Outline for Today

1.

Introduction to MRI

'Quantum' NMR and MRI in 0D

Magnetization, ***m***(*x*,*t*), in a Voxel

Proton T1 Spin Relaxation in a Voxel

Proton Density MRI in 1D

MRI Case Study, and *Caveat*

2.

Sketch of the MRI Device

'Classical' NMR in a Voxel

Free Induction Decay in 1D

T2 Spin-Relaxation

3.

Spin-Echo Acquisition

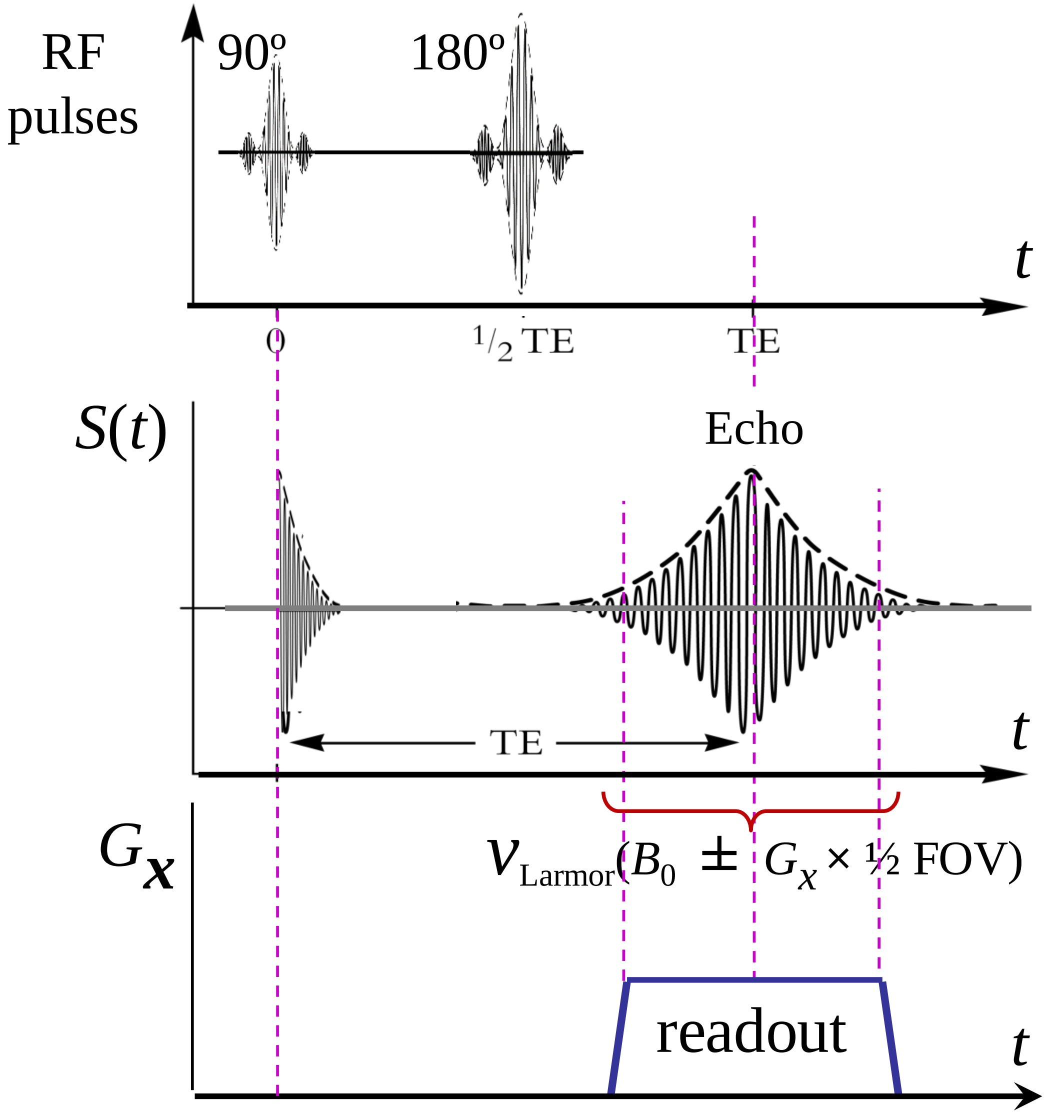
Tissue Contrast-Weighting in SE

Spin-Echo / Spin-Warp in 2D

Spin-Echo

SE Sequence: 90º, 180º RF Pulses, Readout Gradient

e.g., 256 voxels in a row



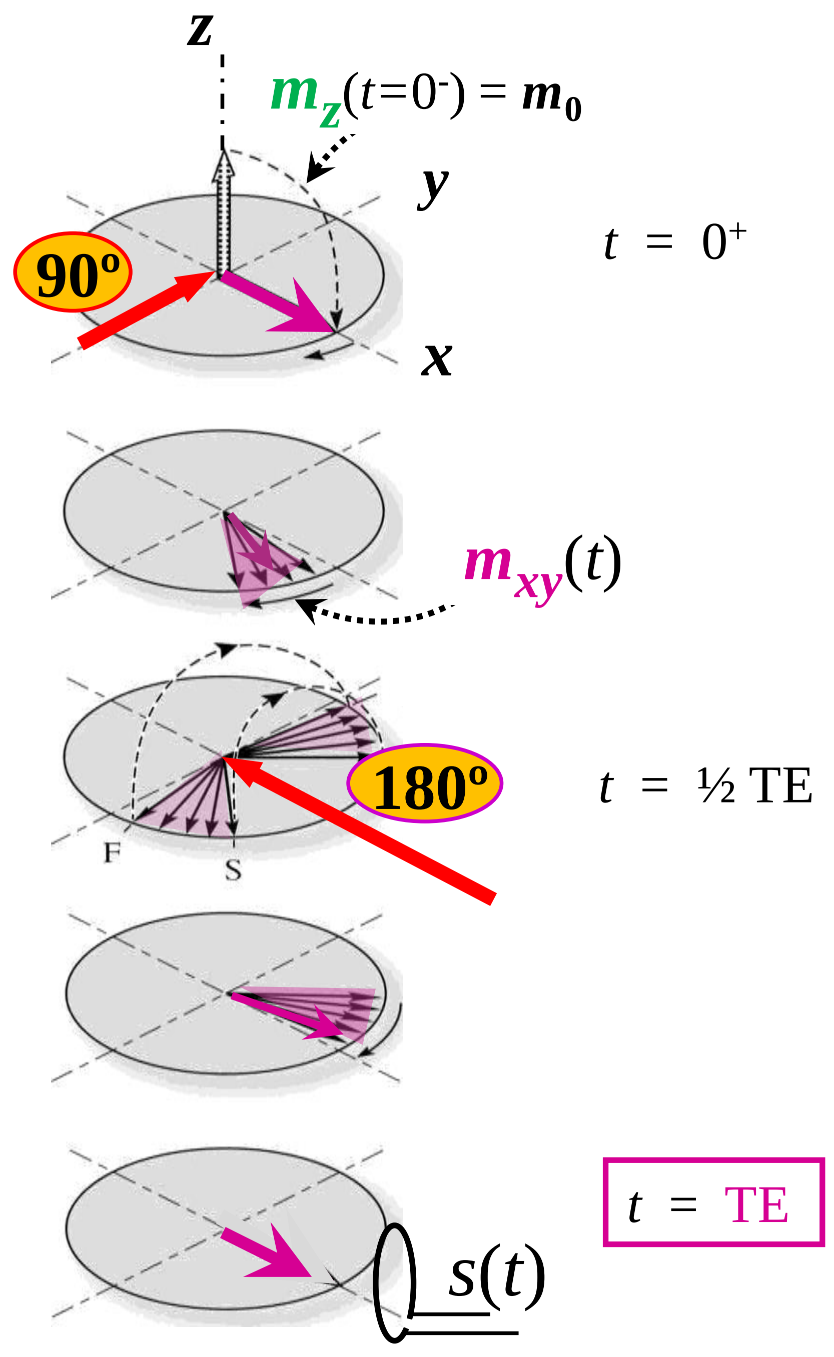
Spin-Echo

Generates an *Echo*

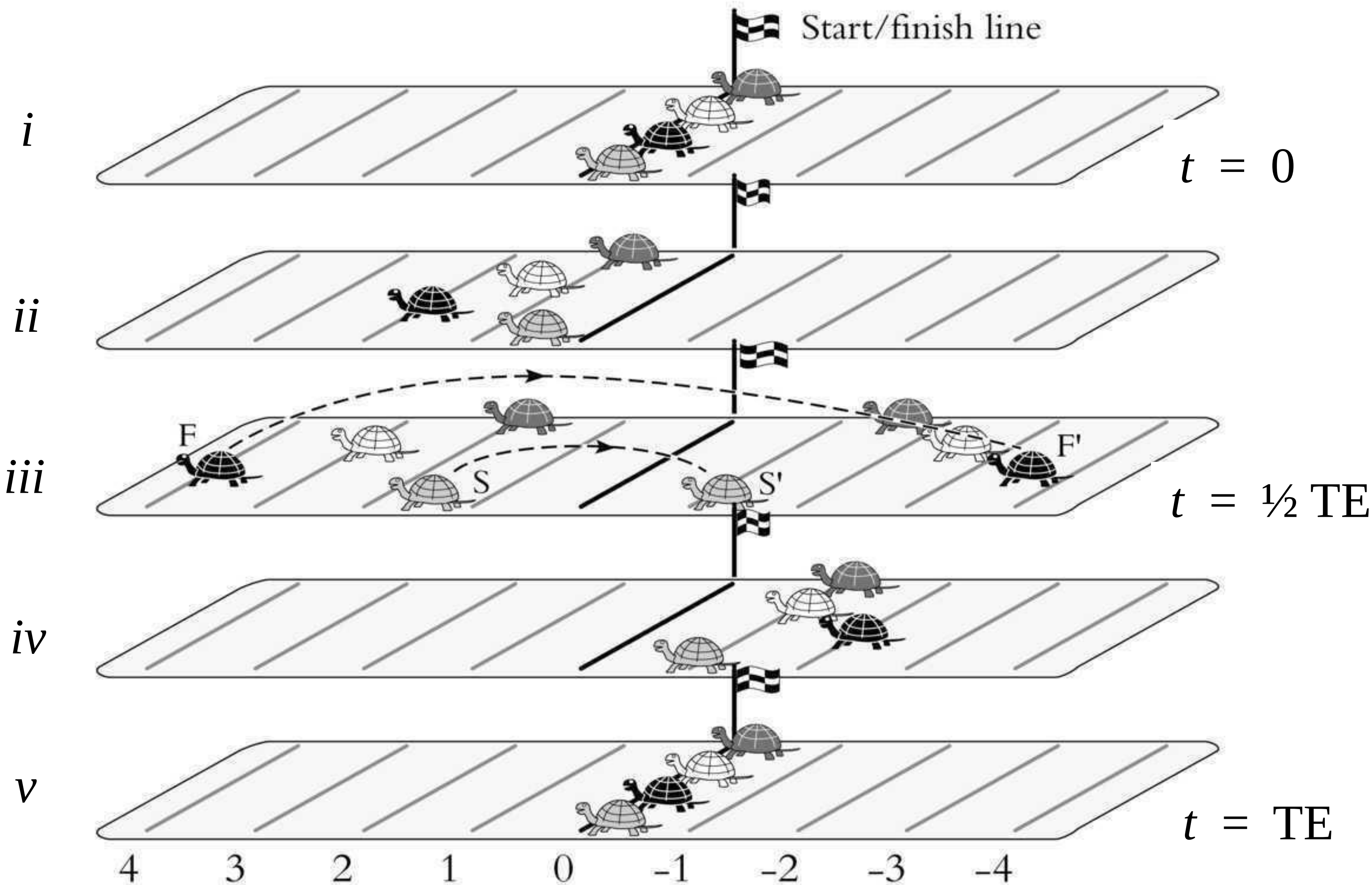
SE introduces a 180º inversion pulse to refocus the spins and create an echo.

Also results in higher SNR reduction of susceptibility contamination.

$m_{xy}(t=TE) \sim m_0 \times e^{-TE/T2}$

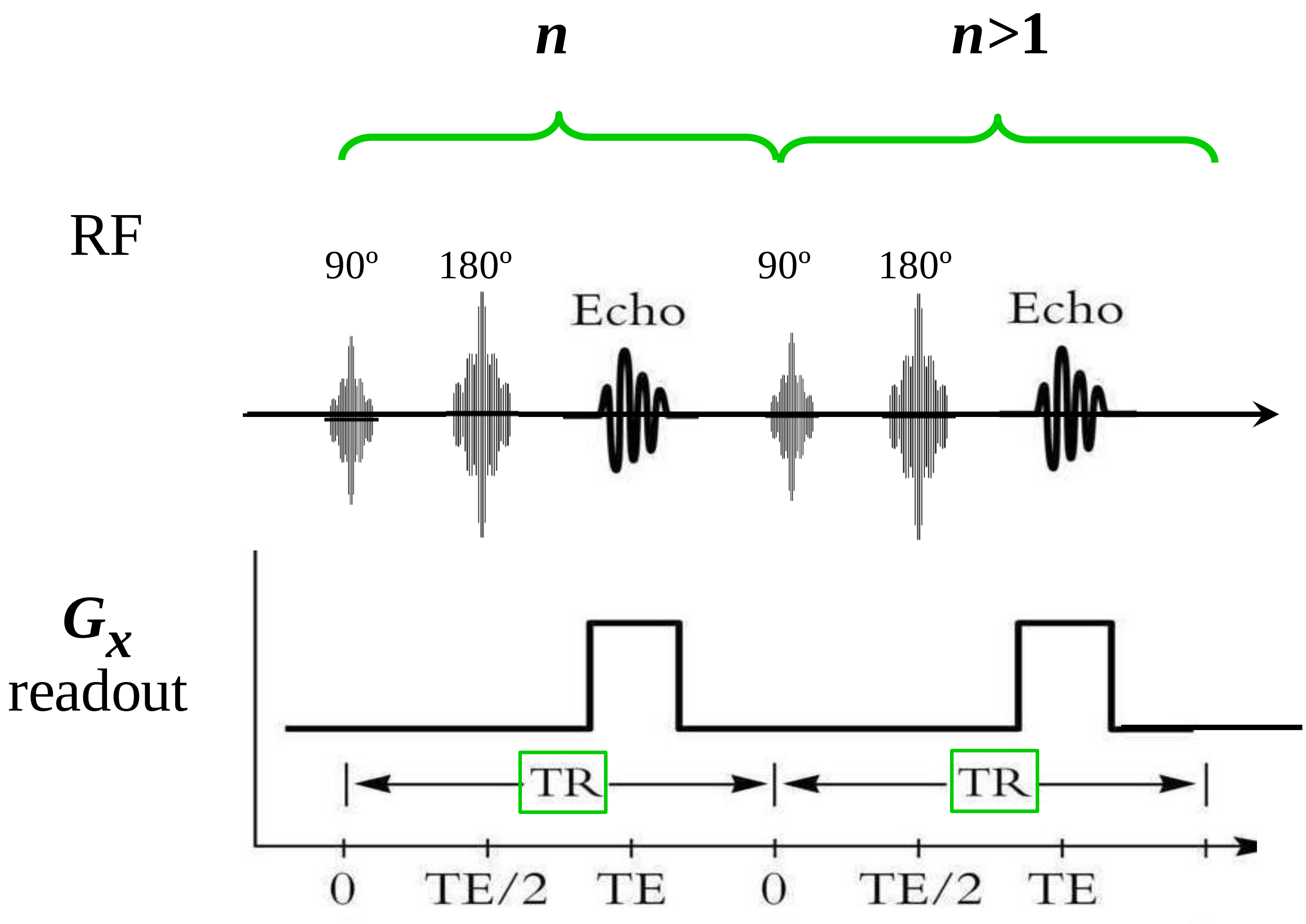


Kentucky Turtle-Teleportation Derby (illustration of S-E)



Multi-SE Pulse Sequence

(*e.g.*, what happens to m_z?)



Spin-Echo

Generates an ***Echo***

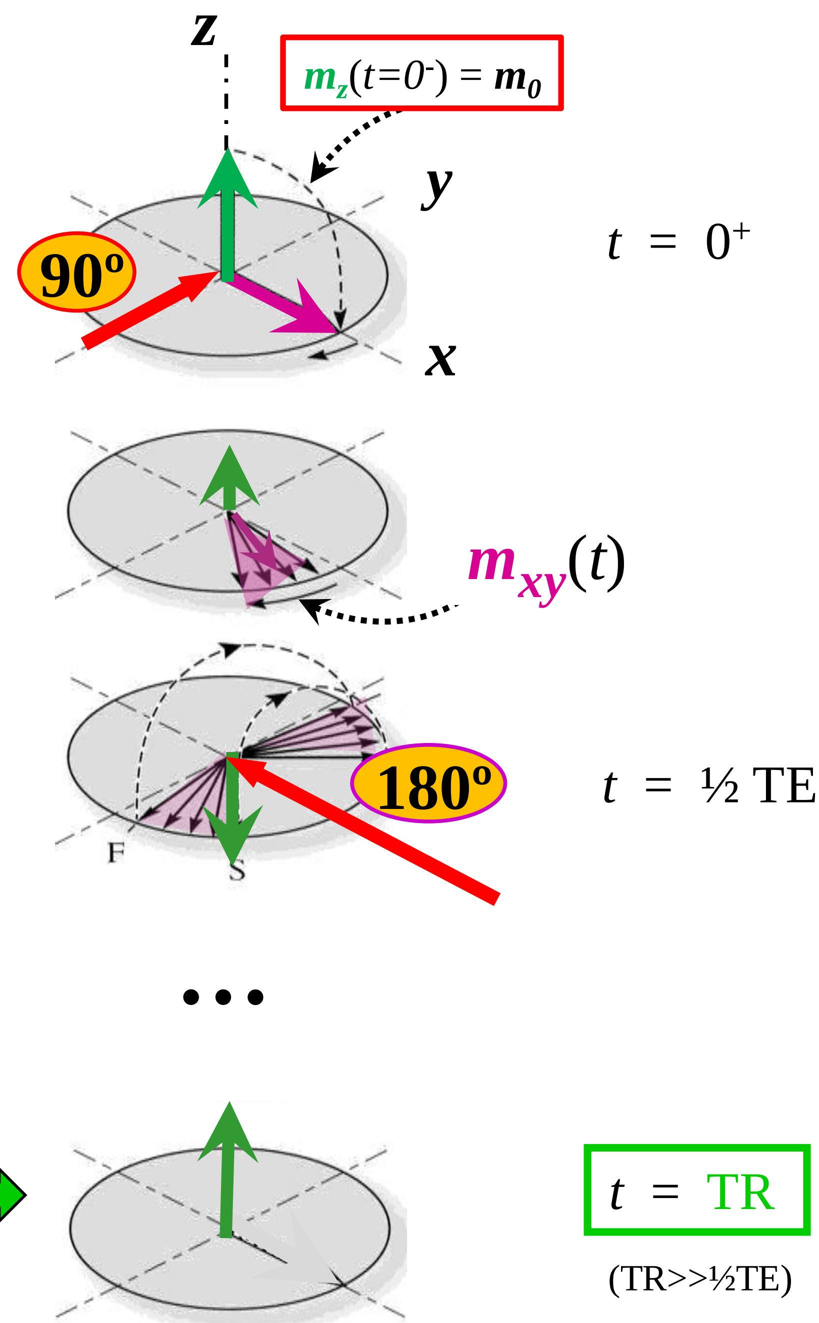
***n*=1**

At end of first excitation, magnetization (m_z) may not have fully recovered.

Depends on the tissue T1 and sequence TR.

This magnetization is passed on to the next excitation (n>1).

$$m_z(t{=}TR^-) \sim m_0 \times (1 - e^{-TR/T1})$$



Spin-Echo

Generates an *Echo*

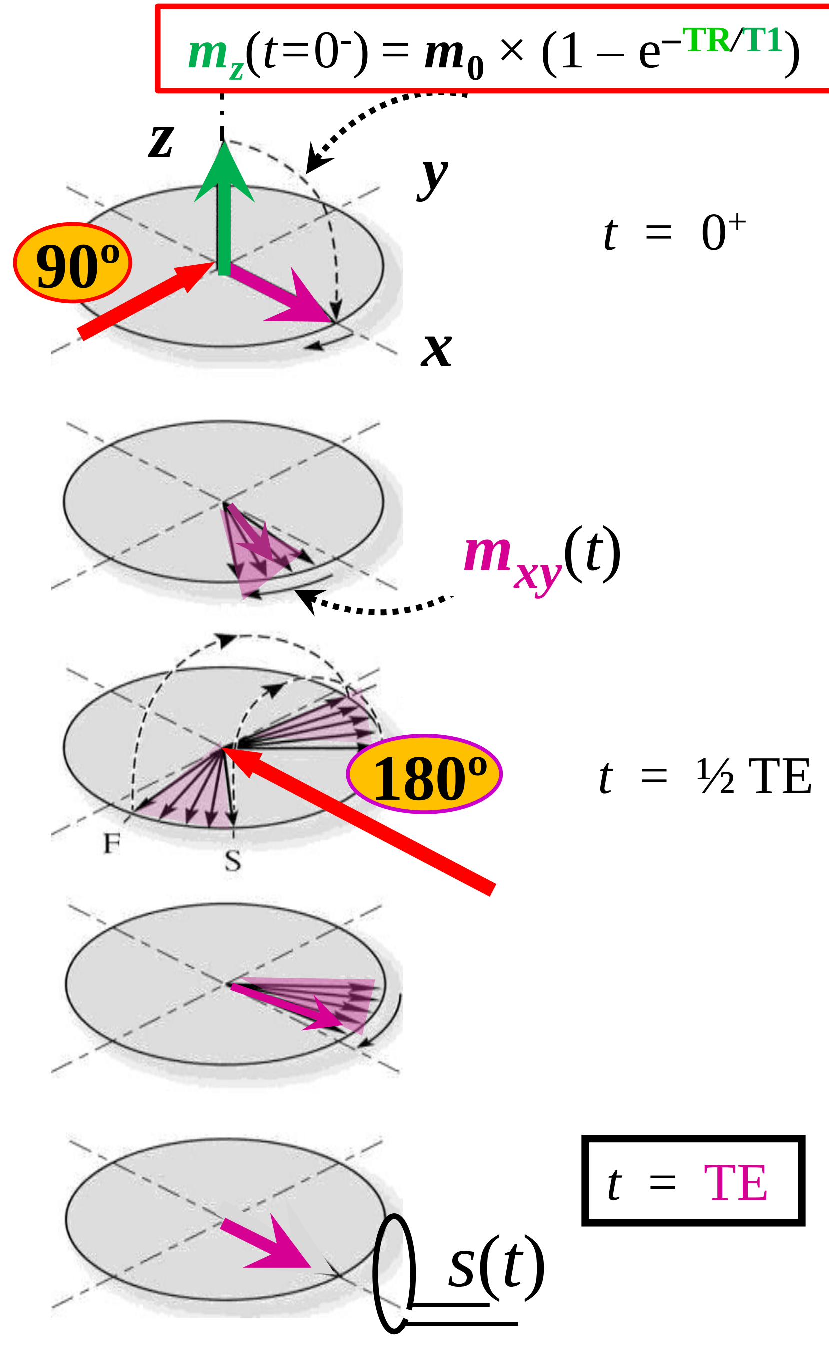
$n > 1$

After subsequent excitation, longitudinal magnetization tipped into transverse plane is a constant function of tissue T1 & TR.

Additional differences in the signal result of tissue T2-induced changes until measurement at TE.

$$m_z(t=0^-) \sim m_0 \times (1 - e^{-TR/T1})$$

$$m_{xy}(t=\text{TE}) \sim m_z(t=0^-) \times e^{-TE/T2}$$

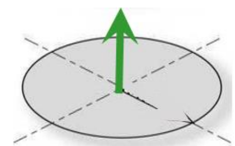


MRI Signal Strength ***at*** t = TE Depends on….

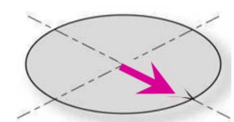
$$s(t = \text{TE}) \;\sim\; \text{PD}\,(1 - e^{-\text{TR}/\text{T1}})\; e^{-\text{TE}/\text{T2}}$$

proton density

prior regrowth along ***z***-axis



current dephasing in ***x-y*** plane



Inherent Parameters	Operator Settings
T1	**TR**
T2	**TE**
PD	

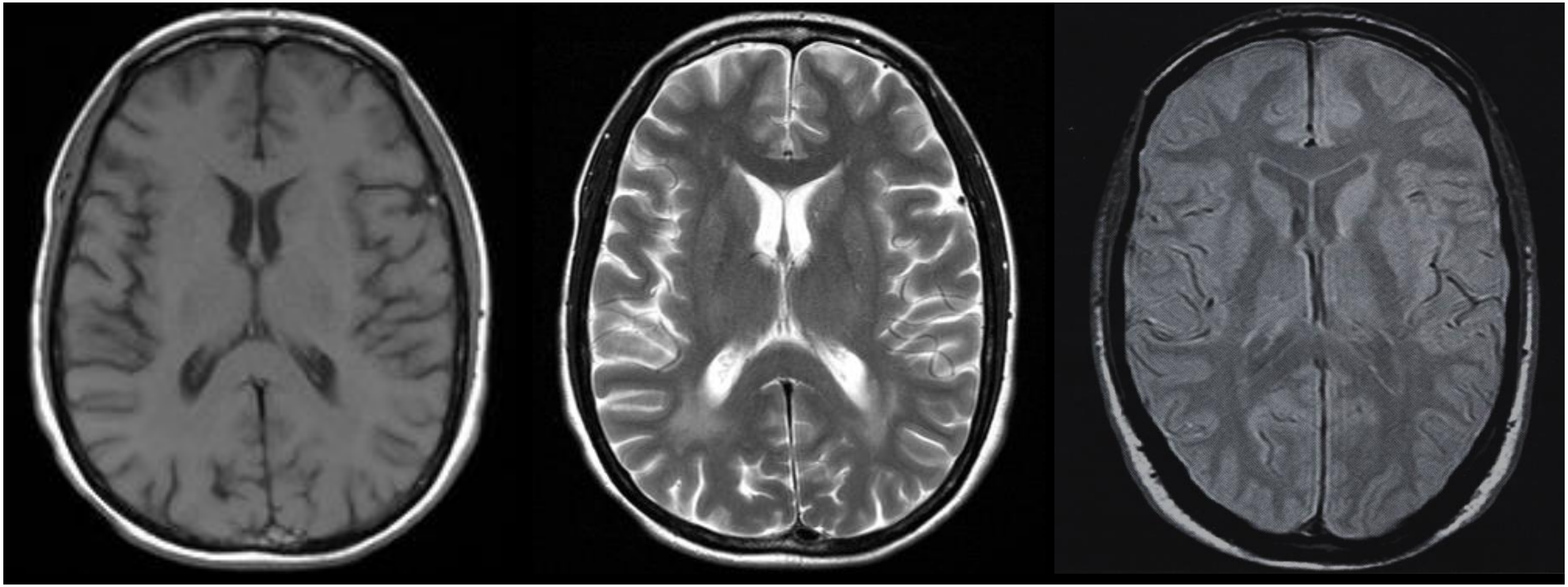
time since previous excitation (→ TR)

Tissue Contrast-Weighting in SE

T1-*w*, T2-*w*, and PD-*w*

Three Different MRI Contrast Weightings

created by, and reflecting, three quite different physical processes



T1 T2 PD

T2-*w* – Long TR to Minimize T1 Differences

For T2-*w* imaging

Long TR: eliminate T1 impact

TE at mid-T2: maximize contrast

$$\boldsymbol{S}(t\sim \mathrm{TE}) \;\sim\; \mathrm{PD}\; \overset{\cancel{(1-e^{-\mathrm{TR}/\mathrm{T1}})}}{1}\; e^{-\mathrm{TE}/\mathrm{T2}}$$

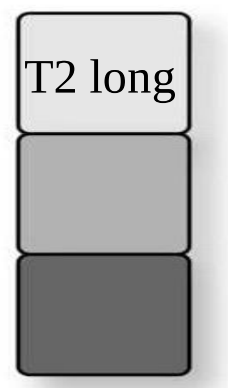
prior regrowth along *z*-axis

current de-phasing in *x*-*y* plane

WM **CSF**

T2-*w*

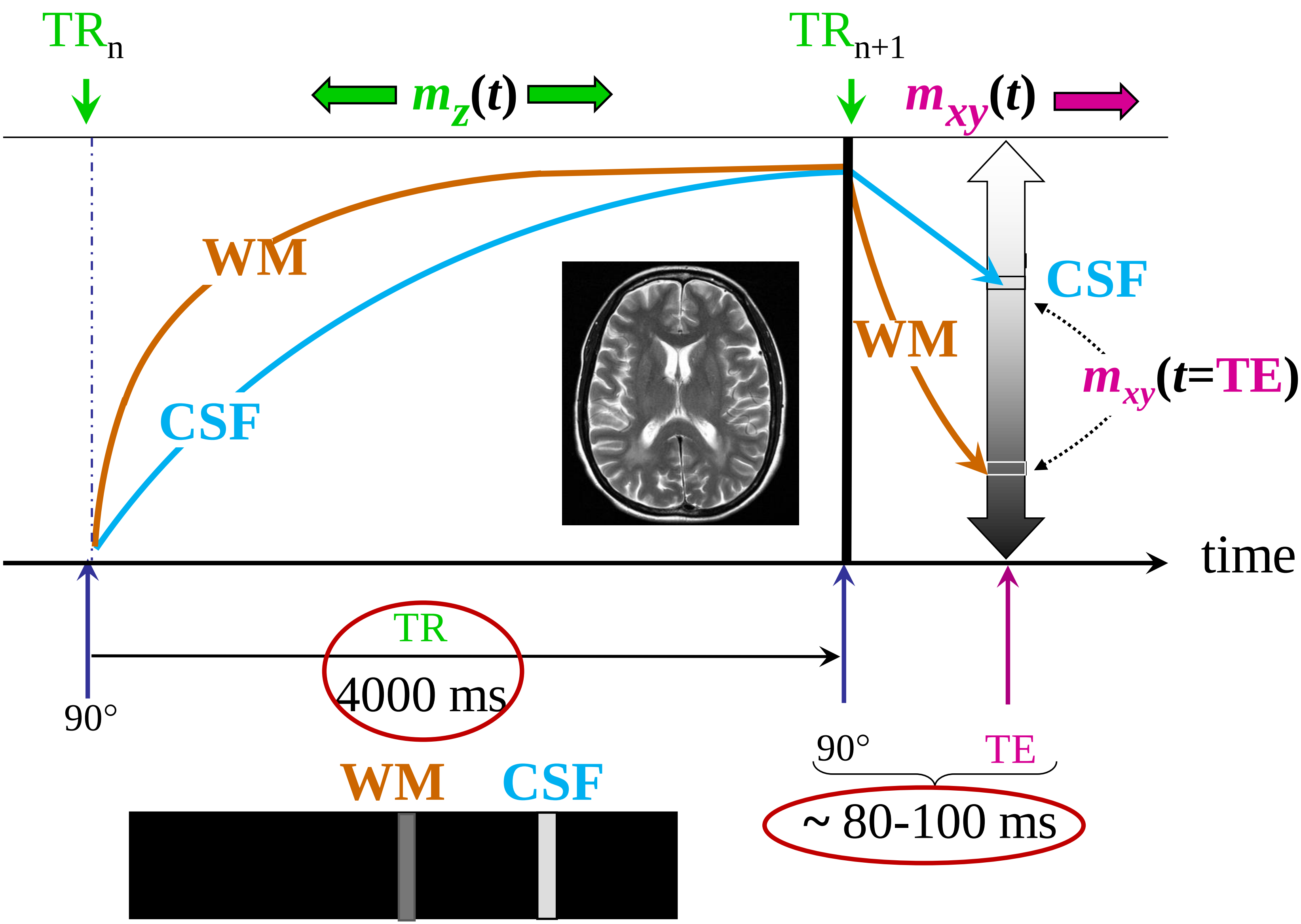
Long-T2 tissues bright



WM = White Matter
CSF = Cerebral Spinal Fluid

T2-*w* – Long TR to Minimize T1 Differences

TE ~ mid-T2 to maximize T2 contrast



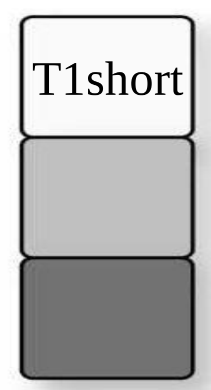
T1-*weighted* – Short TE to Minimize T2 Changes

TR ~ $T1_{av}$ to maximize contrast

Short TE to minimize T2 differences

$$S(t \sim TE) \;\sim\; PD\,(1 - e^{-TR/T1})\;\; \xcancel{e^{-TE/T2}}\;\; \mathbf{1}$$

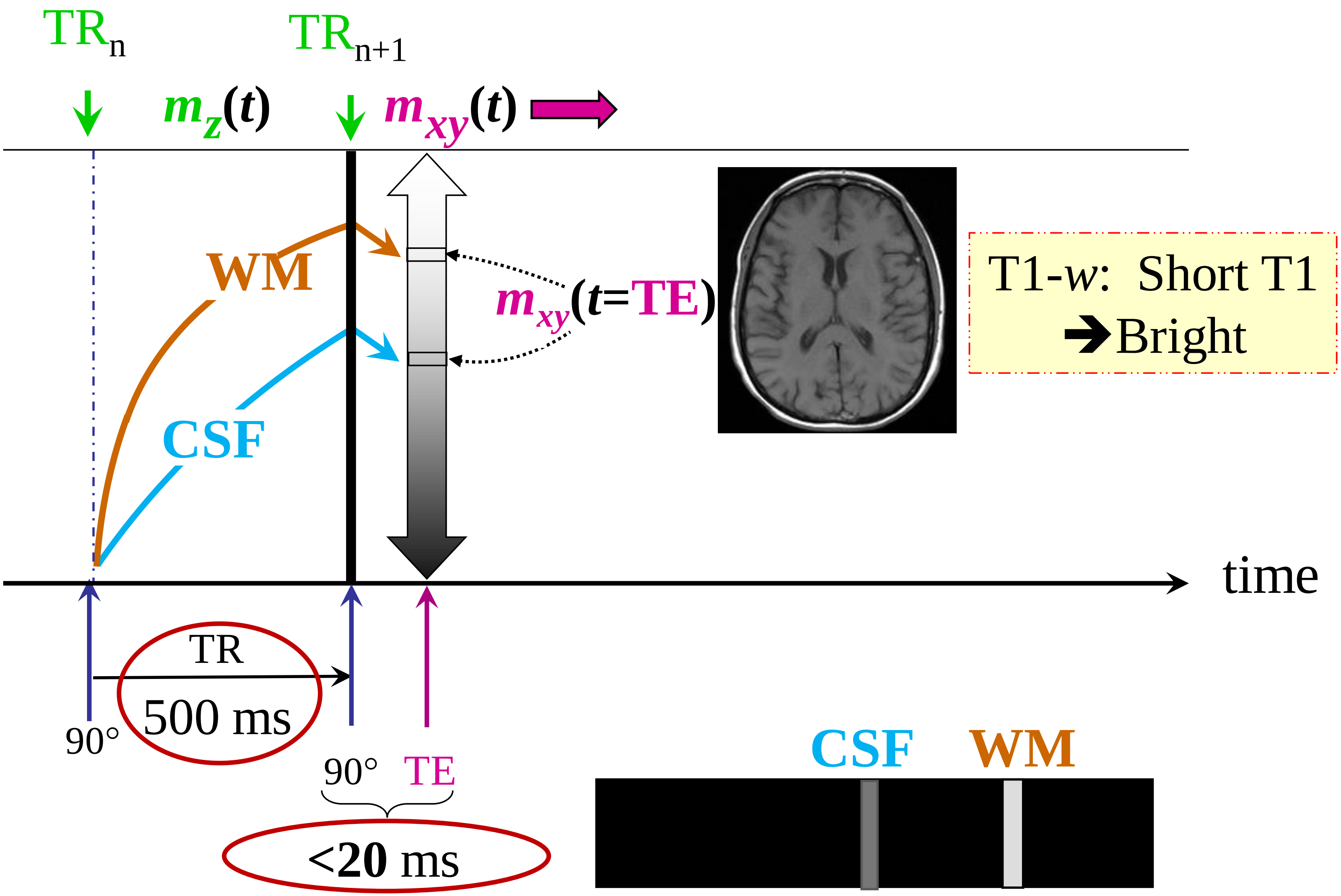
- PD: proton density
- $(1 - e^{-TR/T1})$: prior regrowth along *z*-axis
- $e^{-TE/T2}$ → 1: current de-phasing in *x*-*y* plane



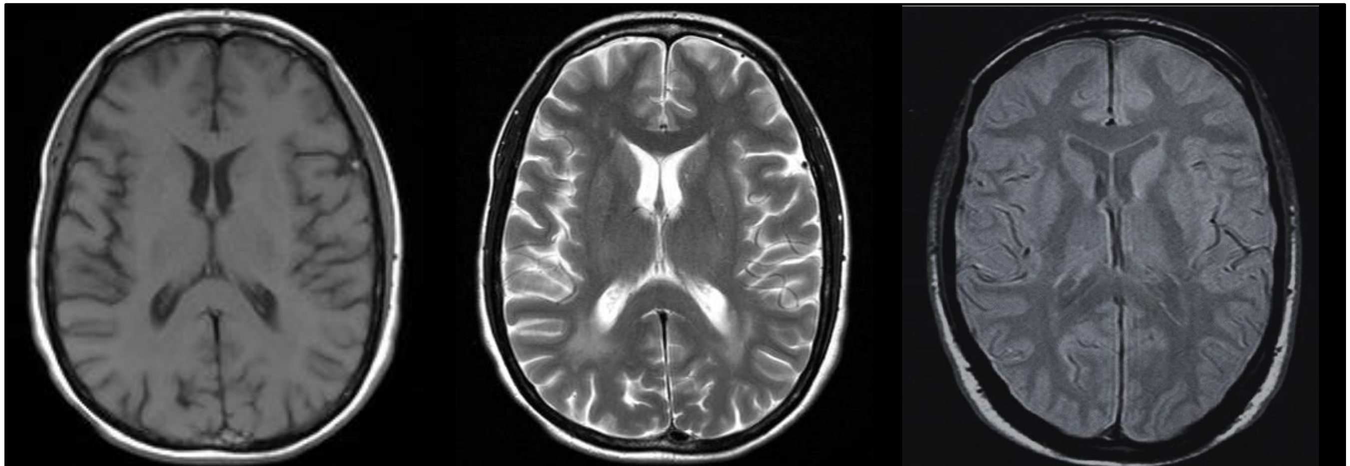
For T1-w: Short-T1 tissues are Bright

T1-*weighted* – Short TE to Minimize T2 Changes

TR ~ $T1_{avg}$ to maximize T1 contrast



PD-, T1-, & T2-Weighted Spin-Echo Images (1.5 T)



Contrast	T1-weighted	T2-weighted	PD-weighted
TR (ms)	Mid **$\sim T1_{avg}$** 300-700	Long $\geq$ 2,000	Long $\geq$ 2,000
TE (ms)	Short $\leq$ 20	Mid **$\sim T2_{avg}$** 60-150	Short $\leq$ 20
Bright	Short T1	Long T2	High PD
SNR	Middle	Lower	Best

Spin-Echo / Spin-Warp in 2D

Signal Modulation in 2D Spatial Encoding

- Signal in 2D plane after slice excitation (rotating frame)

$$S \propto \iint S(x,y) \cdot dx \cdot dy$$

- What happens if we turn on our *linear gradients*?

$$S(G_x, G_y) \propto \iint S(x,y) \cdot \exp[-2\pi i \gamma \int \left(G_x \cdot x + G_y \cdot y\right) d\tau] \cdot dx \cdot dy$$

- This equation can be expressed in the form of a 2D FT of $S(x,y)$

$$S(k_x, k_y) \propto \iint S(x,y) \cdot \exp[-2\pi i \left(k_x \cdot x + k_y \cdot y\right)] \cdot dx \cdot dy$$

with $k_x(t) = \gamma \int^t G_x(\tau) d\tau$ and $k_y(t) = \gamma \int^t G_y(\tau) d\tau$

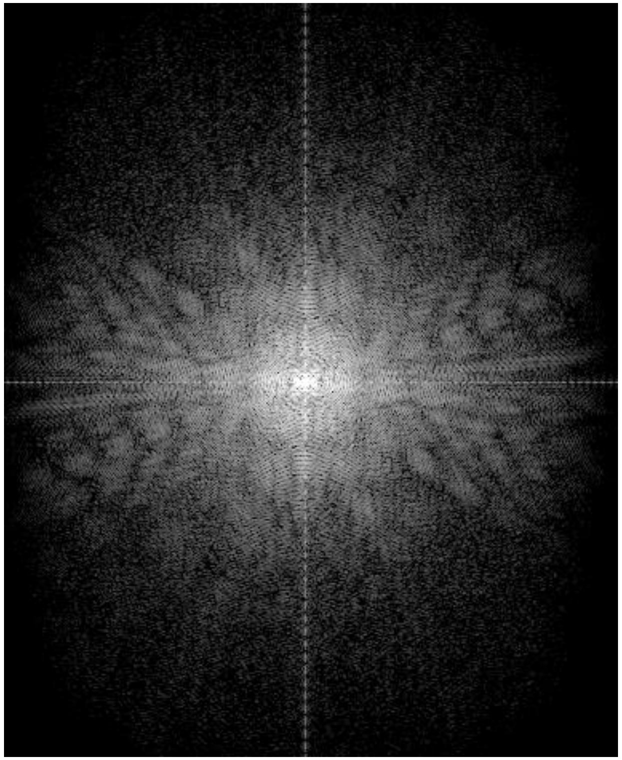
Fourier Transform of MRI Data in ***k***-Space to Real Space

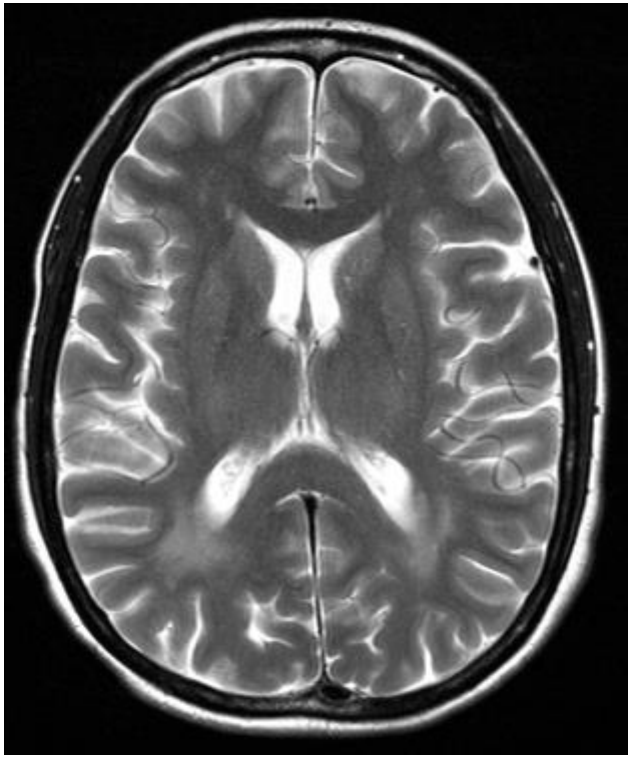
$\mathbf{S}(k_x,k_y)$

Complex k-space

$|\mathbf{S}(x,y)| \sim |\mathrm{FT}\{\mathbf{S}(k_x,k_y)\}|$

Real-space





2D Spatial Encoding

$$k_x(t) = \gamma \int^t G_x(\tau)d\tau \quad \text{and} \quad k_y(t) = \gamma \int^t G_y(\tau)d\tau$$

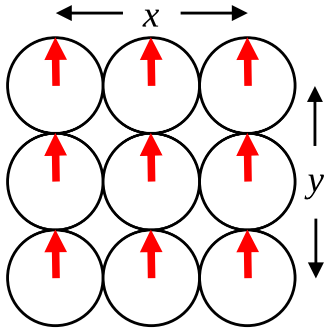
- So, what does this mean?
  - Gradient **ON**: spins precess at different rates as function of location
  - Gradient **OFF**: accumulated phase as a function of location encoded into signal
  - Received signal phase modulated as function of spatial frequency state
  - 'Spatial frequency' = *area under gradient-time curve*.

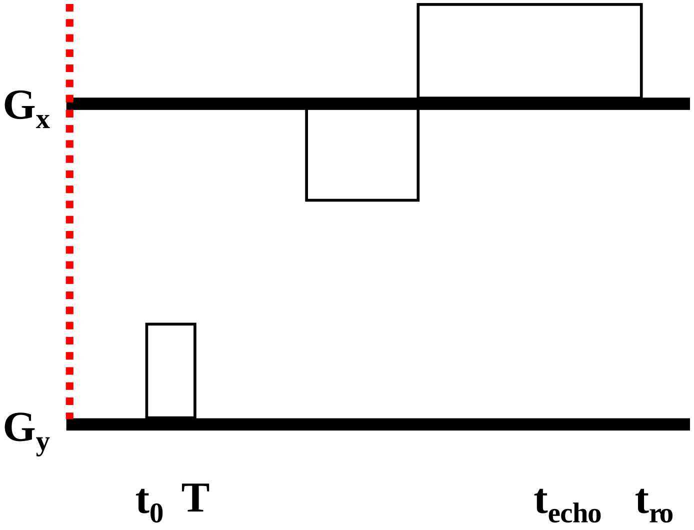
  - Careful coordination of how/when gradients turn on/off facilitates
    - navigation through k-space
    - ability to sample $S(k_x,k_y)$ over necessary k-space domain

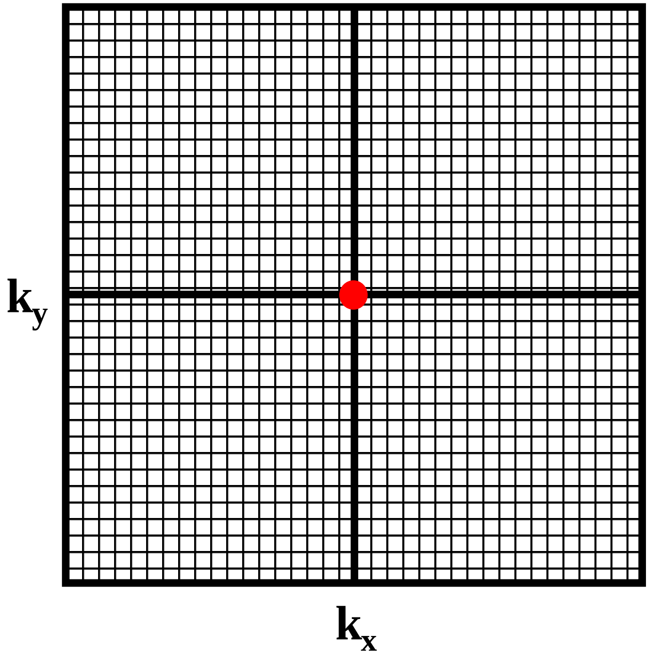
- Let's walk through an example …

2D Spatial Encoding

$$k_x = \gamma \int^t G_x(\tau) d\tau \quad \text{and} \quad k_y = \gamma \int^t G_y(\tau) d\tau$$

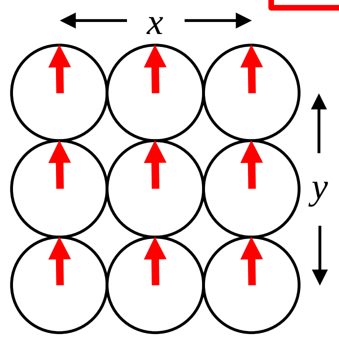


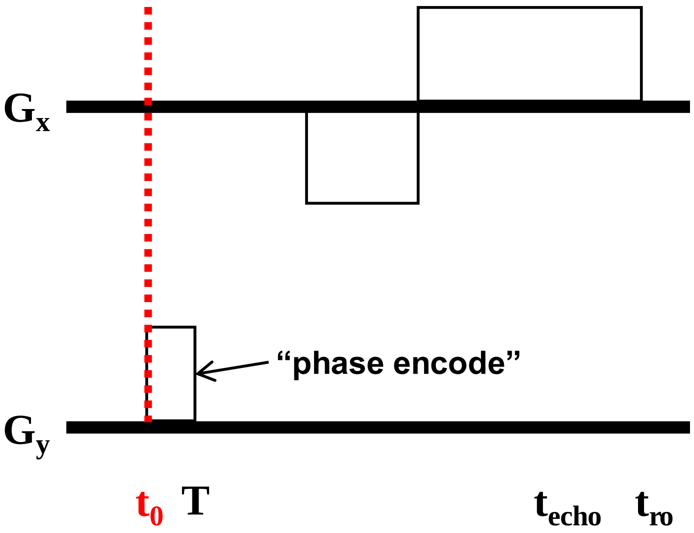


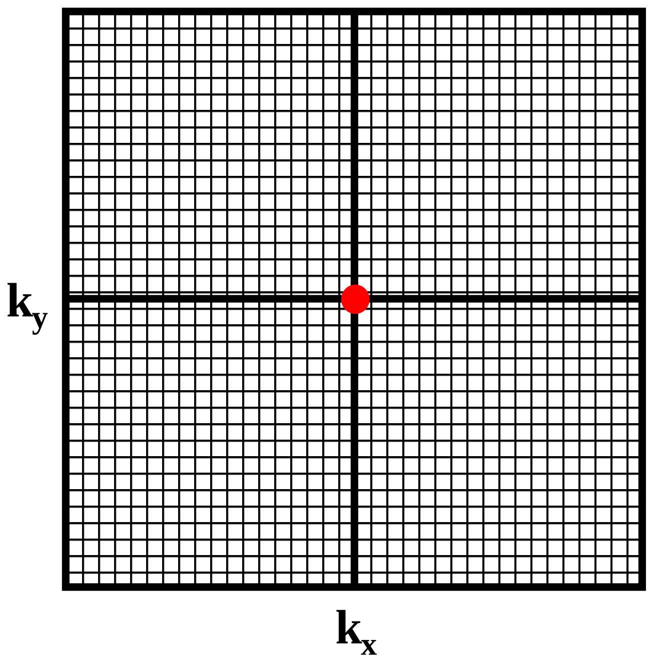


2D Spatial Encoding

$$k_x = \gamma \int^{t} G_x(\tau)d\tau \quad \text{and} \quad \boxed{k_y = \gamma \int^{t} G_y(\tau)d\tau}$$







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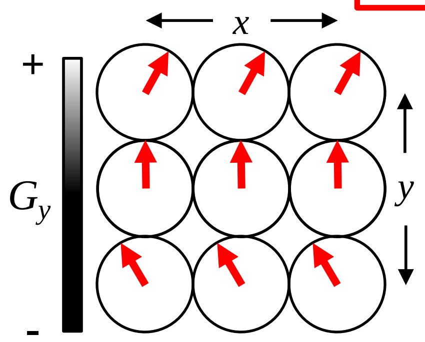

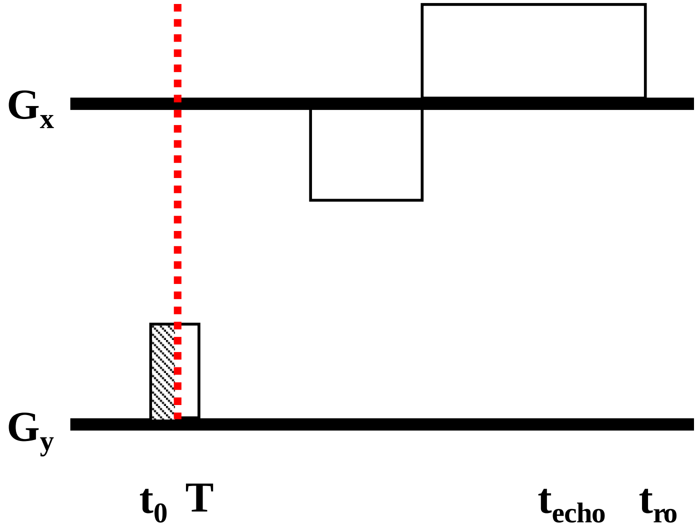

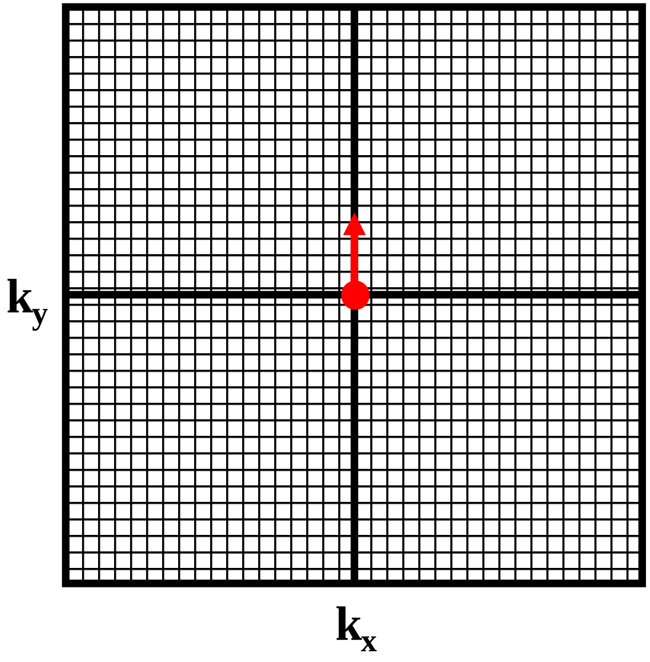

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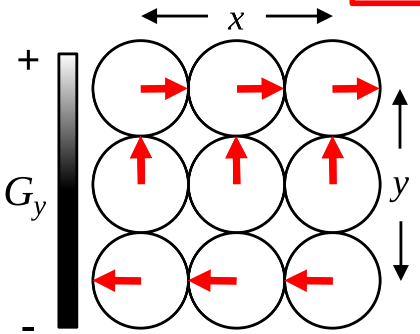

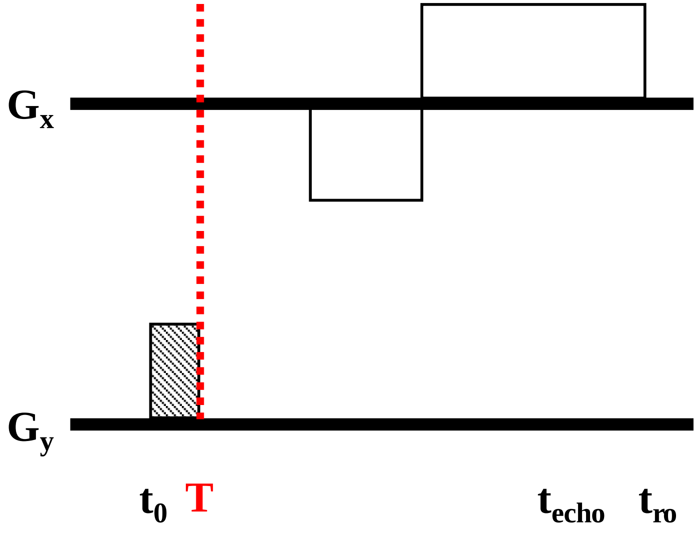

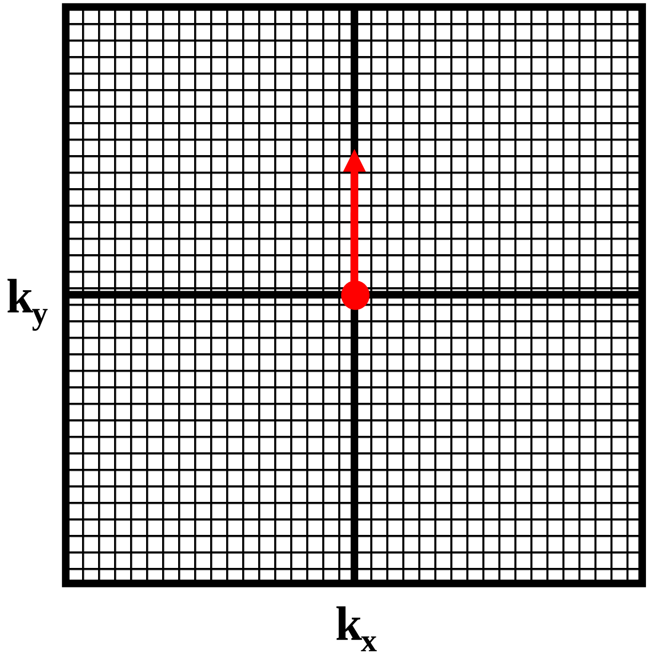

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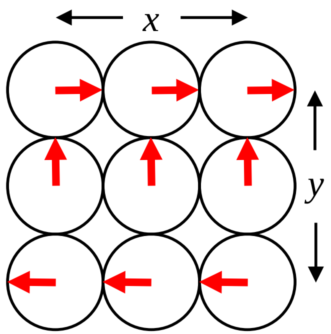

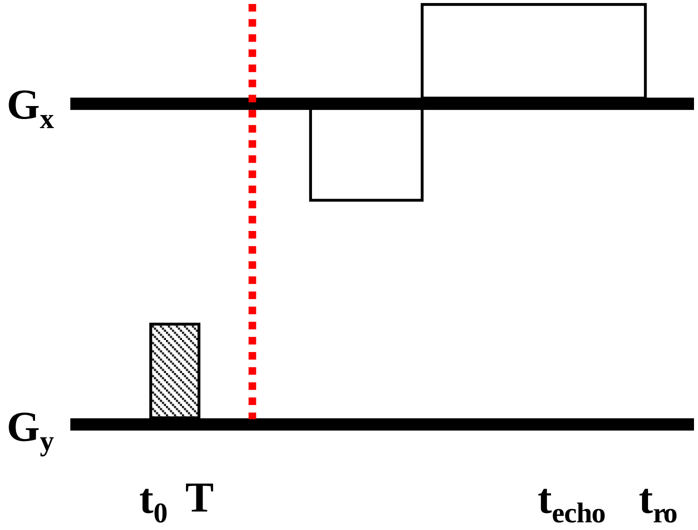

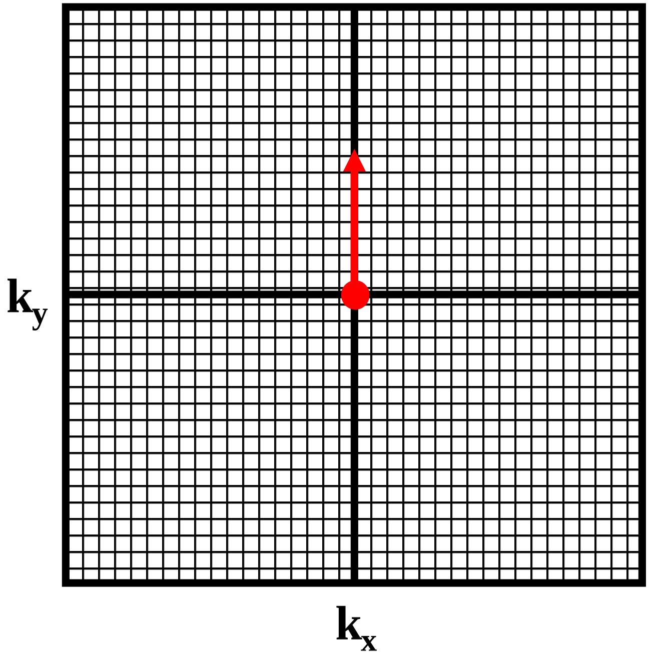

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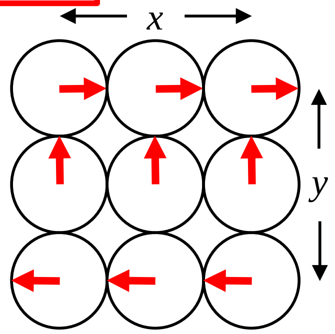

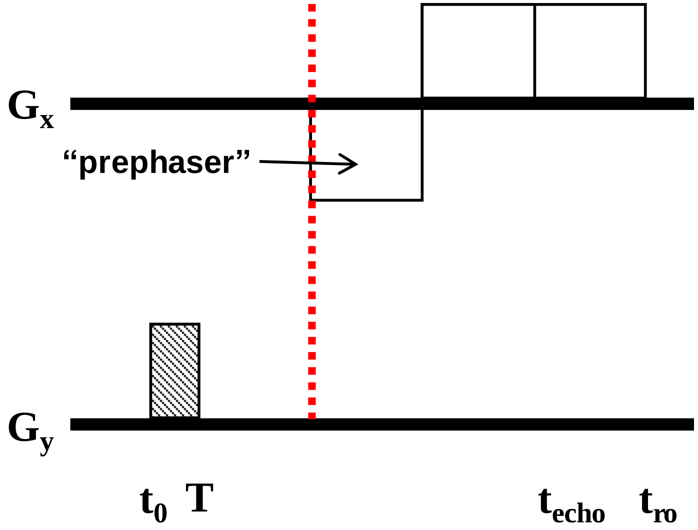

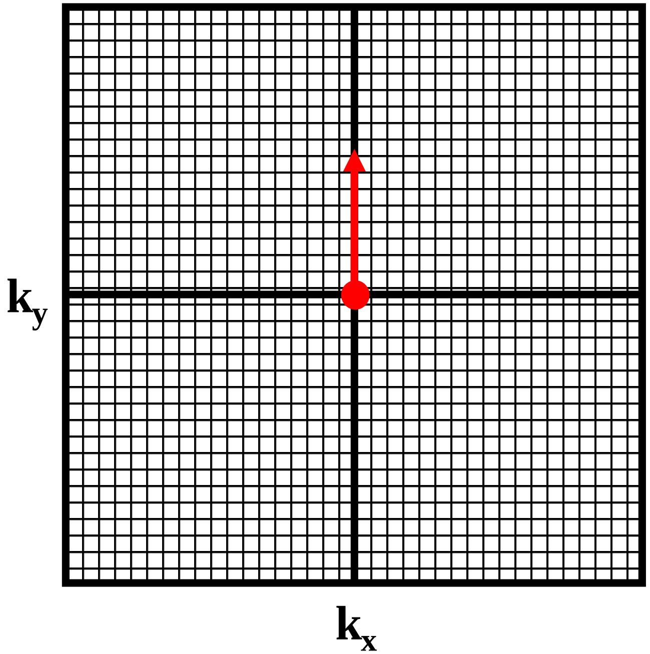

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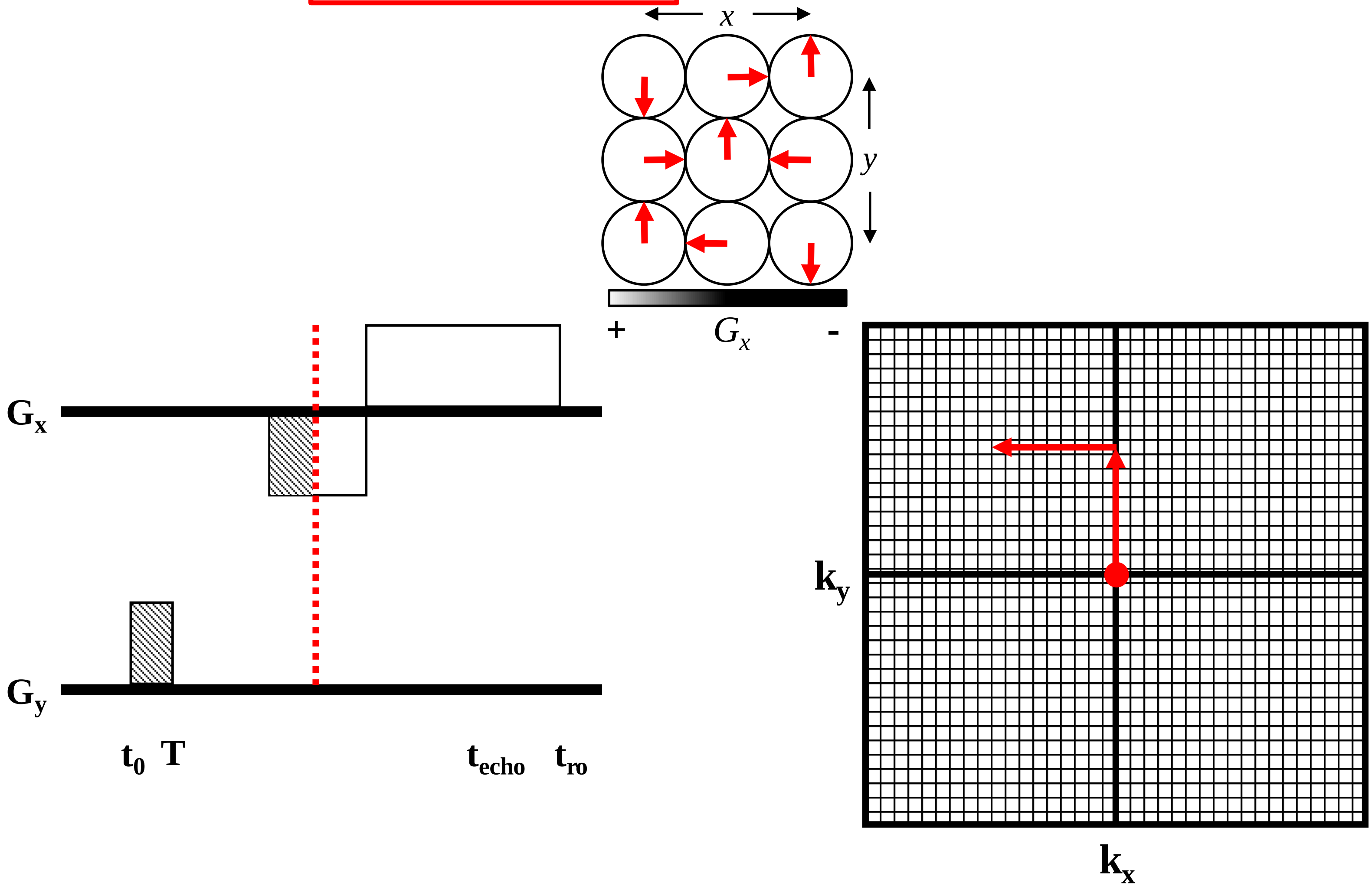

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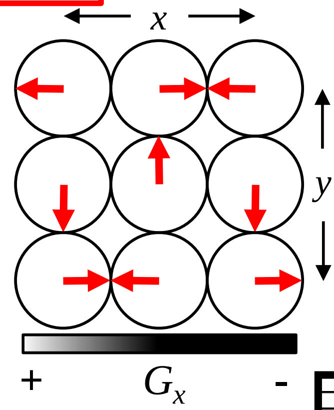

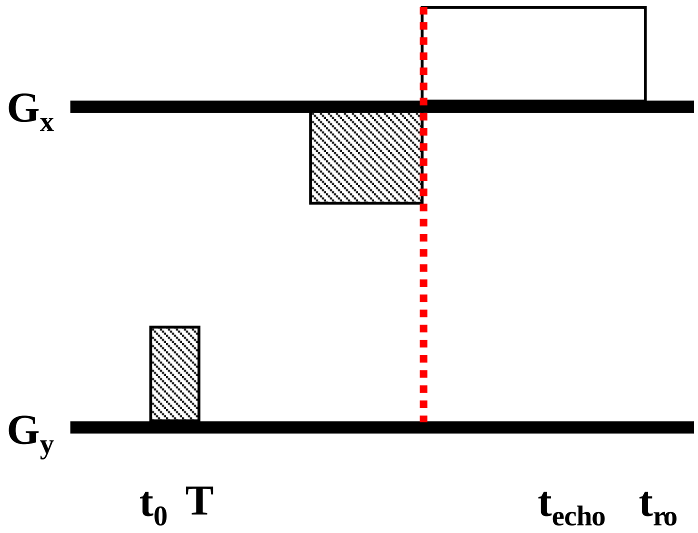

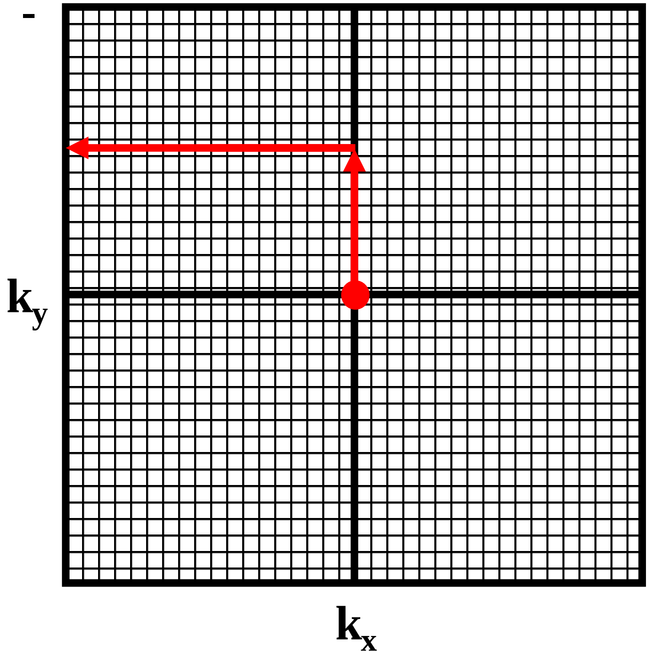

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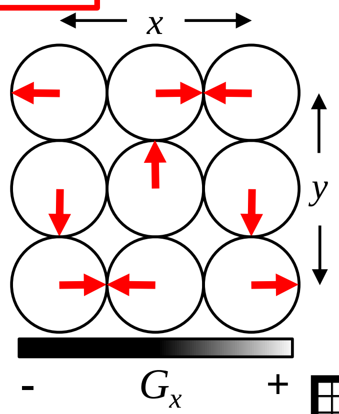

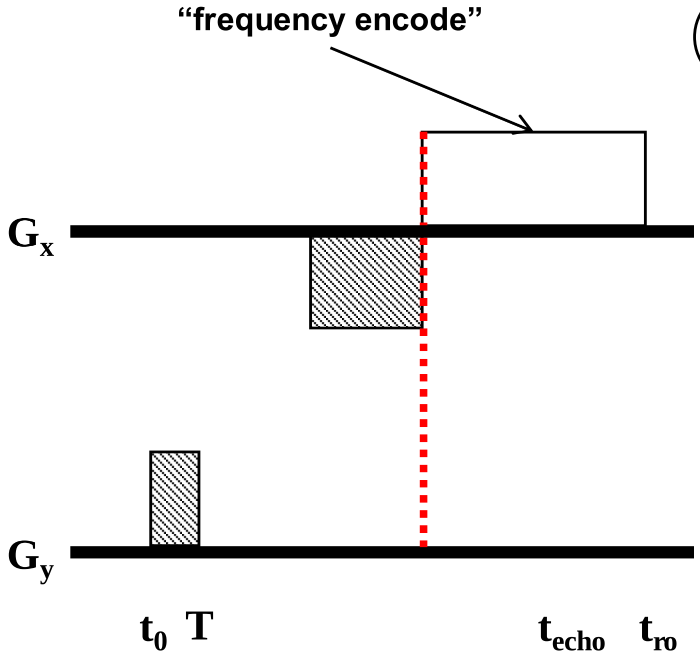

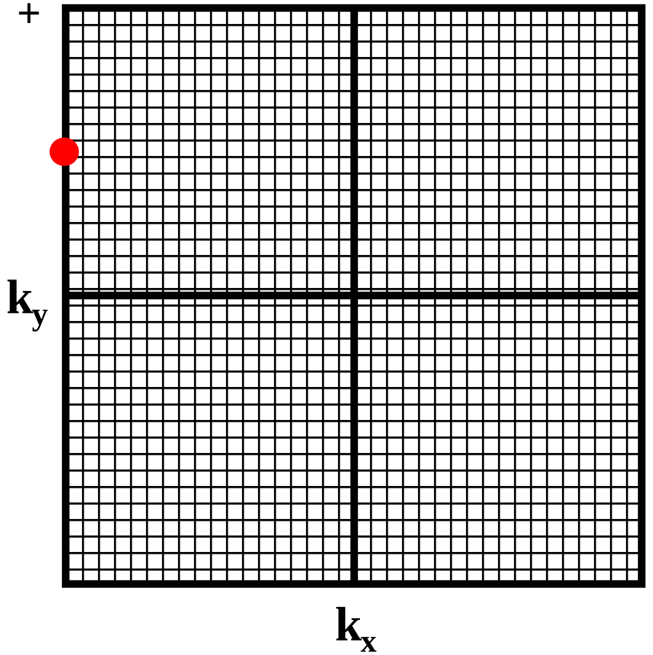

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2D Spatial Encoding

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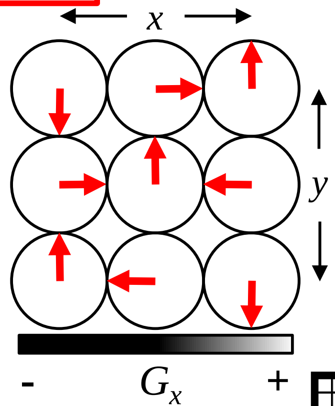

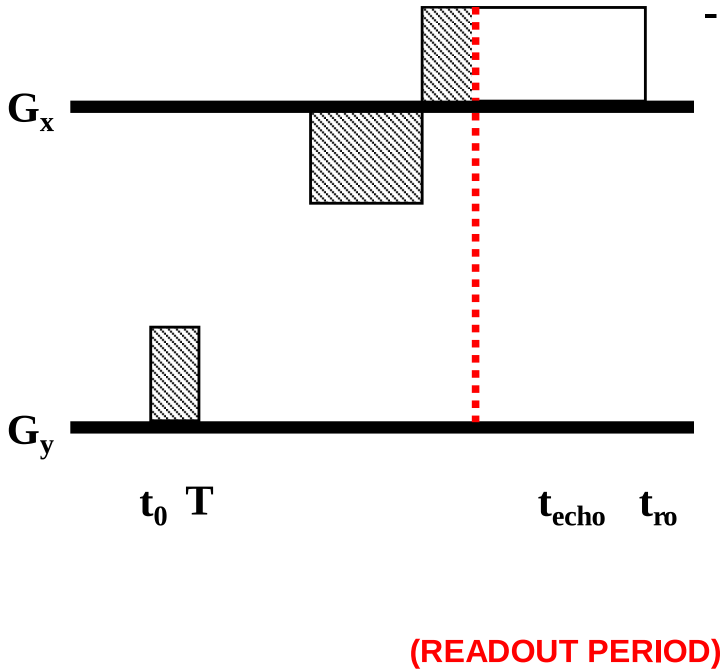

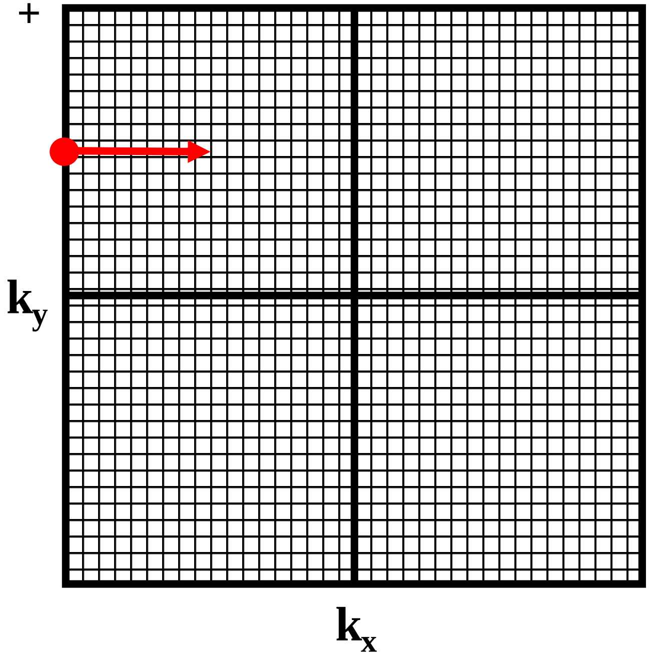

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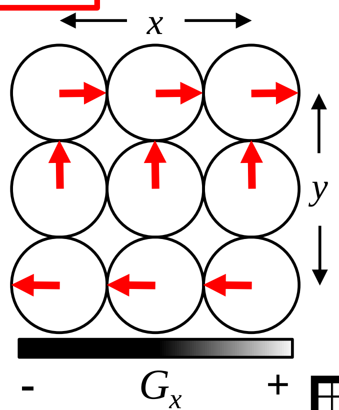

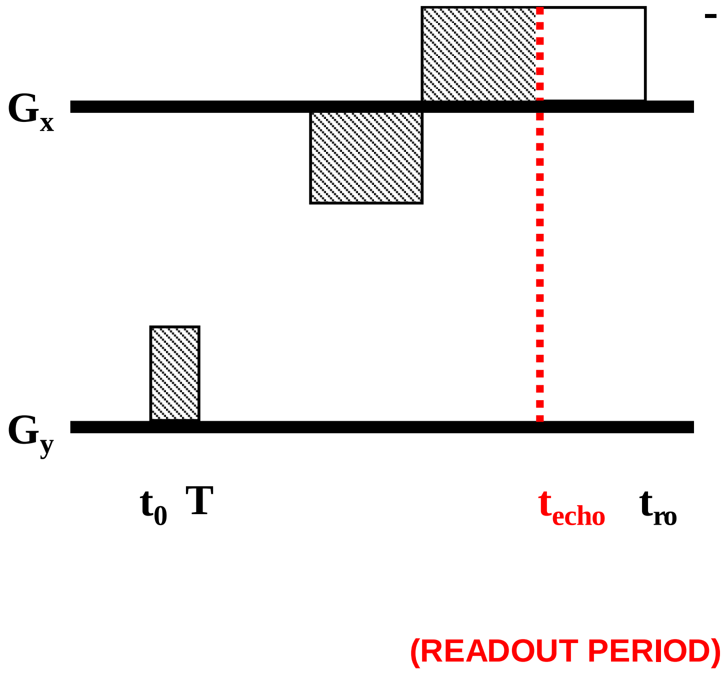

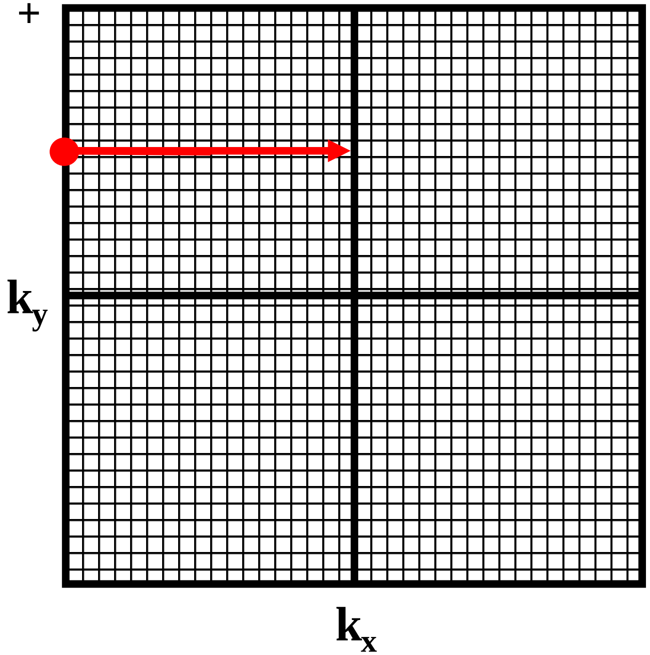

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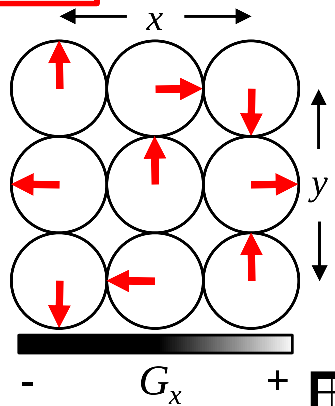

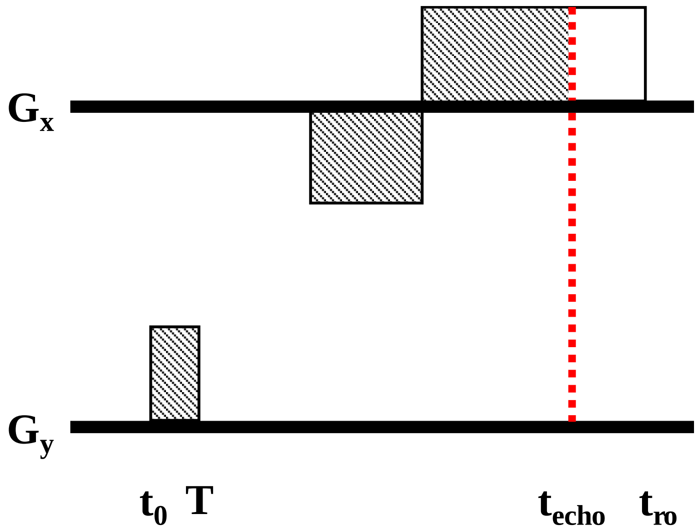

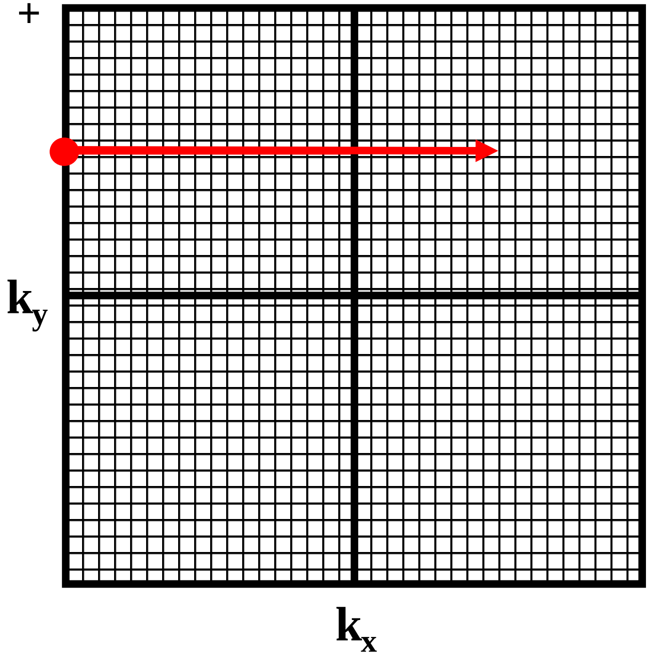

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2D Spatial Encoding

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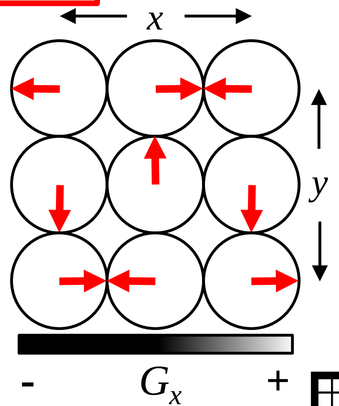
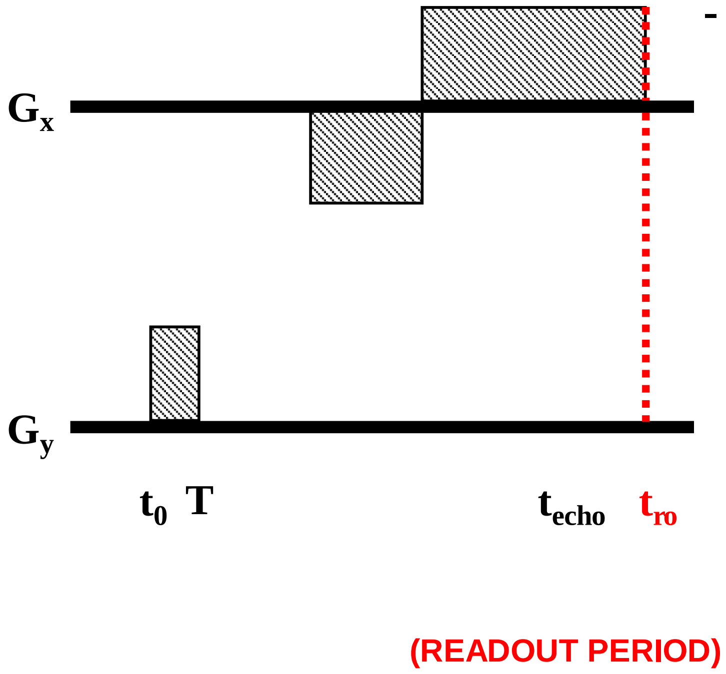
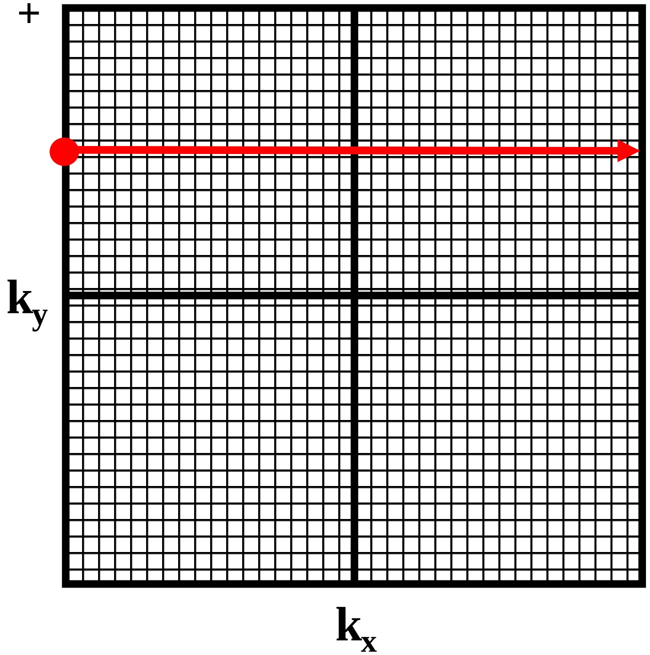
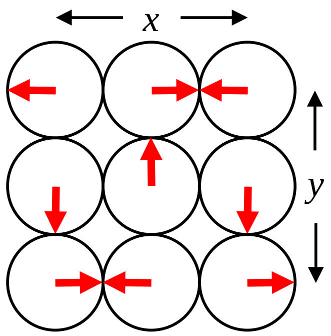


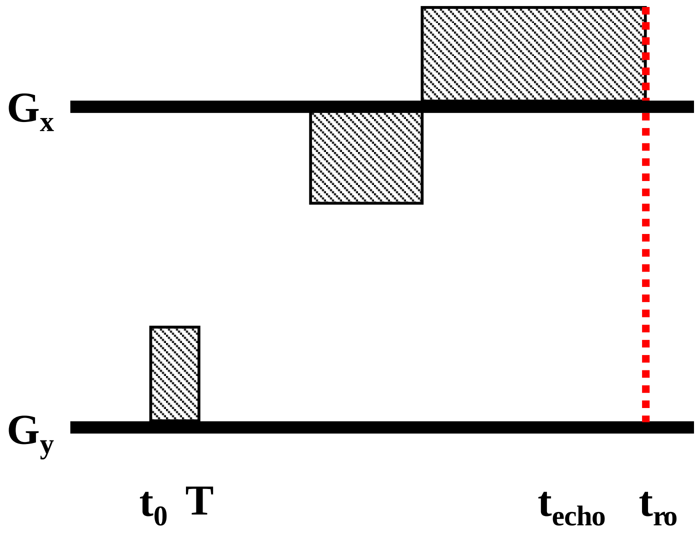


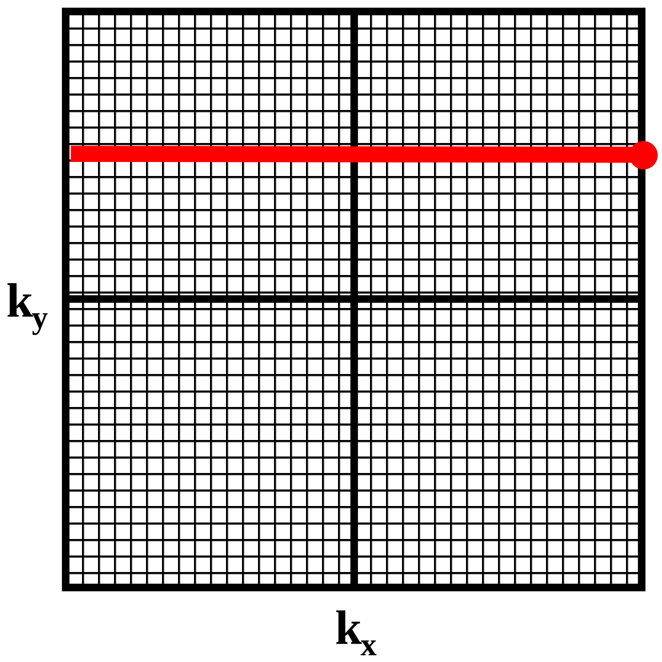


2D Spatial Encoding

$$k_x = \gamma \int^{t} G_x(\tau) d\tau \quad \text{and} \quad k_y = \gamma \int^{t} G_y(\tau) d\tau$$







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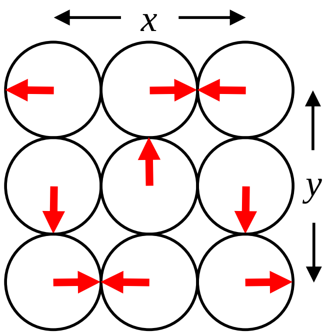
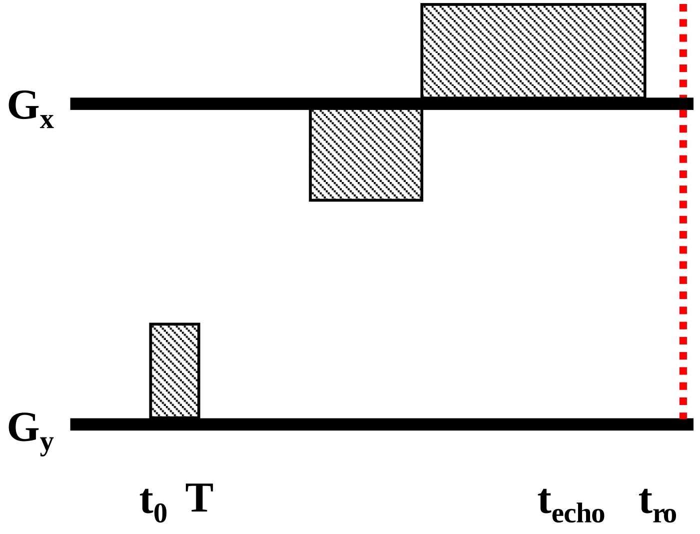
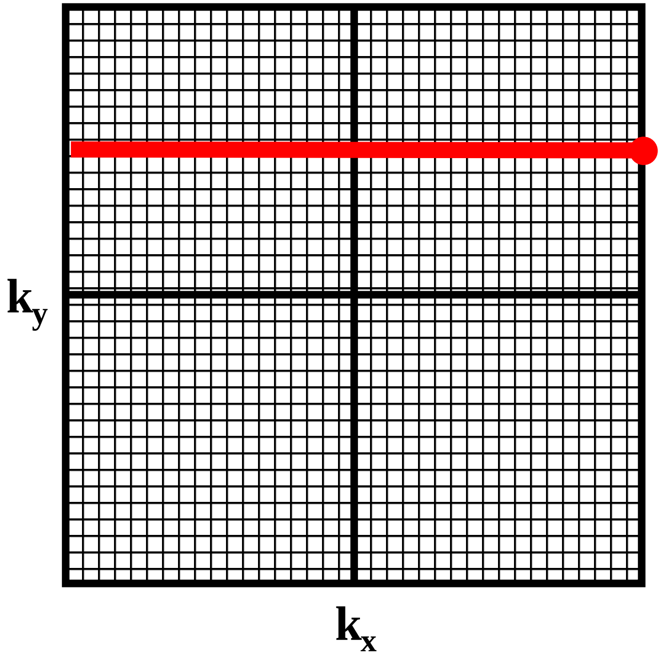


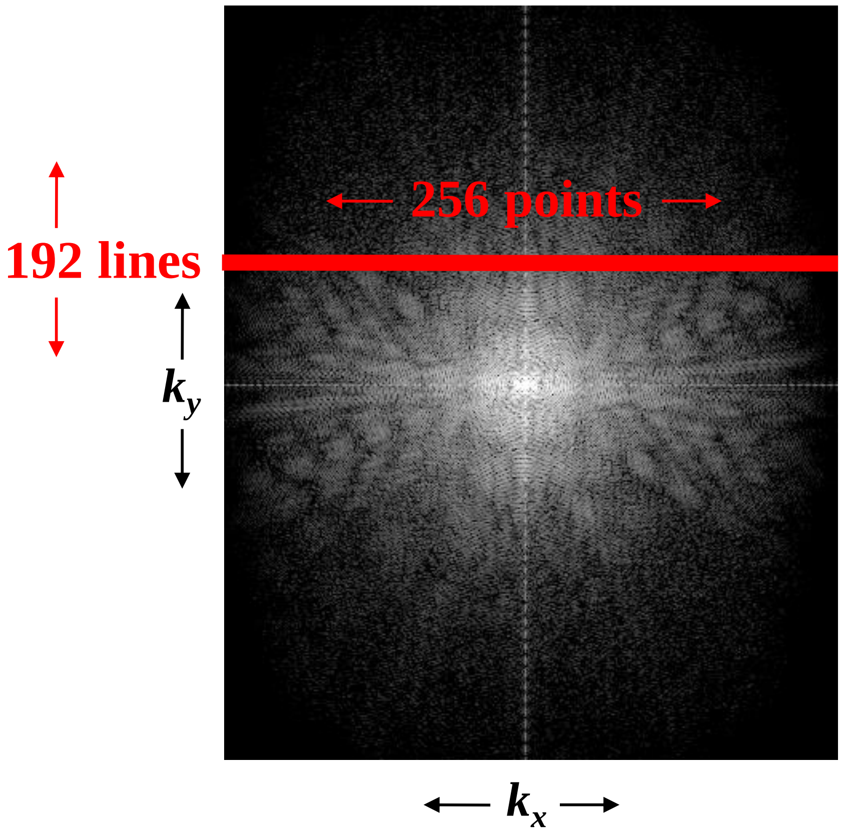




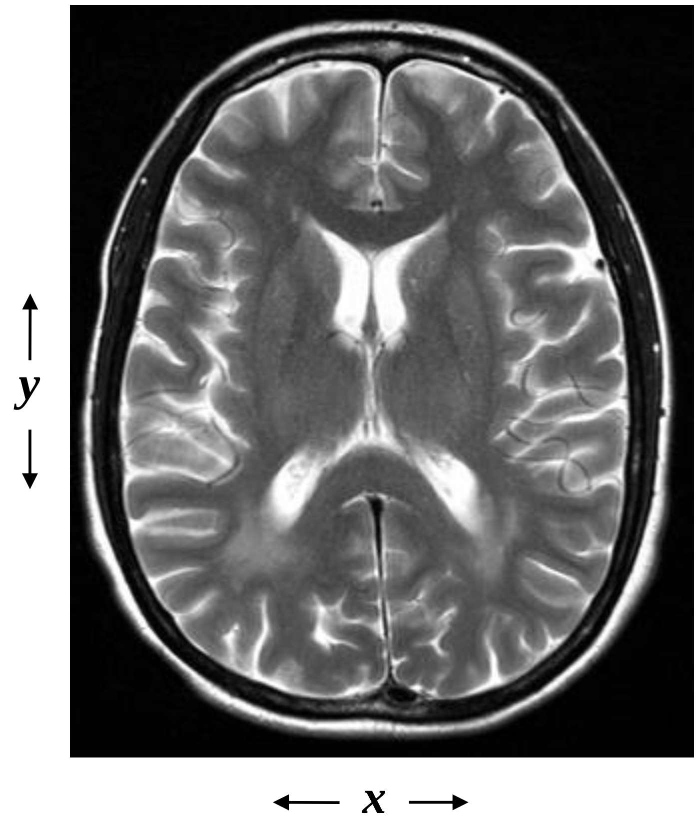
Fourier Transform of MRI Data in ***k***-Space to Real Space

(*e.g.*, 256×192 matrix)

S(k_x,k_y)
Complex k-space



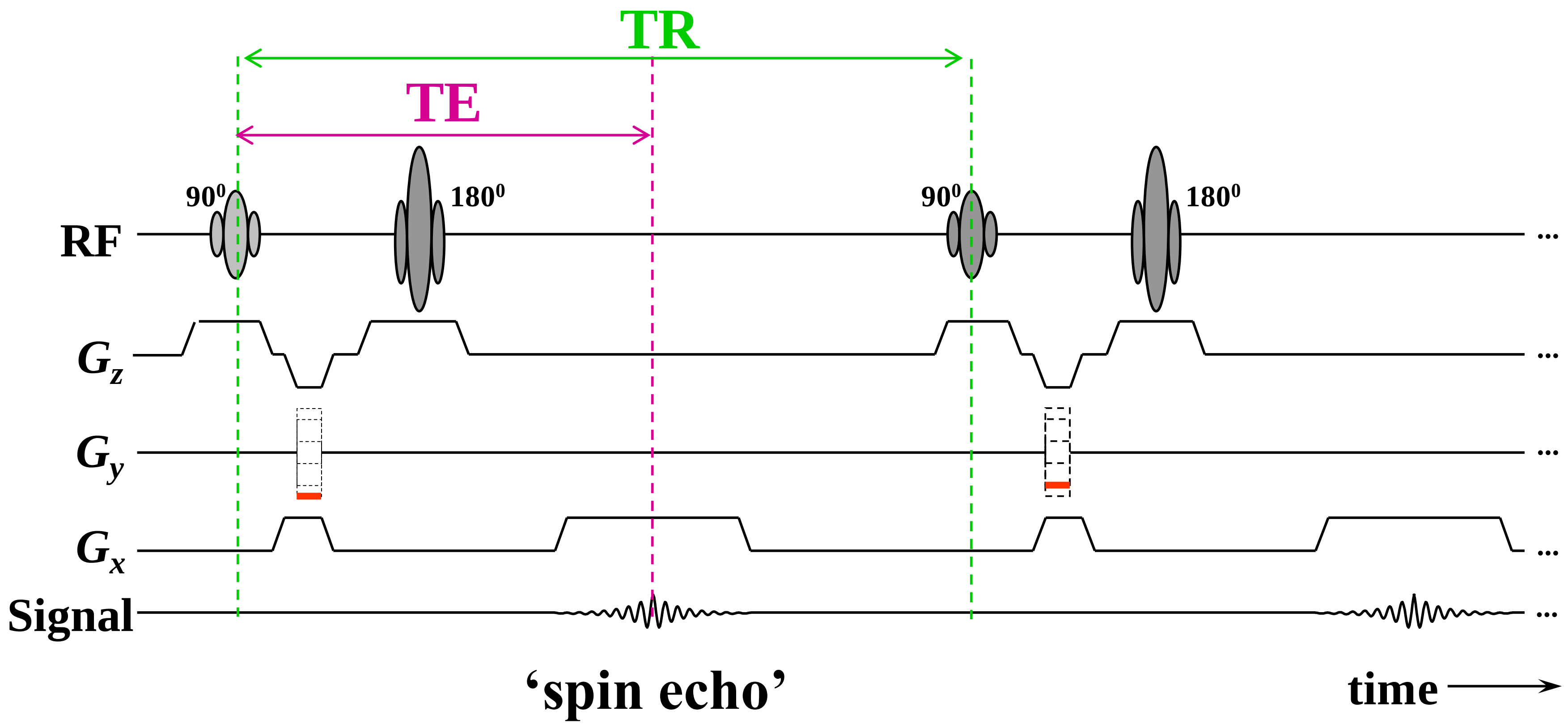
|S(x,y)|~ |FT{S(k_x,k_y)}|
Real-space



$\mathcal{F}$

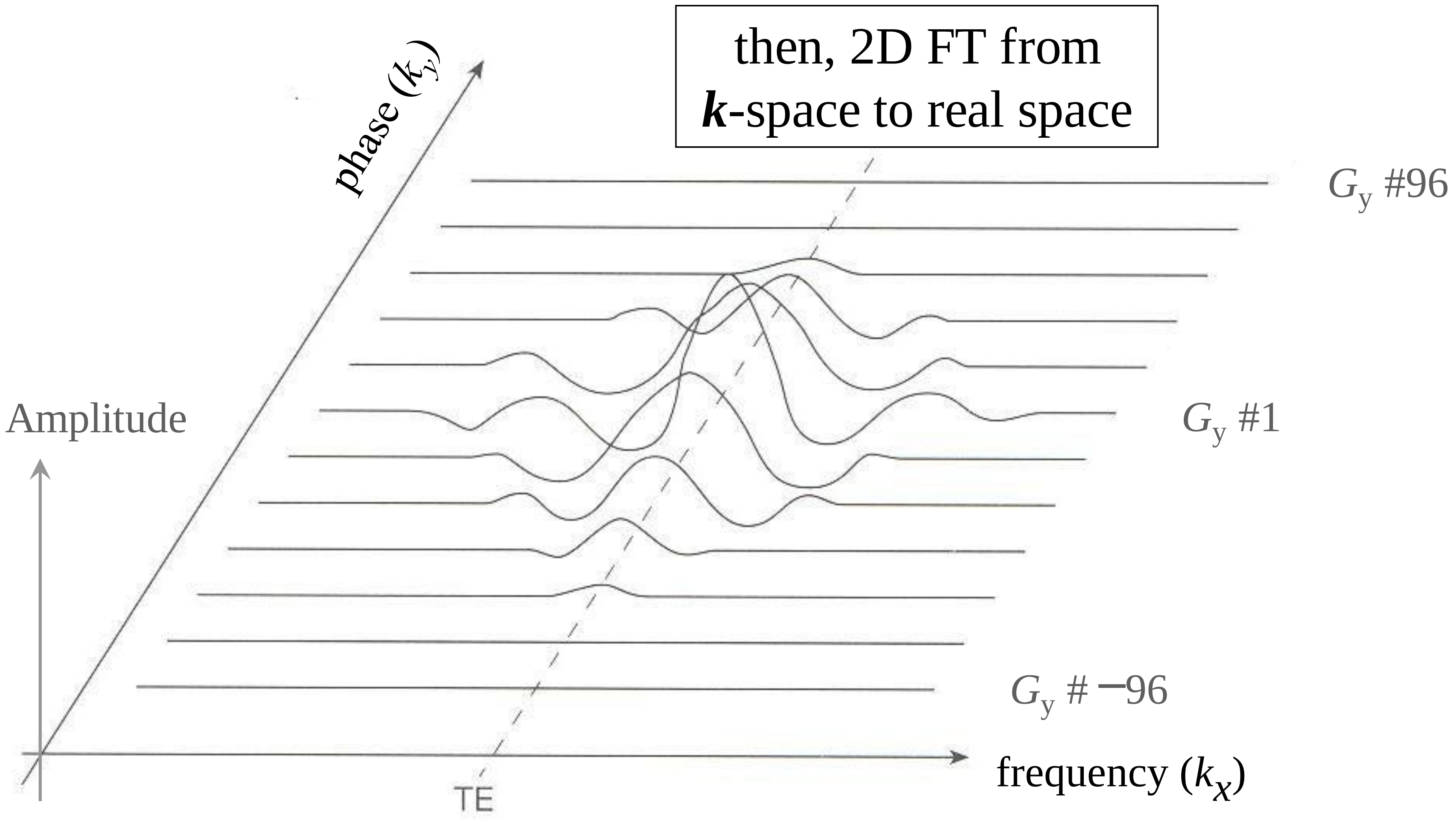
2D Spin-Echo Sequence

$$s(t = \mathrm{TE}) \sim \mathrm{PD}\,(1 - e^{-\mathrm{TR}/\mathrm{T1}})\, e^{-\mathrm{TE}/\mathrm{T2}}$$

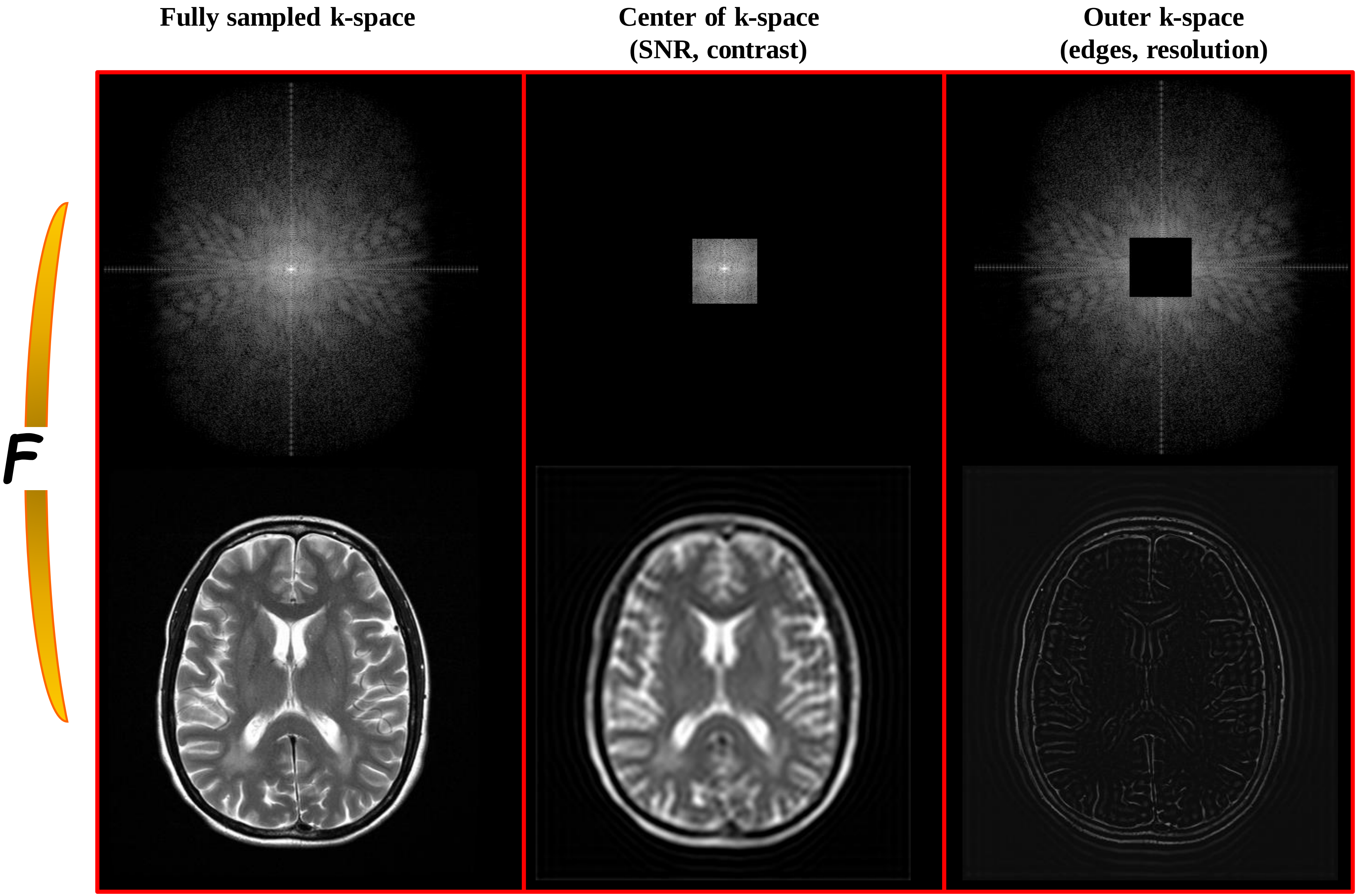


Creation of an MRI 'Image' in 2D *k*-Space

each line in *k*-space from data obtained during one M_{xy}(TE) readout; different lines for different phase-encode gradient strength



Fourier Transform from Parts of *k*-Space to Real Space

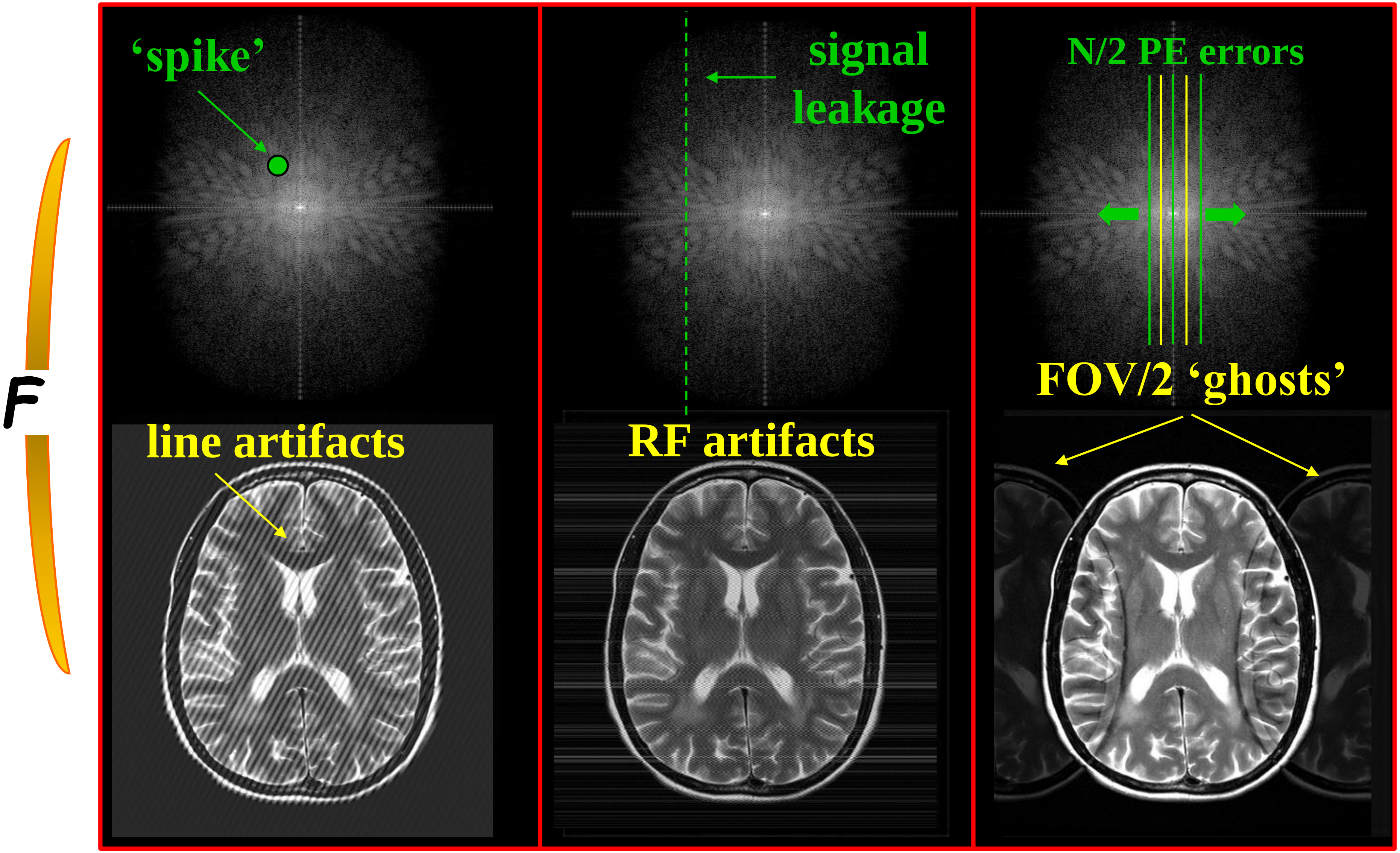


Fourier Transform from Parts of *k*-Space to Real Space

Spike in k-space
(pattern function of location & intensity)

RF Contamination
(door seal, device in-room, etc)

Periodic k-space Errors
(motion, gradient error, etc)



Some Important Topics Not Addressed Today

3D, 4D Imaging
Gradient-Recalled Echo Acquisition
Inversion Recovery (FLAIR and STIR)
Fat Saturation & Suppression
Fast Imaging (e.g., EPI)
Dynamic Contrast Techniques
MR Angiography & Flow
MRI-Elastography
Image SNR Considerations
Image QA, and ACR Accreditation
MRI Safety