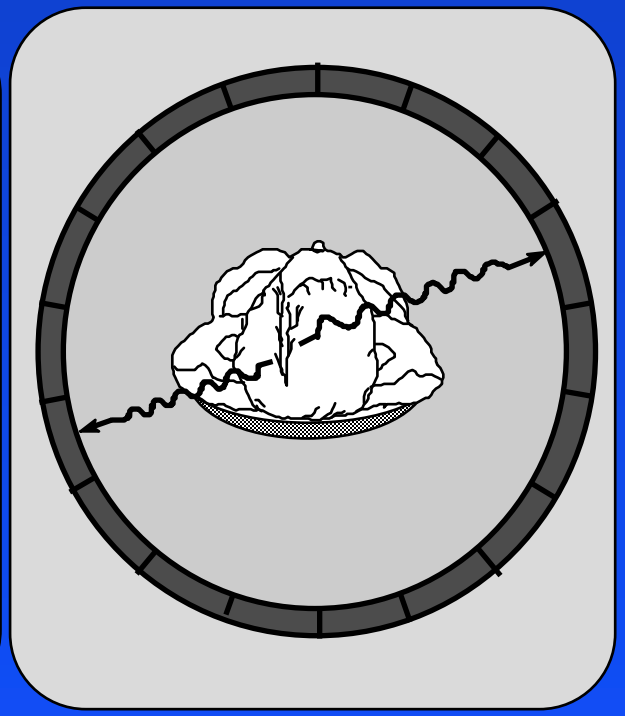
Transmission

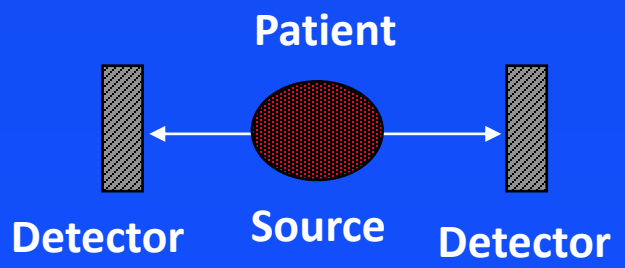




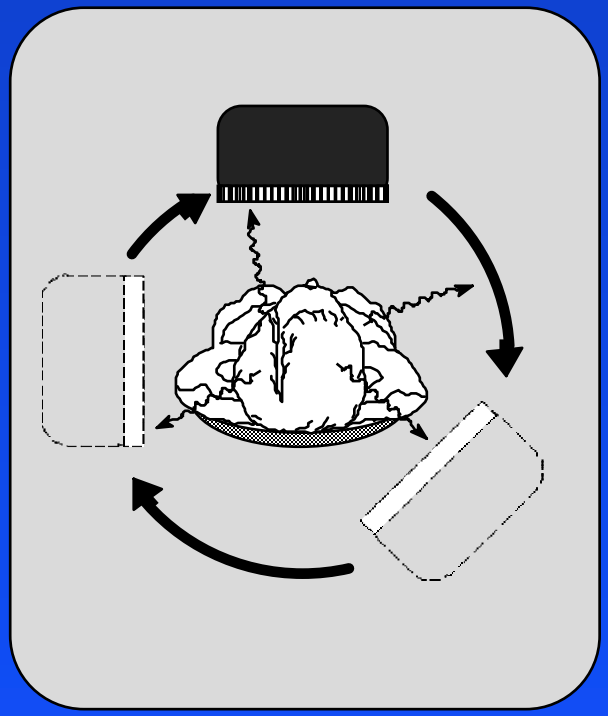
Emission

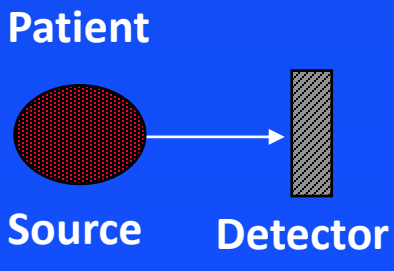
"Dual" Photon





Single Photon

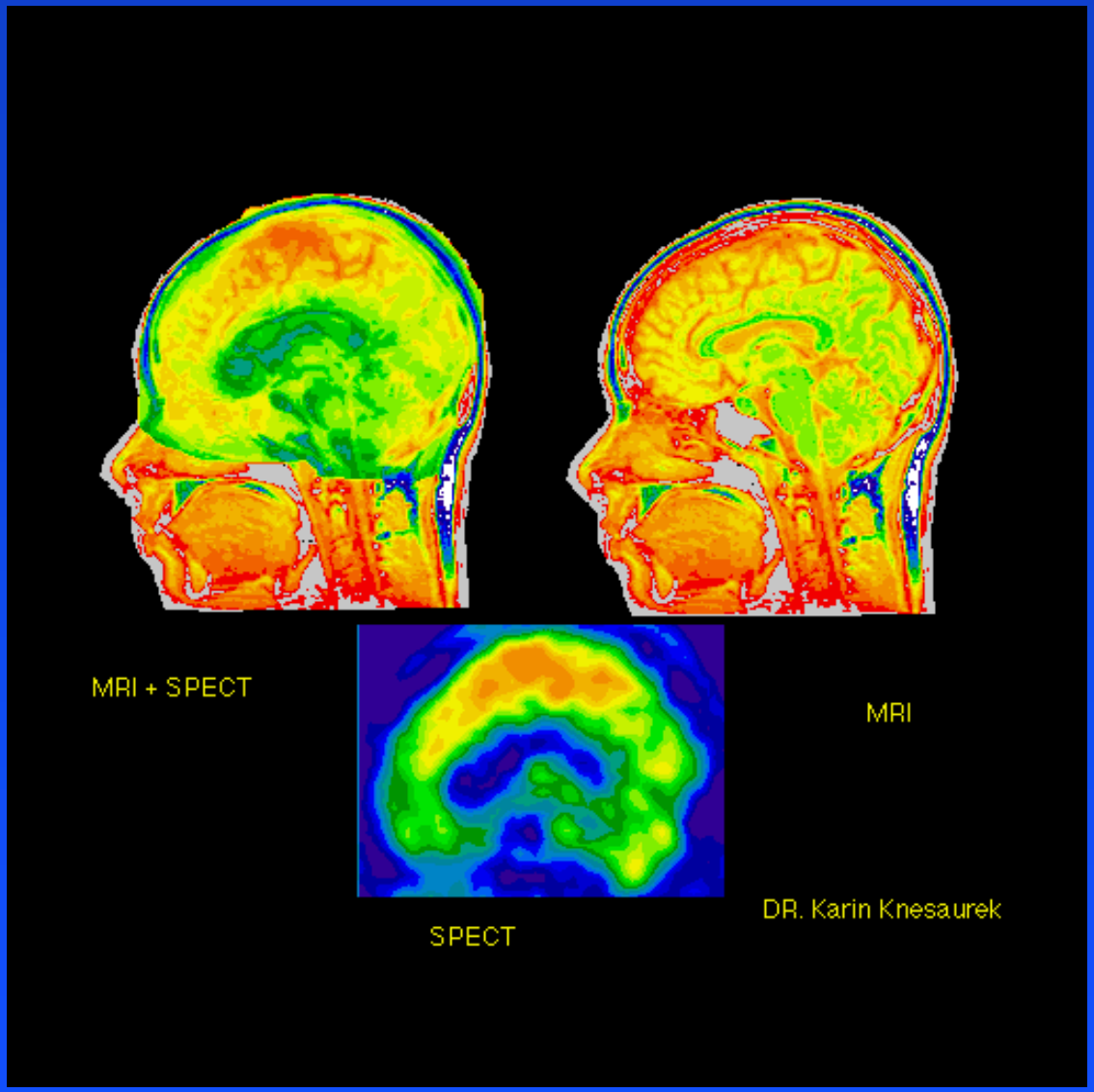




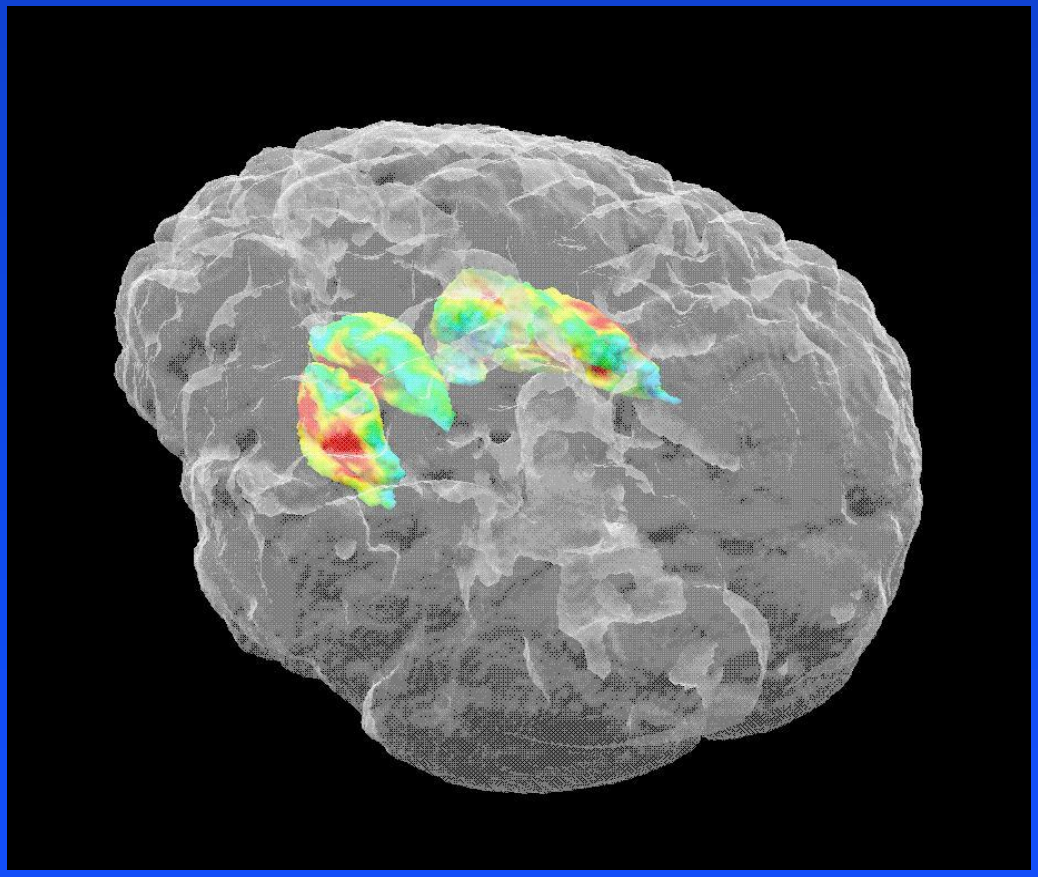
SOFTWARE FUSION

- Transfer of data to common platform (DICOM, ftp-online transfer, PACS)
- Fusion (different techniques)
  - rigid body transforms (max of mutual contest of information)
  - deformable transformations
- Visualization of fused data

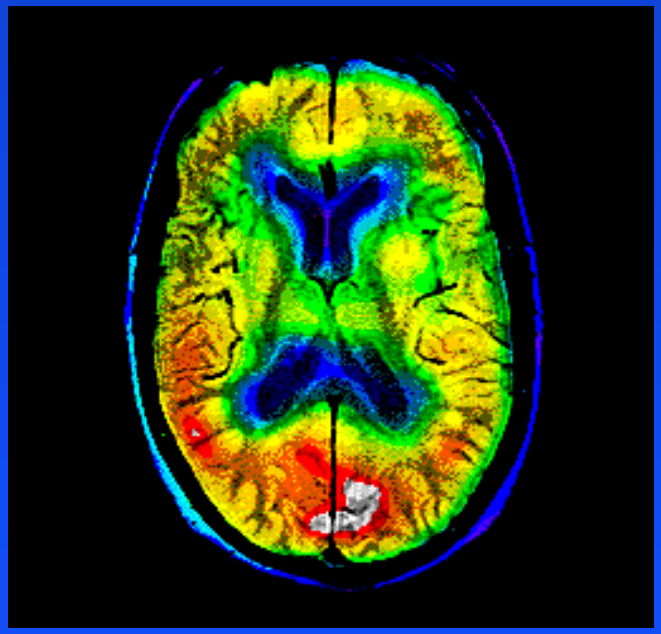
SPECT/MRI Image Fusion



PET/MRI image



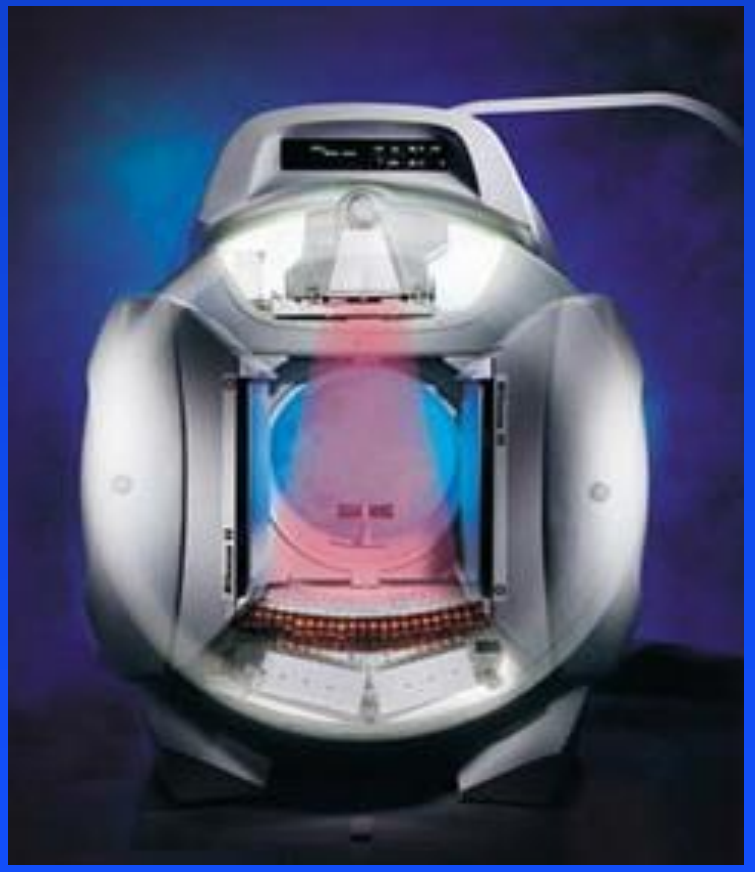
SPECT/MRI Image Fusion



HARDWARE FUSION

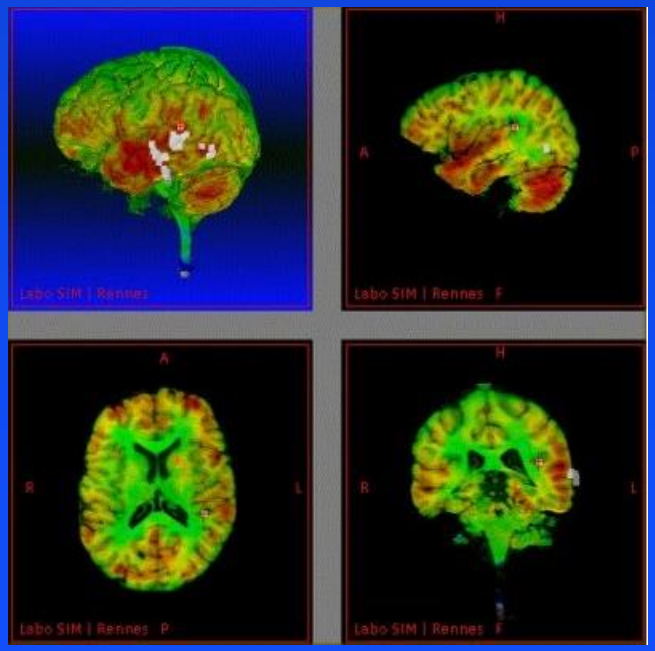
- Combination of two modalities
- High initial costs
- On-line fusion of data

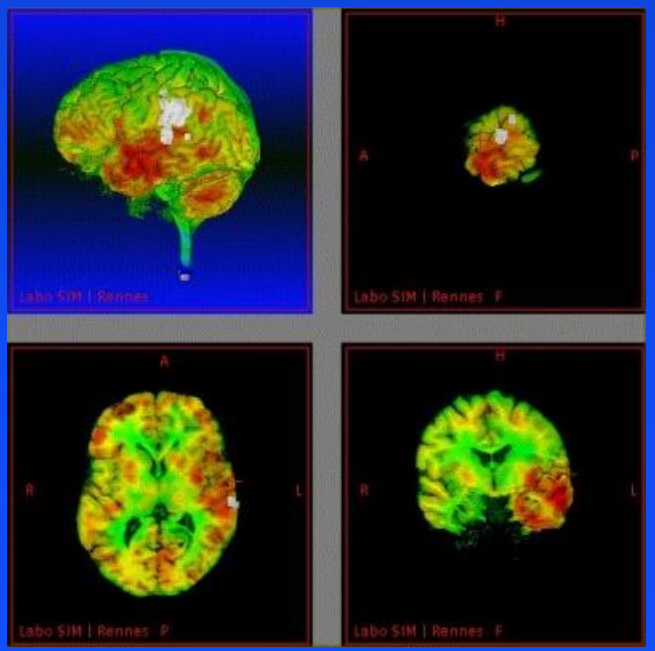
SPECT-CT Imaging



Epilepsy

- SPECT/MRI images

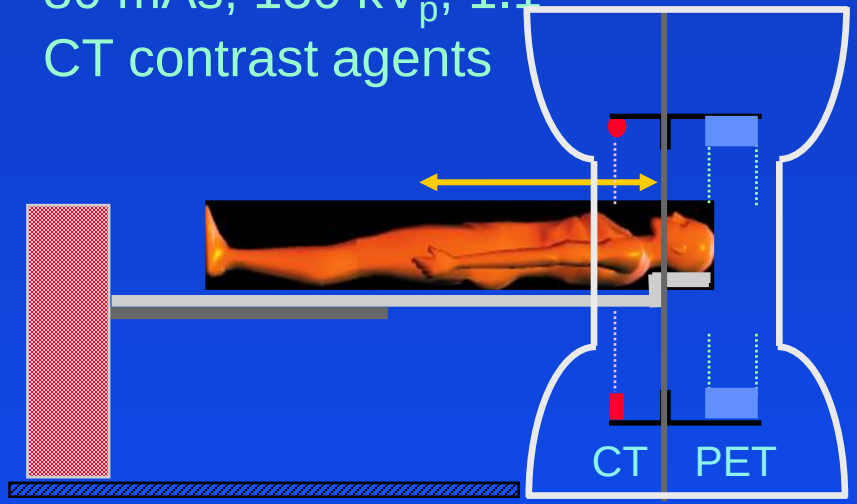




Scan protocol

University of Pittsburgh

spiral CT: 90 s
80 mAs; 130 kV_p; 1.1
CT contrast agents

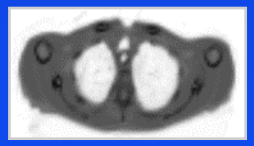


Survey

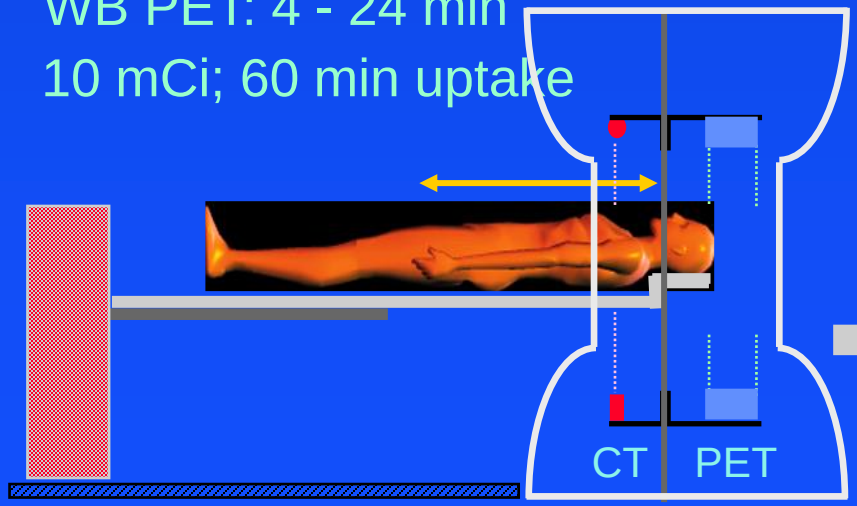
CT

FUSION

scatter correction
attenuation correction



WB PET: 4 - 24 min
10 mCi; 60 min uptake



FORE
AWOSEM

PET

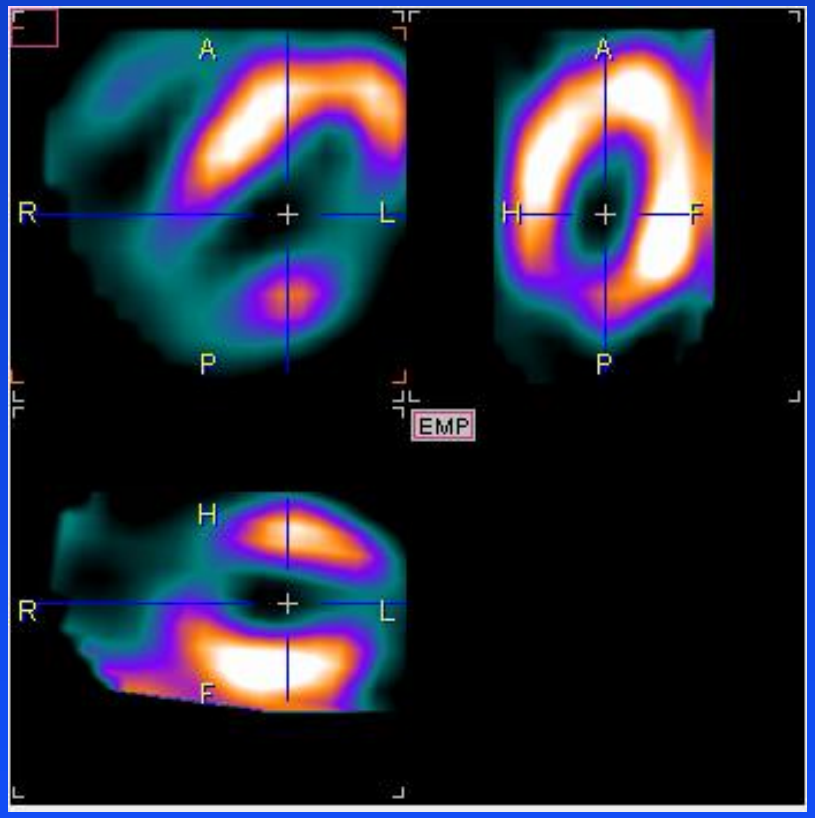
Fused PET/C

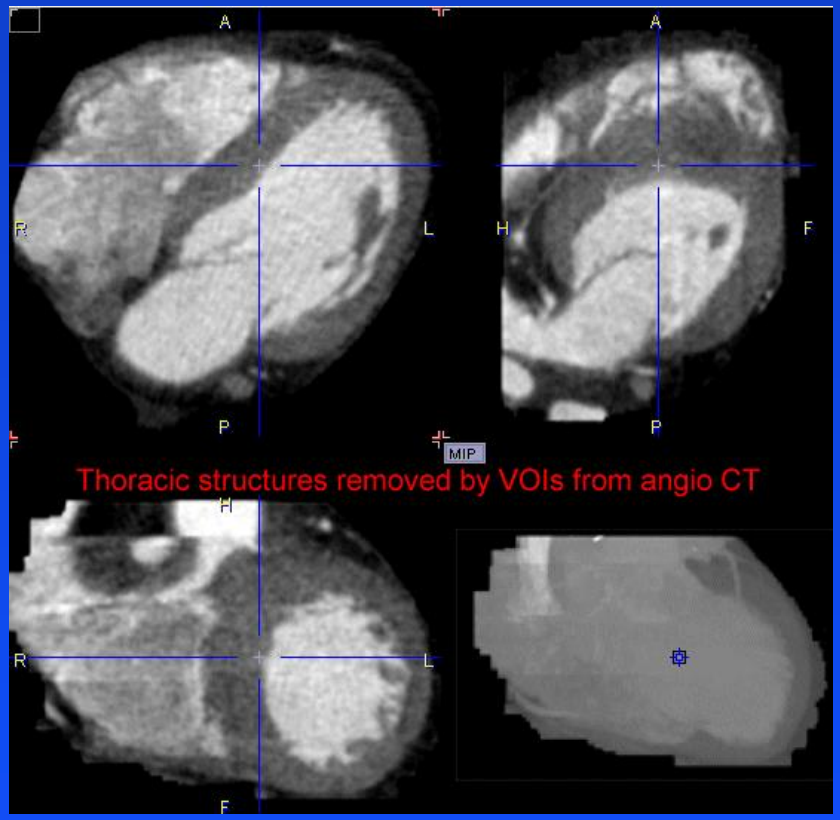
PET/CT scanners

Philips “Gemini”

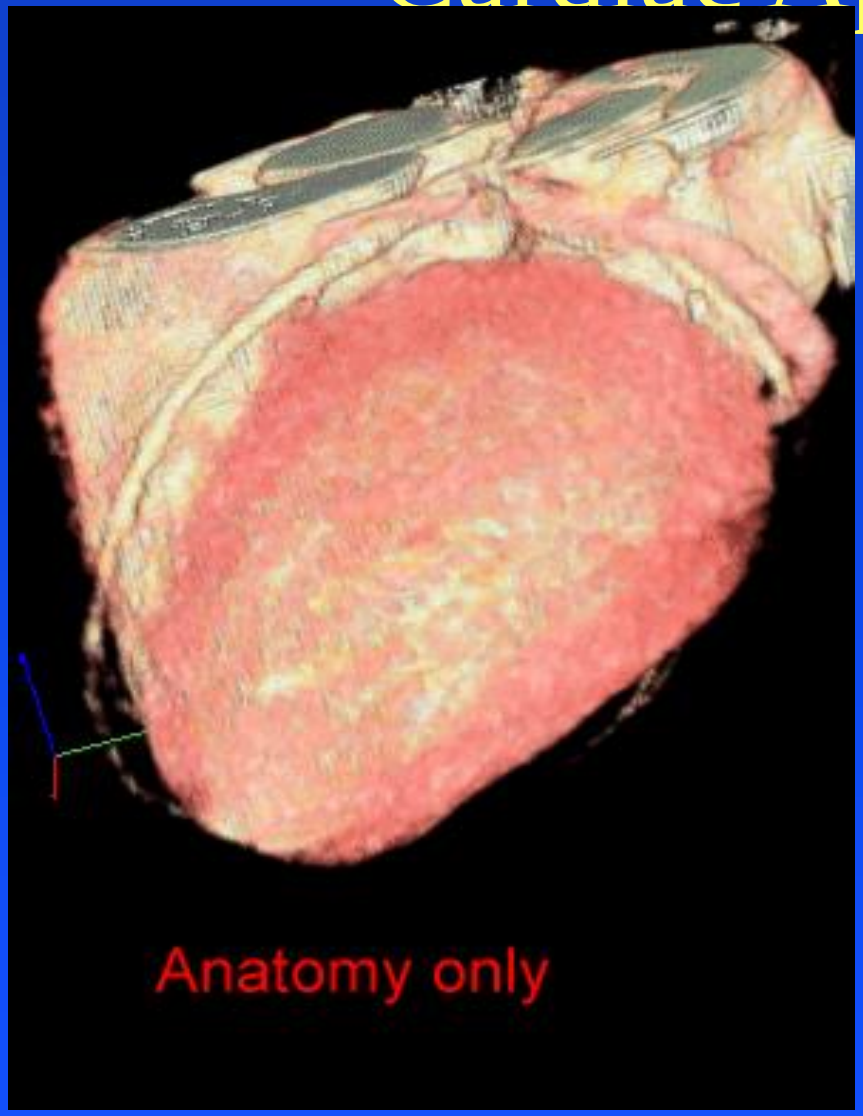
Siemens “Biograph”

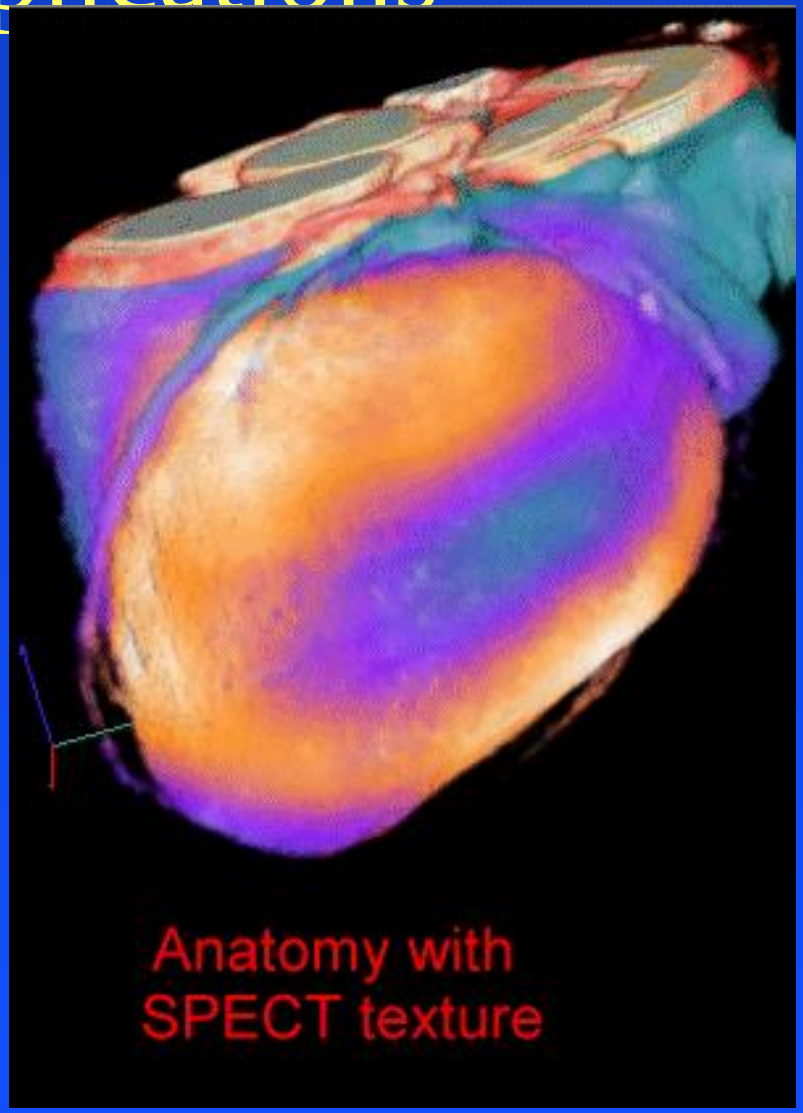
SPECT (or PET) and CT in Cardiac imaging



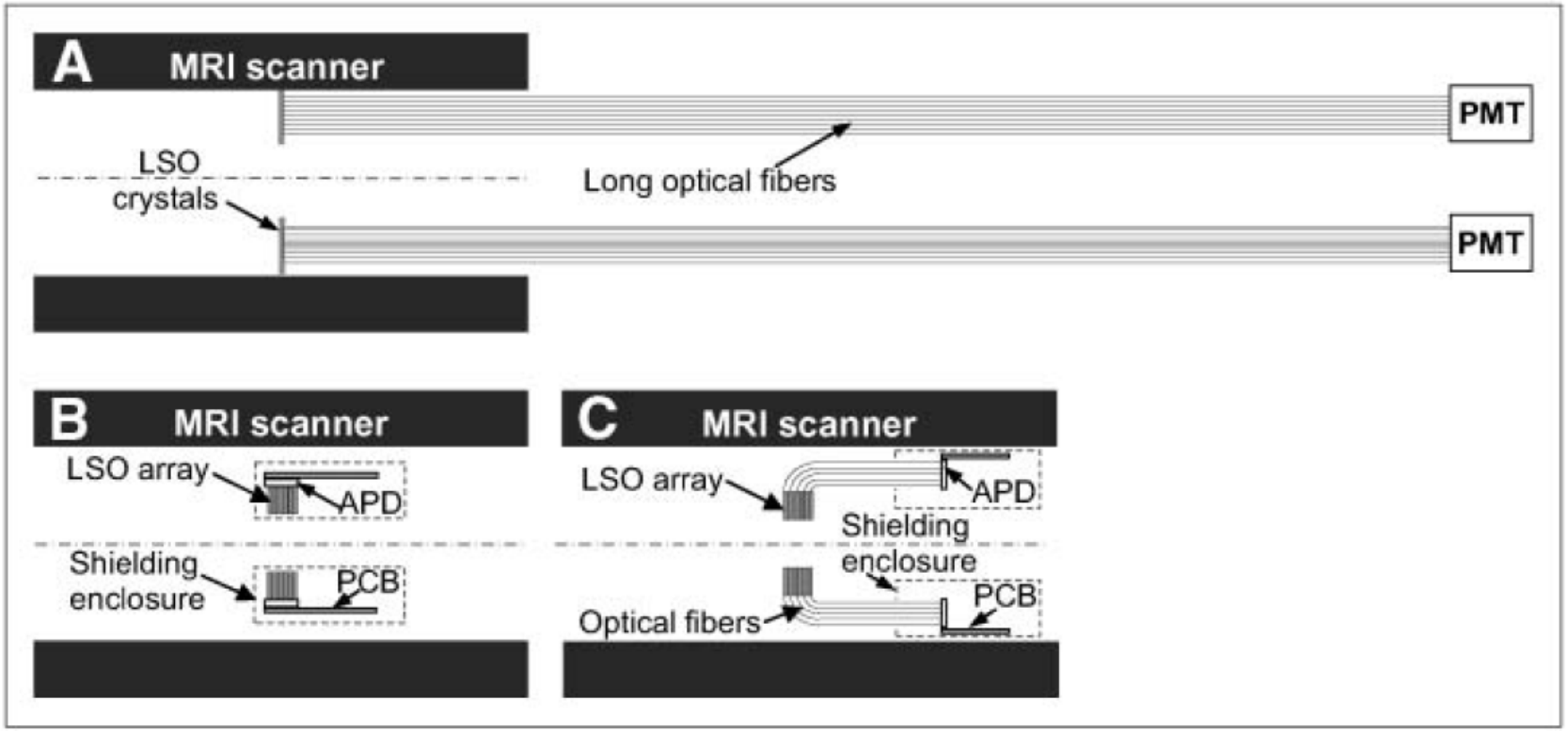


Cardiac Applications



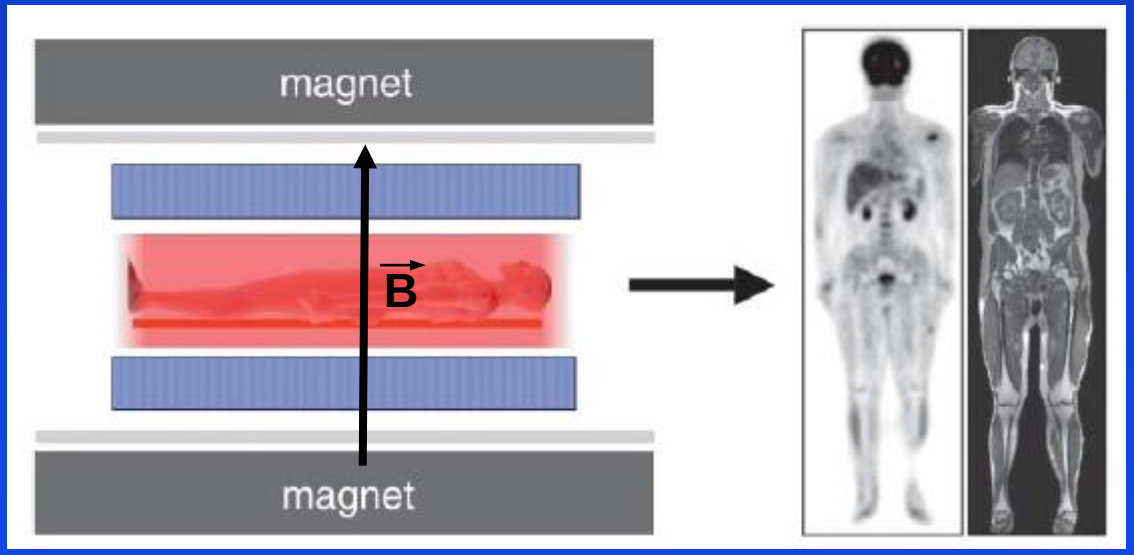


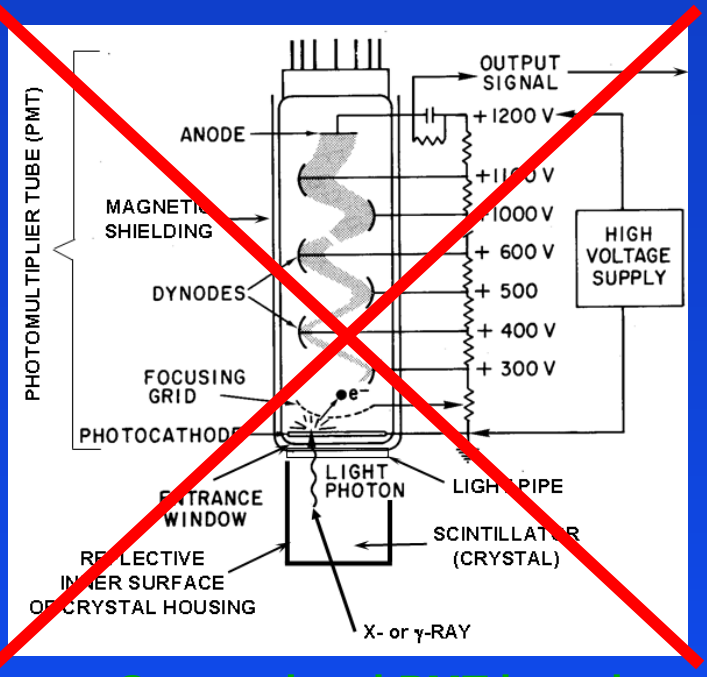
PET- MRI DESIGNES



Catana *et al*. JNM 47:1968, 2006

PET-MRI





Conventional PMT-based Scintillation Detectors

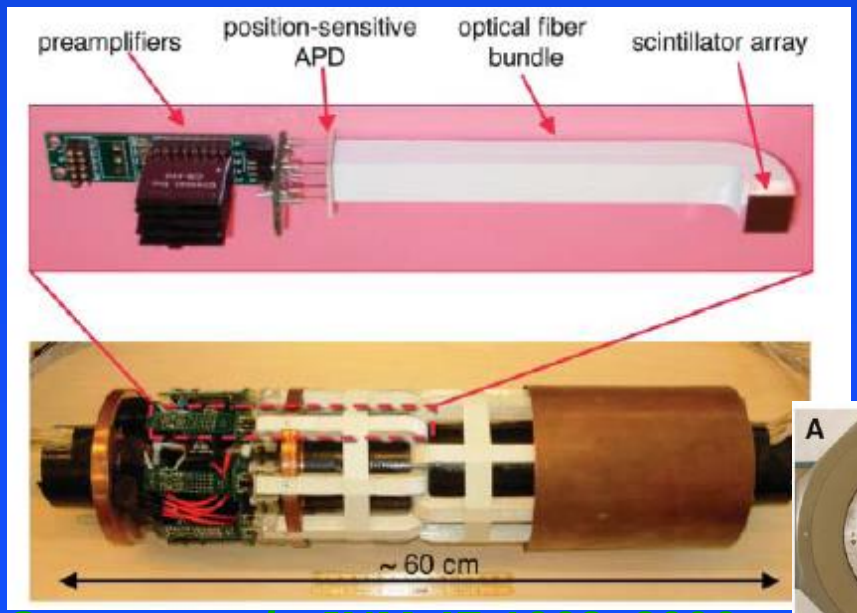
e⁻ trajectory perturbed by $\vec{B}$

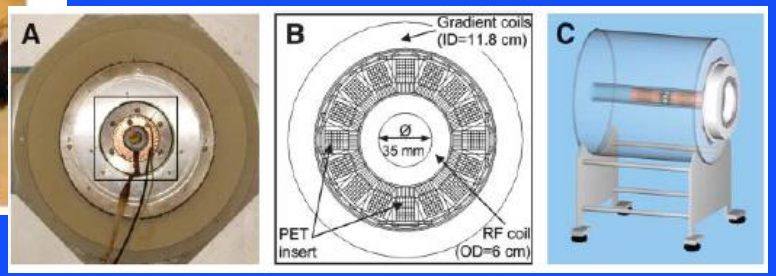
Options

Offset PET and MRI *meters* apart

Use non-PMT-based detectors

eg Avalanche photodiodes (APDs)





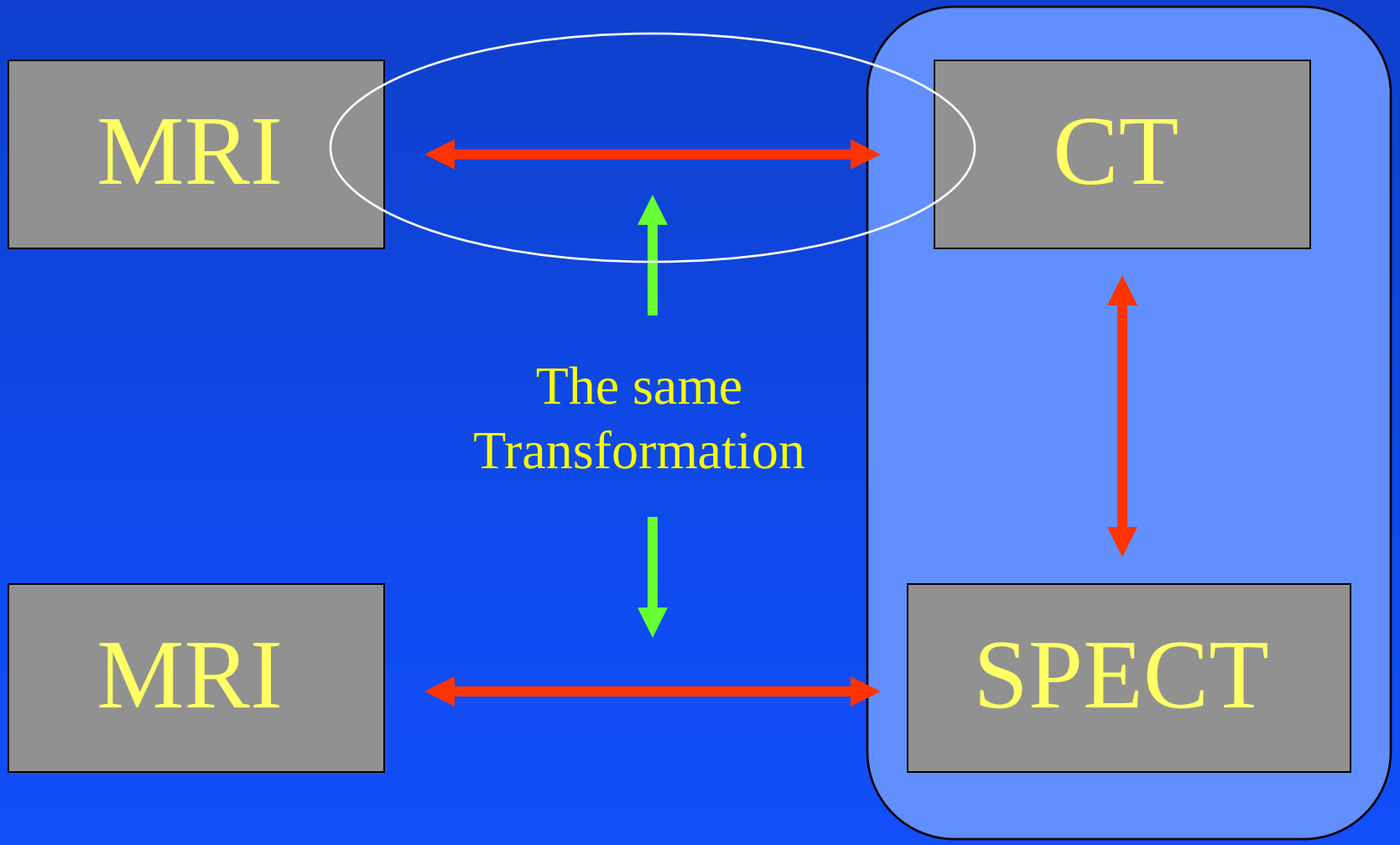
Catana *et al.* JNM 47:1968, 2006

Accurate fusion of In-111 WBC SPECT/CT and MRI in diabetic foot evaluations using CT/MRI correlation

Karin Knešaurek, Dov Kolker, Sridhar Vatti, Josef Machac, Michael Muzinic, Maria DaCosta, Zhuagyu Zhang, Bharat Mocherla, Sherif Heiba

The Mount Sinai Medical Center
New York

Correlation of MRI and SPECT data using CT data from SPECT/CT study



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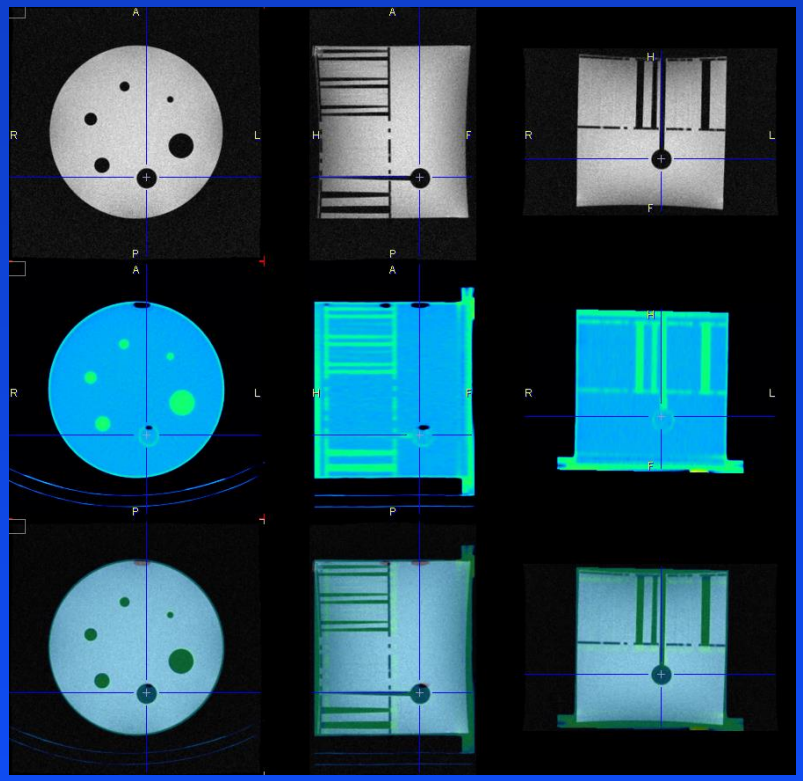

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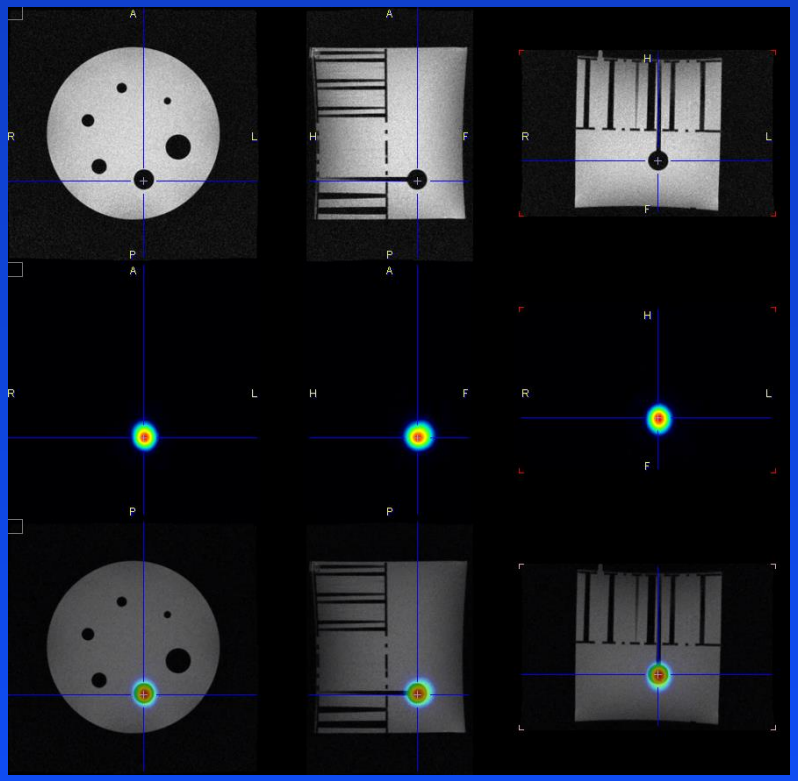
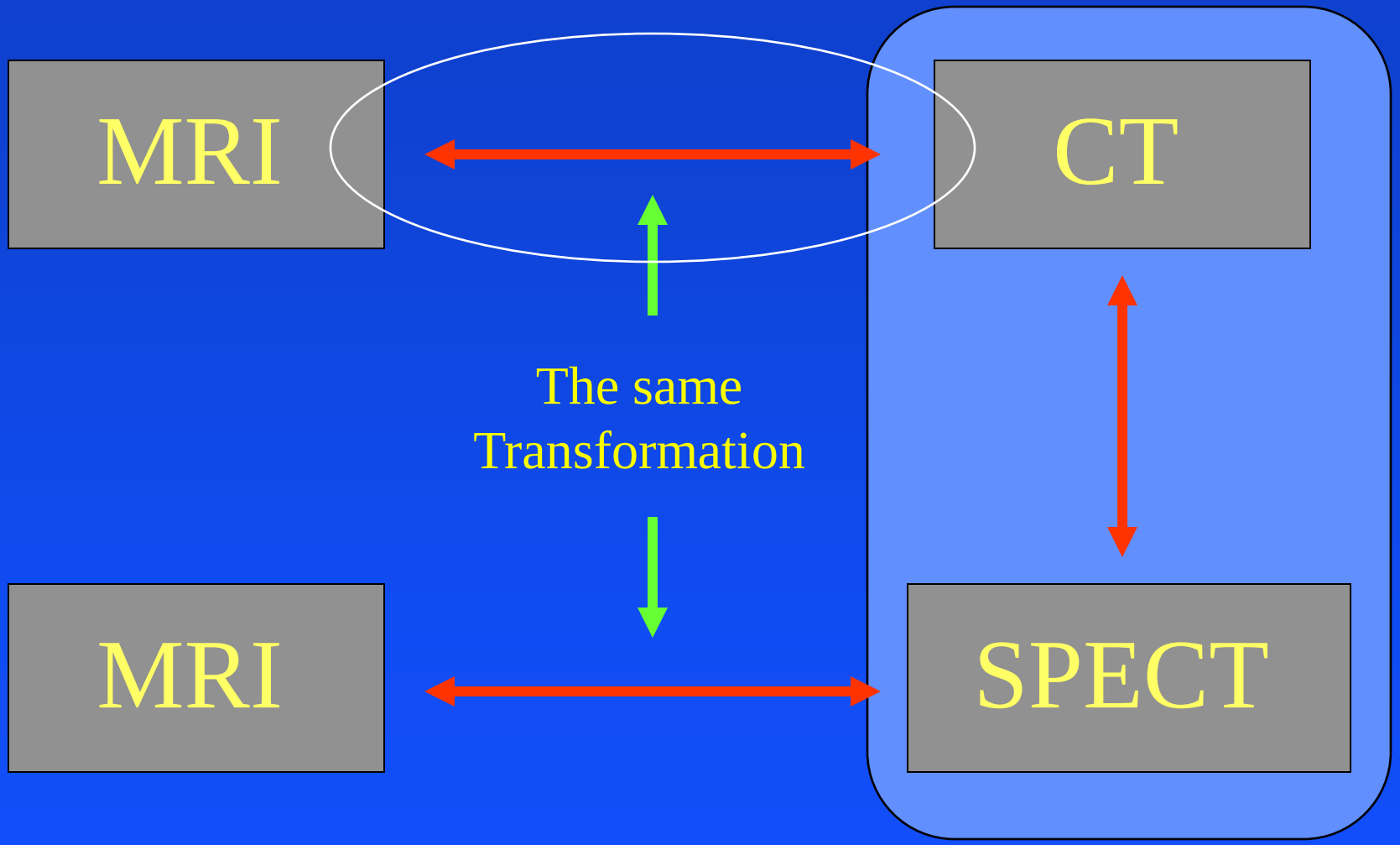


MRI - CT

MRI - SPECT

Correlation of MRI and SPECT data using CT data from SPECT/CT study

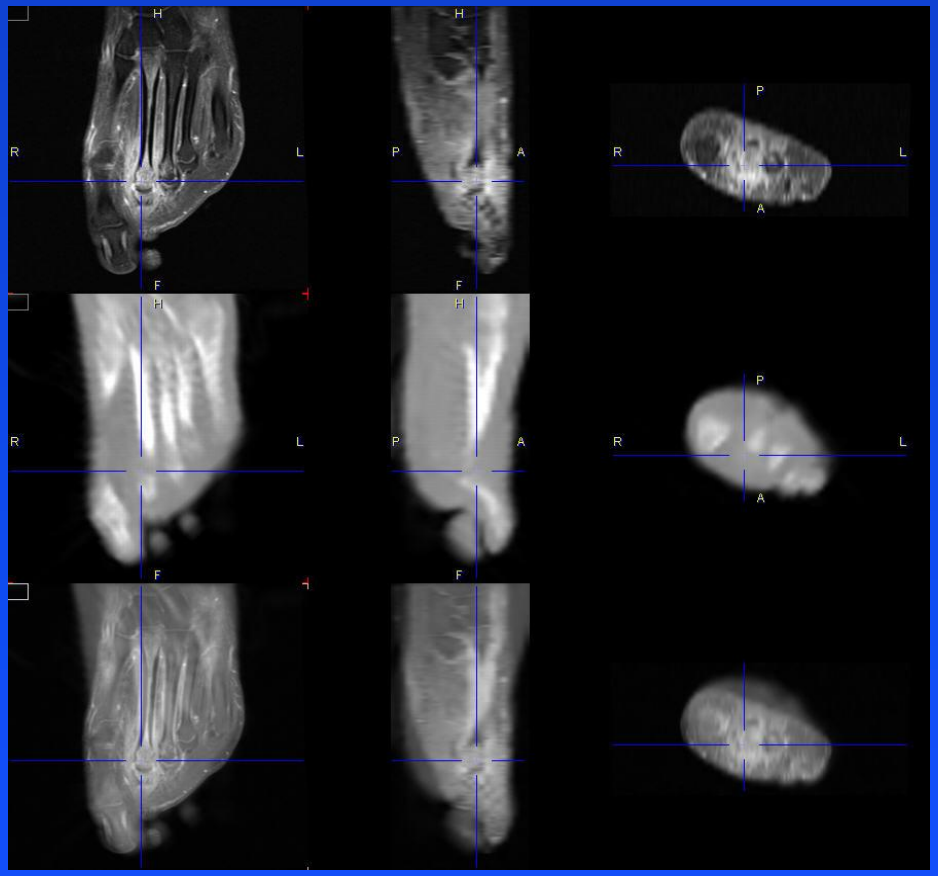


MRI – CT correlation

MRI

CT

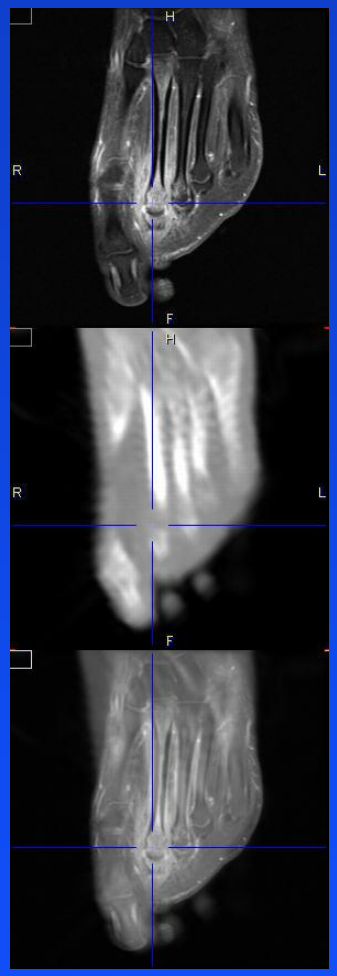
MRI/CT



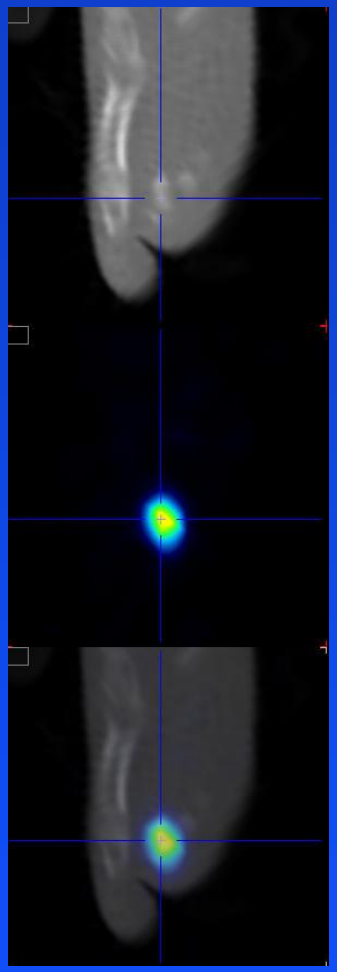
MRI-CT

CT-SPECT

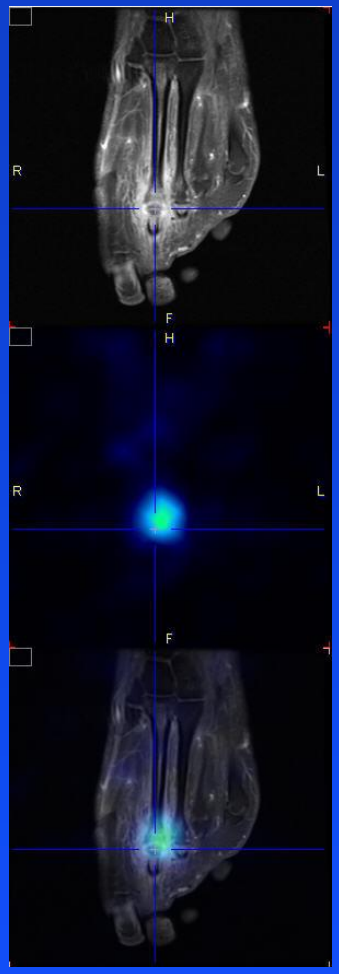
MRI-SPECT



CT-CT



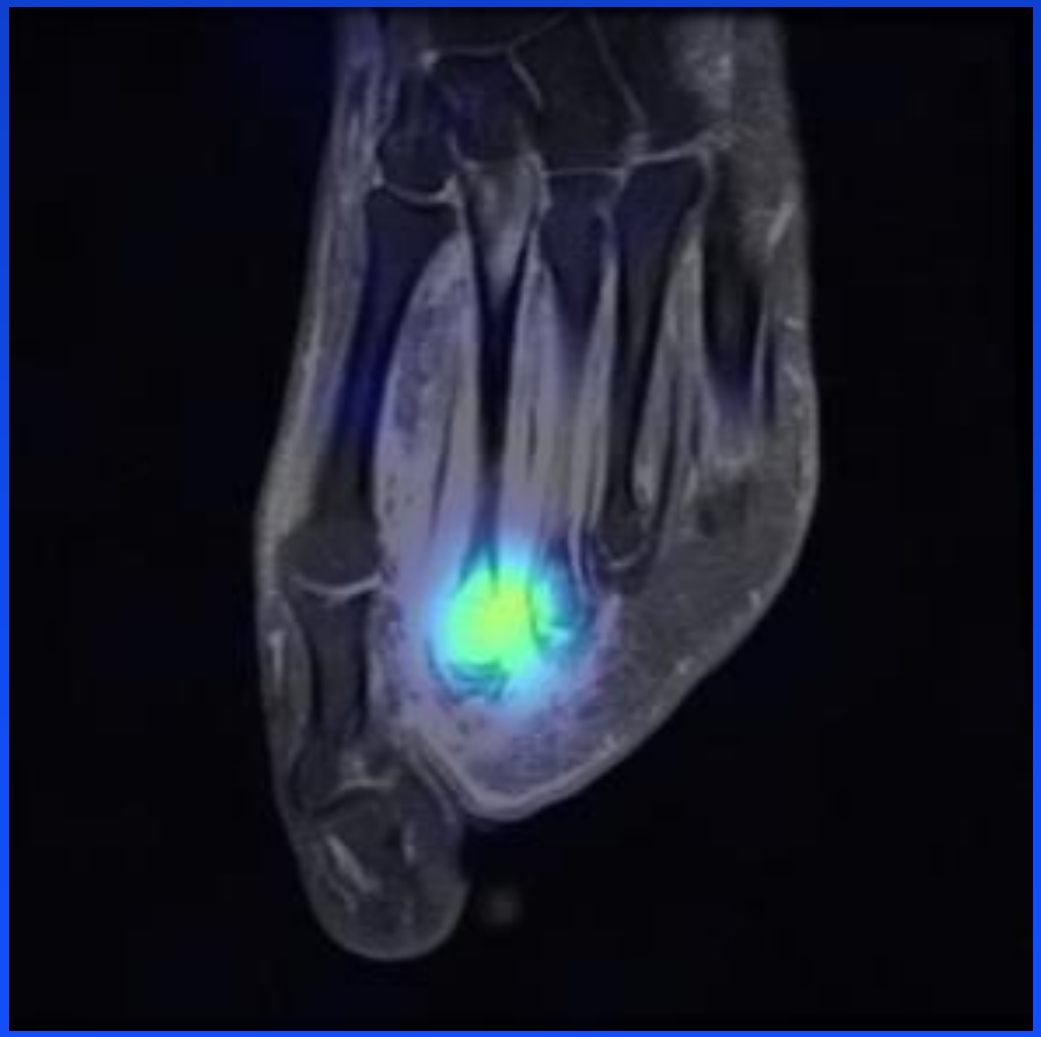
SPECT-SPECT



MRI-SPECT

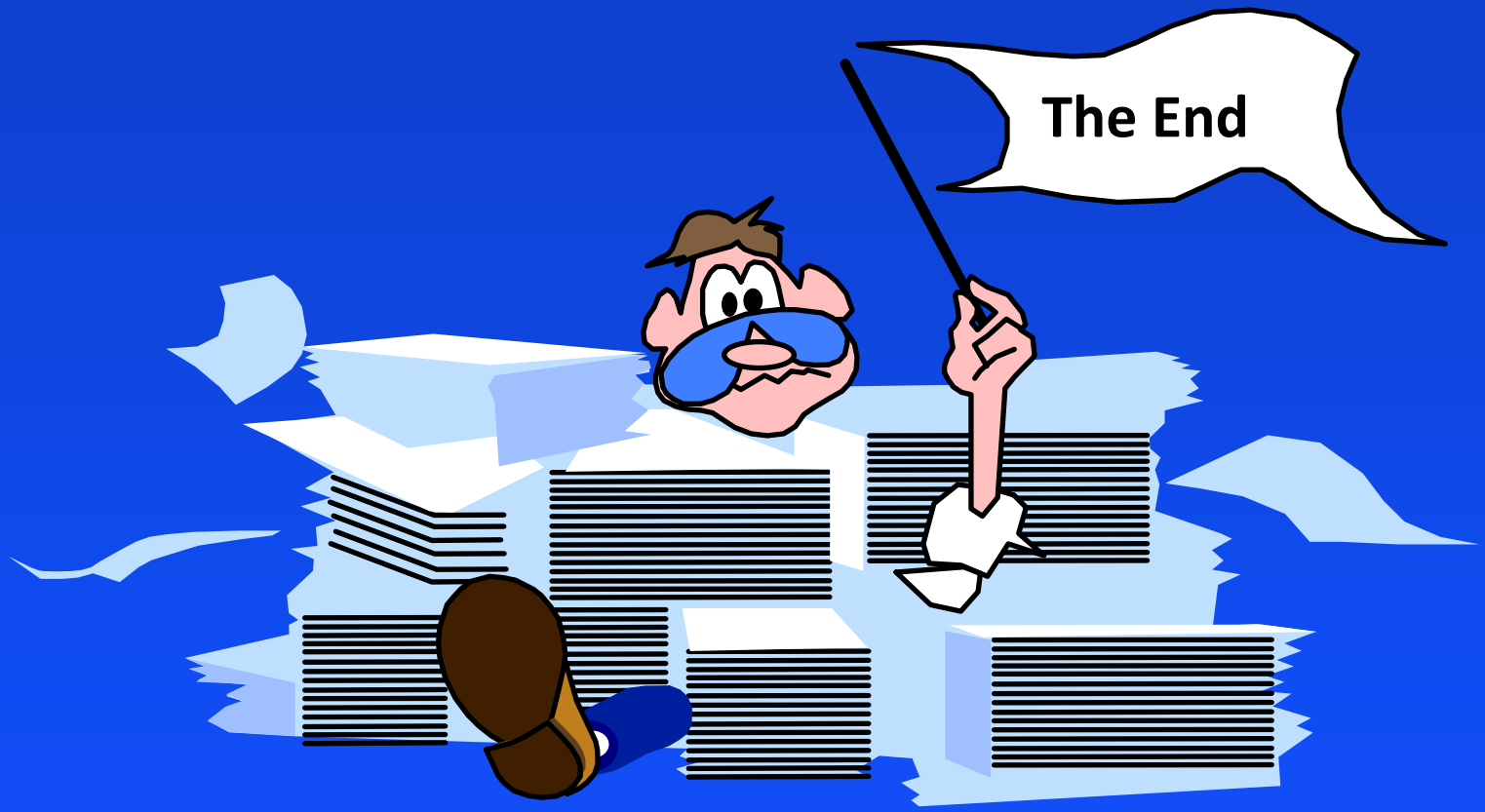
In-111 WBC SPECT/MRI
Image of the Year SNM 2008

MRI provides almost perfect anatomy images and bony structure changes but it may exaggerate the extend of infection. In-111 SPECT imaging is more accurate for infection localization but lacks anatomical reference. So, combination of these images is ***essential***. Based on the image patient underwent selective excision of the second metatarsal head only, **preserving** the rest of her foot.

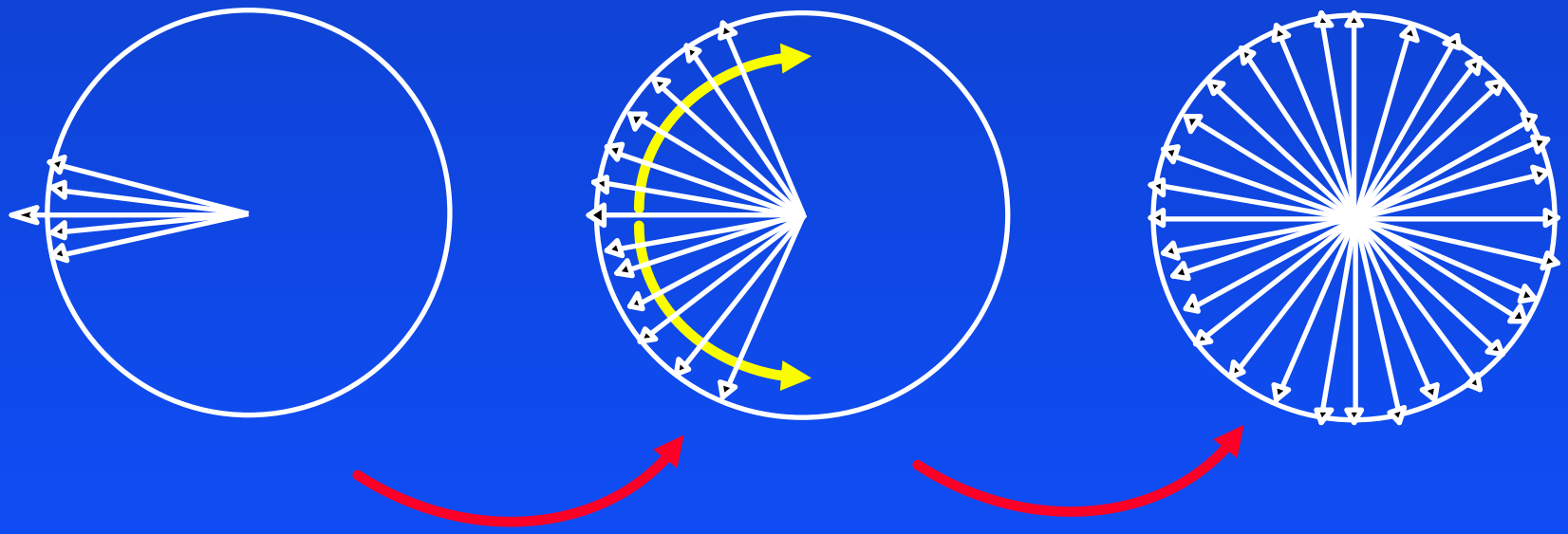


Conclusions

- **MRI excellent imaging modality**
- **In combinations with other modalities (SPECT, PET, CT, etc.) can give even better information**
- **Improvements: Stronger magnetic field, spectroscopy, faster scanning**


The End

Right after RF pulse

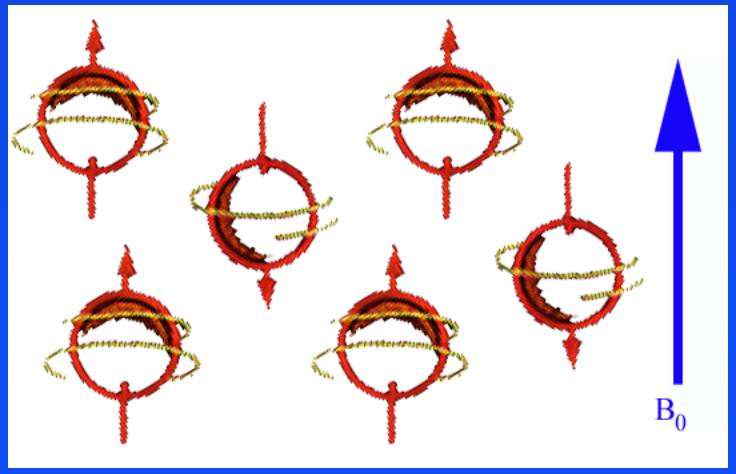


Dephasing

Effect of Main Magnetic

Random orientation of Nuclear Spins
in the **absence** of a
Polarizing Magnetic Field

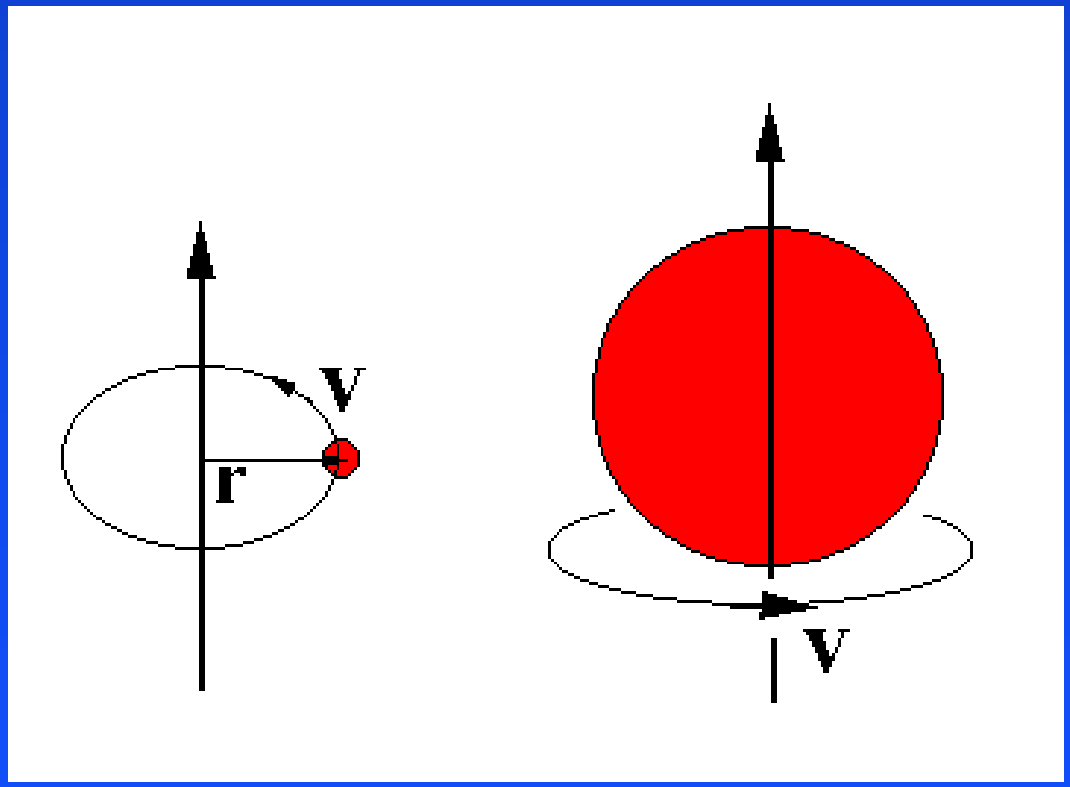
Alignment of Nuclear Spins
in the **presence** of a
Polarizing Magnetic Field



Angular Momentum (Classical)

Property of a rotating object with mass:

Vector $\vec{L} = m\vec{r} \times \vec{v}$



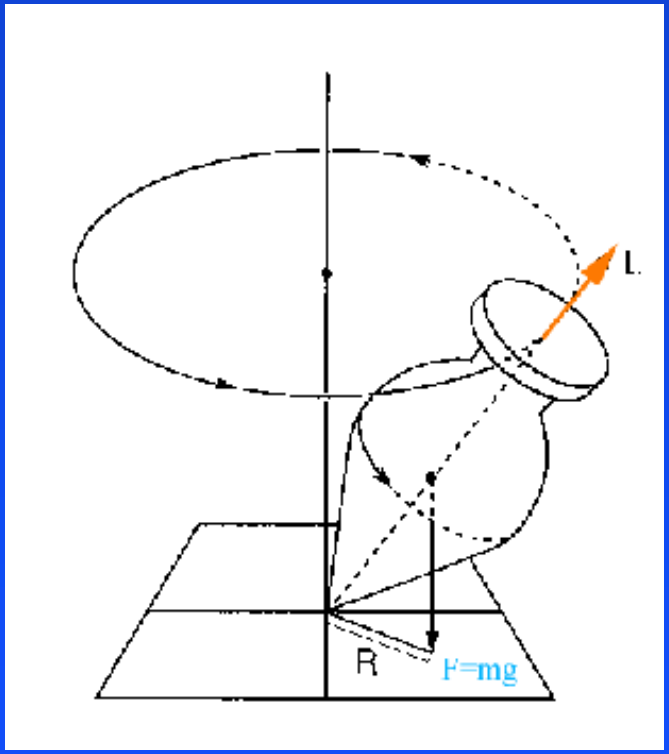
Orbital

Spin

Precession

Result of force acting on object with angular momentum L

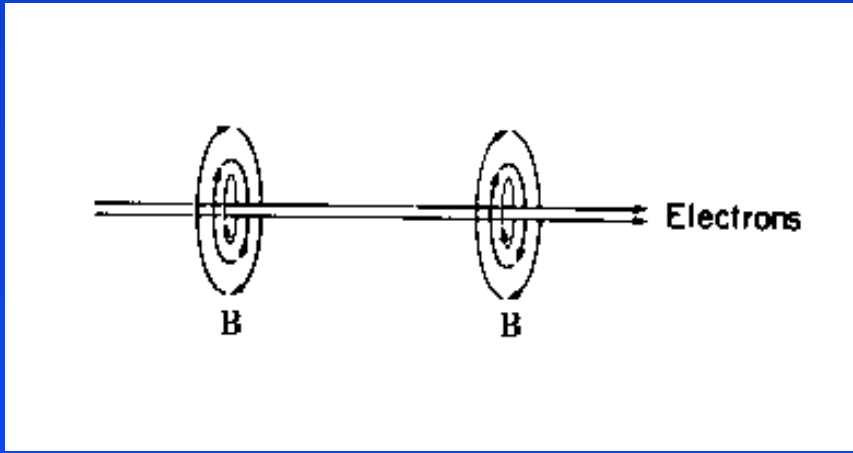
Basic equations: $\frac{d\vec{L}}{dt} = \vec{r} \times \vec{F} = \vec{\tau}$ **torque**

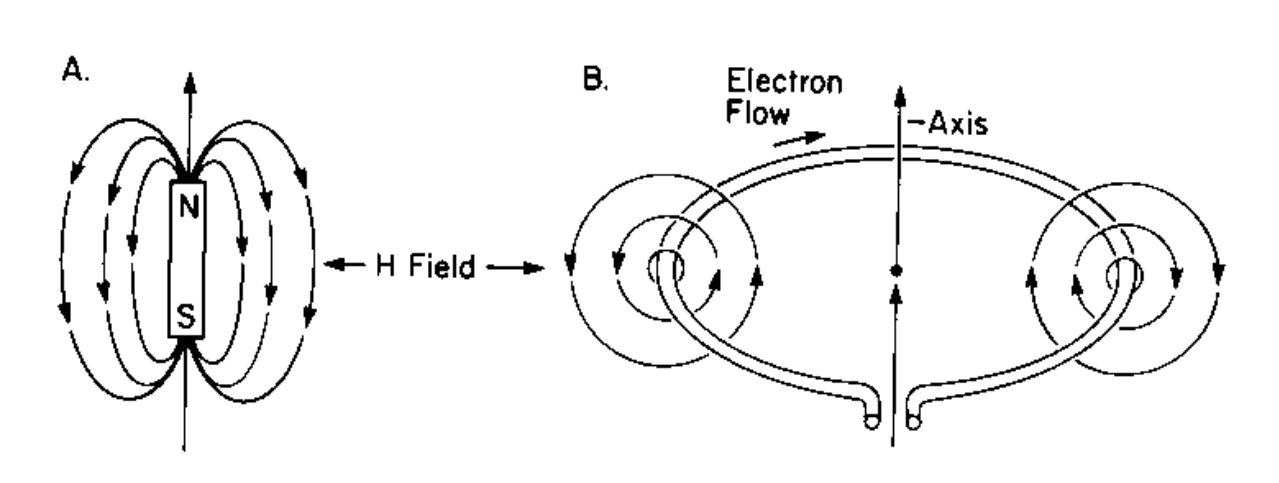


$\omega_p = \frac{mgr}{L}$ Precession frequency

Ampere's law $\nabla \times B = \mu_0 J$

Moving charges generate a magnetic field



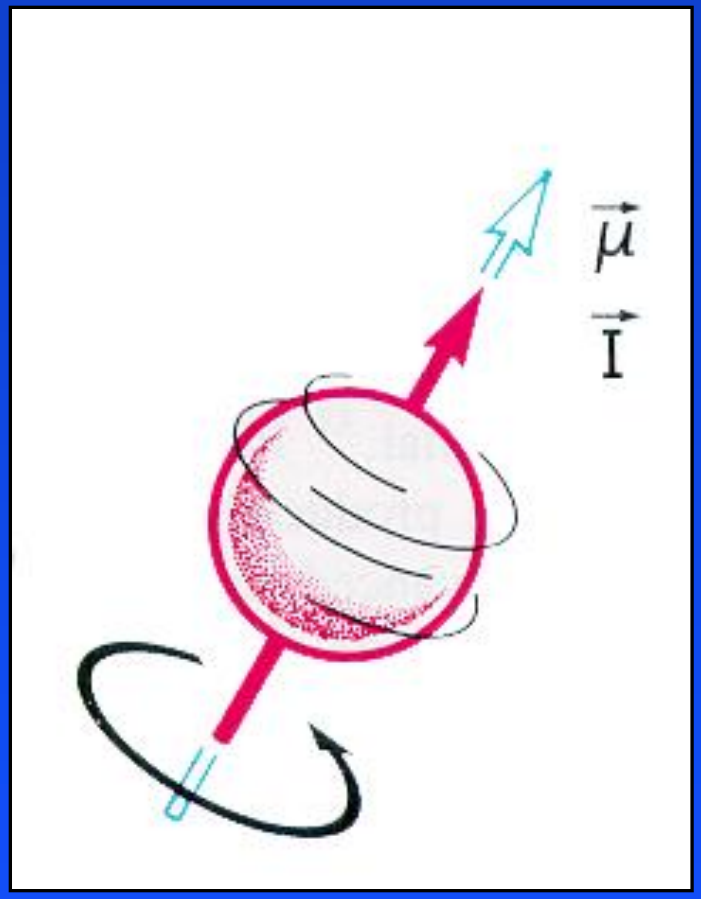


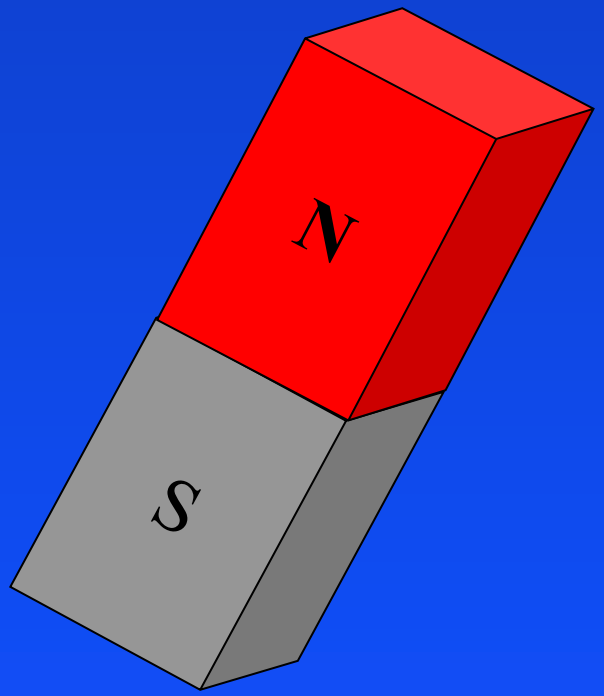
$$B_z = \frac{\mu I R^2}{2(R^2 + z^2)^{3/2}}$$

Magnetic Dipole Moment

Nuclear Magnetic Resonance

Spinning Charge Produces Magnetic Moment: $\vec{\mu}$

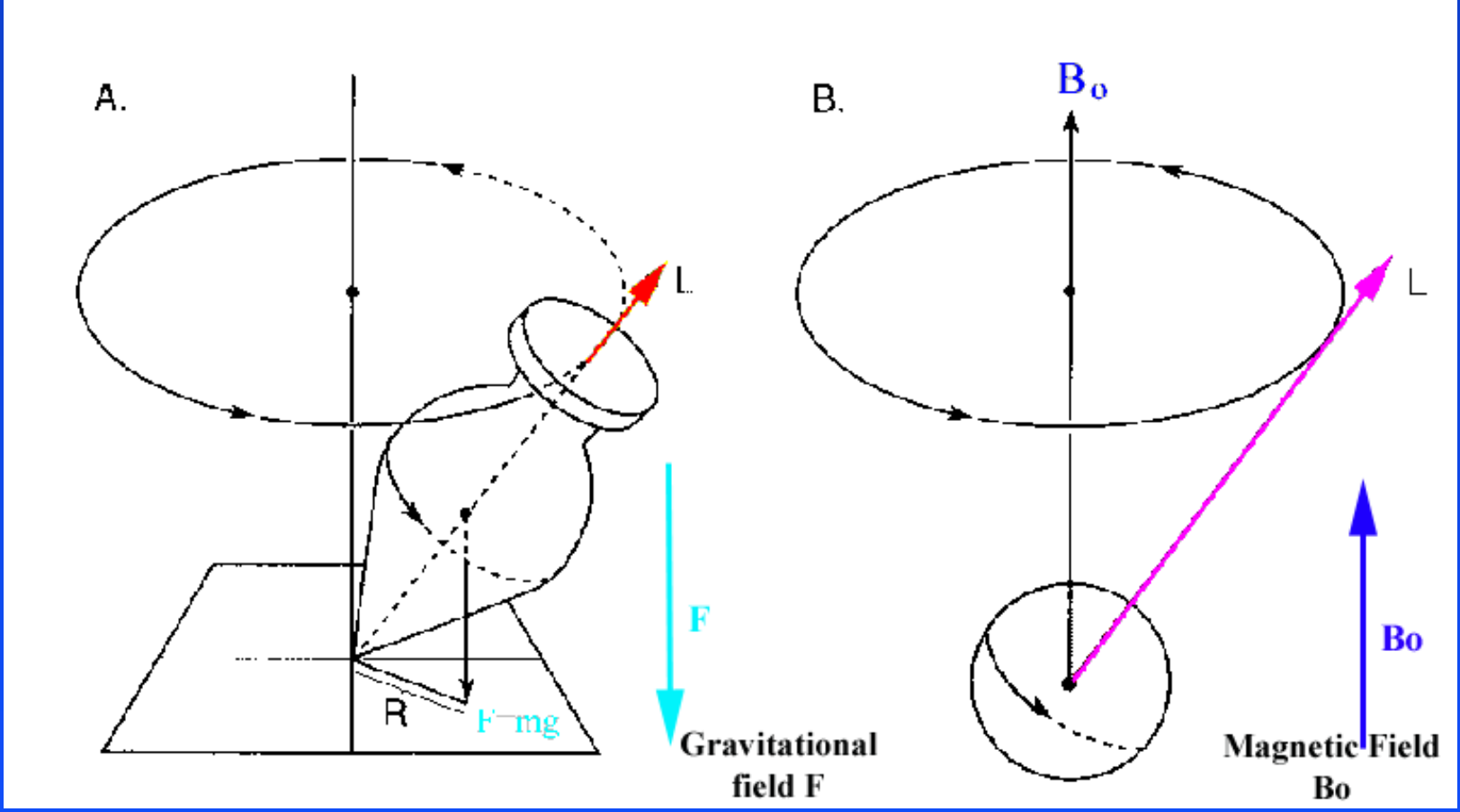




$$\mu_m = \gamma L_{az}$$

Precession:

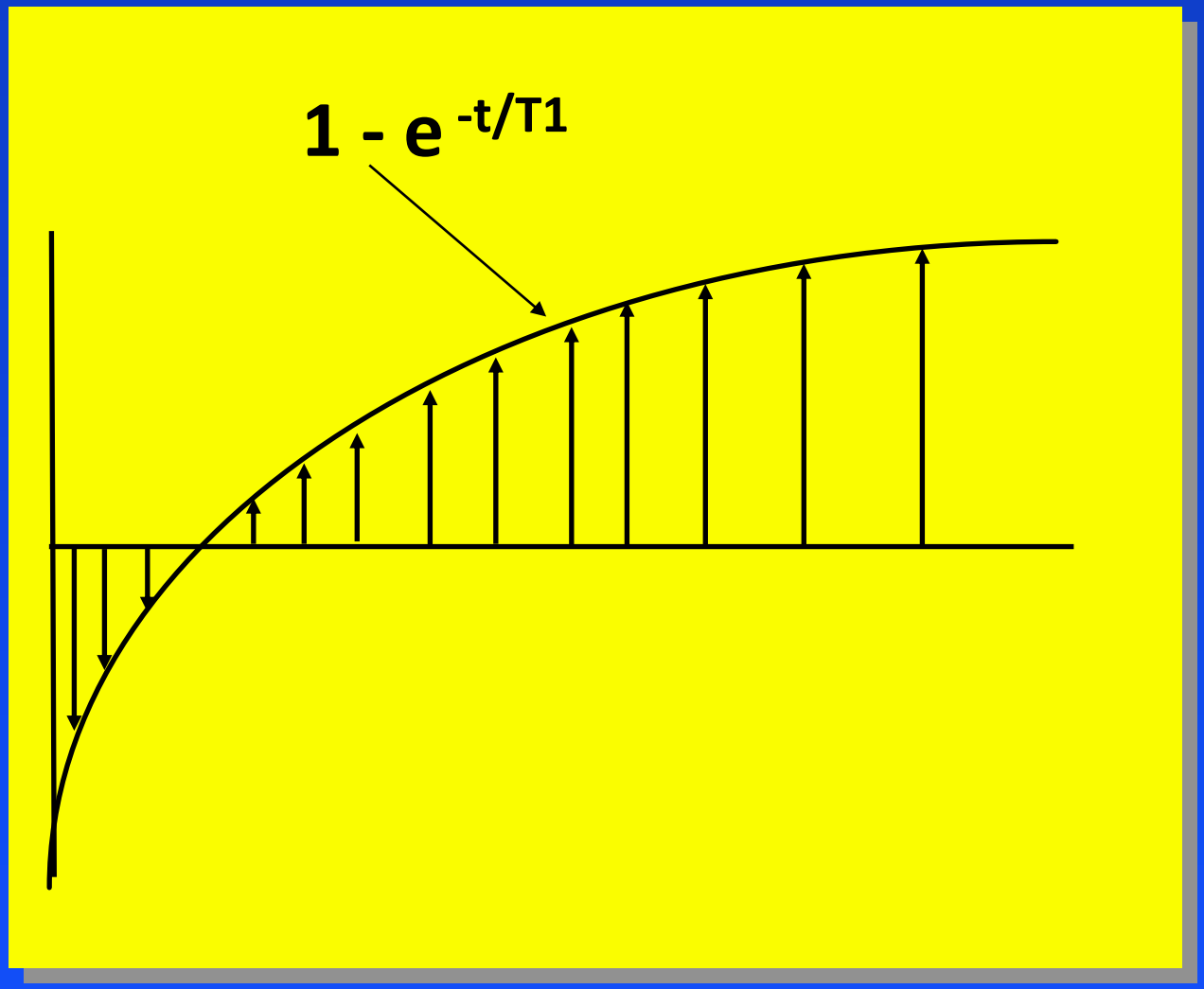
an analogy between spinning top and spinning proton



Spinning Top

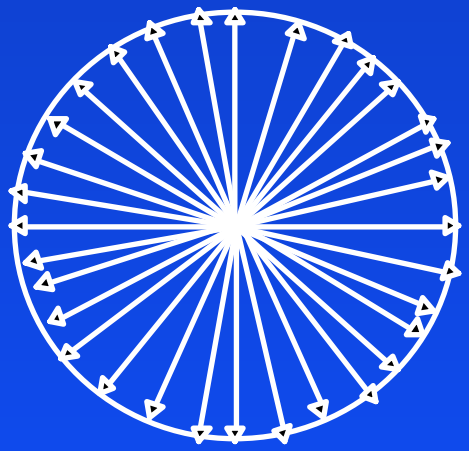
Nuclear Spin

$\vec{\tau} = \vec{r} \times \vec{F}$ **Torque:τ** $\vec{\tau} = \vec{\mu} \times \vec{B}$



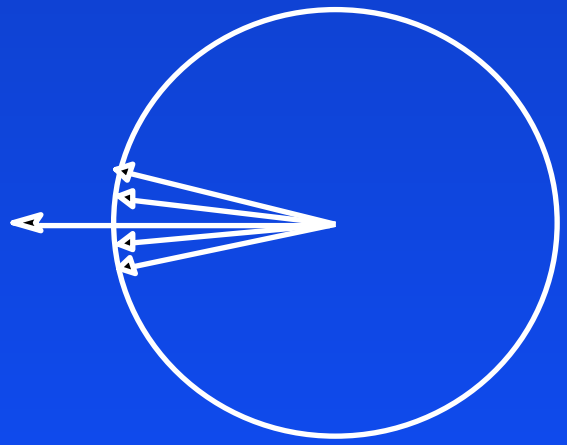
Recovery of net Magnetic Moment
(Depends on Spin-Lattice Interaction)

At Equilibrium



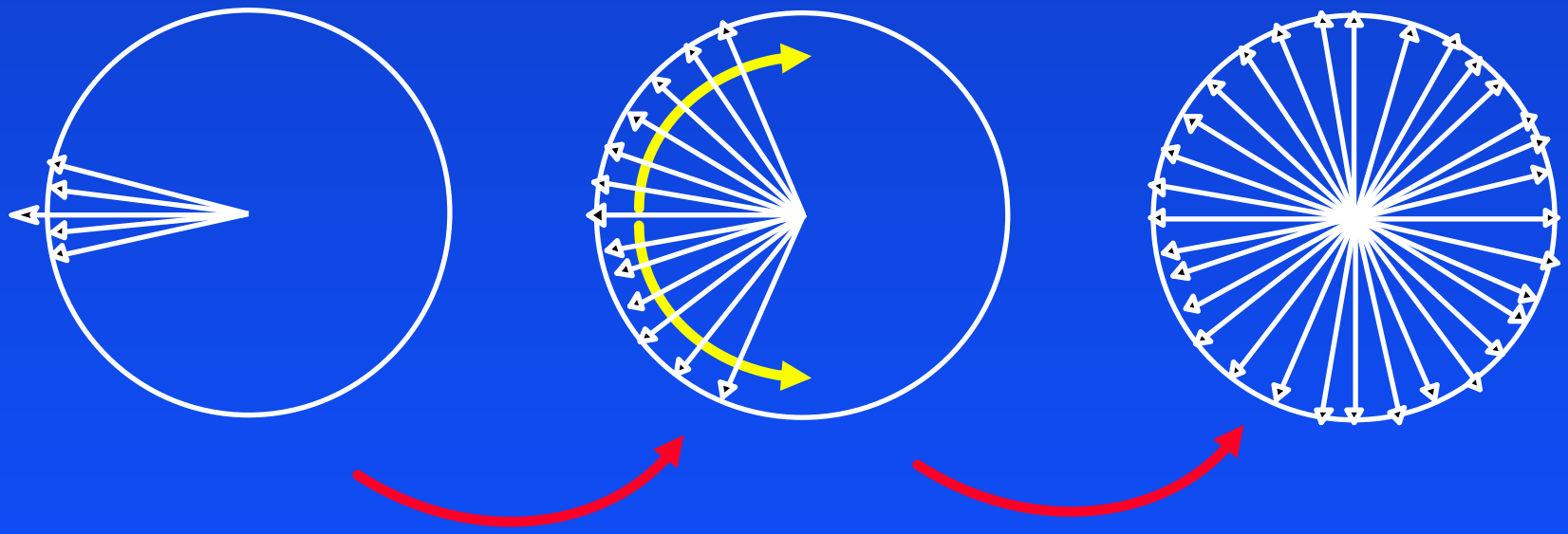
No net transverse moment

After RF Pulse

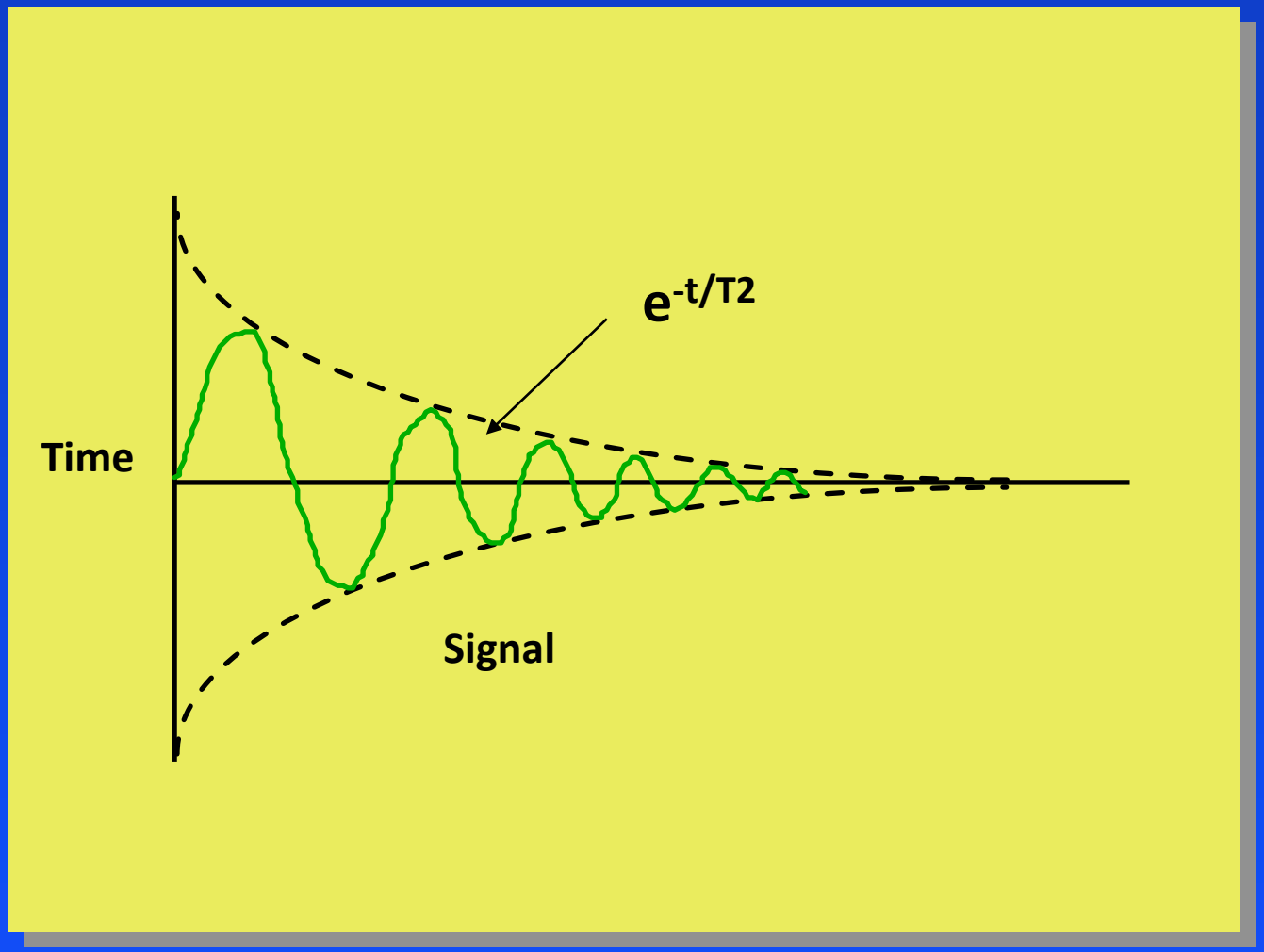


Transverse component

Right after RF pulse



Dephasing



Decay of Net Transverse Magnetic Moment
(Depends on Spin-spin interaction)