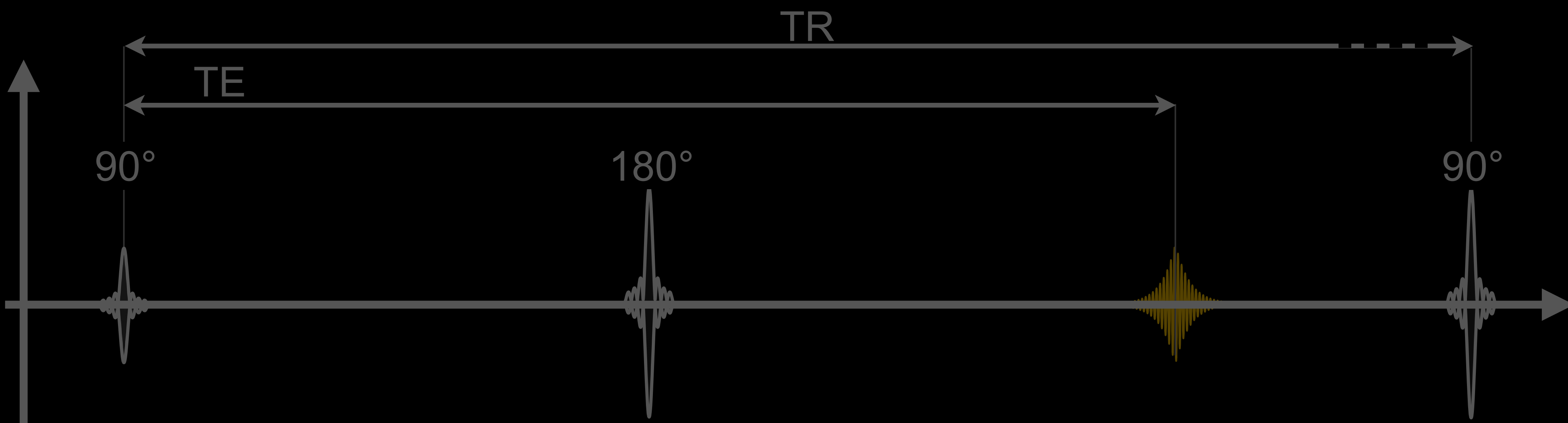

Basic Pulse Sequences II - Spin Echoes

TE=12ms TE=47ms TE=106ms TE=153ms TE=235ms

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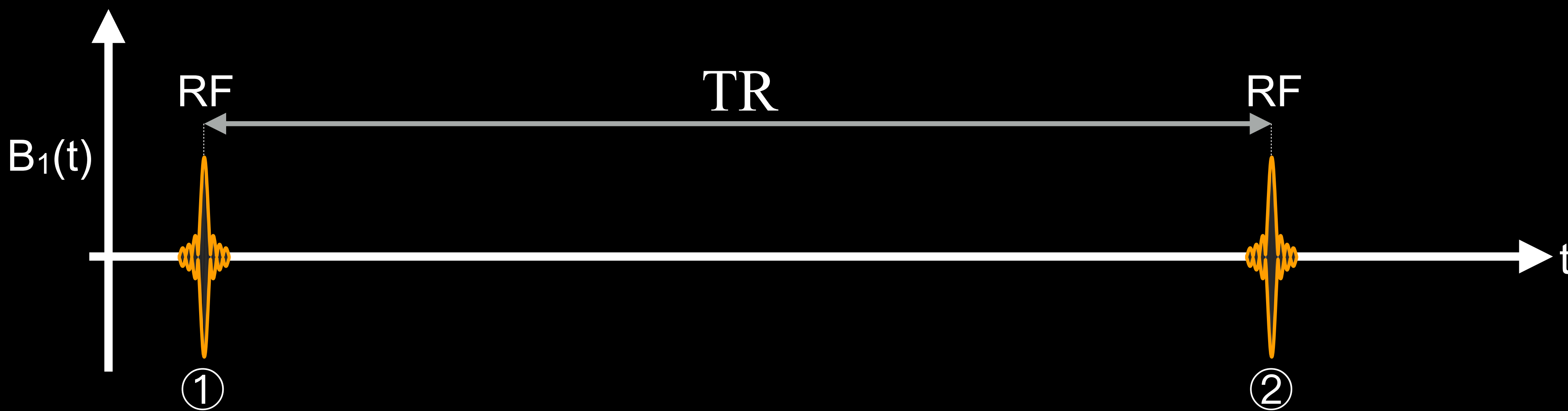
Lecture #6 Summary



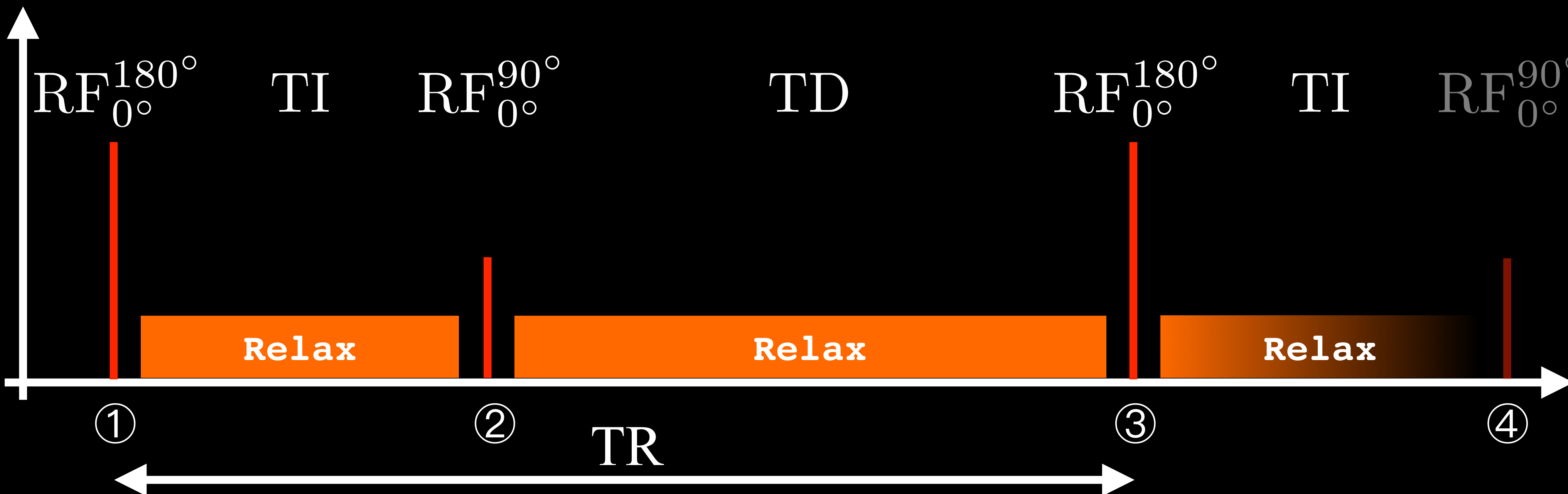
$$\vec{M}^{(1)}(0_-) = \vec{M}_0 = \begin{bmatrix} 0 \\ 0 \\ M_0 \end{bmatrix}$$ Initial Condition

$$\vec{M}^{(1)}(0_+) = RF_\theta^\alpha \vec{M}^{(1)}(0_-)$$ Forced Precession

$$\vec{M}^{(2)}(0_-) = \mathrm{E}(T_1, T_2, TR)\vec{M}^{(1)}(0_+)$$ Free Precession

$$\vec{M}^{(2)}(0_+) = RF_\theta^\alpha \vec{M}^{(2)}(0_-)$$

Inversion Recovery



$$(180^\circ - \mathrm{TI} - 90^\circ - \mathrm{TD})_N$$

IR Contrast

$$A_{fid} \propto \rho \left(1 - 2e^{-TI/T_1} + e^{-TR/T_1}\right)$$

$$I\left(\vec{r}\right) \propto \rho\left(\vec{r}\right)\left(1 - 2e^{-TI/T_1\left(\vec{r}\right)} + e^{-TR/T_1\left(\vec{r}\right)}\right) \quad \text{Eqn. 7.21}$$

The final image is the product of $\rho(r)$ and $f(T_1(r))$.

The final image contrast is controlled by TI and TR.

IR Signal Nulling Effect

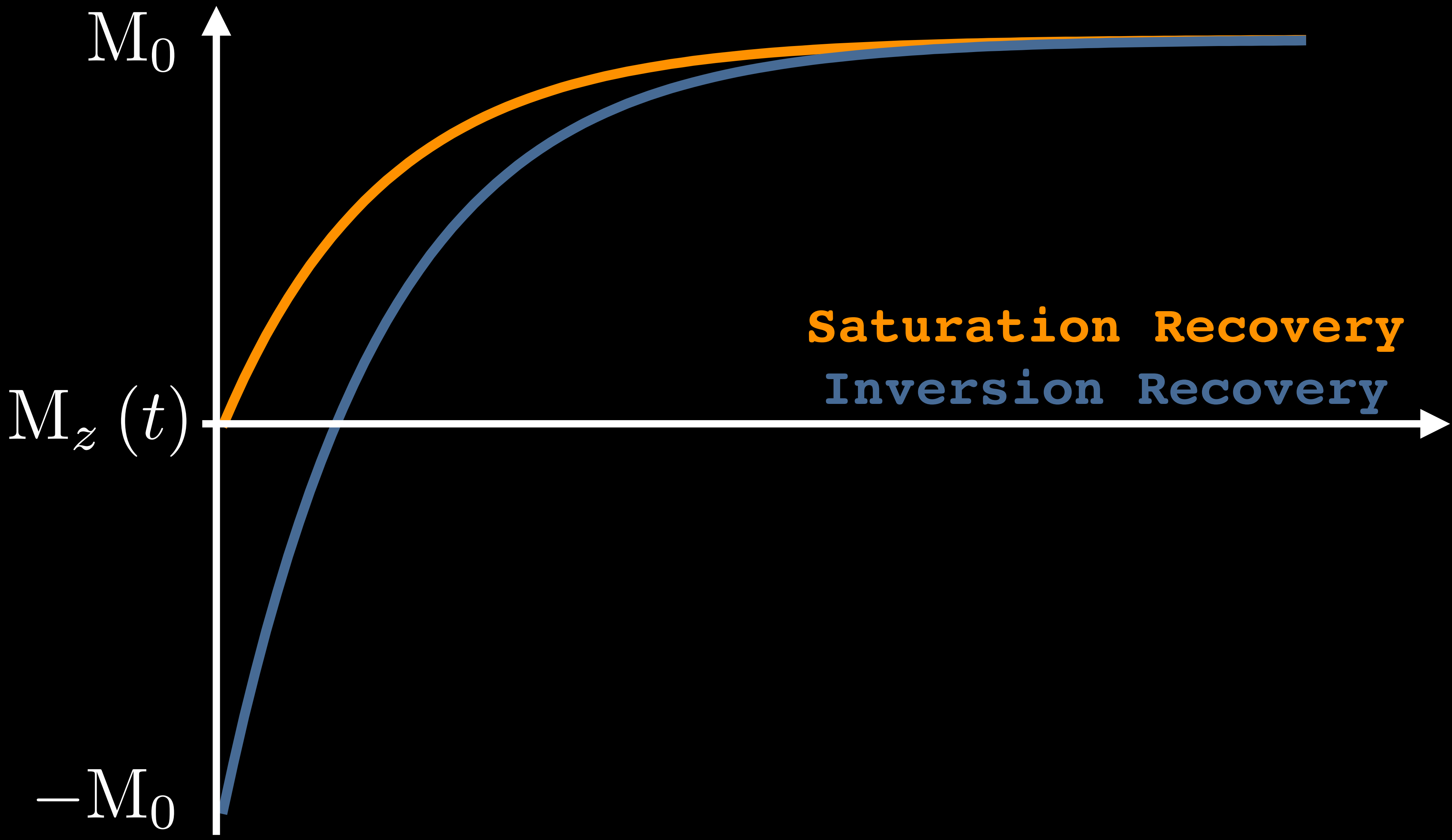
Target T_1 ↓

$$TI_{null} = \left[\ln 2 - \ln\left(1 + \exp^{-TR/T_1^0}\right)\right] T_1^0$$

$$TI_{null} = [\ln 2]\, T_1^0, \text{ if TR} \longrightarrow \infty$$

$$I\left(\vec{r}\right) = 0, \text{ if } T_1\left(\vec{r}\right) = T_1^0\left(\vec{r}\right)$$

SR vs. IR



Inversion Pulse - Applications

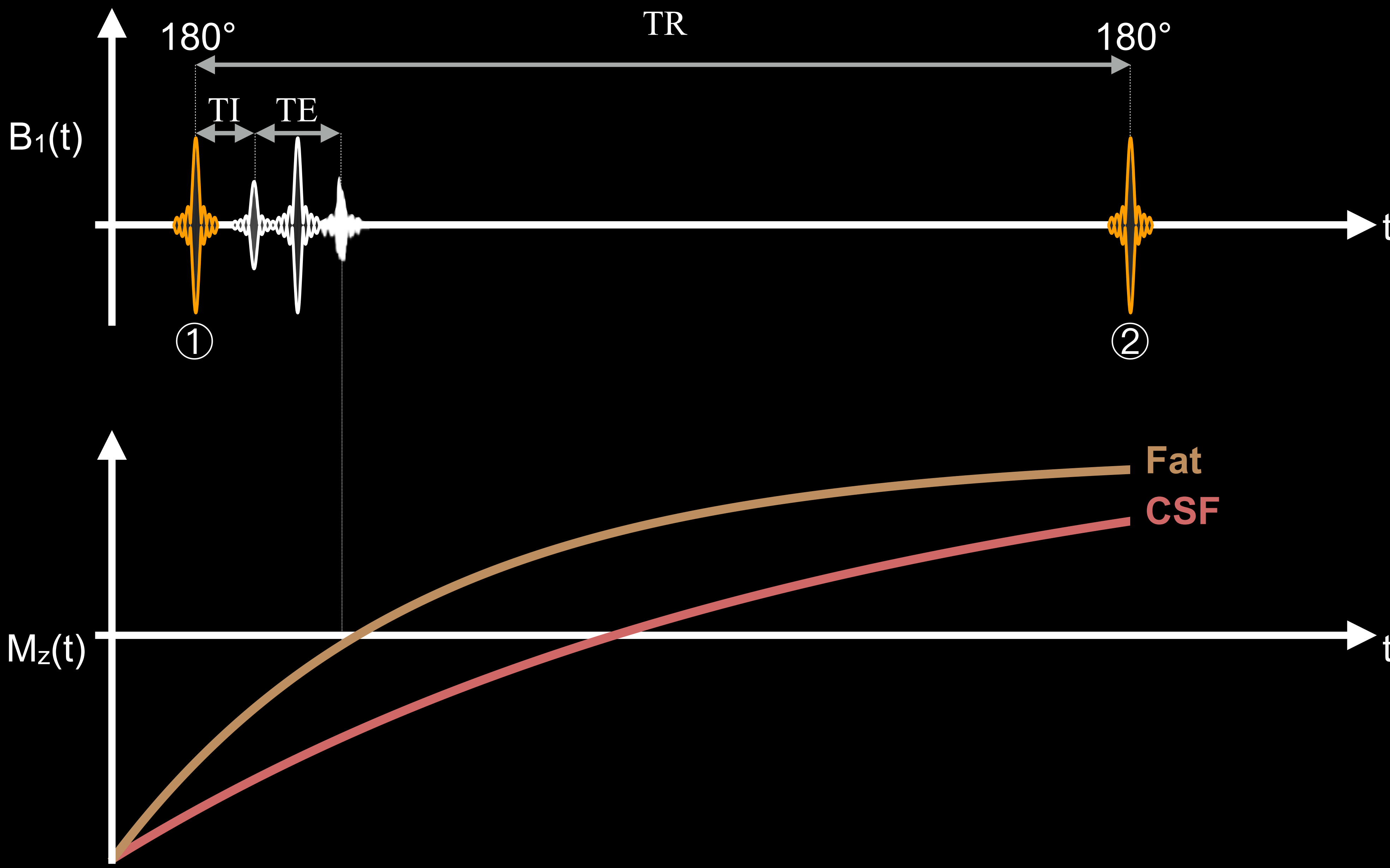
- Greater T_1 contrast than SR
- T_1 species nulling/attenuation
  - FLAIR (Fluid Attenuated Inversion Recovery)
  - STIR (Short Tau Inversion Recovery)
- IR is better than SR for generating contrast when:
  - $\rho(A)=\rho(B)$ and $T_2(A)=T_2(B)$
  - AND
  - $T_1(A)$ and $T_1(B)$ are slightly different
- Quantitative T_1 mapping

$$I(\vec{r}) \propto \rho(\vec{r}) \left(1 - 2e^{-TI/T_1(\vec{r})} + e^{-TR/T_1(\vec{r})}\right) \quad \text{Eqn. 7.21}$$

The final image is the product of $\rho(r)$ and $f(T_1(r))$.

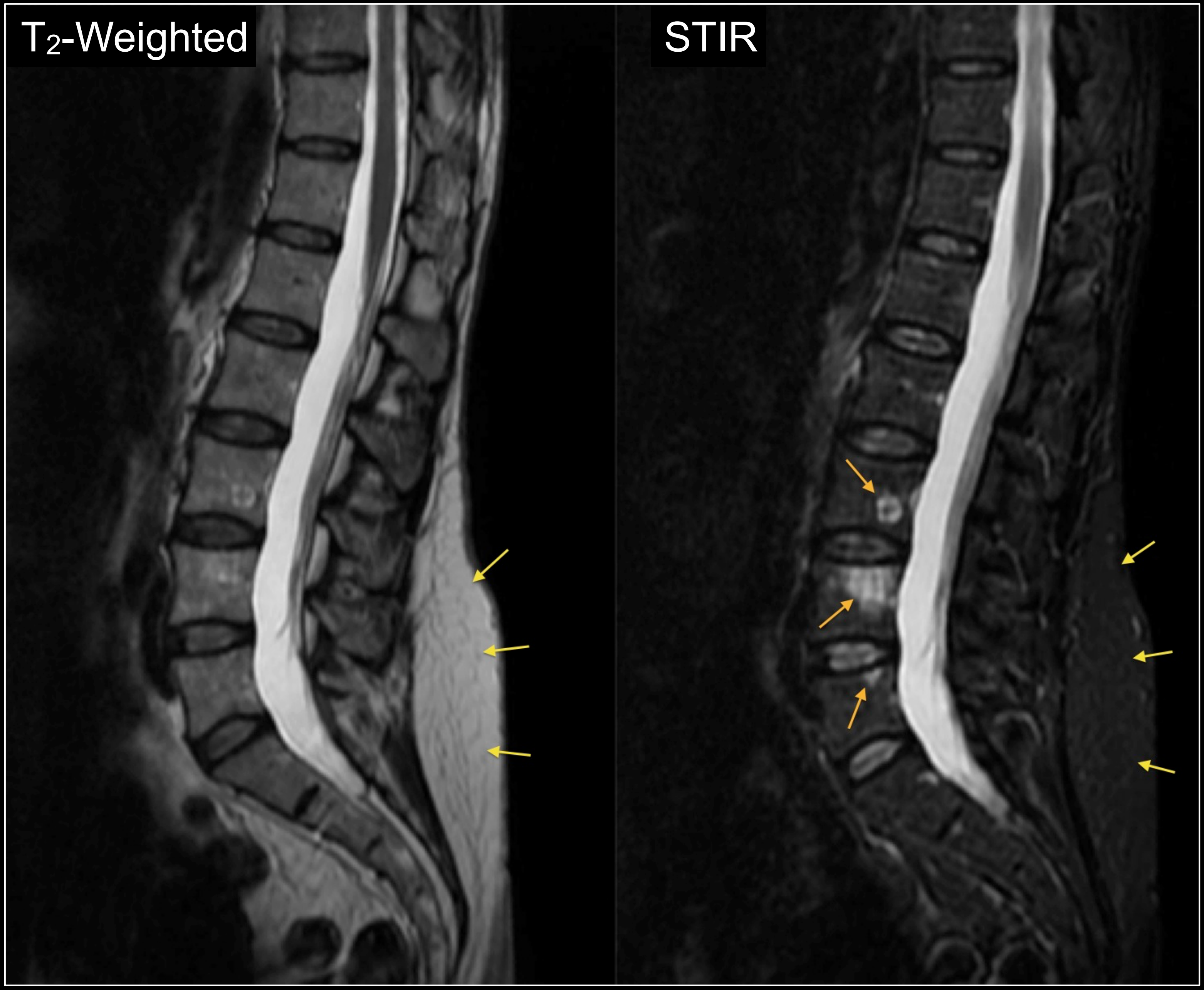
The final image contrast is controlled by TI and TR.

STIR Pulse Sequence



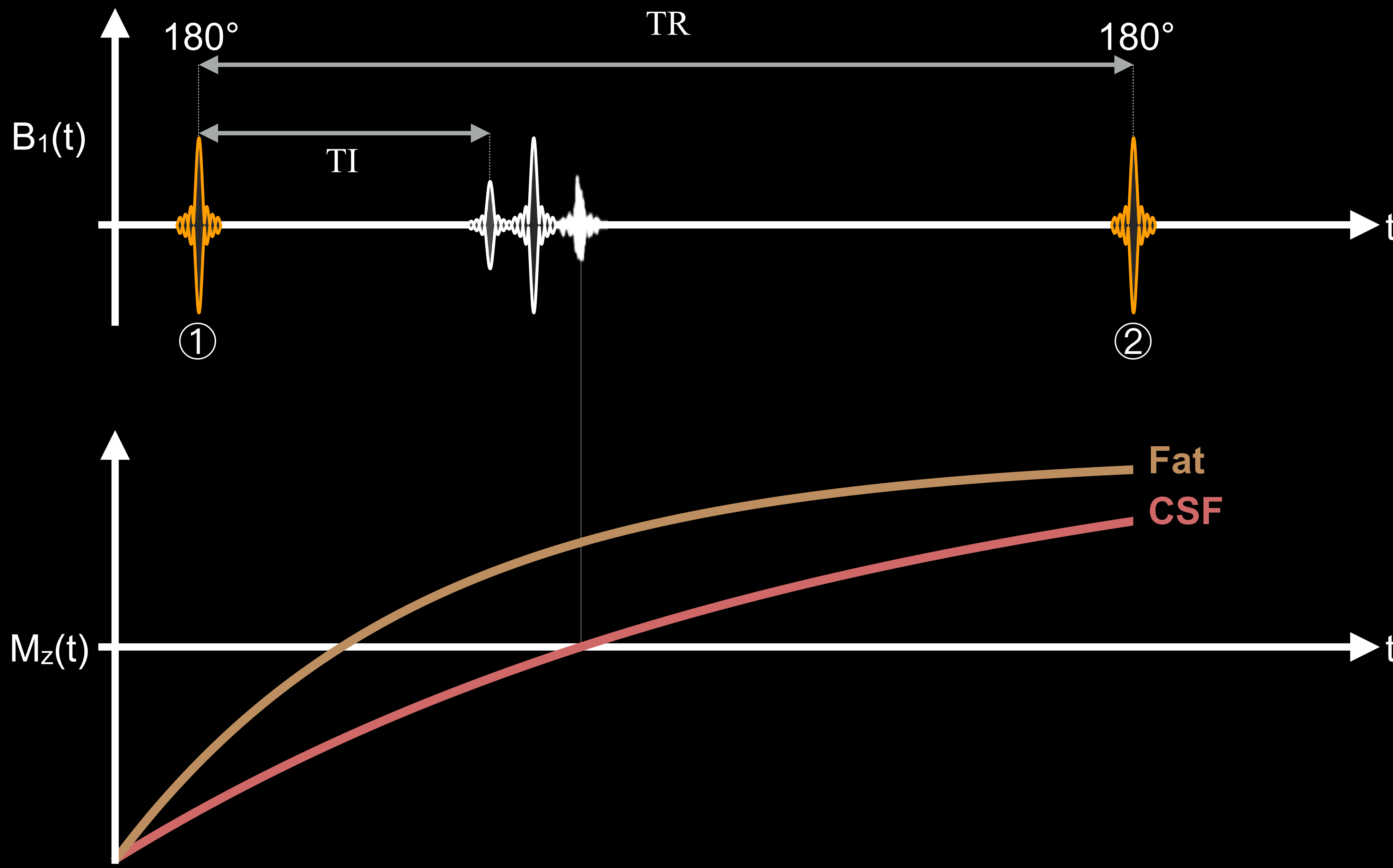
Short Tau Inversion Recovery (STIR) is used to null fat.

STIR Images



http://www.svuhradiology.ie/wp-content/uploads/2015/04/STIRmetscombo.jpg

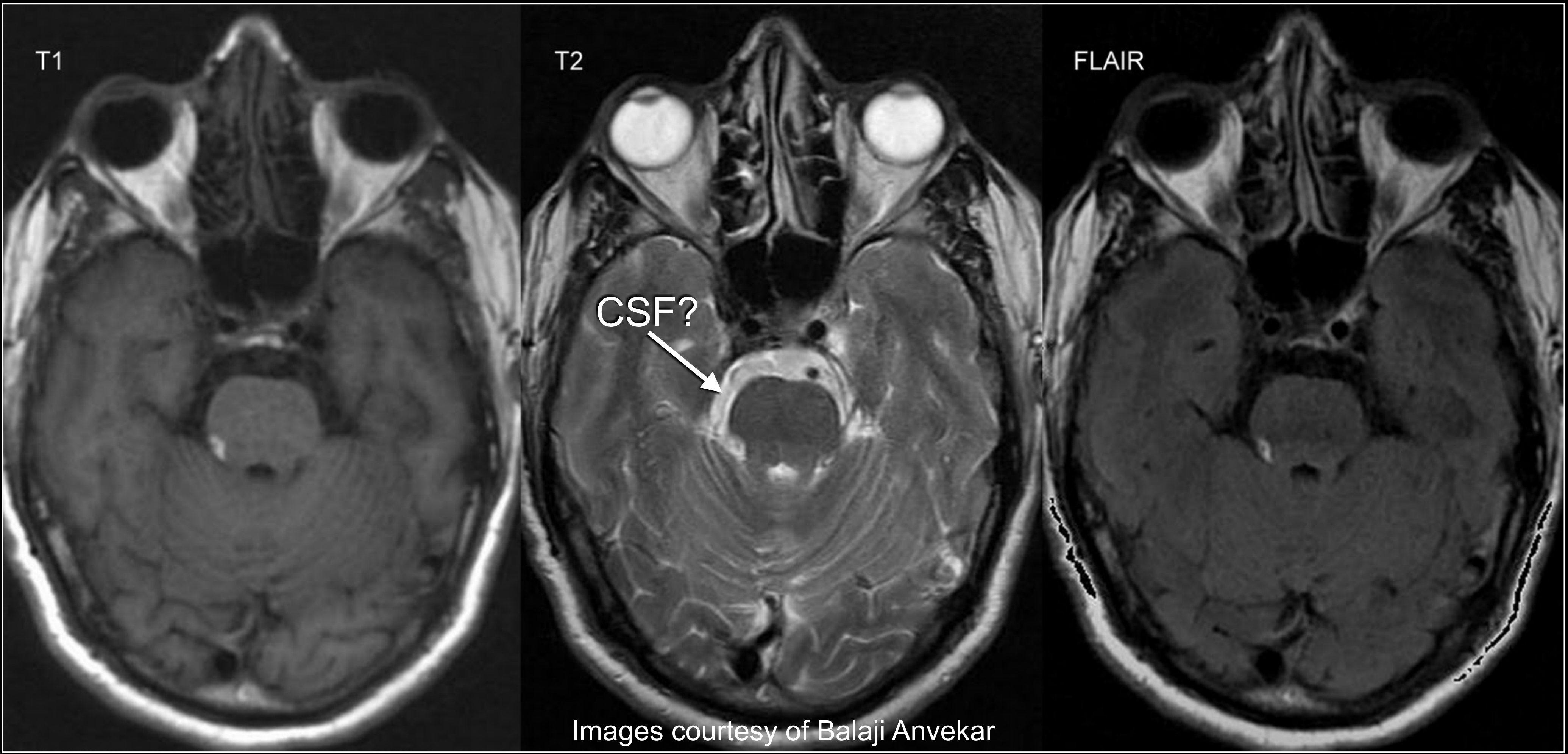
FLAIR Pulse Sequence



FLuid Attenuated Inversion Recovery (STIR) is used to CSF.

FLAIR Images

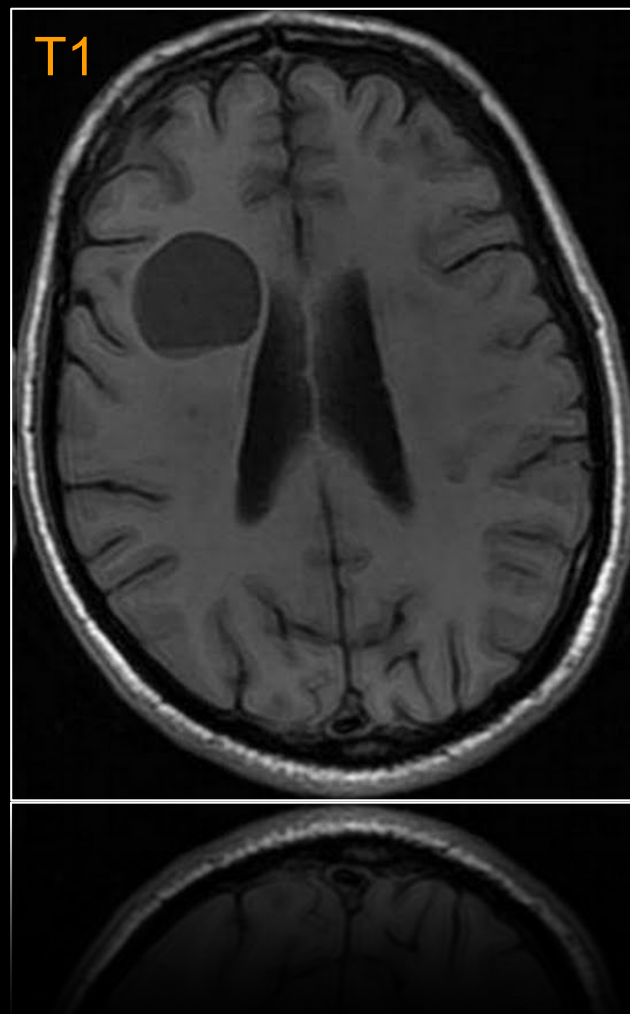
FLAIR can distinguish fat from CSF.



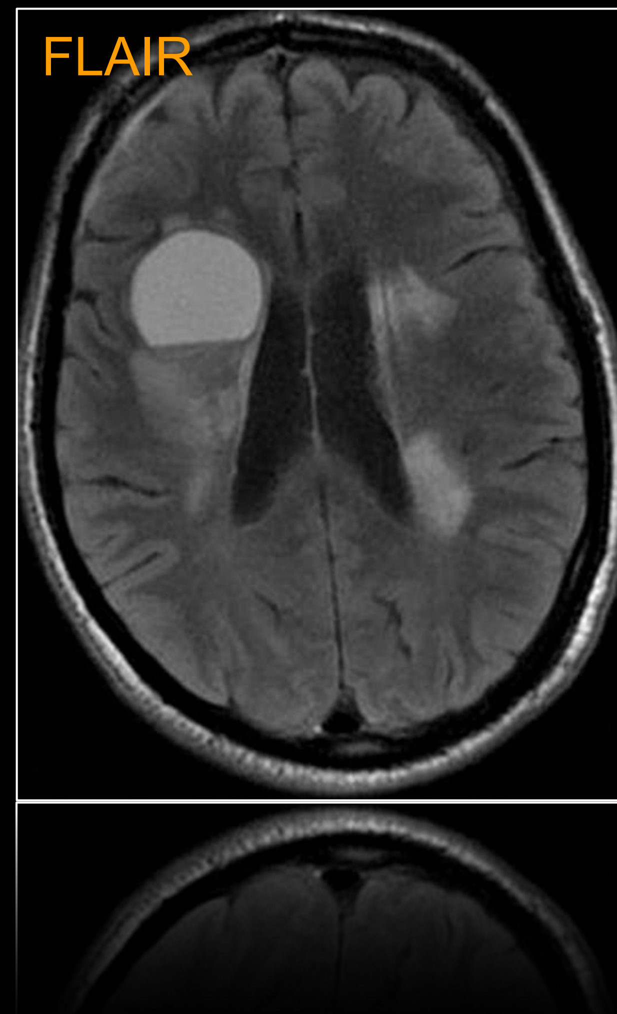
FLAIR Images

Long T2 is bright on T2w.

Short T1 is bright on T1w.



Long T1 is dark on FLAIR.



Lesion has long T2 and intermediate T1. Not fat. Not CSF. Cerebral hydatid.

Lecture #6 Learning Objectives

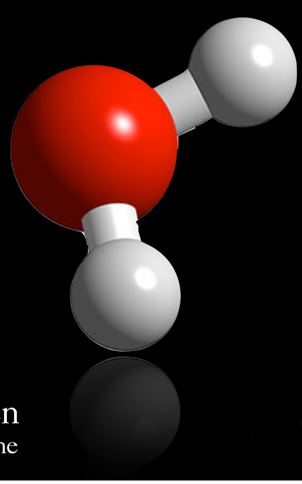
- Appreciate the definition of image contrast.
- Explain what a T1 or T2-weighted image is.
- Describe what a pulse sequence is.
- Understand the saturation recovery pulse sequence and the saturation condition.
- Describe the inversion recovery sequence.
- Distinguish between STIR and FLAIR.

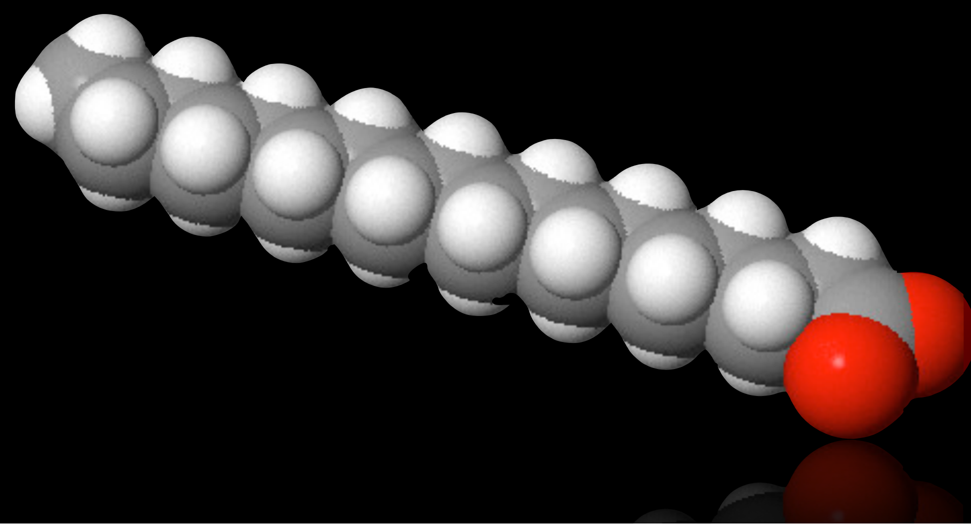
Off-Resonance

Isochromats

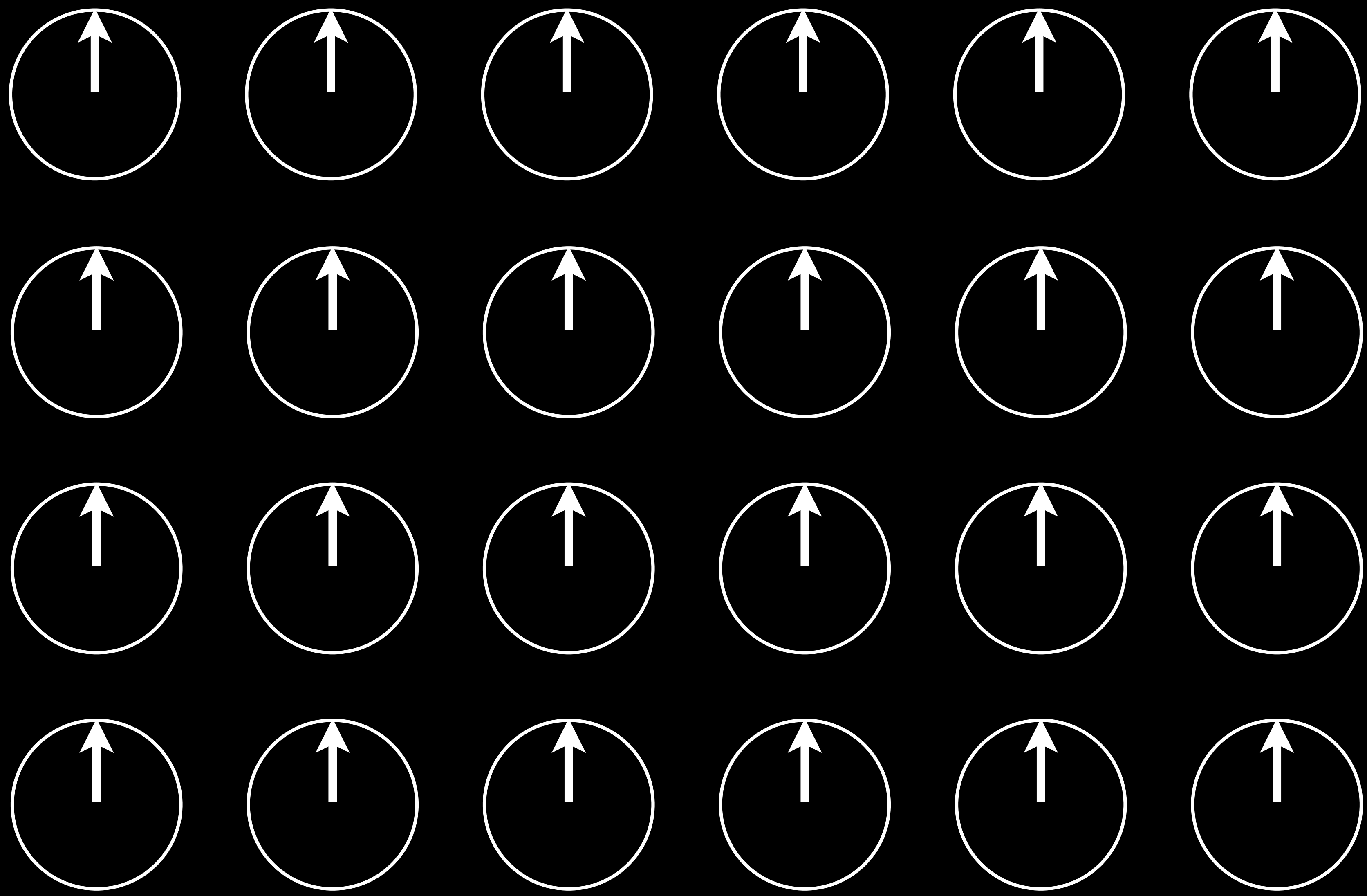
- ***Isochromat*** - Group of nuclear spins with the same resonant frequency
- Ideally all spins in a “system” have the same resonance frequency
- Multiple isochromats arise from:
  - B_0 inhomogeneity (heterogeneity!)
  - Chemical shift effects
  - Magnetic susceptibility differences
  - Gradients

Sources of Off-resonance





Isochromats



Isochromats

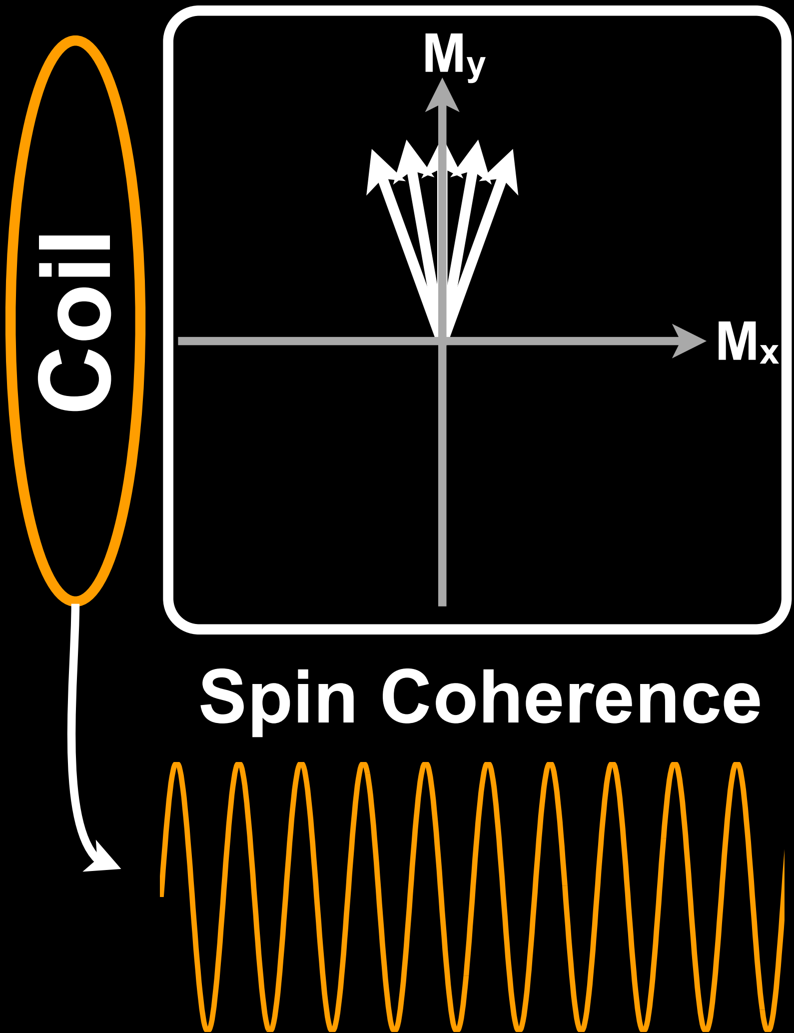
B_0 Inhomogeneity

Spin Dephasing

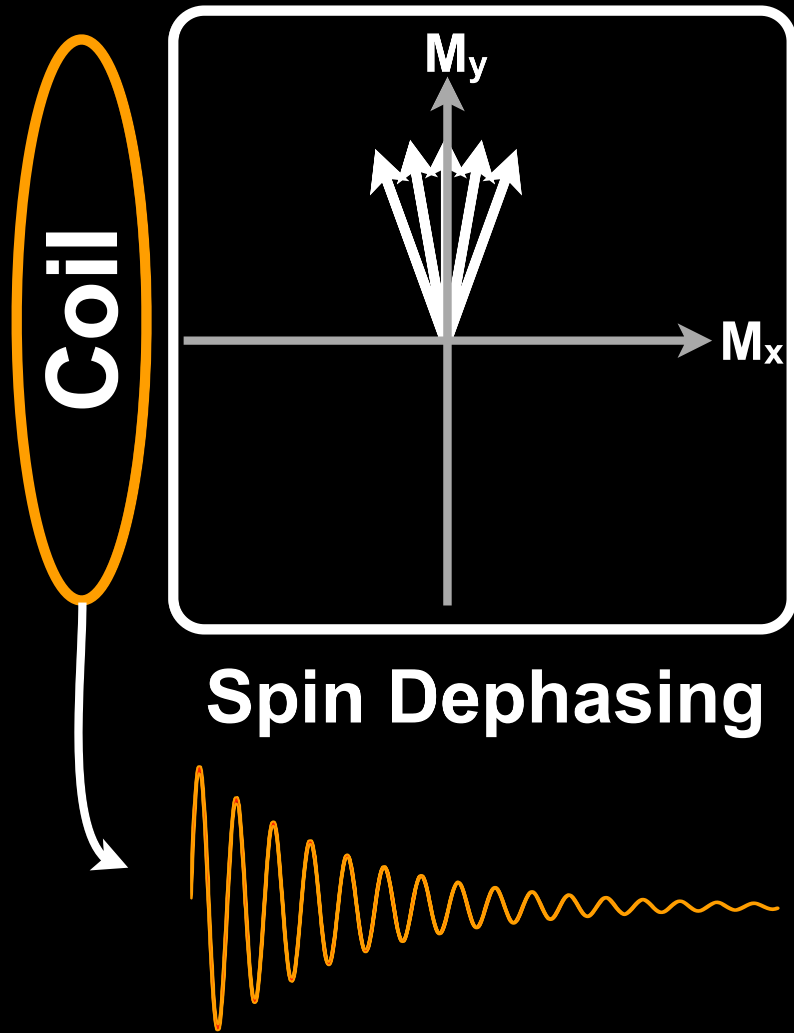
- Intravoxel spin dephasing from:
  - **Off-resonance**
    - B_0 inhomogeneity
    - Chemical shift effects
    - Susceptibility differences (macro and micro)
      - Blood products (***iron***)
      - Blood oxygenation levels
  - Applied gradients
    - Strong gradients produce more spin dephasing
- ... leads to:
  - Loss of spin phase coherence
  - Usually within a voxel
  - Leads to a decreased echo amplitude.
- Minimized by:
  - Field shimming
  - Susceptibility manipulation
  - Refocusing pulses

Intravoxel Spin Dephasing

Homogenous **Intravoxel Field**



Inhomogenous **Intravoxel Field**

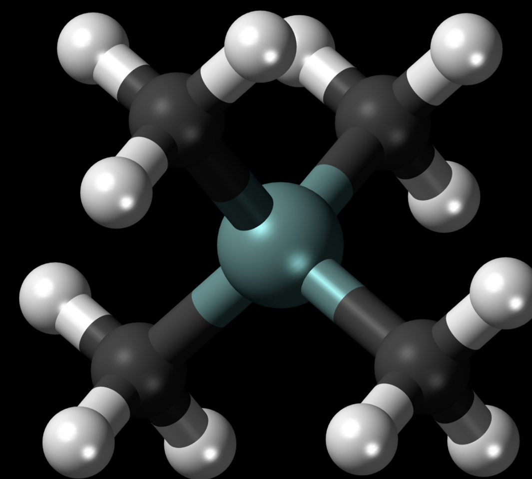


Signal loss from spin dephasing and T_2*.

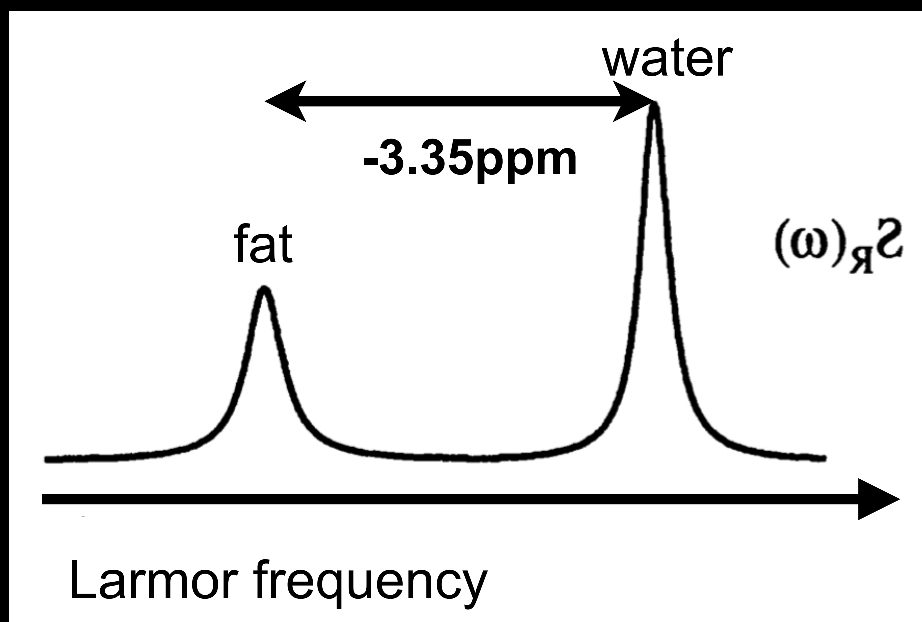
Chemical Shift

Chemical Shift

- **Nuclear (eg ^1H) spins surrounded by different chemical environments**
- **Orbiting electrons shield the nucleus**
- **Referenced against tetramethylsilane**
  - **Assigned a chemical shift of zero**

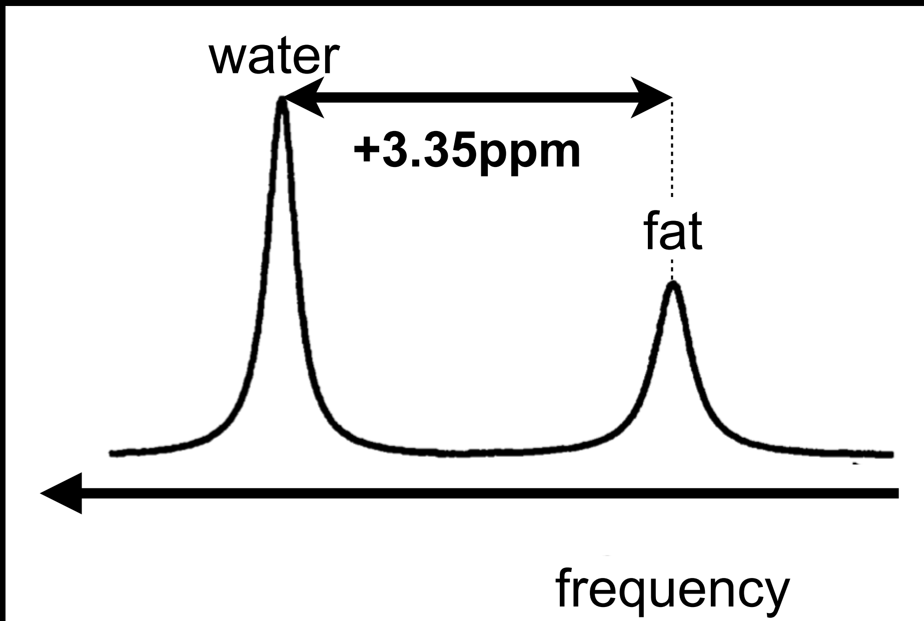


tetramethylsilane

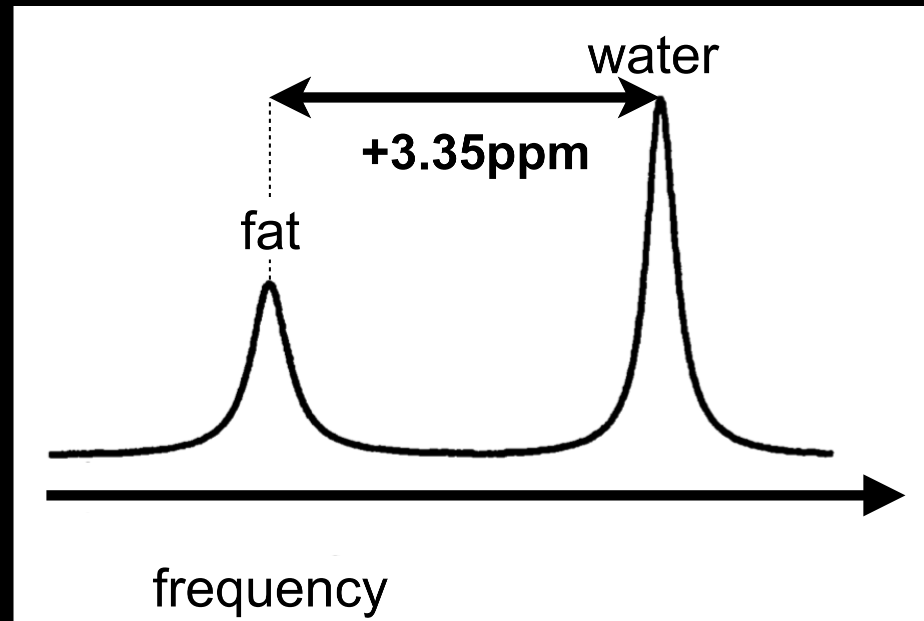


$-CH_2$ is 214Hz *lower* at 1.5T

Chemical Shift



Chemists



Physicists

$$B = B_0 (1 - \delta)$$

$$\delta_{-\mathrm{CH}_2} = 3.35ppm$$

$-CH_2$ is 214Hz *lower* at 1.5T

David Geffen School of Medicine

UCLA Radiology

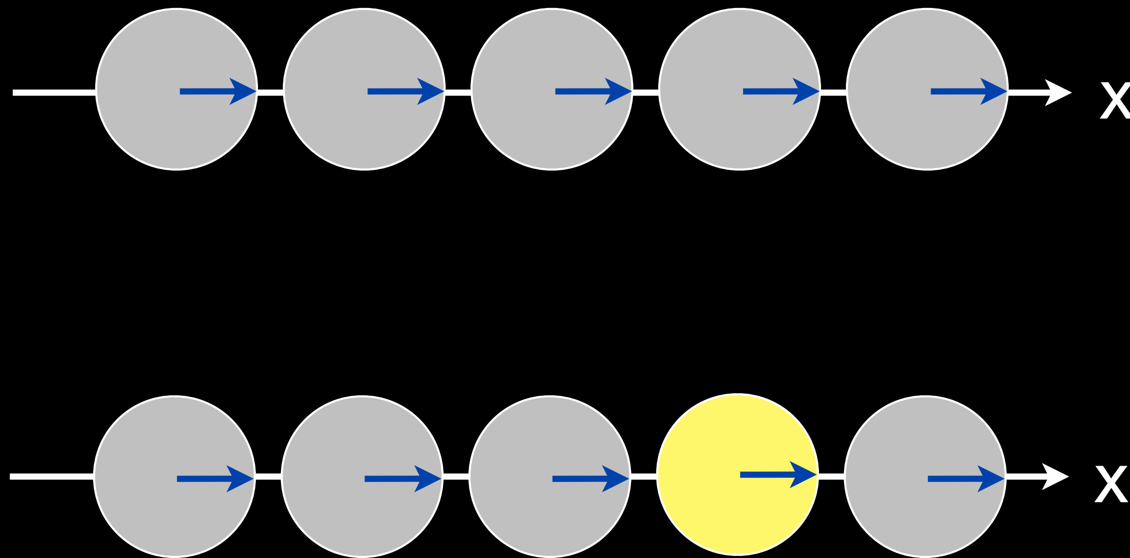
Chemical Shift

Type of Proton	Structure	Chemical Shift, ppm
Cyclopropane	C_3H_6	0.2
Primary	R-CH_3	0.9
Secondary	R_2-CH_2	1.3
Tertiary	R_3-C-H	1.5
Vinylic	C=C-H	4.6-5.9
Acetylenic	triple bond,CC-H	2-3
Aromatic	Ar-H	6-8.5
Benzylic	Ar-C-H	2.2-3

Chemical Shift Artifact

Normal Spins

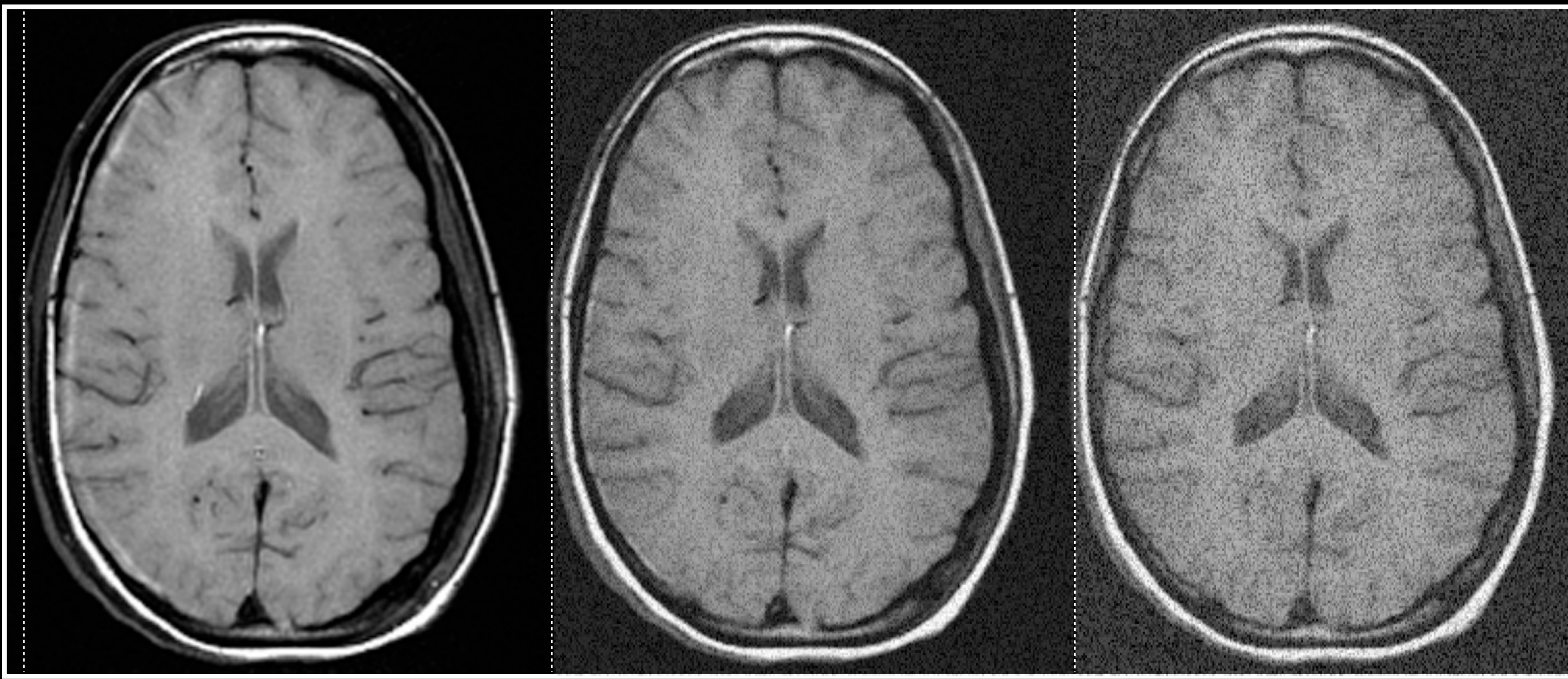
Off-Resonant Spin



Frequency is linearly related to spatial position.

Chemical Shift Artifact

Readout →



BW = ± 4kHz | BW = ± 8kHz | BW = ± 16kHz

Low Bandwidth
Large Fat-Water Shift
High SNR

High Bandwidth
Small Fat-Water Shift
Low SNR

Magnetic Susceptibility

Magnetic Susceptibility (χ)

- Ability of a substance to become magnetized
  - (–) Susceptibility - slightly decreases the magnetic field
    - Its magnetization is oppositely directed
  - (+) Susceptibility - slightly increases the magnetic field
    - Its magnetization is parallel with the main field

$$B = (1 + \chi) B_0$$

	Temperature [°C]	Pressure [atm]	χ [$m^3 \cdot kg^{-1}$]
Vacuum	Any	0	0
Water	20	1	-9.04×10^{-6}
O_2	20	0.209	3.73×10^{-7}
N_2	20	0.781	-5.06×10^{-9}

Magnetic Susceptibility

- Diamagnetic - A substance with a small negative magnetic susceptibility
  - Oxyhemoglobin has a diamagnetism similar to tissue
- Paramagnetic - A substance with a small but positive magnetic susceptibility.
  - Deoxyhemoglobin more paramagnetic than tissue
- Ferromagnetic - A substance that has a large positive magnetic susceptibility.
  - Iron particles
- Large susceptibility gradients at:
  - Tissue-Air interfaces
  - Around metallic implants
  - Can cause large image artifacts

Magnetic Susceptibility

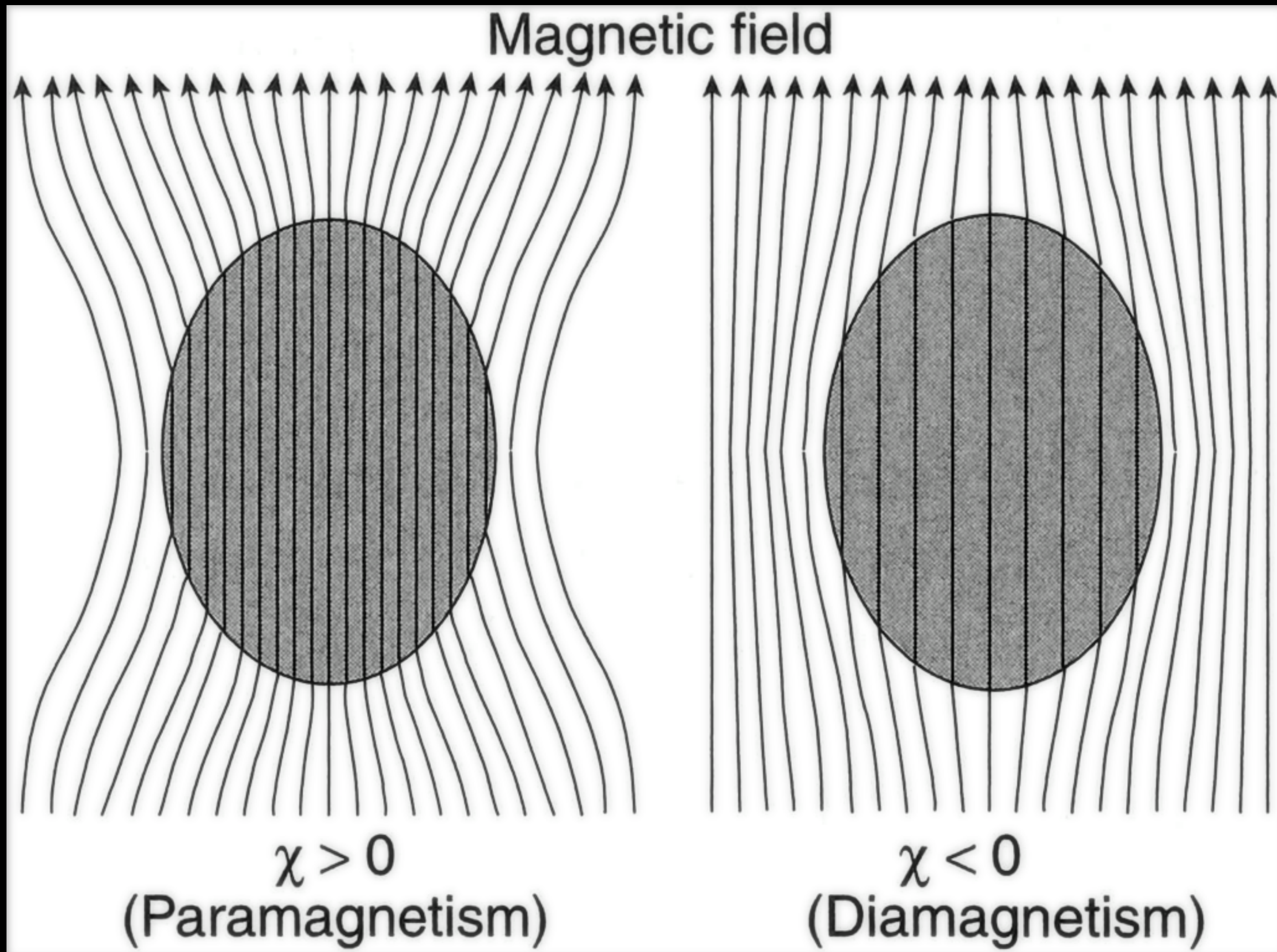
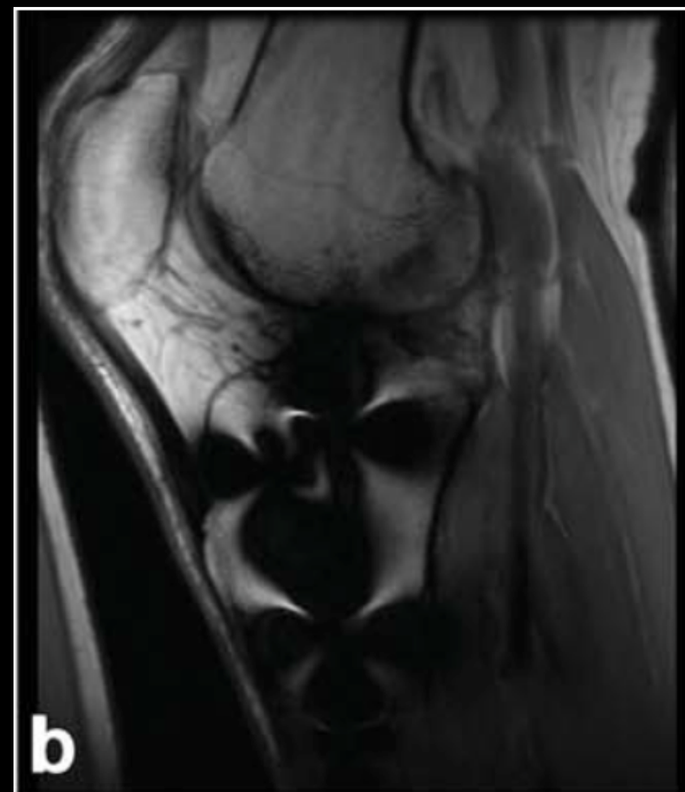


Image from Malcolm Levitt

Metal Artifacts

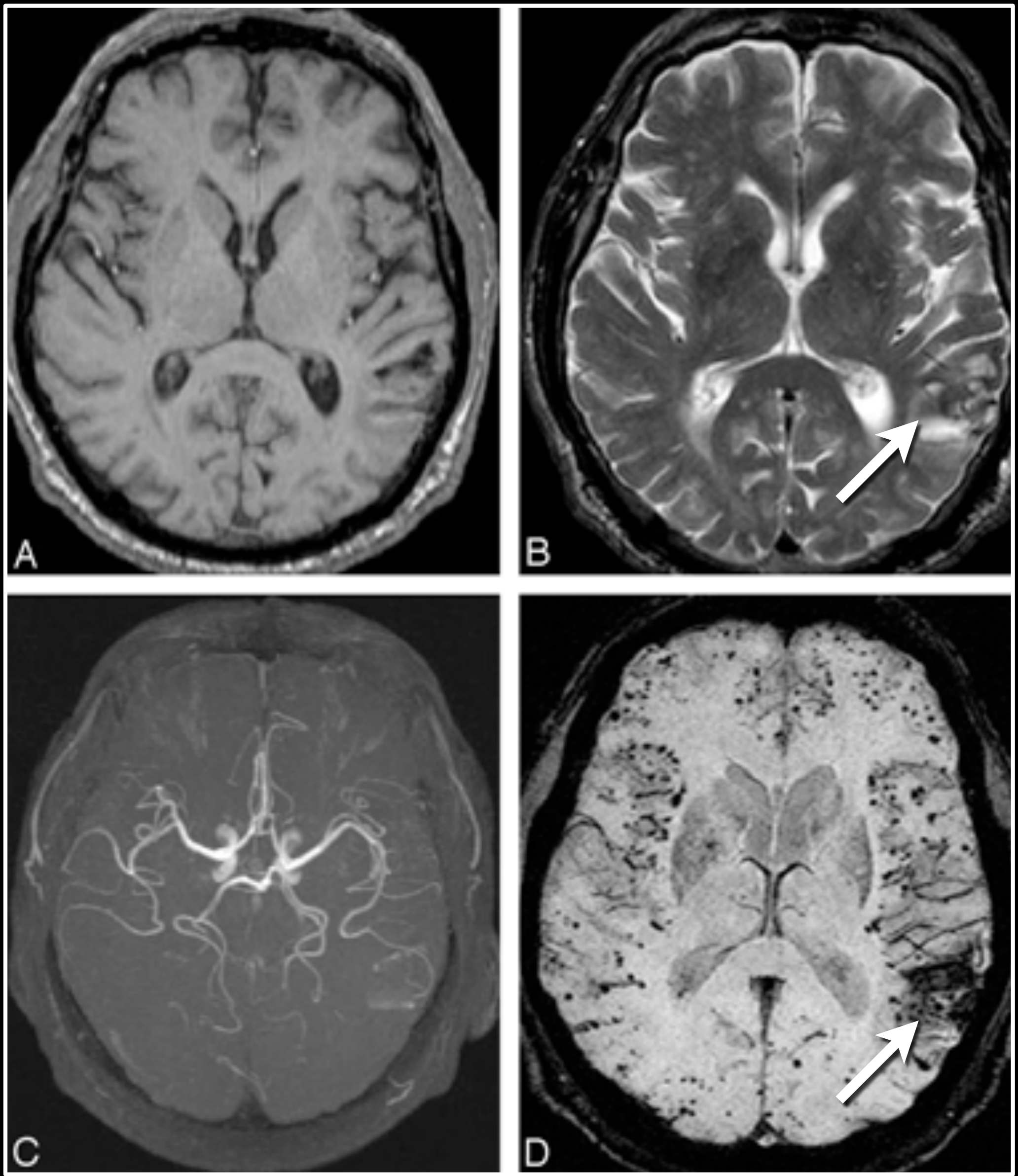
2D FSE of a shoulder.



3D FSE of a knee.

Koch KM et al. Imaging near metal with a MAVRIC-SEMAC hybrid. Magn Reson Med 2011;65(1):71-82 [PMID 20981709].

Susceptibility Weighted Imaging (SWI)



Multiple microbleeds in cerebral amyloid angiopathy (CAA). A and B, T1-weighted (**A**) and T2-weighted (**B**) images do not reveal significant abnormalities except for the lesion in the left temporoparietal area. **C**, MRA shows normal brain vascular structure. **D**, SWI demonstrates, in addition to hemorrhage in the left temporoparietal region, **multiple microbleeds** distributed along the gray/white matter interface in the whole brain, strongly suggesting CAA.

Mittal S *et al*. Susceptibility-weighted imaging: technical aspects and clinical applications, part 2. AJNR Am J Neuroradiol 2009;30(2):232-252.

Free Induction Decay

Free Induction Decay (FID)

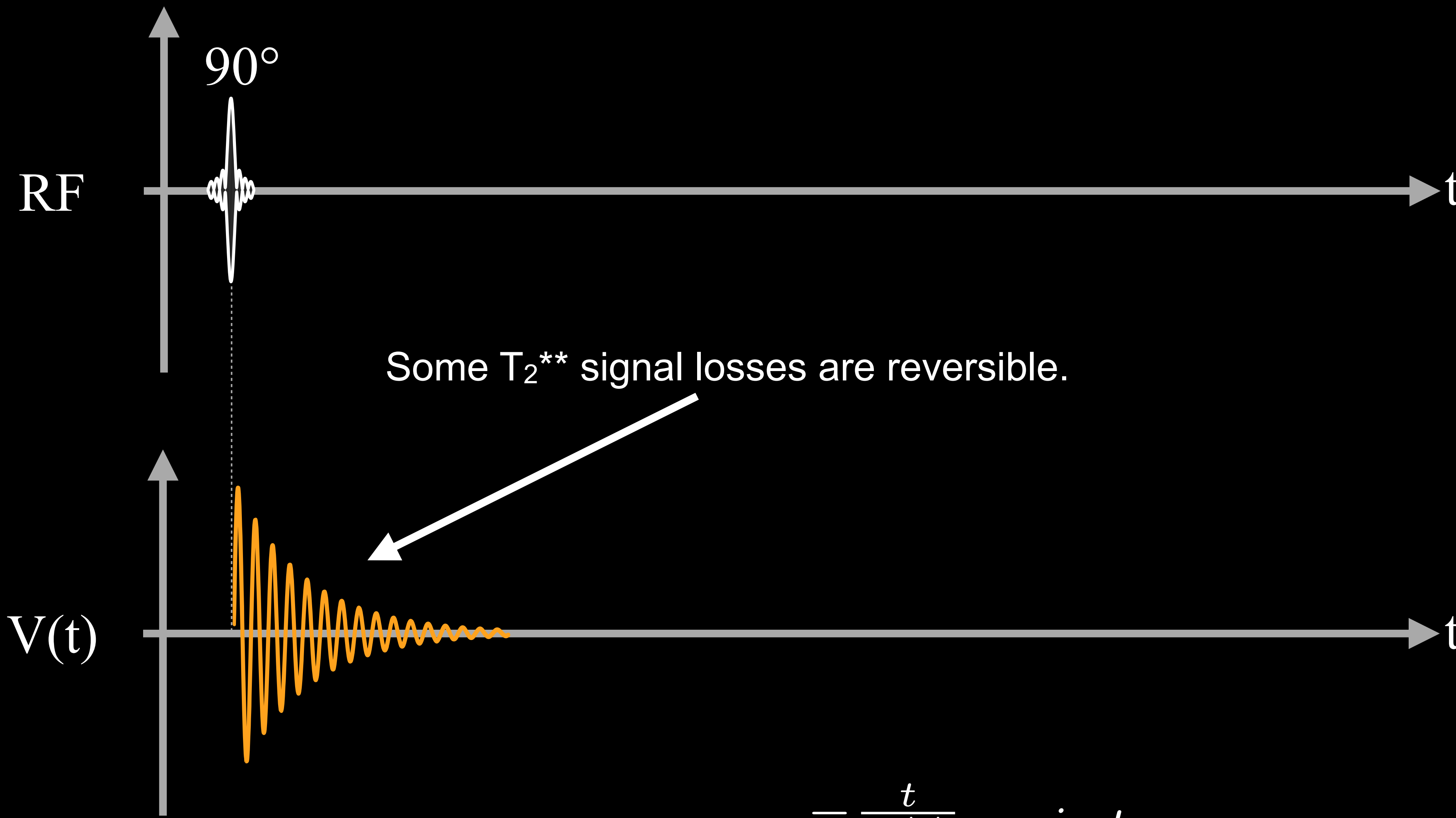
- **Free**
  - Signal arises from precession of bulk magnetization about B_0 after perturbation
- **Induction**
  - Signal is induced in a coil (Faraday's Law)
- **Decay**
  - Decreases in amplitude over time

- **Characteristics:**
  - Amplitude maximum at t=0
  - Decay rate depends on:
    - T_2, T_2^*, and spectral distribution (T_2^{**})

Pixel-level sources of off-resonance

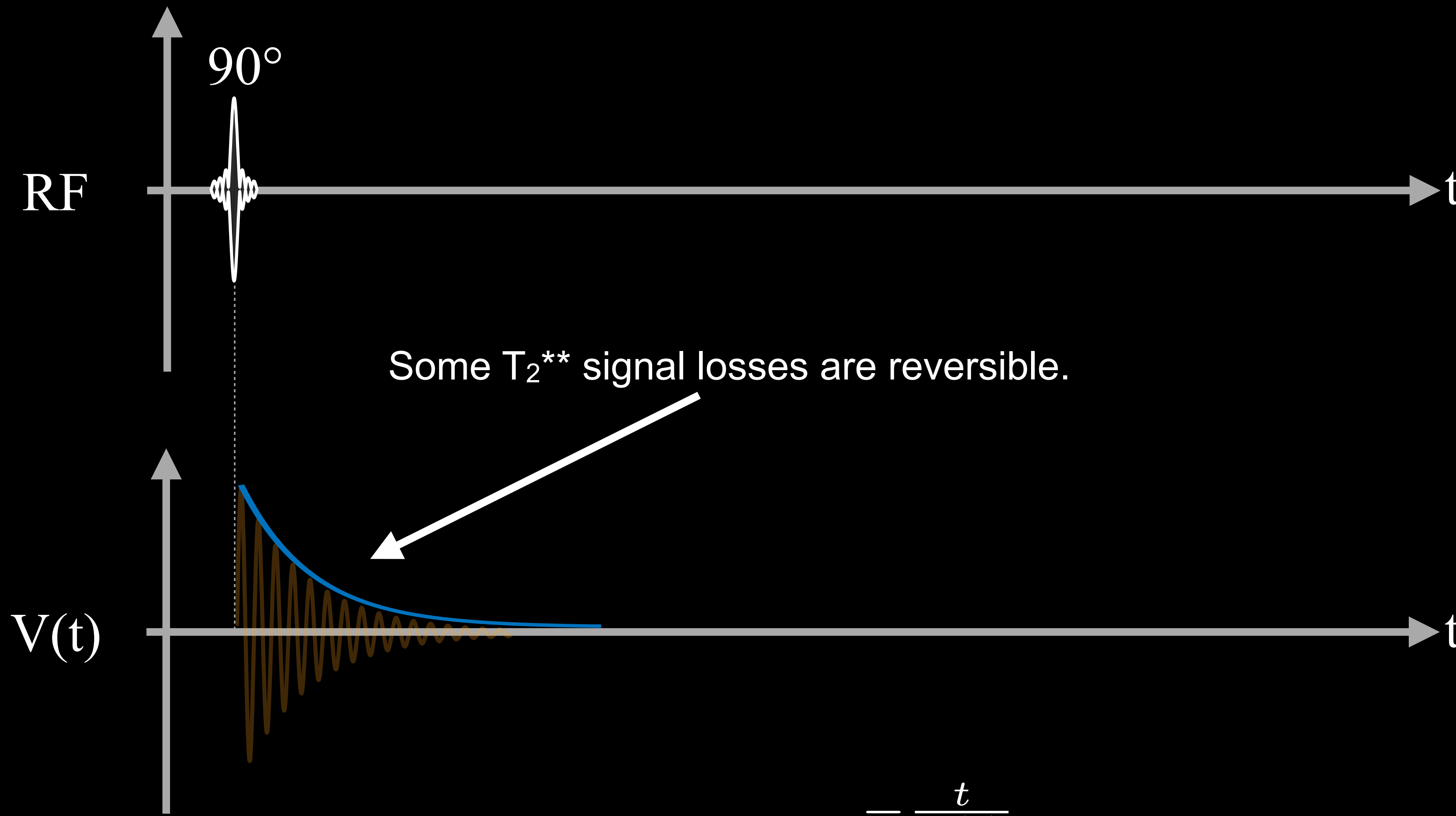
Spin-level sources of off-resonance

Free Induction Decay (FID)



$$M_x = M_0 \sin \alpha e^{-\frac{t}{T_2^{**}}} e^{-i\omega t}$$

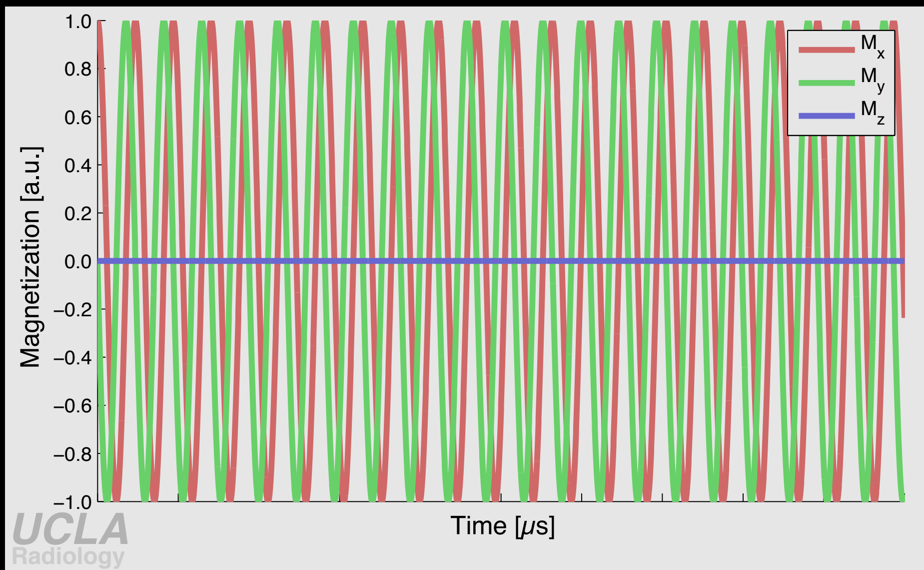
Free Induction Decay (FID)



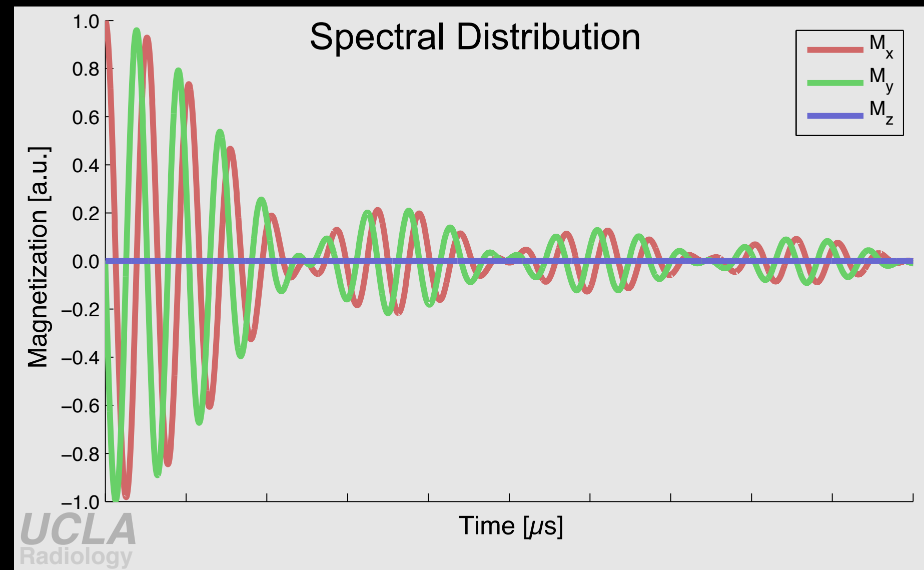
$$|M_{xy}| = M_0 \sin \alpha e^{-\frac{t}{T_2^{**}}}$$

Off-resonance Without Relaxation

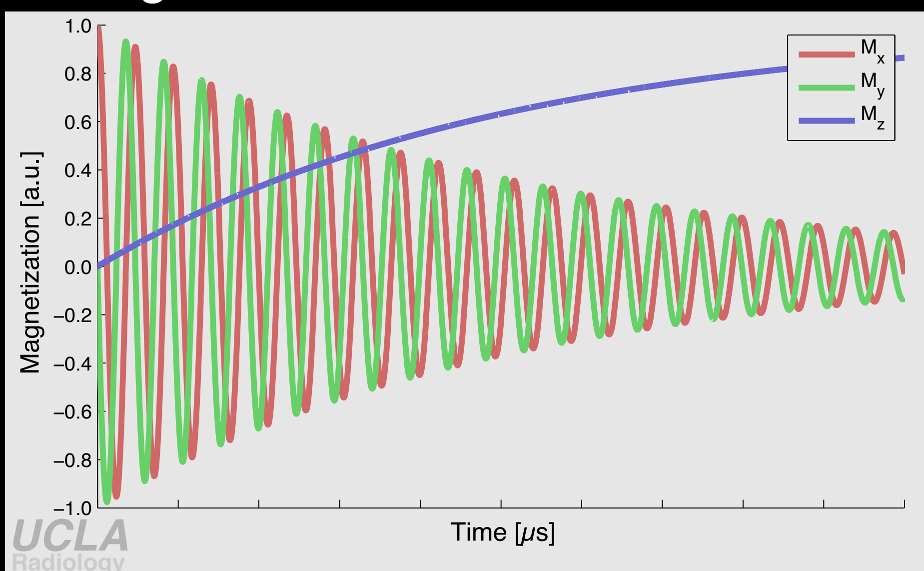
Single Isochromat without Relaxation



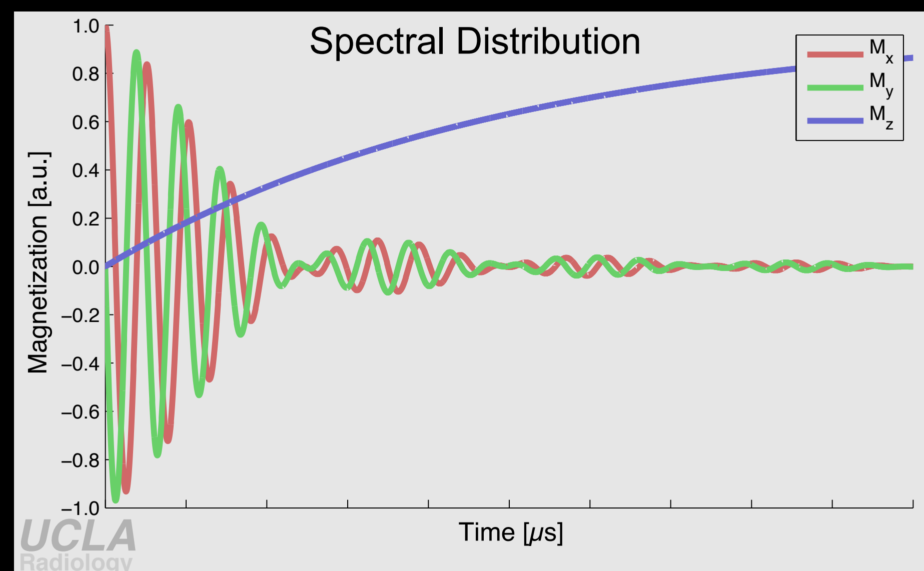
100 Isochromats without Relaxation



Single Isochromat with Relaxation



100 Isochromats with Relaxation



Signal Decay

- **T_2**
  - **Irreversible spin-spin interactions**
- **T_2^***
  - T_2 plus…
  - Spin de-phasing due to spin-level off-resonance
  - Reversible
- **T_2^{**}**
  - T_2^* plus…
  - Spin de-phasing due to voxel-level off-resonance
    - External field imperfections
  - Reversible

T_2^* Relaxation

- Intravoxel Spin Dephasing
  - Spin-spin (T_2) dephasing combined with...
  - Off-resonance
    - B_0 inhomogeneity
      - Typically a few PPM over 30-50cm
        - » 1PPM = 640Hz = 1.5μT
    - Susceptibility differences (macro and micro)
      - Induce small field perturbations, therefore dephasing
    - Chemical shift effects
- Off-resonance can be rephased with a spin echo
  - Not with a gradient echo!
- $T_2^* < T_2$

T_2^* Relaxation

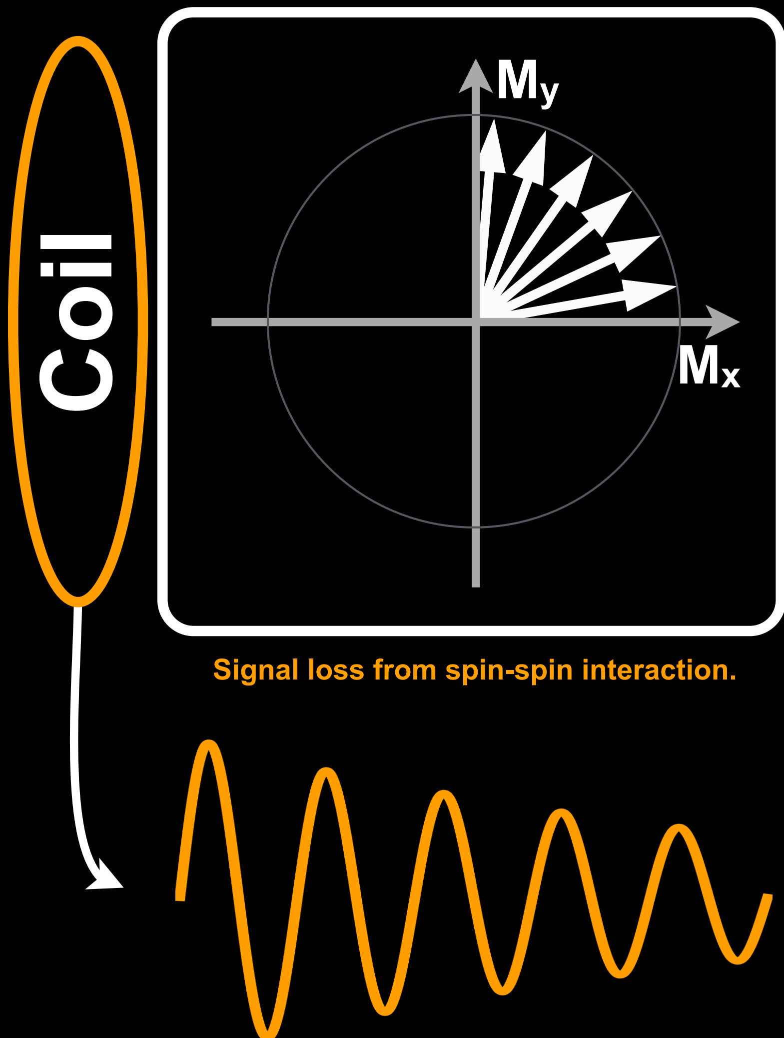
$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma \delta B_0$$

Irreversible Losses ($\frac{1}{T_2}$)

Reversible Losses ($\gamma \delta B_0$)

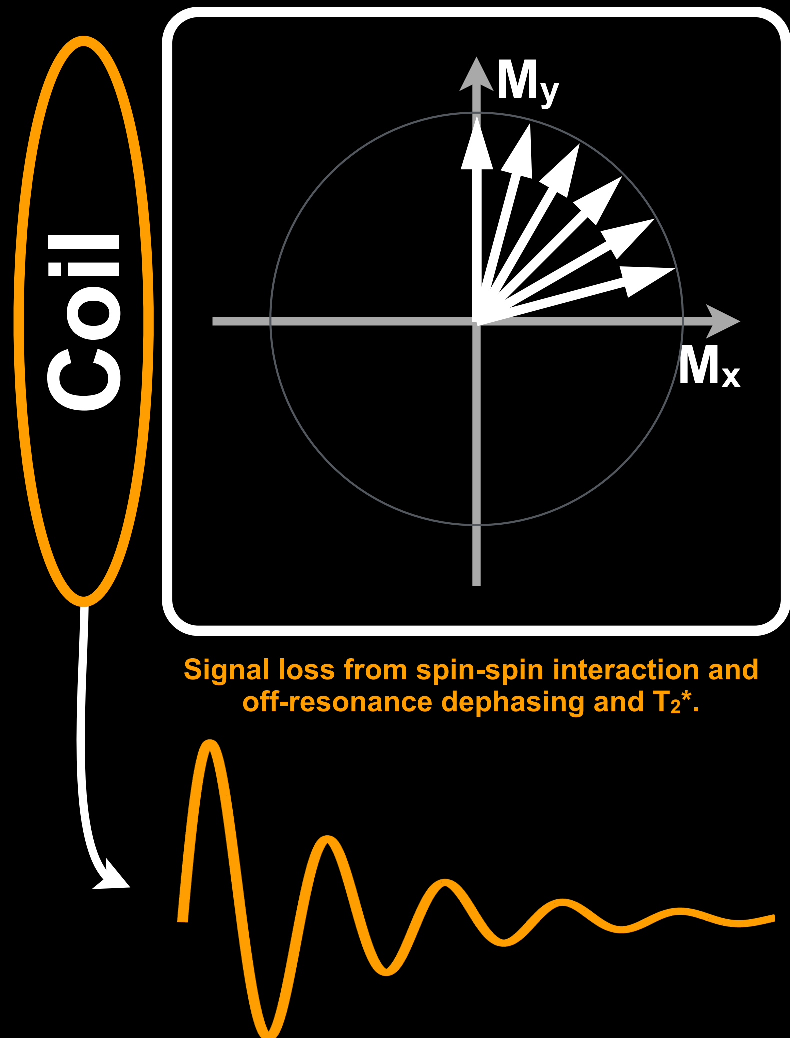
T_2 versus T_2^*

T_2 Decay



Signal loss from spin-spin interaction.

T_2^* Decay



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

Signal loss from spin dephasing and T_2^*.

Range of Off-Resonances

- B_0
  - <4ppm over 50cm DSV
    - ~0.008ppm within a 1mm voxel
    - ~0.5Hz for ^1H at 1.5T within a 1mm voxel
- Susceptibility
  - -5.06ppb for N_2 and 0.37ppm for O_2
  - ~70.5ppb for air (0.8*(-5.06e-9)+0.2*(3.73e-7))
    - ~4.5Hz for *air* at 1.5T
- Chemical shift
  - ~3.4ppm for fat
    - ~217 Hz for ^1H at 1.5T within a voxel
- Gradients
  - 5G/cm or 0.5G/mm
    - 2128Hz for ^1H across a 1mm voxel

Free Induction Decay

- Used for ultrashort echo time imaging of very short T_2 species
  - Positive contrast for bone, ligament, tendon, cartilage, meniscus, etc.
- Spin echoes and gradient echoes are methods that extend the usability of the FID signal

UTE Pulse Sequence

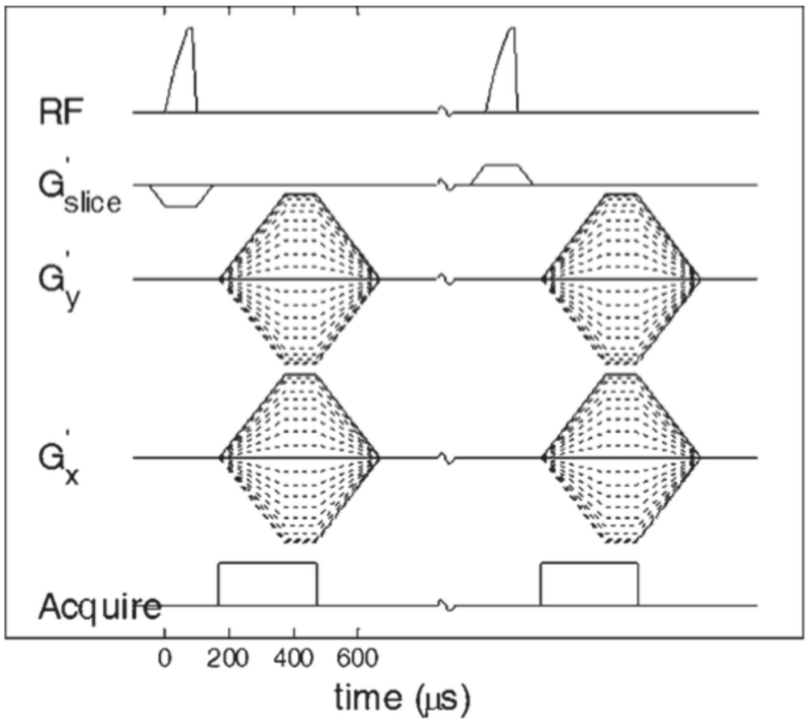


Figure 4. Pulse sequence diagram for a basic UTE sequence. The half rf pulses are applied with the slice selection gradient G_z negative in the first half and with this gradient positive in the second half. The rf pulse is truncated and followed rapidly by the acquisition during which G_x2 and G_y2 are applied to give the radial gradient. These gradients ramp up to a plateau during data acquisition

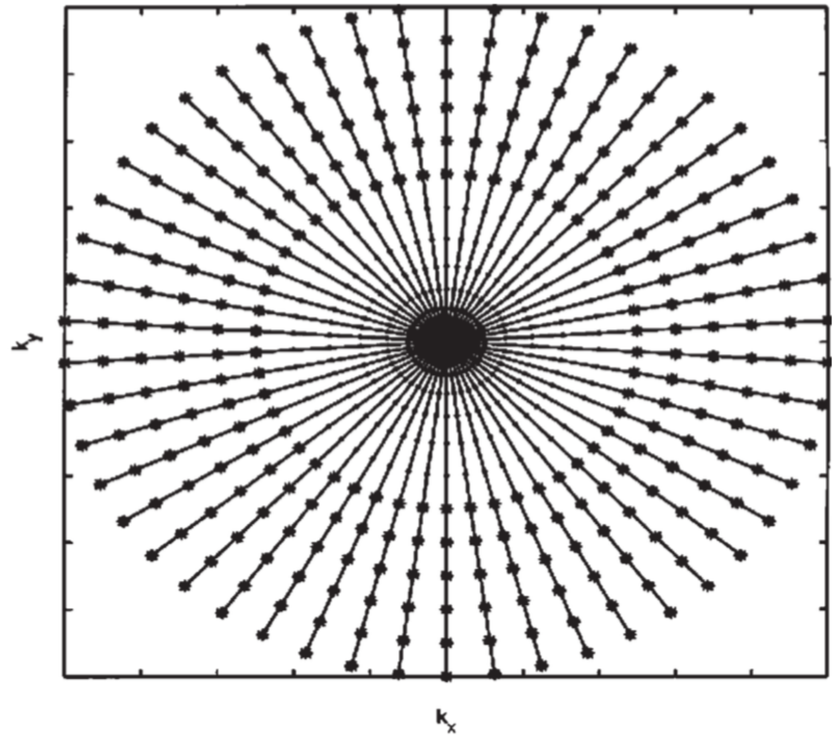
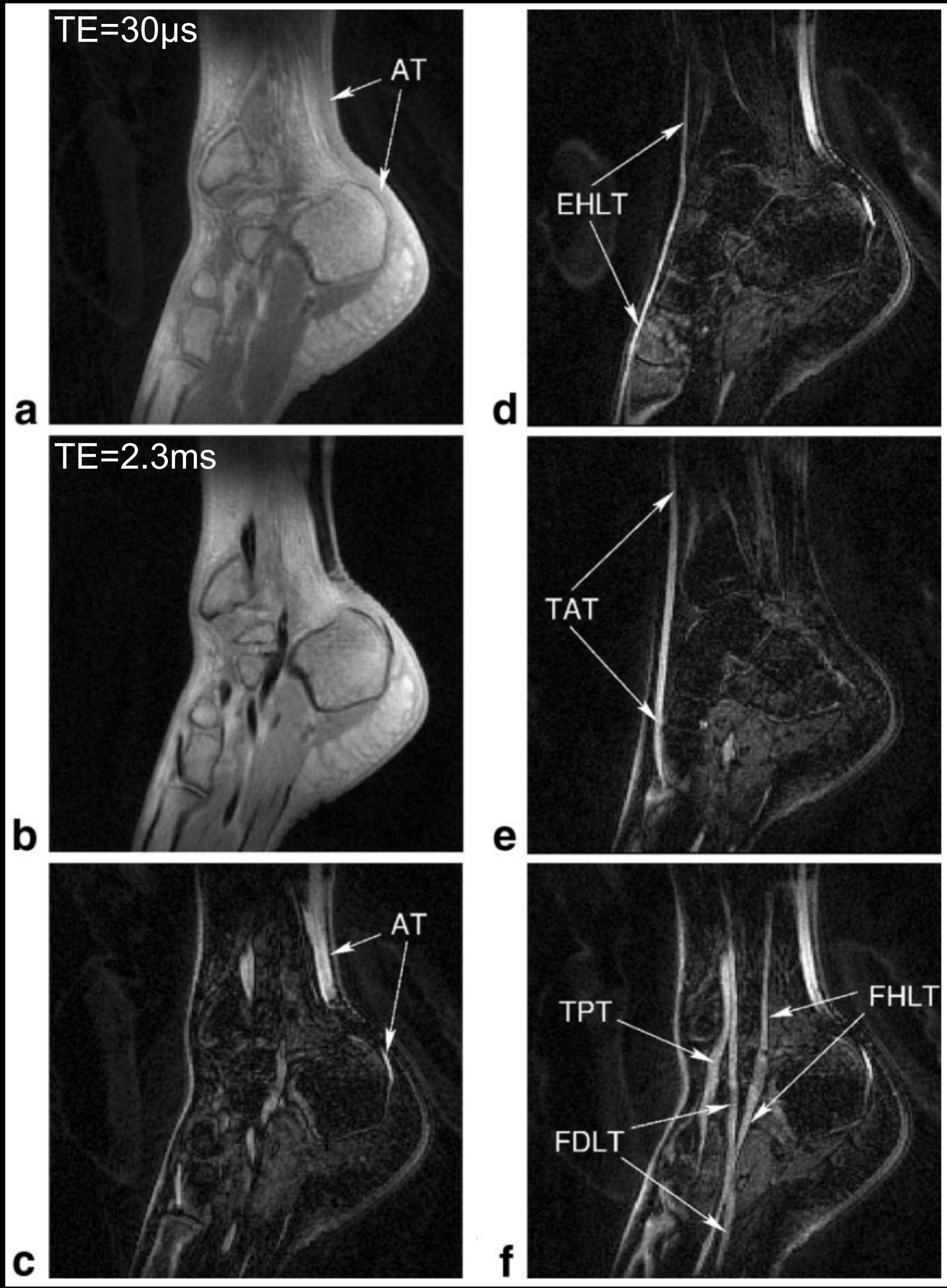


Figure 5. *k*-Space trajectories for the above imaging sequence. Each 'spoke' represents the *k*-space trajectory due to the readout gradients. The dots represent the central points which are sampled on the gradient ramps, and the stars the peripheral points which are sampled on the gradient plateau. Practical acquisitions typically include 128–512 spokes and 256–512 points on each spoke. The data points are regridded onto a Cartesian grid prior to 2D Fourier transformation

Ultra Short TE (UTE) Images



Tendons have a very short T_2.

FIG. 7. 3D UTE dual-echo data of the right ankle. (**a**) FID image at TE 30μs showing high signal from almost all tissues. The arrows indicate the Achilles tendon (AT). (**b**) Echo acquired at TE 2.3 ms. (**c**) Difference image highlighting short-T2 components. (**d–f**) Curved (nonplanar) reformatted views of the 3D difference image data set. The course of several tendons can be followed through the complex anatomy of the ankle. (**d**) Extensor hallucis longus tendon (EHLT). (**e**) Tibialis anterior tendon (TAT). (**f**) Flexor digitorum longus tendon (FDLT) crossing the flexor hallucis longus tendon (FHLT); the tibialis posterior tendon (TPT) is also visible.

Rahmer J, Bornert P, Groen J, Bos C. Magn Reson Med 2006;55(5): 1075-1082 [PMID 16538604].

Echoes

Why echoes?

- Free Induction Decay
  - Signal decays rapidly
    - T_2
      - Spin-spin interaction
    - Spectral (frequency) distribution
      - Micro-scale B-field heterogeneity (T_2*)
      - Macro-scale B-field heterogeneity (T_2**)
  - Imaging requires certain “delays”
    - Slice-selective rephasing
    - Phase encoding
    - Read-out pre-phasing
  - Echoes let us buy some time

What are echoes?

- **Two-sided NMR signals**
  - First half from re-focusing
  - Second half from de-phasing
- **Radiofrequency Echoes**
  - Arise from multiple RF-pulses
- **Gradient Echoes**
  - Arise from magnetic field gradient reversal

“it is easier to generate an echo than to ignore it in multiple-pulse MR experiments”

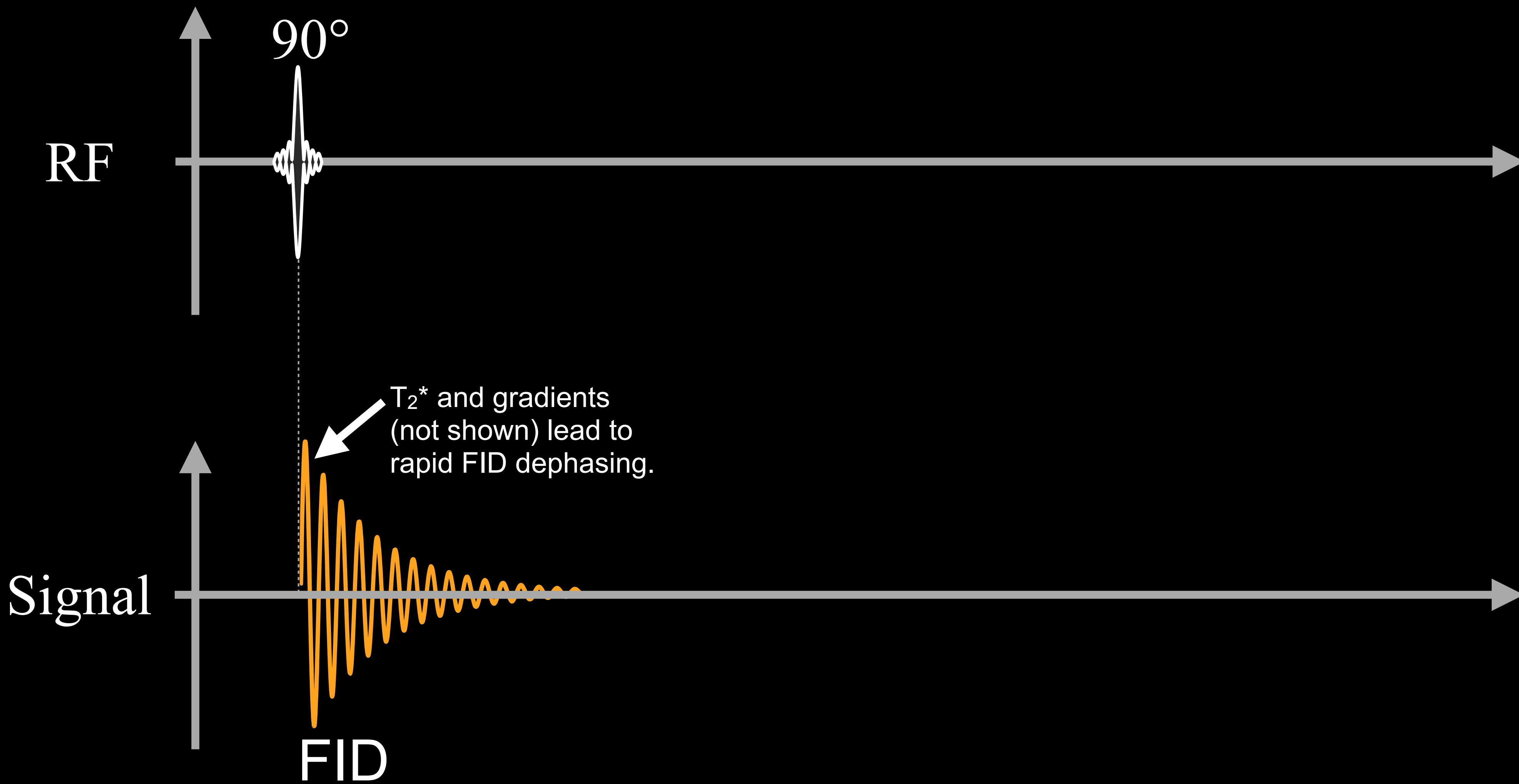
--Liang & Lauterbur, Page 114

Spin Echo Imaging

Spin Echo

- Advantages
  - Insensitive to off-resonance
    - All spins within voxel rephased
    - B_0 inhomogeneity
    - Intravoxel Chemical shift signal loss
    - Susceptibility
  - Great for T_1, T_2, ρ contrast
    - Not T_2^*
  - High SNR
- Disadvantages
  - TR can be long
    - Leads to long scan time
  - SAR can be high
    - Lots of 90s and 180s
    - Leads to patient heating

Free Induction Decay

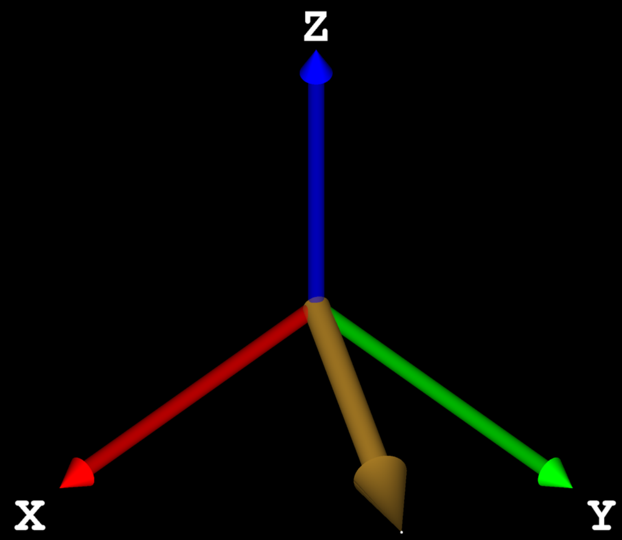


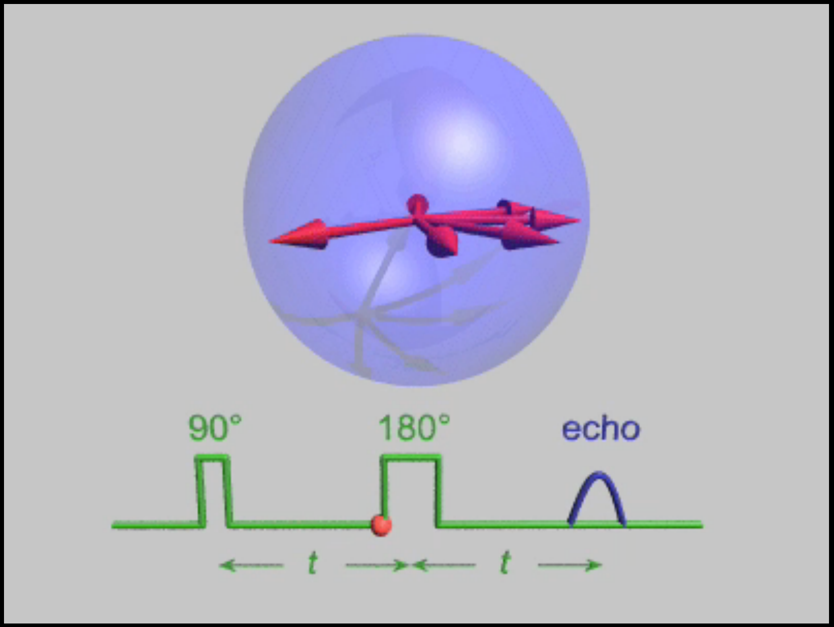
We can “refocus” the signal with a refocusing RF pulse.

Refocusing Pulses

- Typically, 180° RF Pulse
  - Provides optimally refocused M_{XY}
  - Largest spin echo signal
- Refocus spin dephasing due to
  - imaging gradients
  - local magnetic field inhomogeneity
  - magnetic susceptibility variation
  - chemical shift

Refocusing Pulses



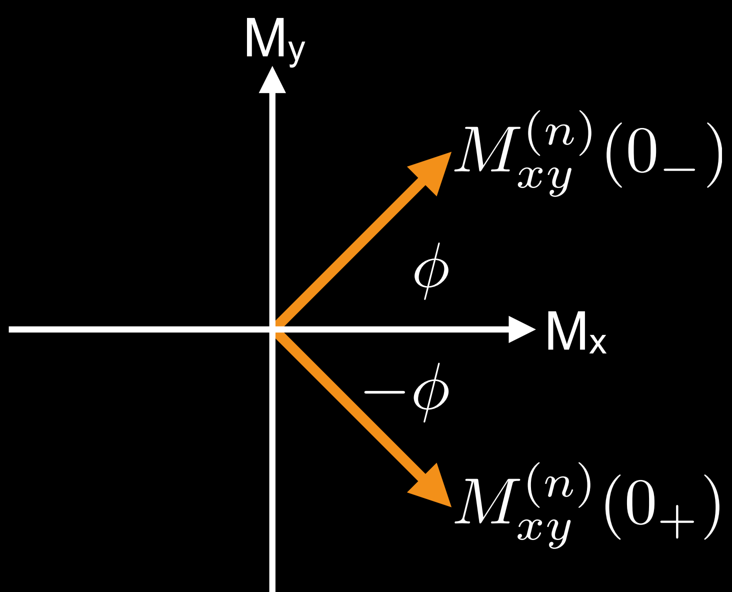


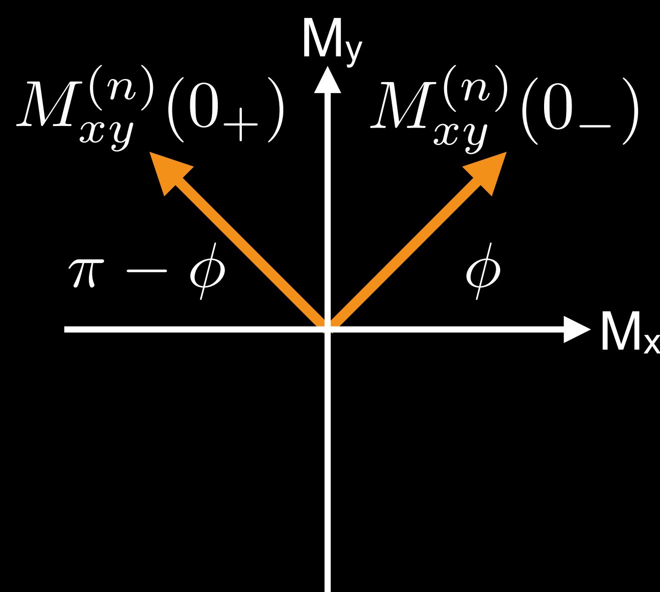
Hard Refocusing Pulses

$$\mathrm{RF}_\theta^\alpha = \begin{bmatrix} \mathrm{c}^2\theta + \mathrm{s}^2\theta\mathrm{c}\alpha & \mathrm{c}\theta\mathrm{s}\theta - \mathrm{c}\theta\mathrm{s}\theta\mathrm{c}\alpha & -\mathrm{s}\theta\mathrm{s}\alpha \\ \mathrm{c}\theta\mathrm{s}\theta - \mathrm{c}\theta\mathrm{s}\theta\mathrm{c}\alpha & \mathrm{s}^2\theta + \mathrm{c}^2\theta\mathrm{c}\alpha & \mathrm{c}\theta\mathrm{s}\alpha \\ \mathrm{s}\theta\mathrm{s}\alpha & -\mathrm{c}\theta\mathrm{s}\alpha & \mathrm{c}\alpha \end{bmatrix}$$

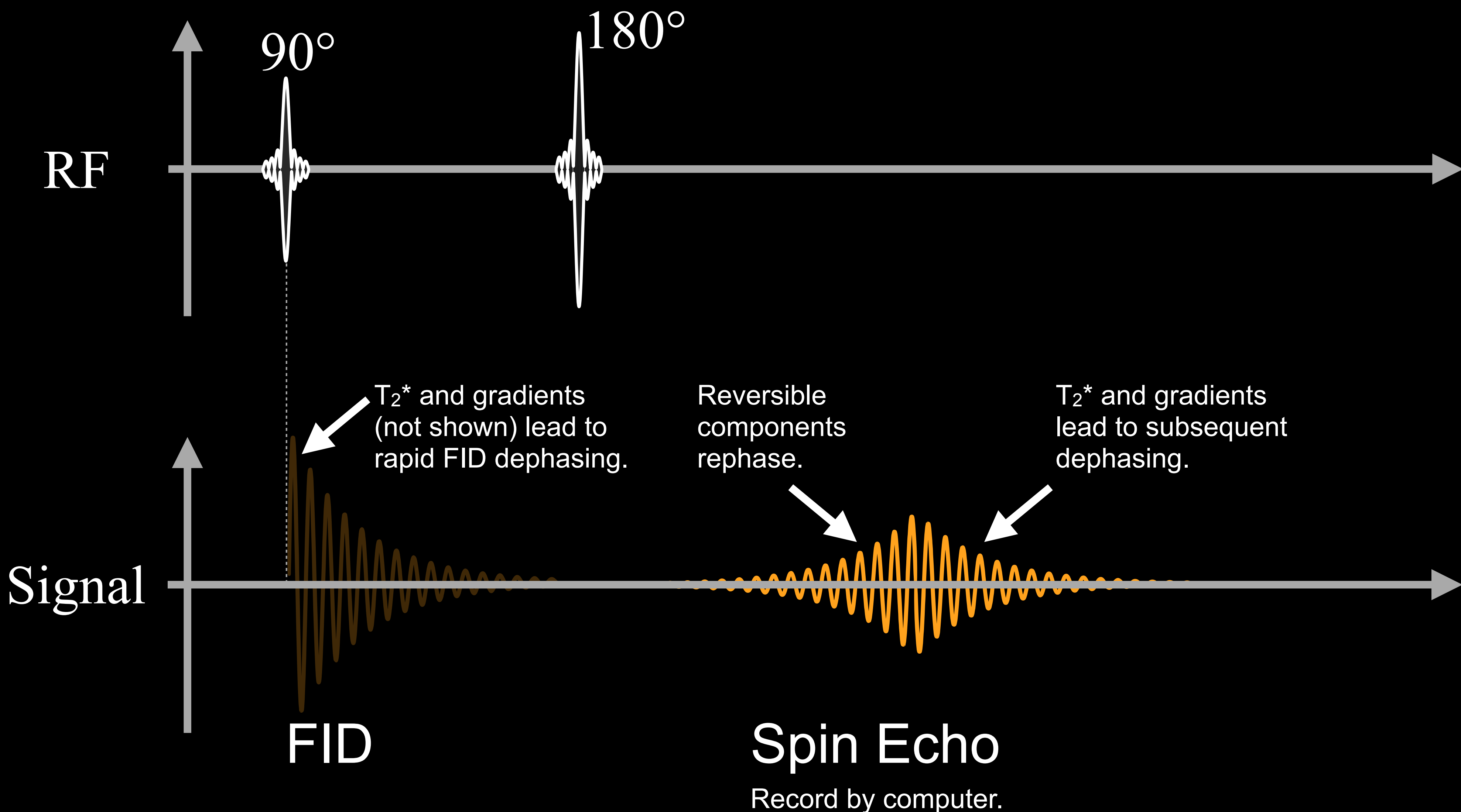
$$\mathrm{RF}_\theta^\alpha = \mathrm{RF}_0^\pi = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}$$

$$\mathrm{RF}_\theta^\alpha = \mathrm{RF}_{\pi/2}^\pi = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

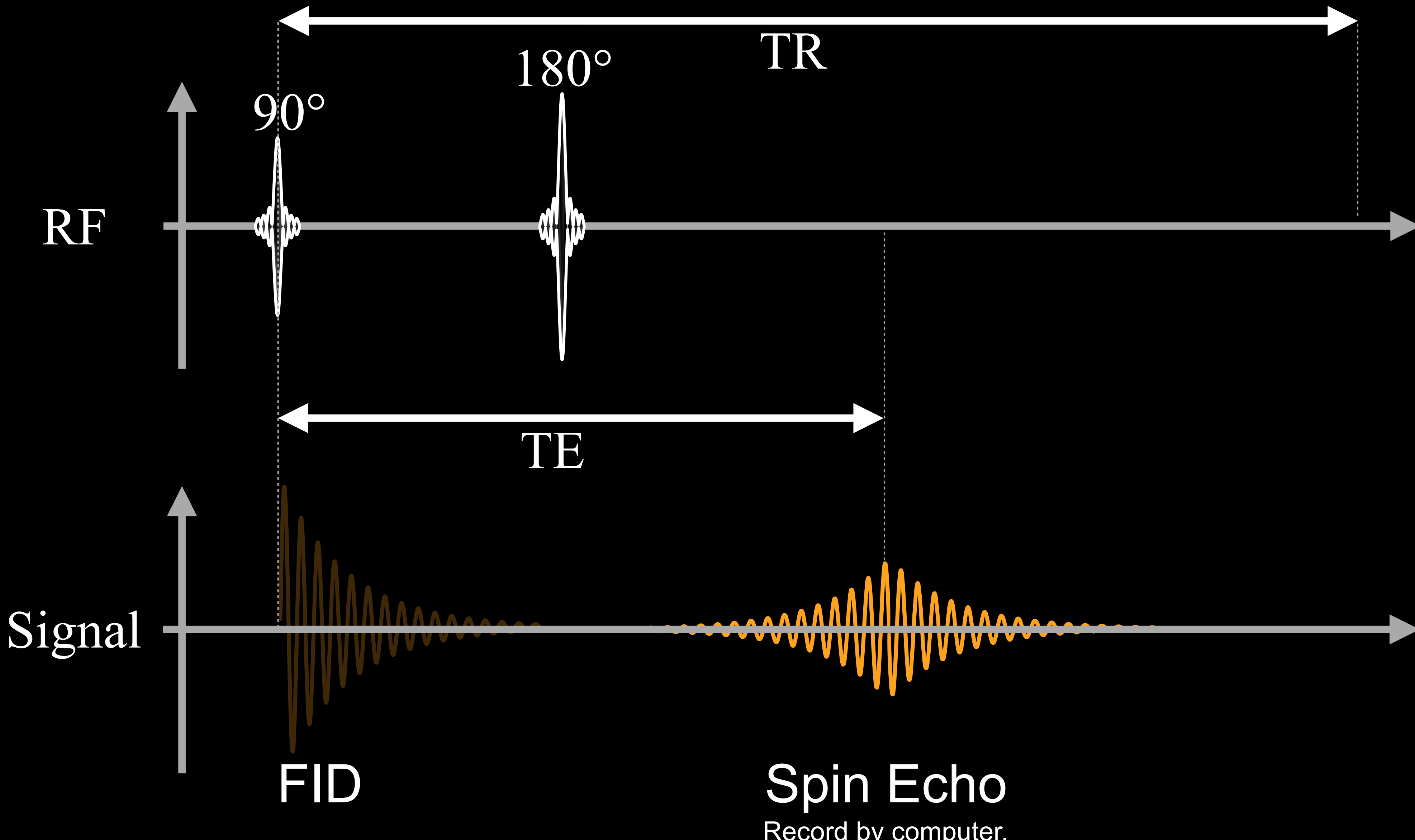




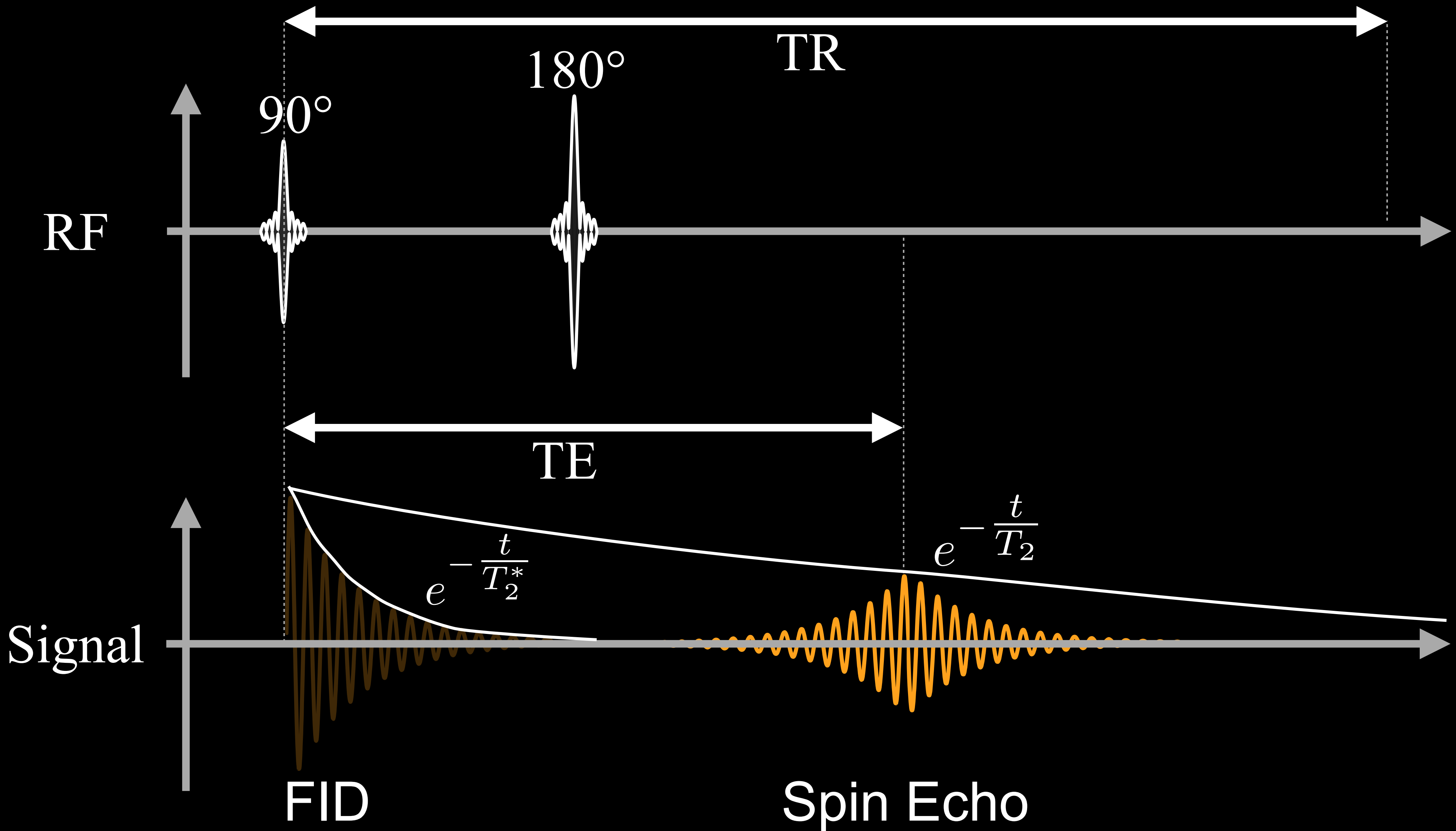
Spin Echo


90°
180°
RF
Signal
T2* and gradients (not shown) lead to rapid FID dephasing.
Reversible components rephase.
T2* and gradients lead to subsequent dephasing.
FID
Spin Echo
Record by computer.

Spin Echo



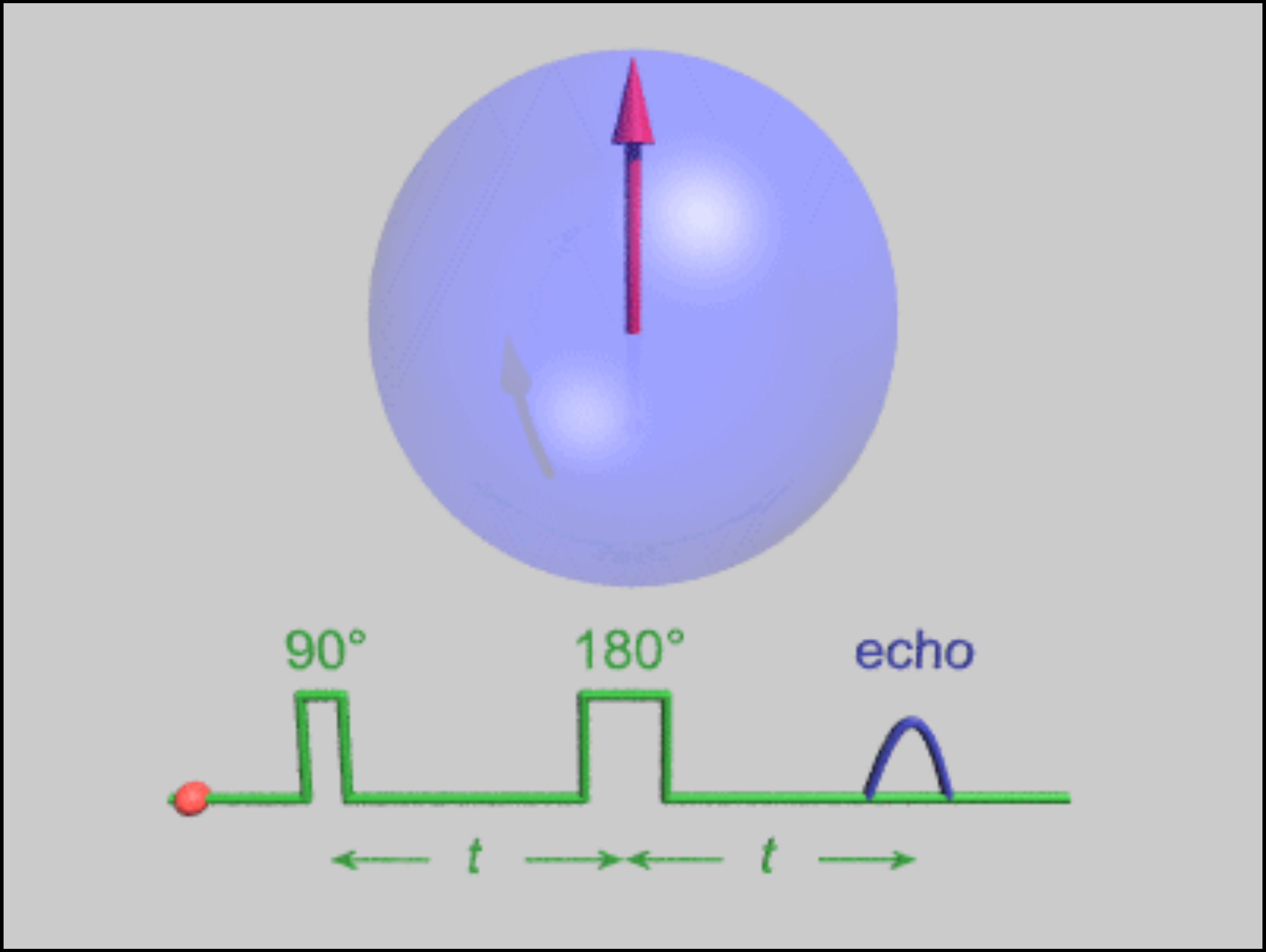
Spin Echo



How do you adjust the TR?

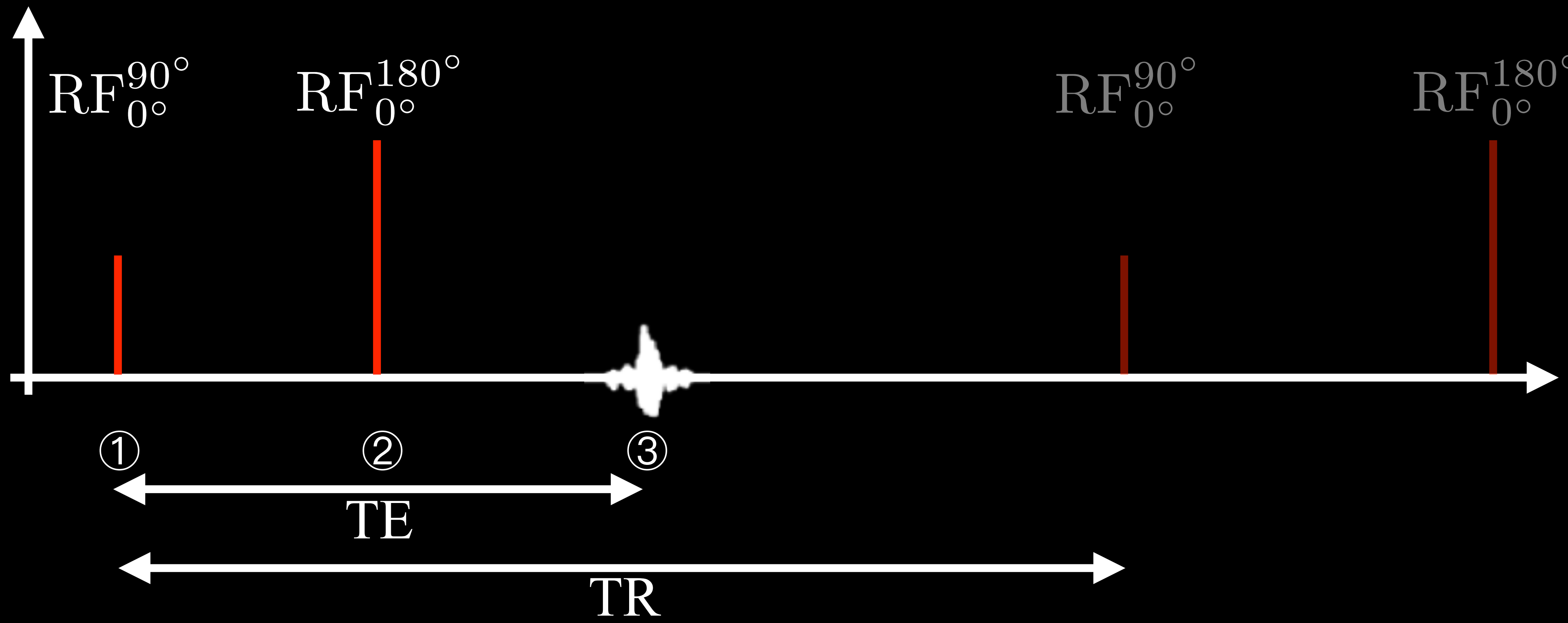
How do you adjust the TE?

Spin Echo - Refocusing



http://en.wikipedia.org/wiki/File:HahnEcho_GWM.gif

Spin Echo



To The Board...

Spin Echo Contrast

$$M_{z'}^{(4)}\left(0_-\right) = M_z^0\left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)$$

This becomes the initial condition for the subsequent TR. Eqn. 7.24

$$A_{Echo} \propto \rho\left(1 - 2e^{-(TR-TE/2)/T_1} + e^{-TR/T_1}\right)e^{-TE/T_2}$$

This the signal at time-point #3 for the second TR. Eqn. 7.25

If $TE \ll TR$, then

$$A_{Echo} \propto \rho\left(1 - e^{-TR/T_1}\right)e^{-TE/T_2}$$

Eqn. 7.26

This the signal at time-point #3 for the second TR when TE<<TR.

Spin Echo Contrast

Spin Echo Parameters

	TE	TR
Spin Density	Short	Long
T_1-Weighted	Short	Intermediate
T_2-Weighted	Intermediate	Long

$$A_{Echo} \propto \rho \left(1 - e^{-TR/T_1}\right) e^{-TE/T_2}$$

Long TR Minimizes This Term

Limits T_1 signal contribution.

Long TE Emphasizes This Term

Adds T_2 contrast.

Short T_1 Maximizes This Term

Leads to T_1 weighting.

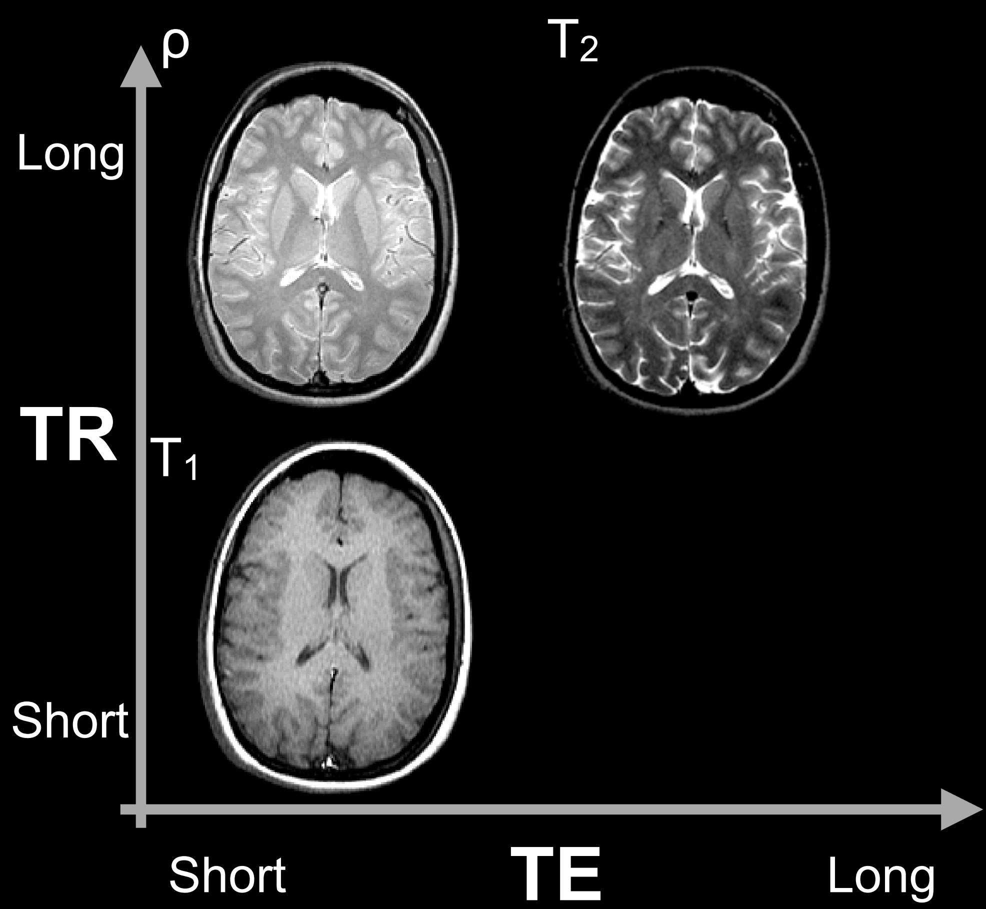
Long T_2 Maximizes This Term

Long T_2 is bright on T_2-weighted images.

Spin Echo Contrast

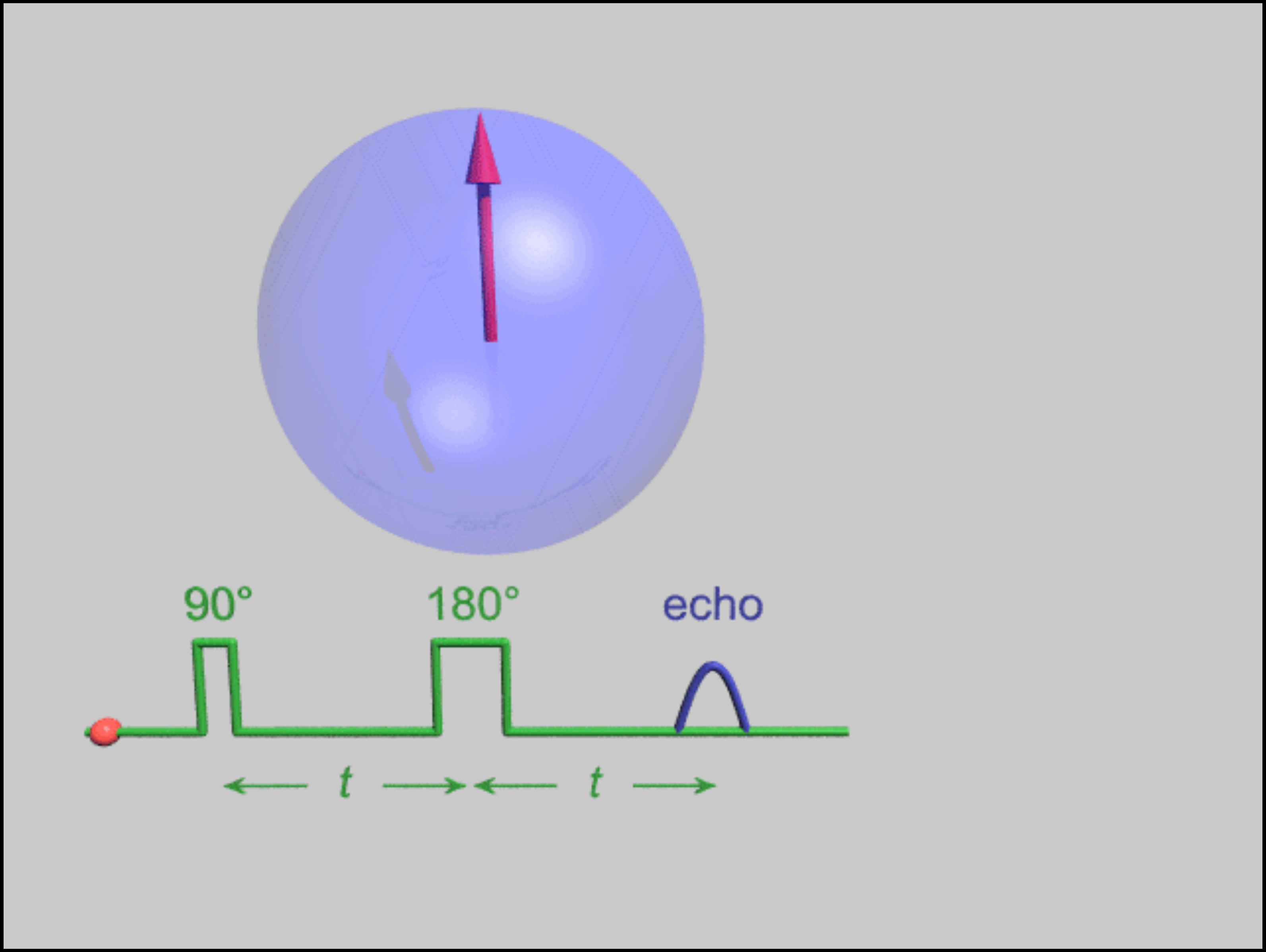
Spin Echo Parameters

	TE	TR
Spin Density	Short	Long
T_1-Weighted	Short	Intermediate
T_2-Weighted	Intermediate	Long



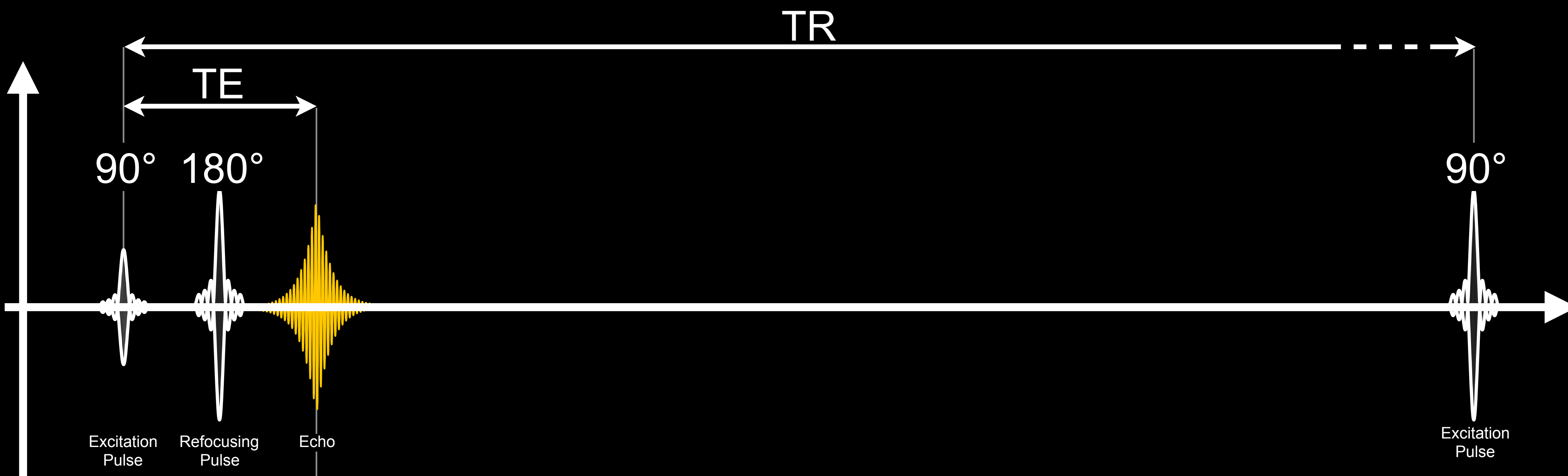
Images Courtesy of Mark Cohen

Spin Echo - Contrast



http://en.wikipedia.org/wiki/File:HahnEcho_GWM.gif

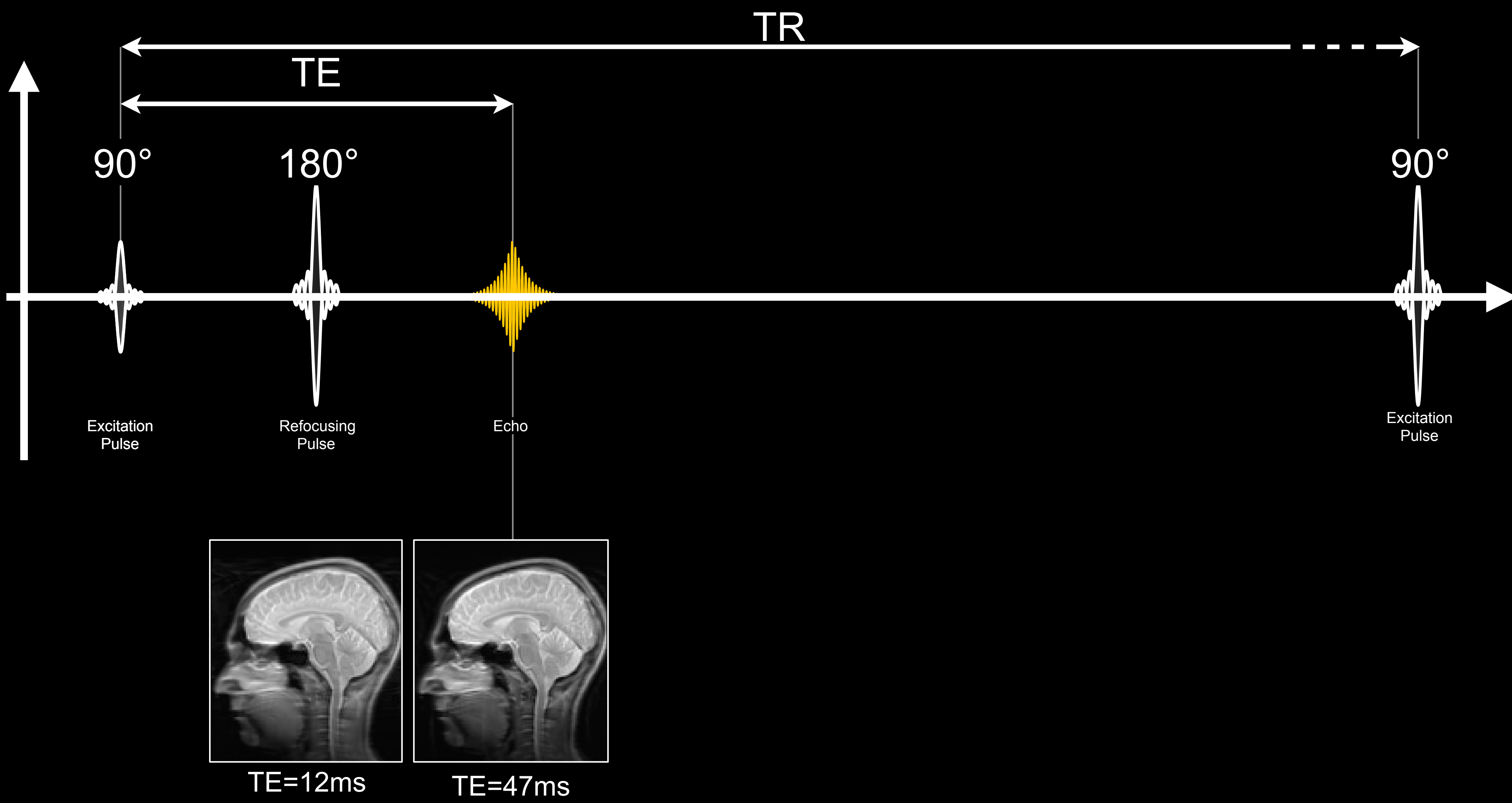
Spin Echo




TE=12ms

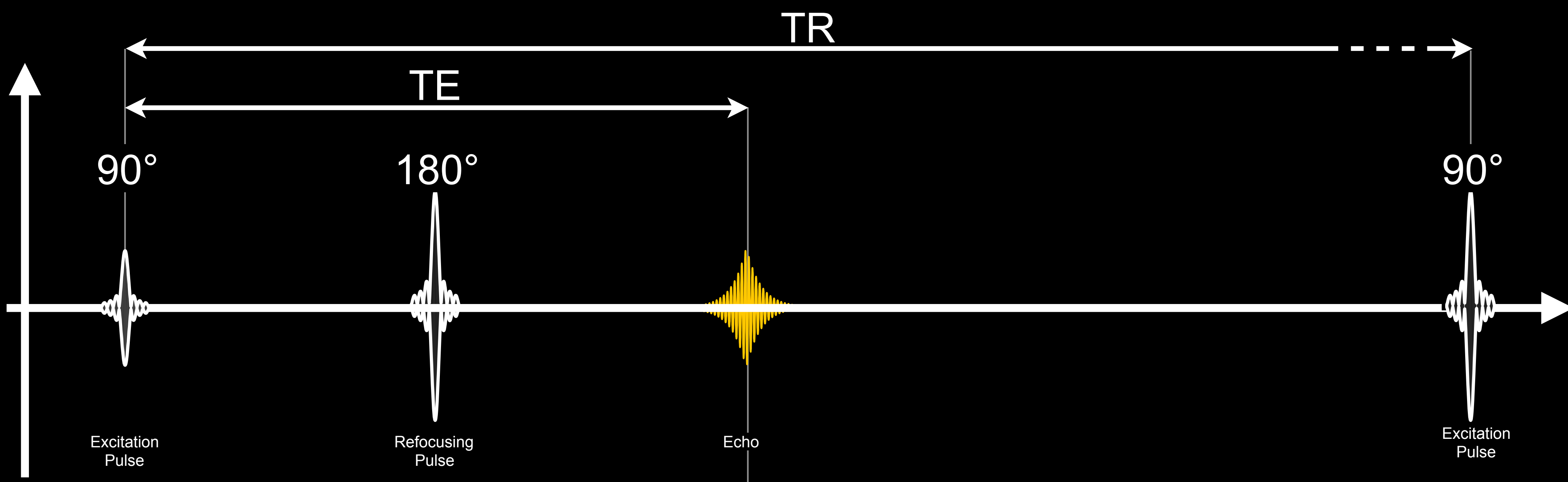
Short TE and Long TR is proton density weighted.

Spin Echo



Delaying the 180° refocusing pulse delays the TE.

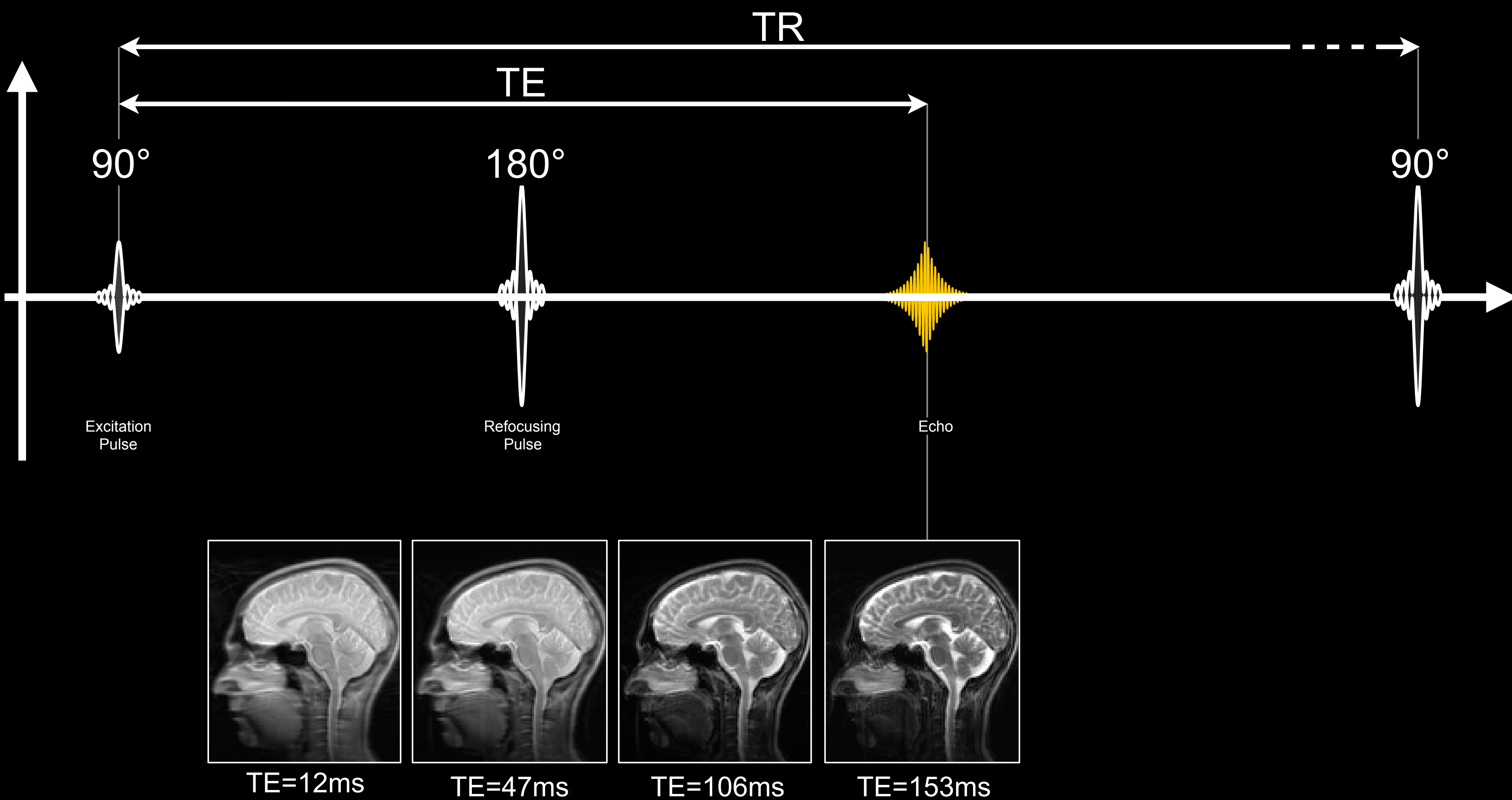
Spin Echo



TE=12ms TE=47ms TE=106ms

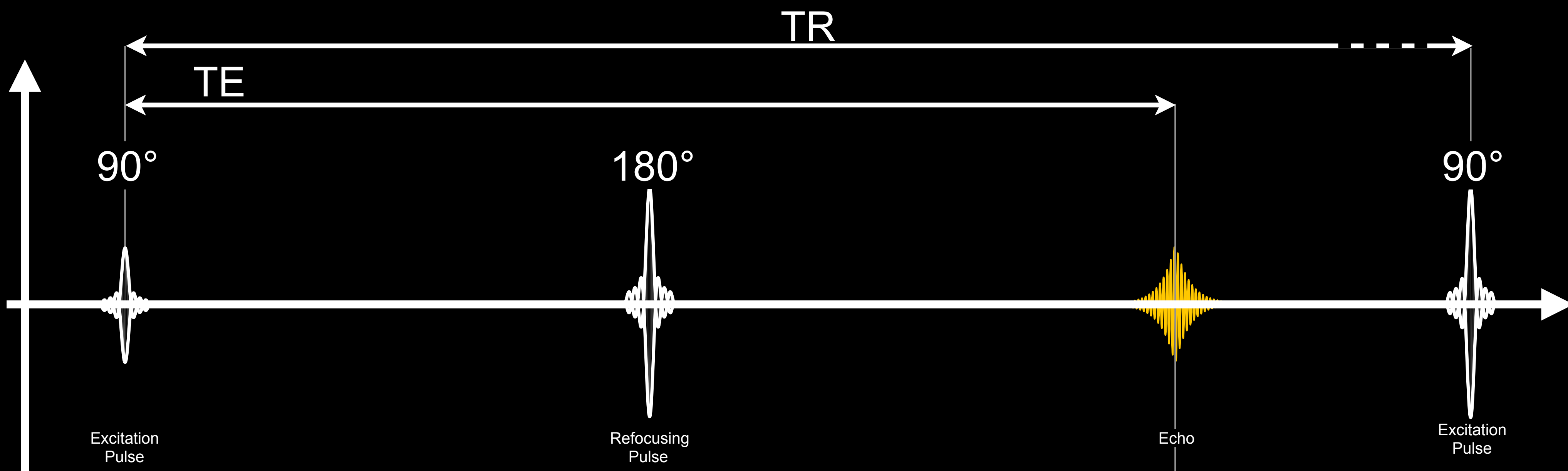
Longer TEs produce more T_2-weighting.

Spin Echo



Longer TEs produce more T_2-weighting.

Spin Echo



TE=12ms TE=47ms TE=106ms TE=153ms TE=235ms

Long T_2 is bright on T_2-weighted (long TE) images.

Thanks

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