Imaging Sequences II

M219 - Principles and Applications of MRI

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2/27/2023

Course Overview

- 2023 course schedule
  - https://mrrl.ucla.edu/pages/m219_2023
- Assignments
  - Homework #3 is due on 3/8
- Final exam
  - 3/20 at 2-4pm
- No office hour this week

Signal Equation

$$s(t) = \int_x \int_y M(x,y) e^{-i2\pi(k_x(t)\cdot x + k_y(t)\cdot y)} dxdy$$

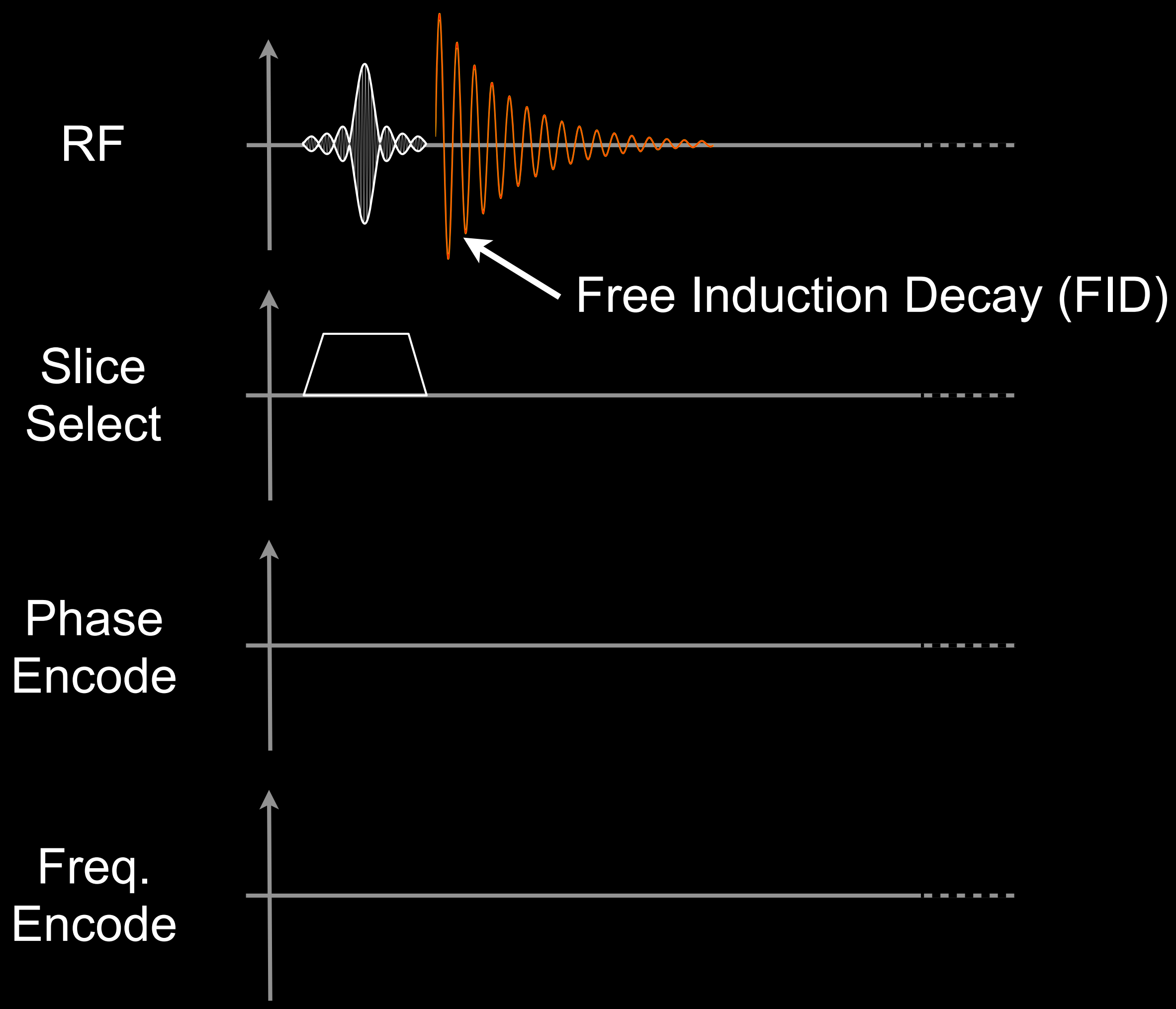
- With off-resonance:

$$s(t) = \int_x \int_y M(x,y) e^{-i\omega_E(x,y)t} e^{-i2\pi(k_x(t)\cdot x + k_y(t)\cdot y)} dxdy$$

- B0 inhomogeneity
- Susceptibility
- Chemical shift

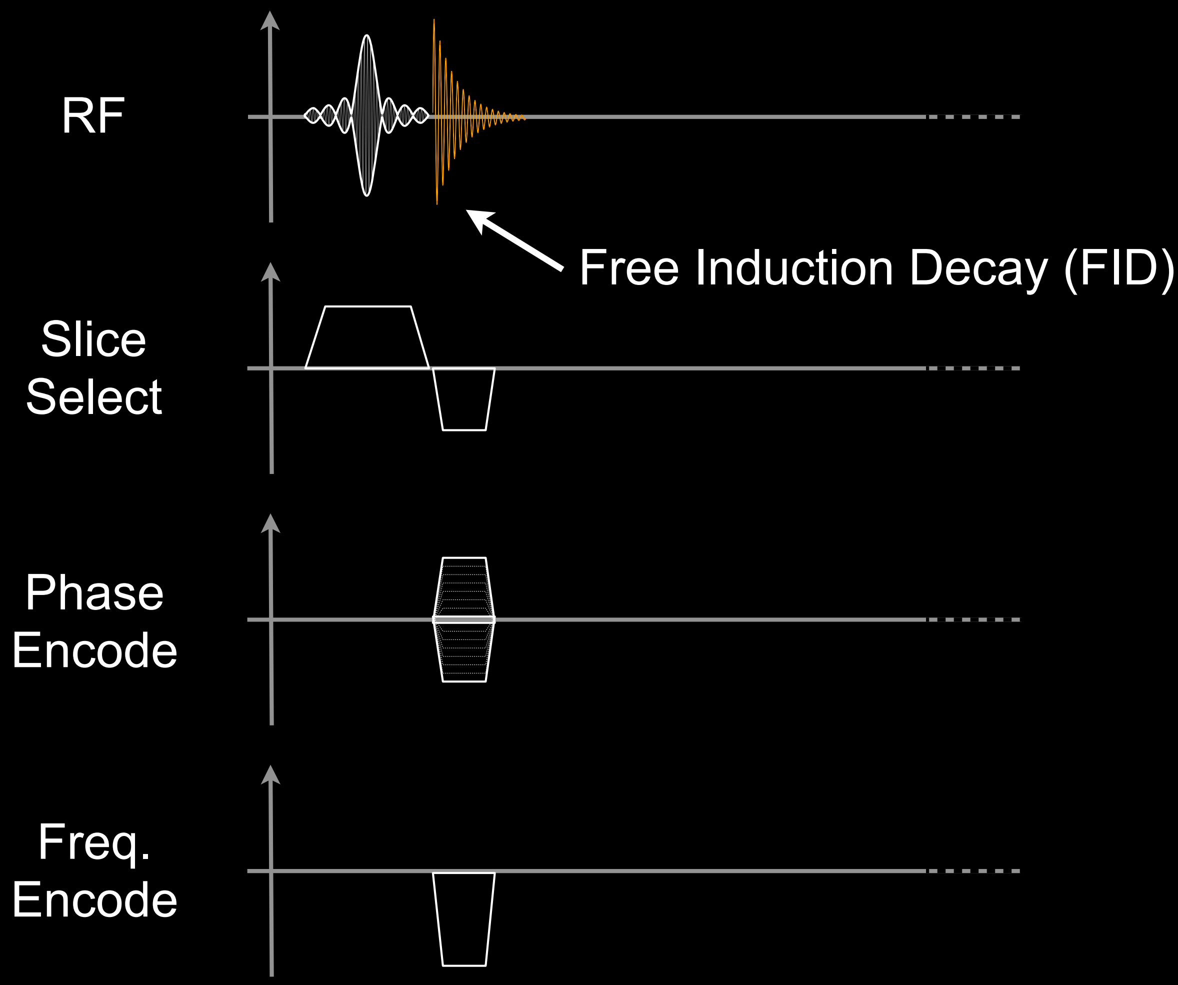
Gradient Echo Imaging

Basic Gradient Echo Sequence



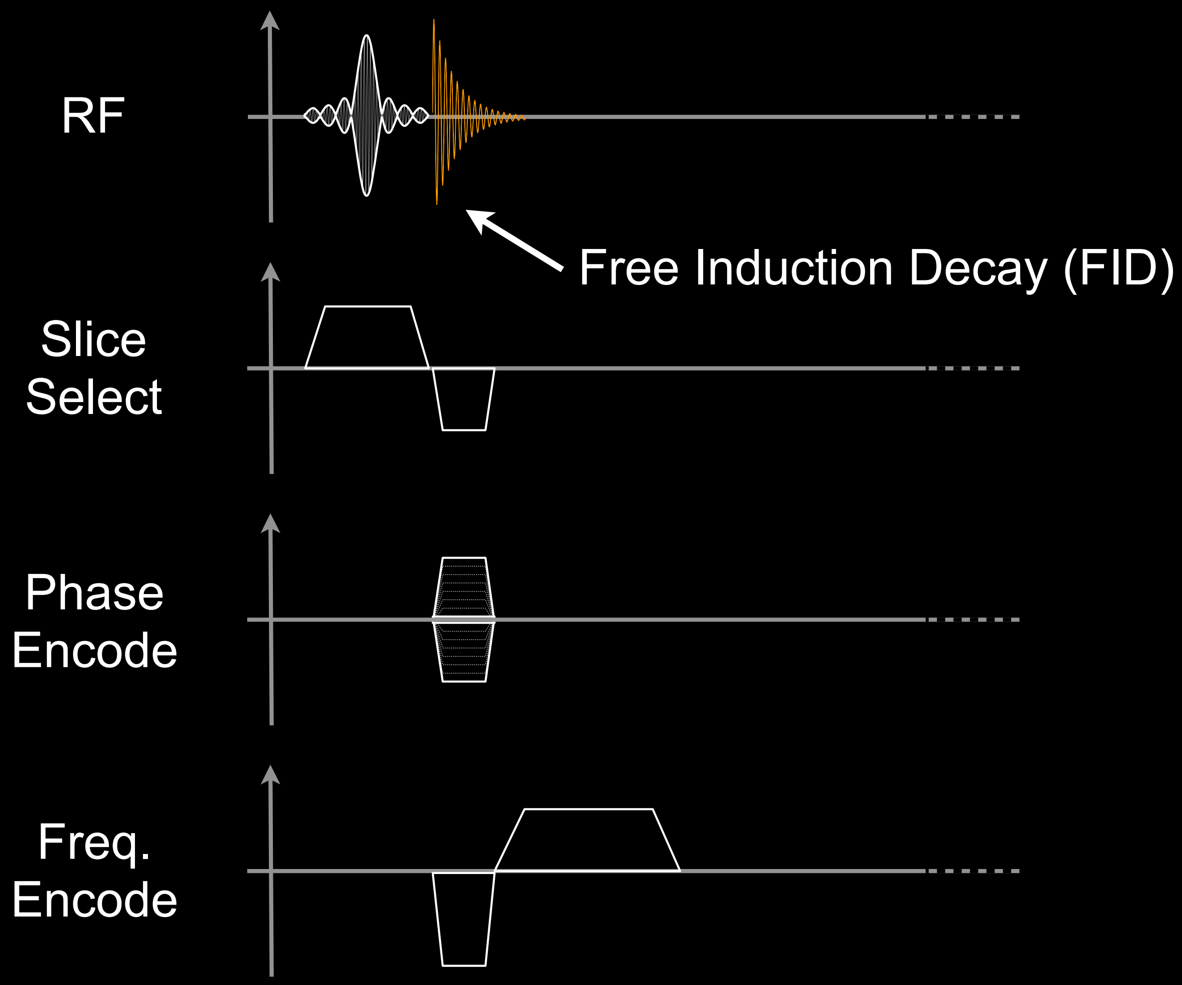
- FID Decay due to
  - T2 decay
  - Spin dephasing

Basic Gradient Echo Sequence



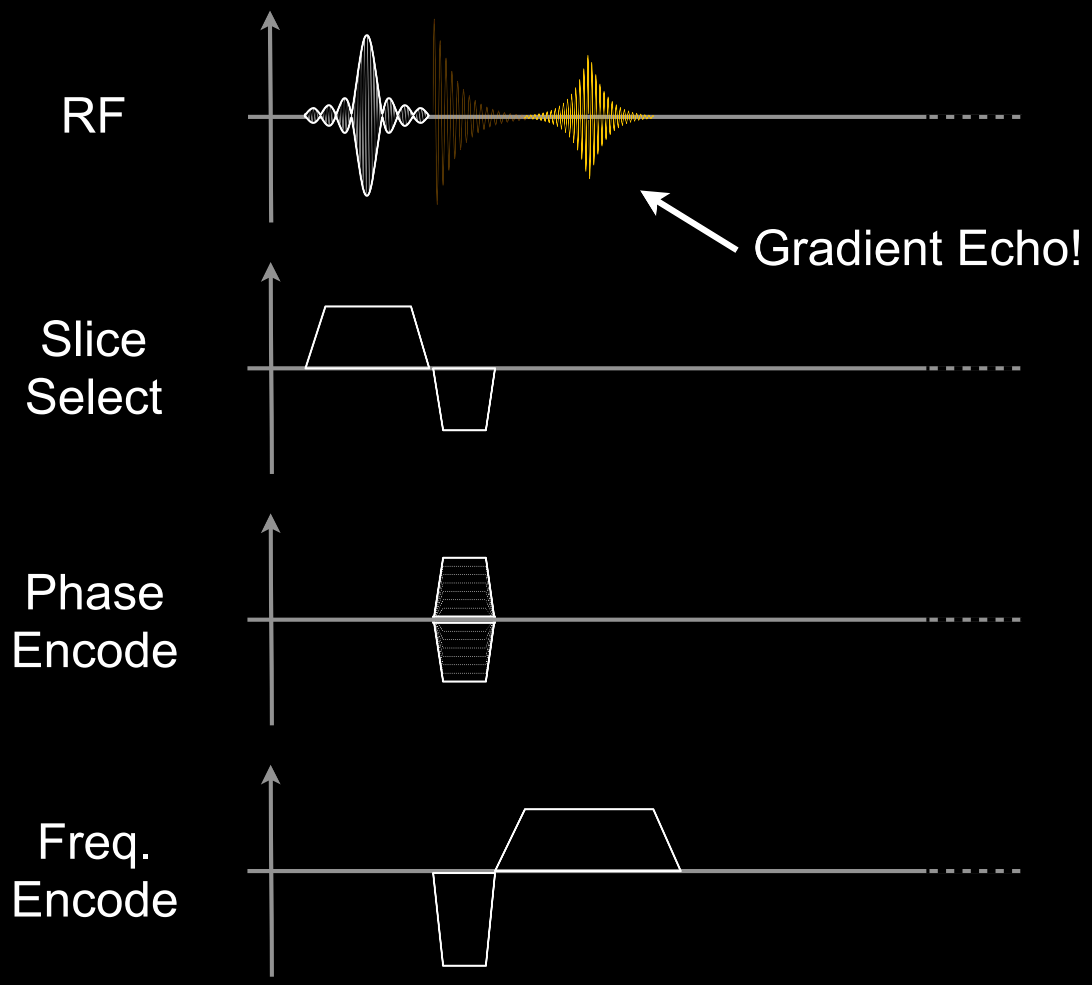
- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing

Basic Gradient Echo Sequence



- FID Decay due to
  - T2 decay
  - Spin dephasing
- Gradients accelerate spin dephasing
- Gradients can undo gradient induced spin dephasing

Basic Gradient Echo Sequence



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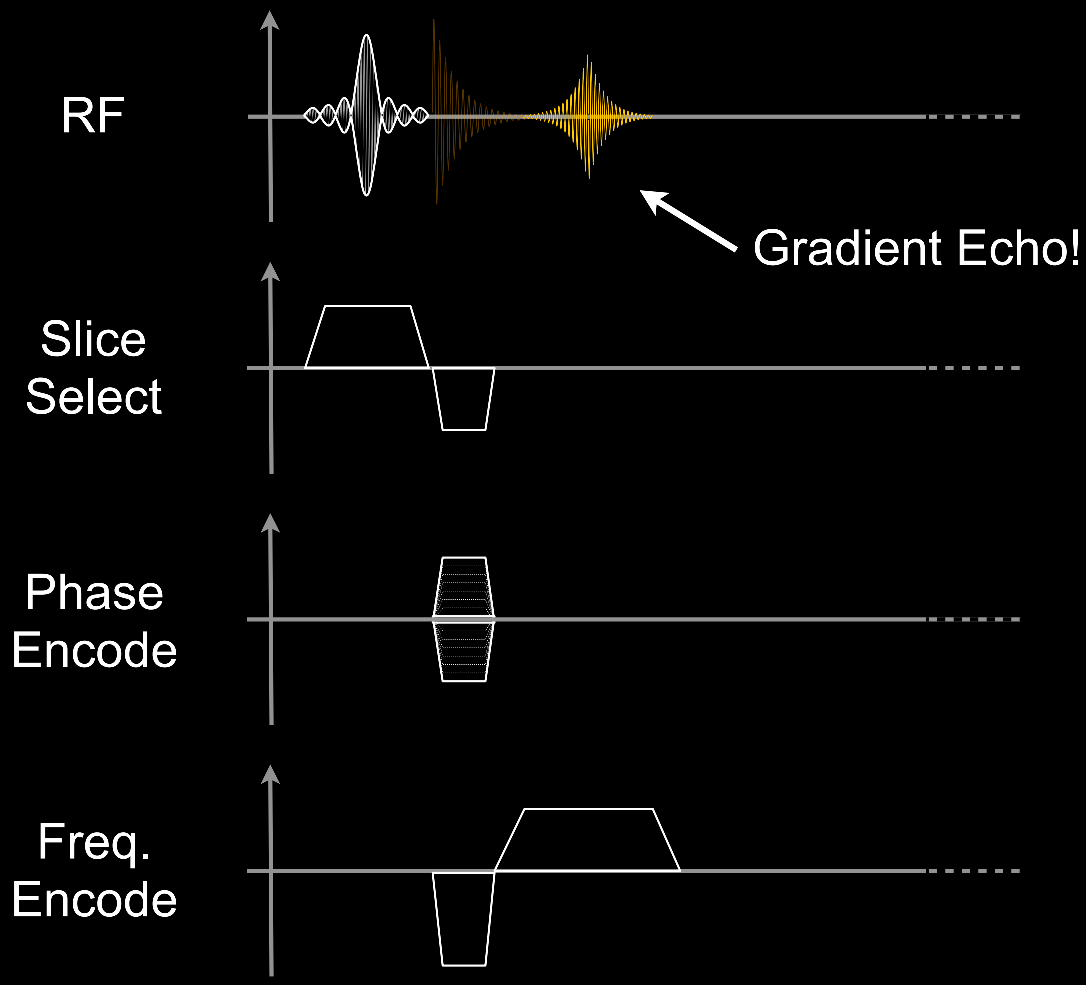

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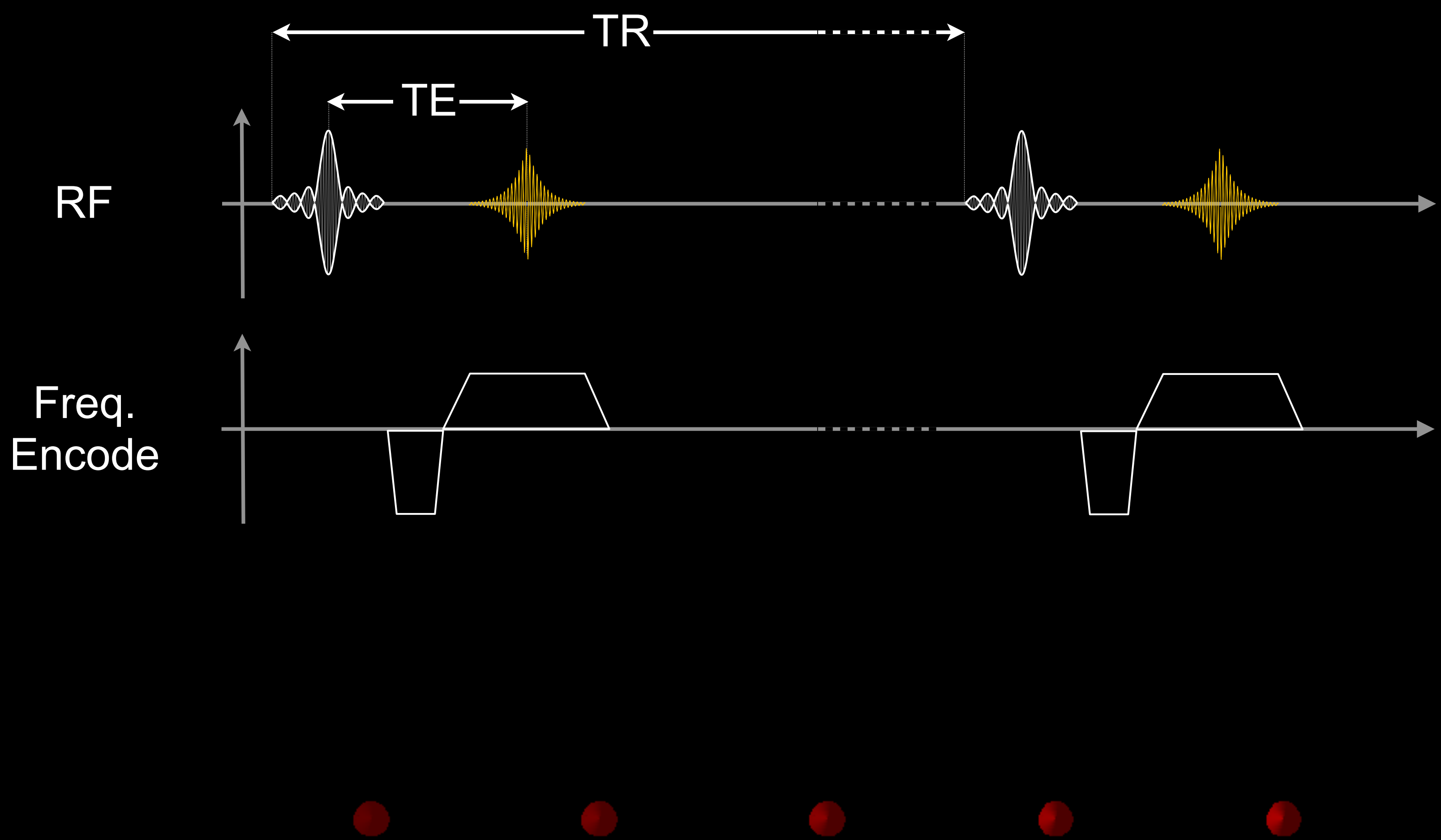
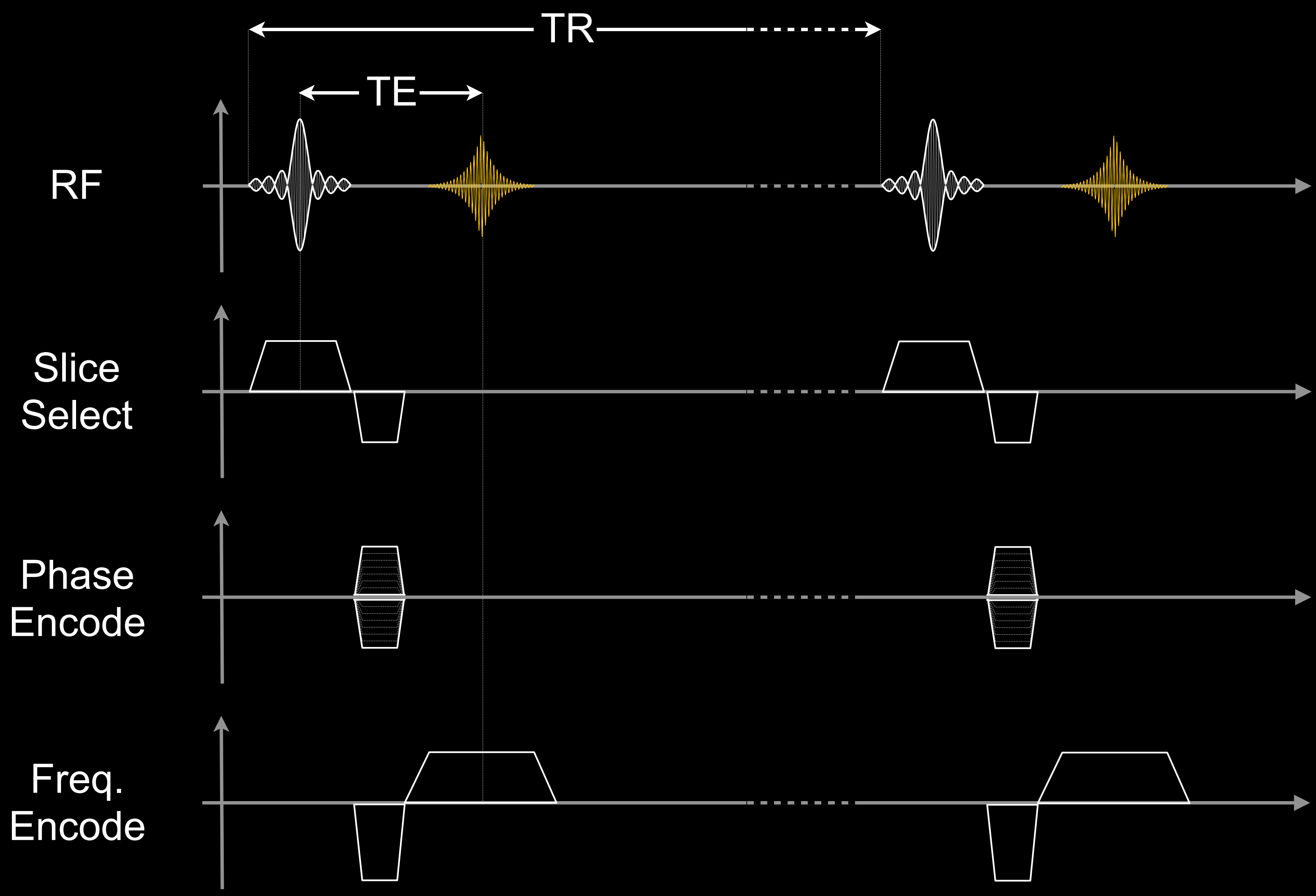
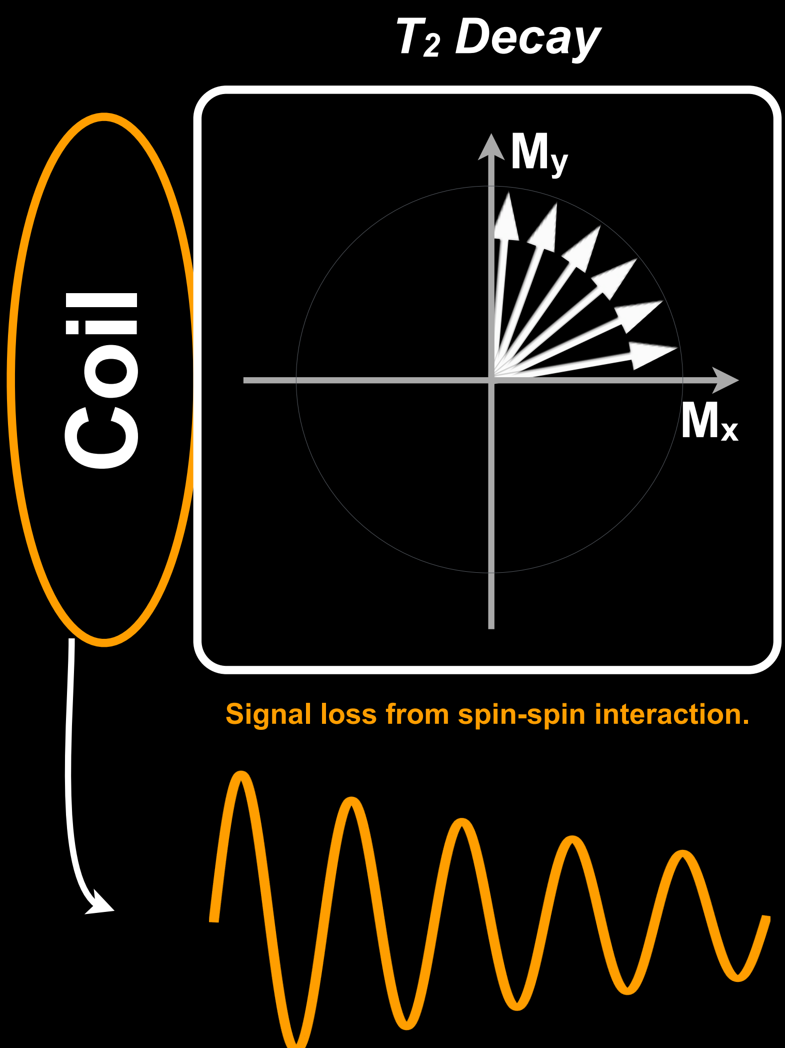


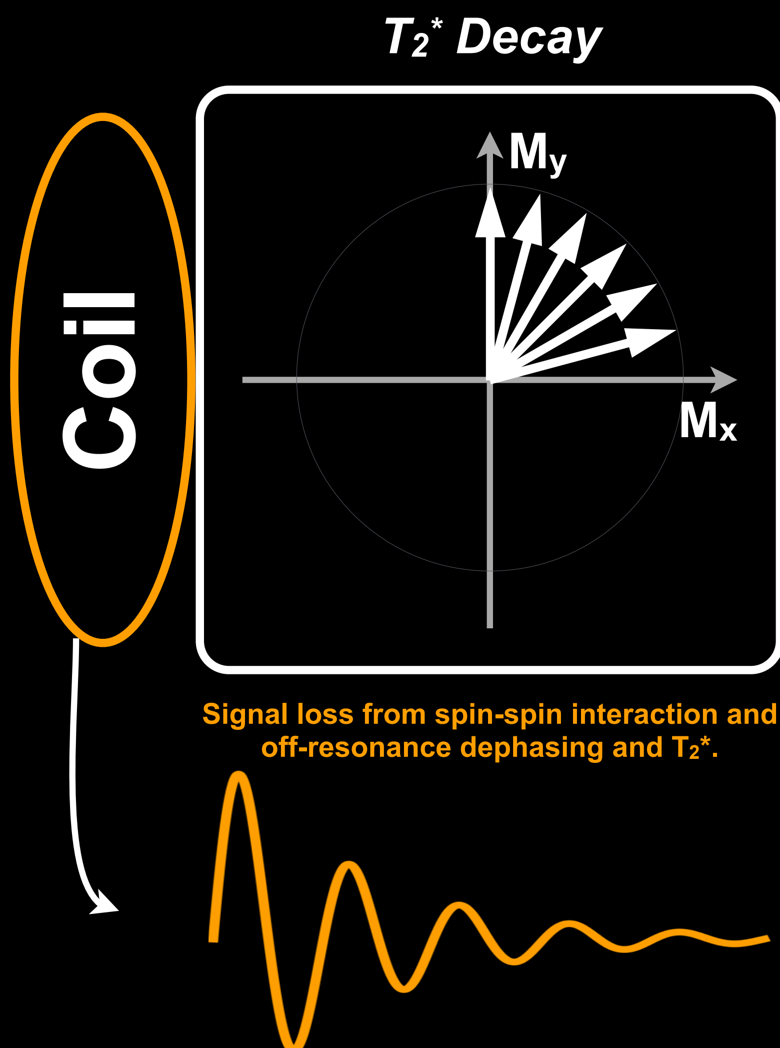
Basic Gradient Echo Sequence



T_2 versus T_2*



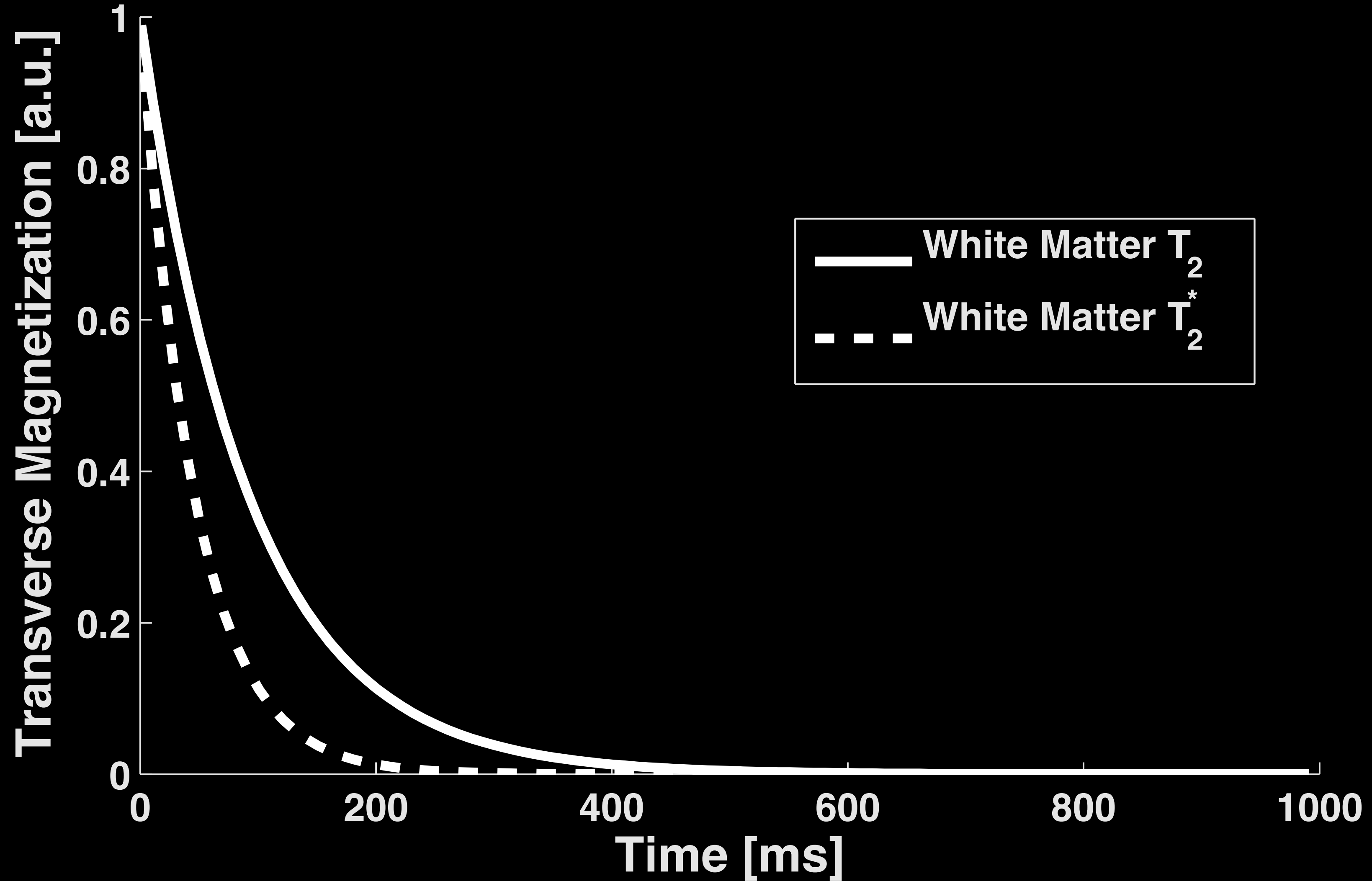
Signal loss from spin-spin interaction.



Signal loss from spin-spin interaction and off-resonance dephasing and T_2*.

T_2* is signal loss from spin dephasing and T_2

T2*<T2 (always!)

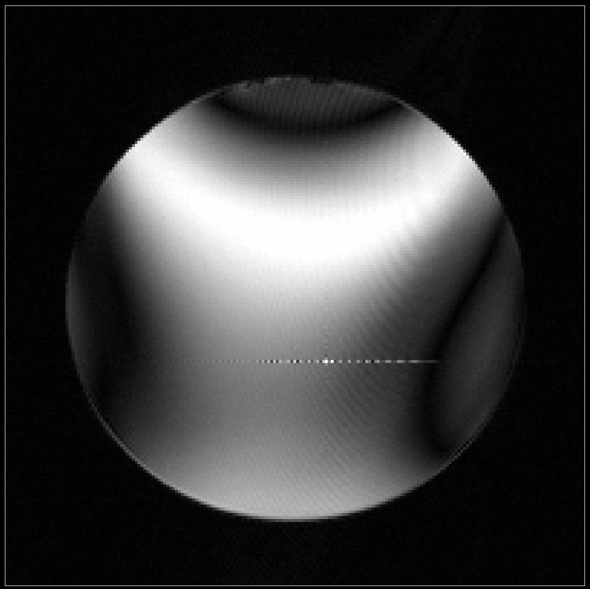


Transverse Magnetization [a.u.]
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
Time [ms]
White Matter T_2
White Matter T_2^*

SE vs. GRE: B_0 Inhomogeneity

- Images acquired with a bad shim
  - Poor B_0 homogeneity (lots of off-resonance)

Spin Echo



Gradient Echo

Images Courtesy of http://chickscope.beckman.uiuc.edu/roosts/carl/artifacts.html

Gradient Echoes & Contrast

Gradient Echo Sequences

- Spoiled Gradient Echo
  - SPGR, FLASH, T1-FFE
- Balanced Steady-State Free Precession
  - TrueFISP, FIESTA, Balanced FFE

Principal GRE Advantages

- Fast Imaging Applications
  - **Why?** *Can use a shorter TE/TR than spin echo*
  - **When?** Breath-held, realtime, & 3D volume imaging
- Flexible image contrast
  - **Why?** Adjusting TE/TR/FA controls the signal
  - **When?** Characterize a tissue for diagnosis
- Bright blood signal
  - **Why?** Inflowing spins haven't "seen" numerous RF pulses
  - **When?** Cardiovascular & angiographic applications

Principal GRE Advantages

- Low SAR
  - **Why?** Imaging flip angles are (typically) small
  - **When?** When heating risks are a concern
- Quantitative
  - **Why?** Multi-echo acquisition are practical.
  - **When?** Flow quantification & Fat/Water mapping
- Susceptibility Weighted Imaging
  - **Why?** No refocusing pulse.
  - **When?** T_2^*-weighted (hemorrhage) imaging
- More...

Principal GRE Disadvantages

- Off-resonance sensitivity
  - **Why?** No refocusing pulse
    - Field inhomogeneity, Susceptibility, & Chemical shift
- T_2^*-weighted rather than T_2-weighted
  - **Why?** No re-focusing pulse
    - Spin-spin dephasing is not reversible with GRE
- Larger metal artifacts than SE
  - Why? No refocusing pulse.
    - Large field inhomogeneities aren't corrected with GRE

Spoiled Gradient Echo Contrast

Contrast depends on tissue's ρ, T_1 and T_2*.

$$A_{echo} \propto \frac{\rho\left(1 - e^{-TR/T_1}\right)}{1 - \cos\alpha e^{-TR/T_1}} \sin\alpha e^{-TE/T_2^*}$$

Contrast adjusted by changing TR, flip angle, and TE

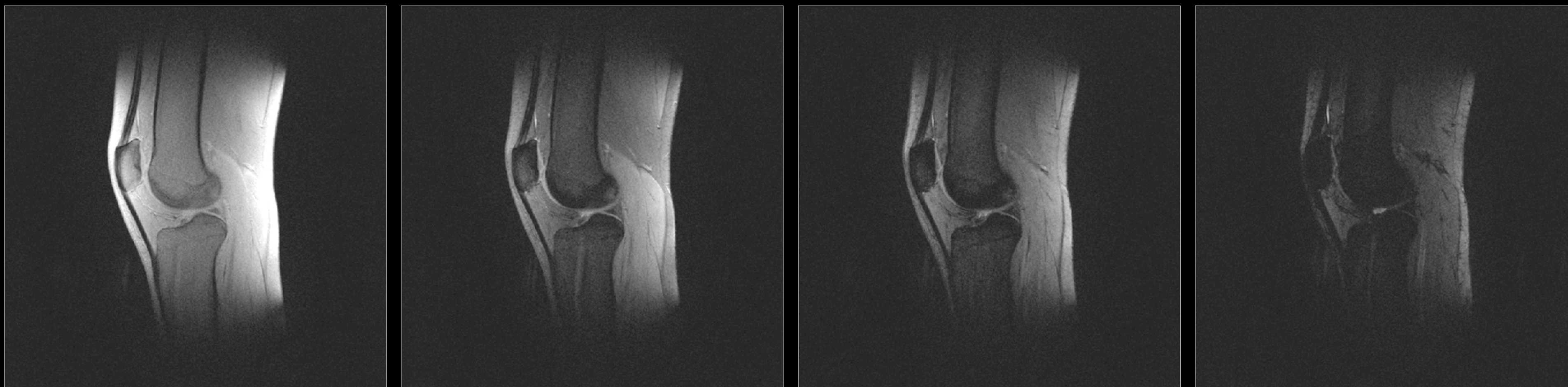
Spoiled Gradient Echo Contrast

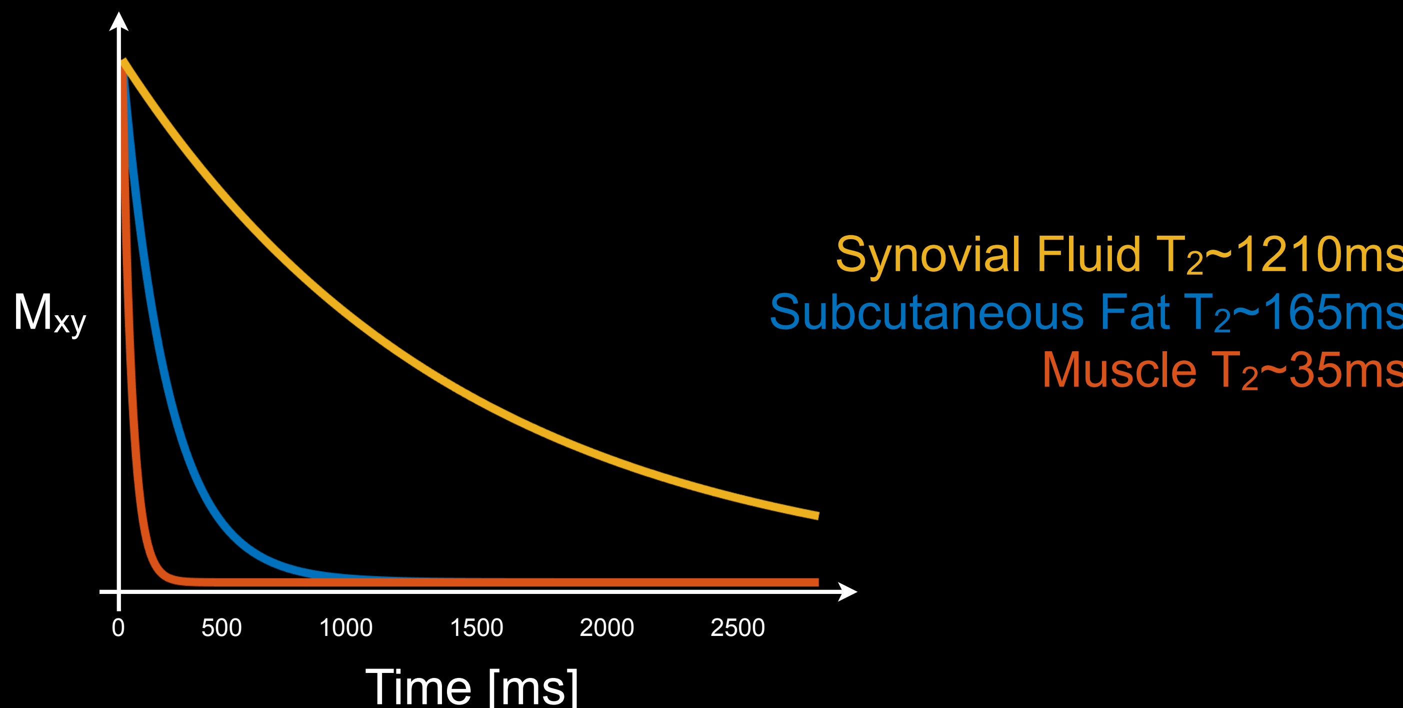
Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	Short	Long	Small
T_1-Weighted	Short	Intermediate	Large
T_2^*-Weighted	Intermediate	Long	Small

T_2^*-weighted Gradient Echo MRI

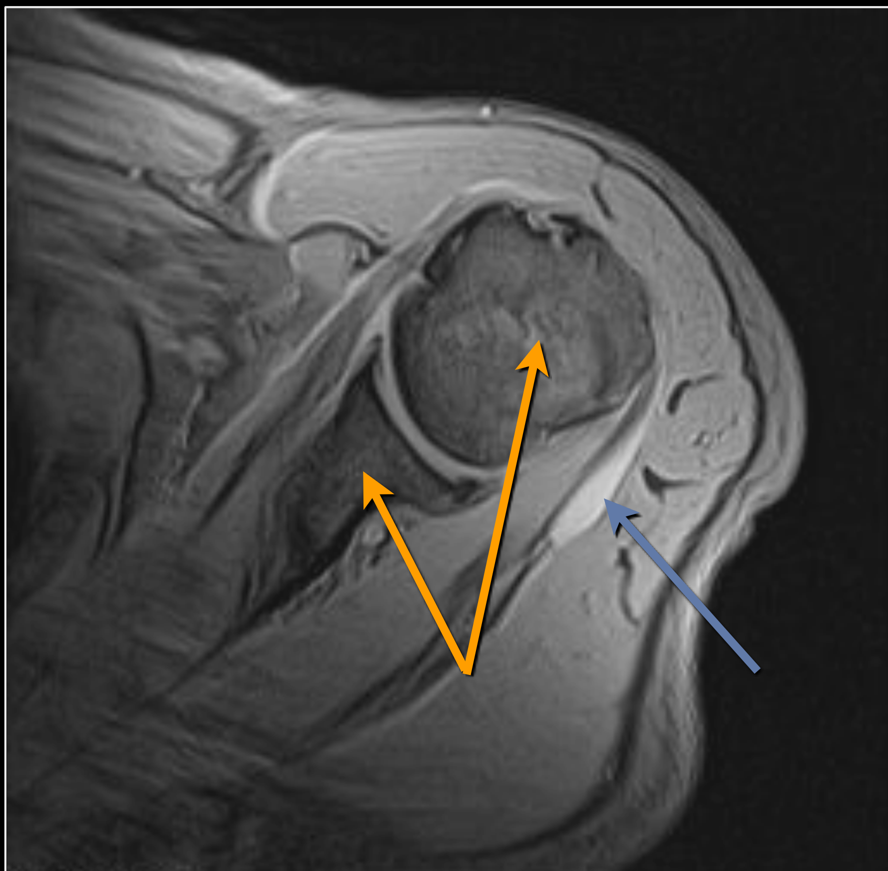
FLASH – TE=4.8ms; TR=200ms | FLASH – TE=14.2ms; TR=200ms | FLASH – TE=24ms; TR=200ms | FLASH – TE=49ms; TR=200ms



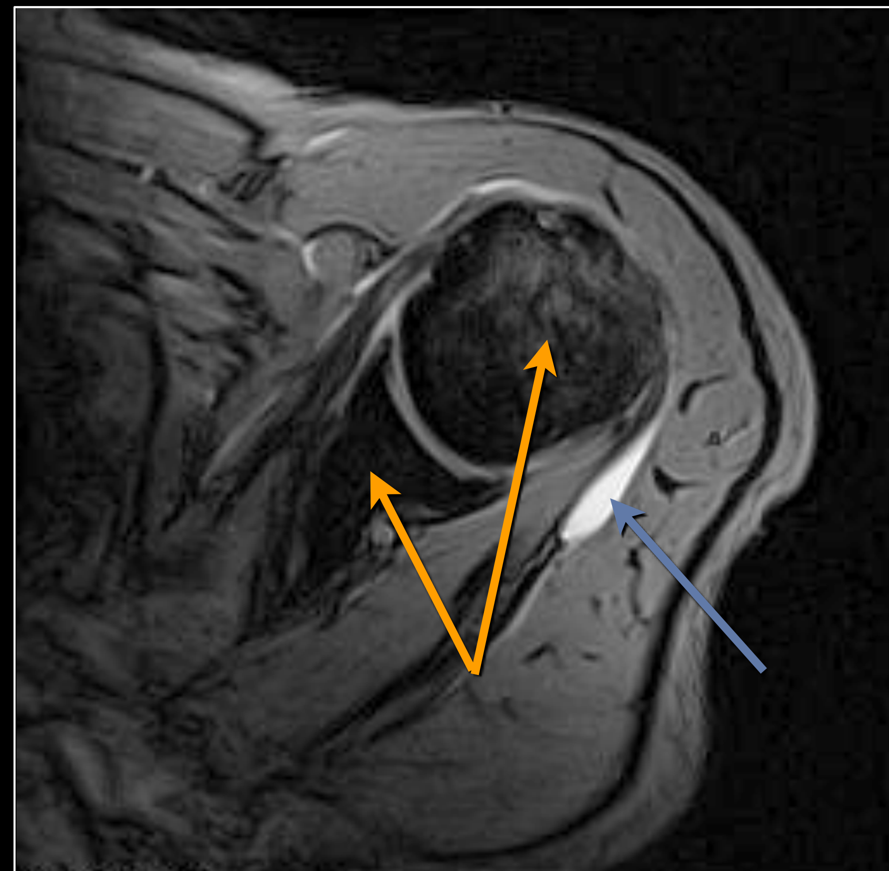


Musculoskeletal MRI at 3.0 T: relaxation times and image contrast. AJR Am J Roentgenol. 2004 Aug;183(2):343-51.

T_2*-weighted Gradient Echo MRI



TE=9ms



TE=30ms

Susceptibility Weighting (darker with longer TE)

Bright fluid signal (long T_2* is "brighter" with longer TE)

Images Courtesy of Brian Hargreaves

Gradient vs Spin Echo Contrast

Gradient Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	<5ms	>100ms	<10°
T_1-Weighted	<5ms	<50ms	>30°
T_2^*-Weighted	>20ms	>100ms	<10°

Spin Echo Parameters

Type of Contrast	TE	TR	Flip Angle
Spin Density	10-30ms	>2000ms	90+180
T_1-Weighted	10-30ms	450-850ms	90+180
T_2-Weighted	>60ms	>2000ms	90+180

Gradient Echoes & Flip Angle

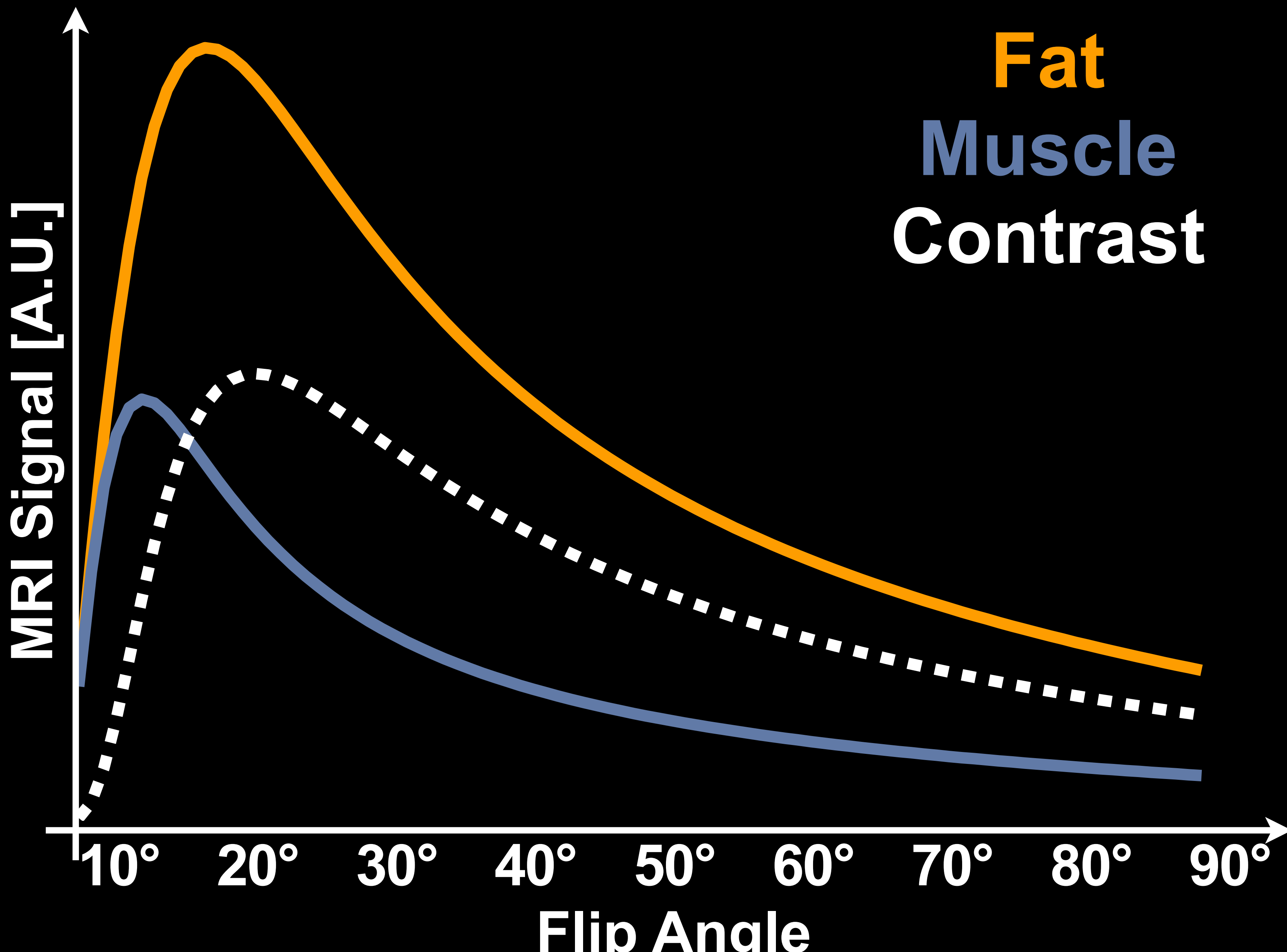
Spoiled GRE & Ernst Angle

$$\alpha_{Ernst} = \arccos\left(e^{-\frac{TR}{T_1}}\right)$$

Produces the largest MRI signal for a given TR and T_1

Tissue	T_1 [ms]	T_2 [ms]
muscle	875	47
fat	260	85

Spoiled GRE & Ernst Angle



Spoiled GRE & Ernst Angle

1°

5°

10°
High Muscle Signal

20°
High Fat Signal

30°
Highest Contrast

45°

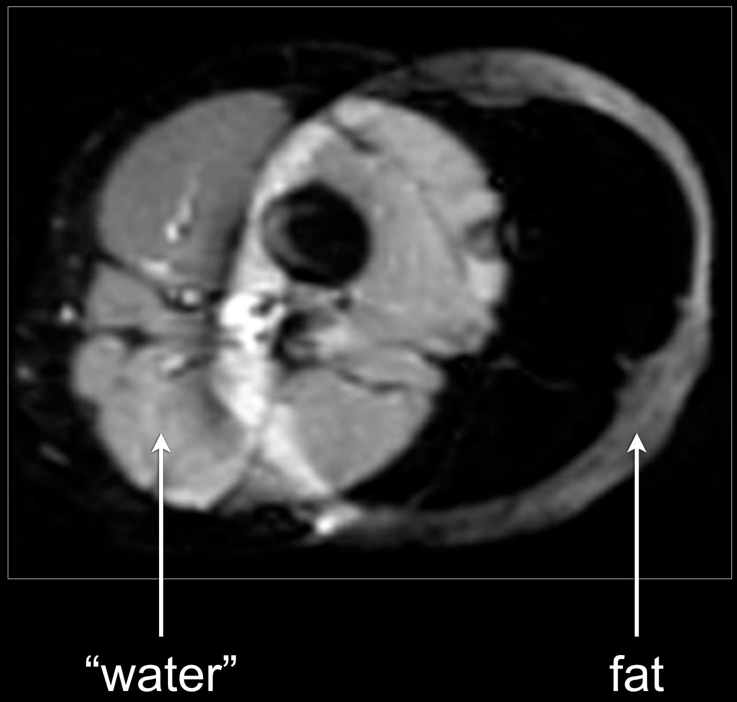
60°

90°

Gradient Echoes & Fat

Chemical Shift - Type 1

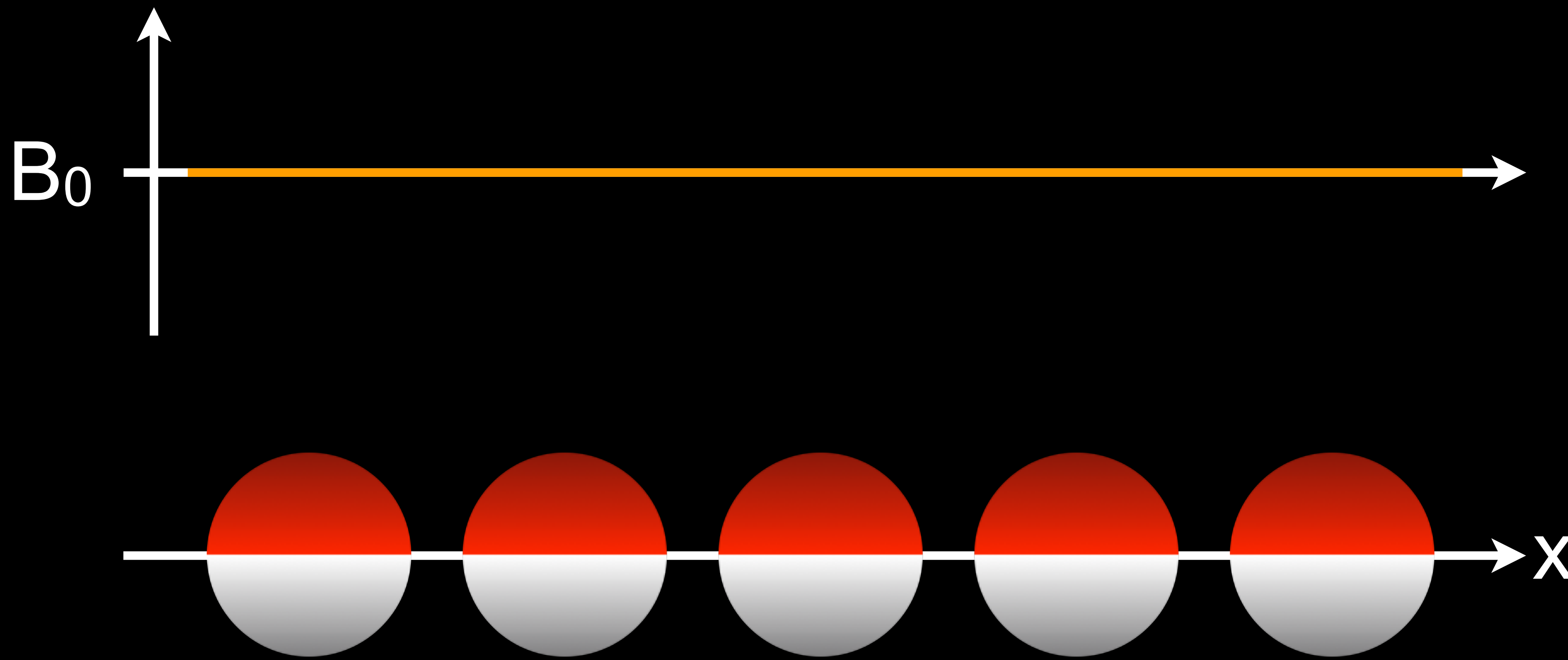
- Fat and water have different Larmor frequencies
  - ~220Hz different at 1.5T
  - ~440Hz different at 3.0T
- Spatial position is related to spin frequency in MRI.
  - Fat is *more* spatially mis-registered @ 3T



Chemical Shift – Fat (–CH_2) is ~220Hz *lower* at 1.5T

Image Courtesy of Brian Hargreaves

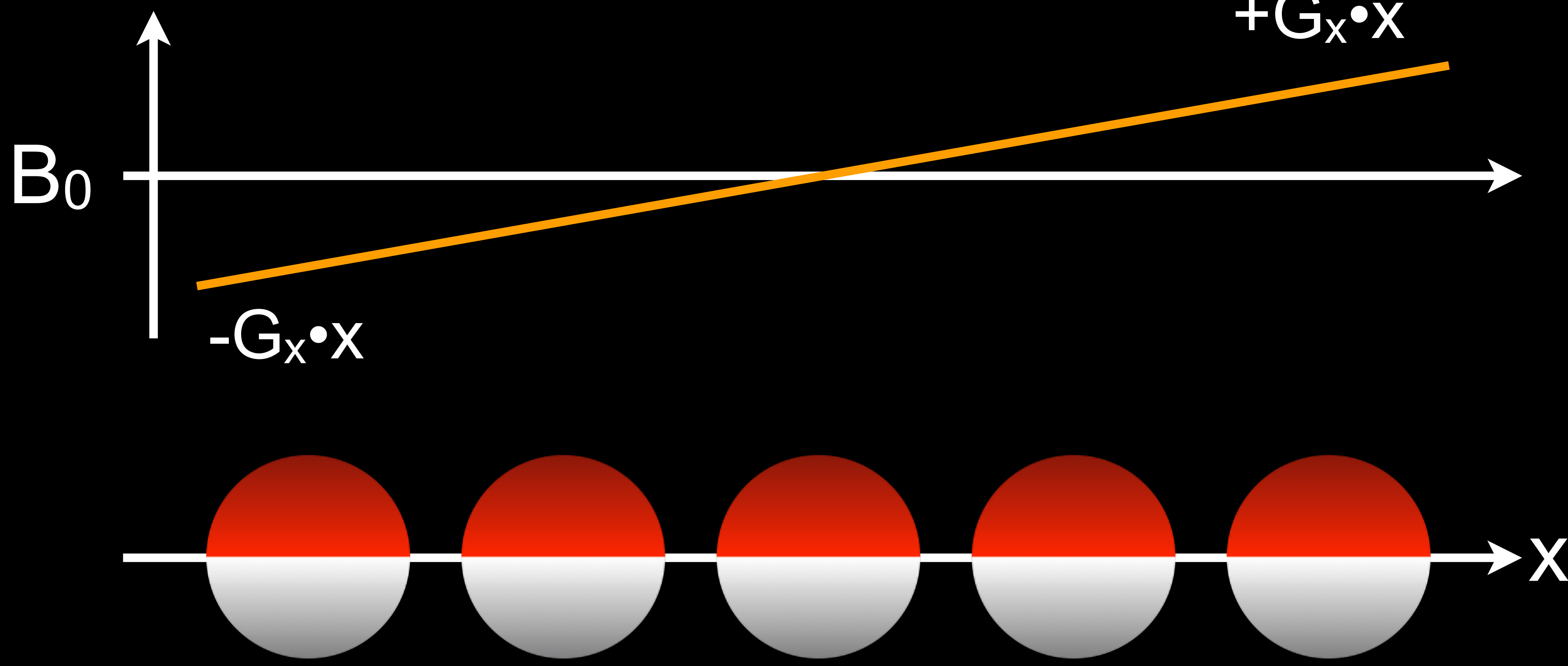
GRE & Fat/Water Frequency



Water Spins in a *Uniform* Field

Water spins precess at the same Larmor frequency in a uniform B_0 field.

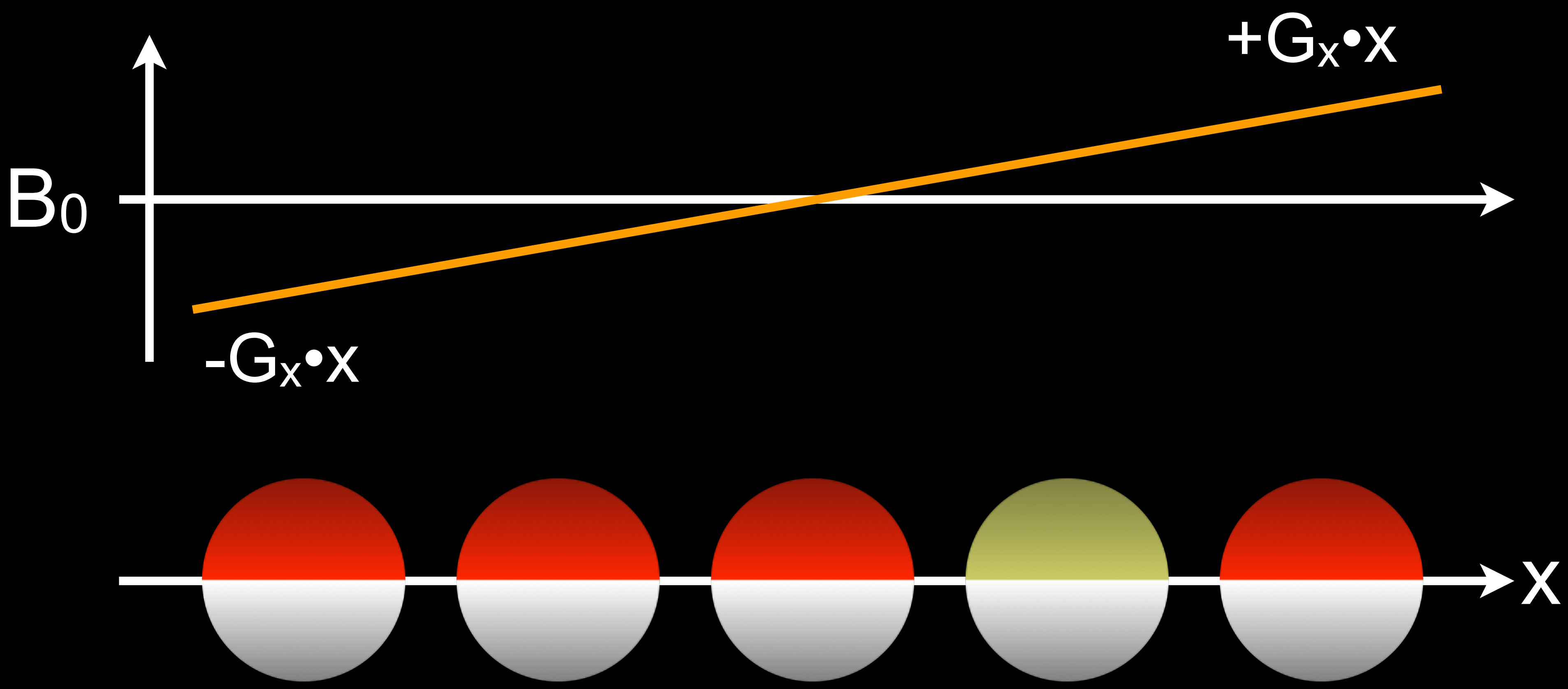
GRE & Fat/Water Frequency



Water Spins in a *Gradient* Field

Water spins precess at ***different*** Larmor frequencies in a non-uniform B_0 field.

GRE & Fat/Water Frequency

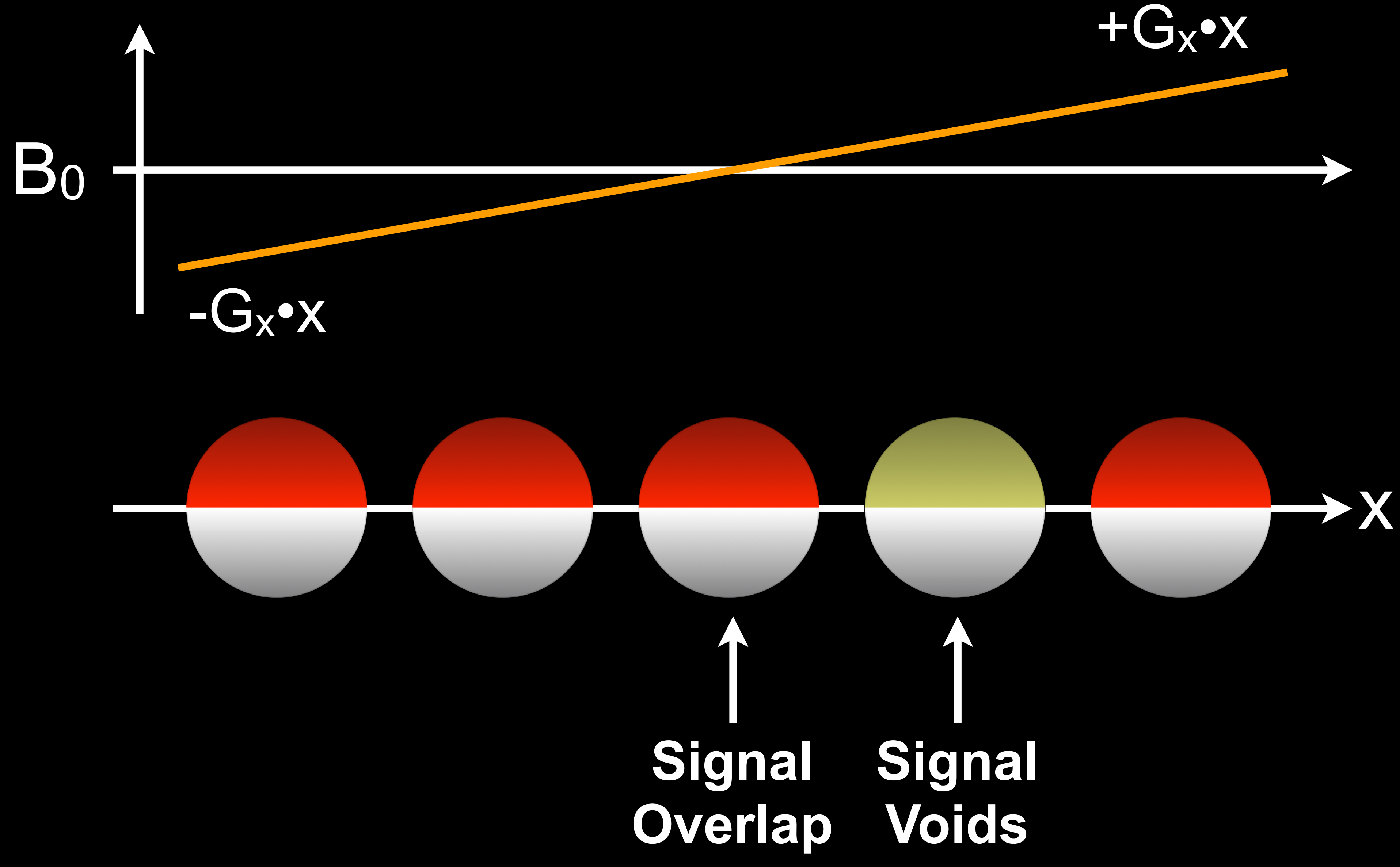


Water & Fat Spins in a Gradient Field

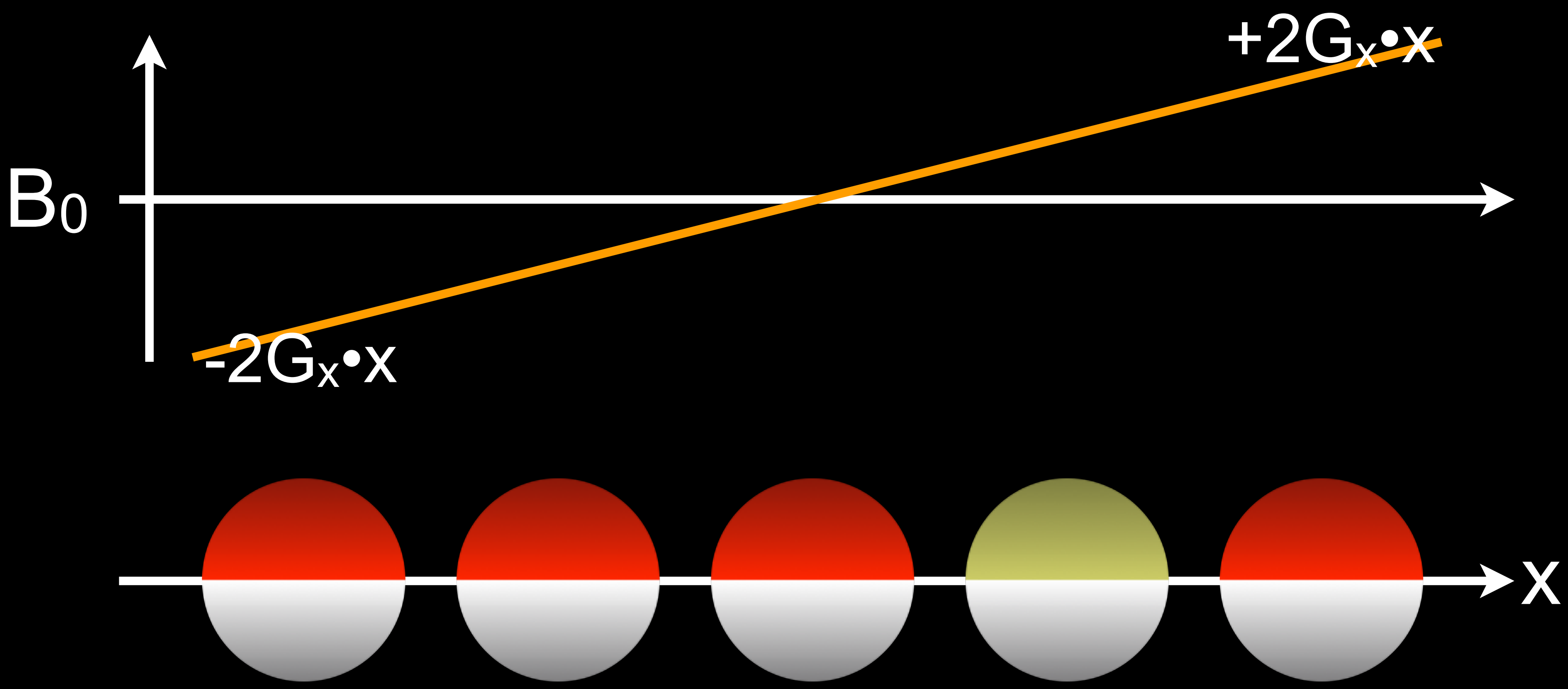
Fat Spins ~220Hz slower than water @ 1.5T

Spatial ***position*** is inferred from Larmor frequency.
Chemical (frequency) shift produces and apparent spatial shift.

GRE & Fat/Water Frequency

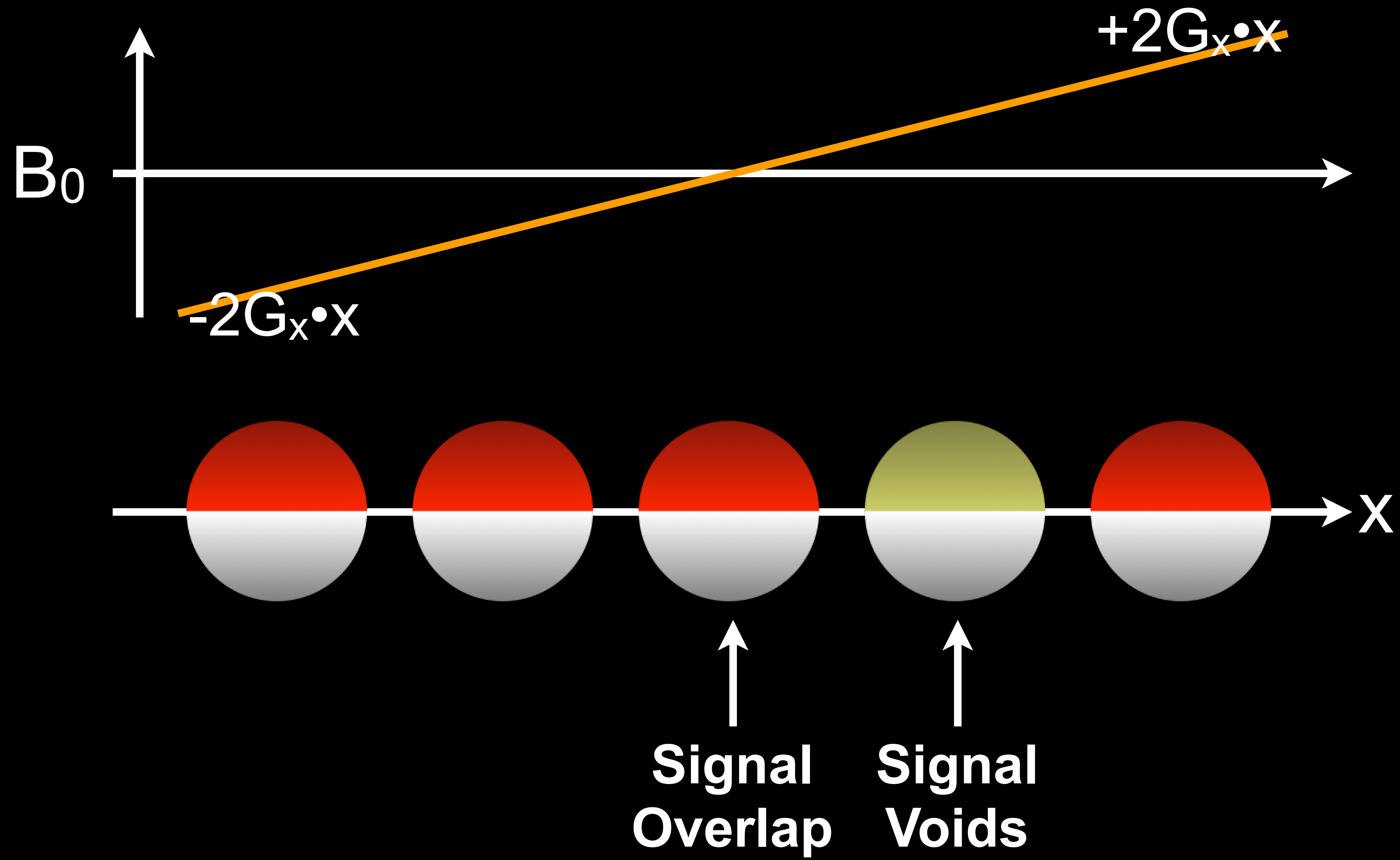


GRE and Bandwidth



Higher bandwidths use stronger gradients and result in larger frequency differences along x.
Chemical shift (frequency) is fixed for B_0, therefore chemical shift (Δx) is a smaller percentage.

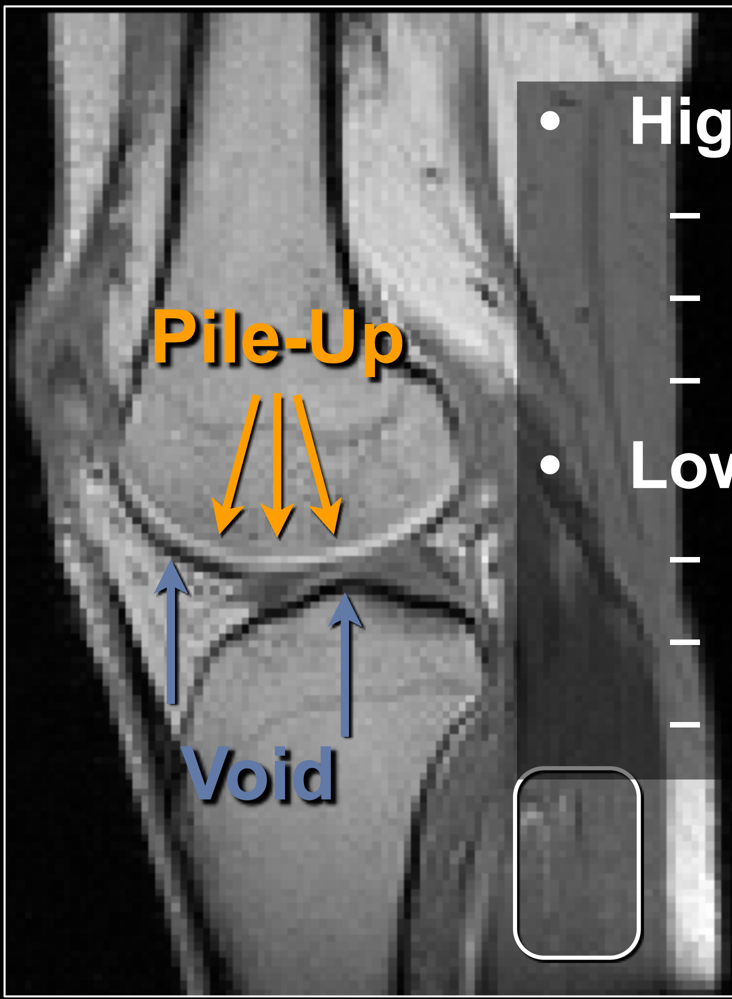
GRE and Bandwidth



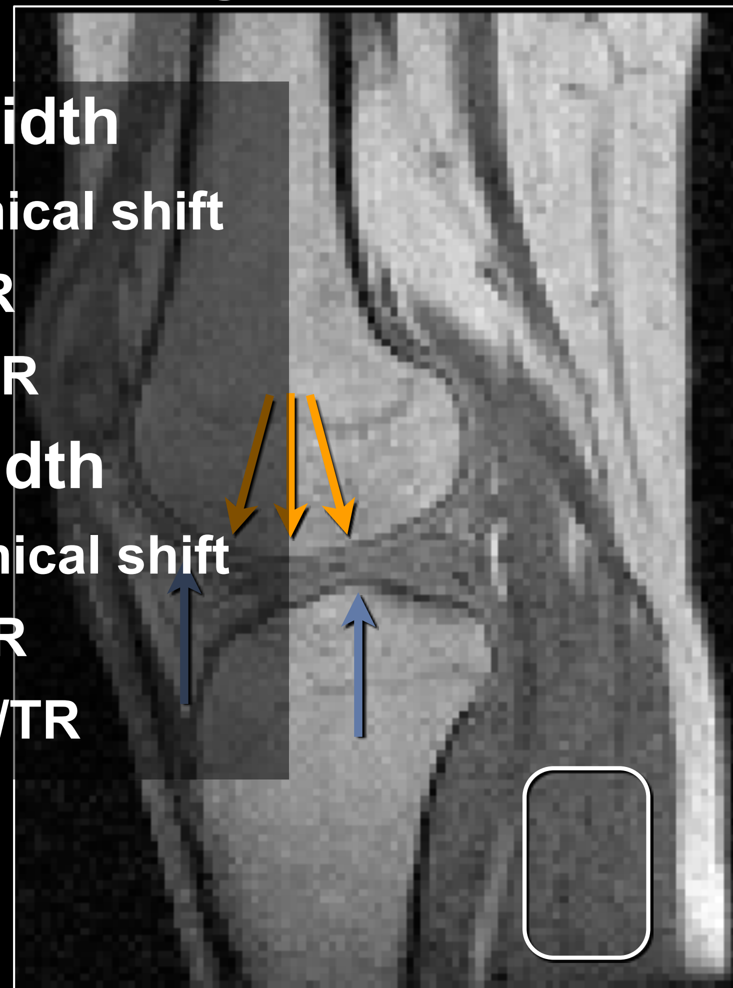
High bandwidth scans have less chemical shift.

GRE, Fat/Water & Bandwidth

Low Bandwidth



High Bandwidth

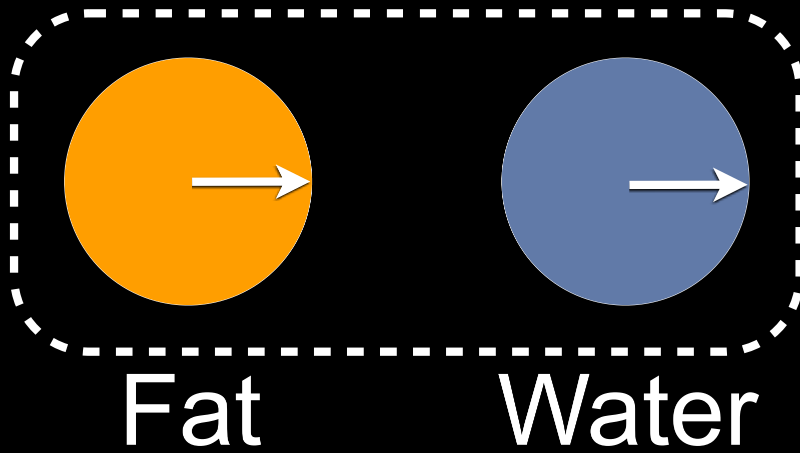


- **High Bandwidth**
  - **Less chemical shift**
  - **Lower SNR**
  - **Short TE/TR**
- **Low Bandwidth**
  - **More chemical shift**
  - **Higher SNR**
  - **Longer TE/TR**

Acquisition ***bandwidth*** is related to the ***speed*** with which an echo is acquired. If the ***bandwidth*** (speed) is high, then there is less time for chemical shift, less time for signal acquisition (lower SNR), and a shorter TE/TR.

Chemical Shift - Type 2

- Pixels are frequently a mixture of fat and water
- Pixel intensity is the vector sum of fat and water



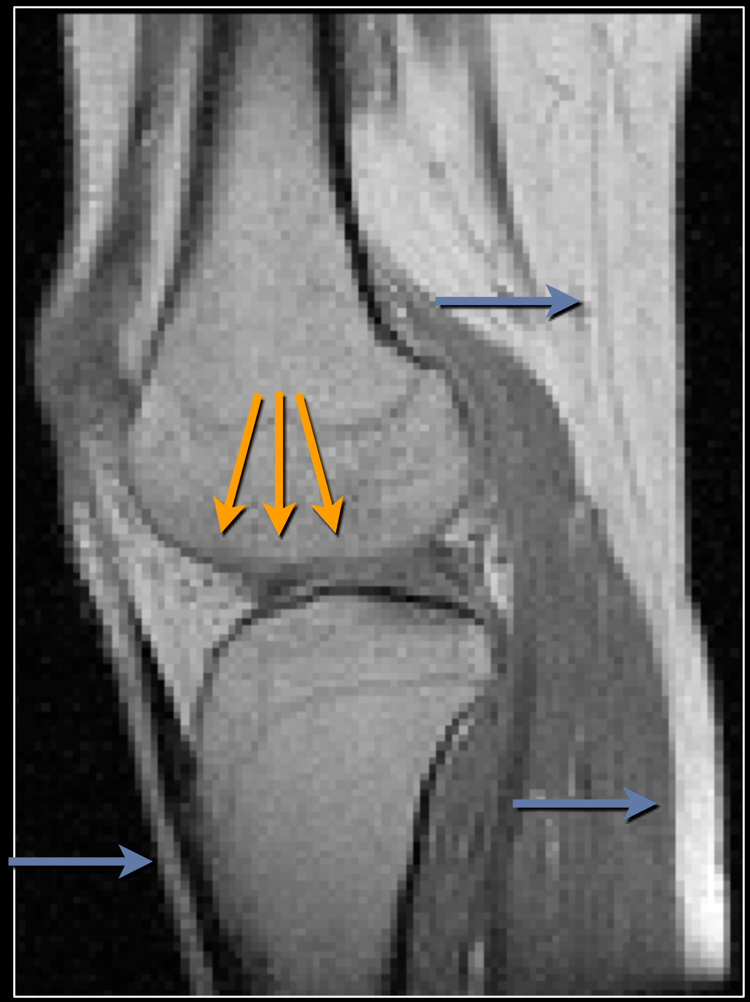
In-Phase: $\rightarrow + \rightarrow > 0$

Opposed-Phase: $\leftarrow + \rightarrow = 0$

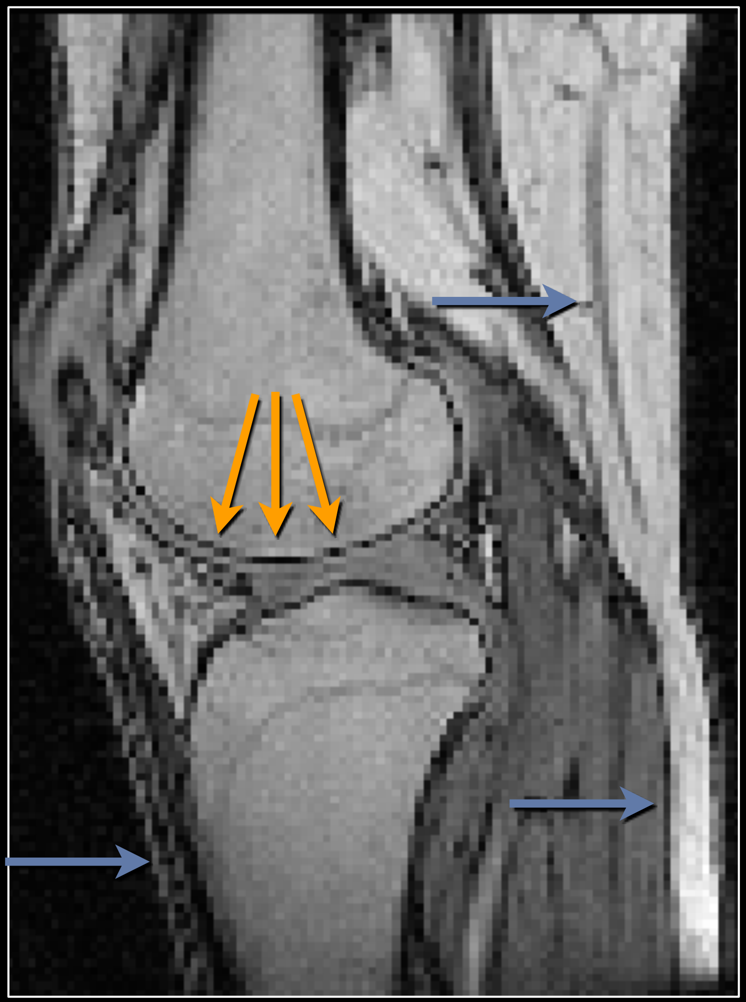
The TE controls the phase between fat and water.

GRE and Fat/Water Phase

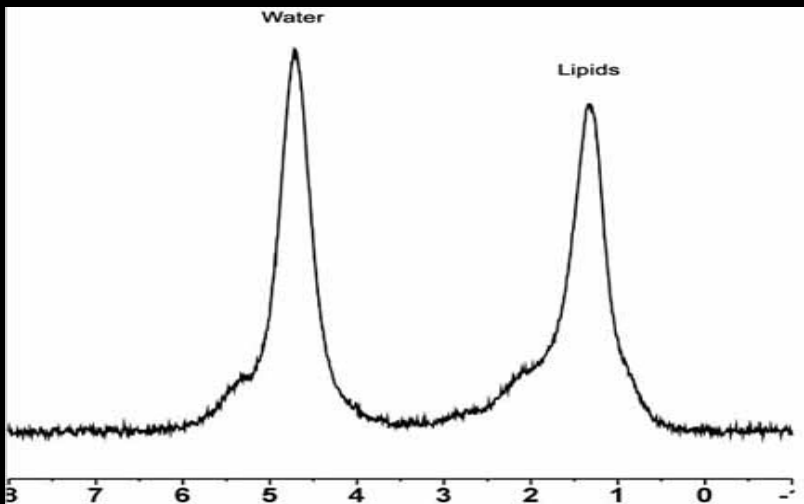
In-Phase

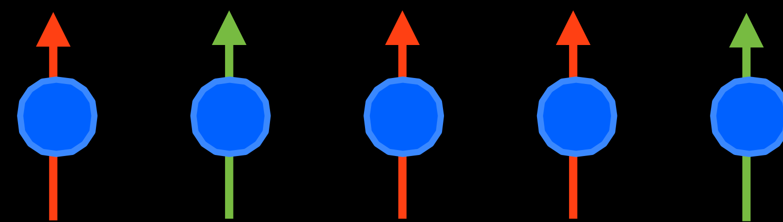


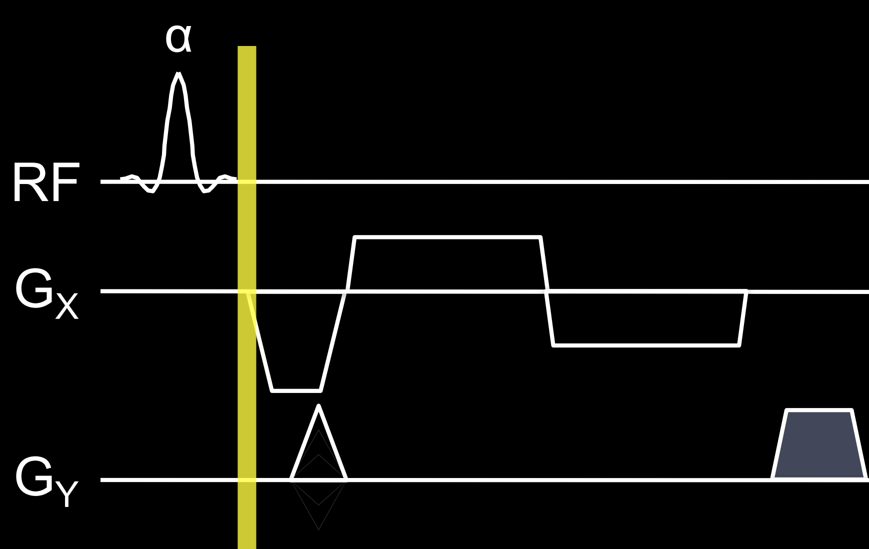
Opposed-Phase

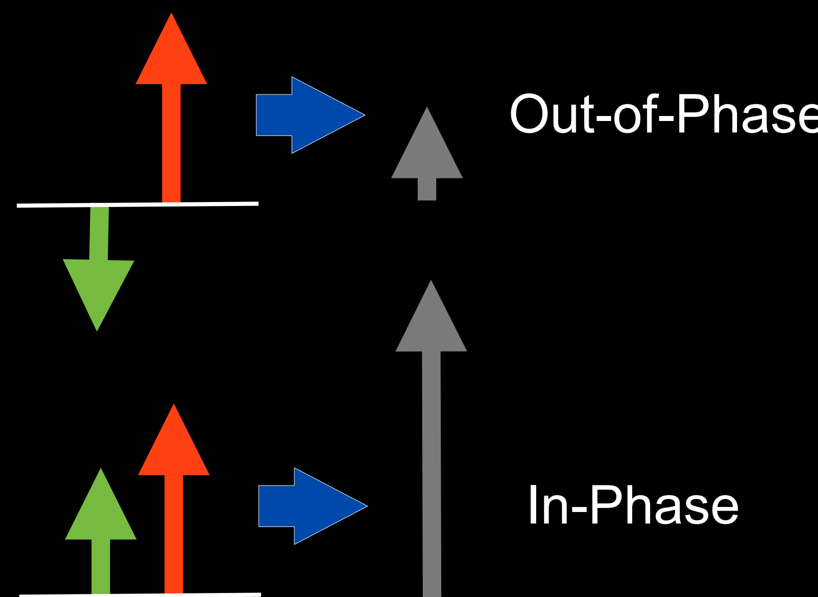


Dual-Echo Acquisition



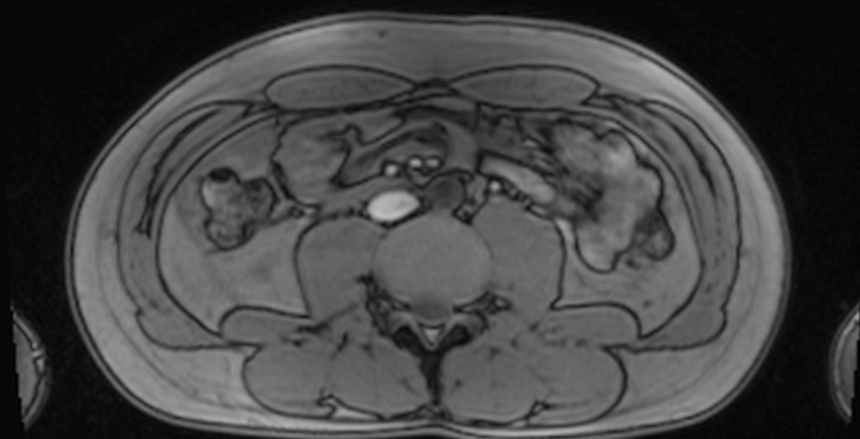




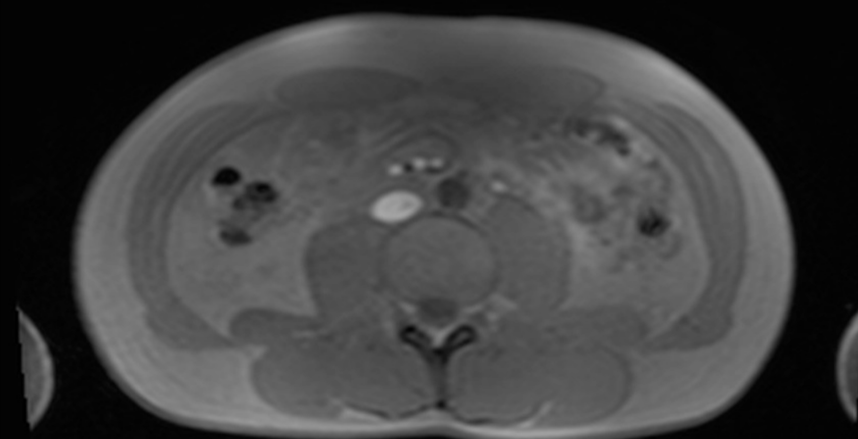


In-phase and Out-of-phase

Example: 3 T abdominal scan



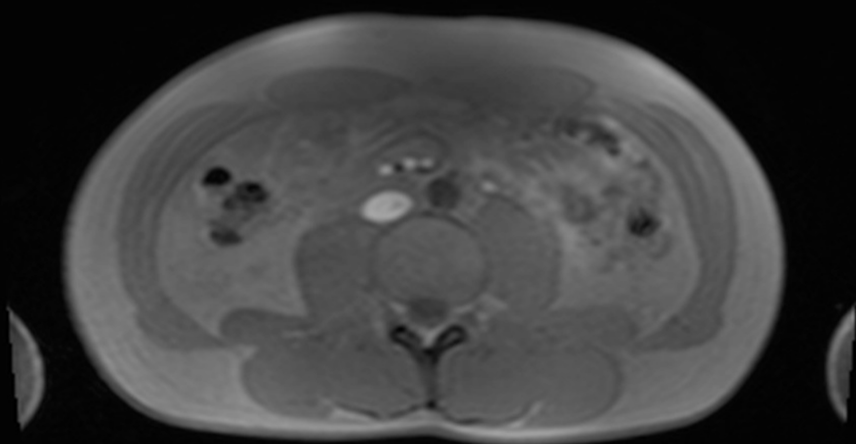
Out-of-phase (3 T), TE = 1.3 ms



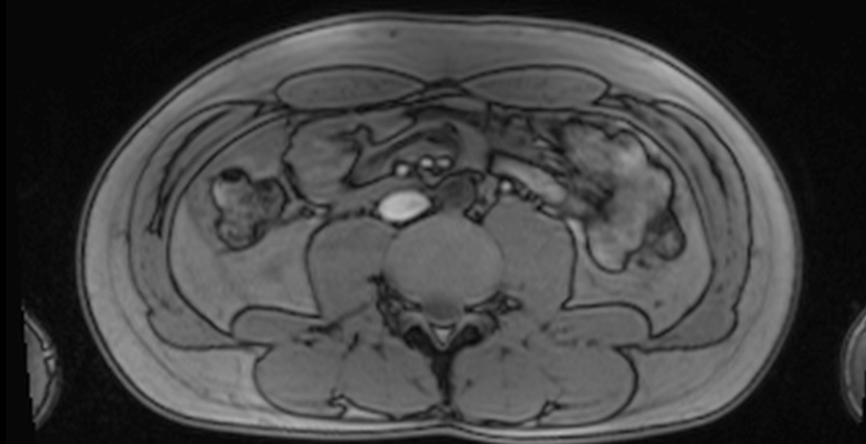
In-phase (3 T), TE = 2.6 ms

2-Point Dixon

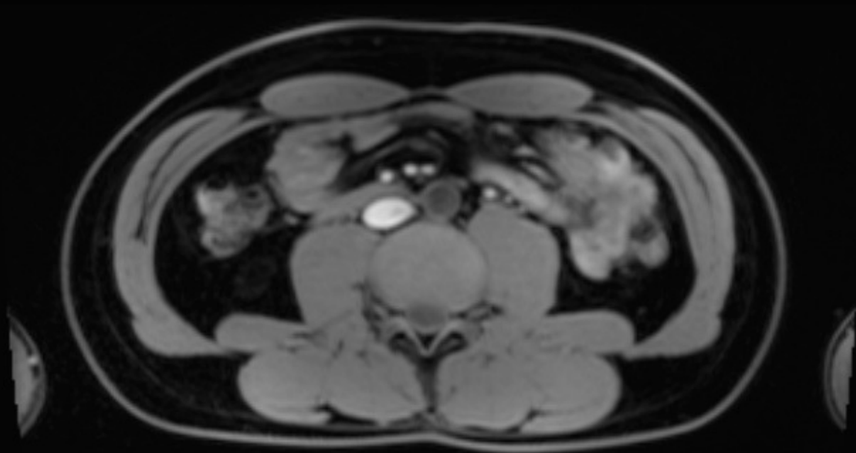
Example: 3 T abdominal scan



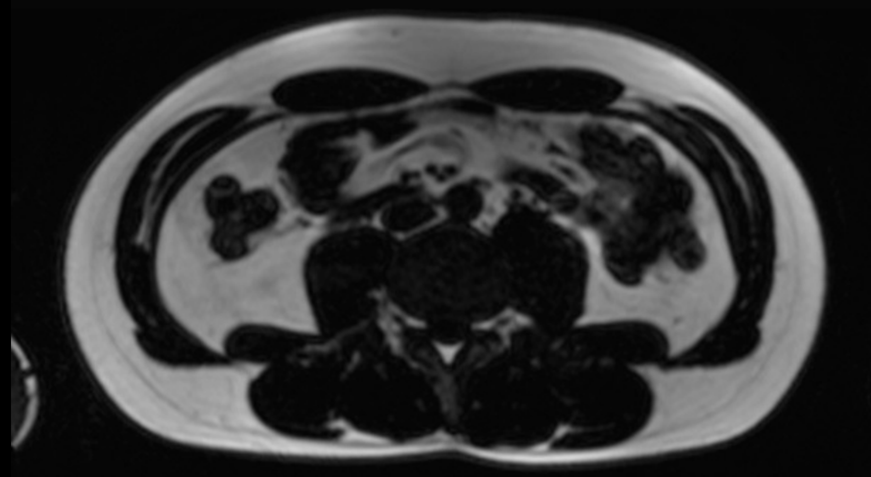
In-phase (3T), TE = 2.6 ms



Out-of-phase (3T), TE = 1.3 ms



Water



Fat

Gradient Echo – Summary

- Advantages
  - Fast Imaging Applications
  - Flexible contrast (T_1 or T_2*)

- Disadvantages
  - Off-resonance sensitivity
  - T_2^*-weighted rather than T_2-weighted

Questions?

- Related reading materials
  - Nishimura - Chap 7

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