Introduction to MRI

- Spin & Magnetic Moments
- Relaxation (T1, T2)
- Spin Echoes
- 2DFT Imaging
  - Selective excitation, phase & frequency encoding
- K-space & Spatial Resolution
- Contrast (T1, T2)

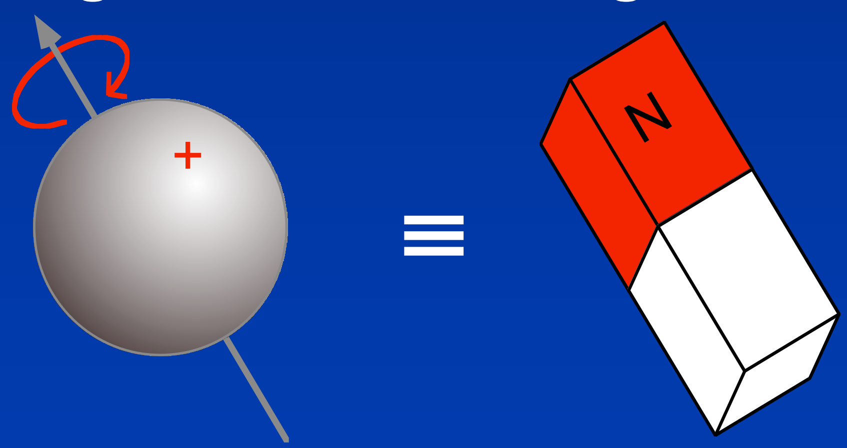
Acknowledgement: Dr. Glyn Johnson

Spin

- Spin & Magnetic Moments
- Precession
  - Larmor frequency, NMR signals
- Excitation
- Relaxation
  - T1, T2
- Spin Echoes
  - T2*

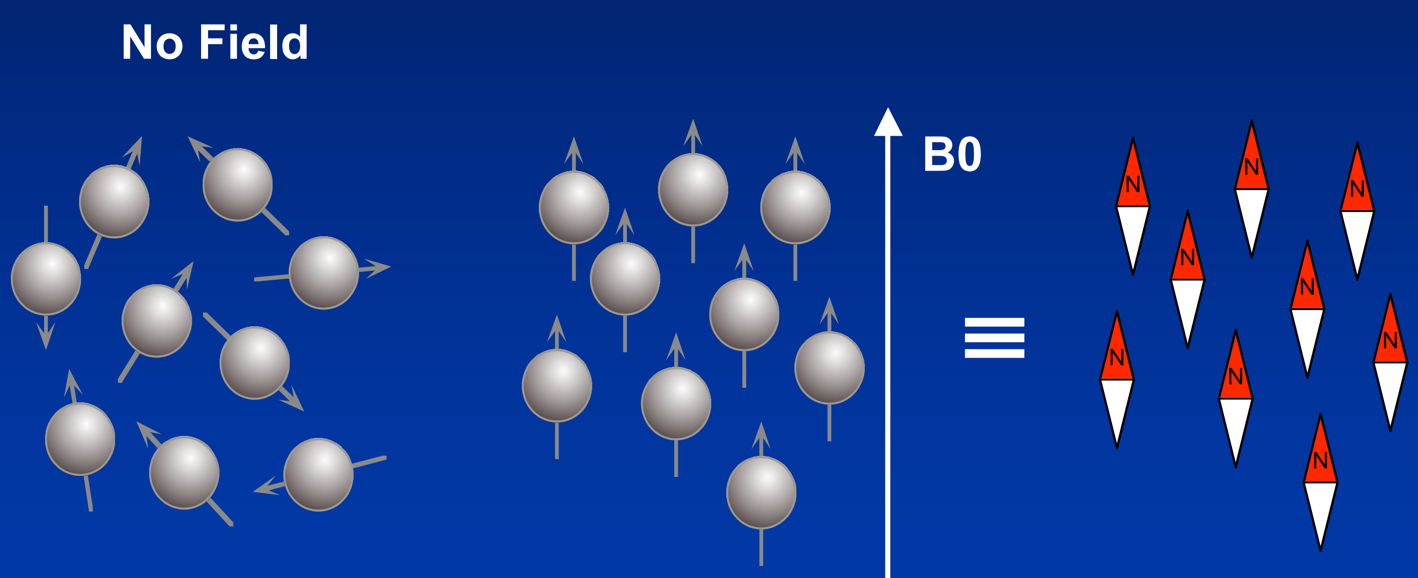
Spin

- Spin = nucleus with an odd number
  - protons
  - neutrons
  - both
- E.g. 1H, 13C, 23Na, 31P
- The nucleus has a positive charge
  - Spin + charge = current = magnetic moment



Spin Alignment I

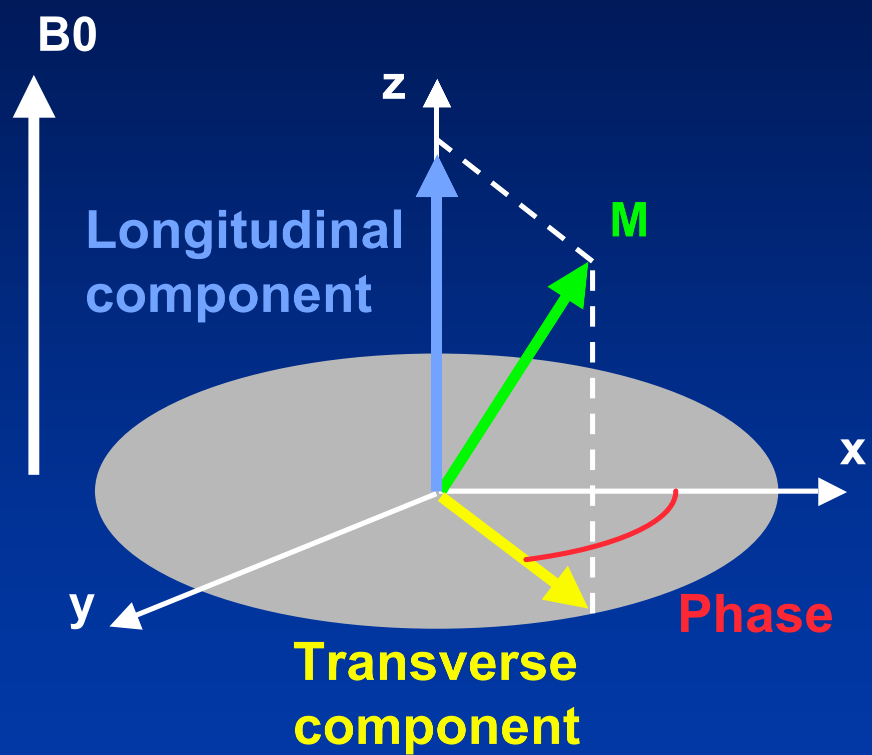
- No magnetic field – random
- External field, B0 – aligned (0.5T-15T *vs*. 0.00005T Earth)
  - cf. Compass needles



Spin Alignment II

- Room temperature, normal magnetic fields
  - Only small energy advantage in alignment
- Spins are jostled by molecular motions
  - Most spins are randomly oriented
  - Only about 1 in 10^5 spins are aligned
- No need for quantum mechanics
  - 10^{23} protons/g → 10^{18} aligned protons

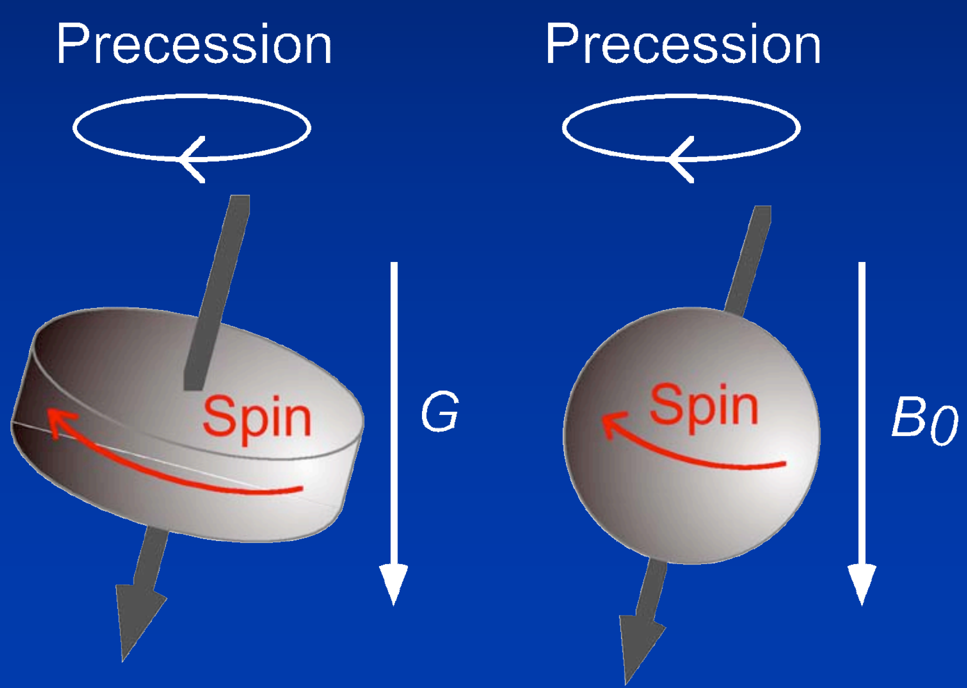
Magnetization Vector



- In general **net magnetic moment, M** is not aligned with B0
- Two components:
  - **Longitudinal** Parallel to B0
  - **Transverse** Perpendicular to B0
  - **Phase** Angle of $M_{Transverse}$

Precession

- Spins aligned with field don't do much
- Spins which are out of alignment with B0 **precess** about the direction of B0
- cf. gyroscope



- Spin
  - Fast
  - All the time
- Precession
  - Slower
  - Only when spins are out of alignment

Larmor Frequency

- Precession frequency is proportional to field strength
  Larmor equation:
  □ = □B0
- **Larmor frequency** – □
  - Hertz, Hz (cycles per second)
- **Static field strength** – B0
  - Tesla, T
- **Gyromagnetic ratio** – □
  - Hz / T

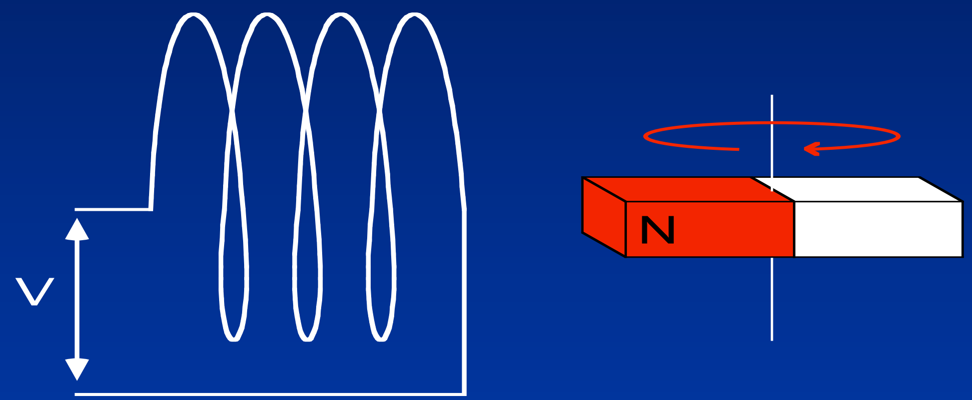
Larmor Frequency

Larmor frequencies lie in radiofrequency band

Nucleus	? / $MHzT^{-1}$	? / MHz (1.5 T)	? / MHz (7.05 T)
^{1}H	42.6	63.9	300
^{13}C	10.7	16.1	75.4
^{23}Na	11.3	16.9	79.7
^{31}P	17.2	25.9	121.3

NMR Signals

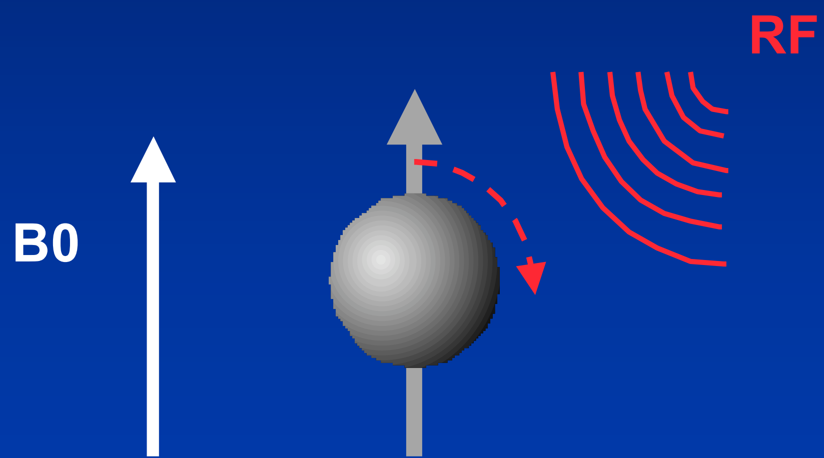
- Precession of net magnetic moment
  - Rotating magnetic field
  - Induces voltage in wire coil



- NMR signal = ac voltage at Larmor frequency

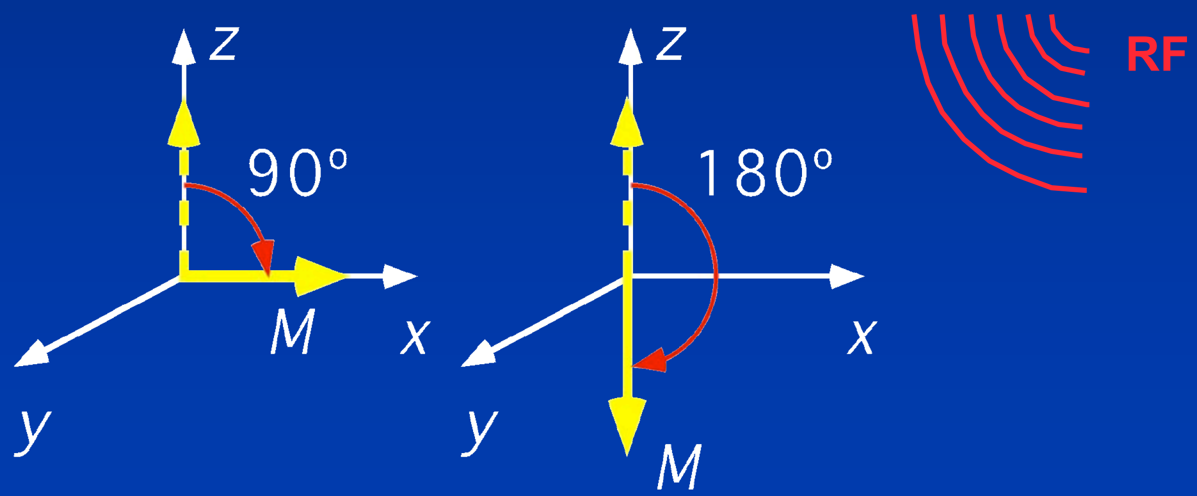
Excitation

- Apply magnetic field rotating at Larmor frequency
- Spins absorb energy (resonance)
- Tip out of alignment



Tip angles

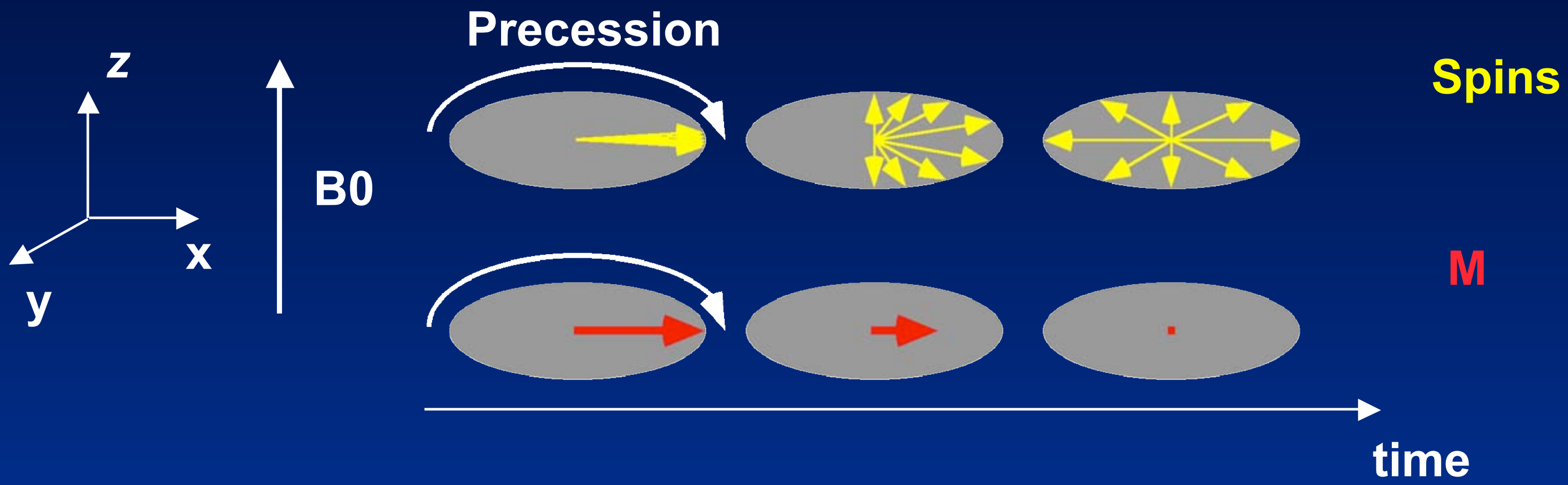
- Apply rotating magnetic field in short pulse
  - RF pulse
- Angle through which spins and M tip is determined by strength and duration of RF
- 90° and 180° pulses
- Tip angle is independent of initial orientation



Relaxation

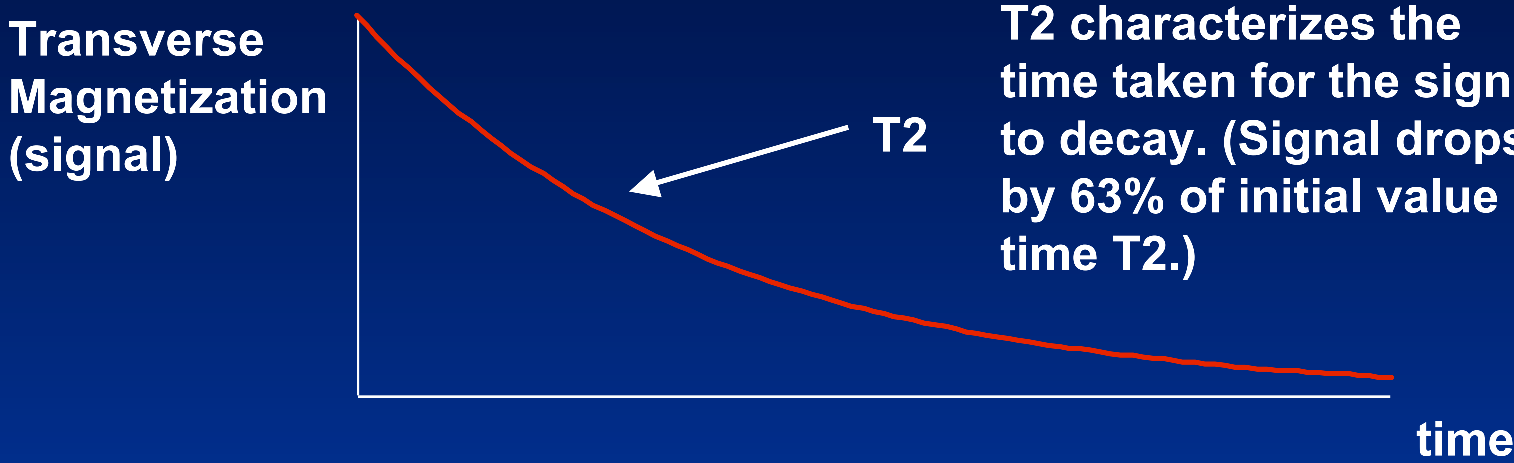
- After 90° pulse spins lie in transverse plane
  - Excited
- Relaxation is process by which excited spins return to equilibrium position in longitudinal direction
- Relaxation times
  - T1 (slow)
  - T2 (fast)

T2 Decay



- Initially spins **in phase** in transverse plane
  - Large M
- Random fluctuating fields due to molecular motion
  - Spins precess at different average frequencies
- Spins **dephase**
  - Transverse component of M decays

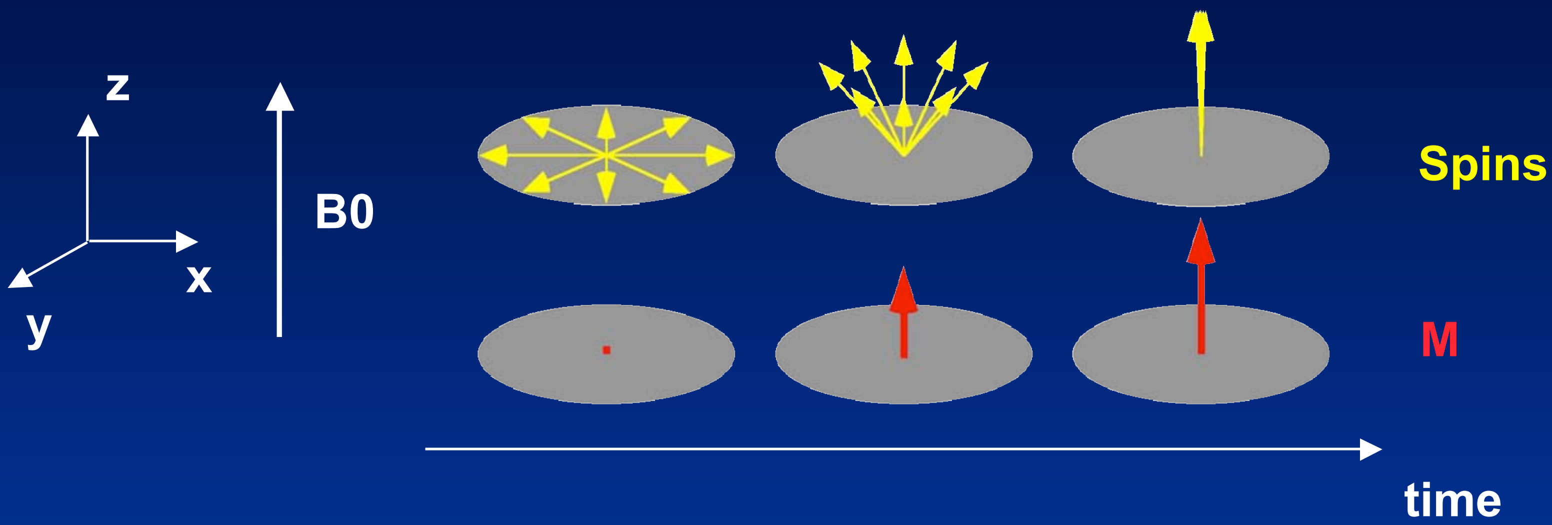
T2 Decay



T2 characterizes the time taken for the signal to decay. (Signal drops by 63% of initial value in time T2.)

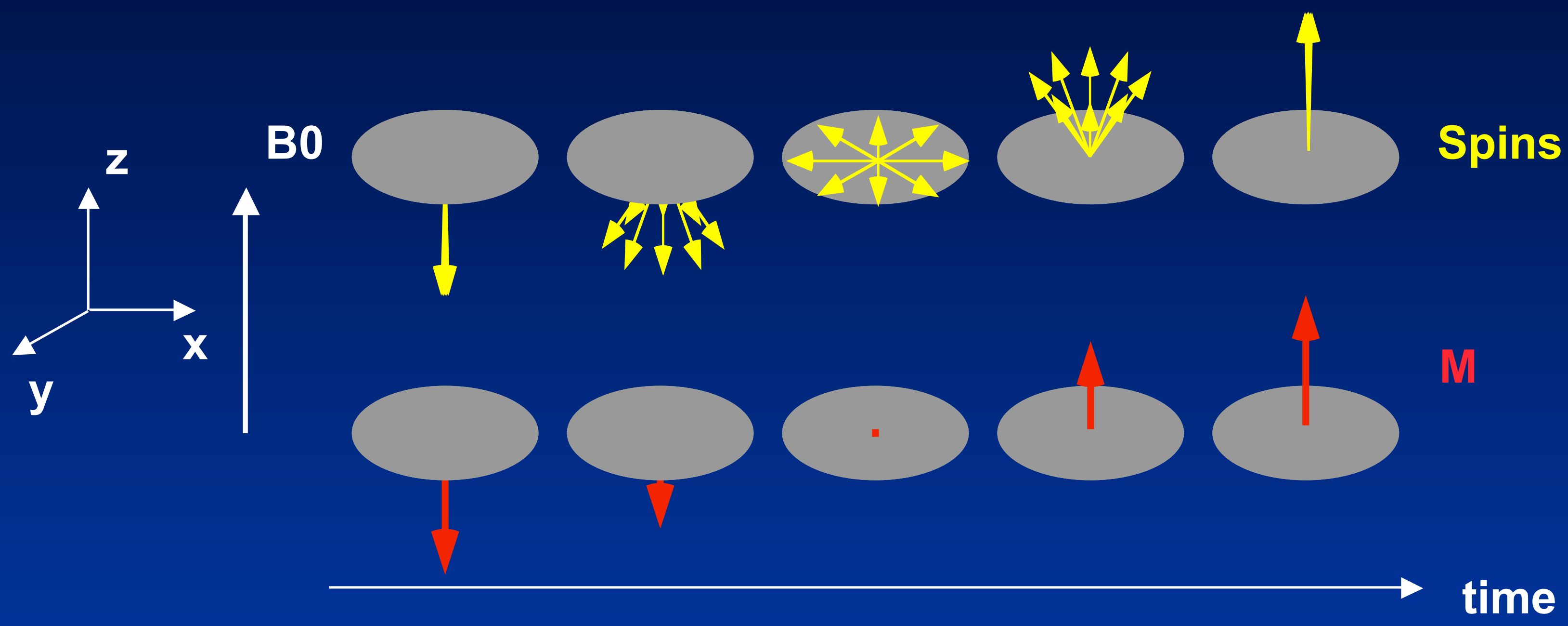
- Spins dephase
  - Exponential loss of transverse magnetization
  - Loss of signal
- Exchange of energy between spins
- T2 decay / relaxation
  - Transverse relaxation
  - Spin-spin relaxation

T1 Recovery



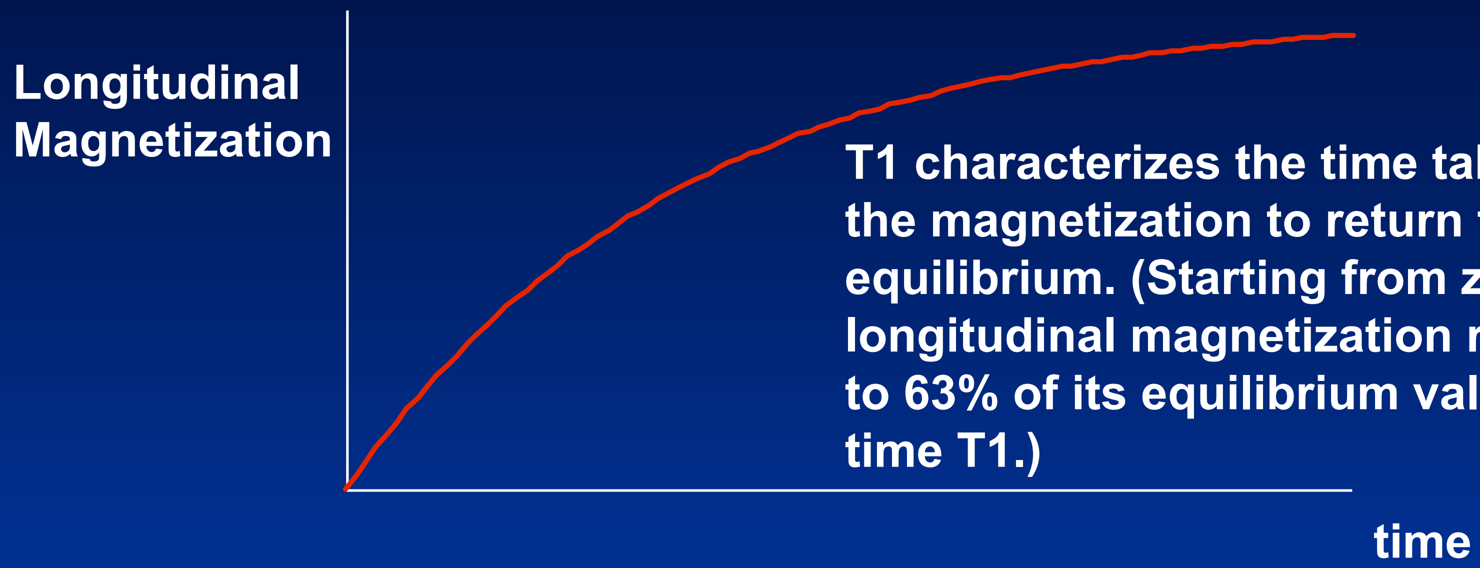
- After T2 decay
- Transverse magnetization completely dephased
  - M = 0
  - M still not in equilibrium position
- Spins lose energy and return to equilibrium
  - M grows along longitudinal direction

T1 Recovery After 180° Pulse



- Spins initially inverted
- M always longitudinal
- Never any transverse magnetization
  - No signal

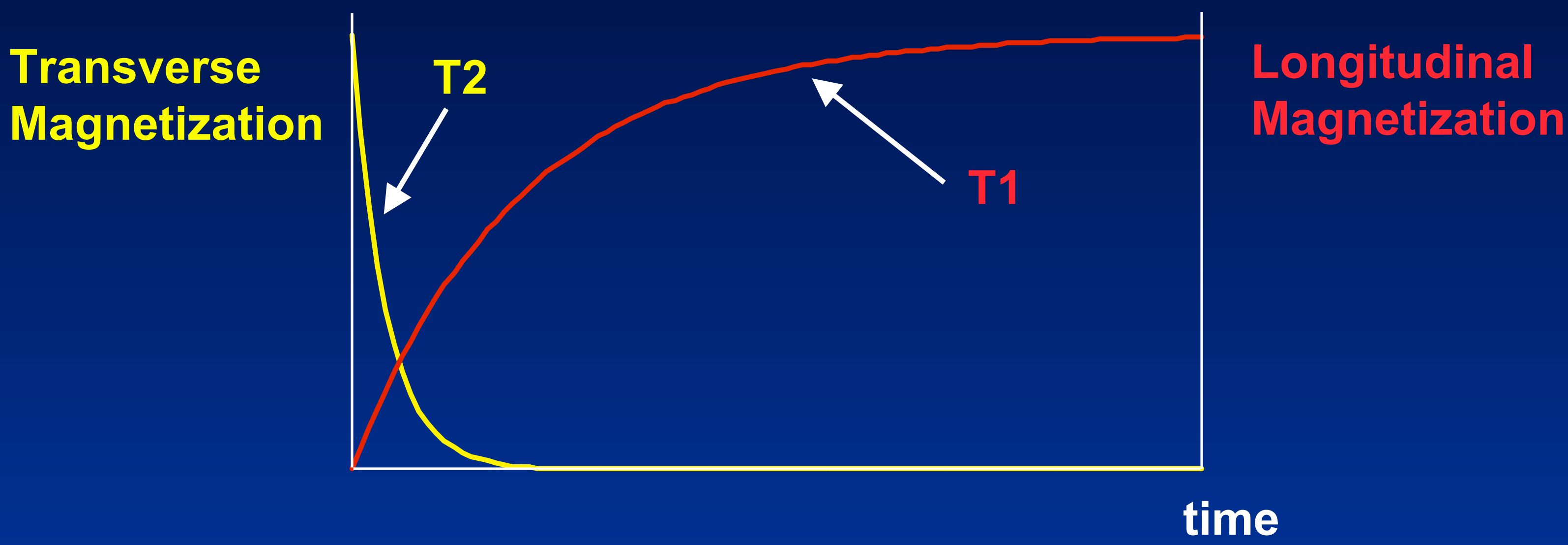
T1 Recovery



T1 characterizes the time taken for the magnetization to return to equilibrium. (Starting from zero, longitudinal magnetization recovers to 63% of its equilibrium value in time T1.)

- Spins recover towards equilibrium position
  - Exponential growth of longitudinal magnetization
- Loss of energy
- T1 recovery / relaxation
  - Longitudinal relaxation
  - Spin-lattice relaxation

T1 & T2



- T1 – recovery of longitudinal magnetization
- T2 – decay of transverse magnetization (signal)
- T1 and T2 relaxation occur simultaneously
- T1 is generally 5-10 x T2
  - Fluids can be exceptions

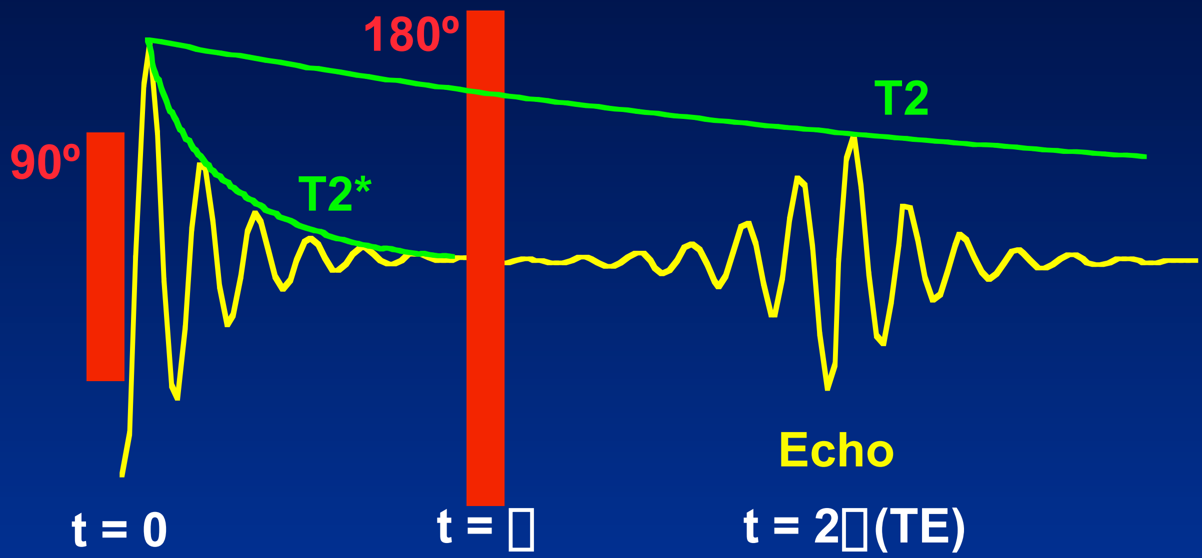
T2* Relaxation

- Random fluctuating magnetic fields
  - Spins see different field at different times
  - Spin dephasing
  - T2
  - Field difference varies with time
- Static field inhomogeneities due to imperfections in magnet (and tissue susceptibility differences)
  - Spins at different positions see different fields
  - Spin dephasing
  - T2*
  - Field difference is same at all times

Spin Echoes

- T2* leads to signal loss
  - Lower signal to noise ratio
  - Image intensity varies with position
- T2
  - Due to field differences that vary over time
- T2*
  - Due to constant field differences
- Can reverse T2* effects
  - Spin echo

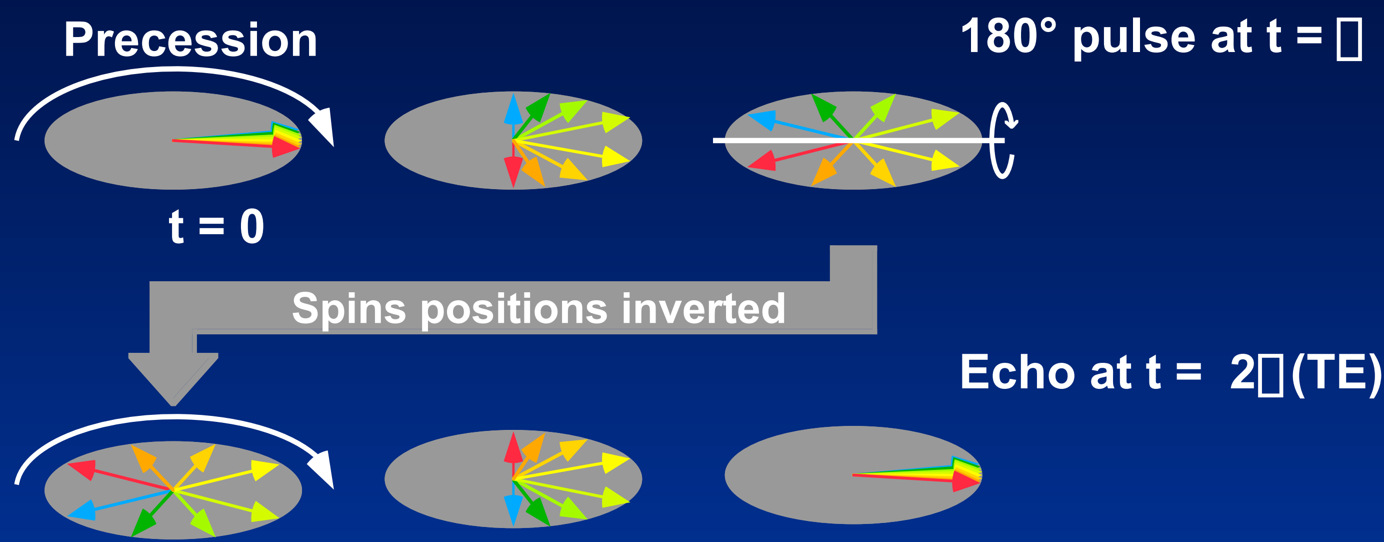
Spin Echo Pulse Sequence



- Signal immediately after 90° pulse decays as T2*
- 180° pulse at t = □ rephases the spins to form a **spin echo** at time t = 2□(TE)
- Echo amplitude decays as T2

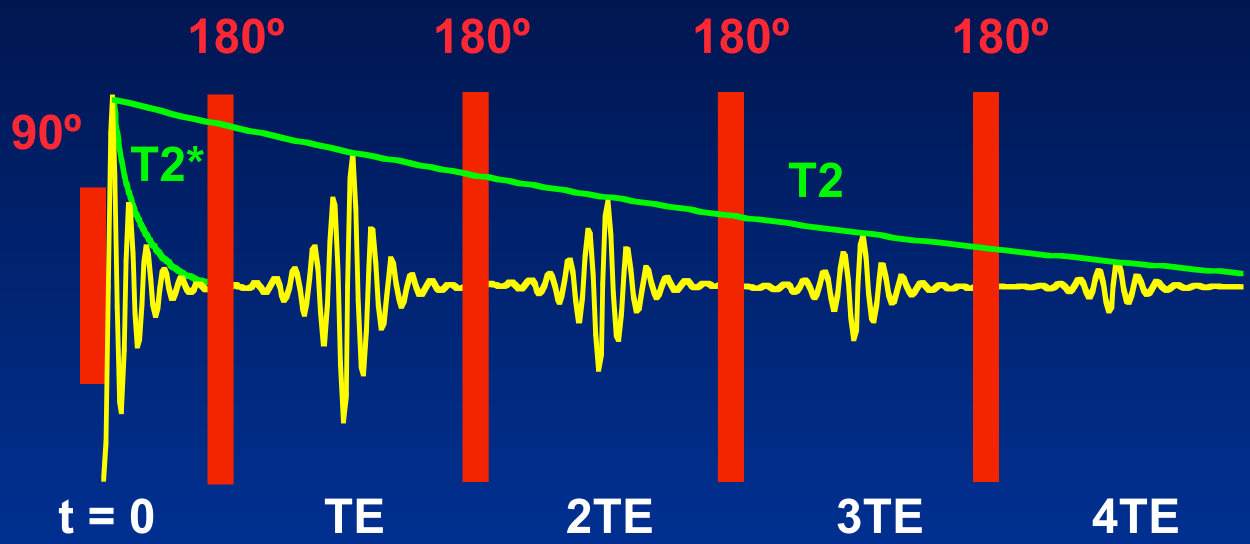
Spin Echoes

Red spins see a higher field than blue spins and precess faster



- Red spins precess faster than blue spins
  - Spins dephase
- 180° pulse reverses relative positions of spins
  - Spins rephase
- All spins in phase at t = 2τ
- Only reverses effects of static inhomogeneities

Multiecho Sequence



- Repeat 180° pulses
- Train of echoes
- Carr-Purcell-Meiboom-Gill (CMPG) sequence
  - Multi-echo sequence

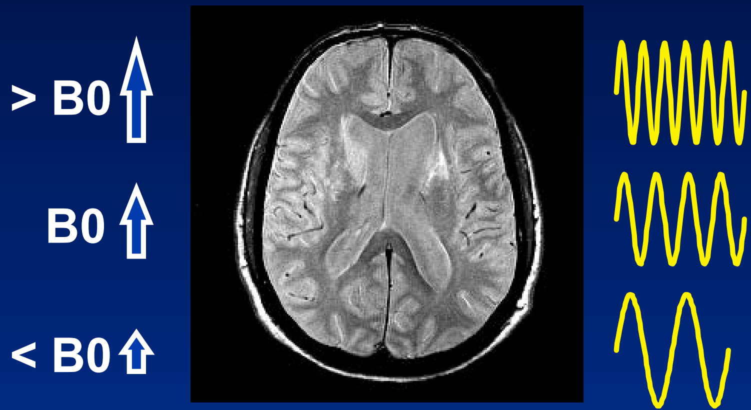
Summary: An NMR Experiment

- Place sample containing **spins** in magnetic field
- Spins align to give the **net magnetic moment**
- **Excite** spins with **RF pulse** at the **Larmor frequency**
- Spins tip out of alignment and **precess** at Larmor frequency
- Precession of net magnetic moment induces voltage in coil – NMR signal
- Signal decays with time **T2***
- (Rephase spins with 180° pulses to form **spin echoes** which decay with time **T2**)
- Spins return to equilibrium with time **T1**

Uniform Field

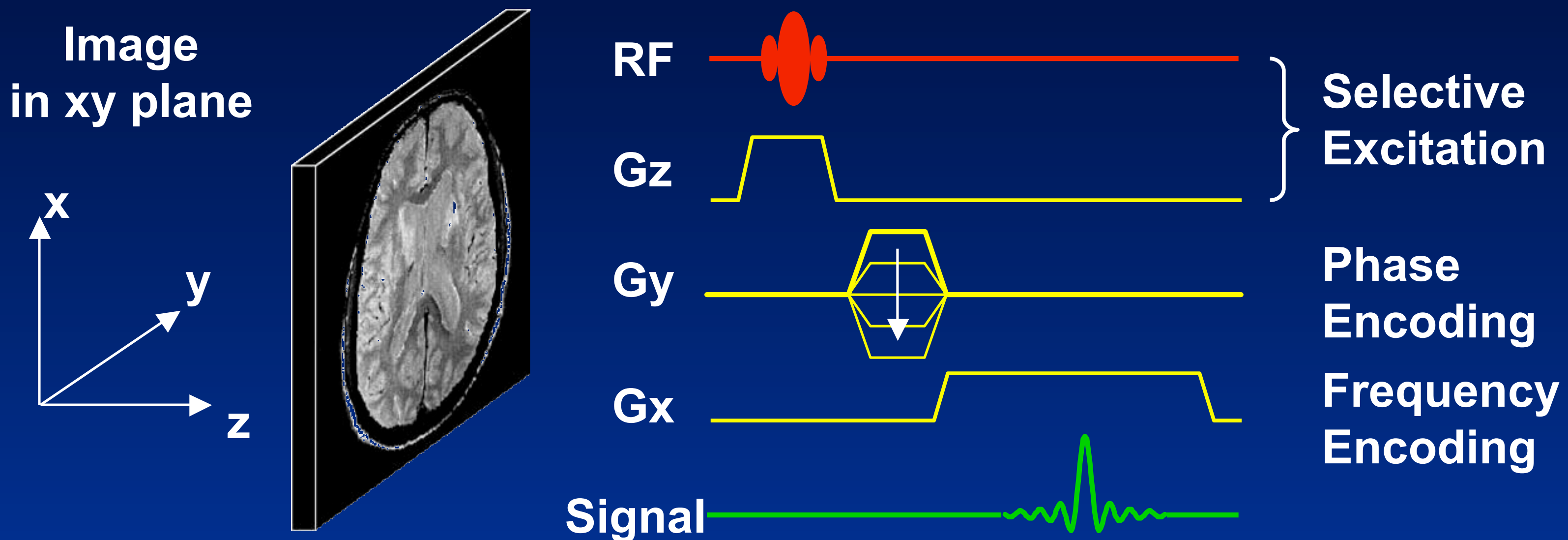
- **Larmor equation**
  - $\omega = \gamma B0$
- **Uniform B0 field**
  - **All spins see the same field**
  - **Resonate at the same frequency**

Static Field Gradients



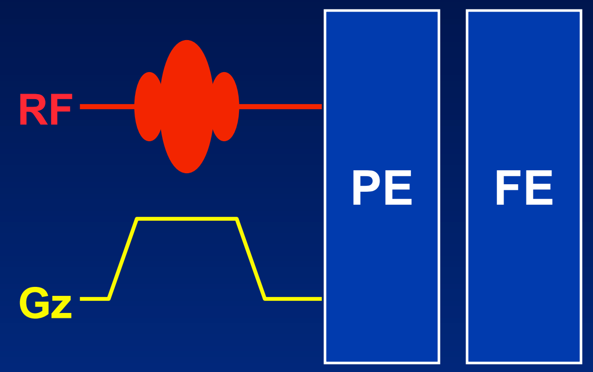
- Gradients modify field strength depending on position
- With gradient
  - Spins at the top see a higher field
  - Spins at the top resonate at a higher frequency
- Apply in three directions

2DFT Imaging



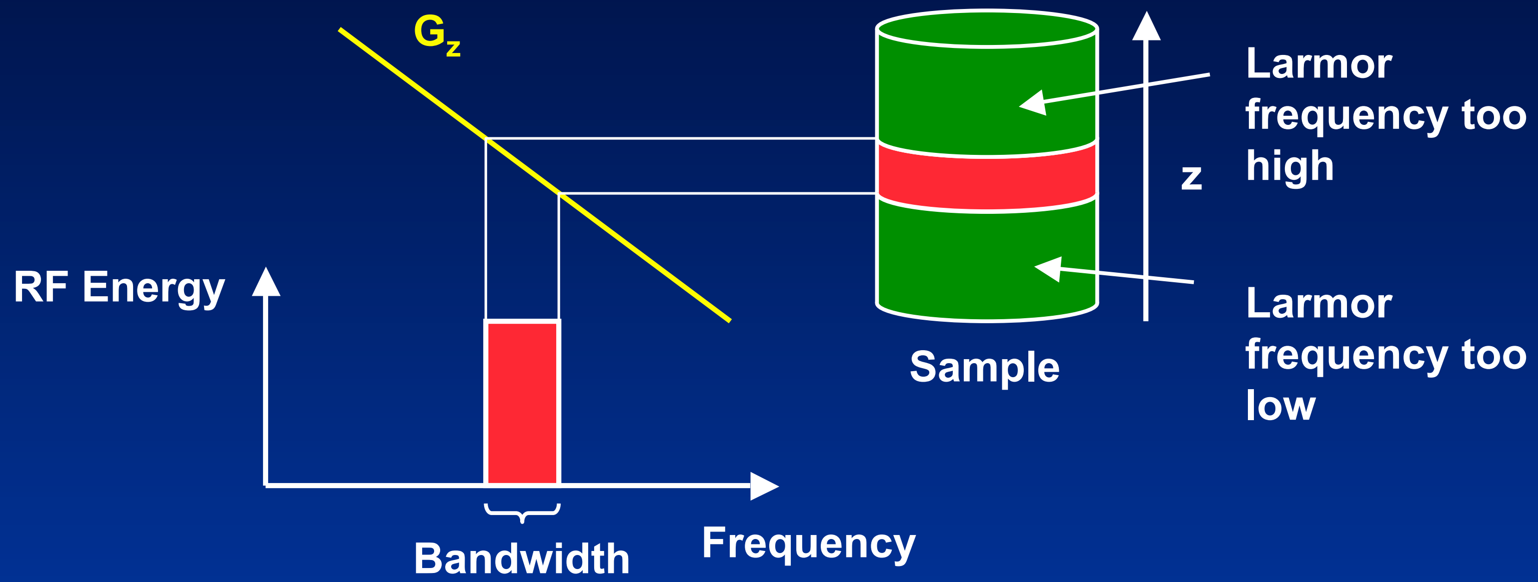
- Selectively excite slice in presence of G_z
- Phase encode with G_y pulse
- Frequency encode with G_x and acquire NFE samples
- Repeat with different phase encoding pulse amplitudes

Selective Excitation I



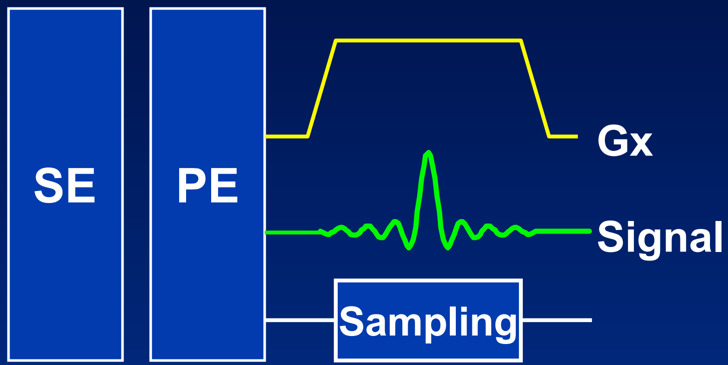
- RF pulse in presence of gradient G_z
- Before phase encoding and frequency
- Excites signal in a narrow slice only
- Selective excitation (slice selection)
- 90° or 180° pulses

Selective Excitation



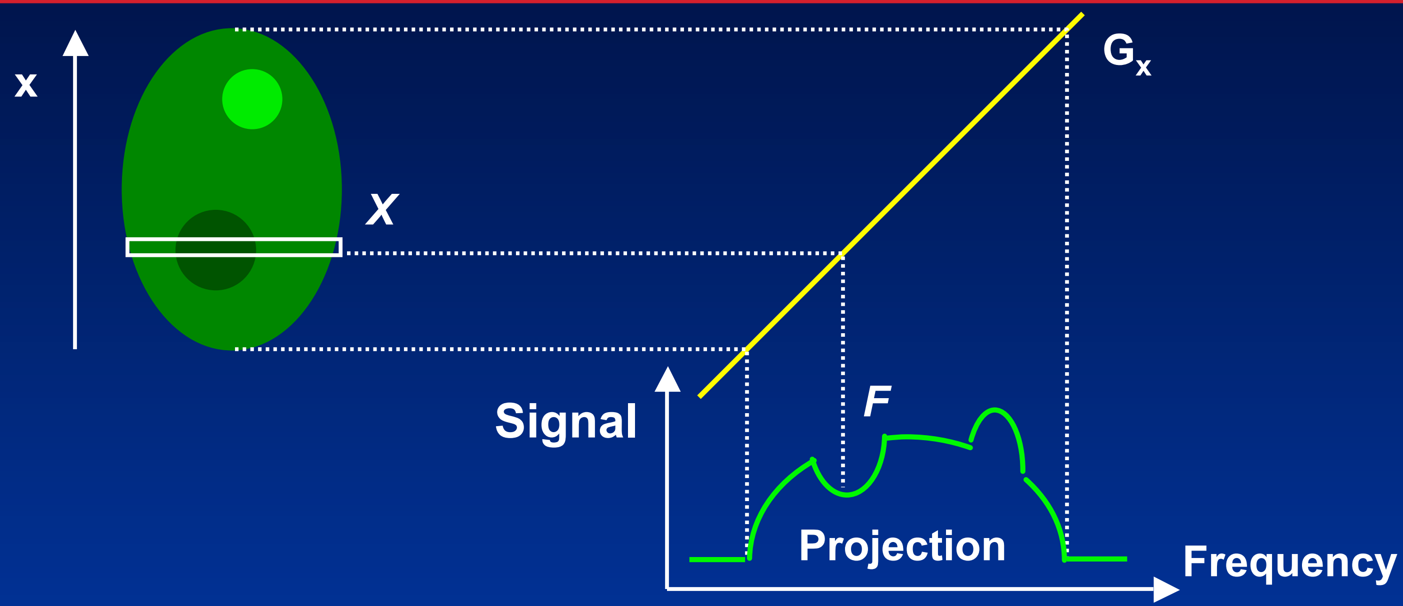
- Pulse contains narrow range of frequencies (bandwidth)
- Gradient maps frequency onto position
- Bandwidth corresponds to narrow slice in sample
- Only spins within slice are tipped

Frequency Encoding



- Occurs after selective excitation and phase encoding
- Data sampling in presence of G_x (readout gradient)
- Gives one dimensional projection of object

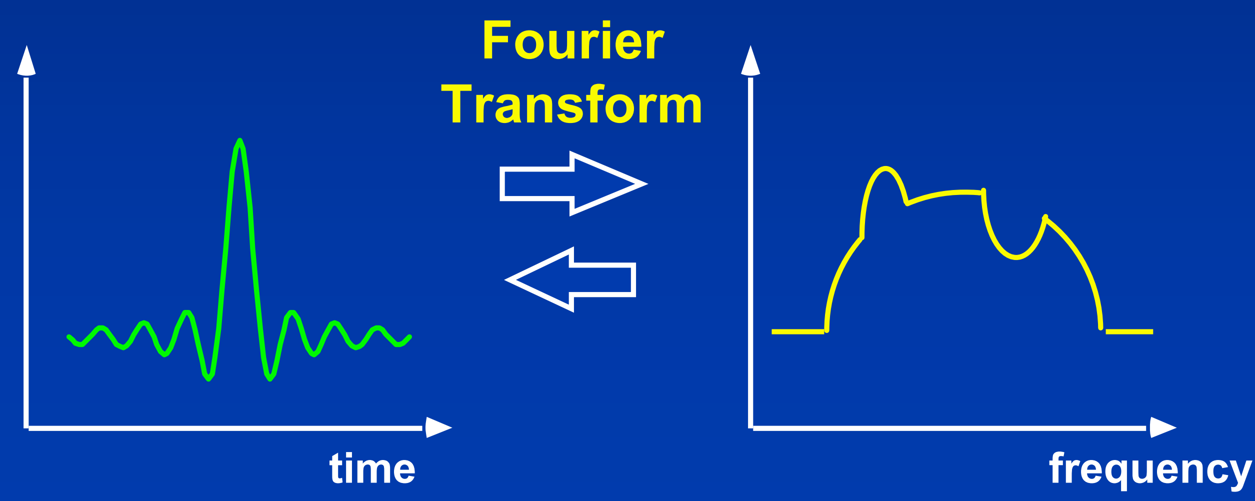
Frequency Encoding



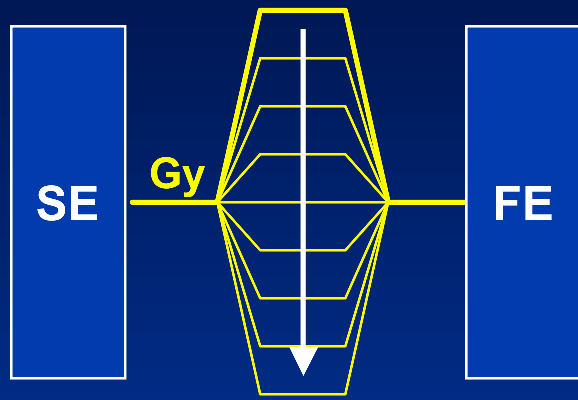
- Gradient maps position onto frequency
  - Larmor frequency position
- Signal at frequency *F* total number of spins in column at *X*
- Plot of signal against frequency is 1D projection of sample

The Fourier Transform

- Projection
  - Signal vs. frequency
- Measured signal
  - Signal vs. time
- The Fourier transform translates between time and frequency

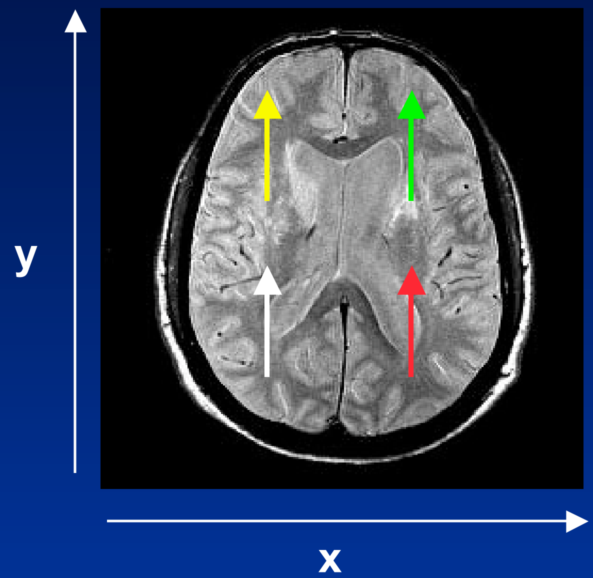


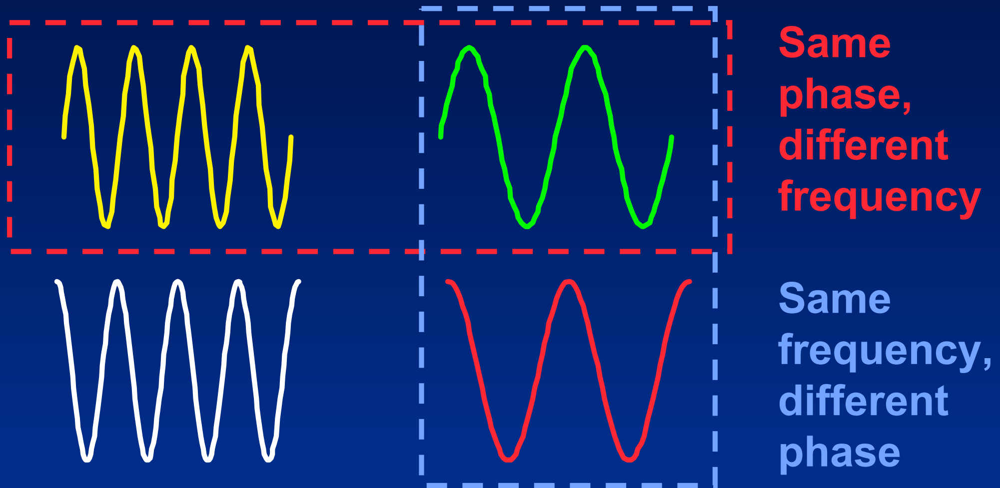
Phase Encoding



- Short phase encoding pulse applied between selective excitation and frequency encoding
- During pulse Larmor frequency   position
- After pulse phase   position

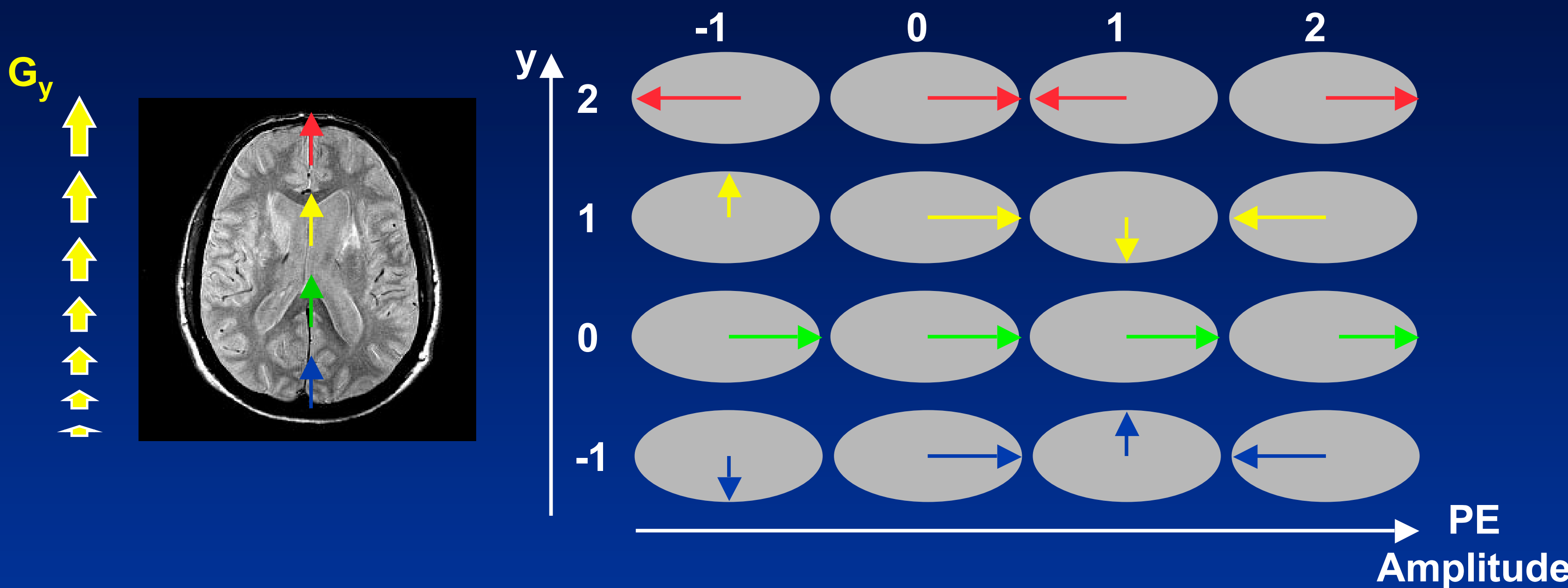
Frequency and Phase Encoding





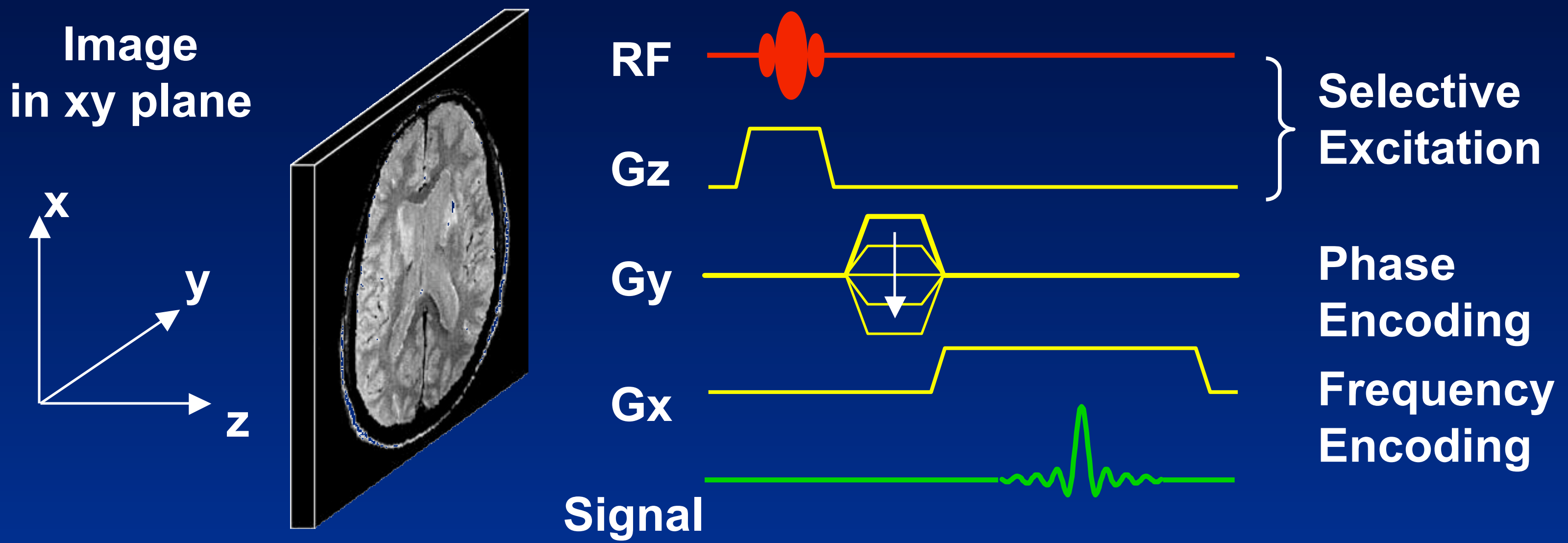
- All spins at same x position resonate at same frequency
- Encode phase of spins with y position
- Signal is vector sum of all spin magnetization
  - Requires multiple phase measurements

Phase Encoding of Four Spins



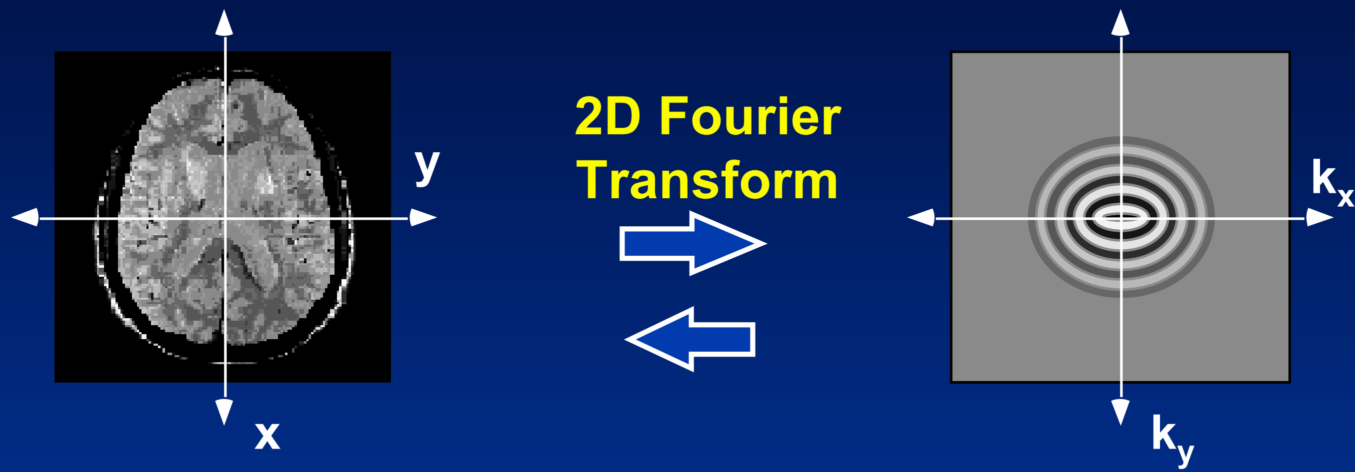
- PE = 0: No phase shift at any position
- PE = 1: y = 1, phase = 90°; y = 2, phase = 180°; etc
- PE = 2: y = 1, phase = 180°; y = 2, phase = 360°; etc
- “Pseudo-precession”: frequency position
- Fourier transform -> spatial projection

2DFT Summary



- **Selectively excite** slice in presence of G_z
- **Phase encode** with G_y pulse
- **Frequency encode** with G_x and acquire multiple samples
- Repeat with different phase encoding amplitudes
- 2D Fourier transform gives image

Spatial Frequency - K-space



- The Fourier domain paired with real space is "k-space"
- Coordinates of real space = cm
- Coordinates of k-space = cycles/cm
- MRI data are acquired directly in k-space

Why is K-space Relevant?

Fourier transform of NMR signal distribution, *s(x)*

$$S(k) = \int s(x)\exp(-i2\pi kx)\,dx$$

MRI time signal derived from same NMR signal distribution, *s(x)*

$$S(t) = \int s(x)\exp(-i2\pi A(t)x)\,dx$$

where *A*(*t*) is the area of Gx at time *t*

- **Formally identical**
- **Each signal sample has a well defined k-space coordinate**
  - **A phase encoding G_y pulse moves us to a particular k_y coordinate**
  - **A G_x frequency encoding gradient scans a line of k_x values**

Raw Data

Raw data before processing (k-space)

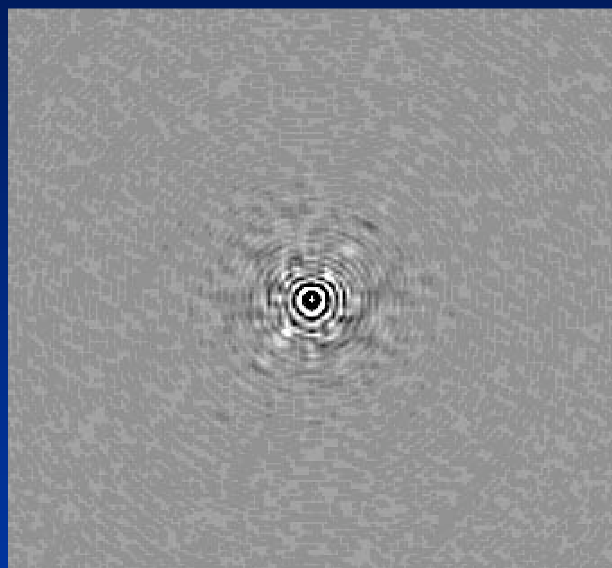
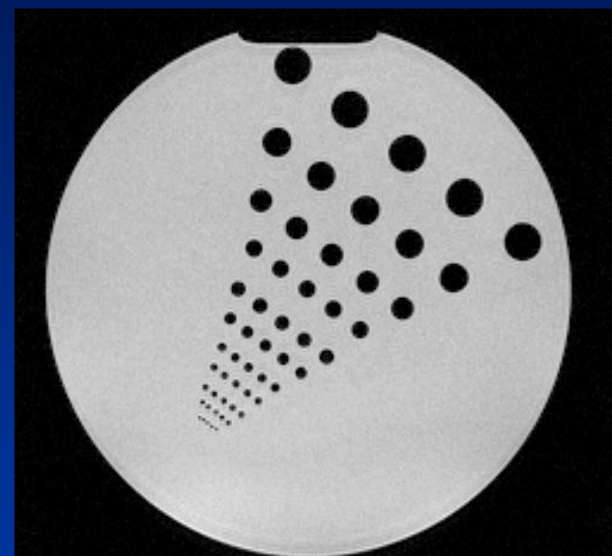
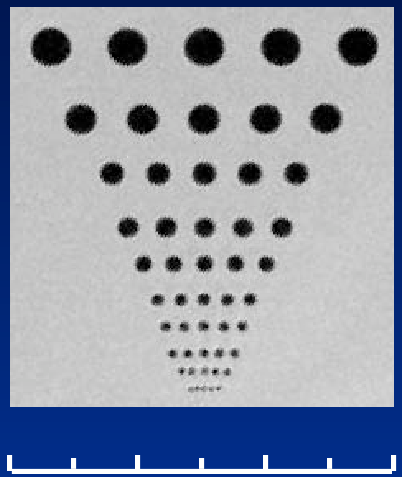


Image – 2D FT of raw data (Real space)



- K-space sample
  - Does not correspond directly to a particular position in real space
  - Contains information from entire object

K-space and Spatial Resolution I

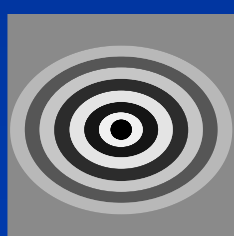


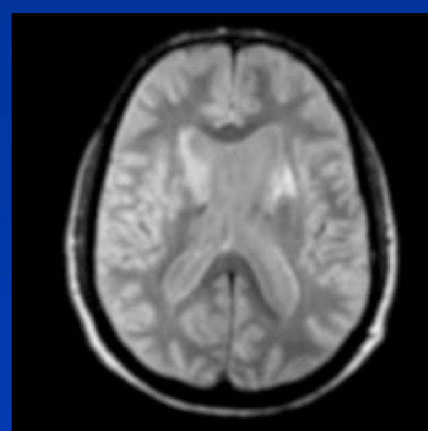
- K-space coordinates are measured in
  - cycles per cm
  - equivalent to “objects per cm”
- Low k-space coordinates
  - Small number of objects per cm
  - i.e., large objects
- High k-space coordinates
  - Large number of objects per cm
  - i.e., small objects
- High k-space samples contain information on small objects and edges

K-space and Spatial Resolution II

- Resolution determined by extent of sampling in k-space

Large area of k-space
Good resolution
(More samples)



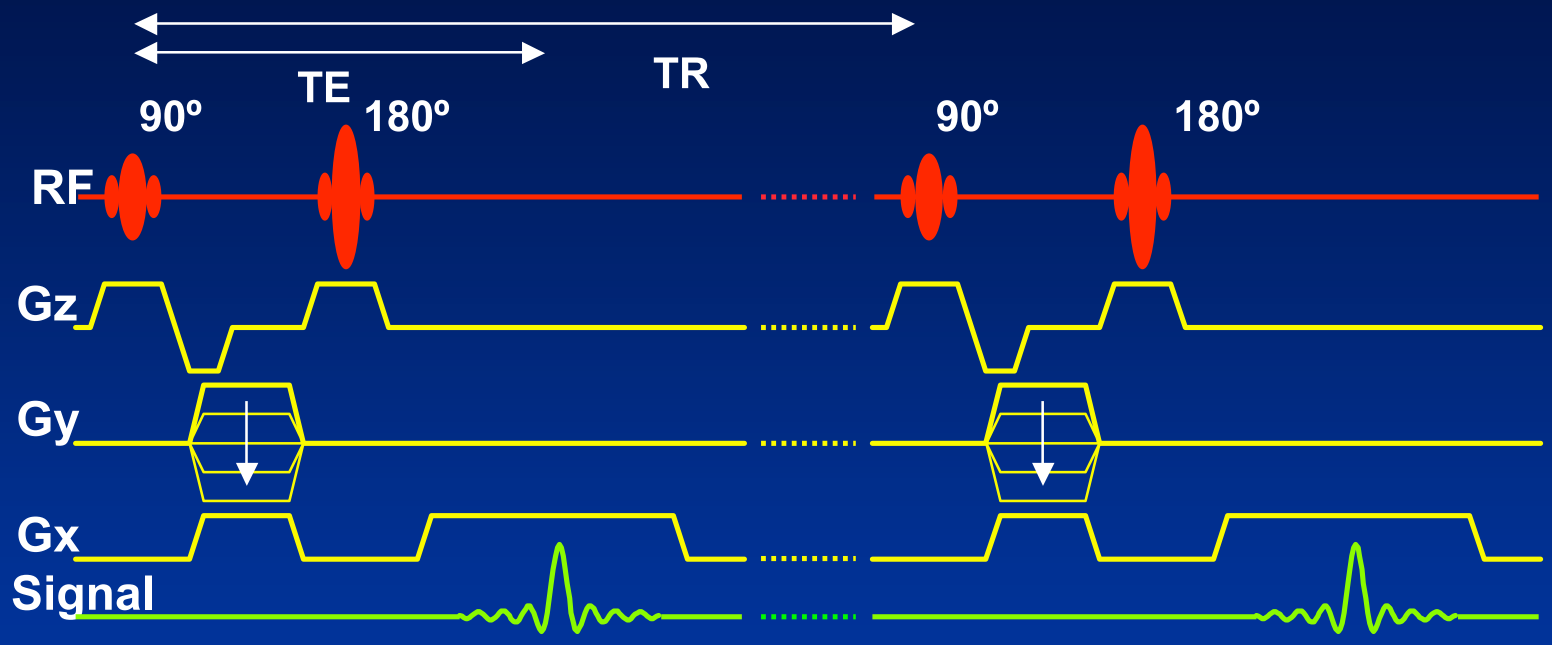


Small area of k-space
Poor resolution
(Fewer samples)

Contrast

- Contrast – difference in image intensity between different tissues
- Modify 2DFT sequence to emphasize differences in tissue parameters
  - “Weighting”
- Spin echo sequences
  - T1 weighted
  - T2 weighted
  - Proton density weighted

Spin Echo Sequence Parameters



- **TE: Echo time**
  - **Interval between 90° pulse and data collection**
- **TR: Repetition time**
  - **Interval between consecutive 90° pulses**

How to Increase SNR

- Increase voxel size
  - Increase slice thickness, FOV
  - Decrease number of phase or frequency encoding steps
- Increase TR
  - Decreases saturation
- Decrease TE
  - Decreases signal decay
- Increase number of averages, N_{EX}

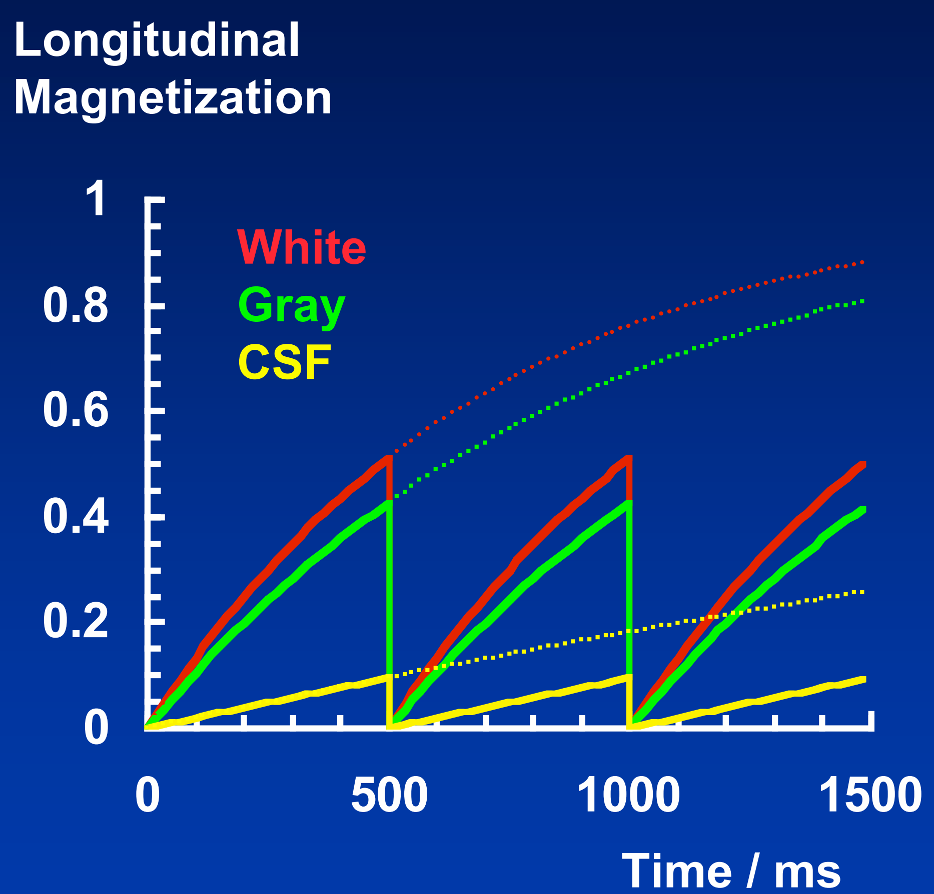
Spin Echo Contrast Mechanisms

- Two mechanisms
- Saturation
  - T1 effect
- Signal decay
  - T2 effect

Saturation I

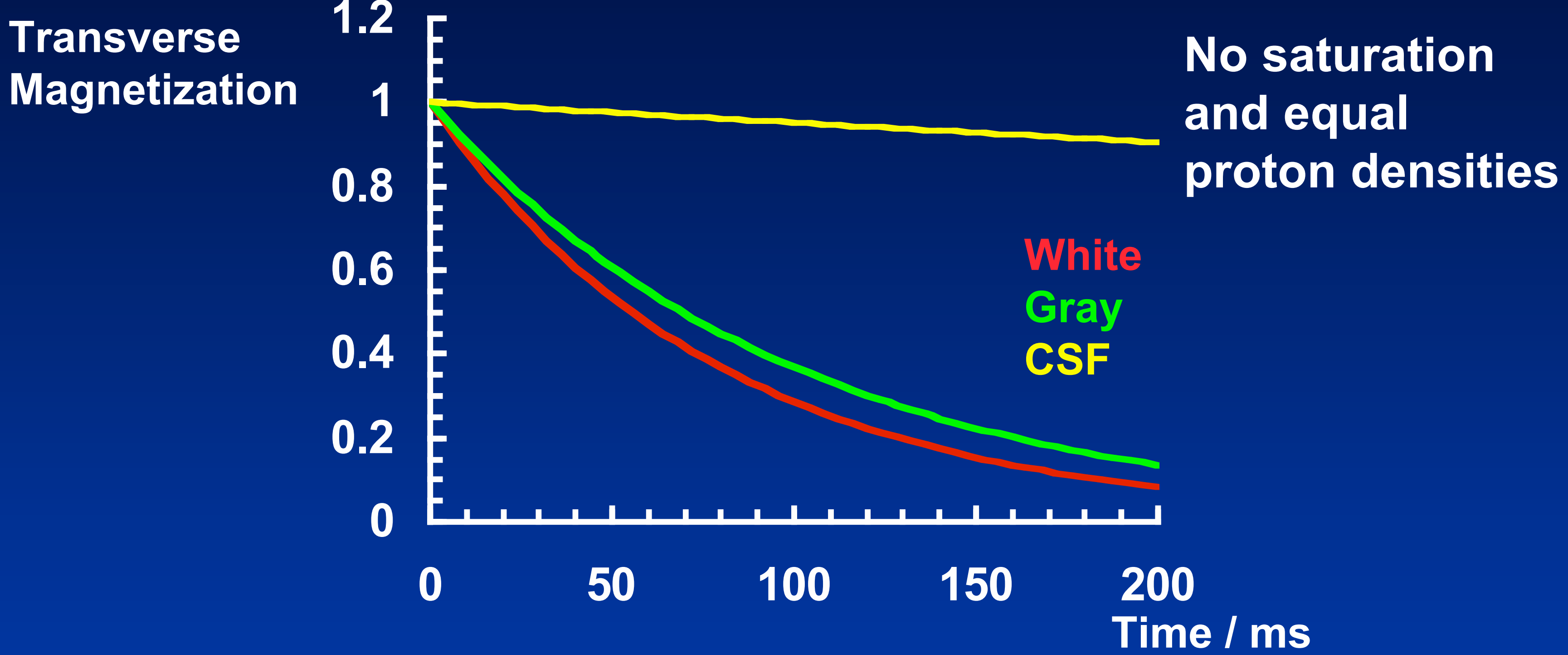
- At start of sequence 90º pulse tips longitudinal magnetization into transverse plane
  - Longitudinal magnetization zero
- Recovers with T1
- Before equilibrium reached, the next 90° pulse again tips recovered longitudinal magnetization into transverse plane
- Magnetization never allowed to return to equilibrium
  - “Saturation”
  - Signal loss
  - Long T1 => more saturation

Saturation II



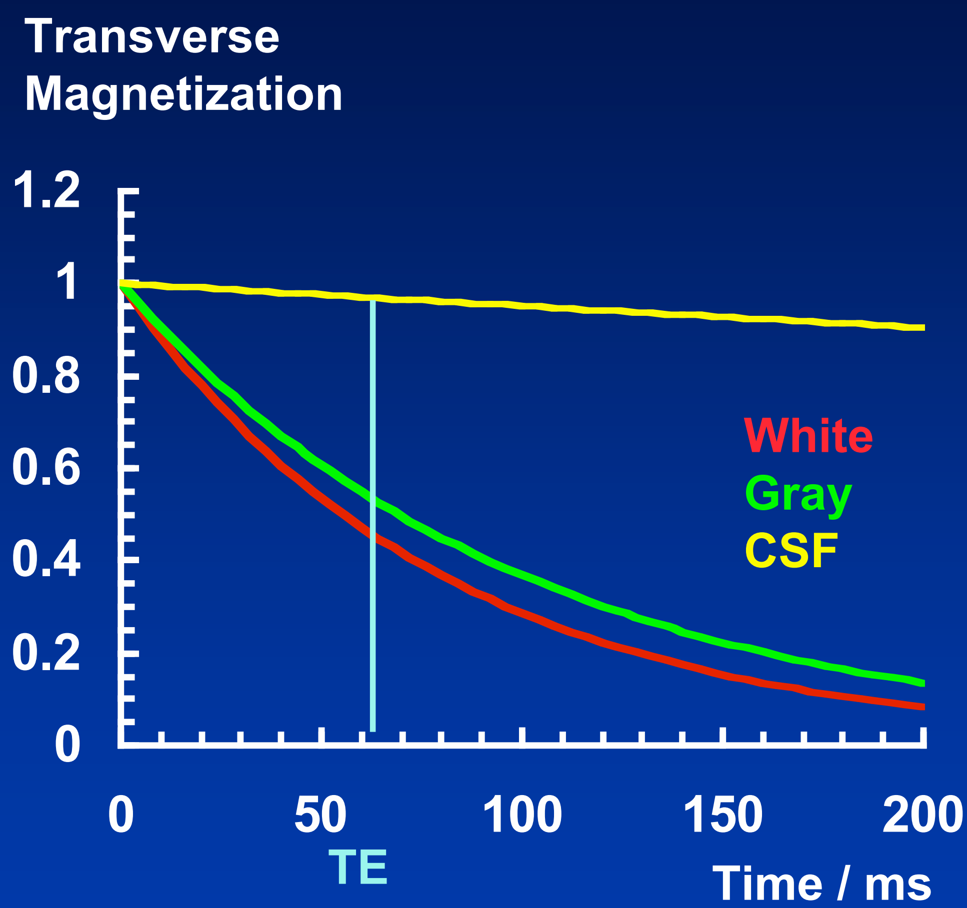
- White matter
  - Short T1
  - Recovers rapidly
  - Large signal
- CSF
  - Long T1
  - Recovers slowly
  - Small signal

Signal Decay I



- 90º pulse tips spins into transverse plane
  - Signal generated
- Signal decays with T2

Signal Decay II



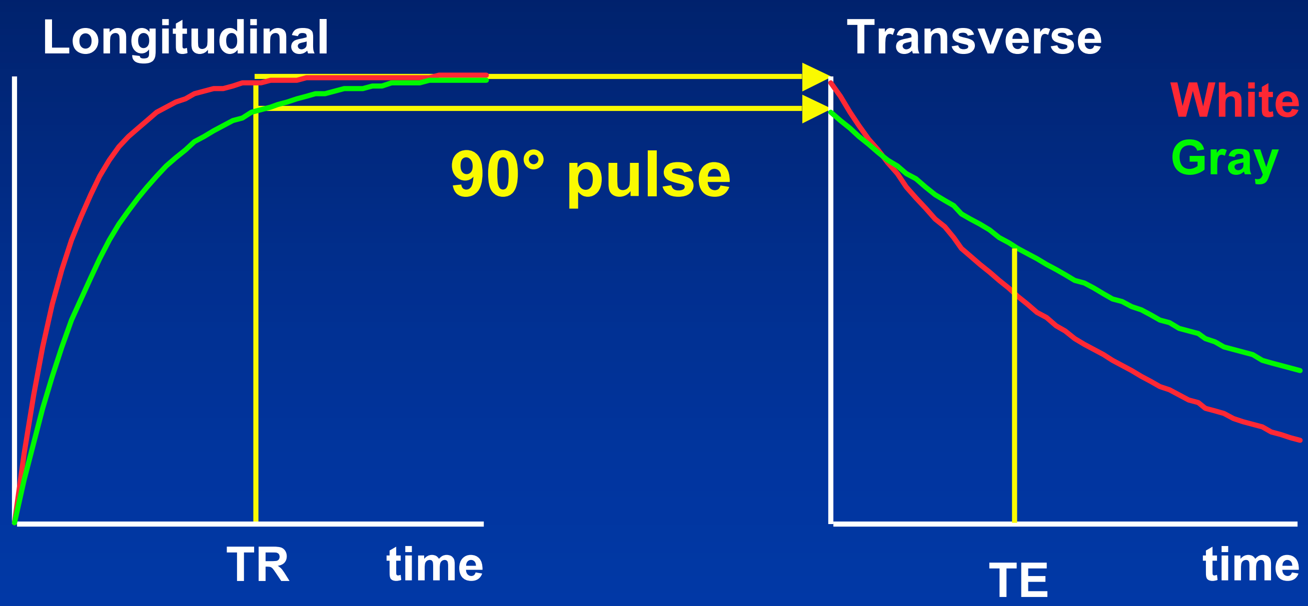
- Read signal at TE
- White matter
  - Short T2
  - Signal decays quickly
  - Lower signal
- CSF
  - Long T2
  - Signal decays slowly
  - Higher signal

Contrast Mechanisms

- Saturation
  - Longitudinal magnetization
  - Function of T1, TR
  - Decreased signal with long T1s
  - Minimized with long TR
- Decay
  - Transverse magnetization
  - Function of T2, TE
  - Increased signal with long T2s
  - Minimized with short TE

Spin Echo Contrast Diagram

- Contrast is a function of saturation and signal decay
- Contrast depends on relative size of effects

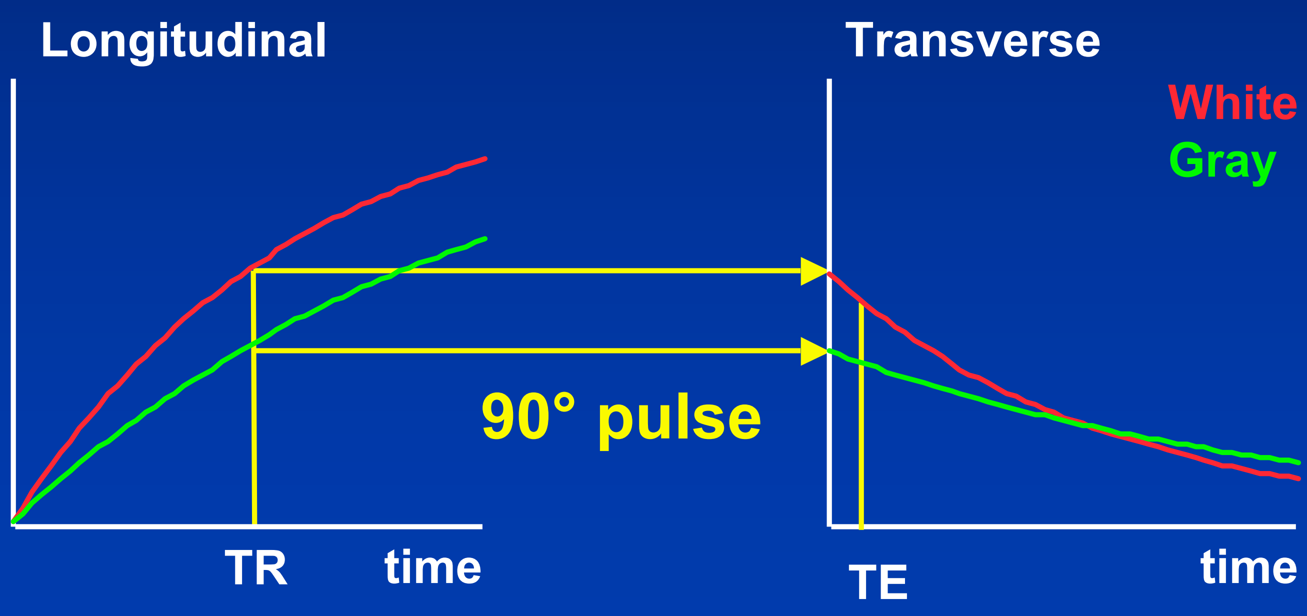


LHS: Recovery of longitudinal magnetization

RHS: decay of transverse magnetization

T1 Weighting

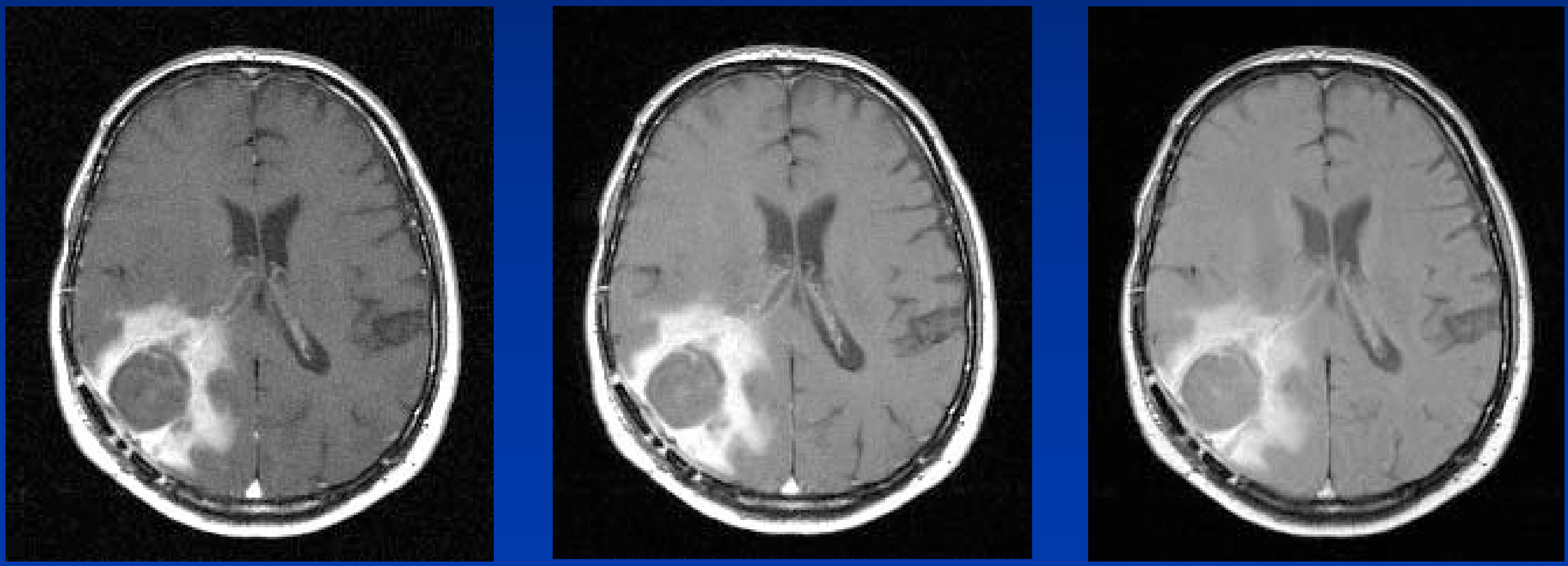
- Short TR (~T1, 500 ms)
  - Significant saturation – signal dependent on T1
- Short TE (< T2, 20 ms)
  - Negligible decay – signal independent of T2
- Short relaxation time tissues bright



T1 Weighted Spin Echo Images

- Short TR, short TE
- Short relaxation time tissues bright
- Contrast fine tuned by TR

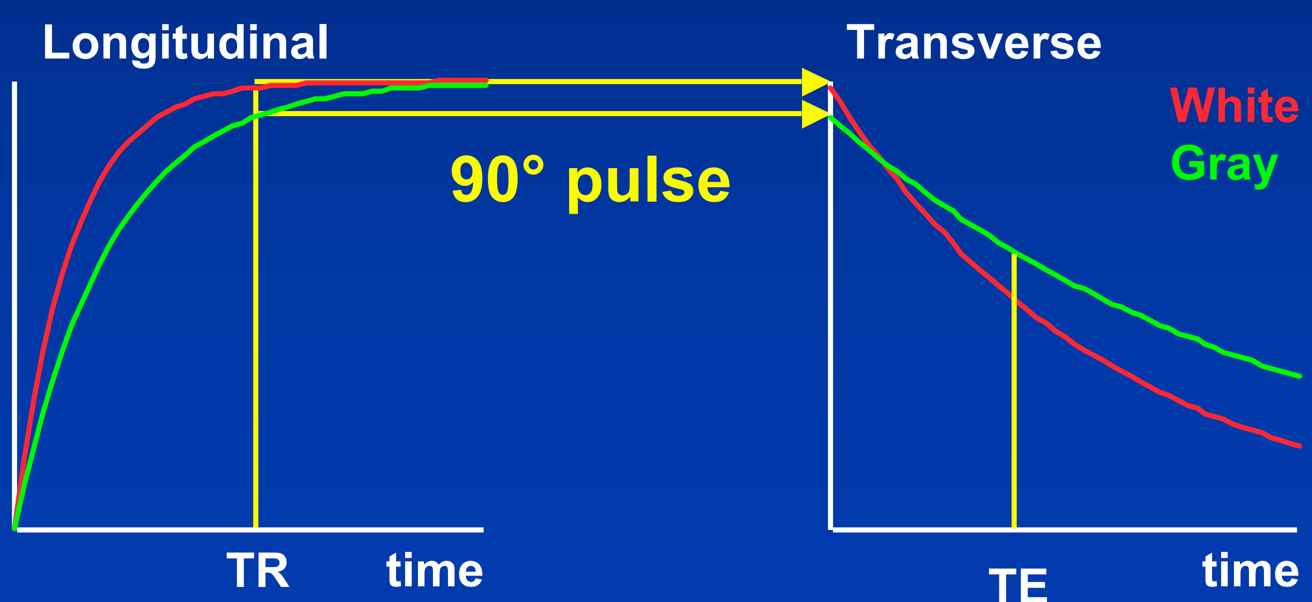
TR = 300 ms   TR = 600 ms   TR = 1200 ms



TE = 12 ms

T2 Weighting

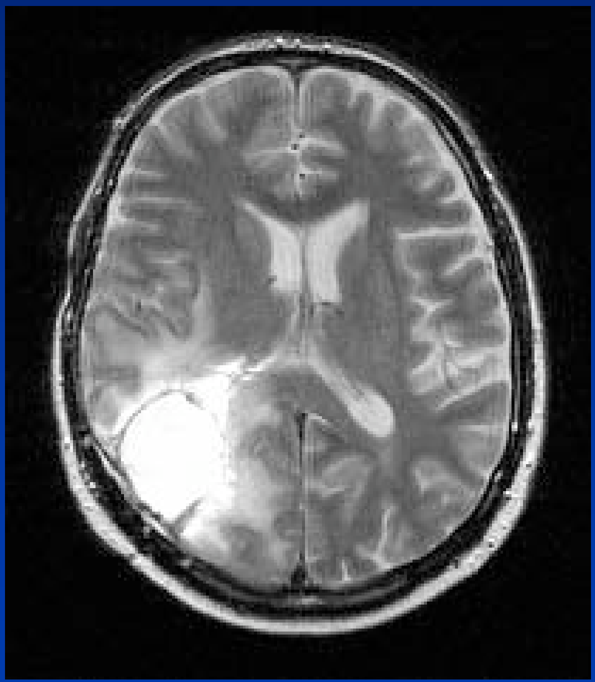
- Long TR (>> T1, >2000 ms)
  - Minimizes saturation – signal independent of T1
- Long TE (~T2, 100 ms)
  - Significant decay – Signal highly dependent on T2
- Long relaxation time tissues bright



T2 Weighted Images

- Long TR, long TE
- Long relaxation time tissues bright
- Contrast fine tuned by echo time

TE = 75 ms



TE = 135 ms

TR = 3000 ms

Spin Echo Contrast Summary

		TR	
		Short (T1 weighting)	Long (Little T1 weighting)
TE	Short (Little T2 weighting)	T1 weighted	(Proton density weighted)
	Long (T2 weighting)	Little contrast*	T2 weighted

* T1 and T2 contrast cancel