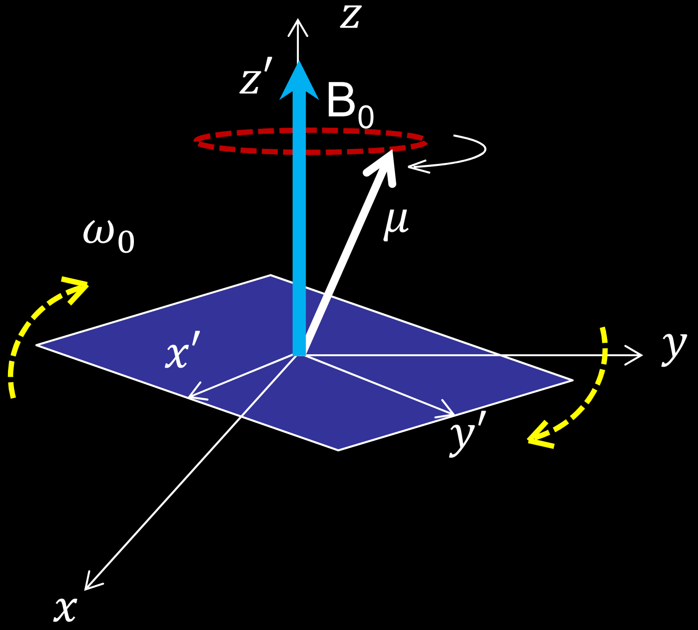
Chapter 8 – Signal acquisition Methods

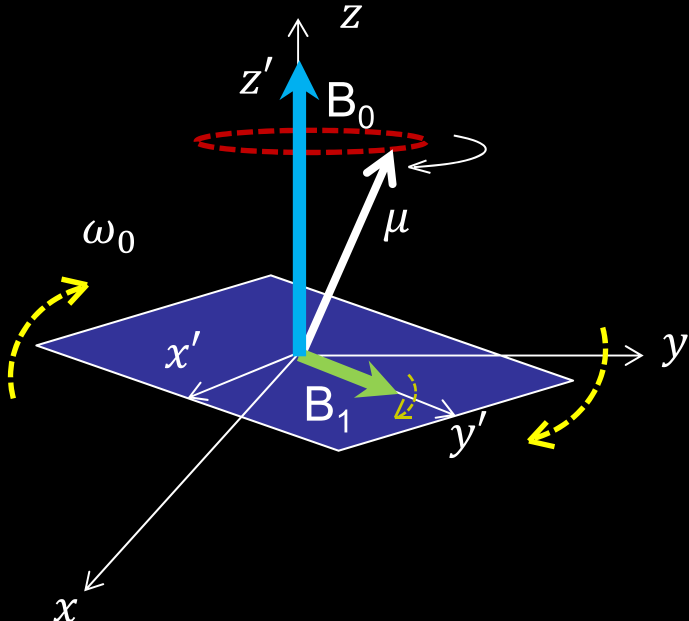
Quick Recap:



Quick Recap:

A rotating B_1 field - ON

… circularly polarized



Resonance Condition

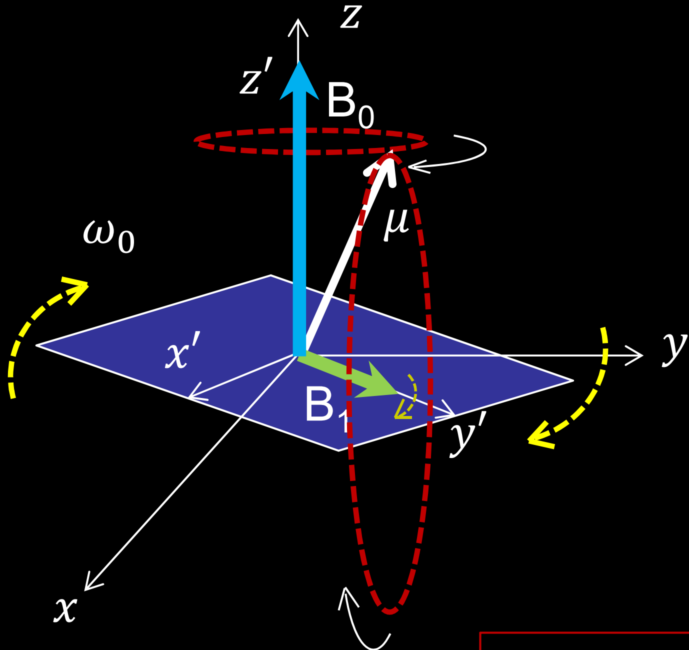
$$\omega' = \omega_0 = -\gamma \cdot B$$

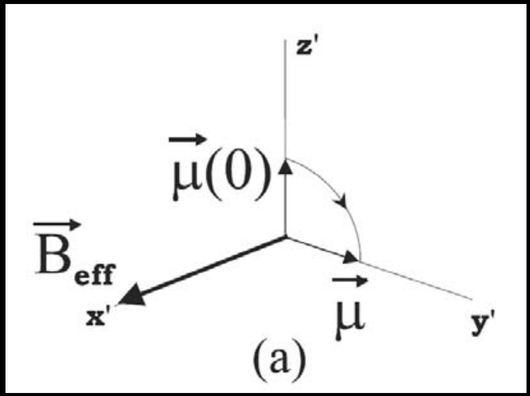
$$\boxed{\omega_0 = -\gamma \cdot B_0}$$

Larmor Frequency

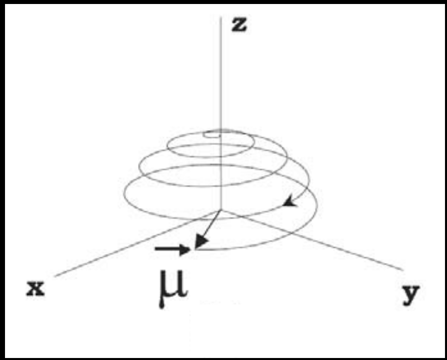
Quick Recap:

A rotating B_1 field - ON





$$\omega_1 = -\gamma \cdot B_1$$



$$\boxed{\theta = \omega_1 \cdot \tau = -\gamma \cdot B_1 \cdot \tau}$$

θ – Flip angle / tipping angle

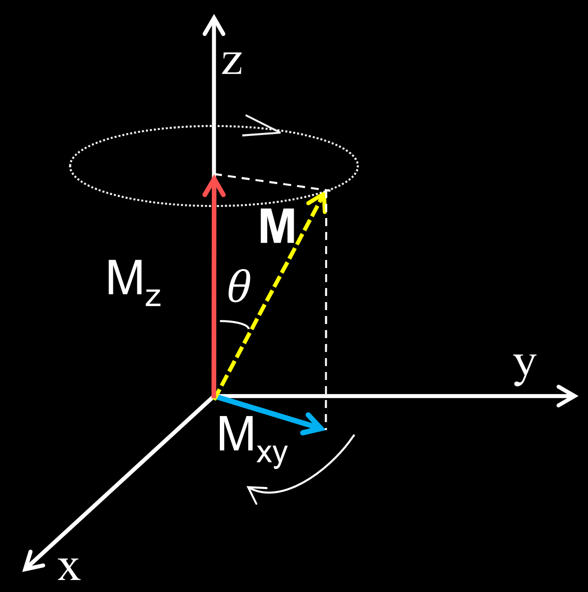
Quick Recap:

Relaxation effects

$$\frac{d\vec{M}}{dt} = \gamma \cdot \vec{M} \times B + \frac{M_0 - M_z}{T_1} - \frac{M_{xy}}{T_2}$$

M_0 is the equilibrium magnetization

M_{xy} is the transverse magnetization



Quick Recap:

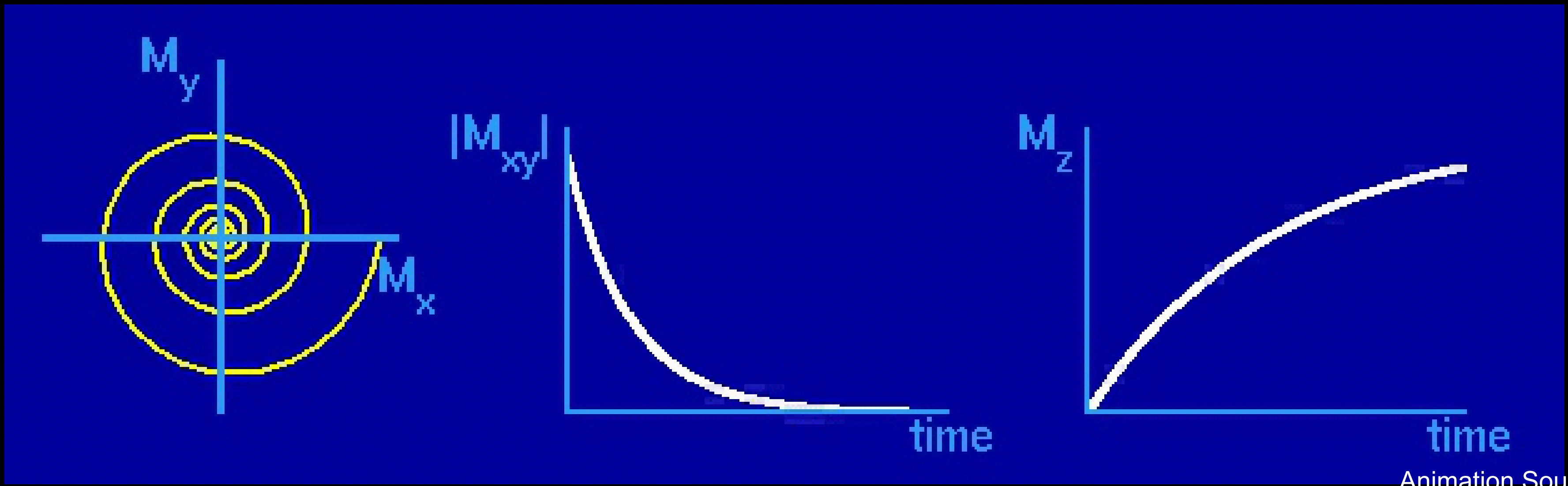
Relaxation effects

Transverse Magnetization Decay

$$M_{xy}(t) = M_{xy}(0) \cdot e^{-\frac{t}{T_2}}$$

Longitudinal Magnetization Recovery

$$M_z(t) = M_z(t=0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$



Animation Source:
http://www-mrsrl.stanford.edu/~brian/intromr

Basic Contrast Mechanisms: Relaxation effects

Longitudinal Magnetization - Recovery

$$M_z(t) = M_z(t=0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$

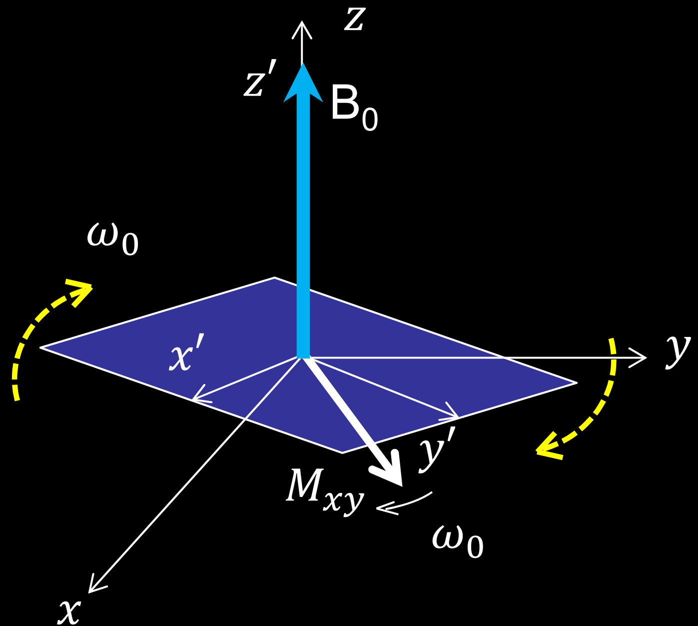
T_1 is the time it takes the magnetization to recover to 63.2% of its equilibrium value M_0.

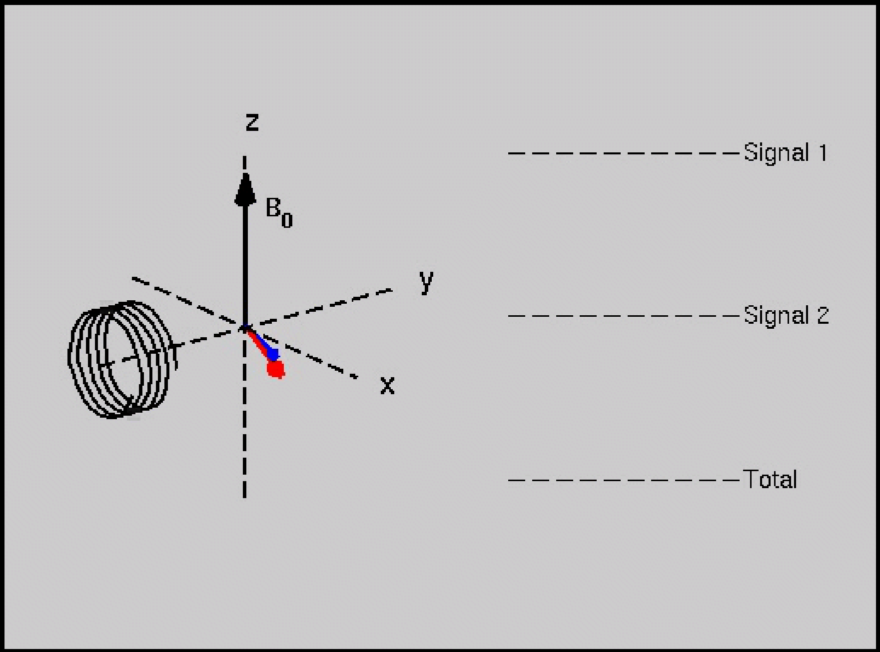
$$M_{xy}(t) = M_{xy}(0) \cdot e^{-\frac{t}{T_2}}$$

T_2 is the time it takes the transverse magnetization to decays to 36.7% of its initial value M_{xy}.

Quick Recap:

A rotating B_1 field - OFF



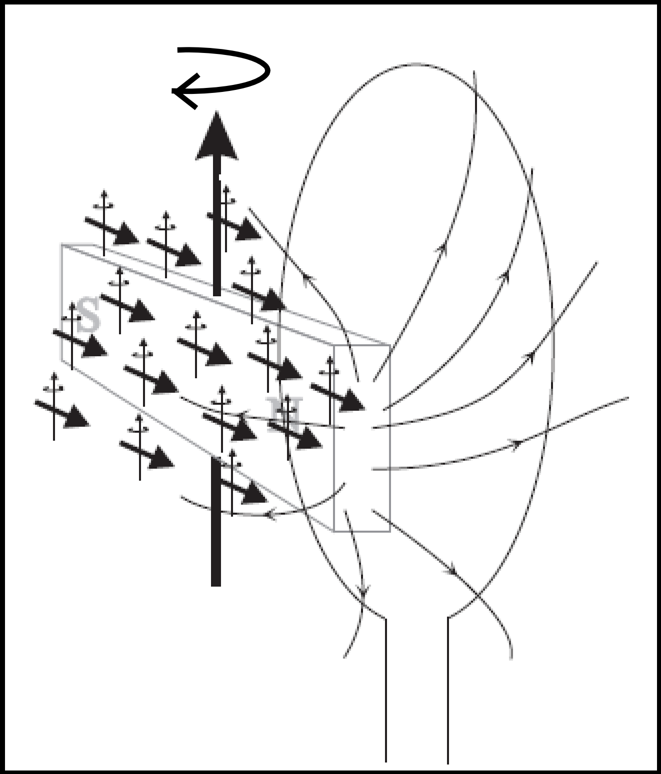


Animation Source:
http://www-mrsrl.stanford.edu/~brian/intromr

Quick Recap:

Signal Detection

Faraday's Law of Electromagnetic induction



$$emf = -\boxed{\frac{d\Phi}{dt}}$$

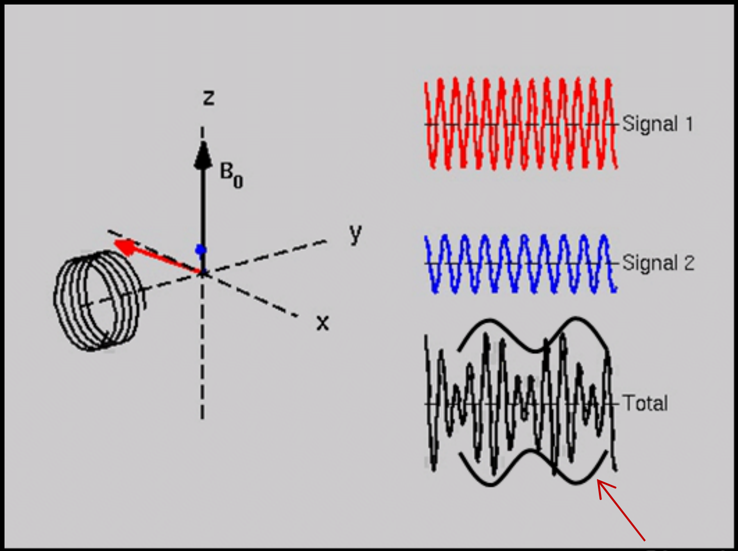
Induced signal is proportional to rate of change of flux

$$\omega_0 = -\gamma \cdot B_0$$

$$\Rightarrow emf \propto \omega_0$$

$$s(t) \propto \omega_0 \int d^3r e^{-t/T_2(\vec{r})} \mathcal{B}_\perp(\vec{r}) \underline{M_\perp(\vec{r},0)} e^{i\underline{((\Omega-\omega(\vec{r}))t+\phi_0(\vec{r})-\theta_{\mathcal{B}}(\vec{r}))}}$$

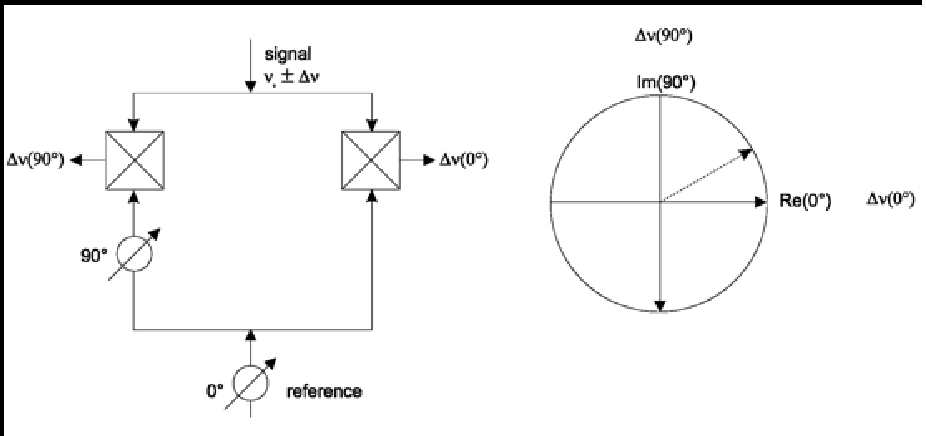
Signal Demodulation and quadrature detection



Signal envelope from demodulation

Demodulation

Quadrature detection or phase sensitive detection:



Quadrature detection allows us to record both x and y components of the transverse magnetization

Key Points in Chapter 8

- Free Induction Decay
- Spin Echo
- Repeated rf pulse structures –

  Magnetization and signal equations for different rf pulse structures

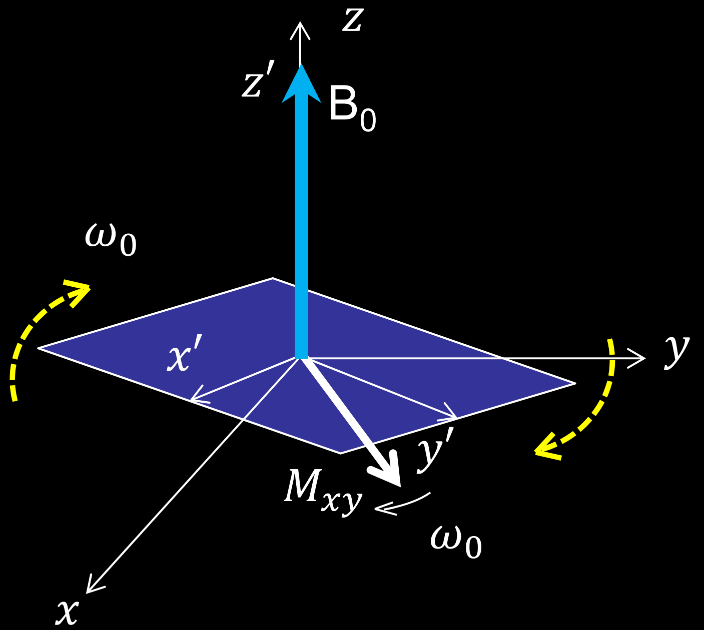
  Introducing sequence timing diagram
- Inversion Recovery

Demodulated Signal

$$s(t) \propto \omega_0 \int d^3r e^{-t/T_2(\vec{r})} \mathcal{B}_\perp(\vec{r}) M_\perp(\vec{r},0) e^{i((\Omega-\omega(\vec{r}))t+\phi_0(\vec{r})-\theta_\mathcal{B}(\vec{r}))}$$

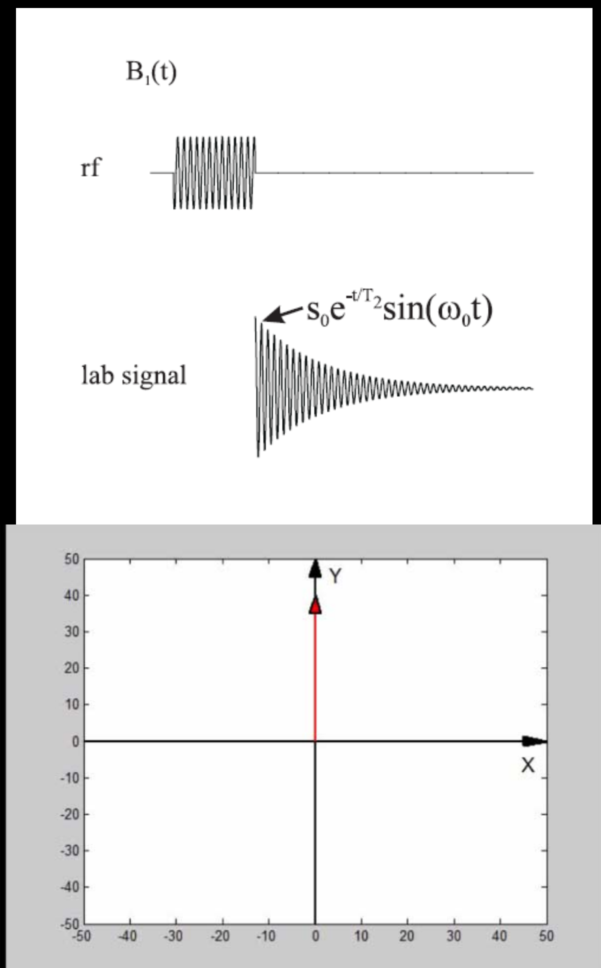
Dropping spatial dependence of T2…

$$s(t) \quad \propto \quad \omega_0 e^{-t/T_2} e^{i((\Omega-\omega_0)t+\phi_0-\theta_\mathcal{B})} \int d^3r \mathcal{B}_\perp(\vec{r}) M_\perp(\vec{r},0)$$



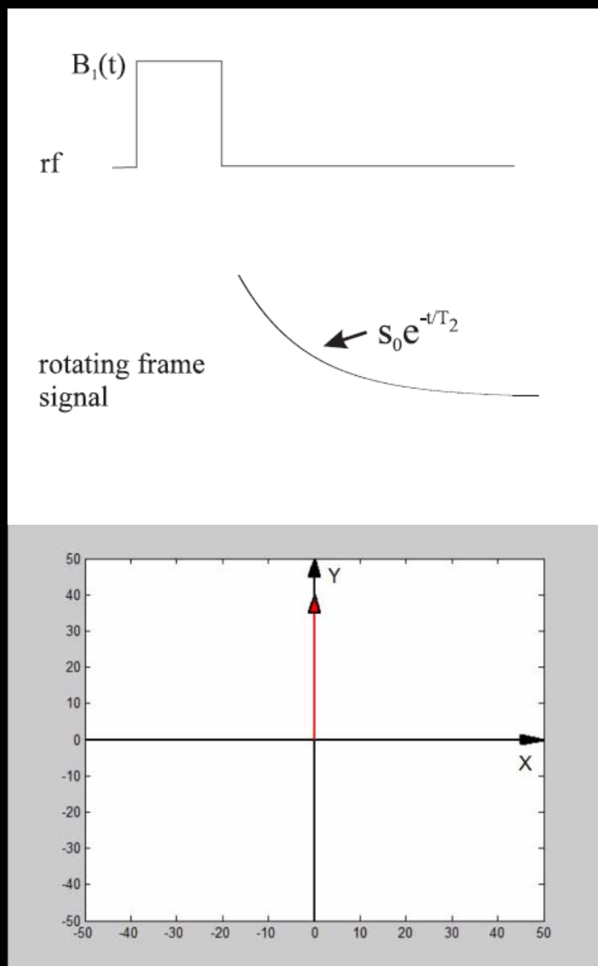
Let's assume uniform coil reception field and magnetization in the sample…

Demodulation



Laboratory reference frame

Demodulated signal



Rotating reference frame

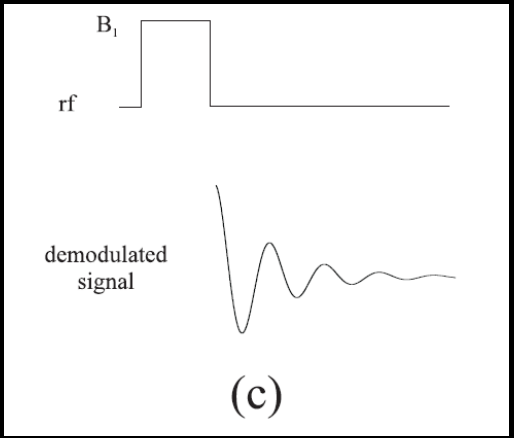
$$M_{xy} = M_0 \cdot e^{-\frac{t}{T_2}}$$

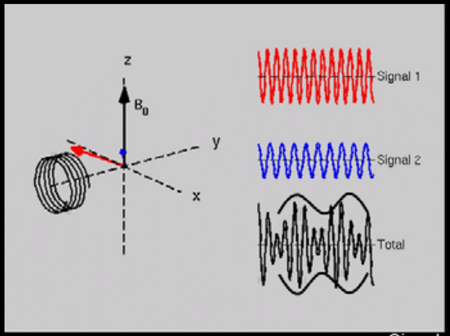
Animation Source:
Dr. Yongquan Ye, WSU

Free induction decay

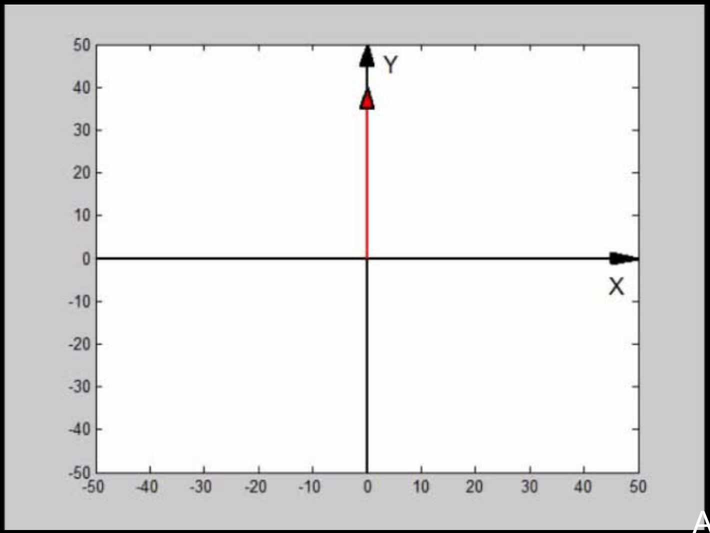
$$s(t) \;\; \propto \;\; \omega_0 e^{-t/T_2} e^{i((\Omega-\omega_0)t+\phi_0-\theta_{\mathcal{B}})} \int d^3r \mathcal{B}_\perp(\vec{r}) M_\perp(\vec{r},0)$$

$\Omega \neq \omega_0$ Or $\omega \neq \omega_0$





Signal envelope from demodulation

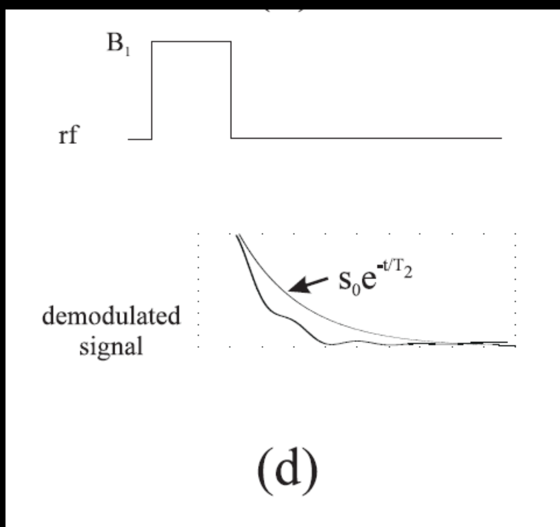


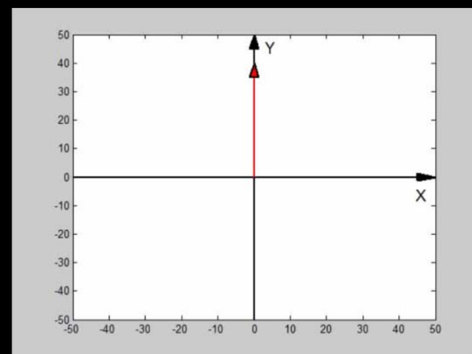
Animation Source:
Dr. Yongquan Ye, WSU

Free induction decay

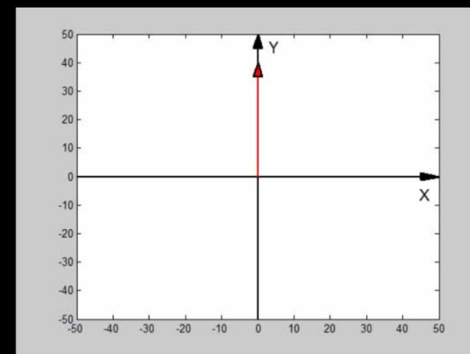
Practical issue: local & global field inhomogeneity exist

$$S(t) = S_0 \int e^{-t/T_2} e^{i(\Omega - \omega(\vec{r}))t} + \phi_0$$

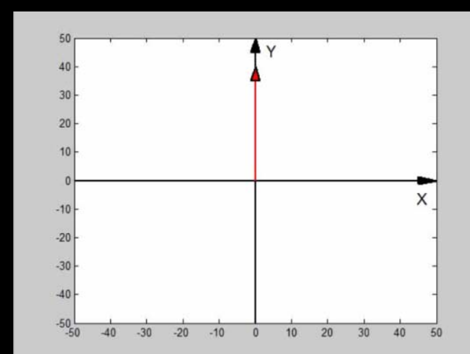




90% $\Omega - \omega(\vec{r})$=0Hz
10% $\Omega - \omega(\vec{r})$=50Hz



75% $\Omega - \omega(\vec{r})$ = 0Hz
25% $\Omega - \omega(\vec{r})$ =±50Hz
40 spins



75% $\Omega - \omega(\vec{r})$=0Hz
25% $\Omega - \omega(\vec{r})$□±50Hz
40,000 spins

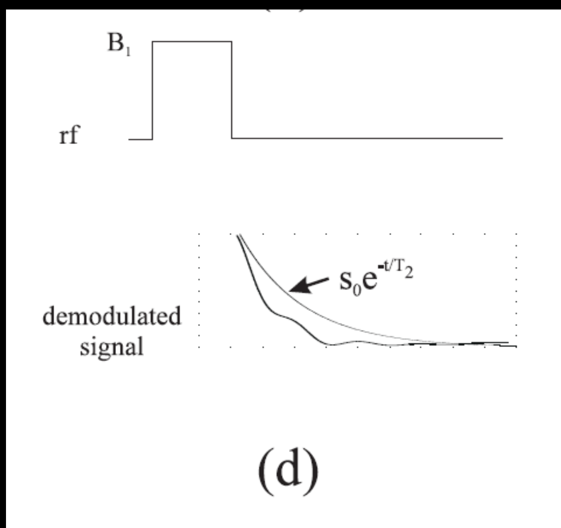
Animation Source:
Dr. Yongquan Ye, WSU

T_2^* and T_2'

Practical issue: local & global field inhomogeneity exist

$$S(t) = S_0 \int e^{-t/T_2} e^{i(\Omega - \omega(\vec{r}))t} \; + \phi_0$$

$$\boxed{\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2'}}$$



Faster decay of signal from transverse magnetization occurs due the presence of local field inhomogeneities

The additional decay time constant is empirically given by T_2'
($1/T_2' = R_2'$ is the additional relaxation rate)

$$1/T_2^* = R_2^*$$
$$1/T_2 = R_2$$

$$\boxed{M_{xy} = M_0 \cdot e^{-\frac{t}{T_2^*}}}$$

T_2'

Practical issue: local & global field inhomogeneity exist

$$S(t) = S_0 \int e^{-t/T_2} e^{i(\Omega - \omega(\vec{r}))t\ +\ \phi_0}$$

The additional decay rate, T_2', could be estimated by:

$$e^{-\frac{t}{T_2'}} \sim \int e^{i(\Omega - \omega(\vec{r}))t}$$

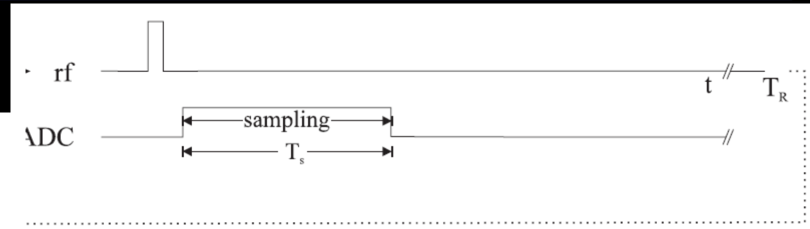
$$\varphi(r,t) = \left(\Omega - \omega(\boldsymbol{r})\right) \cdot t + \phi_0$$

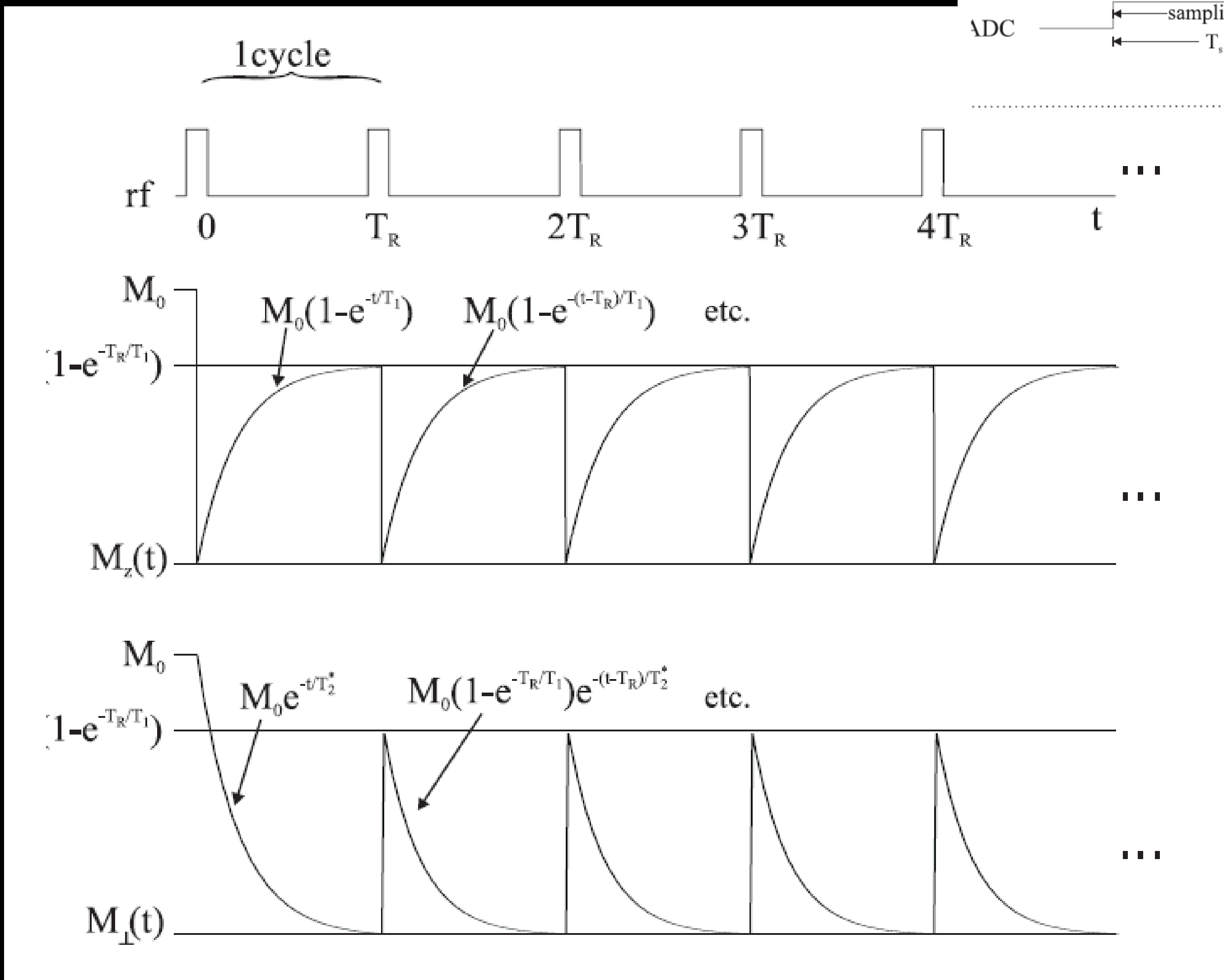
$$\varphi(r,t) = \gamma\left(\mathrm{B}_0 - B(\boldsymbol{r})\right) \cdot t + \phi_0 \qquad \varphi(r,t) = \gamma\left(\mathrm{B}_0 - (B_0 + \Delta B(\boldsymbol{r})\right) \cdot t + \phi_0$$

$$\boxed{\varphi(r,t) = -\gamma \cdot \Delta B(\boldsymbol{r}) \cdot t + \phi_0}$$

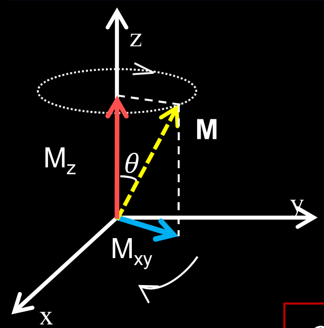
$$\boxed{e^{-\frac{t}{T_2'}} \sim \int e^{i\varphi(r,t)}}$$

Multi-pulse experiments





Magnetization equations



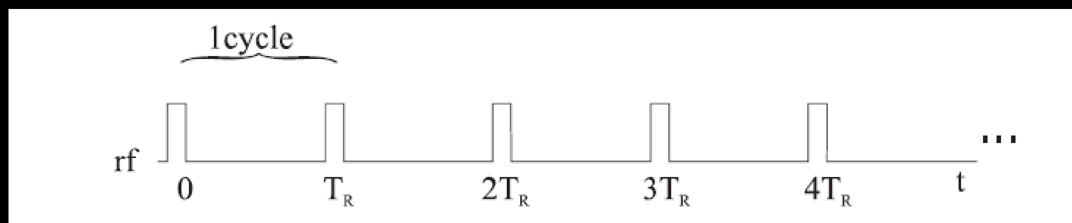
$$M_z(t) = M_z(0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$

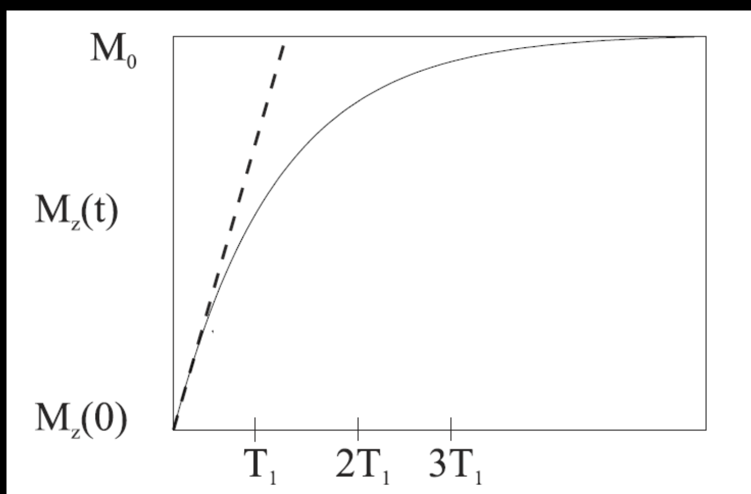
$$M_{xy}(t) = M_{xy}(0) \cdot e^{-\frac{t}{T_2^*}}$$

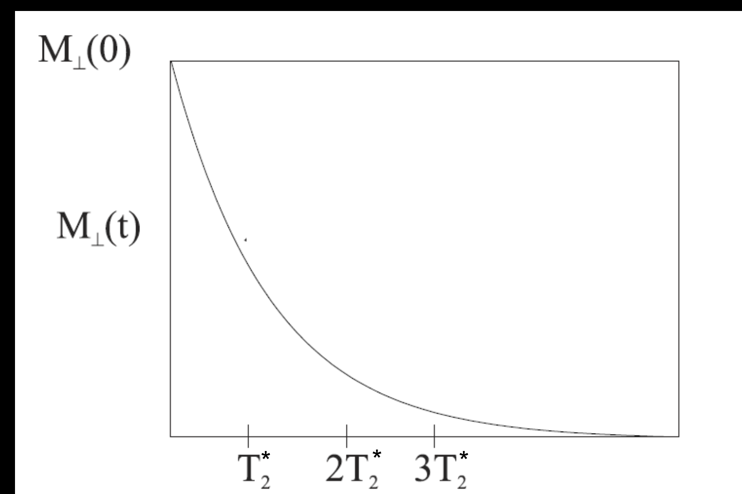
$$M_z(0) = M_0 \cdot \cos(\theta)$$

$$M_{xy}(0) = M_0 \cdot \sin(\theta)$$

$\theta = 90^o$



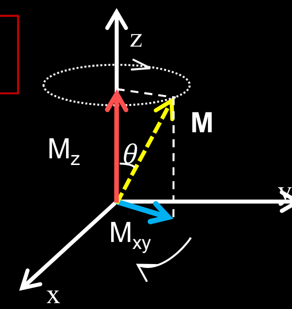




$TR \gg T_2^*$

FID sampling and repeated scans

$\theta = 90^o$



With a 90° excitation:

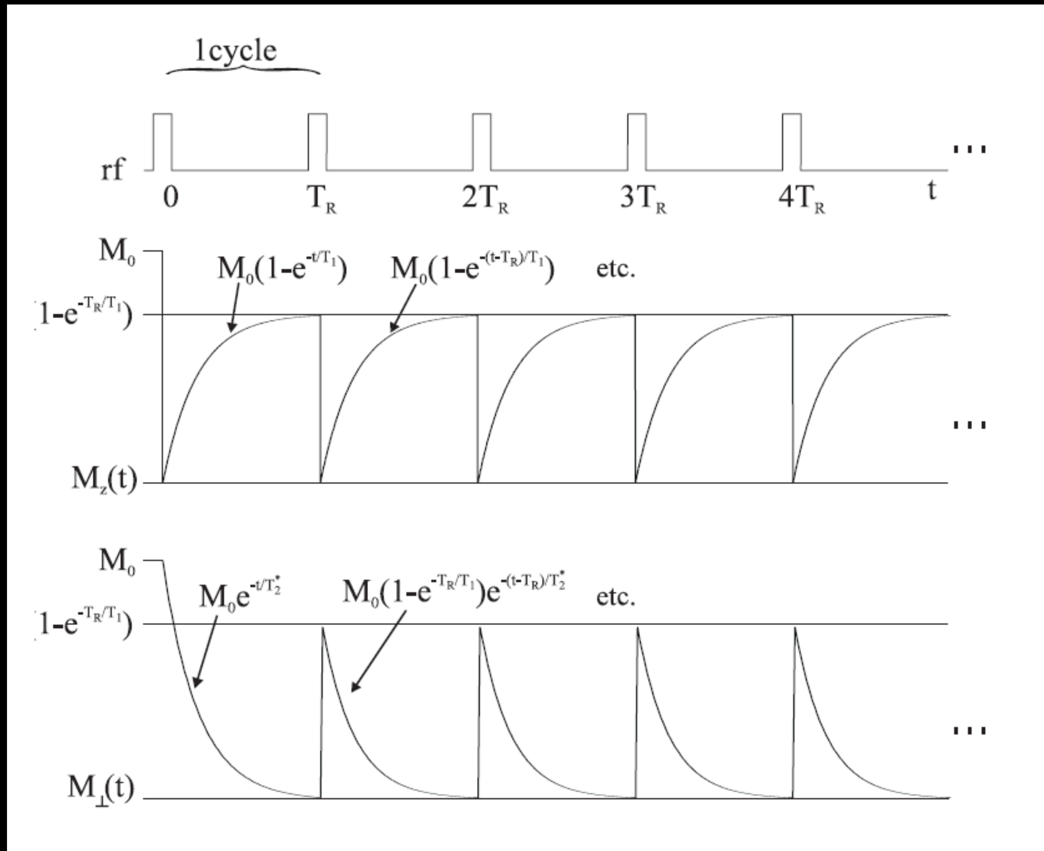
$TR \gg T_2^*$

$$\begin{cases} M_z(0^+) = 0 \\ M_\perp(0^+) = M_0 \end{cases}$$

$$\begin{cases} M_z(TR^-) = M_0(1 - e^{-TR/T1}) \\ M_\perp(TR^-) = M_0 e^{-TR/T_2^*} \end{cases}$$

$$\vdots$$

$$\begin{cases} M_z(nTR^-) = M_0(1 - e^{-TR/T1}) \\ M_\perp(nTR^-) = M_0(1 - e^{-TR/T1})e^{-TR/T_2^*} \end{cases}$$

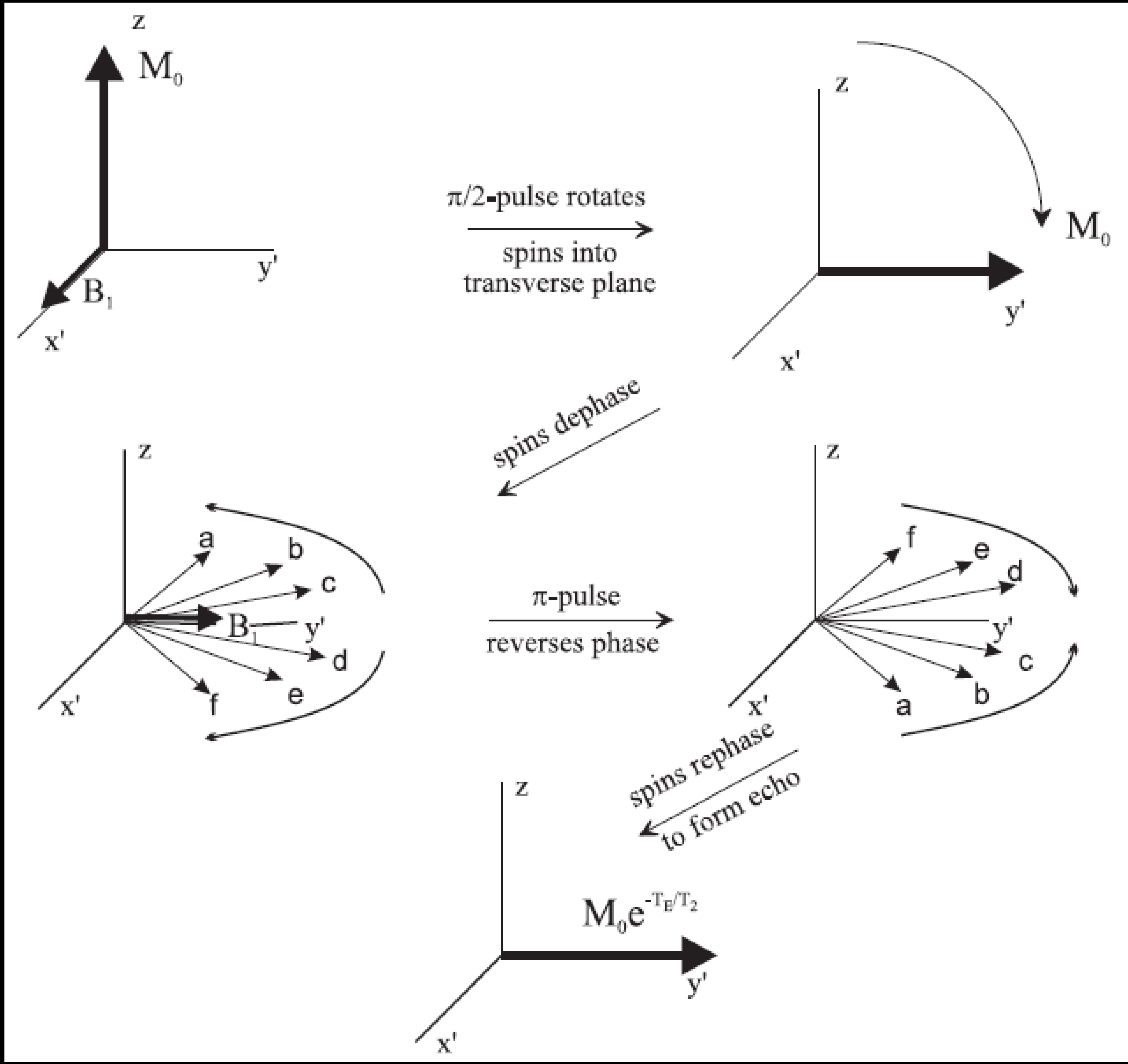


Note that both T1 and T2 affect the signal's amplitude*

Spin echo (rf echo)

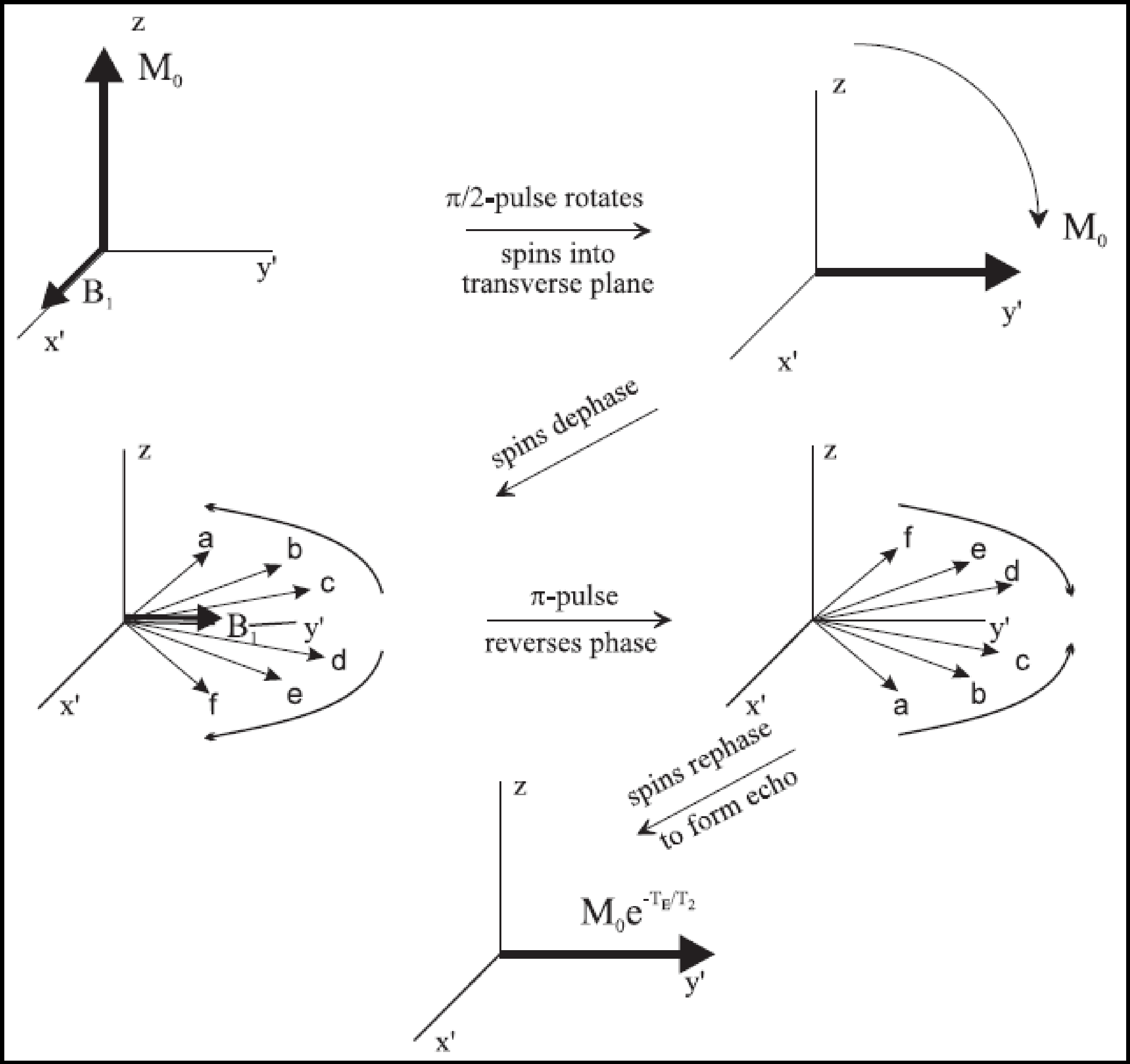
$\pi/2$ rf pulse about the x' axis

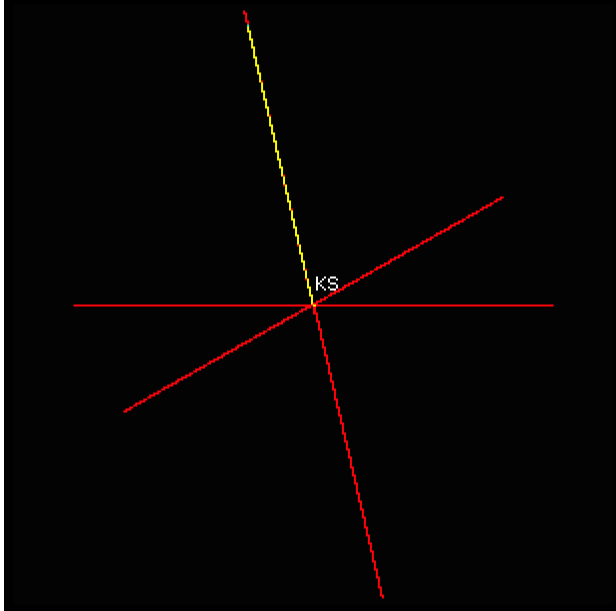
π refocusing rf pulse about the y' axis



Echo occurs along the y' axis

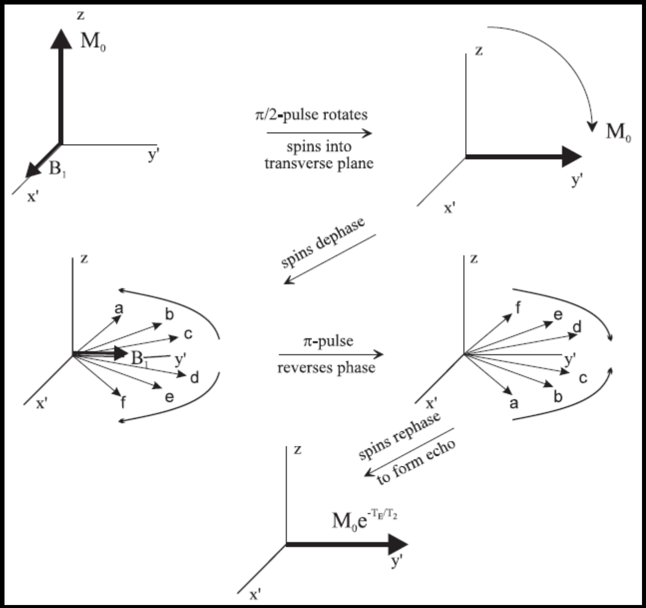
Spin echo (rf echo)

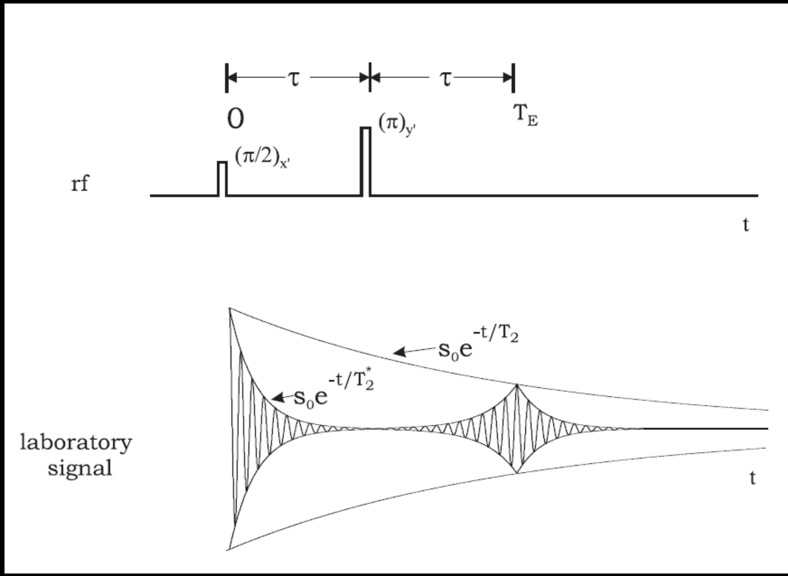


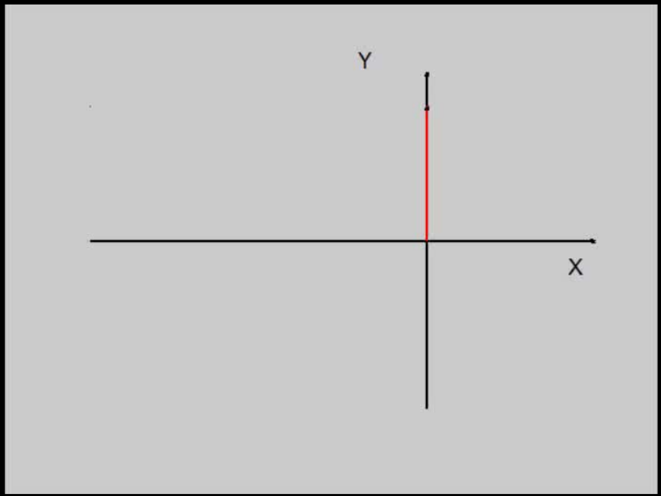


Animation source:
www.kyb.tuebingen.mpg.de/research/dep/ks/spinzoo.html

Spin echo (rf echo)







Animation Source:
Dr. Yongquan Ye, WSU

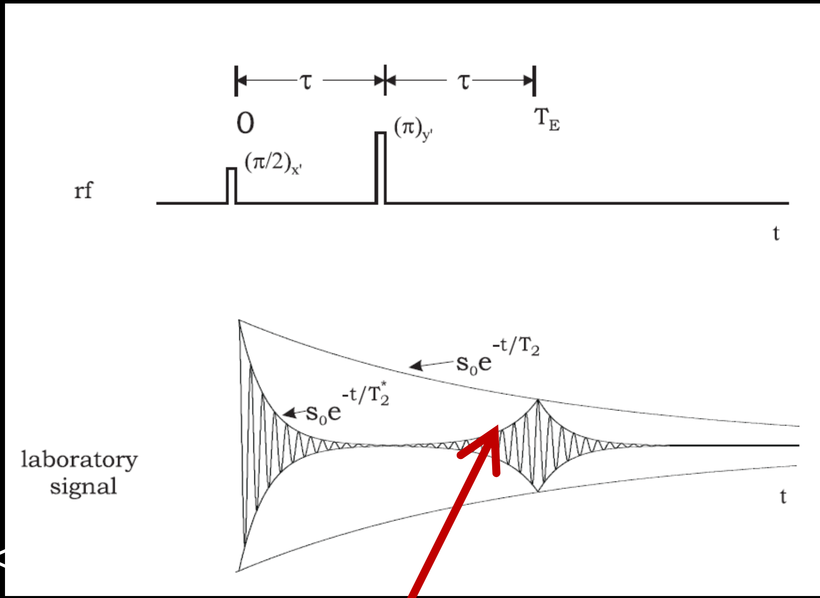
Spin echo (rf echo)

How SE works

1. $\phi(\vec{r},t) = -\gamma\Delta B(\vec{r})t, 0 < t < \tau$

Refocusing π pulse after time τ…

2. $\phi(\vec{r},\tau^{+}) = -\phi(\vec{r},\tau^{-}) = \gamma\Delta B(\vec{r})\tau, t = \tau$



3. $\phi(\vec{r},t) = -\gamma\Delta B(\vec{r})(t-\tau) + \gamma\Delta B(\vec{r})\tau\ ,\ \tau <$
   $t < \tau$

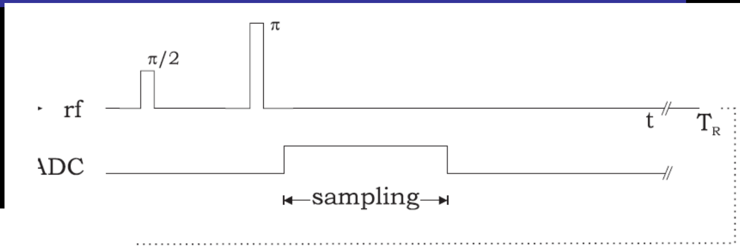
$$S(t) = S_0 \cdot e^{-t\left(\frac{1}{T_2} - \frac{1}{T_2'}\right)}$$

4. $\phi(\vec{r},2\tau) = 0, t = 2\tau \equiv TE$

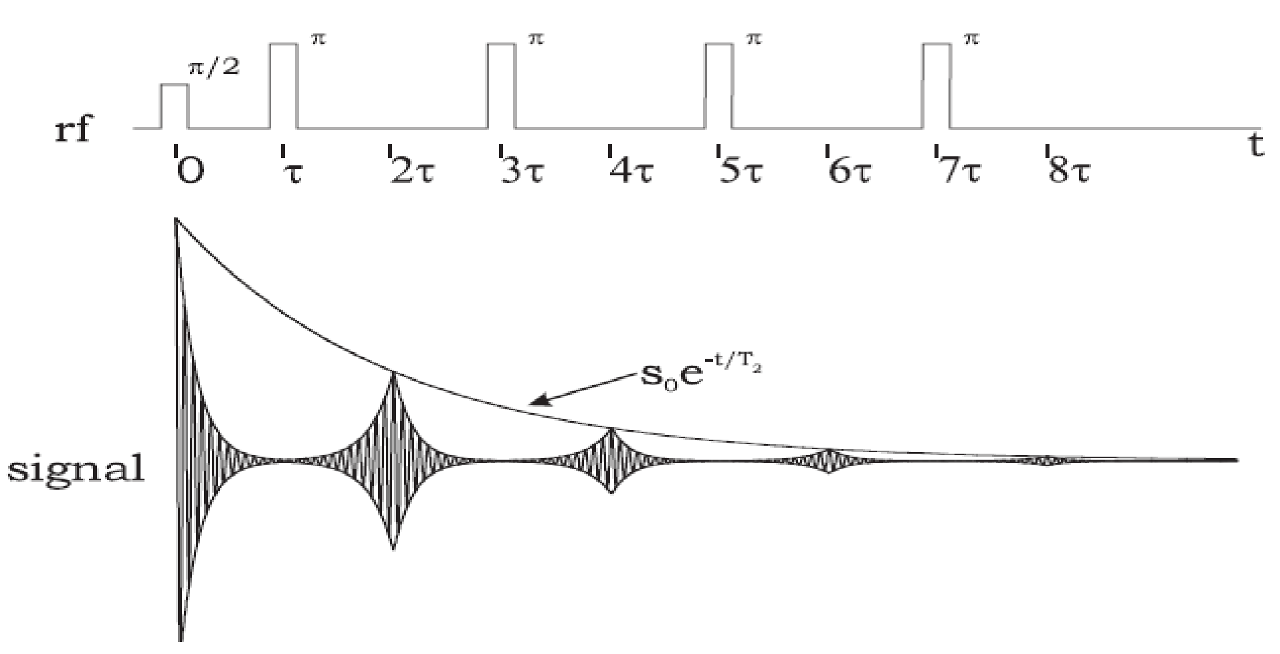
5. $\phi(\vec{r},t) = -\gamma\Delta B(\vec{r})(t-2\tau,)\ \ t > 2\tau$

T_2^* dephasing continues…

Multi-echo Spin Echo



$TR \gg T_2^*$



$$S(TE_1) = S_0 \cdot e^{-\frac{TE_1}{T_2}}$$

$$S(TE_2) = S_0 \cdot e^{-\frac{TE_2}{T_2}}$$

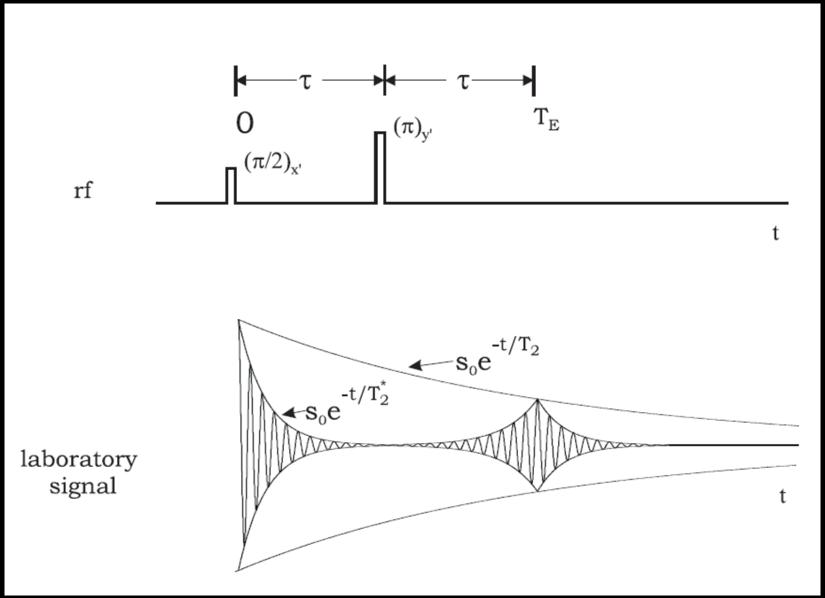
$$\boxed{T_2 = \frac{TE_2 - TE_1}{\ln\left(\frac{S(TE_1)}{S(TE_2)}\right)}}$$

Note:
The phase of refocusing pulses greatly affects the signal of ME-SE. Consider the following rf pulse schemes:

1) 90°(x) - 170°(y) - 170°(y) - 170°(y) - 170°(y) …
2) 90°(x) - 170°(y) - 170°(-y) - 170°(y) - 170°(-y) … (CPMG seq)

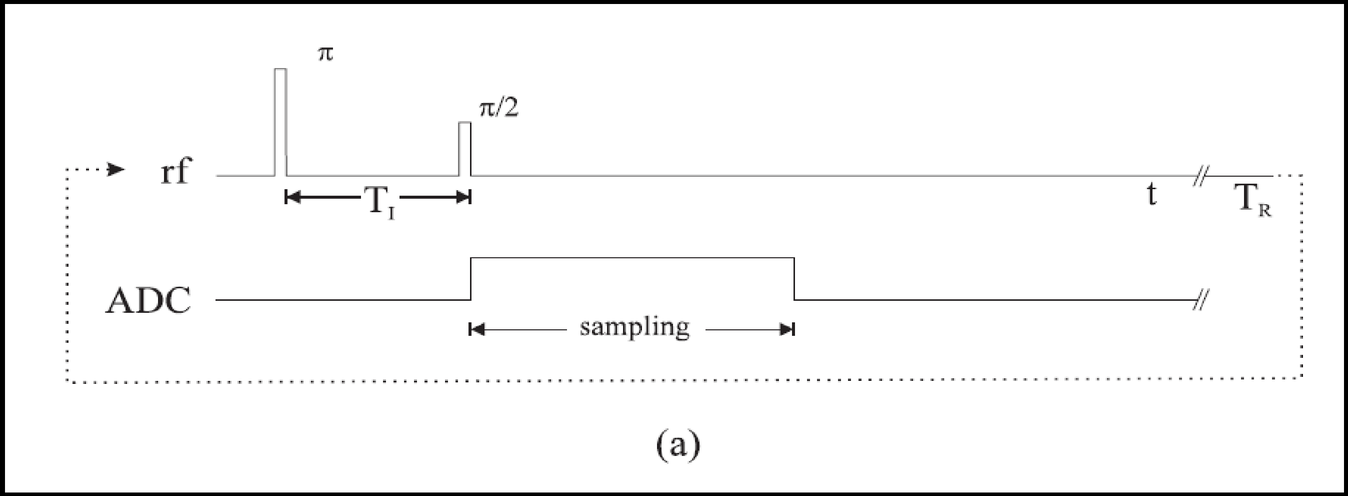
T2

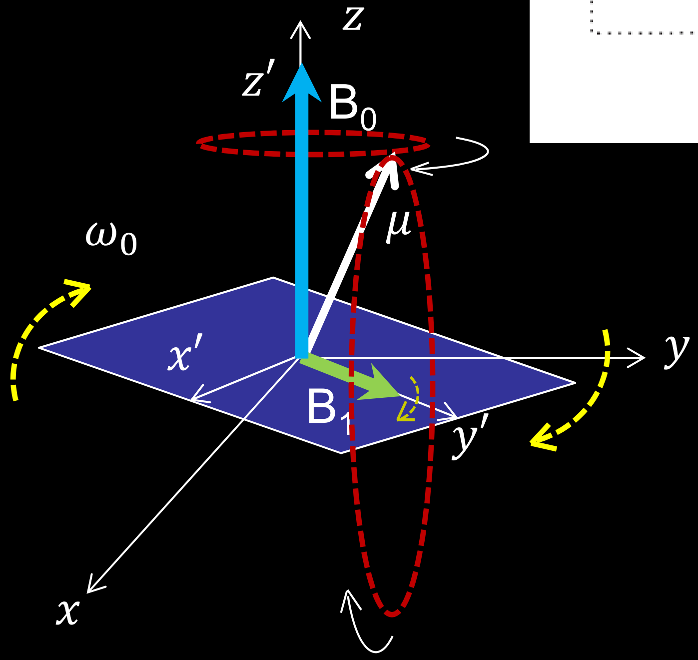
- Maximal signal limited to T2 decay which is not recoverable
- T2' decay on both sides of the echo acts as low pass filter, blurring the image (Chap. 13)
- True T2 is difficult for precise quantification
  - Motion, partial volume effects, RF pulse, data acquisition, etc.
- Extra consideration for multiple spin echo acquisition
  - RF pulse phase
  - RF energy deposition
  - Multiple signal pathways $(TR < T_2^*)$
- Long scan time



Inversion Recovery

$$M_z(t) = M_z(t=0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$





Inversion Recovery

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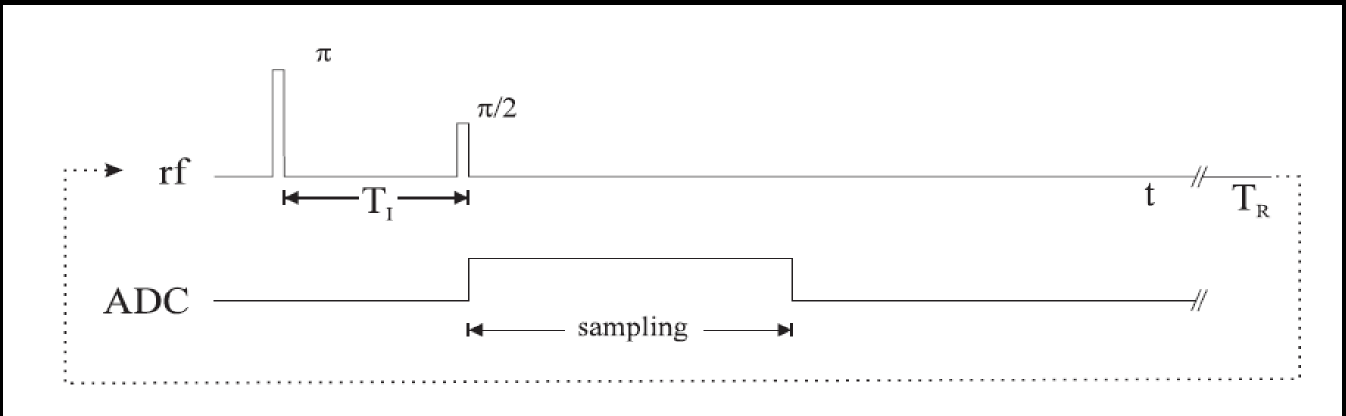
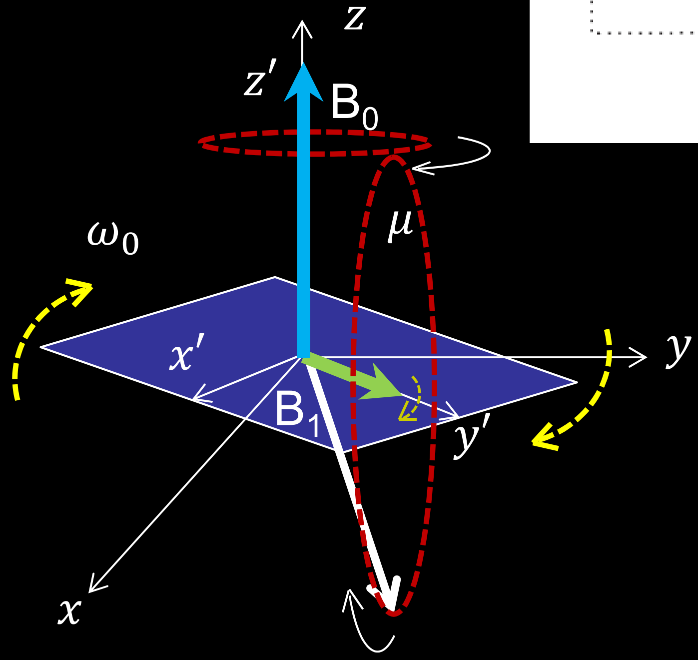
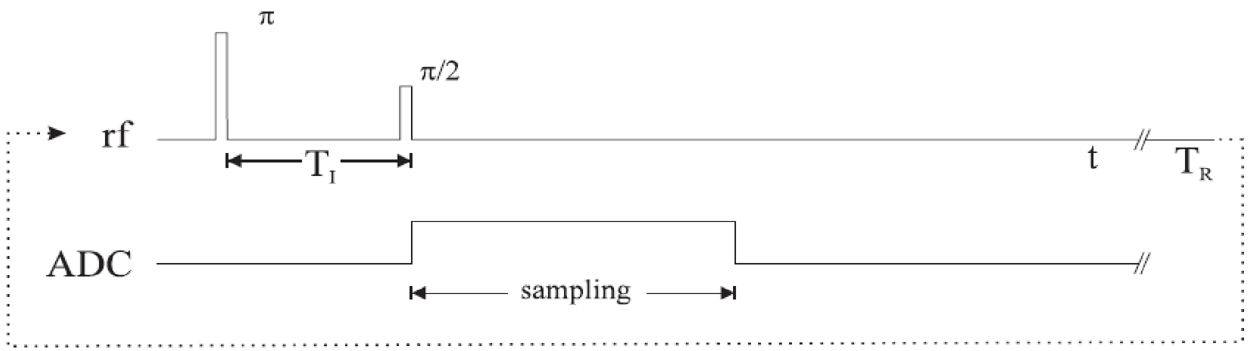


(a)



Inversion Recovery

$$M_z(t) = M_z(t=0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$



(a)

$$M_z(0^+) \quad = \quad -M_0$$

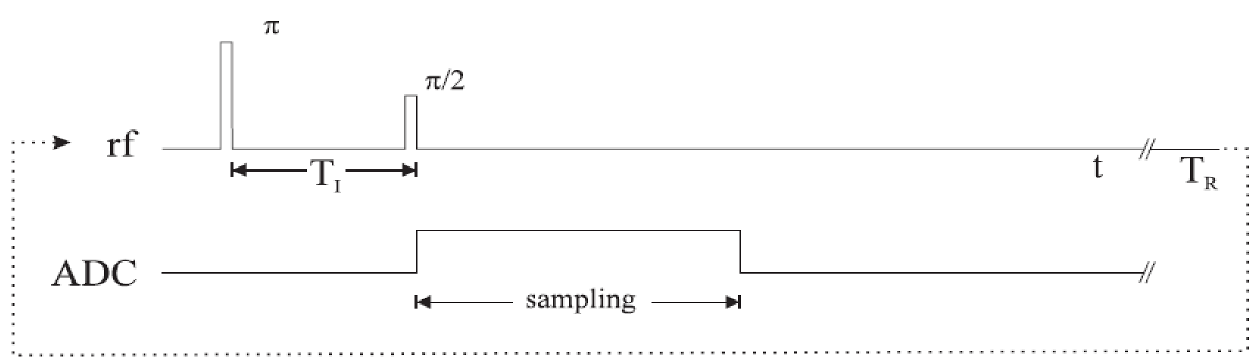
$$M_z(t) = -M_0 e^{-t/T_1} + M_0(1 - e^{-t/T_1}) = M_0(1 - 2e^{-t/T_1})$$

$$0 < t < T_I$$

$$M_\perp(t) = \left| M_0(1 - 2e^{-T_I/T_1}) \right| e^{-(t-T_I)/T_2^*}, \qquad t > T_I$$

Inversion Recovery

$$M_z(t) = M_z(t=0) \cdot e^{-\frac{t}{T_1}} + M_0 \cdot \left(1 - e^{-\frac{t}{T_1}}\right)$$

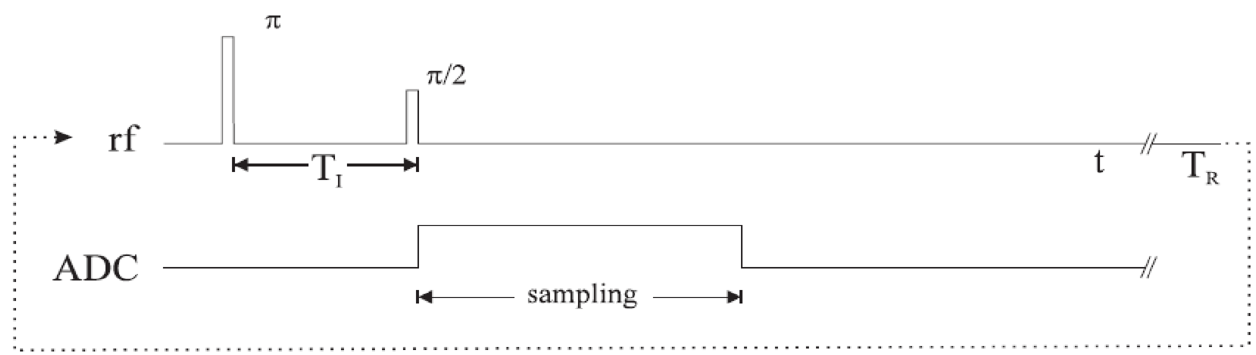


(a)

$$M_\perp(t) = \left| M_0(1 - 2e^{-T_I/T_1}) \right| e^{-(t-T_I)/T_2^*}, \qquad t > T_I$$

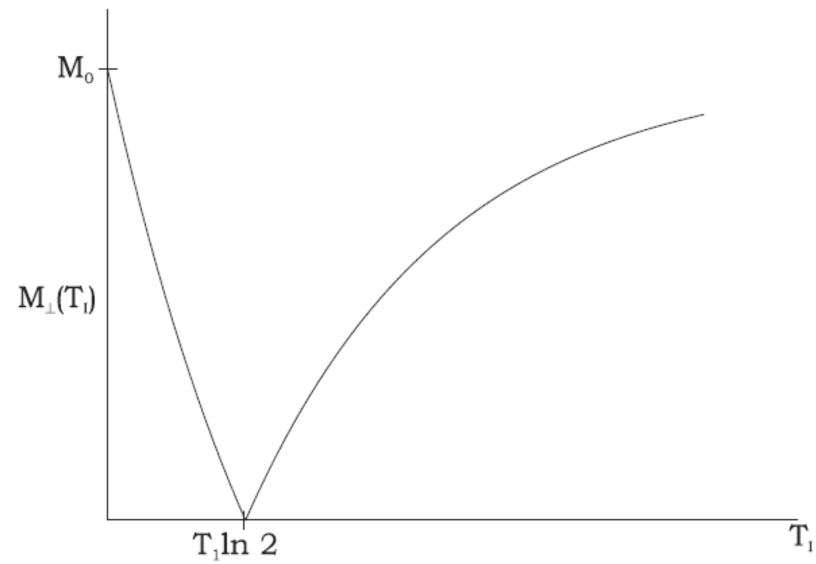
$$T_{I,null} = T_1 \ln 2$$

Inversion Recovery



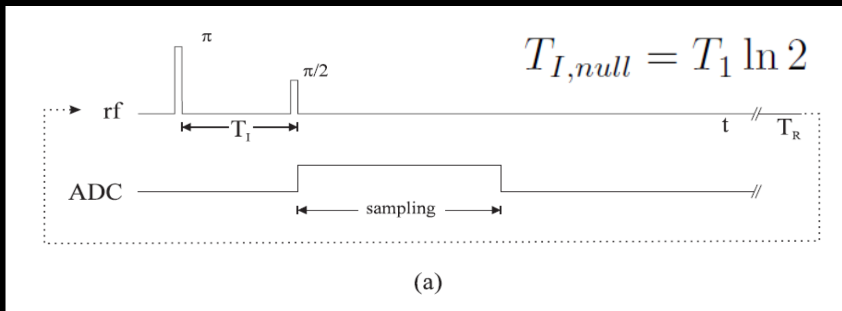
(a)

$$T_{I,null} = T_1 \ln 2$$



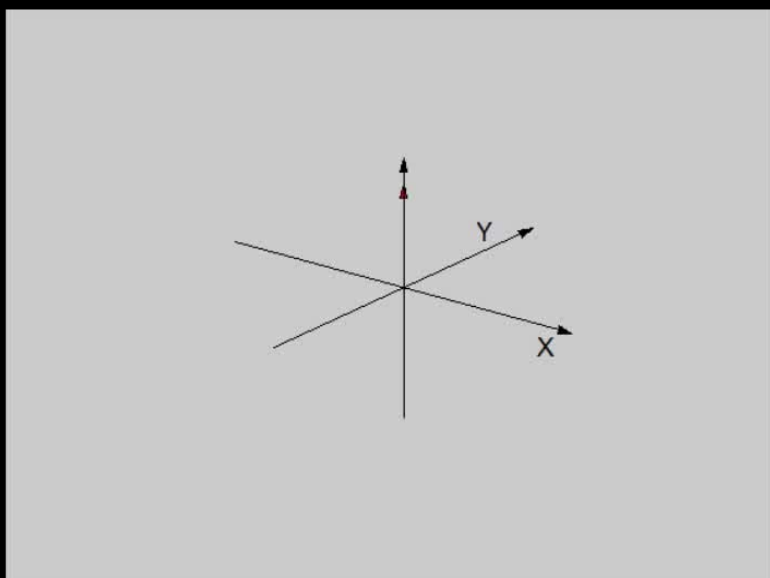
By sampling the signal at varying TIs (inversion time), T_1 of a tissue could be quantified

Inversion Recovery

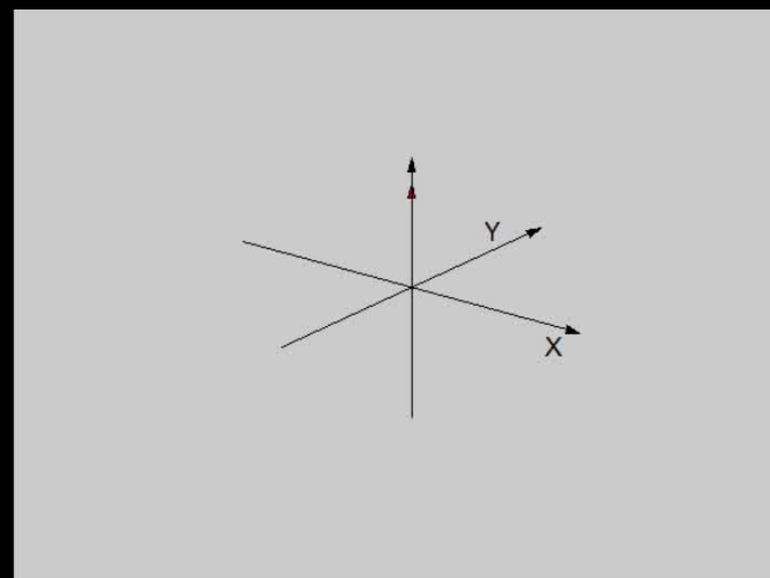


Can also be used to null the signal from a tissue by appropriately timing the $\pi/2$ pulse if the T1 of the tissue is known

T1=300/1000ms



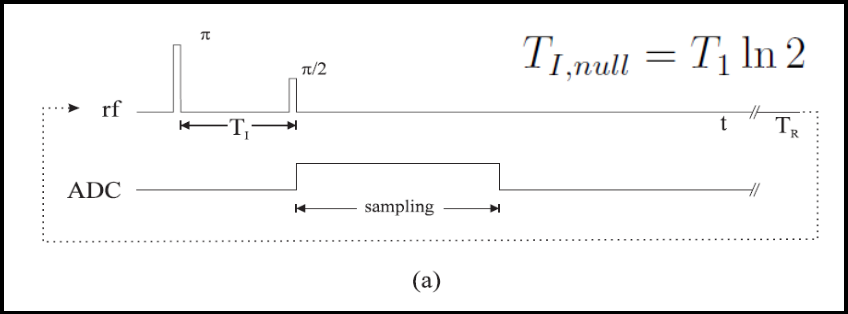
TI=100ms



TI=208ms

Animation Source:
Dr. Yongquan Ye, WSU

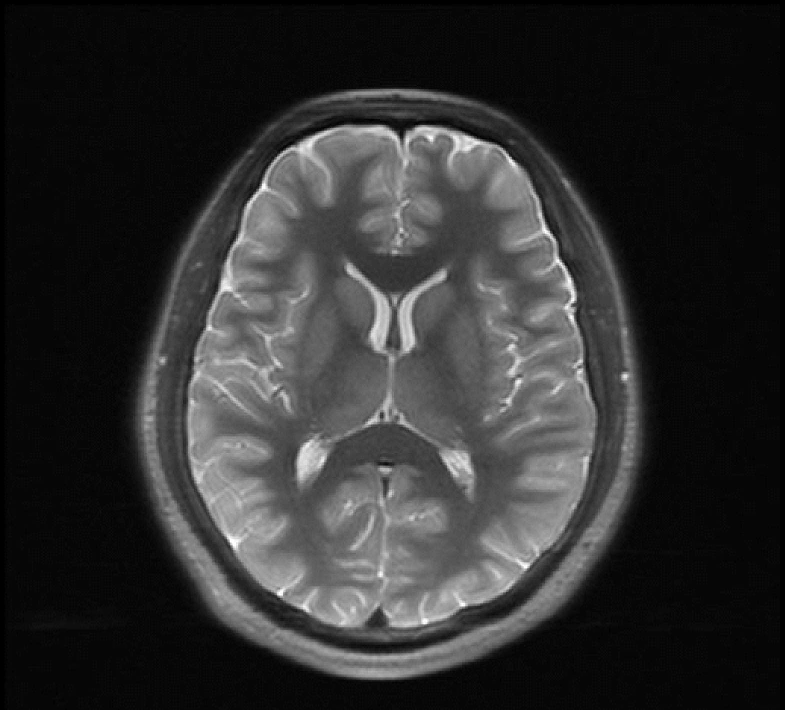
Inversion Recovery



$$T_{I,null} = T_1 \ln 2$$

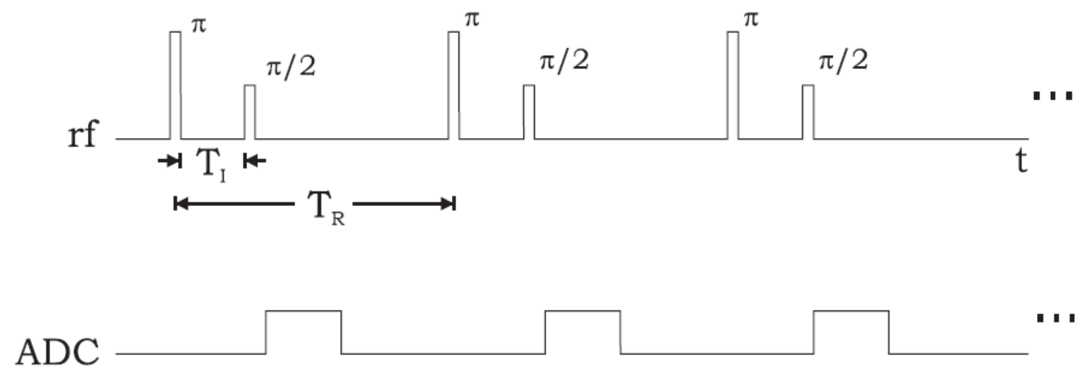
Can also be used to null the signal from a tissue by appropriately timing the $\pi/2$ pulse if the T1 of the tissue is known

T1=300/1000ms



Images acquired with different inversion times
(TIs from 100 to 1500 msec @1.5T)

Repeated IR scans



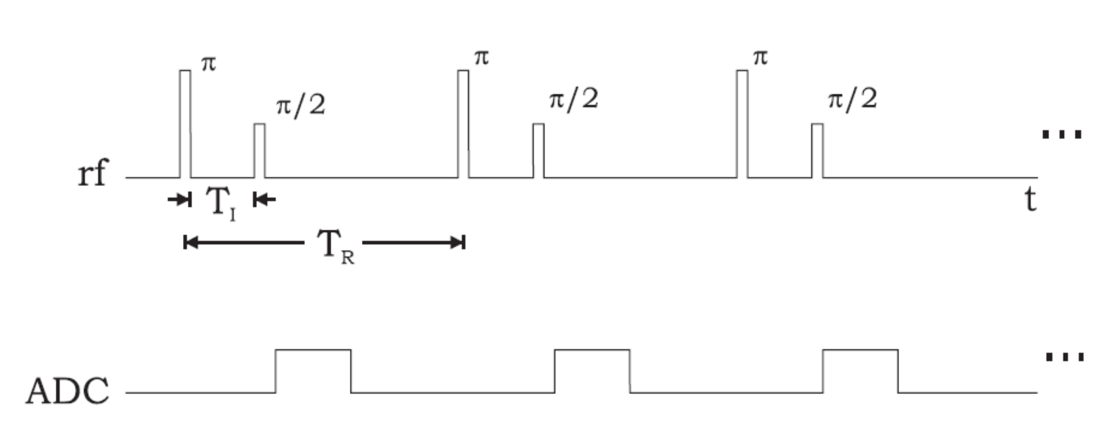
$$
\begin{aligned}
M_z(0^+) &= -M_z(0^-) = -M_0 \\
M_\perp(0^+) &= 0
\end{aligned}
$$

$$
\begin{aligned}
M_z(t) &= -M_z(0^-)e^{-t/T_1} + M_0(1 - e^{-t/T_1}) = M_0(1 - 2e^{-t/T_1}) \\
M_\perp(t) &= 0
\end{aligned}
$$

$0 < t < T_I$

$$
\begin{aligned}
M_z(T_I^+) &= 0 \\
M_\perp(T_I^+) &= \left| -M_z(0^-)e^{-T_I/T_1} + M_0(1 - e^{-T_I/T_1}) \right| = |M_0(1 - 2e^{-T_I/T_1})|
\end{aligned}
$$

Repeated IR scans

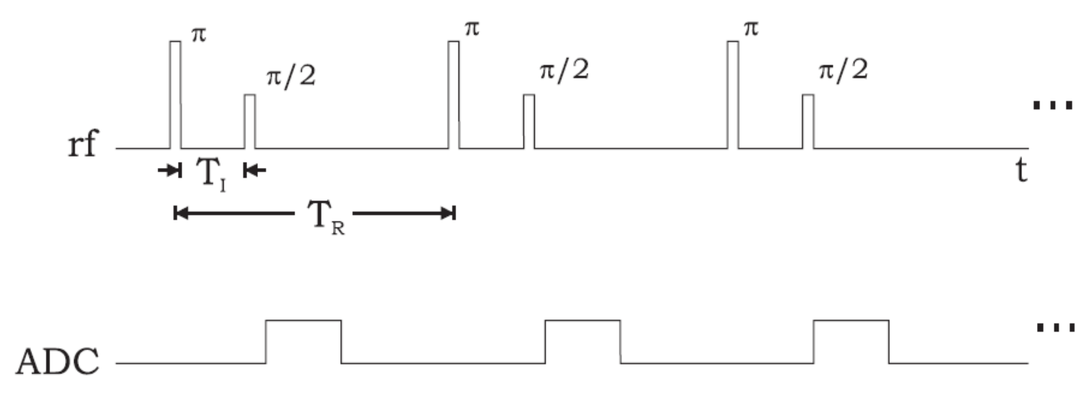


$$
\begin{aligned}
M_z(t) &= M_0\left(1 - e^{-(t-T_I)/T_1}\right) \\
M_\perp(t) &= \left| -M_z(0^-)e^{-T_I/T_1} + M_0(1 - e^{-T_I/T_1}) \right| e^{-(t-T_I)/T_2^*} \\
&= \left| M_0(1 - 2e^{-T_I/T_1}) \right| e^{-(t-T_I)/T_2^*}
\end{aligned}
$$

$$T_I < t < T_R$$

$$M_z(T_R^-) = M_0\left(1 - e^{-(T_R-T_I)/T_1}\right)$$

Repeated IR scans



$$
\begin{aligned}
M_\perp(t_n) &= \left| -M_0\left(1 - e^{-(T_R - T_I)/T_1}\right) e^{-T_I/T_1} + M_0\left(1 - e^{-T_I/T_1}\right) \right| e^{-(t_n - T_I)/T_2^*} \\
&= M_0 \left| 1 + e^{-T_R/T_1} - 2e^{-T_I/T_1} \right| e^{-(t_n - T_I)/T_2^*} \\
&\qquad\qquad\qquad\qquad T_I < t_n < T_R
\end{aligned}
$$

$$
T_{I_{\text{null}}} = T_1 \ln\left(\frac{2}{1 + e^{-T_R/T_1}} \right)
$$

Homework

- Prob. 8.1-8.5

Next Class

Chapter 9.1-9.4