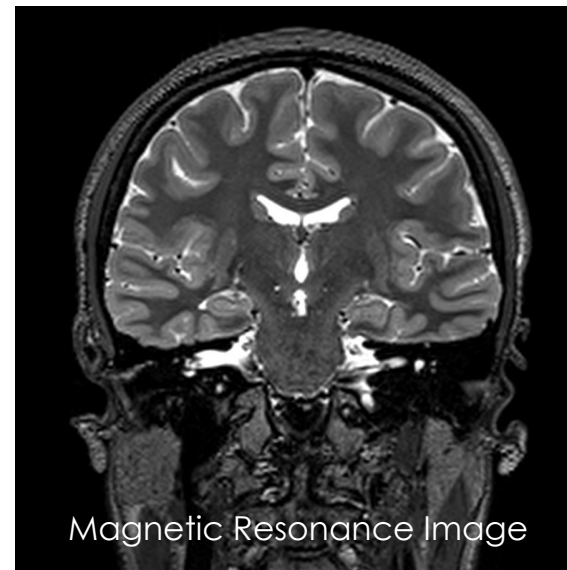
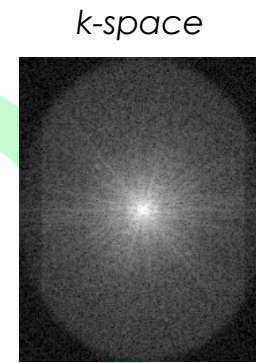
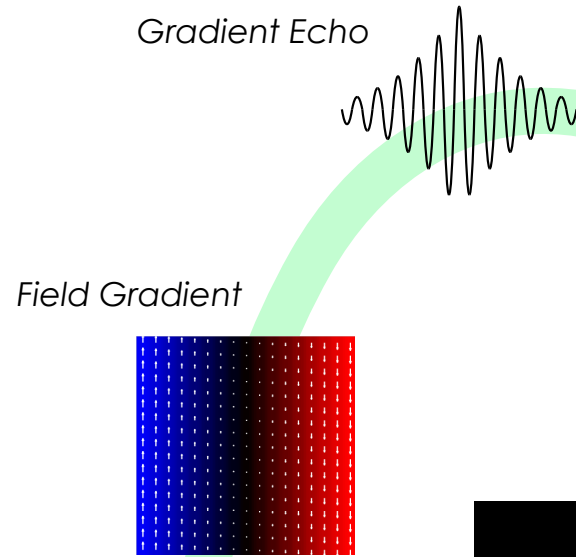
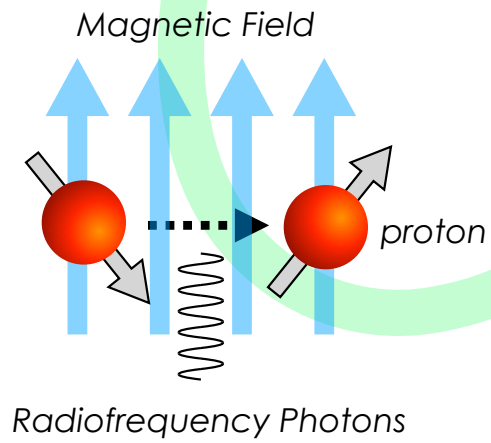
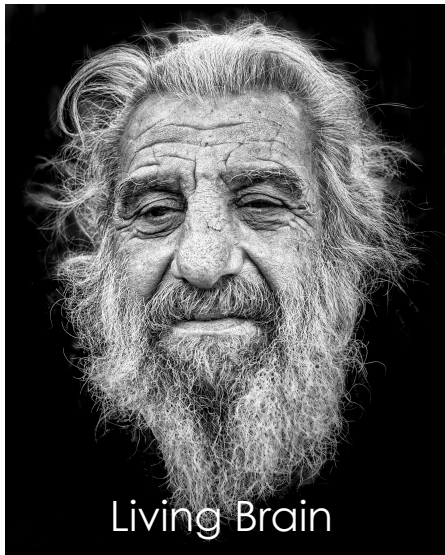


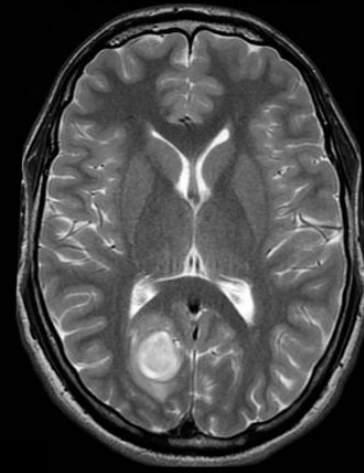
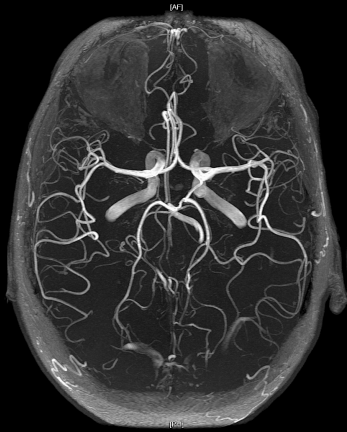
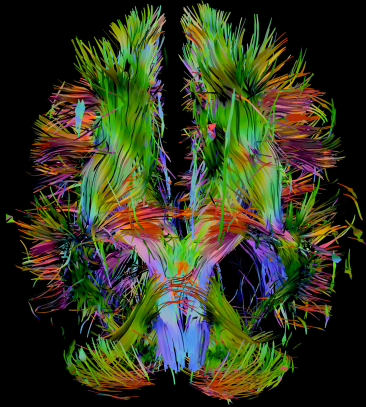
# Day 1 - Principles of MRI

CBIC MRI Bootcamp 2025

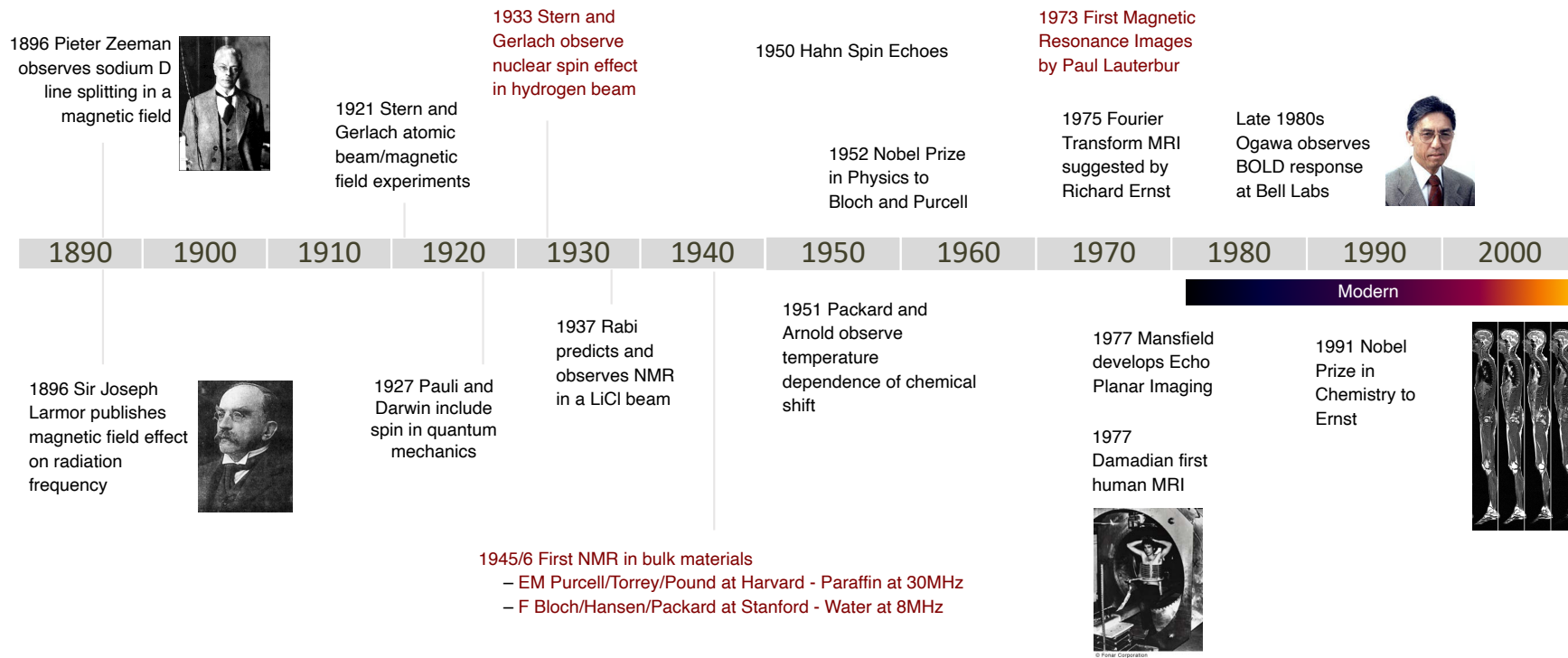
Mike Tyszka  
Caltech Brain Imaging Center

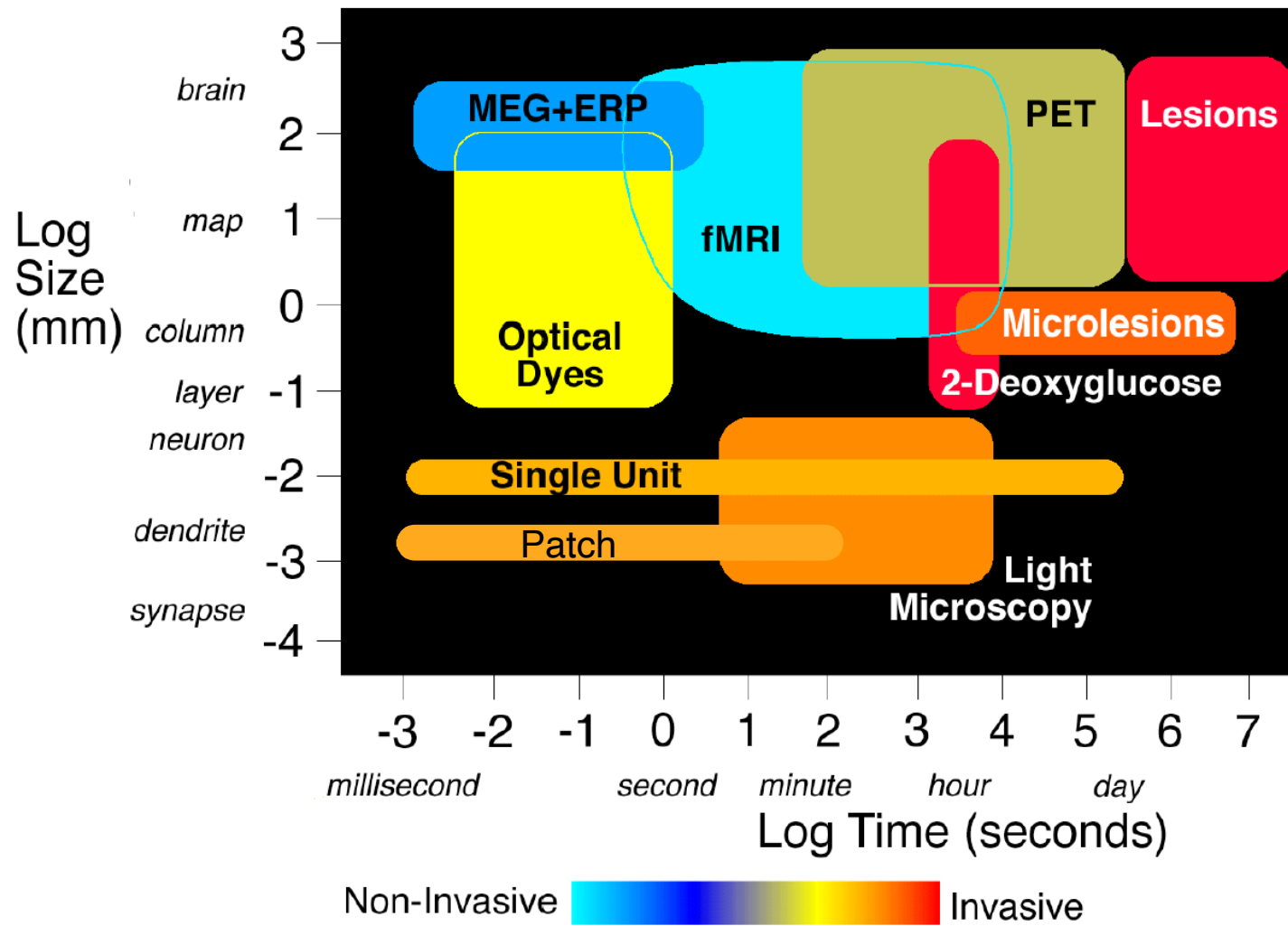
Caltech



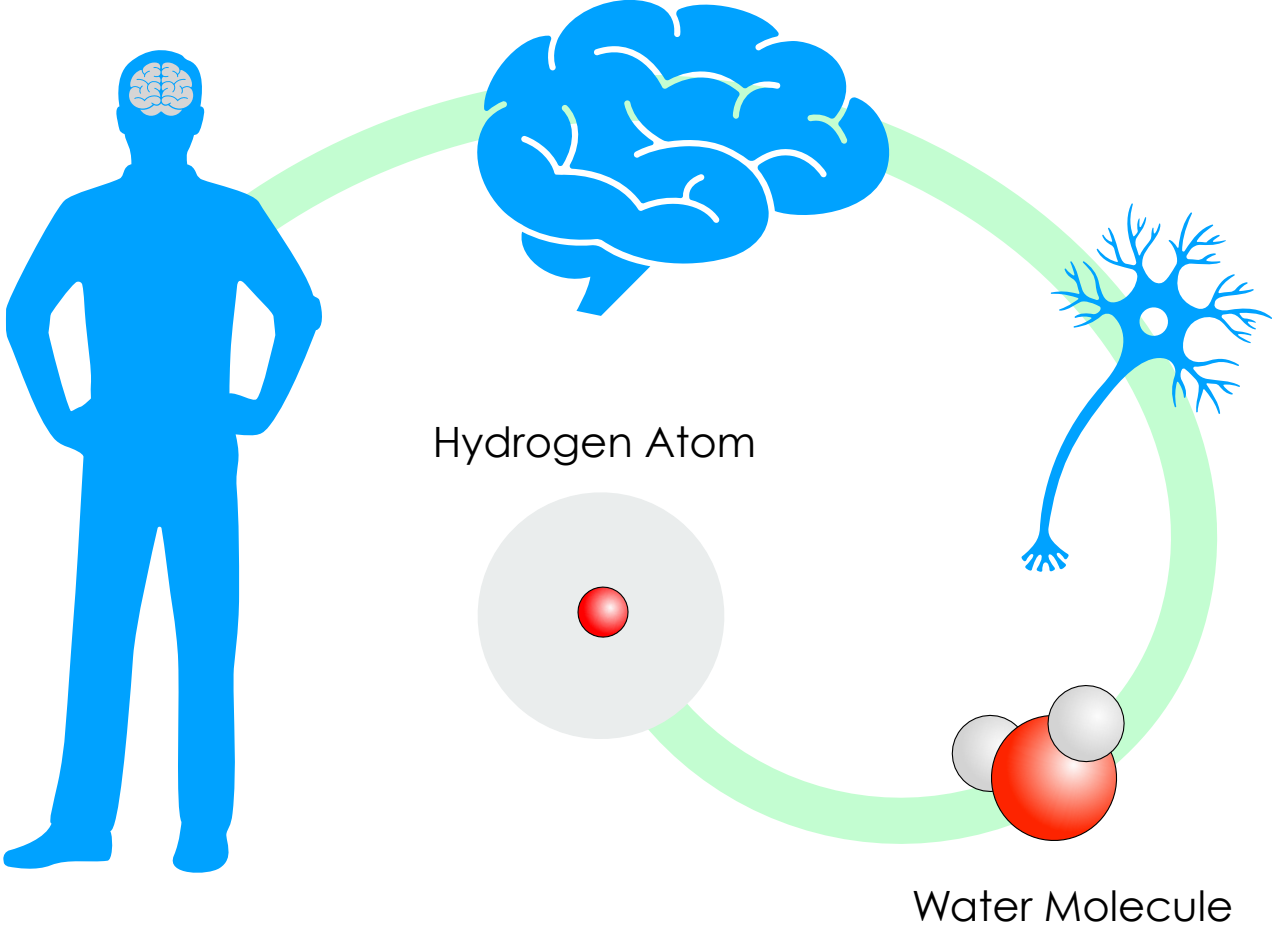


# Timeline of MRI

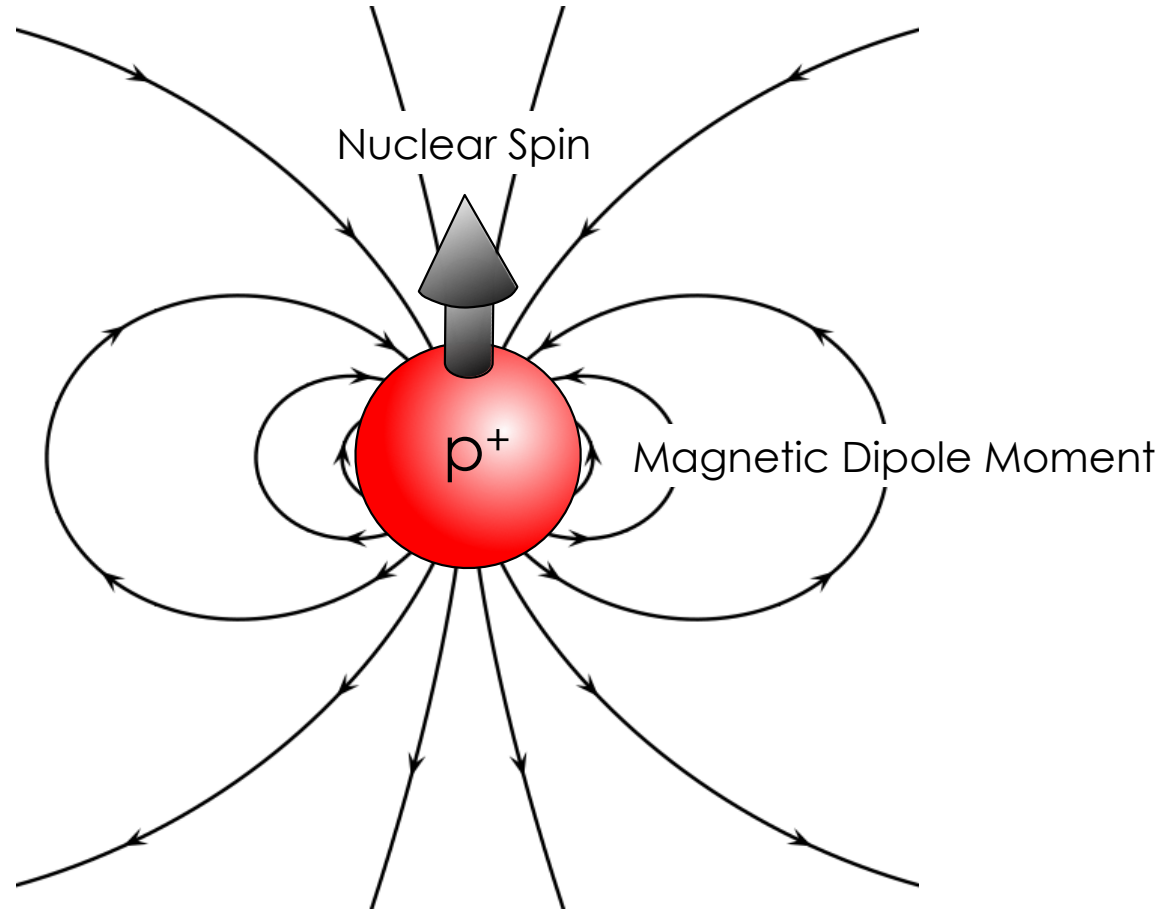




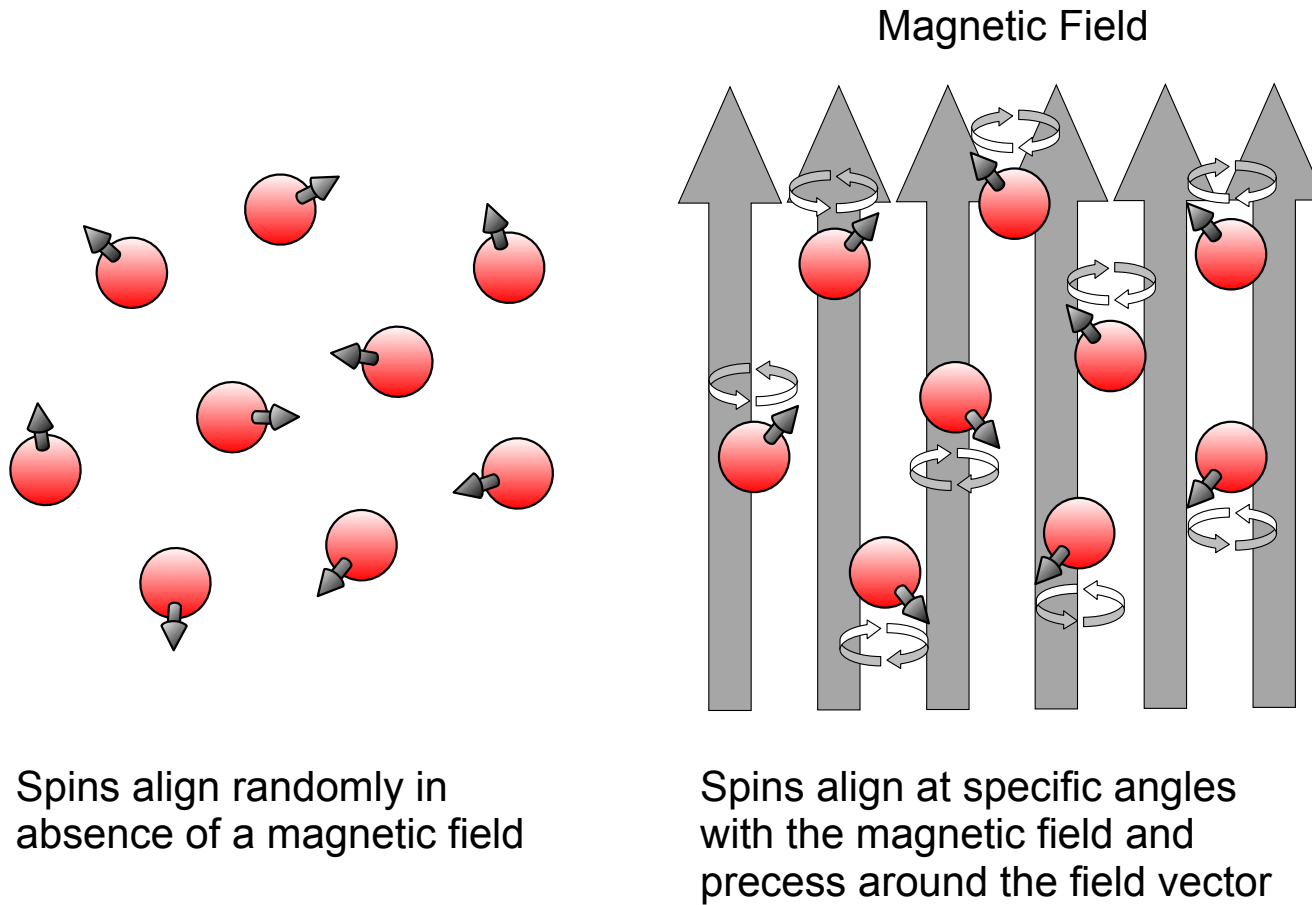
# Principles of MRI



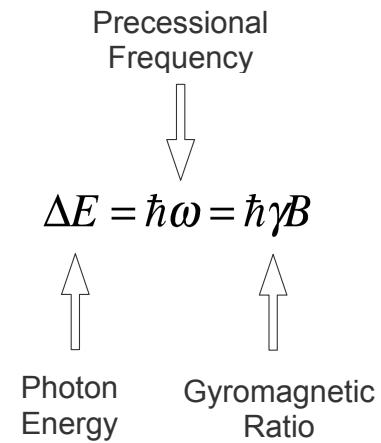
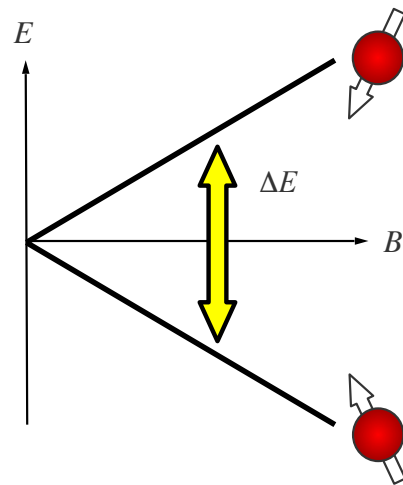
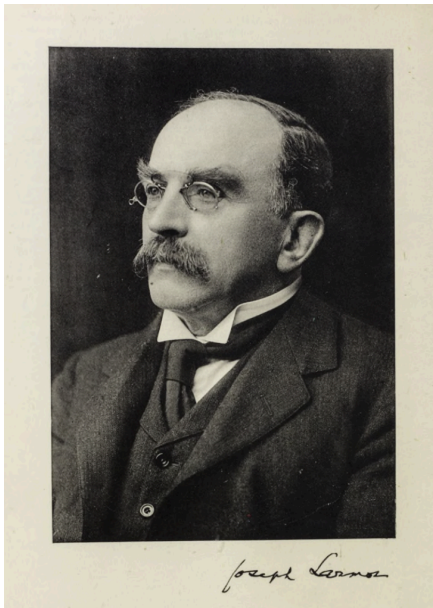
# Nuclear Magnetism



# Nuclear Zeeman Effect



# The Larmor Relation



“The Influence of a Magnetic Field on Radiation Frequency.”  
 Communication from Dr. J. LARMOR, F.R.S. Received  
 and read February 11, 1897.

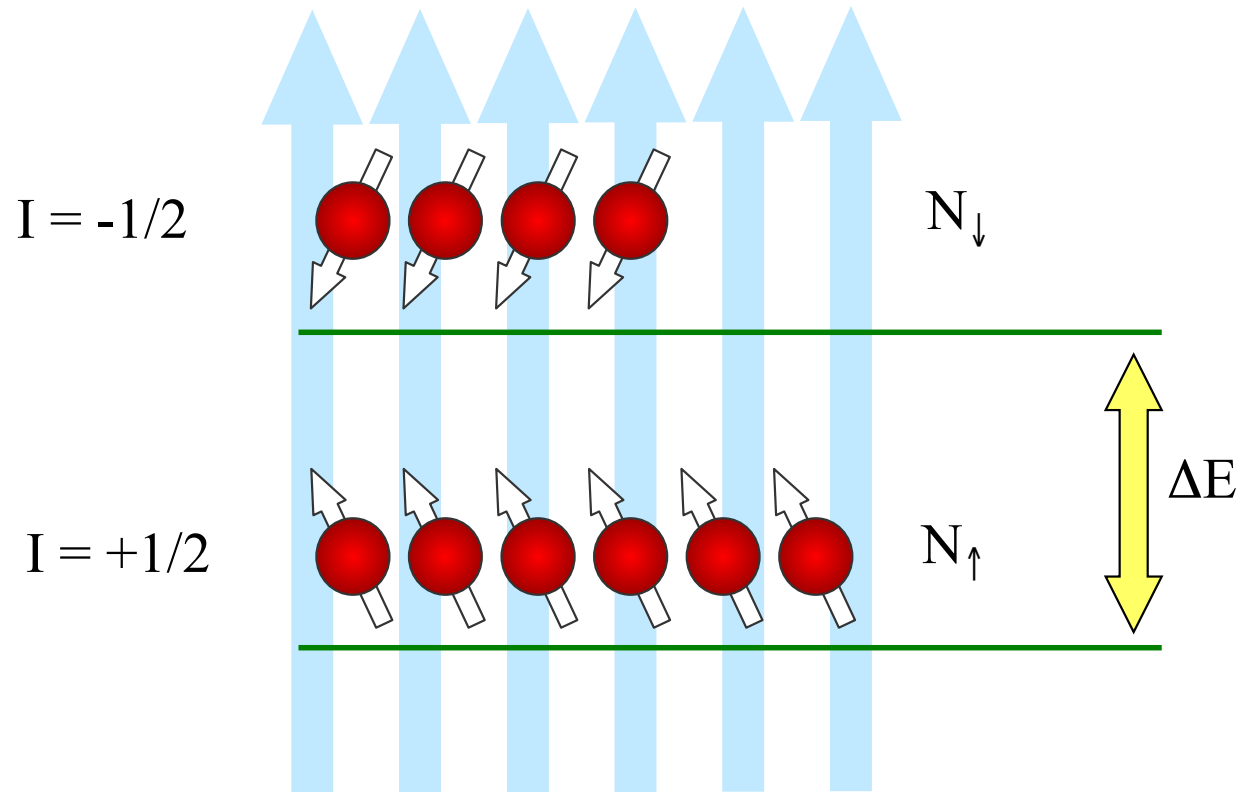
In the course of the development of a dynamical hypothesis\* I  
 have been led to express the interaction between matter and ether  
 as wholly arising from the permanent electrons associated with the  
 matter; and reference was made to von Helmholtz (1893) and Lorentz  
 (1895) as having followed up similar views. A footnote in Dr.

## Magnetic Resonance Nuclei \*

\* Biologically Relevant

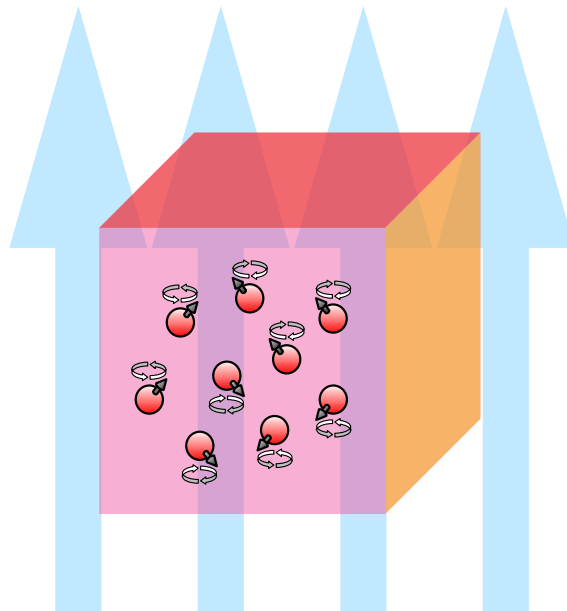
Nucleus	Spin	$\gamma$ (MHz/T)	Abundance	Sensitivity
$^1\text{H}$	1/2	42.58	99.9	100
$^{12}\text{C}$	0	-	-	-
$^{13}\text{C}$	1/2	10.71	1.1	1.59
$^{14}\text{N}$	1	3.08	99.63	0.101
$^{31}\text{P}$	1/2	17.24	100	6.63

# Population of Energy Levels

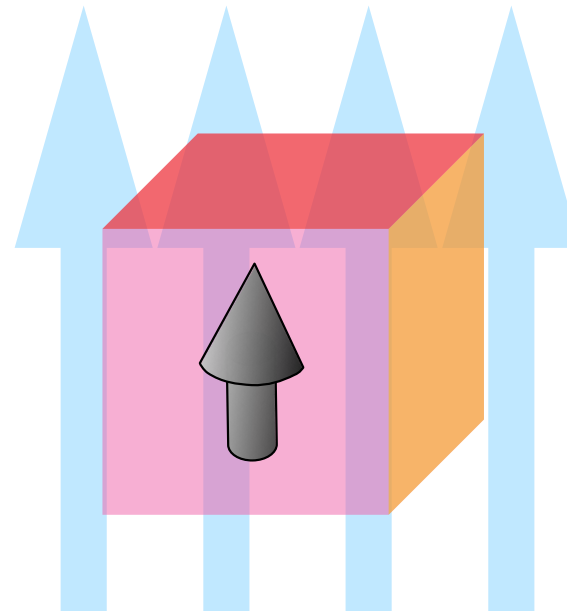


# Bulk Magnetization

Spin Ensemble



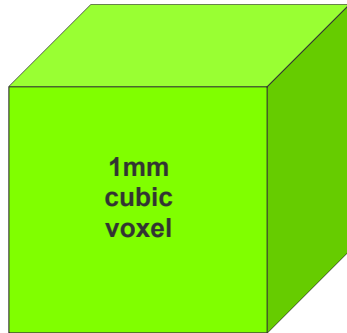
Bulk Magnetization



- Equilibrium Bulk Magnetization does NOT precess
- Tiny fraction of spins contribute to bulk magnetization

## Clinical MRI

Human Brain

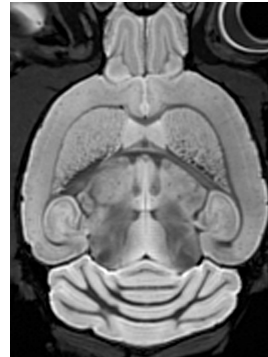


$3 \times 10^{19}$  water molecules/voxel

$7 \times 10^{14}$  detectable spins

## Magnetic Resonance Microscopy

Mouse Brain

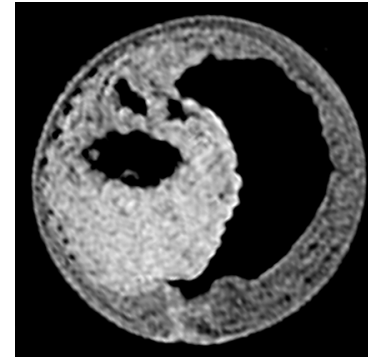



 75µm  
cubic  
voxel

$1 \times 10^{16}$

$9 \times 10^{11}$

Frog Embryo

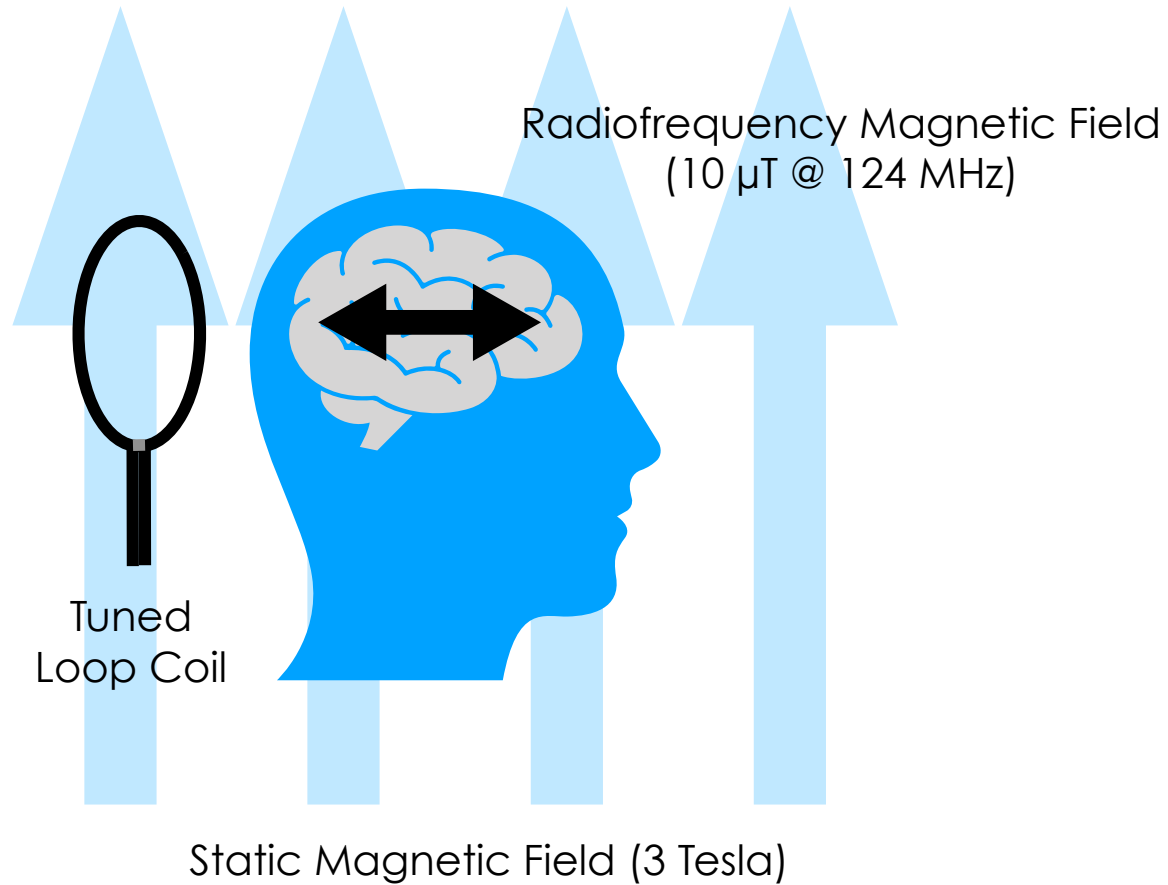


 16µm  
cubic  
voxel

$1 \times 10^{14}$

$1 \times 10^{10}$

# Probing Nuclear Magnetization



# Radiofrequency Coils

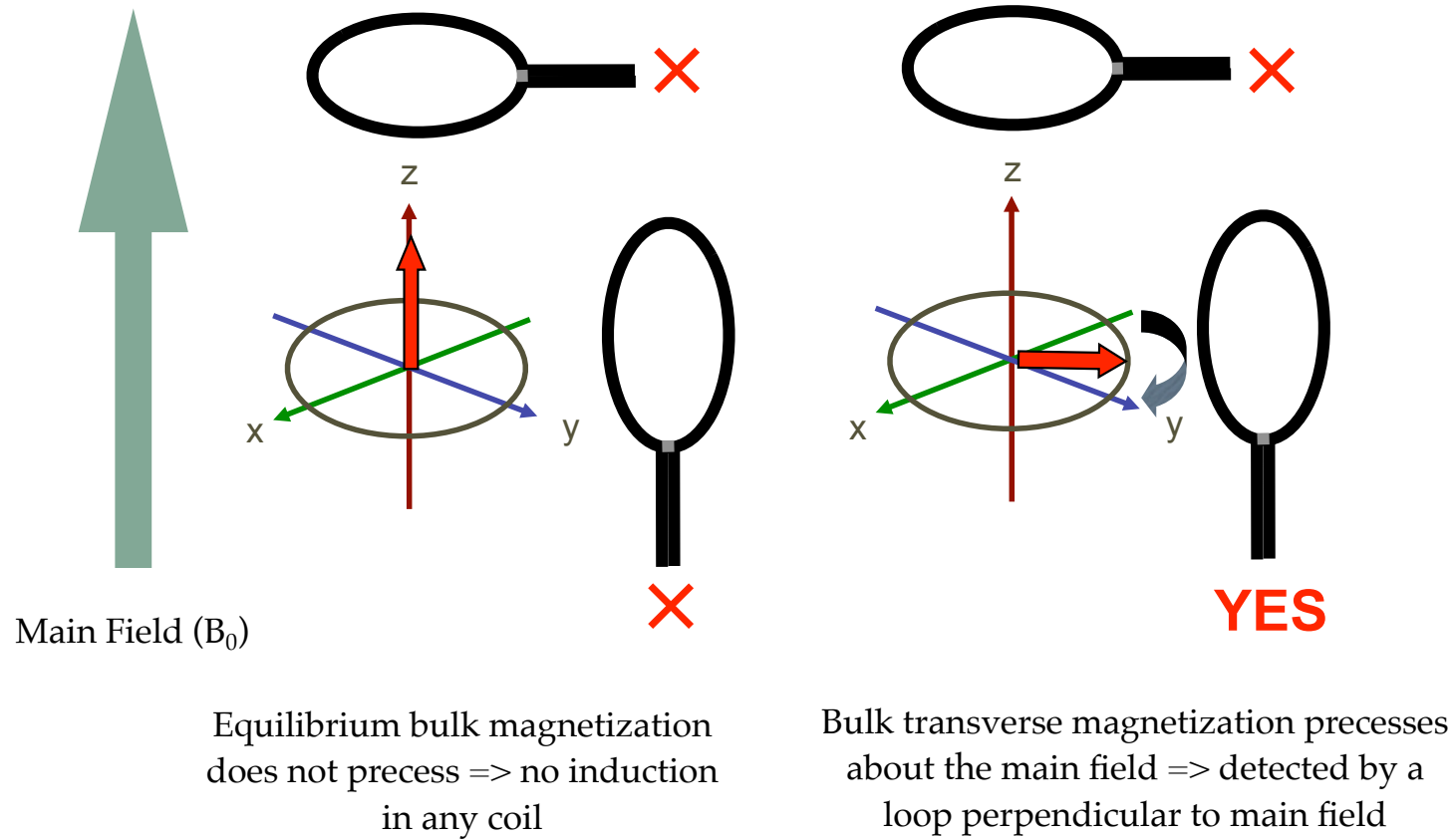


Circularly Polarized  
Transmit/Receive Head  
Coil



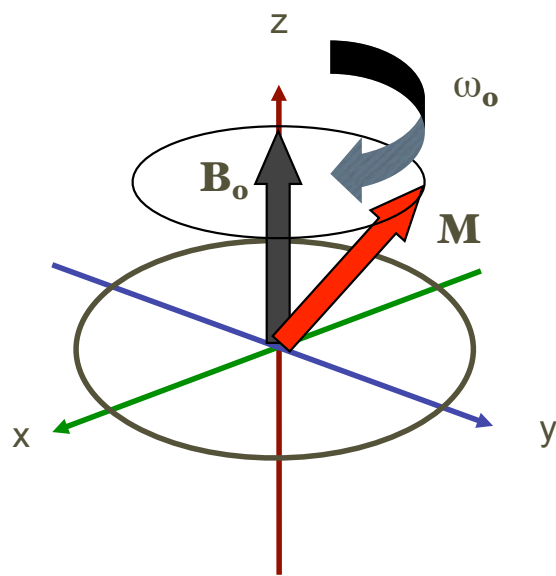
32 channel RF Receive  
Phased Array

# Detecting Magnetization

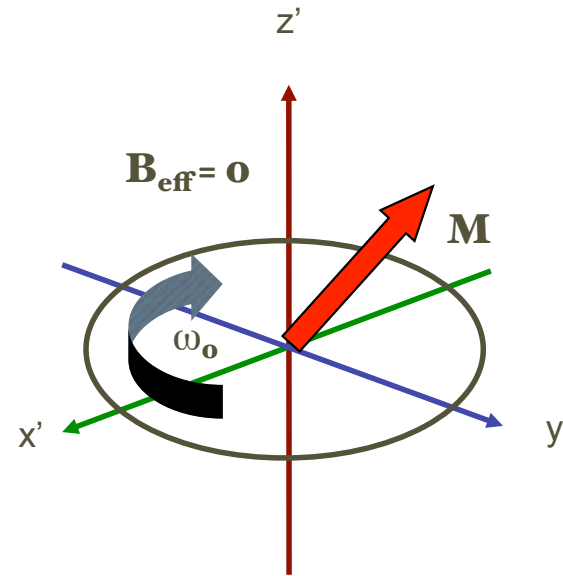


# New Concept : The Rotating Frame

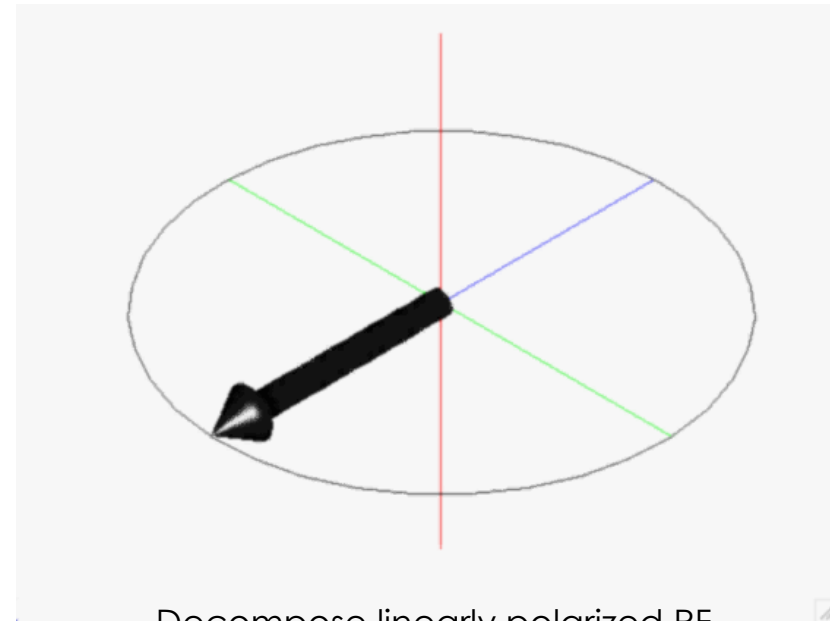
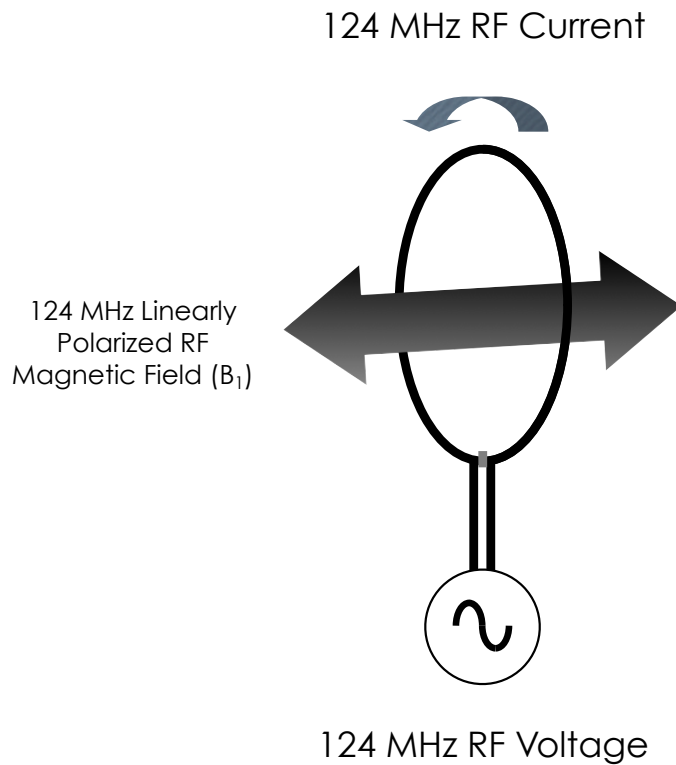
Laboratory Frame



Rotating Frame

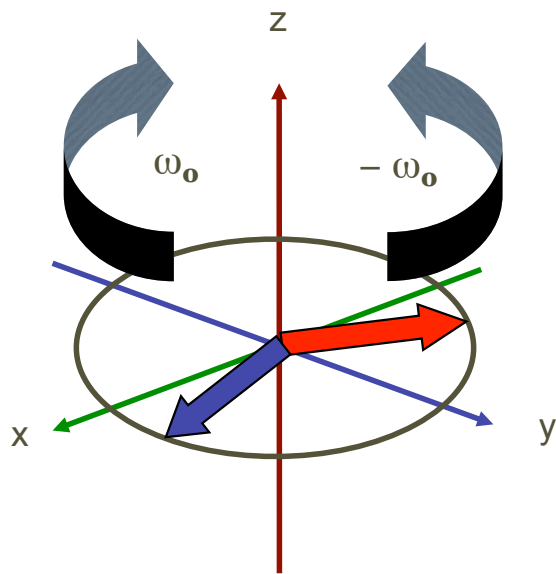


# New Concept : Circular Polarization

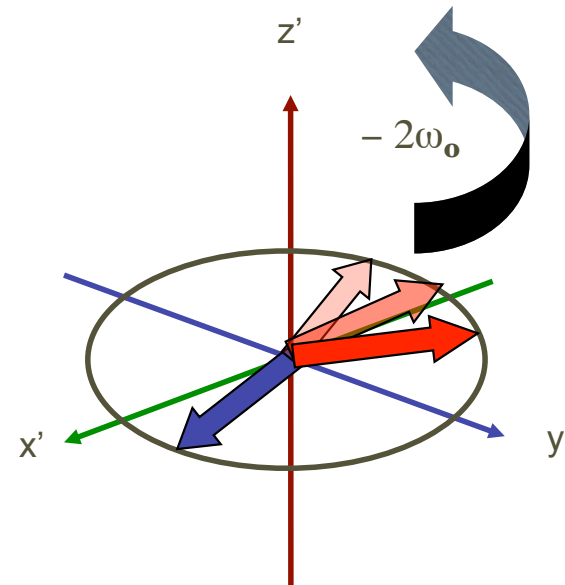


Decompose linearly polarized RF magnetic field into two, counter-rotating circularly polarized fields

## Circularly polarized $B_1$ fields in the rotating frame



Laboratory Frame



Rotating Frame

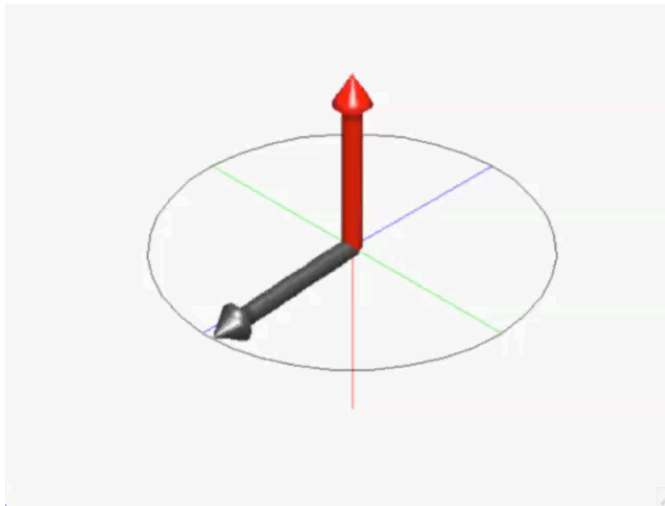
# RF Excitation and Flip Angles

Introduce B1 field into rotating frame

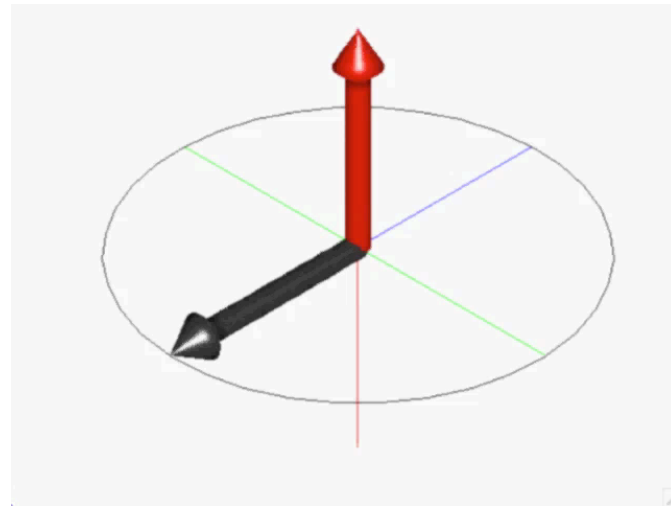
Equilibrium magnetization precesses about the B1 field

Switch off B1 field after a given rotation or flip angle

Laboratory Frame



Rotating Frame



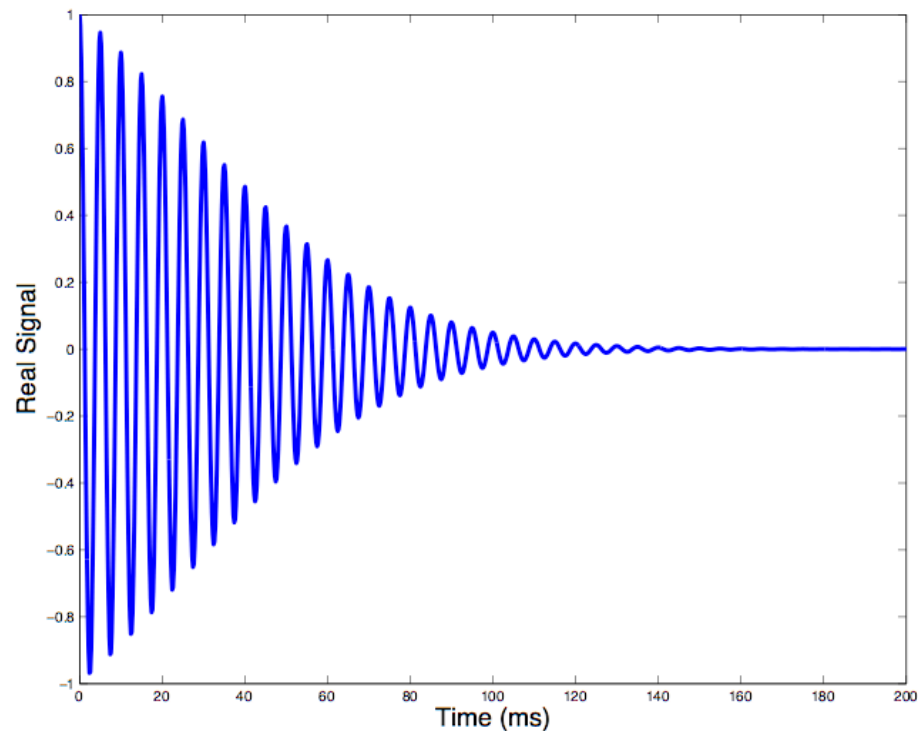
And that's how we generate  
transverse magnetization!

From NMR to MRI

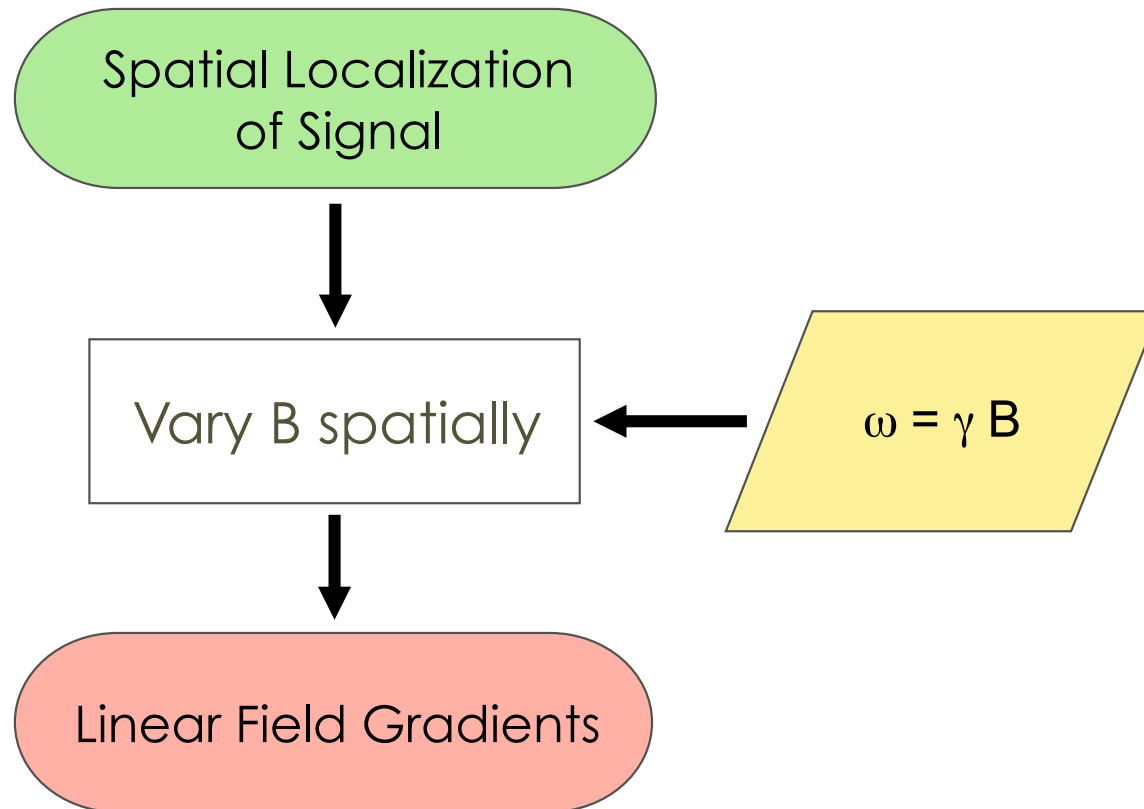
Frequency Encoding

# The Free Induction Decay

Natural signal decay of transverse magnetization following an RF pulse  
 $x'$  and  $y'$  components of magnetization ( $M_x$  and  $M_y$ ) extracted from receive coil signal  
Can be treated as complex-valued ( $M_x = \text{real}$ ,  $M_y = \text{imaginary}$ )

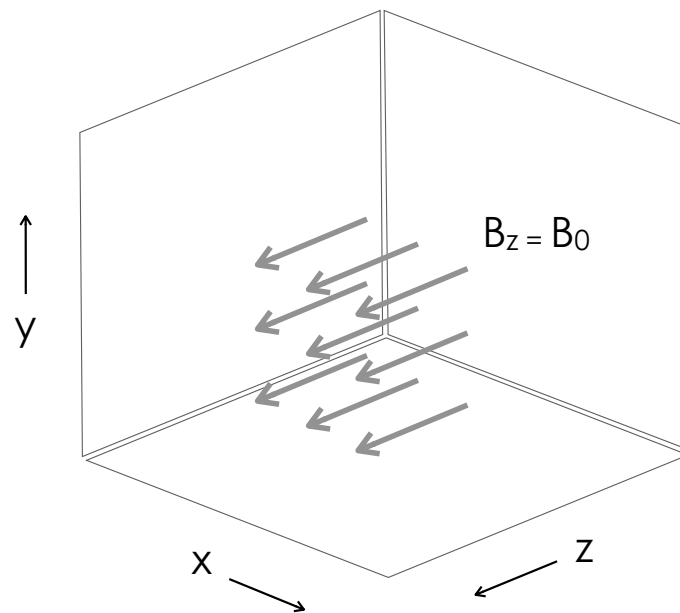


## New Concept : Using Frequency to Encode Space



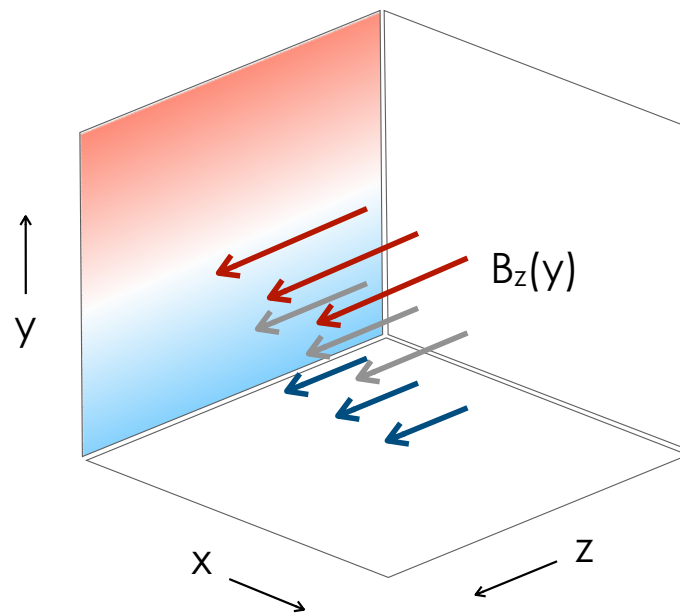
# Homogeneous Magnetic Field

No Gradient

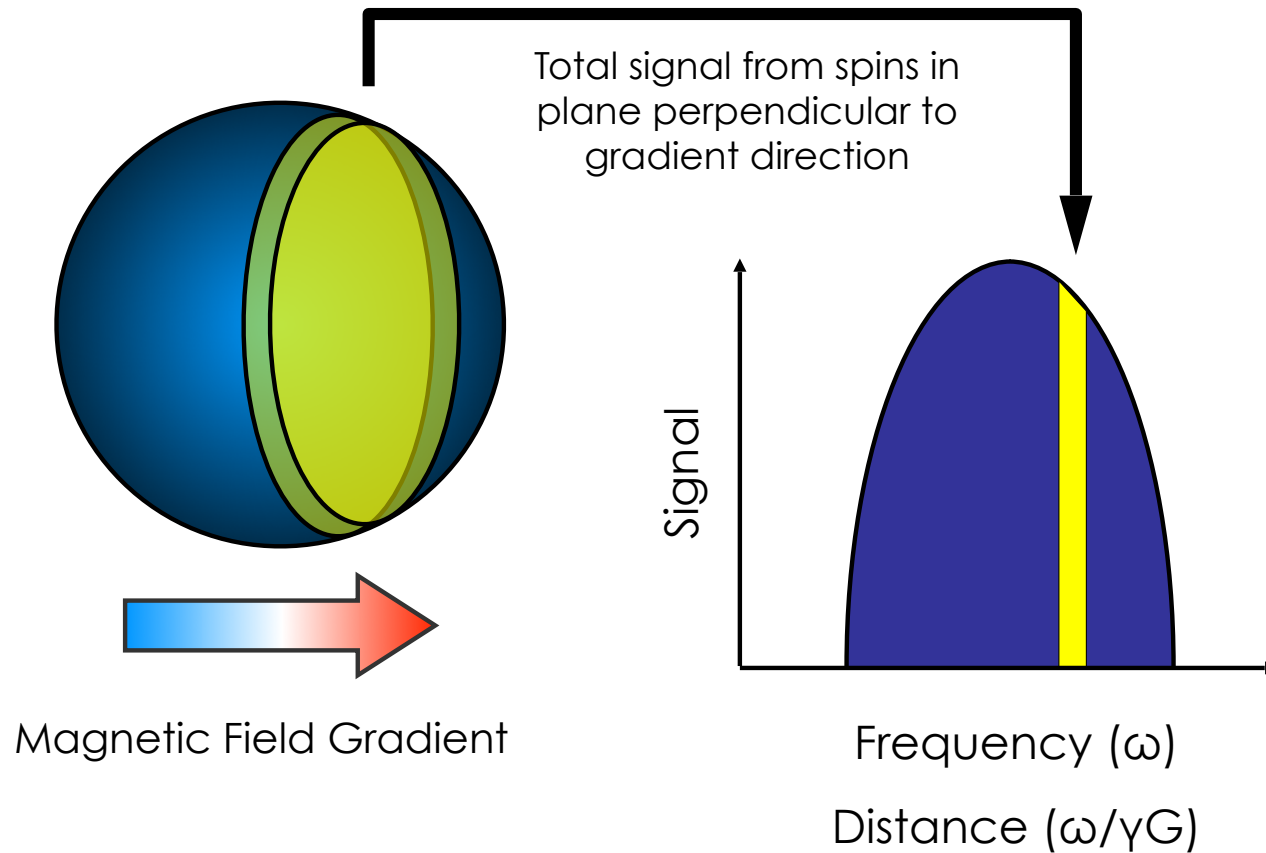


# Linear Magnetic Field Gradient

Y Gradient



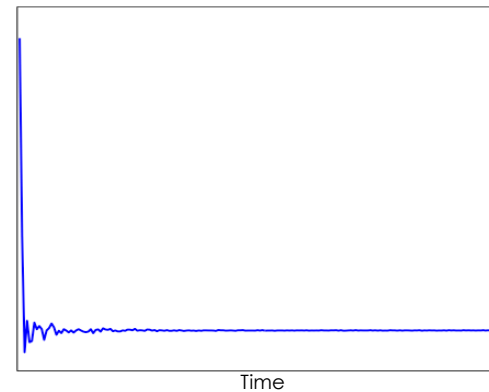
# Frequency Encoding of a Water Sphere



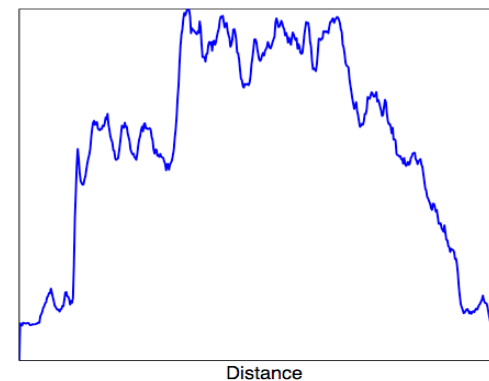
# Real object FID in a field gradient

- FID contains total signal from all spins at all frequencies/ locations.
- Each frequency component represents the total signal from a plane perpendicular to the gradient direction.
- Frequency analysis of FID reveals “projection” of object.

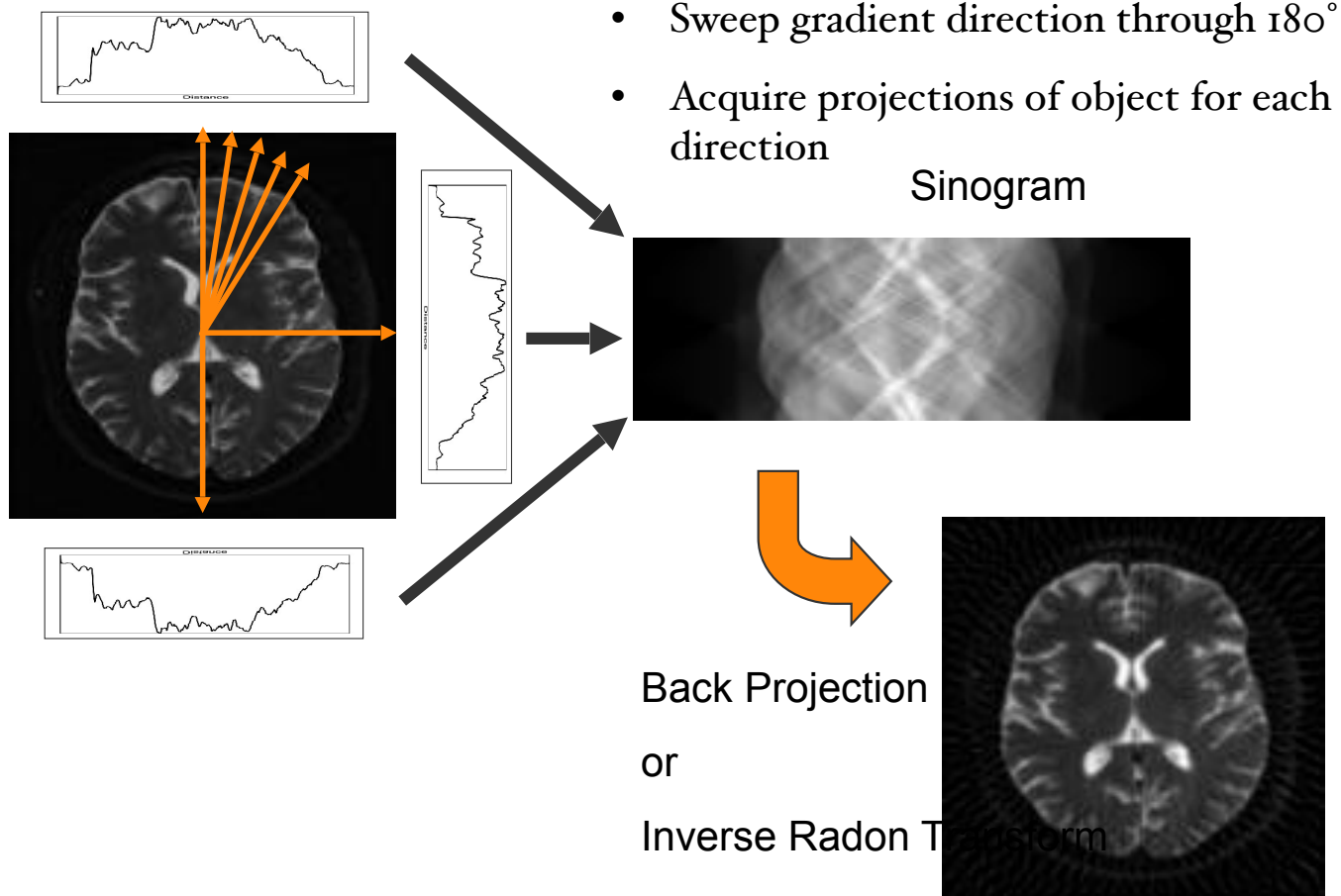
FID with gradient on



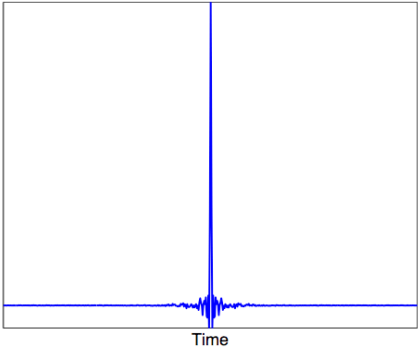
Magnitude frequency spectrum of FID



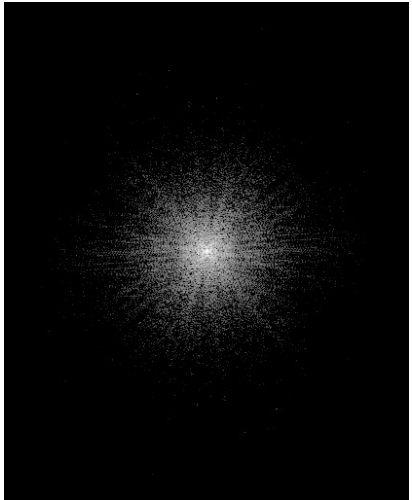
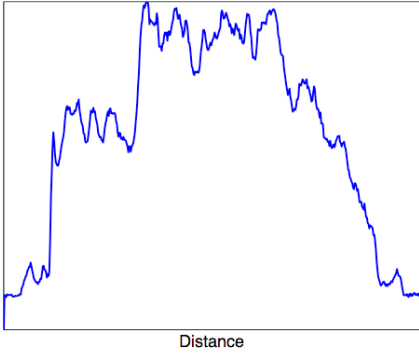
# Back Projection



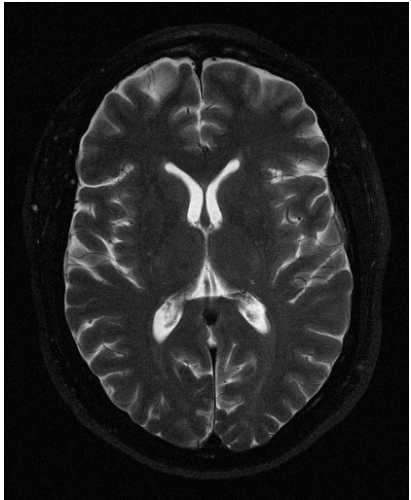
# The Two Dimensional Fourier Transform



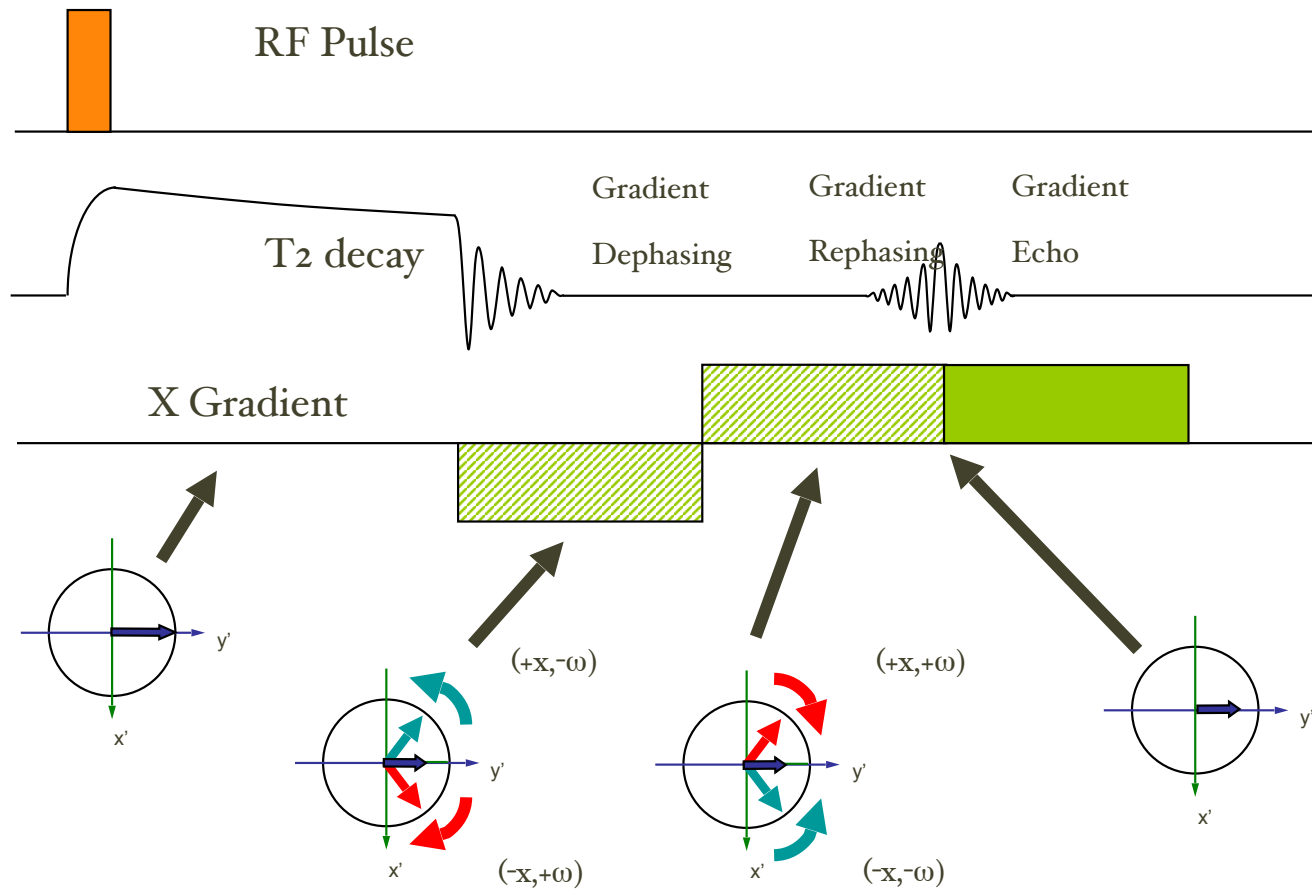
1D FT



2D FT



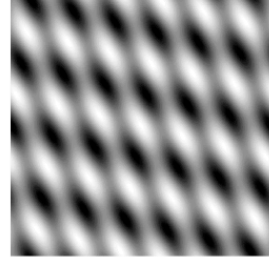
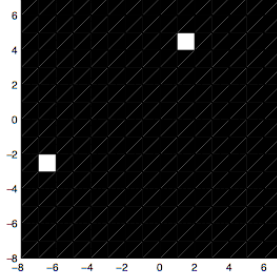
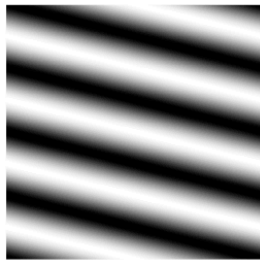
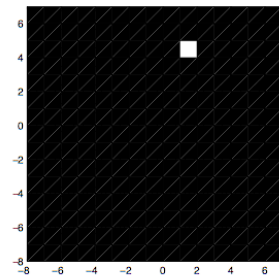
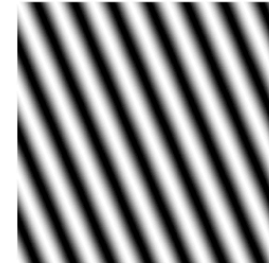
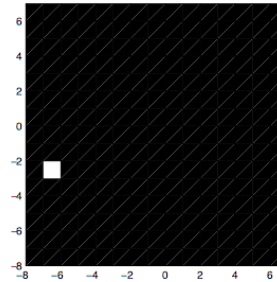
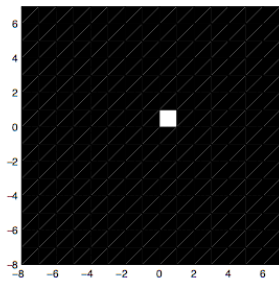
# The Gradient Echo



# Spatial Frequencies and k-space

k-space

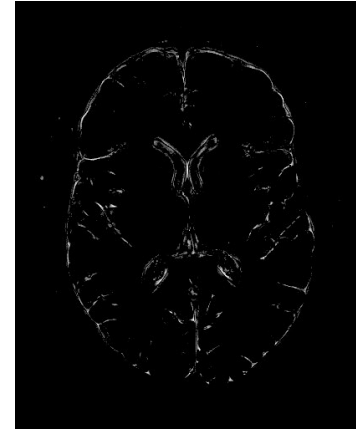
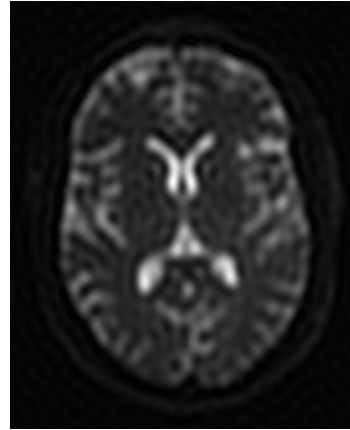
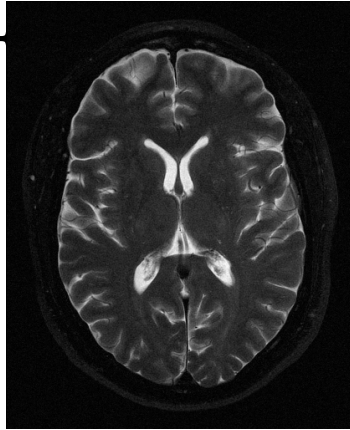
Real space



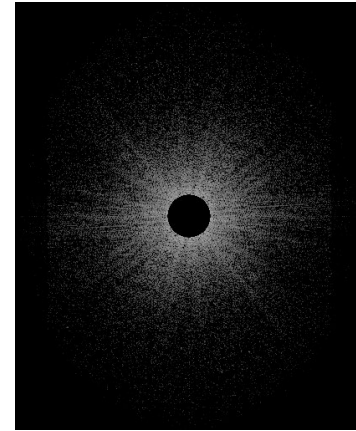
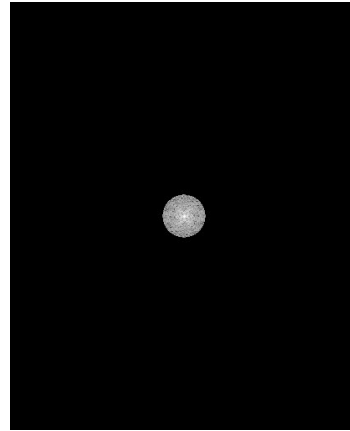
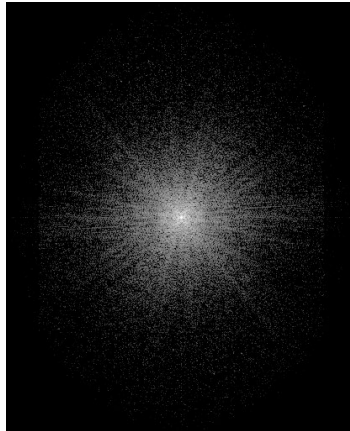
Coordinates in k-space equate to spatial frequency.

# k-space Spatial Frequency Regions

Real Space



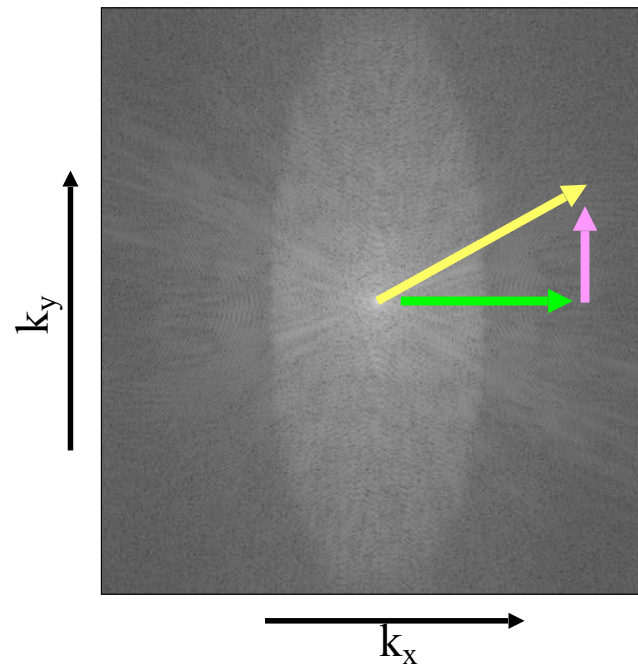
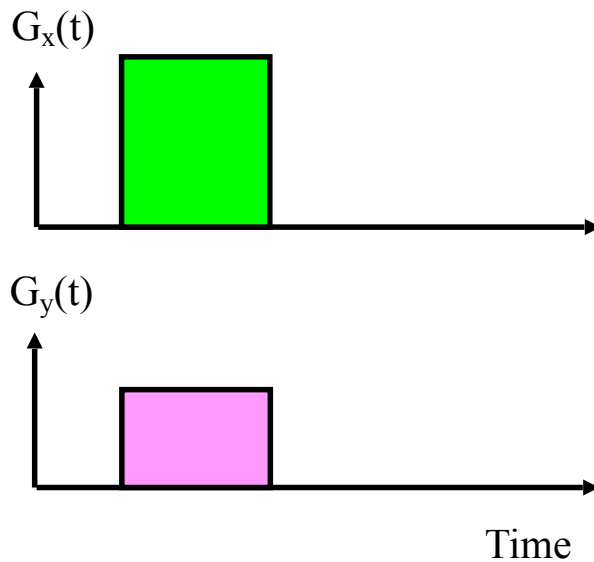
k Space



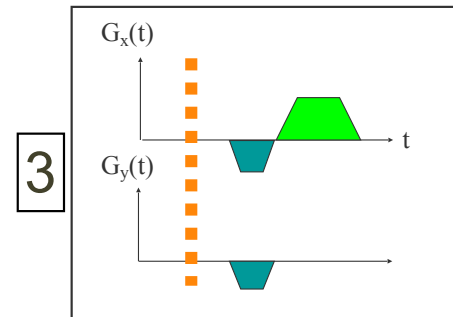
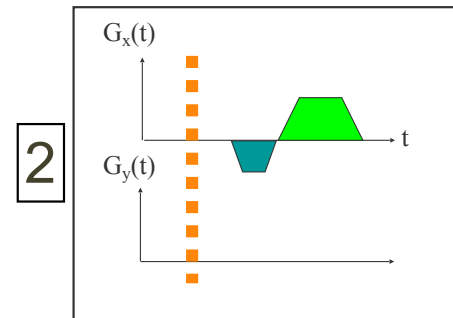
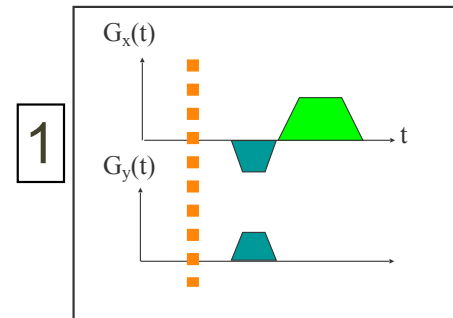
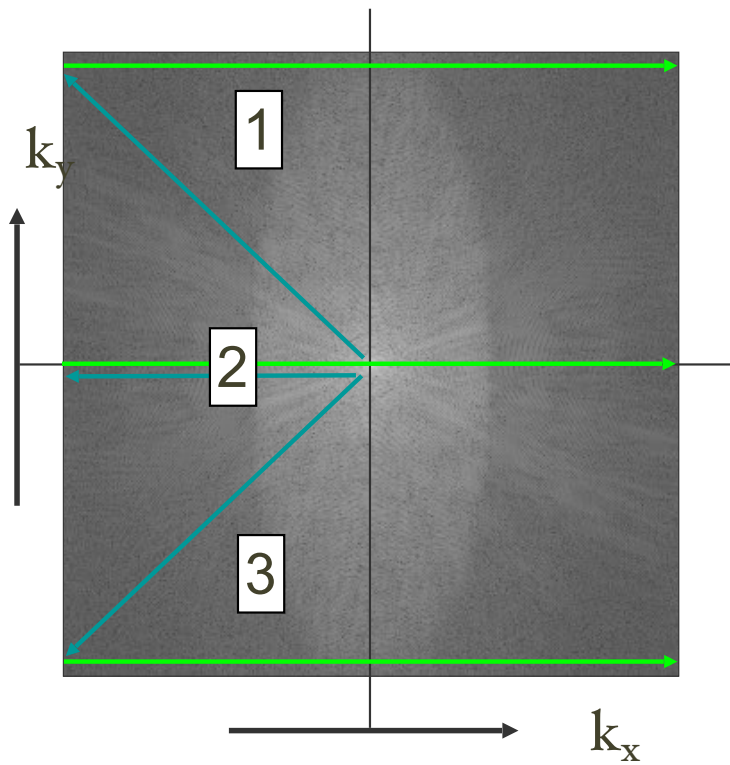
# k-space Trajectory

$$\mathbf{k}(t) = \int_0^t dt' \gamma \mathbf{G}(t')$$

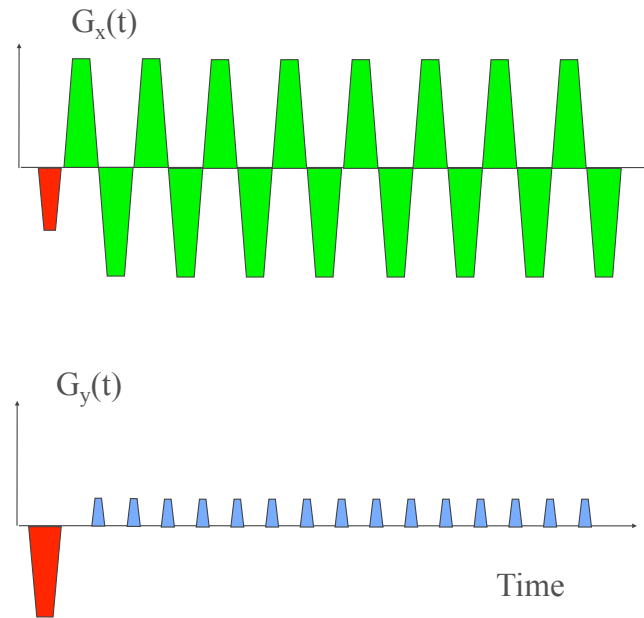
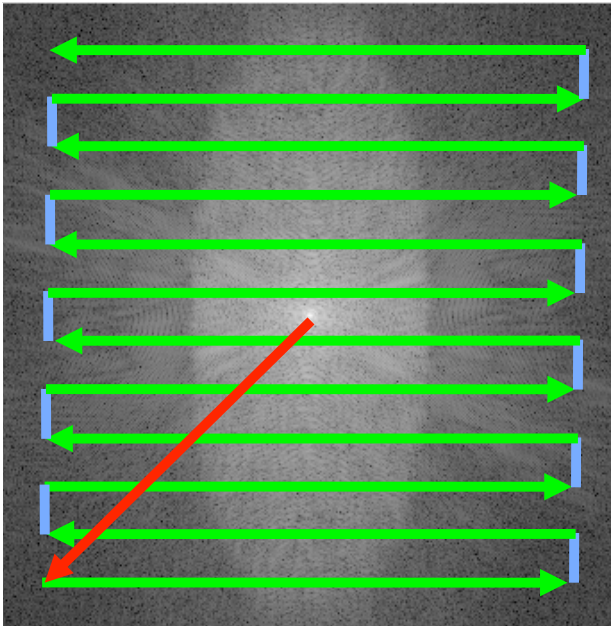
Gradient pulses move the spin system in k-space.



# k-space Trajectories



# Echo-planar Imaging



k-space

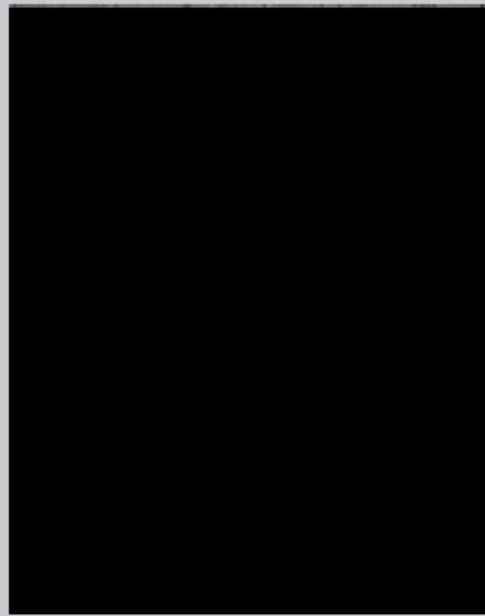
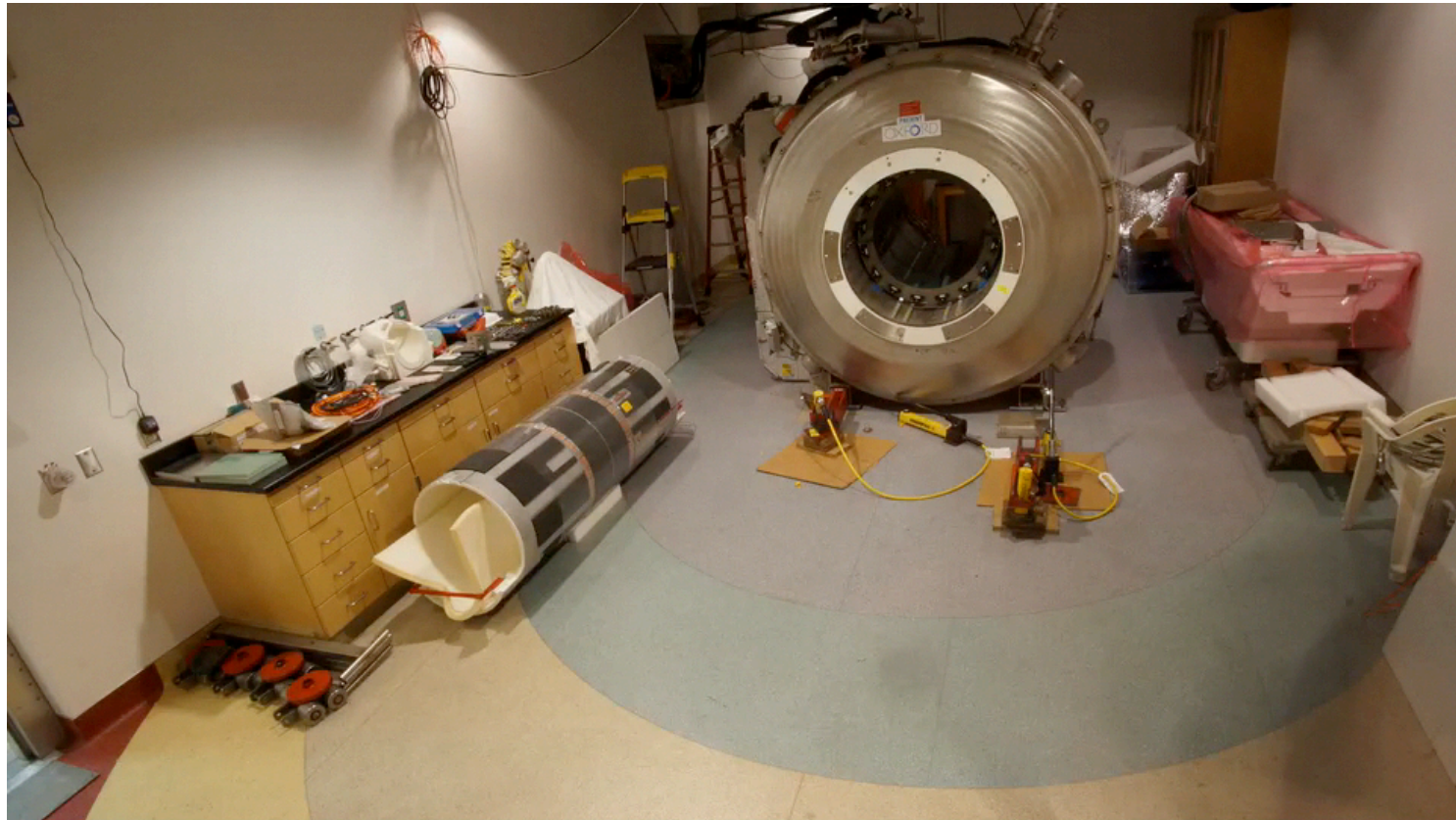


Image space



# MRI Hardware

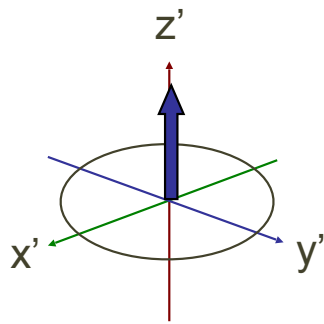


**MRI Tissue Contrast**

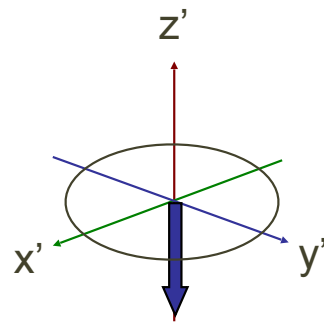
**Relaxation Weighting**

# T<sub>1</sub> (Spin-Lattice or Longitudinal) Relaxation

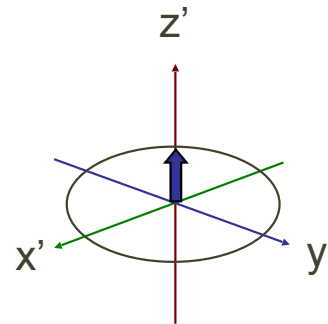
Equilibrium



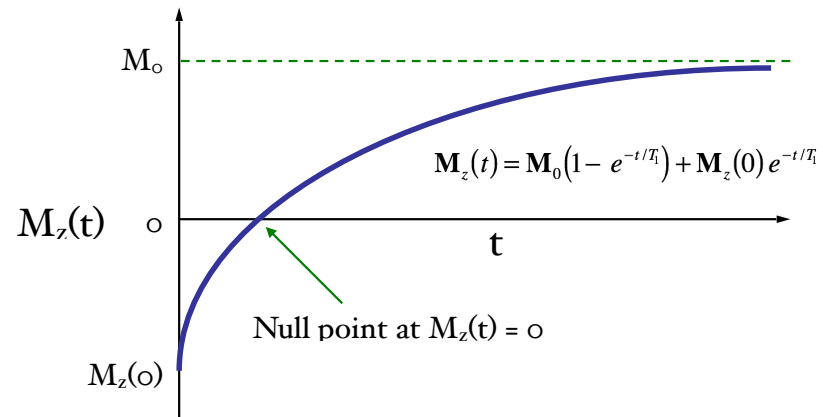
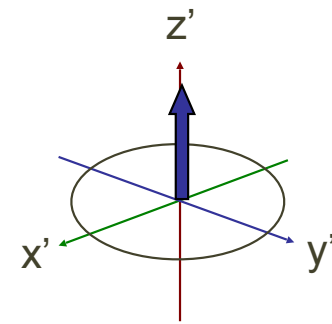
180° Flip



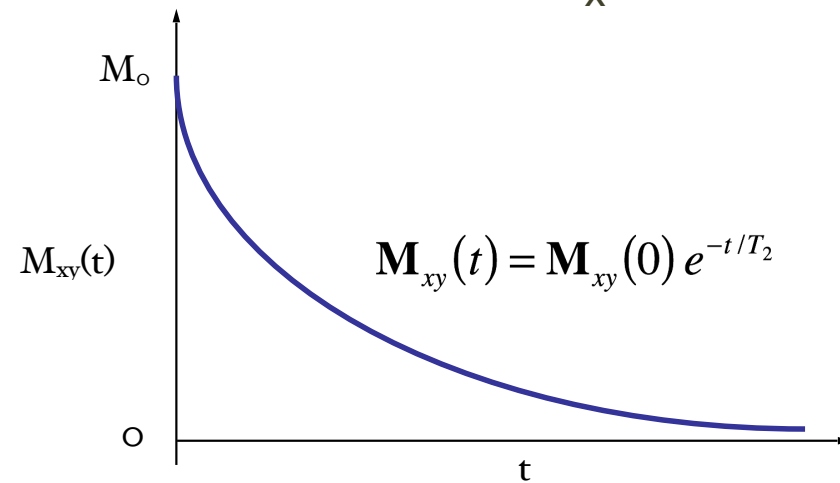
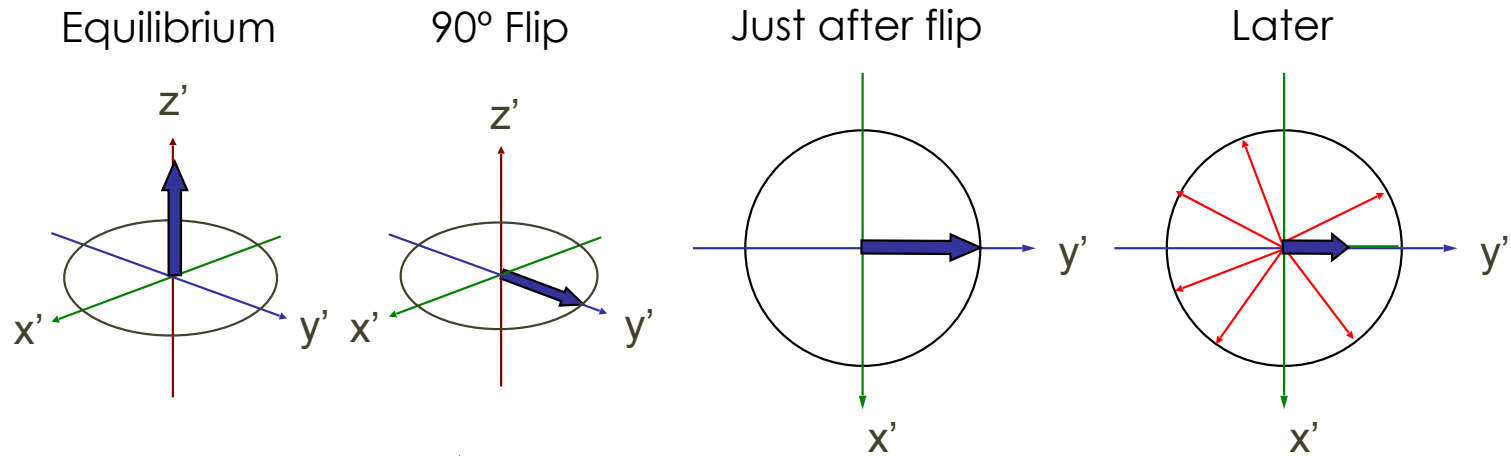
T<sub>1</sub> relaxation



Equilibrium



# T<sub>2</sub> (Spin-Spin) Relaxation



# Typical Tissue Relaxation Times

Relaxation times are field dependent

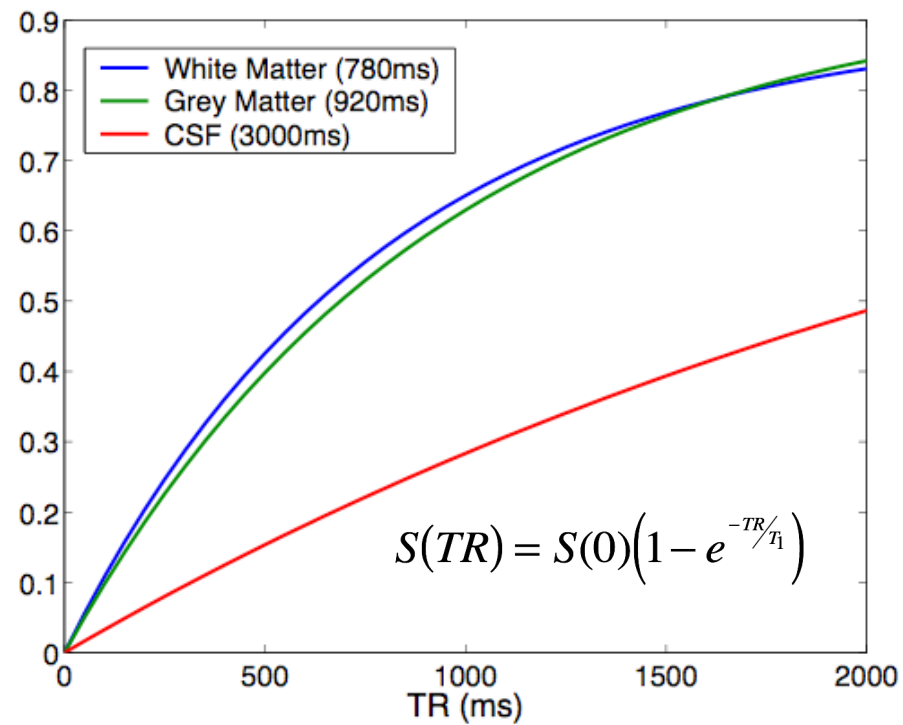
Generally, tissue T1s increase and converge at higher field strengths

Tissue T2s decrease at higher field strengths

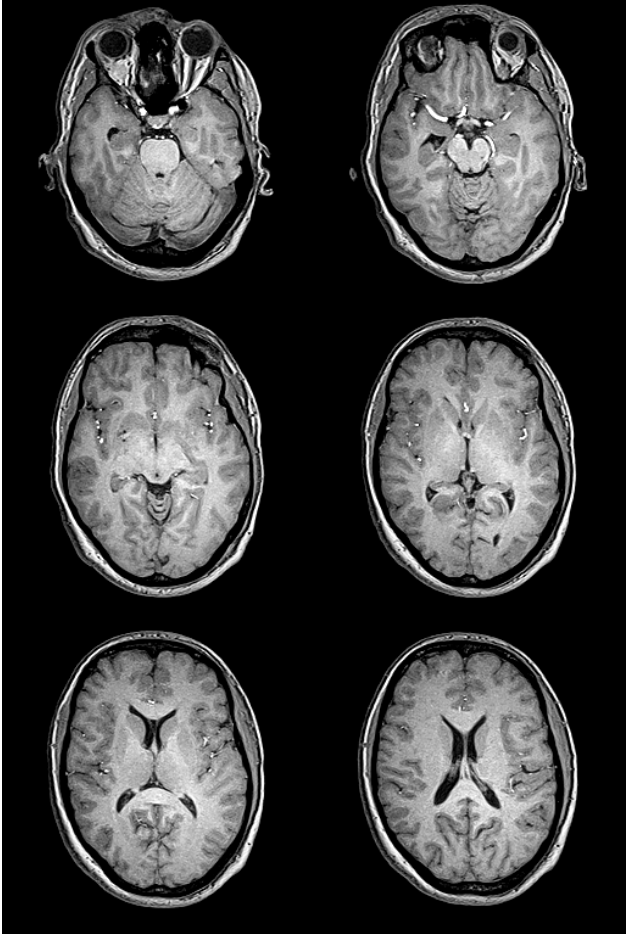
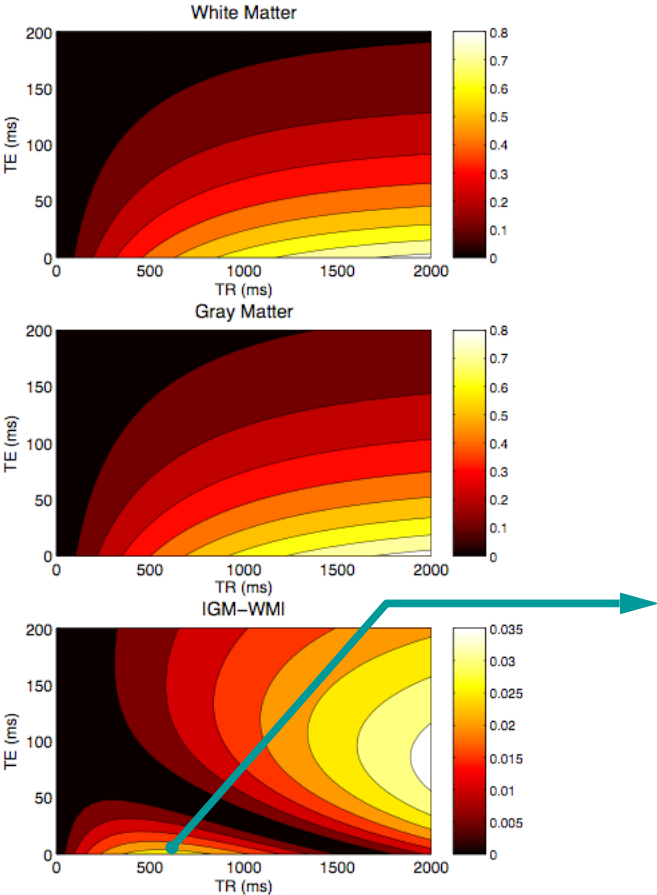
Tissue	T1 (ms)	T2 (ms)
Cortical GM	~1400	~90
Subcortical GM	~1200	~90
WM	~900	~80
Ventricular CSF	~4500	~2400

# Saturation Recovery T1-weighting

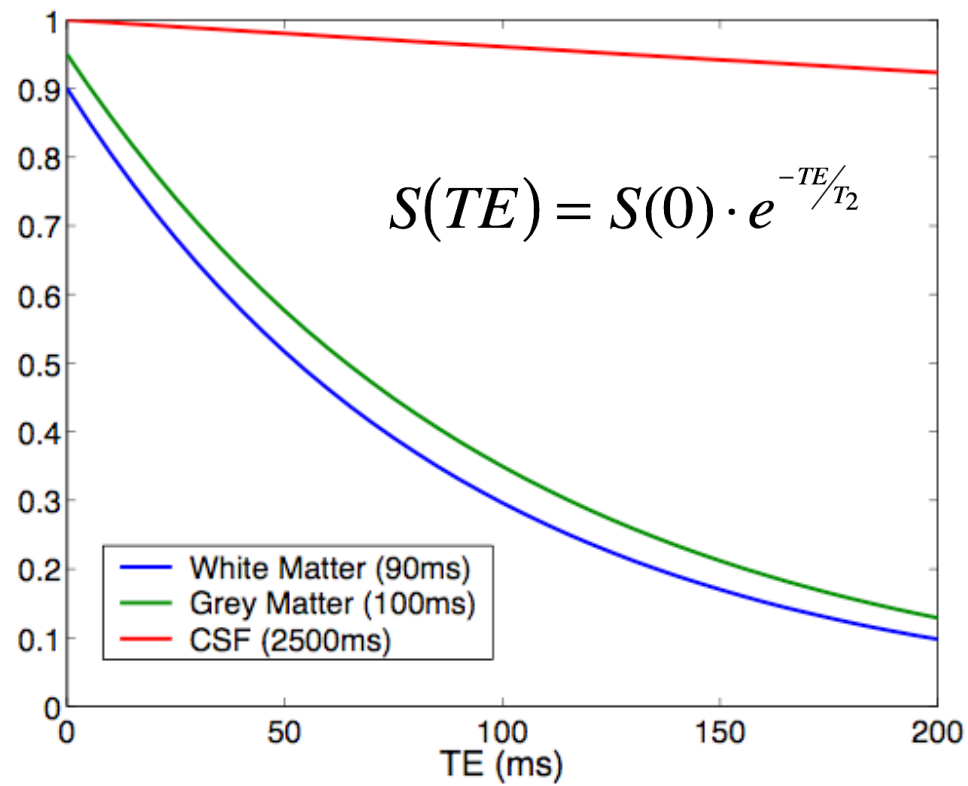
Use RF pulse repetition time shorter than about 5 x T1  
Magnetization does not have time to fully re-equilibrate  
Lower Mz and excited Mxy than from full equilibrium



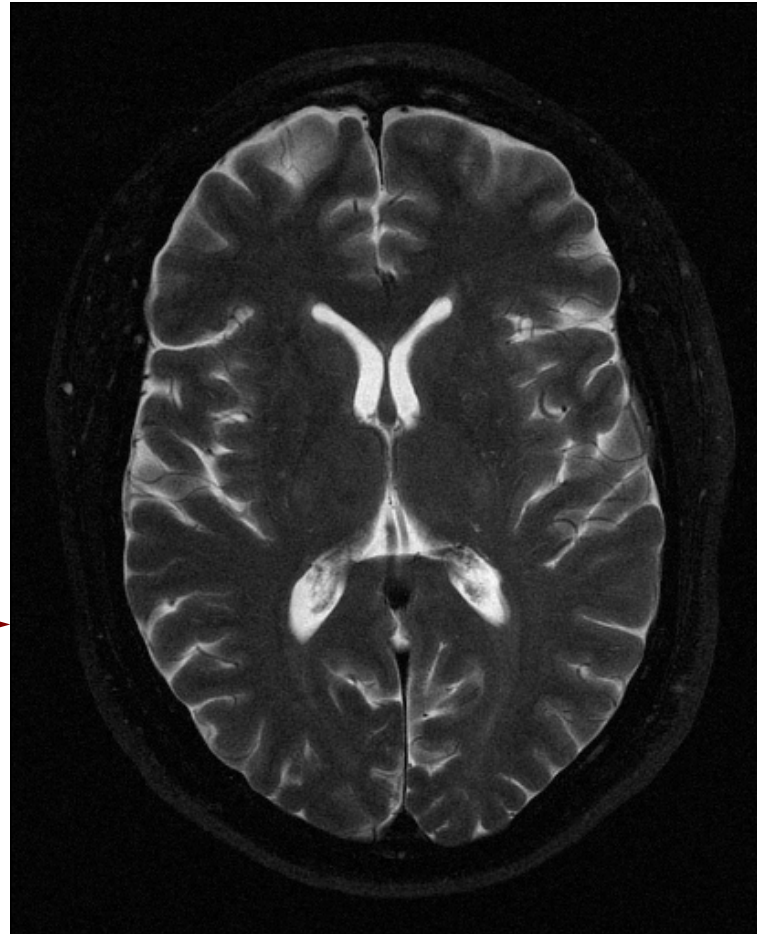
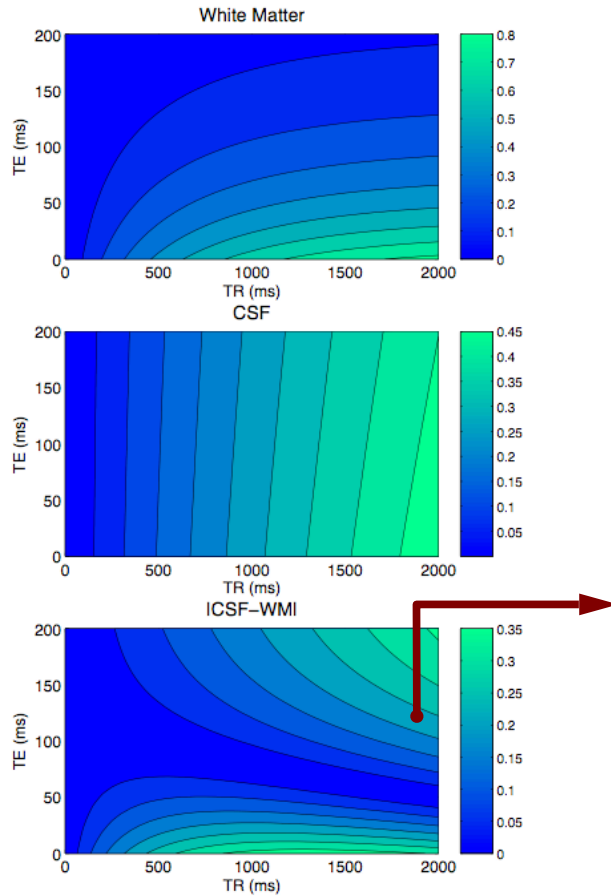
# Saturation Recovery Contrast ( $T_1$ -weighted)



# Echo Time T2-weighting



# T<sub>2</sub>-weighted Contrast



# Next Time

- Volume selection
- Spin Echo
- Flow and Motion
- fMRI Pulse Sequences