

The Magnetic Resonance Phenomenon

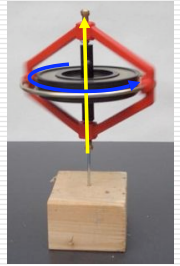
Mark Cohen

UCLA Brain Mapping Division

Departments of Psychiatry, Neurology, Radiology, Psychology,
Biomedical Physics. Biomedical Engineering

Nuclear Spin

- “Spin” is a property of many particles. It is a type of angular momentum.
- Angular momentum is a vector quantity.
- Quantum properties prohibit knowing both magnitude *and* three-dimensional orientation. We *can* know both the z-component and magnitude.

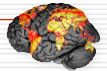


$$\mathbf{S} = \hbar\sqrt{s(s+1)}, \text{ where } s = \{0, \frac{1}{2}, 1, \frac{3}{2}, 2, \dots\}$$



$$\hbar = 1.0546 \times 10^{-34} \text{ J}\cdot\text{s}$$

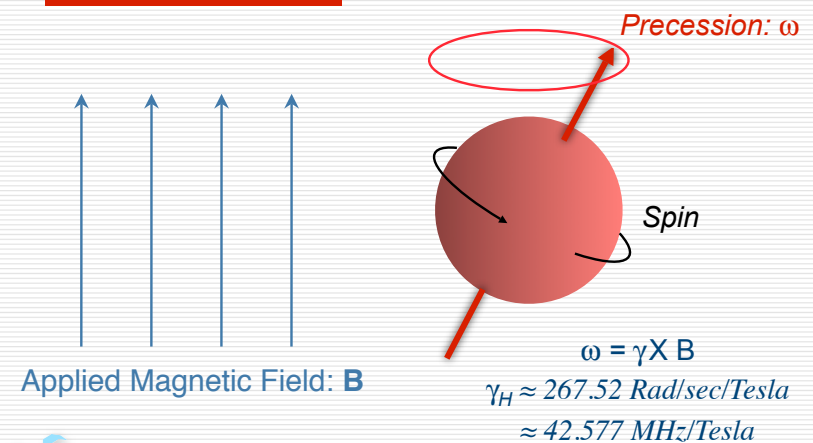
©2007 Mark Cohen, all rights reserved



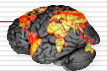
Spin States

- A Spin 1/2 particle has two states (“up/down”, “1 and 2”, α/β)
- In a magnetic field, B_0 , the two states have different energies

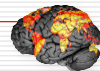
Proton Precession



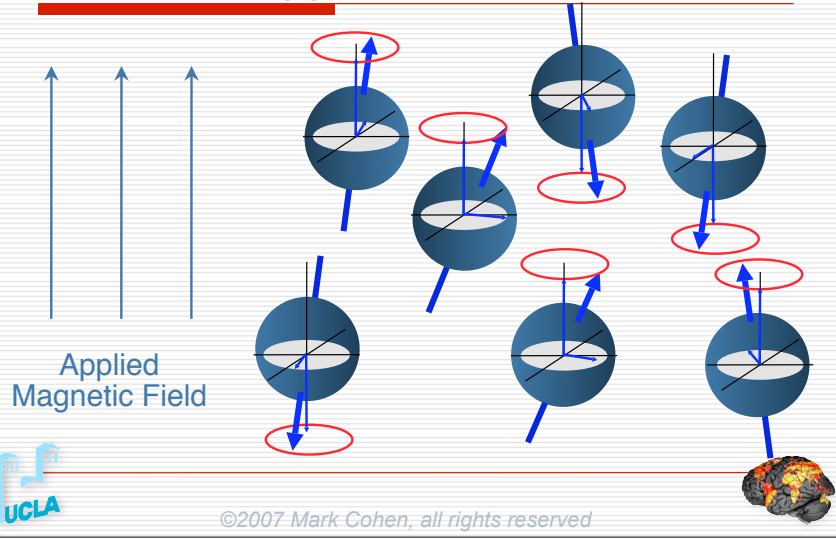
©2007 Mark Cohen, all rights reserved



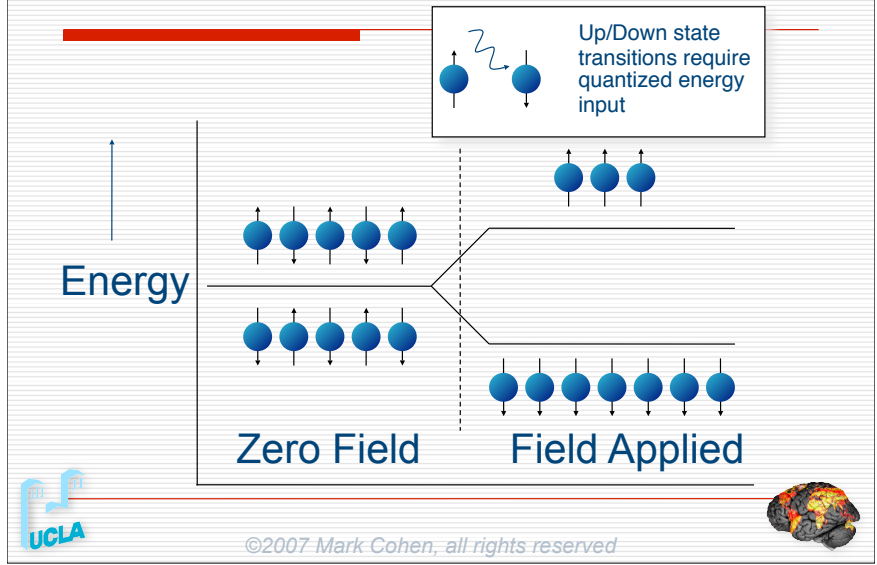
©2007 Mark Cohen, all rights reserved



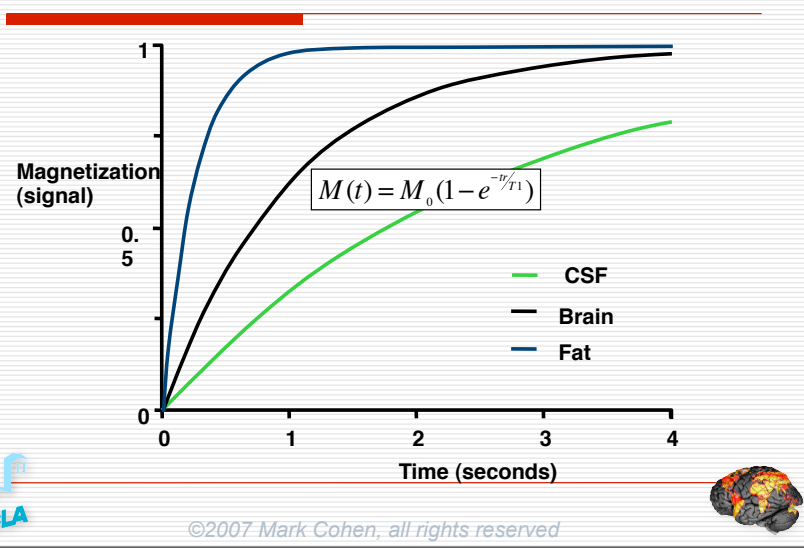
Protons in Applied Field



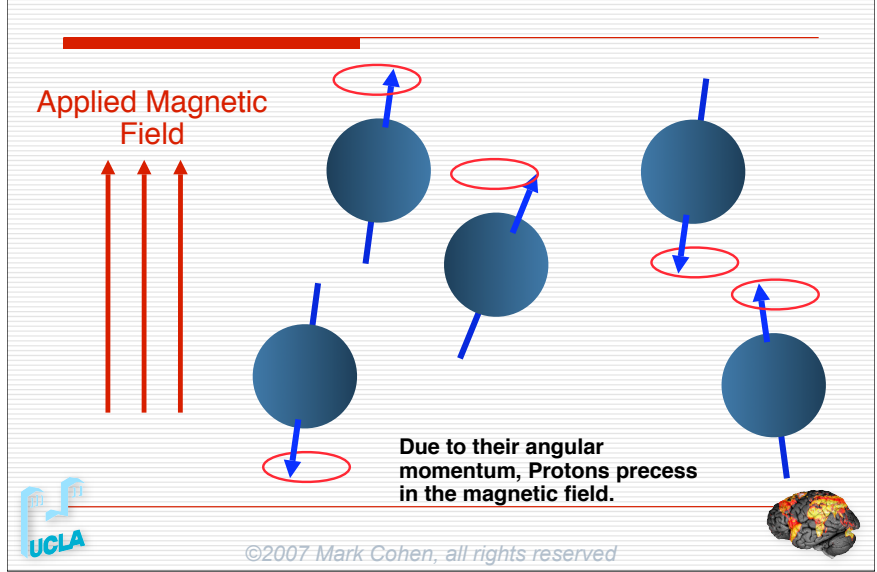
Transition to Equilibrium



T1



Protons in Applied Field

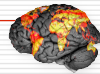


Proton Responses to Applied Magnetic Field

- Spin Alignment Along Net Applied Field
spins align parallel or anti-parallel to the applied field
- Precession About the Magnetic Field
at a precession frequency of: $\gamma \times B$, known as the Larmor frequency
- Spin Alignment Occurs at the Rate, T1



©2007 Mark Cohen, all rights reserved

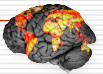


T1:

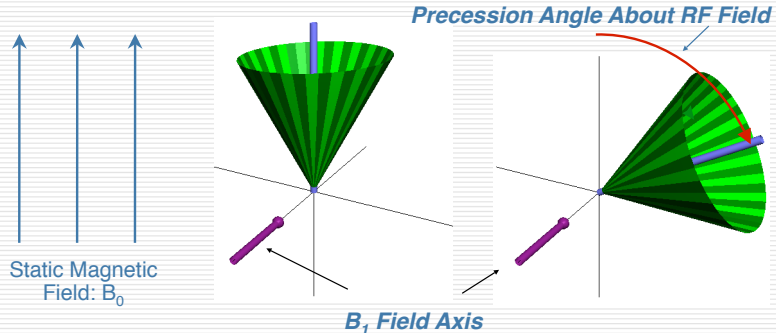
The Characteristic Time for Longitudinal Relaxation



©2007 Mark Cohen, all rights reserved



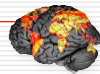
the Resonance Phenomenon



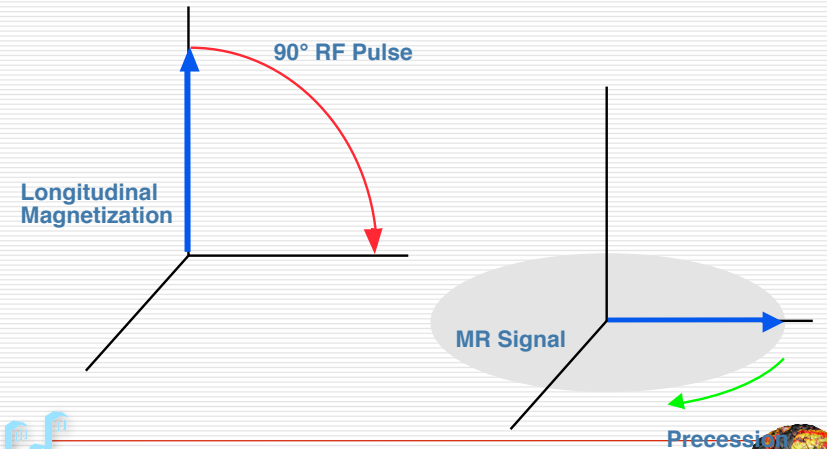
When a second magnetic field (B_1) is applied, rotating at the Larmor rate, the proton will precess about it.



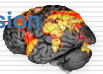
©2007 Mark Cohen, all rights reserved



An RF Pulse Converts Longitudinal Magnetization to Signal

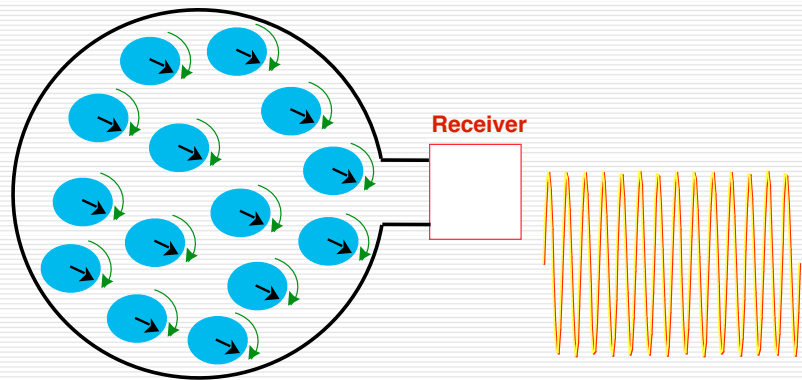


©2007 Mark Cohen, all rights reserved



In-Phase Precession

N

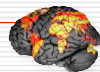


S

NMR Signal

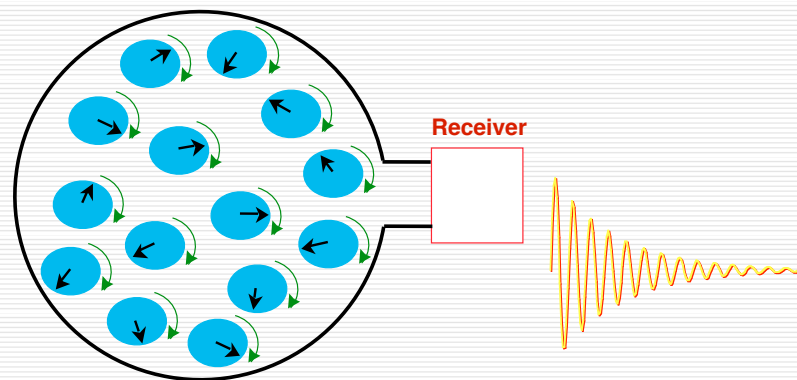
UCLA

©2007 Mark Cohen, all rights reserved



Out of Phase

P
N

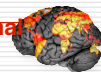


S

NMR Signal

UCLA

©2007 Mark Cohen, all rights reserved

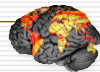


T2

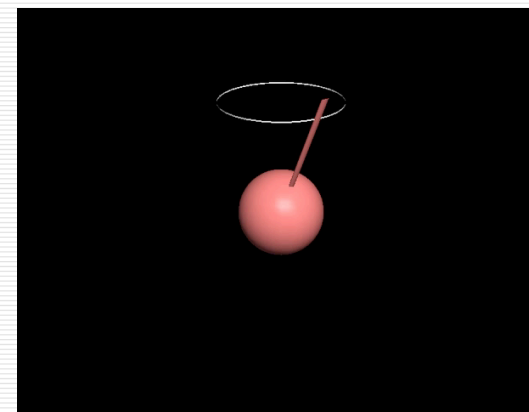
The Characteristic Time for Transverse Decay

UCLA

©2007 Mark Cohen, all rights reserved

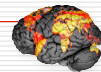


Summary Animation

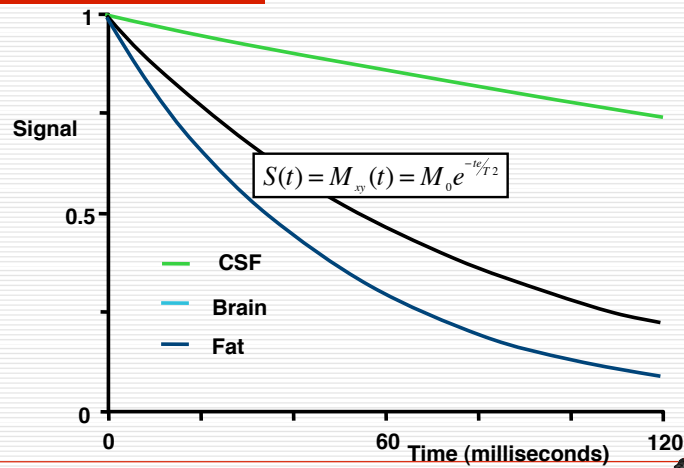


UCLA

©2007 Mark Cohen, all rights reserved



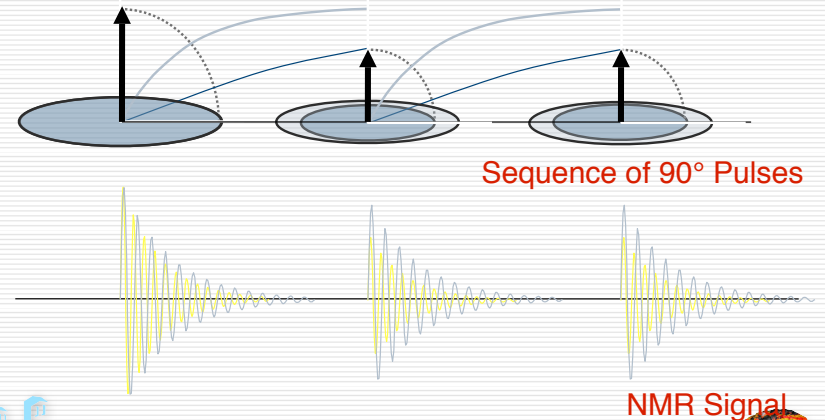
T2 and TE



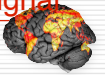
©2007 Mark Cohen, all rights reserved



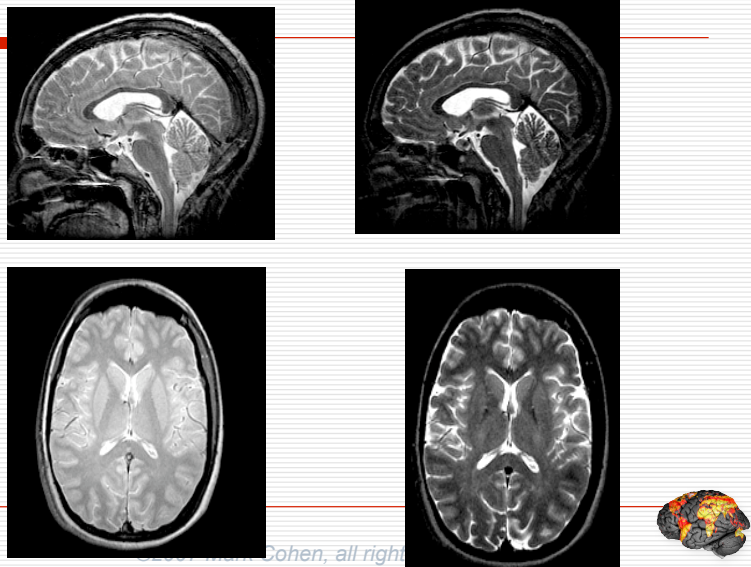
Partial Saturation Sequence



©2007 Mark Cohen, all rights reserved



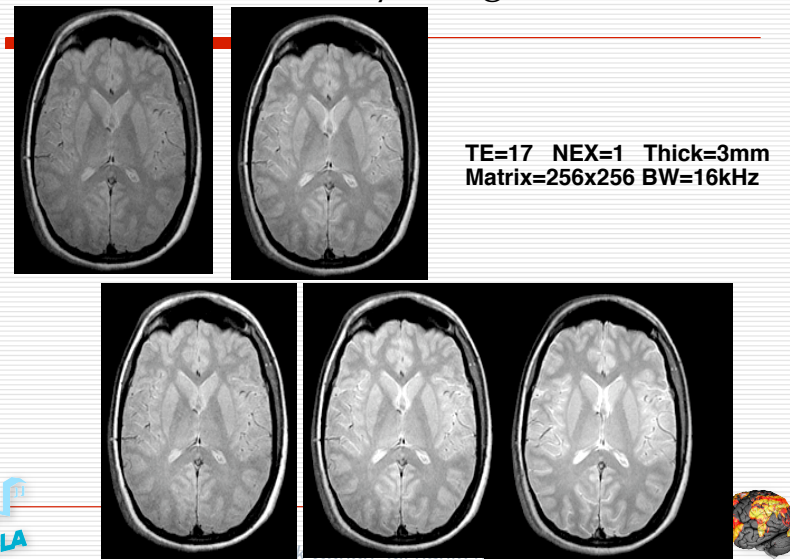
Effects of TE at long TR



©2007 Mark Cohen, all rights reserved



Effects of TR (density weighted)

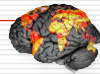


Contrast, TR and TE

TR	Long	Proton Density	T2-Weighted
	Short	T1-Weighted	
		Short	Long
		TE	



©2007 Mark Cohen, all rights reserved

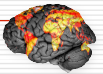


Contrast, TR and TE

		Density	T2
TR	Long		
	Short		
		Short	Long
		TE	



©2007 Mark Cohen, all rights reserved



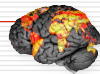
Contrast, TR and TE

$$S = k\rho M_0(1 - e^{-TR/T1})e^{-TE/T2}$$

TR	Long	Proton Density	T2-Weighted
	Short	T1-Weighted	
		Short	Long
		TE	



©2007 Mark Cohen, all rights reserved

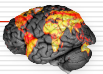


Contrast, TR and TE

		Density	T2
TR	Long		
	Short		
		Short	Long
		TE	

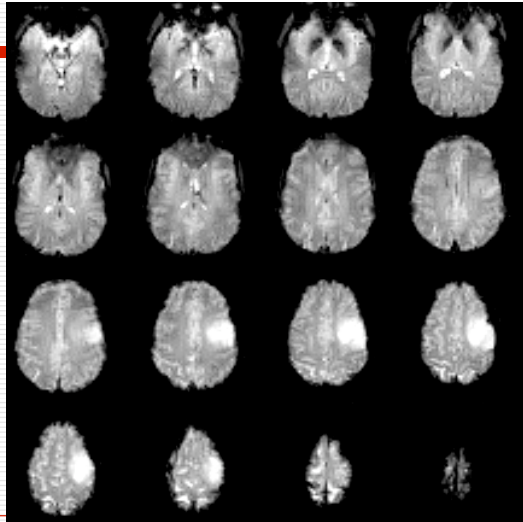


©2007 Mark Cohen, all rights reserved



T2-weighted EPI scan

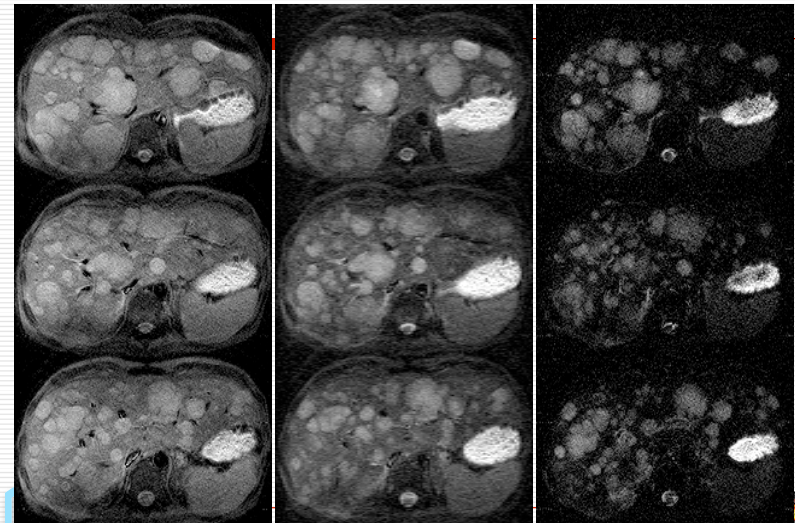
Metastatic
(cancer) lesions,
and many
others, typically
appear bright on
T2-weighted MR
images



©2007 Mark Cohen, all rights reserved



Liver Mets



TE = 26

©2007 Mark Cohen, all rights reserved

TE = 50

TE = 100



the Observed Transverse
Relaxation Rate, $T2^*$,
is the sum of several
components:

$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2'} + \frac{1}{T2_D}$$

Molecular
Field Inhomogeneity
Diffusion



©2007 Mark Cohen, all rights reserved



MR Formulæ

Contrast Summary:

$$\text{Spin Echo Signal} = k\rho M_0(1 - e^{-tr/T1})e^{-te/T2}$$

ρ is the proton density
 k represents instrument effects

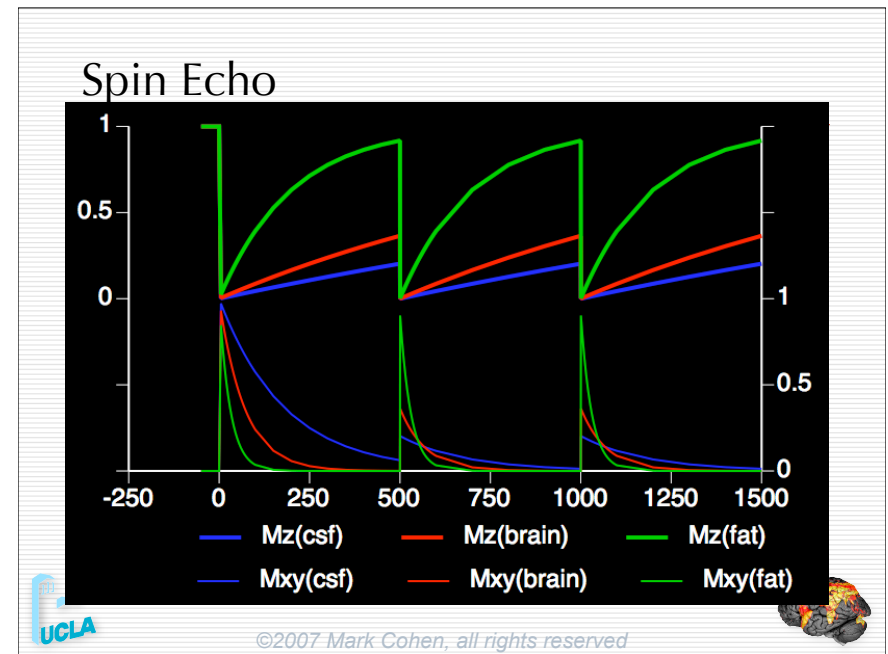
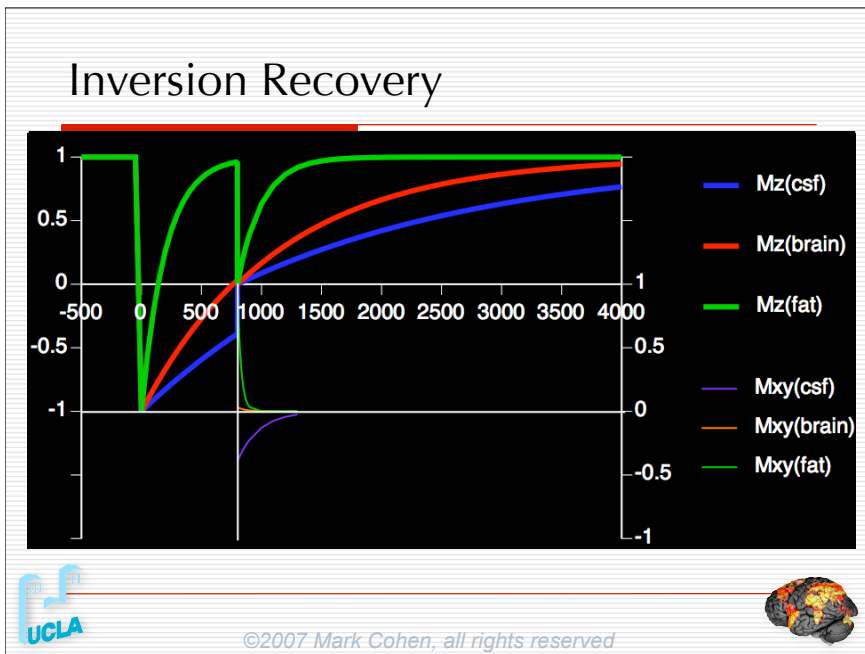
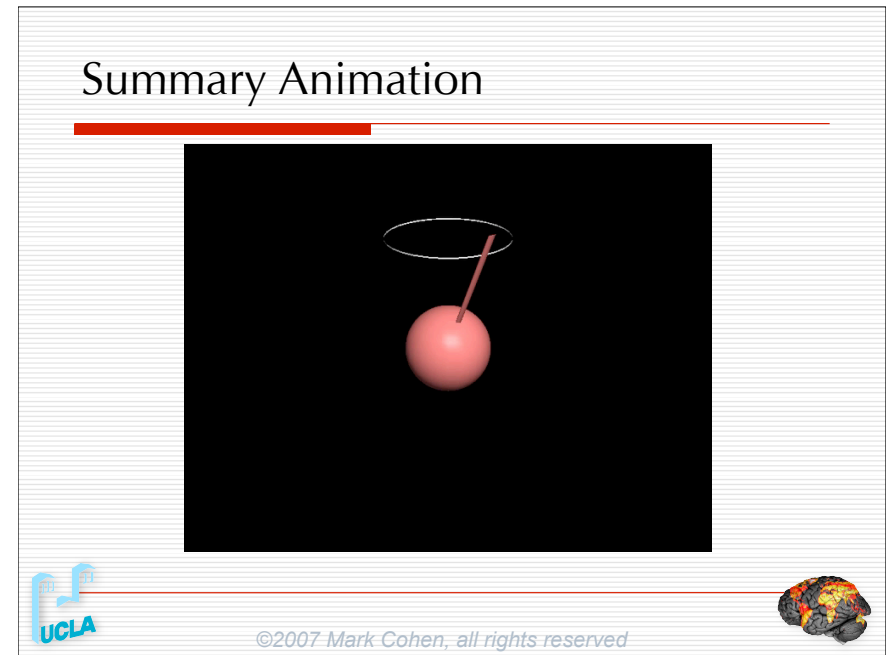
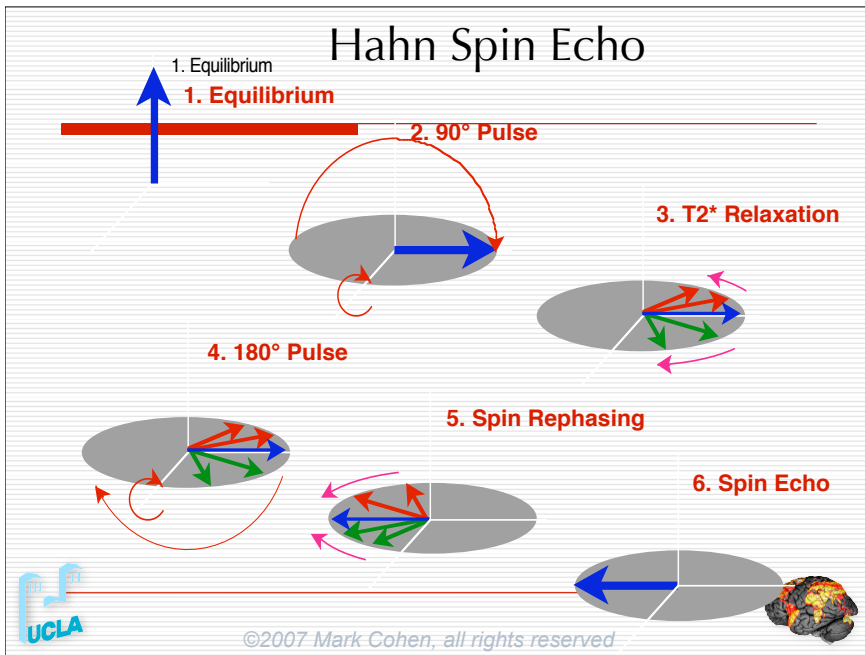
The “Bloch” Equation:

$$\frac{d\mathbf{M}}{dt} = \gamma\mathbf{M} \times \mathbf{B}_1 + (\mathbf{M}_0 - \mathbf{M}_z)/T_1 - (\mathbf{M}_x + \mathbf{M}_y)/T_2$$



©2007 Mark Cohen, all rights reserved





3D T1 In

TE = 3.2
 TR = 14.4
 124 slices
 1.25 mm thick
 1 NEX
 Flip Angle 20°
 TI = 500

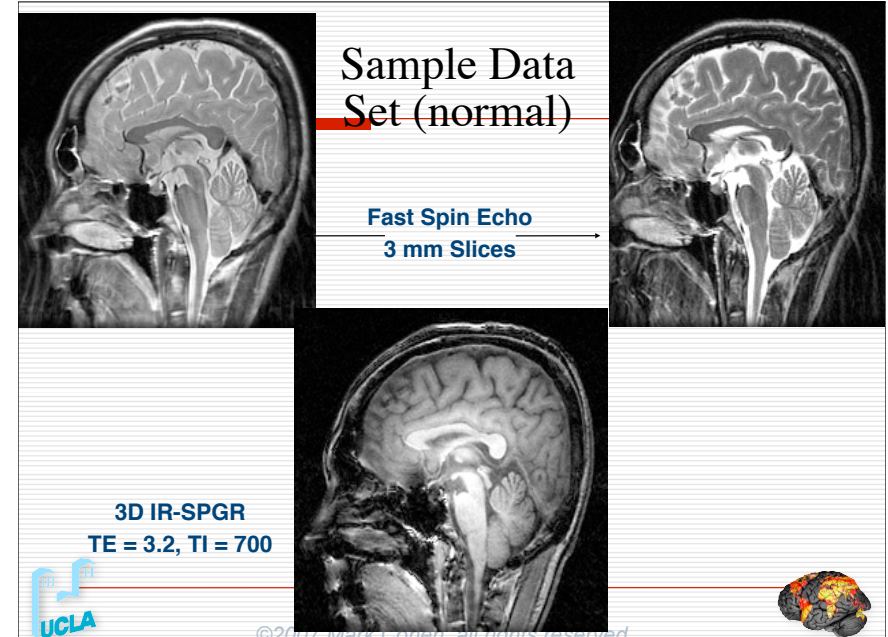


©2007 Mark Cohen, all rights reserved

UCLA Brain Mapping

Sample Data Set (normal)

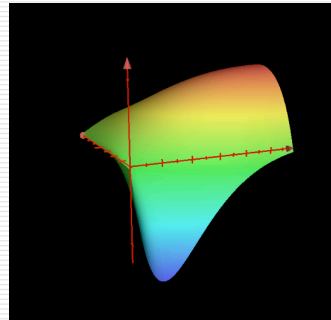
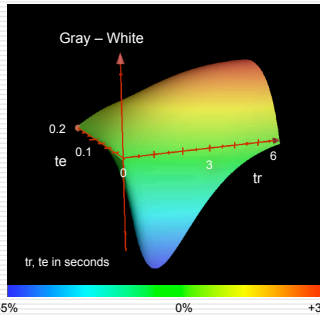
Fast Spin Echo
 3 mm Slices



3D IR-SPGR
 TE = 3.2, TI = 700

©2007 Mark Cohen, all rights reserved

Contrast to Noise Ratio

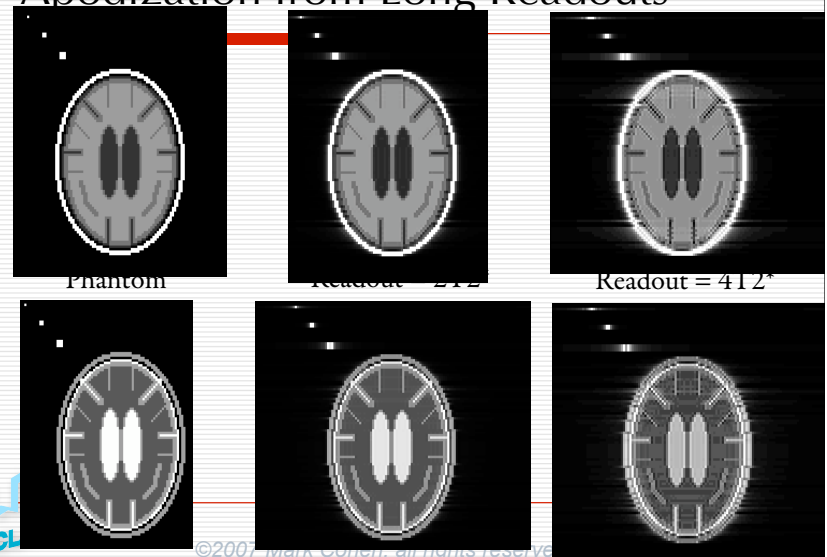


$$\text{Contrast} = [(1 - e^{-tr/1.2})e^{-te/1.08}], \text{ gray matter}$$

$$- [(1 - e^{-tr/1.0})e^{-te/1.07}], \text{ white matter}$$

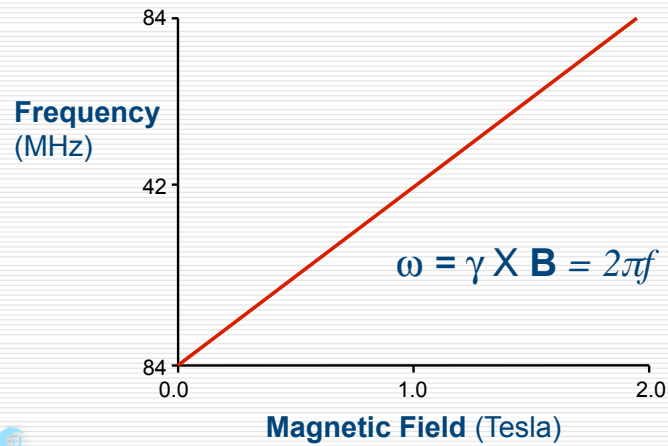
©2007 Mark Cohen, all rights reserved

Apodization from Long Readouts

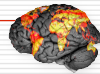


©2007 Mark Cohen, all rights reserved

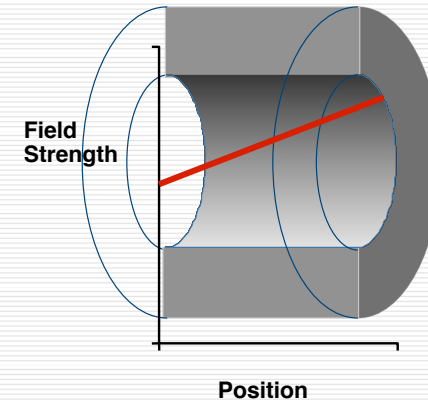
The Larmor Relation



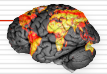
©2007 Mark Cohen, all rights reserved



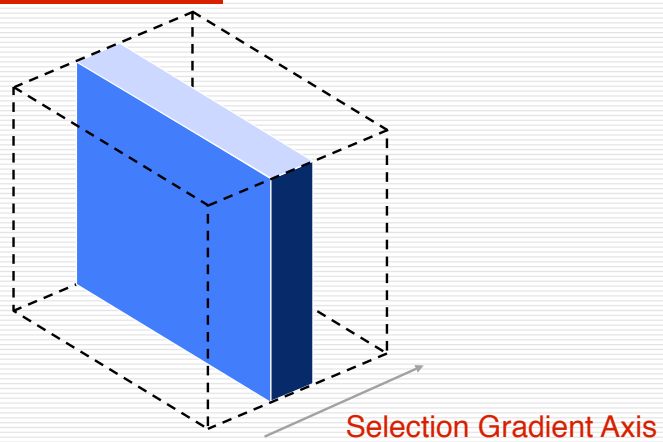
Magnetic Field Gradients



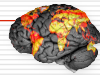
©2007 Mark Cohen, all rights reserved



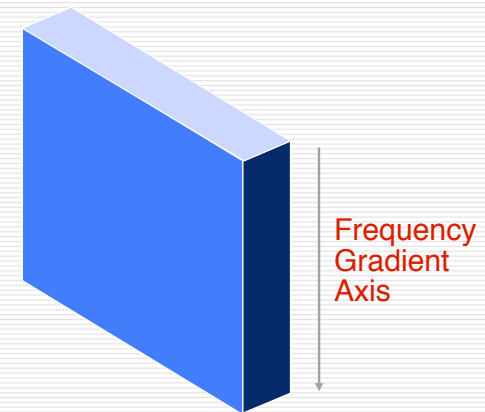
Slice



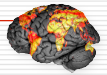
©2007 Mark Cohen, all rights reserved



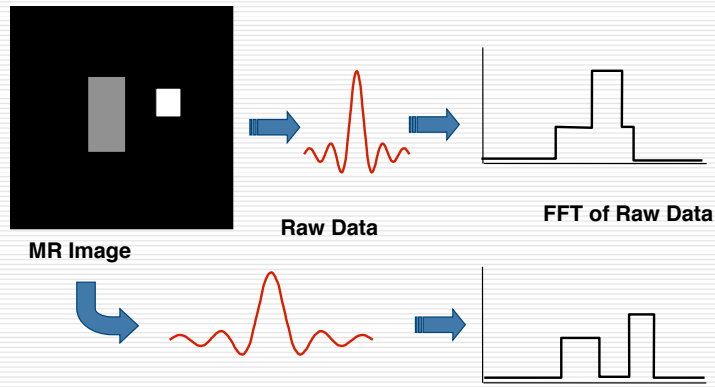
Frequency Encoding



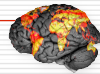
©2007 Mark Cohen, all rights reserved



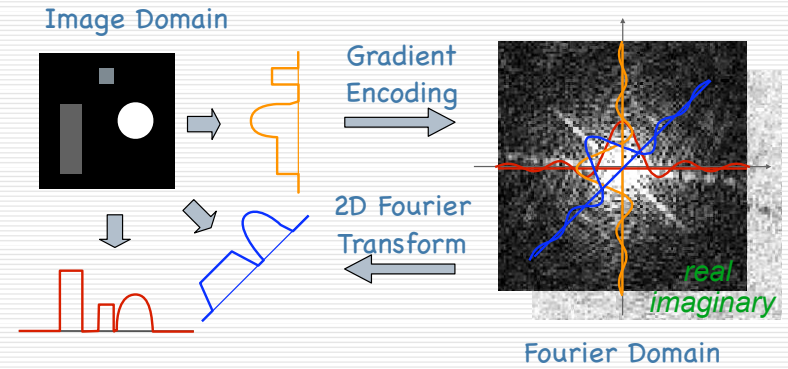
Fourier Projections^s



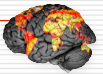
©2007 Mark Cohen, all rights reserved



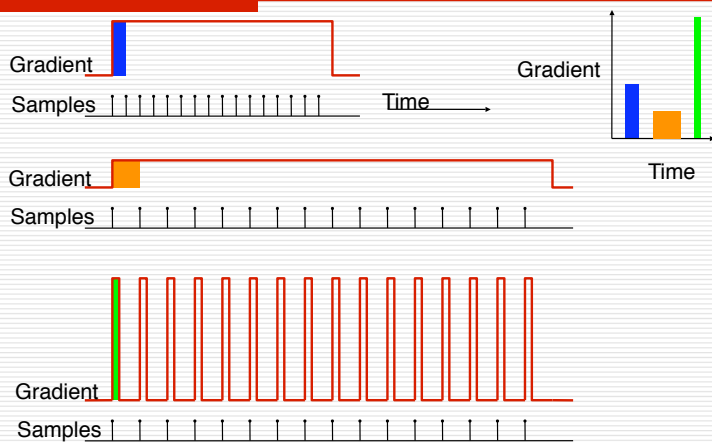
Back Projection



©2007 Mark Cohen, all rights reserved

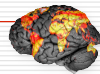


Equivalent Strategies in k-space*

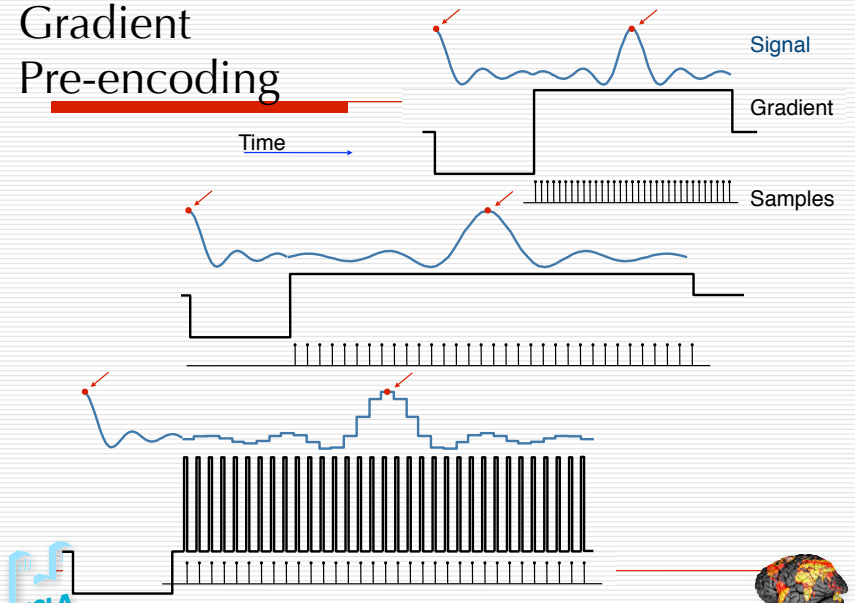


*Ignoring effects of signal decay and sample motion

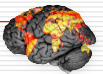
©2007 Mark Cohen, all rights reserved



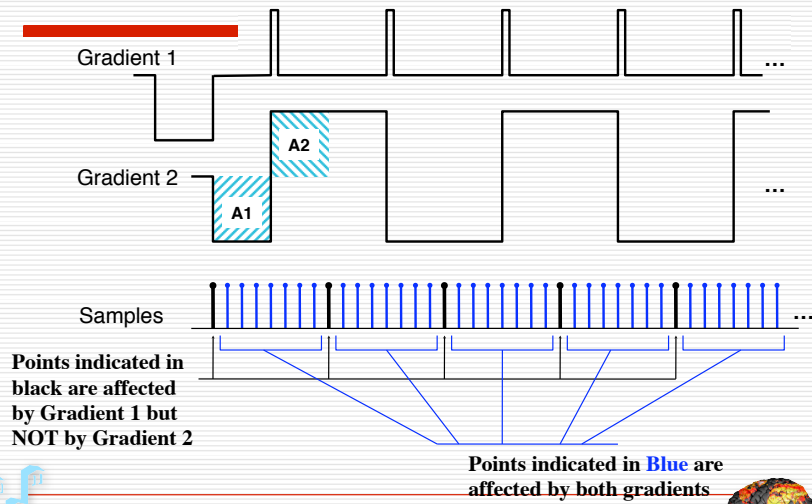
Gradient Pre-encoding



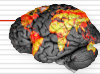
©2007 Mark Cohen, all rights reserved



Interleaved Spatial Encoding



©2007 Mark Cohen, all rights reserved

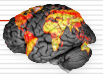


Scan Time

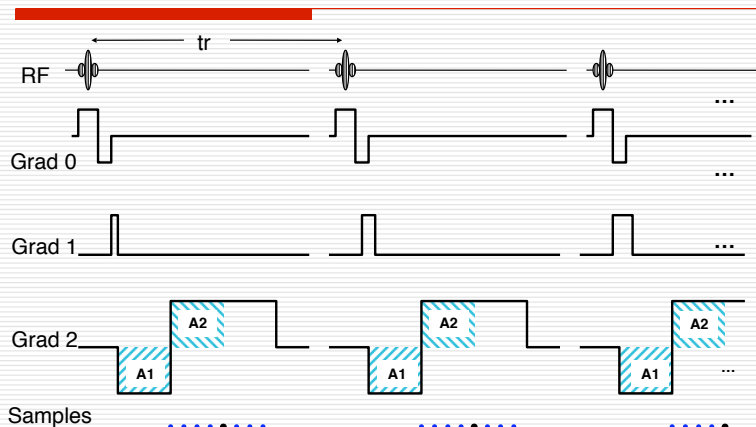
In Conventional MRI
Sampling is Apportioned
Into Brief Episodes
Separated by a "TR" Period



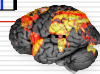
©2007 Mark Cohen, all rights reserved



Spatial Encoding in a Pulse Sequence

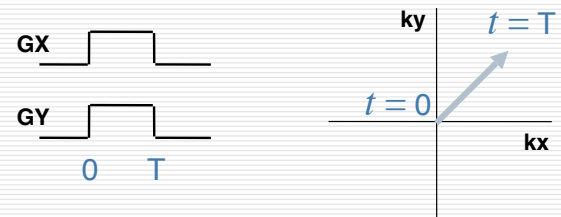


©2007 Mark Cohen, all rights reserved

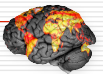


k-space

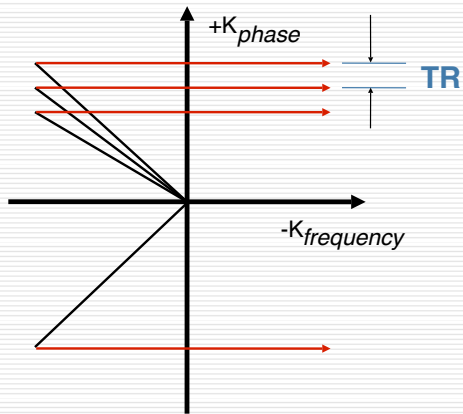
$$k(x,y,t) = \gamma \int_{t=0}^T G(x,y,t) dt$$



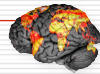
©2007 Mark Cohen, all rights reserved



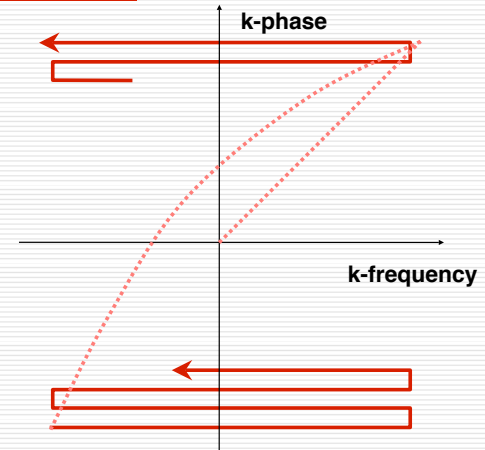
Conventional K-Space Trajectory



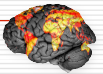
©2007 Mark Cohen, all rights reserved



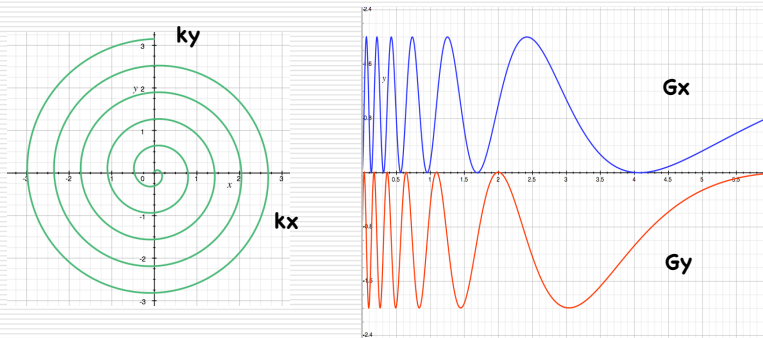
Echo-Planar k-space Trajectory



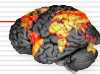
©2007 Mark Cohen, all rights reserved



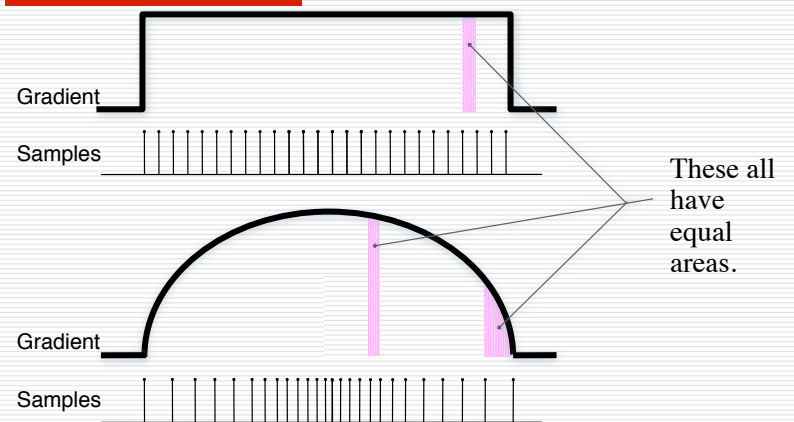
Spiral



©2007 Mark Cohen, all rights reserved

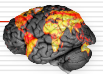


Equivalent Strategies in k-space*



*Ignoring effects of signal decay and sample motion

©2007 Mark Cohen, all rights reserved

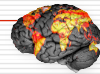


A Pulse Sequence Controls

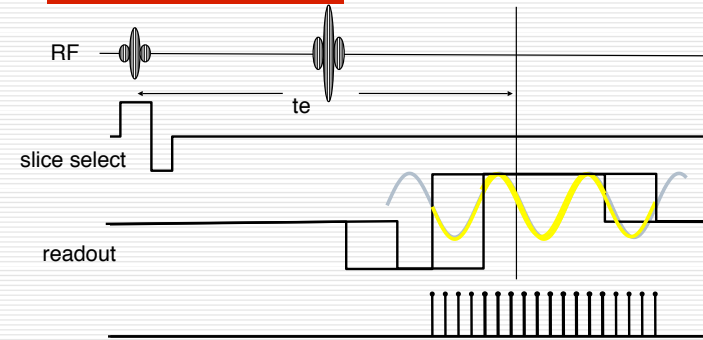
- Slice Location
- Slice Orientation
- Slice Thickness
- Number of Slices
- Resolution (*FOV and Matrix*)
- Contrast
- *TR, TE, TI, Flip Angle, Diffusion, etc...*
- Artifact Correction
- *Saturation Pulses, Flow Comp, Fat Suppression, etc...*



©2007 Mark Cohen, all rights reserved



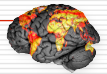
Phase Maps



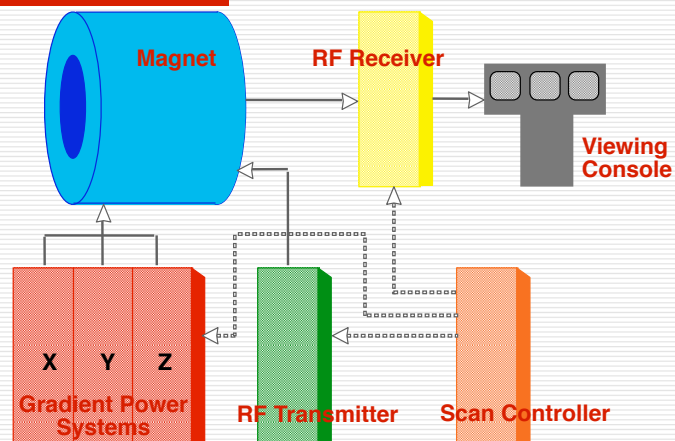
- Time shift in data collection amounts to a phase offset
- Spins precessing at different rates (different magnetic fields) will acquire different phase shifts



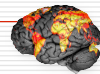
©2007 Mark Cohen, all rights reserved



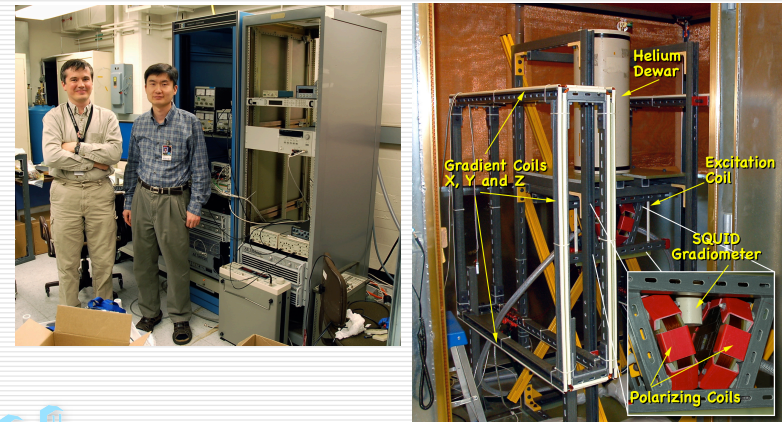
Imaging System Components



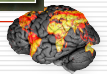
©2007 Mark Cohen, all rights reserved



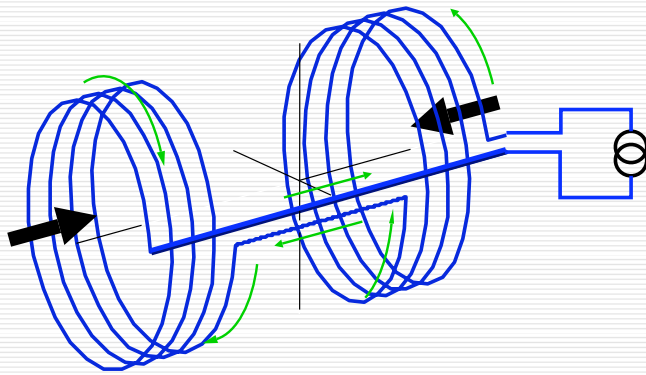
System Components



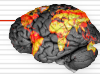
©2007 Mark Cohen, all rights reserved



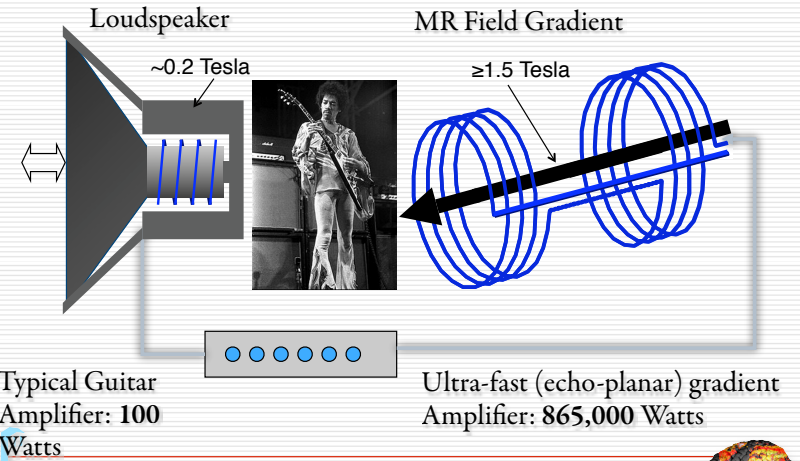
MR Field Gradient Coil



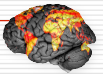
©2007 Mark Cohen, all rights reserved



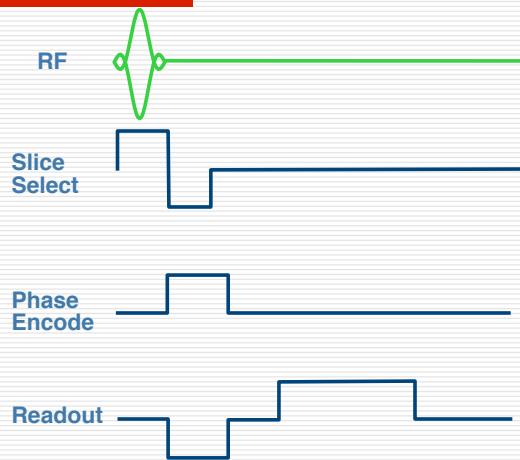
Why is MRI So Noisy?



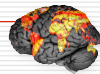
©2007 Mark Cohen, all rights reserved



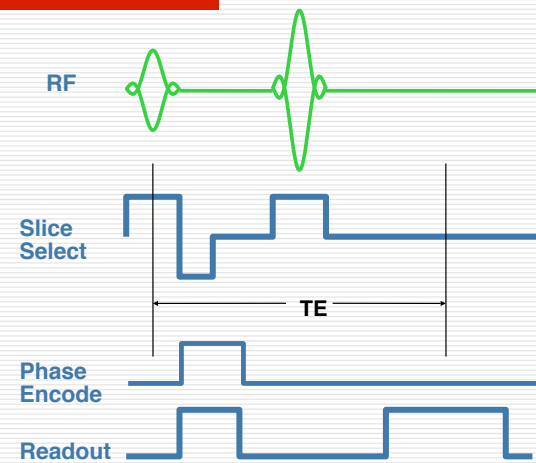
Gradient Echo Sequence



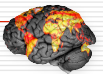
©2007 Mark Cohen, all rights reserved



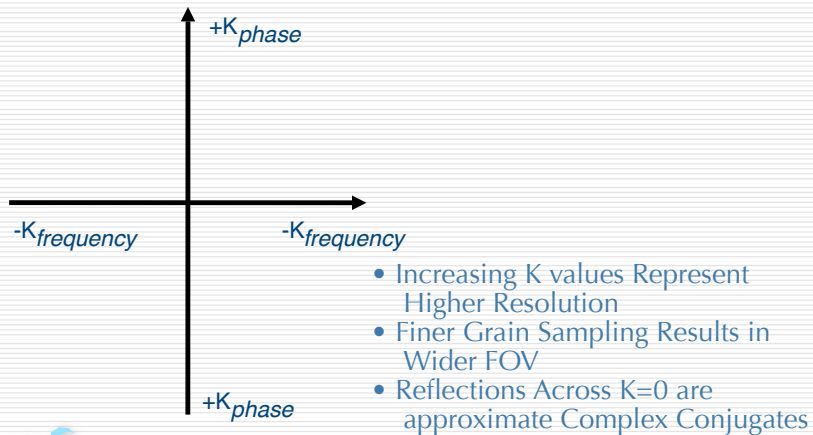
Spin Echo Sequence



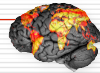
©2007 Mark Cohen, all rights reserved



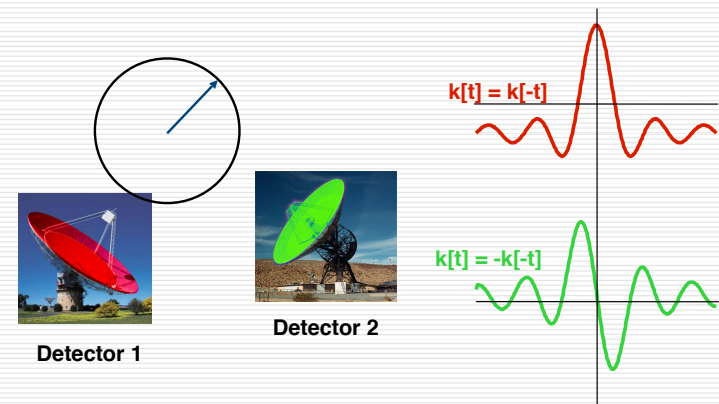
Properties of K-Space



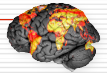
©2007 Mark Cohen, all rights reserved



Raw Data Symmetry



©2007 Mark Cohen, all rights reserved



k-space conjugate symmetry

For a Stationary Object,
in a Homogeneous Field:

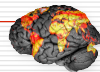
$$S(k_x, k_y) = \overline{S(k_x, -k_y)}$$

where $S(k_x, k_y)$ is the signal at (k_x, k_y) .

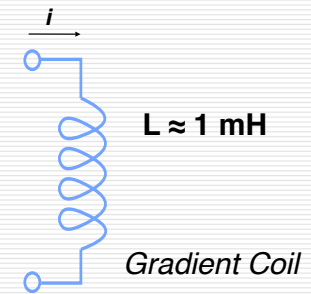
Example: if $S(k_x, k_y) = a + ib$,
then $S(k_x, -k_y) = a - ib$.



©2007 Mark Cohen, all rights reserved



Gradient Coil Characteristics

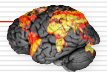


Gradient Strength = $k i$

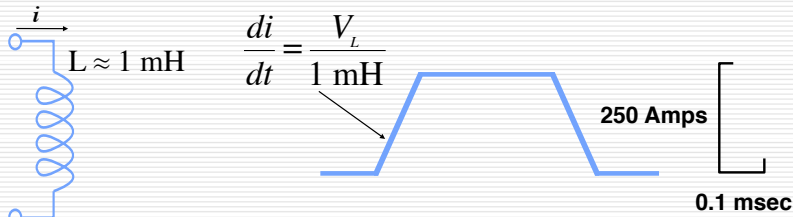
$k \approx 1 \text{ Gauss/cm} / 100 \text{ Amps}$



©2007 Mark Cohen, all rights reserved



Rise Time, Current and Voltage



For: 250 Amps in 100 μsec
 $V_L = 2500 \text{ Volts}$

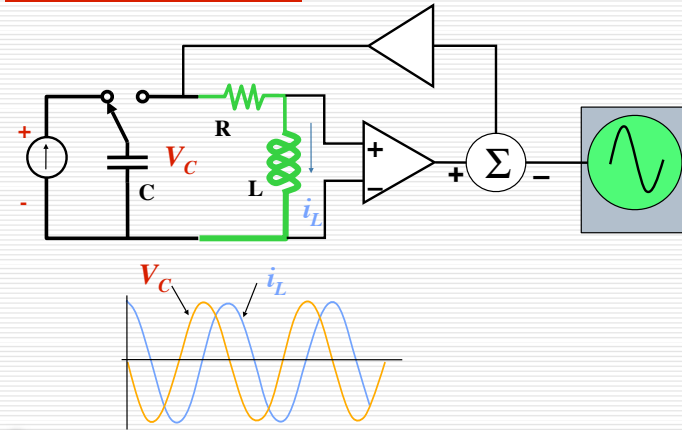
Power = 2500 Volts \times 250 Amps
= $6.25 \times 10^5 \text{ Watts}$



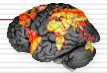
©2007 Mark Cohen, all rights reserved



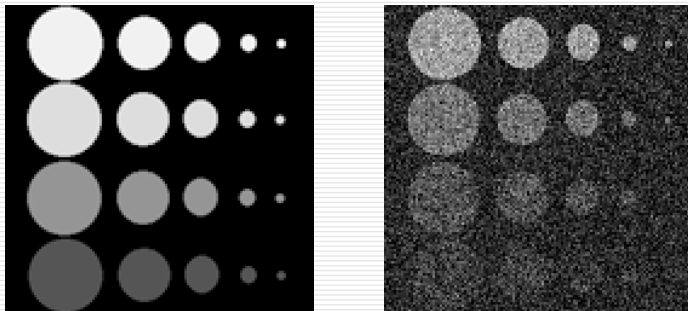
Resonant Gradient



©2007 Mark Cohen, all rights reserved



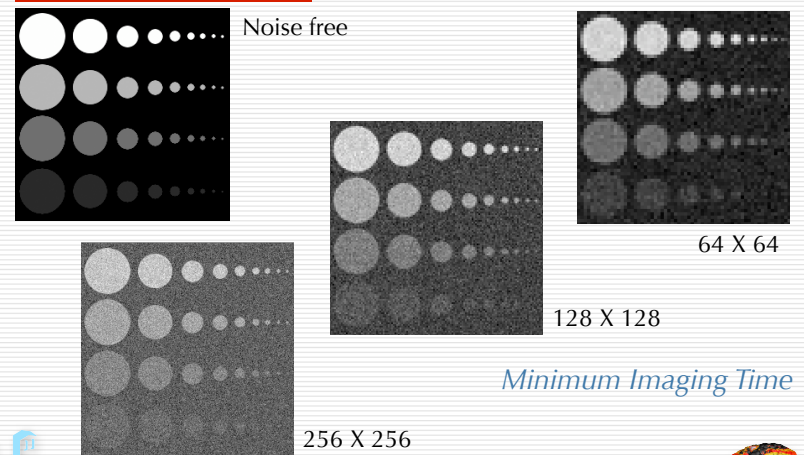
Contrast to Noise Ratio



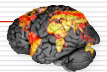
©2007 Mark Cohen, all rights reserved



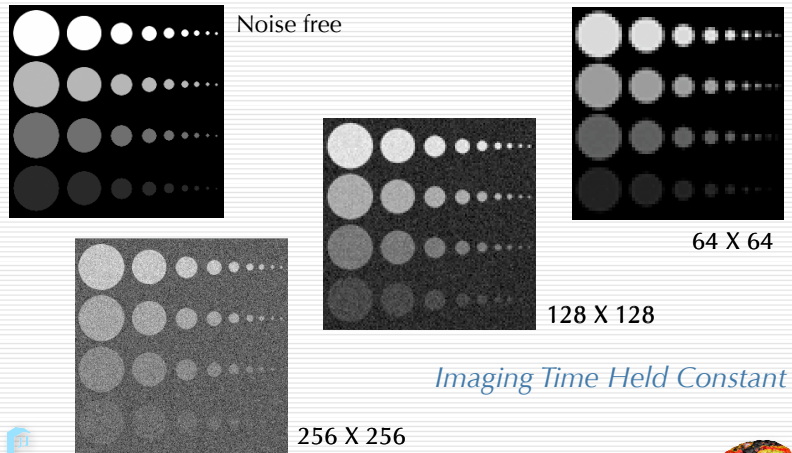
CNR vs. Resolution



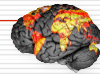
©2007 Mark Cohen, all rights reserved



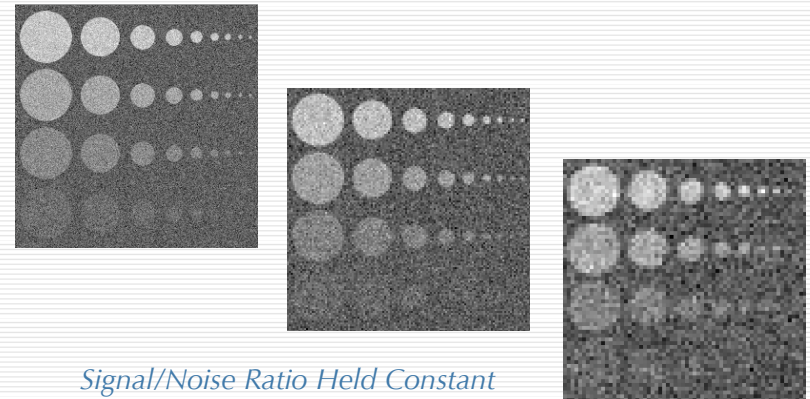
CNR vs. Resolution



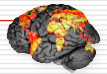
©2007 Mark Cohen, all rights reserved



CNR vs. Resolution



©2007 Mark Cohen, all rights reserved



An "Equation" in Resolution

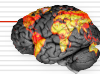
Because MR is an emission modality the temporal resolution, spatial resolution and contrast are inter-dependent:

$$\text{Signal} = k B_0 \text{voxel size} \sqrt{\text{imaging time}} \\ \text{– contrast}$$

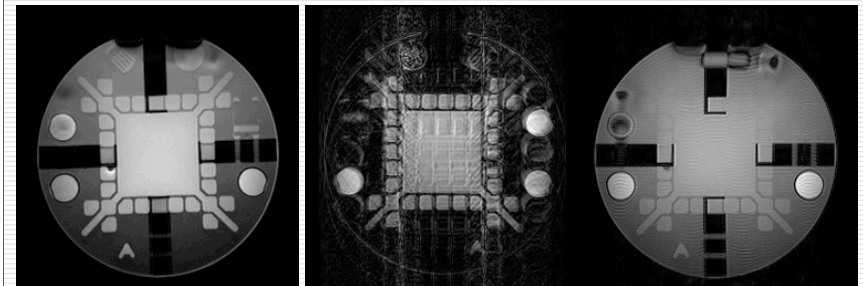
where B_0 is the field strength.



©2007 Mark Cohen, all rights reserved



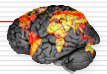
Motion Artifact



http://porkpie.loni.ucla.edu/BMD_HTML/SharedCode/Motion/motion.html



©2007 Mark Cohen, all rights reserved



Bandwidth and Readout

- Position is encoded by FREQUENCY
- Bandwidth refers to the Frequency Difference from the center of the image to its edge:
$$\text{Frequency per pixel} = \frac{2 * \text{Bandwidth}}{\text{number of pixels}} = \frac{1}{\text{readout duration}}$$
- Bandwidth decreases with readout duration:
$$\text{Bandwidth} = 2 * \text{readout duration}$$



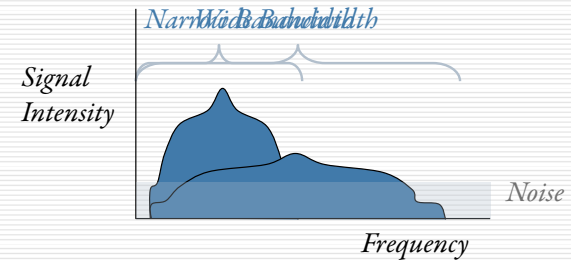
©2007 Mark Cohen, all rights reserved



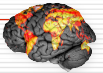
Bandwidth and SNR

Decreasing the Bandwidth Improves SNR:

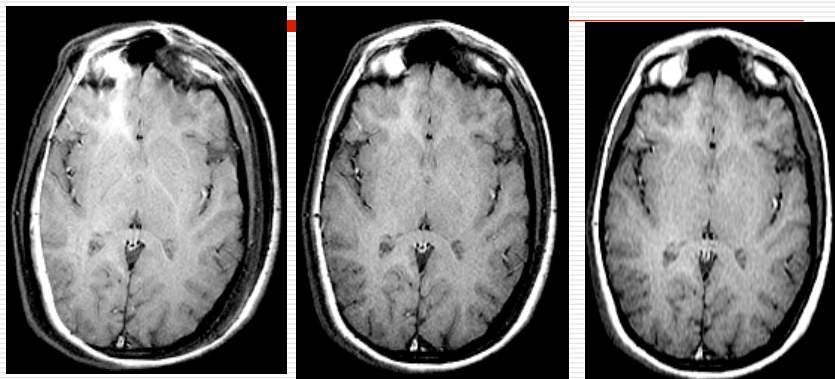
Imaging Time is INCREASED and high frequency noise is excluded



©2007 Mark Cohen, all rights reserved



Bandwidth



BW=4kHz

BW=8kHz

BW=16kHz

TE=11-14 NEX=1 Thick=3mm
TR=500 Matrix=256x256

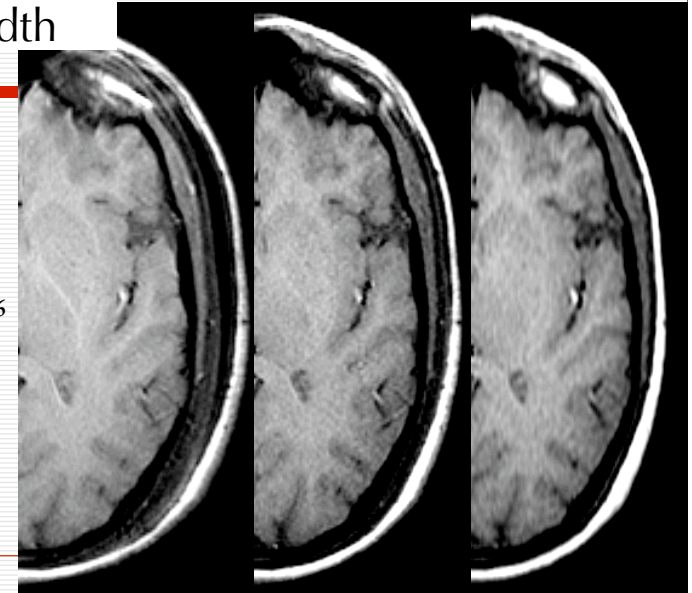


©2007 Mark Cohen, all rights reserved



Bandwidth

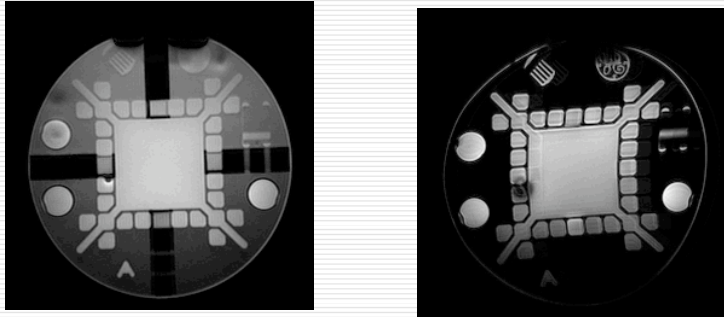
TE=11-14
NEX=1
Thick=3mm
TR=500
Matrix=256x256



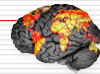
©2007 Mark Cohen, all rights reserved



Shape and Bandwidth



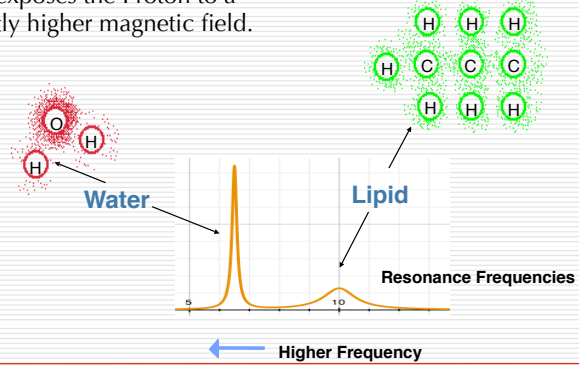
©2007 Mark Cohen, all rights reserved



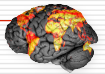
The Origin of Chemical Shift

In water, electrons move from Hydrogen towards Oxygen.
This exposes the Proton to a slightly higher magnetic field.

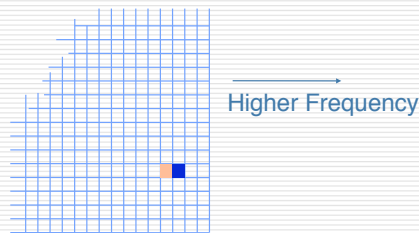
Electrons in lipid are shared equally between Hydrogen and Oxygen



©2007 Mark Cohen, all rights reserved



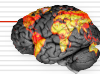
Chemical Shift Artifact



If the frequency *width* of each pixel is less than the frequency *difference* between **water** and **lipid**, then **water** and **lipid** will appear in separate pixels



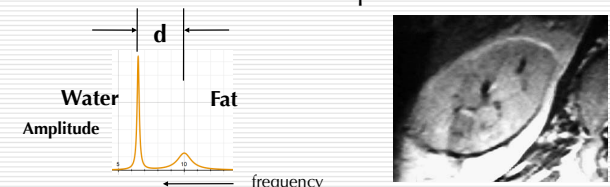
©2007 Mark Cohen, all rights reserved



Chemical Shift

The Fat-Water chemical shift is about 3.5 ppm or:

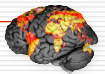
<i>Which is:</i>	<i>with a 32 kHz readout</i>
75 Hz @ 0.5 Tesla	< 1 pixel
150 Hz @ 1.0 Tesla	≈ 1 pixel
220 Hz @ 1.5 Tesla	> 1 pixel
440 Hz @ 3.0 Tesla	≈ 3.5 pixels



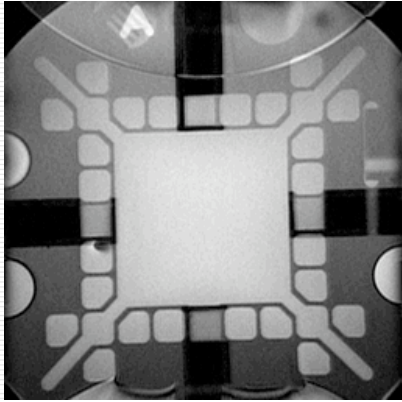
Lowering the Bandwidth/pixel increases the Chemical Shift in pixels



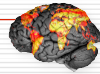
©2007 Mark Cohen, all rights reserved



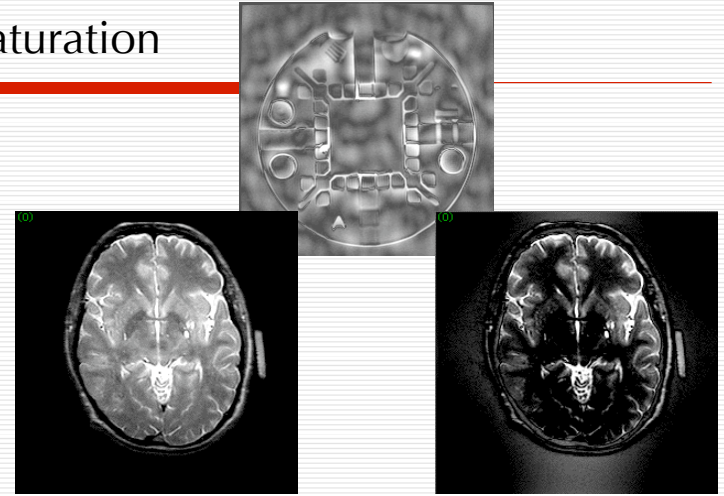
Aliasing



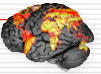
©2007 Mark Cohen, all rights reserved



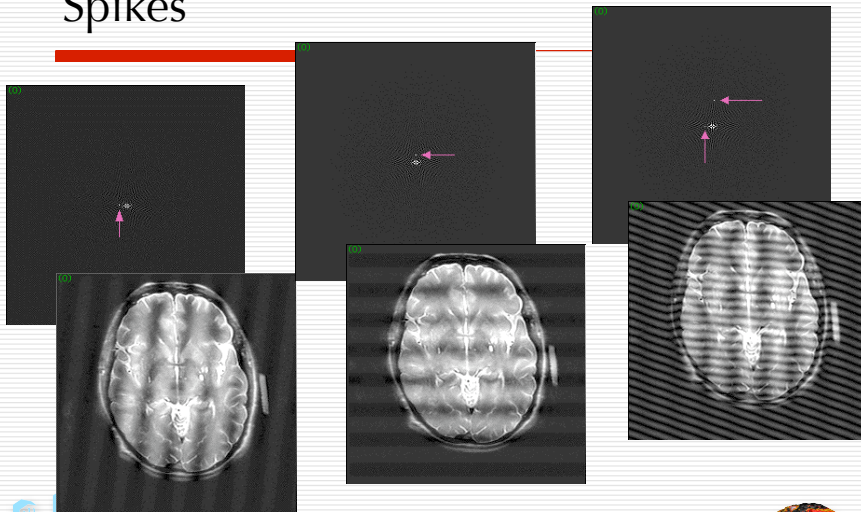
Saturation



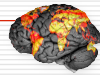
©2007 Mark Cohen, all rights reserved



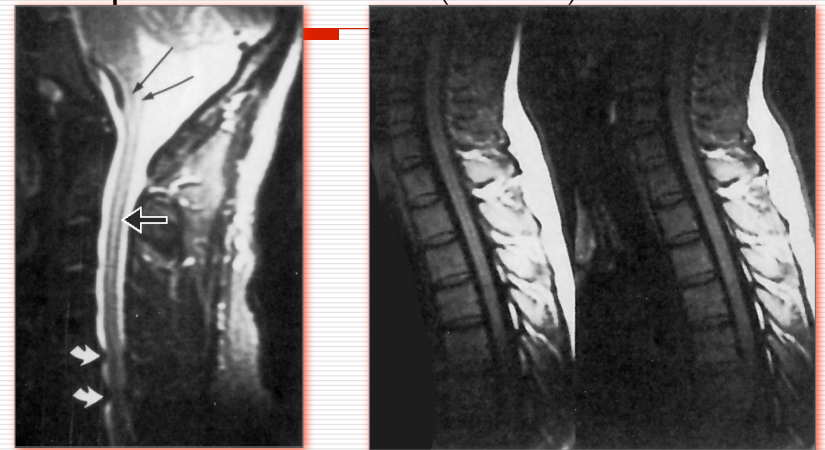
Spikes



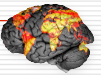
©2007 Mark Cohen, all rights reserved



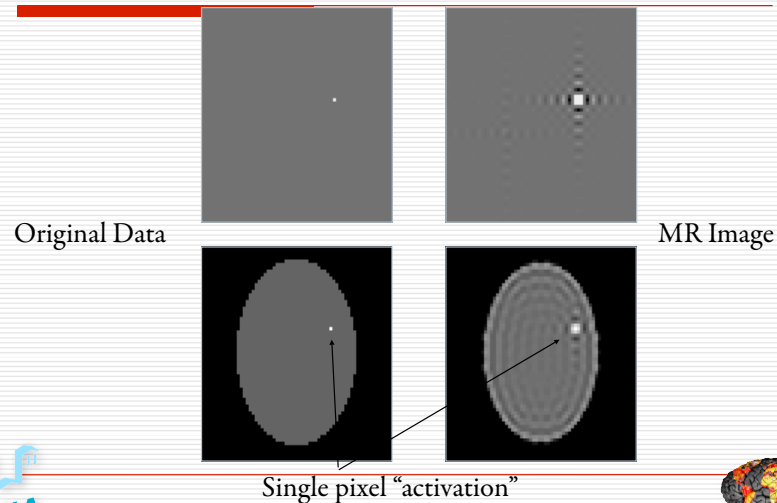
k-Space Truncation (Gibbs)



©2007 Mark Cohen, all rights reserved

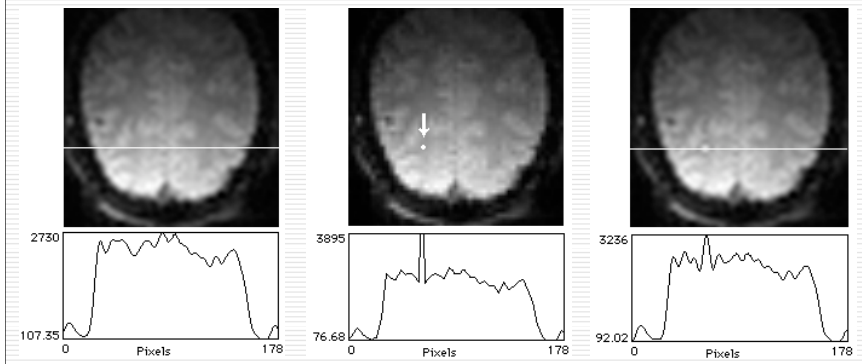


What is the actual resolution of MRI?



©2007 Mark Cohen, all rights reserved

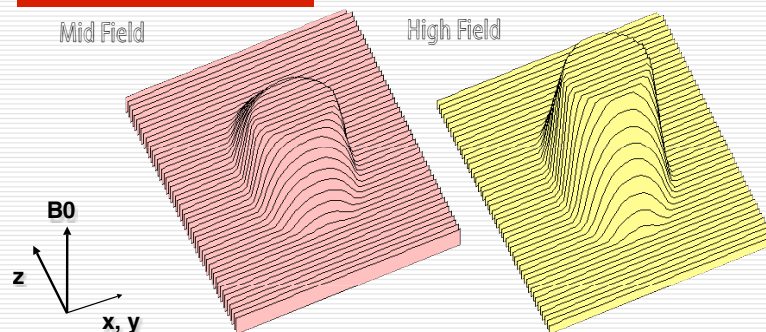
The Actual Resolution of *f*MRI



http://porkpie.loni.ucla.edu/BMD_HTML/SharedCode/MRArtifacts/MRArtifacts.html

©2007 Mark Cohen, all rights reserved

Distortions are More Severe at High Magnetic Field Strength



Variation in sample magnetization of is proportional to field strength.

→ High Field images lose more signal from field inhomogeneity

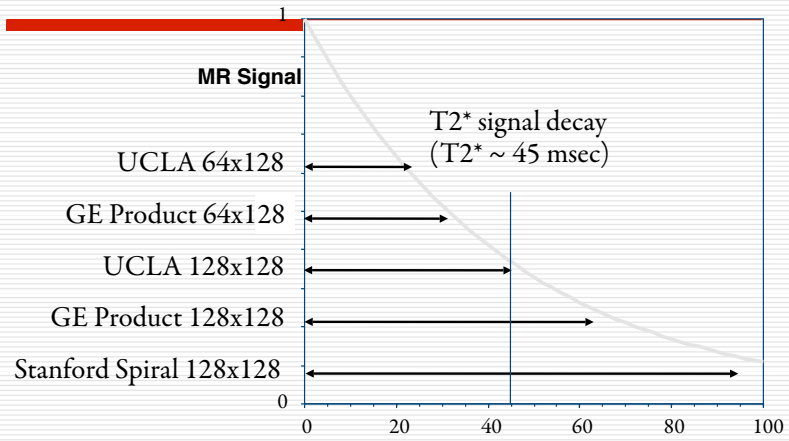
Research supported under DA13054
©2007 Mark Cohen, all rights reserved

Crucial Tradeoffs

- Magneto-stimulation, spatial resolution, chemical shift artifact, gradient power and signal to noise ratio are ALL interdependent

©2007 Mark Cohen, all rights reserved

EPI Readout Durations



Apodization from Long Readouts

