Imaging Principles

M219 - Principles and Applications of MRI

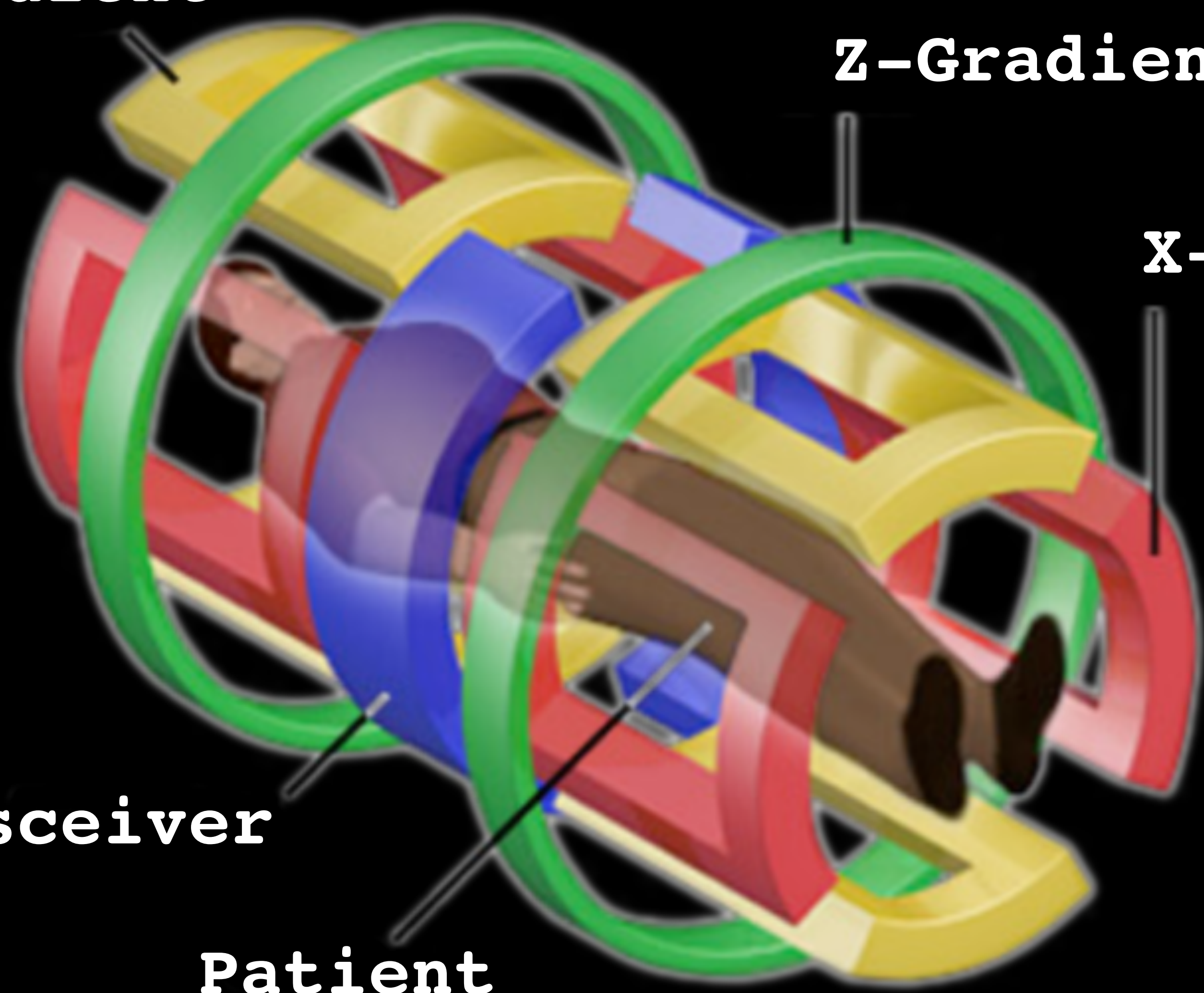
Kyung Sung, Ph.D.

1/29/2025

Course Overview

- 2025 course schedule
  - https://mrrl.ucla.edu/pages/m219_2025
- Assignments
  - Homework #1 due today by 5pm
- TA office hours, Mon 4-6pm
- Office hours, Fri 10-11am

Gradient Hardware



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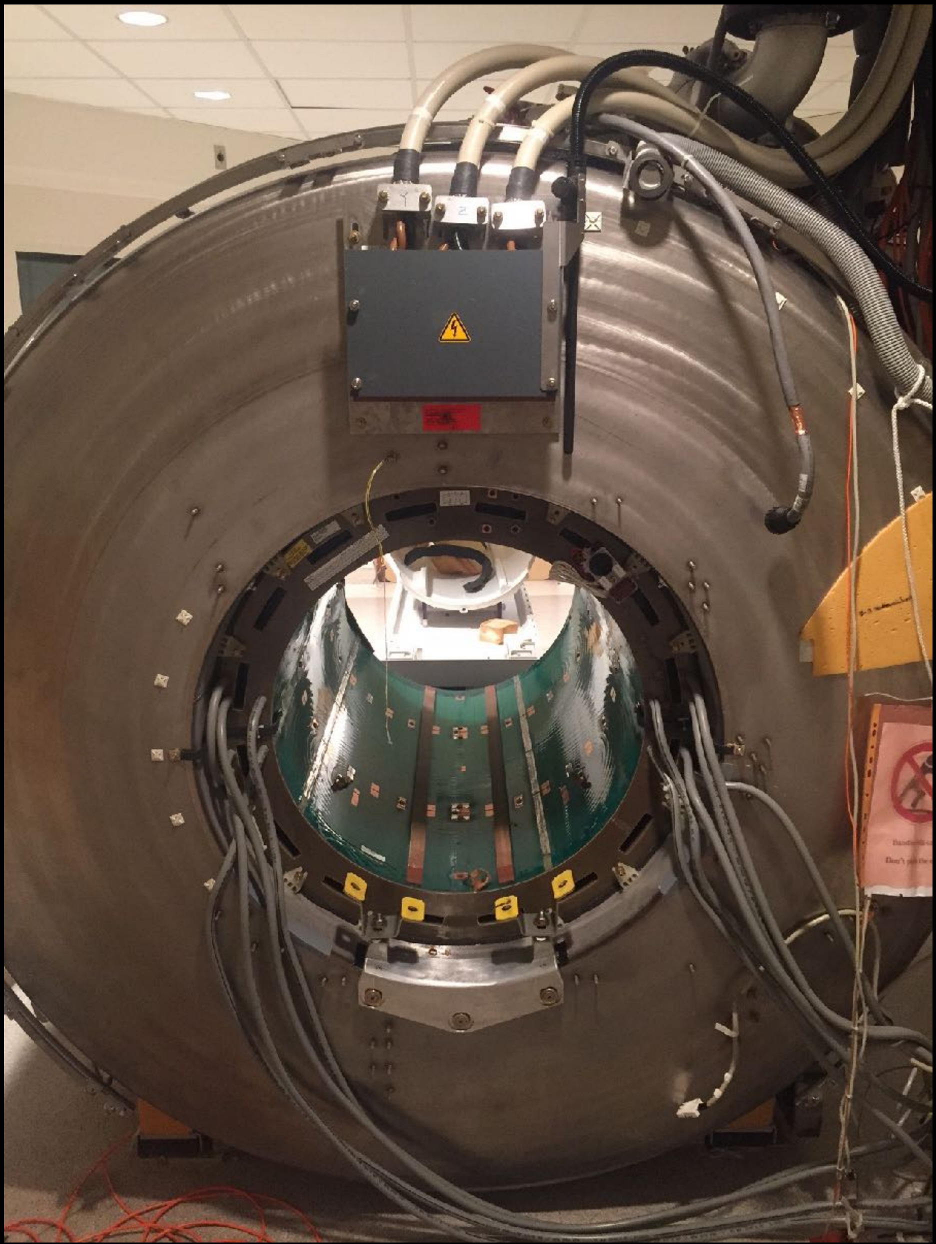

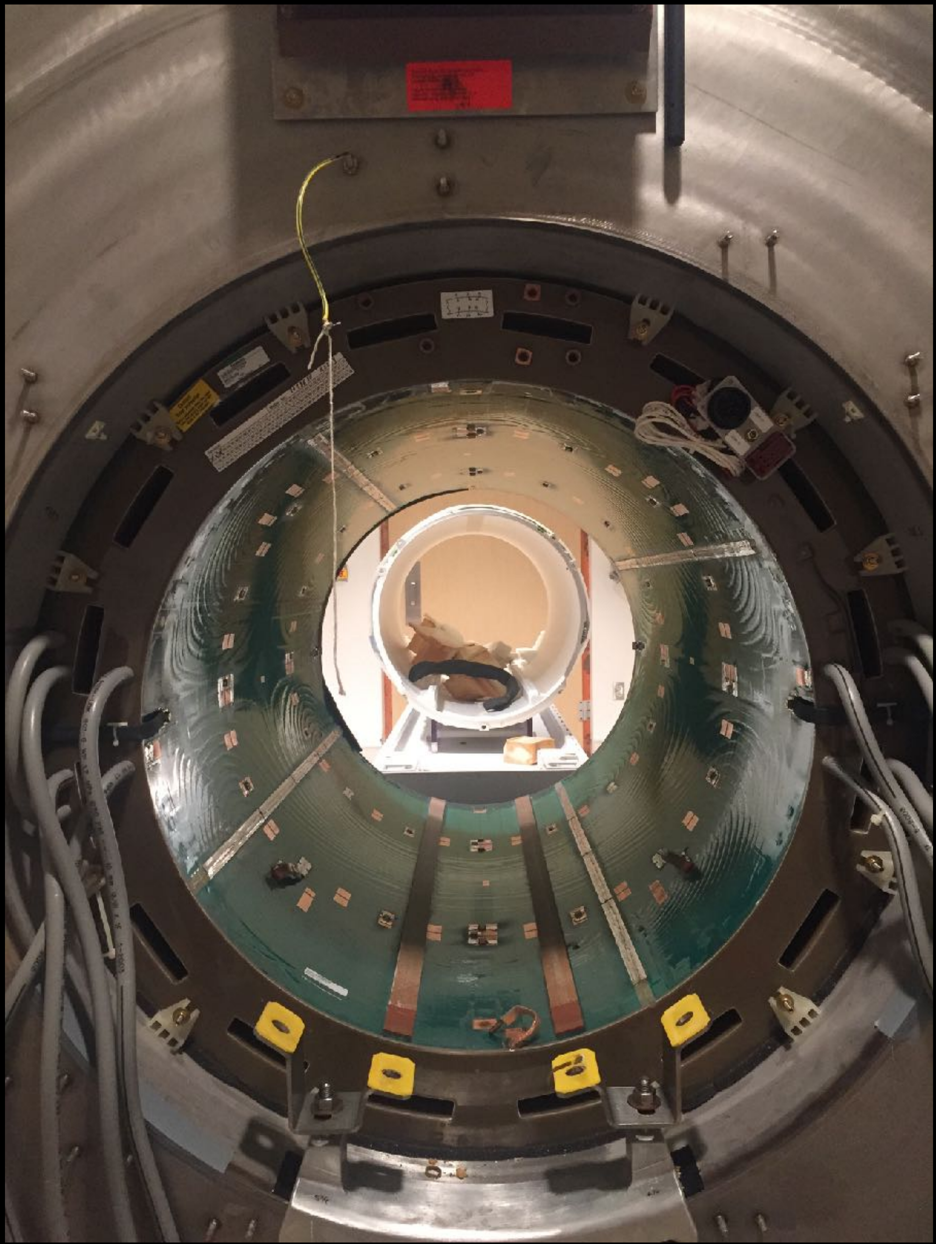

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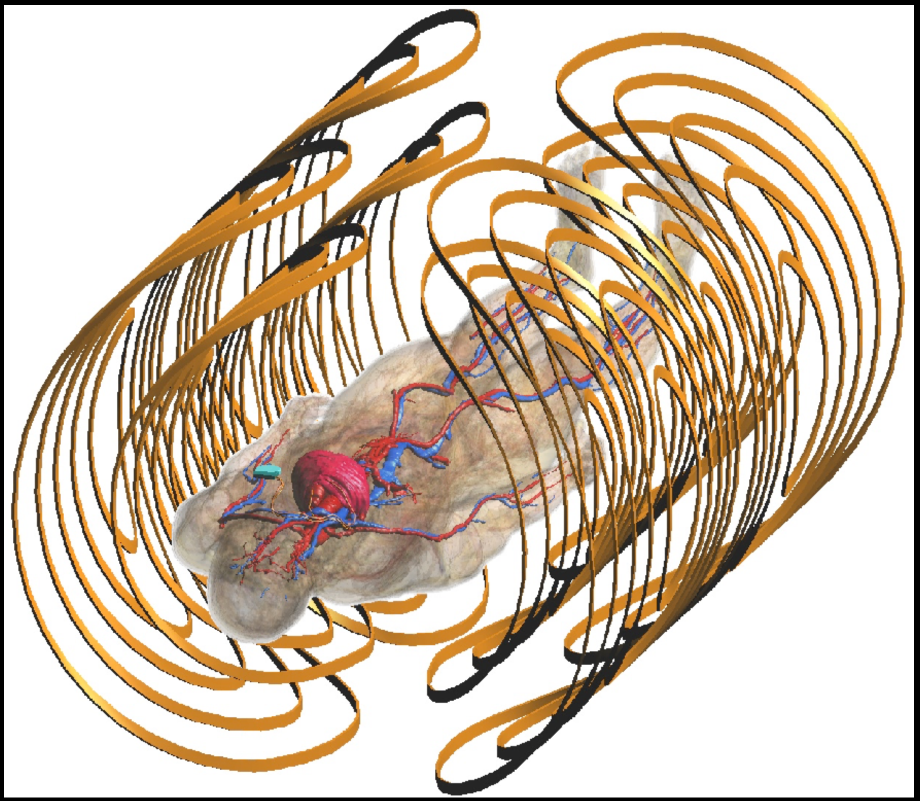

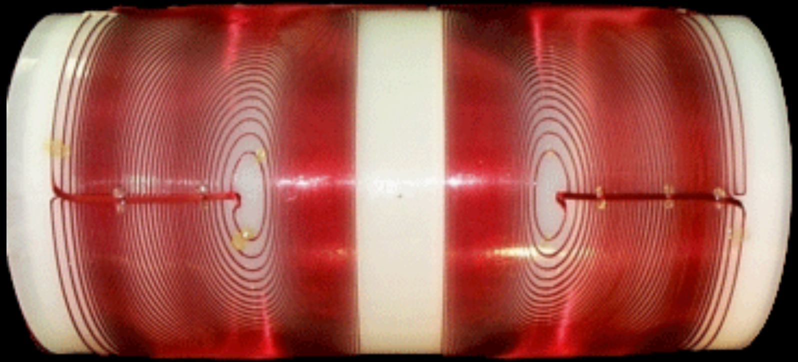

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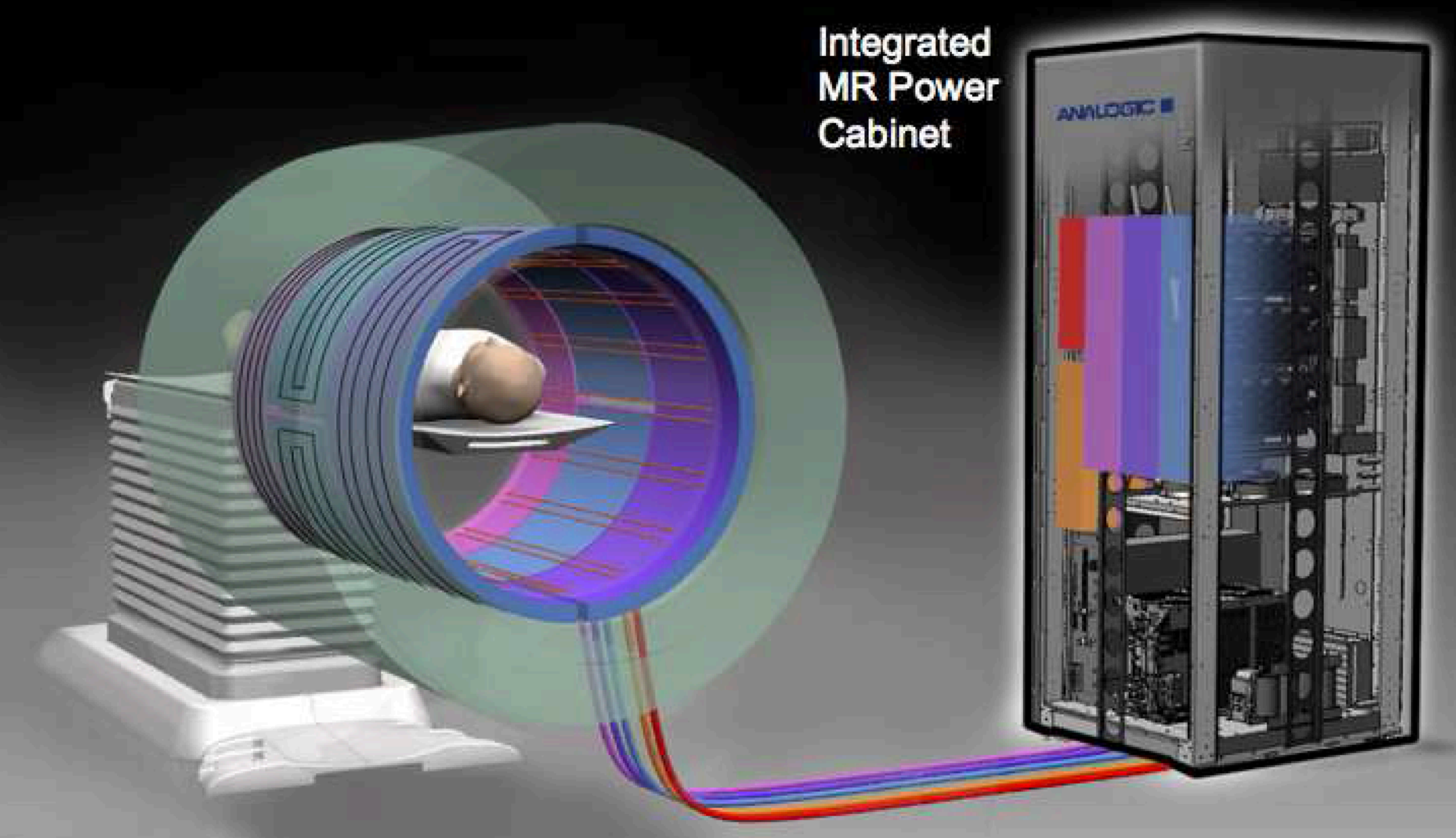


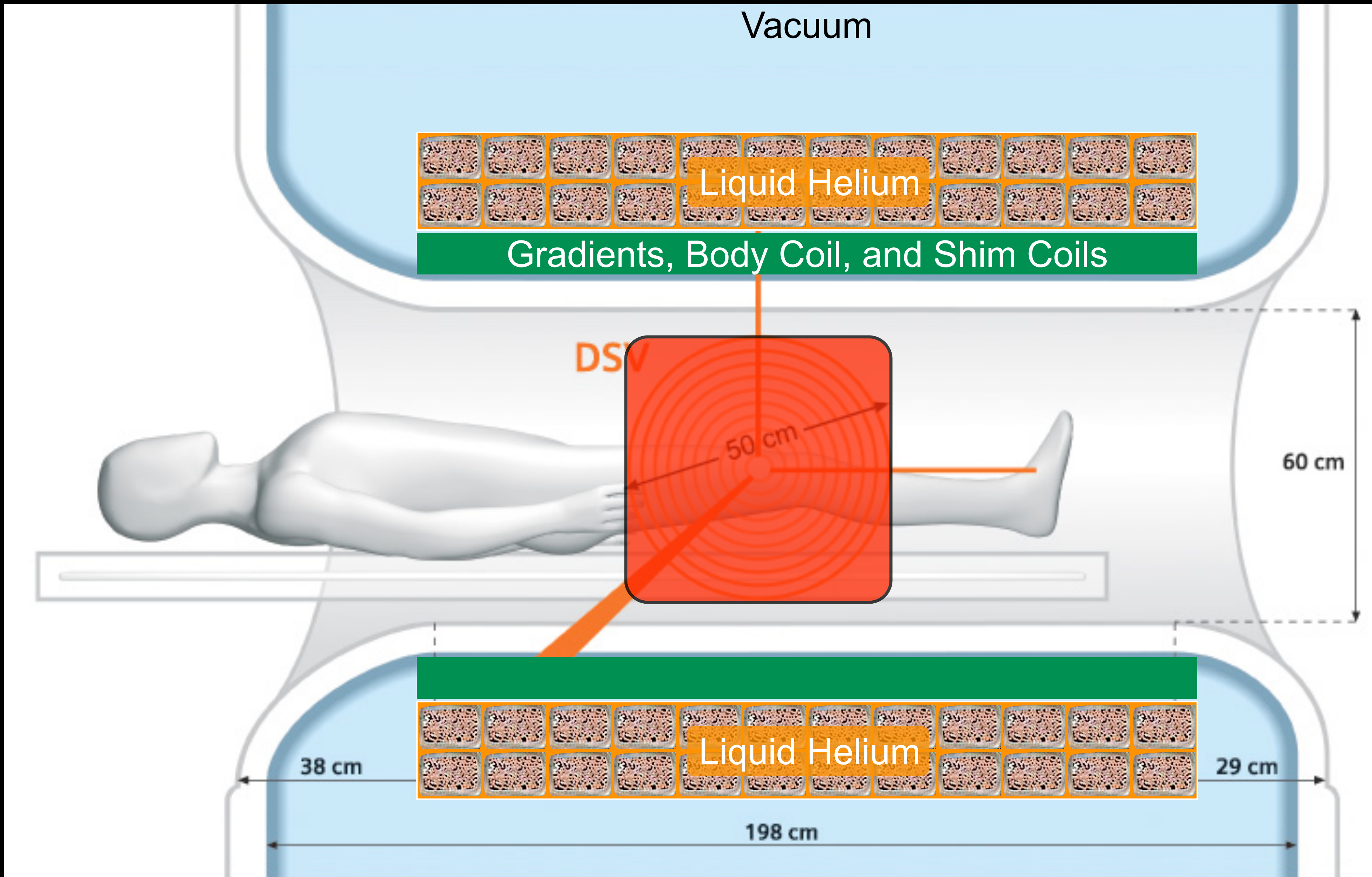
Gradients

- Primary function
  - Encode spatial information
    - Slice selection
    - Phase encoding
    - Frequency encoding
- Secondary functions
  - Sensitize/de-sensitize images to motion
  - Minimize artifacts (crushers & spoilers)
  - Magnetization re-phasing in slice selection
  - Magnetization de-phasing during readout

Gradients

- Gradients are a:
  - Small
    - <5G/cm (<0.0075T @ edge of 30cm FOV)
  - Spatially varying
    - Linear gradients
    - Adds to B_0 only in Z-direction
  - Time varying
    - Slewrate Max. ~150-200mT/m/ms
  - Magnetic field
    - Adds/Subtracts to the B_0 field
  - Parallel to B_0
- Gradients are NOT:
  - Fields perpendicular to B_0

Gradients



Gradients are “linear” over ~40-50cm on each axis.

B-Field Assumptions in MRI

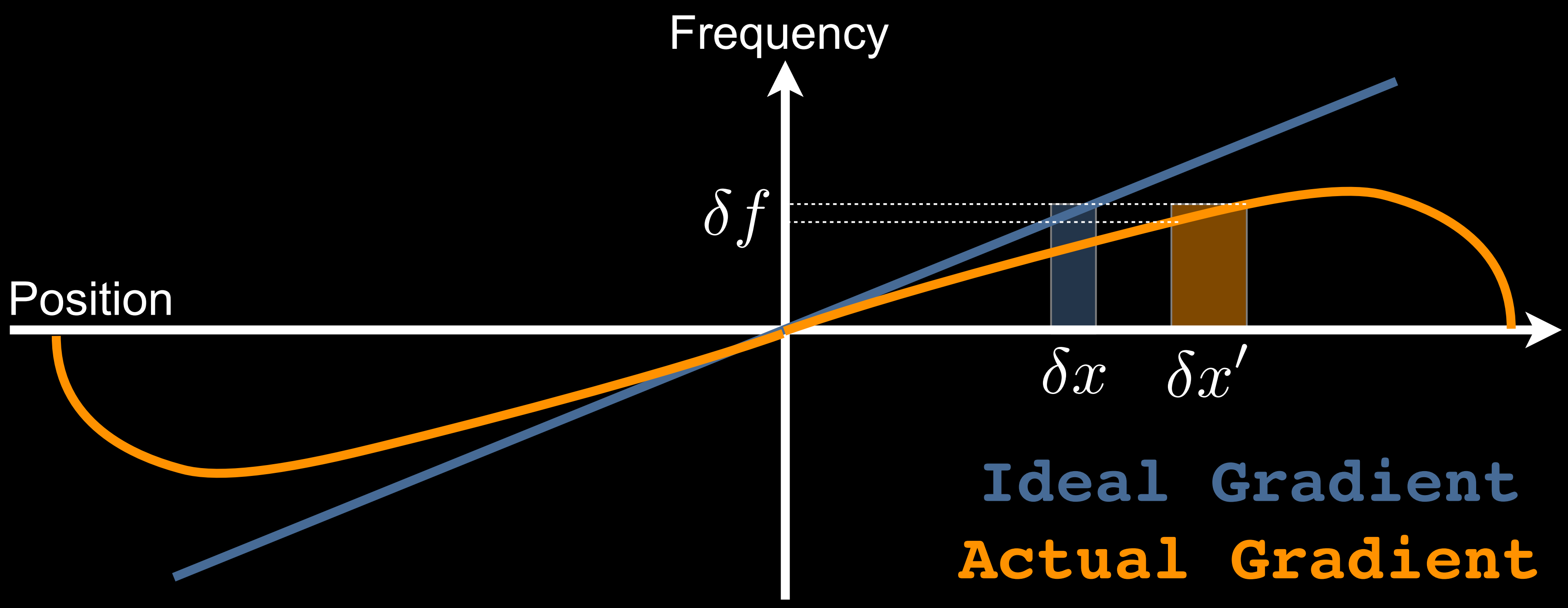
- **B_0-field is:**
  - Perfectly uniform over space.
    - "B_0 homogeneity"
  - Perfectly stable with time.
- **B_1-field is:**
  - Perfectly uniform over space.
    - "B_1 homogeneity"
  - Temporally modulated exactly as specified.
- **Gradient Fields are:**
  - Perfectly linear over space.
    - "Gradient linearity"
  - Temporally modulated exactly as specified

Imperfections of Gradient Fields

- Gradient coils aren't perfect
  - Non-linearity
  - Eddy Currents
  - Maxwell terms (Concomitant fields)
  - But they are small
    - *Much* smaller than B_0
    - We will ignore them...but they exist...

Gradient Non-linearity

Gradient Non-linearity



Ideally spatial position is linearly related to frequency.

Gradient Non-linearity

- **Basic *assumption* in MRI is that the z-component of the B-field created by the gradient coils varies linearly with x, y, or z over the FOV.**
- **Higher gradient amplitudes and slewrates can be achieved by compromising on spatial linearity.**
- **Gradient non-linearity causes geometric and intensity distortions.**

Gradient Non-linearity

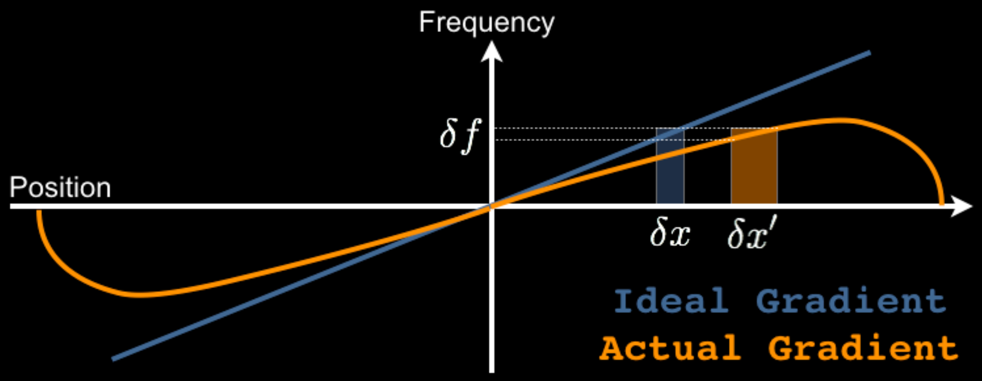


Image Courtesy of M.T. Alley & B.A. Hargeaves

Solution

- Improve hardware and linearity!
- Pay attention to FOV!
- Image warping parameters that are system specific and applied to all images.
  - Works well qualitatively.
  - Can be problematic quantitatively.

B-Field Assumptions in MRI

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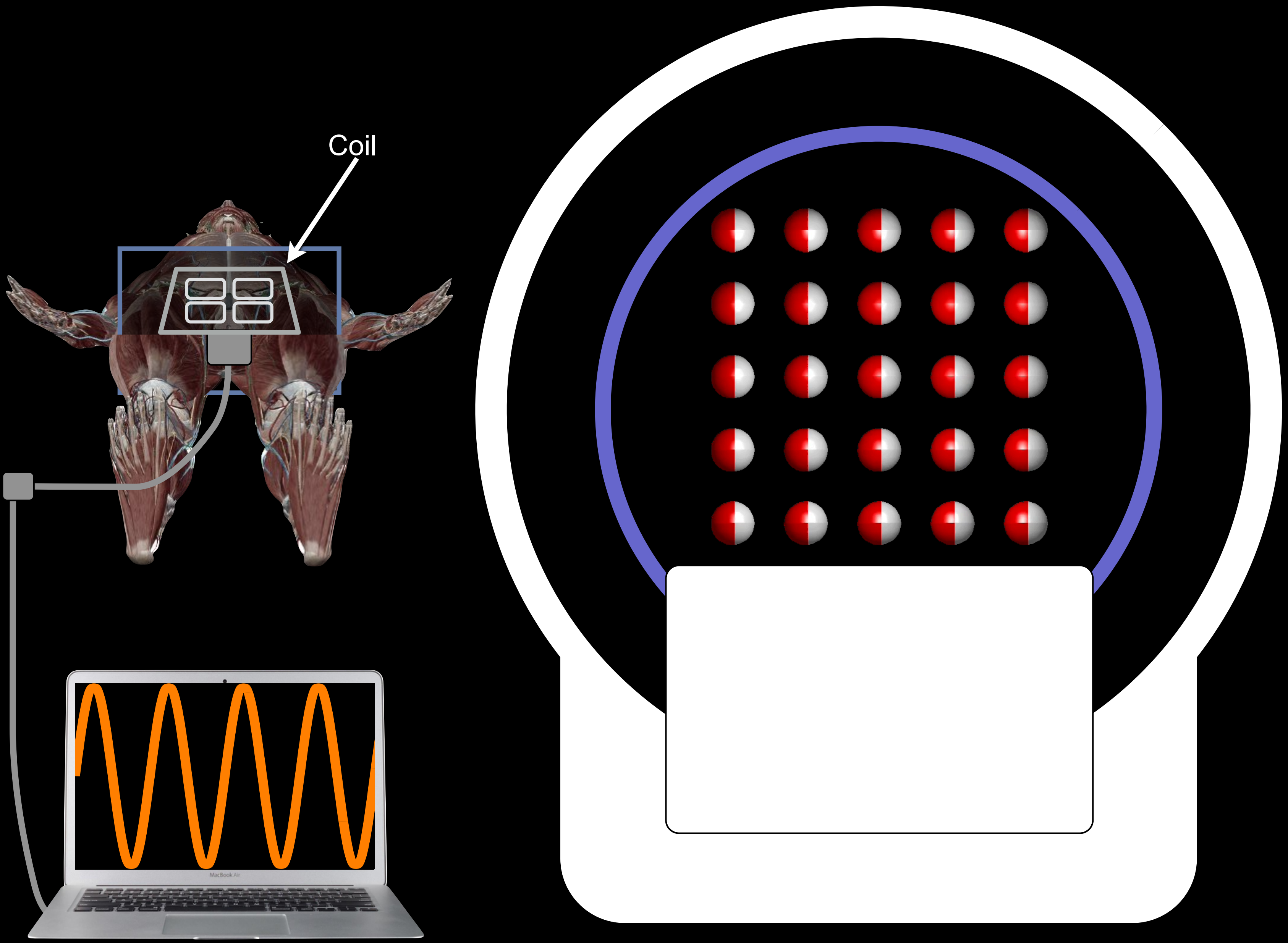
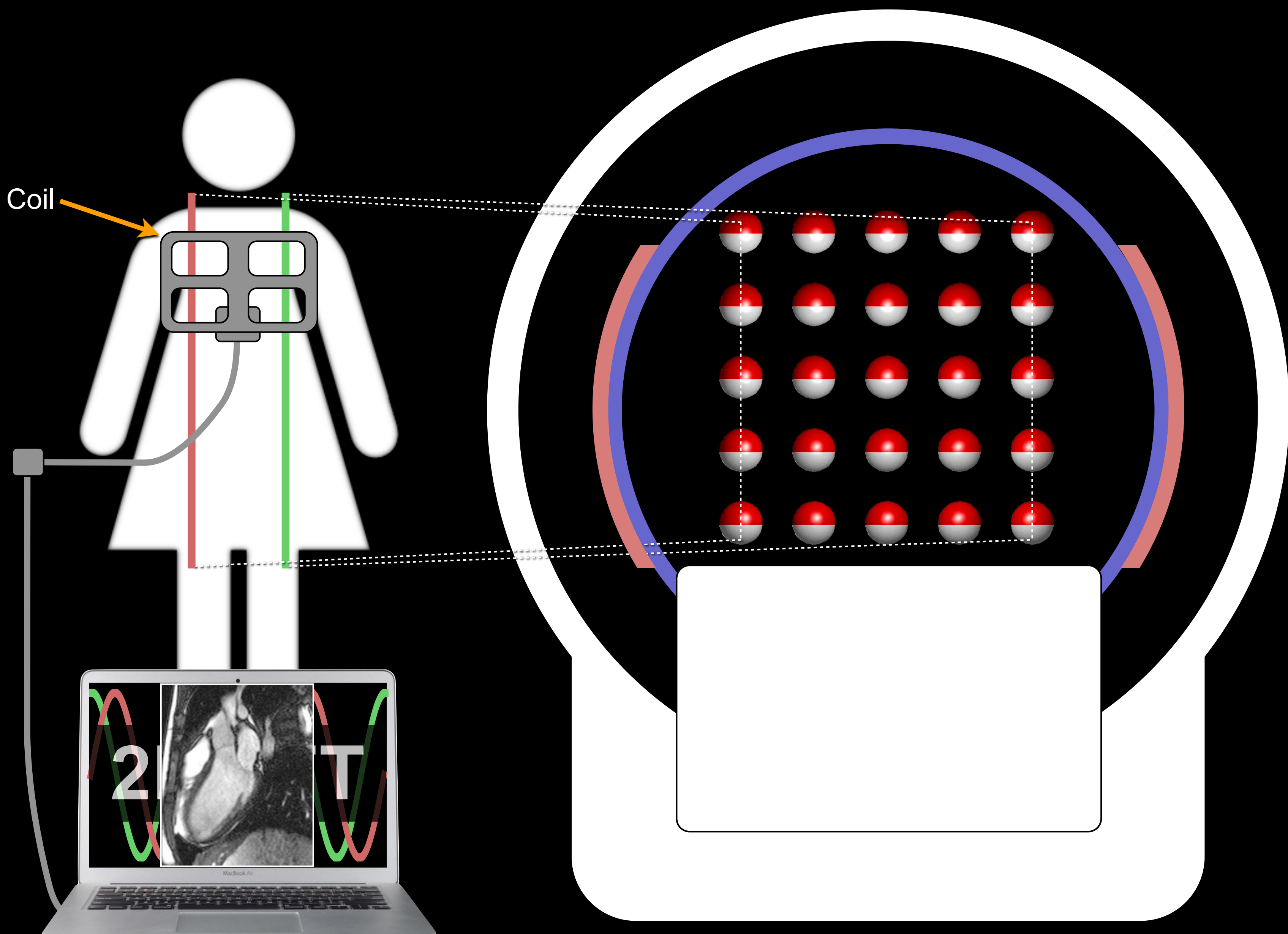
How do we measure M_{xy}?

Faraday's Law of Induction



Precessing spins *induce* a current in a nearby coil.

Faraday's Law of Induction



The trick is to encode spatial information and image contrast in the echo.

Basic Detection Principles

We get here

$$S(t) = \int_{\text{object}} M_{xy}(\mathbf{r}, 0) e^{-i\gamma \Delta B(\mathbf{r}) t} d\mathbf{r}$$

From Here

$$V(t) = -\frac{\partial \Phi(t)}{\partial t} = -\frac{\partial}{\partial t} \int_{object} \vec{B}(\vec{r}) \cdot \vec{M}(\vec{r}, t)\, d\vec{r}$$

with 25 pages of Math!

Basic Detection Principles

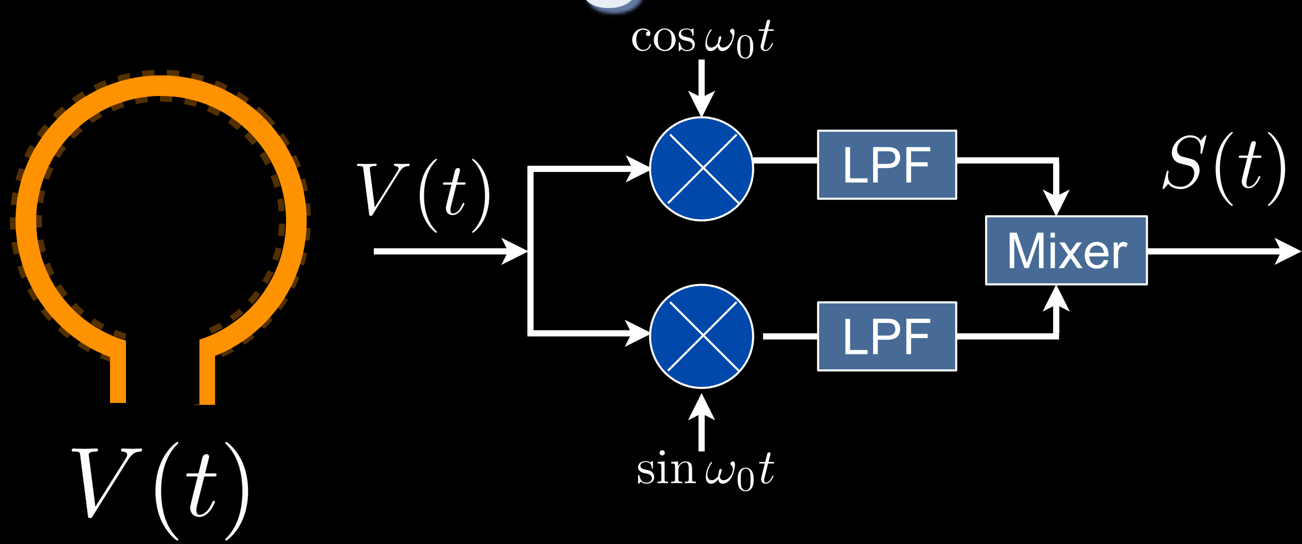
$$S(t) = \int_{\text{object}} M_{xy}(\boldsymbol{r}, 0) e^{-i\gamma \Delta B(\boldsymbol{r}) t} d\boldsymbol{r}$$

Observations

Detected signal is the vector sum of all transverse magnetizations in the “rotating frame” within the imaging volume.

The Larmor frequency precession (Lab frame rotation) is necessary for detection, although only the baseband signal matters for imaging

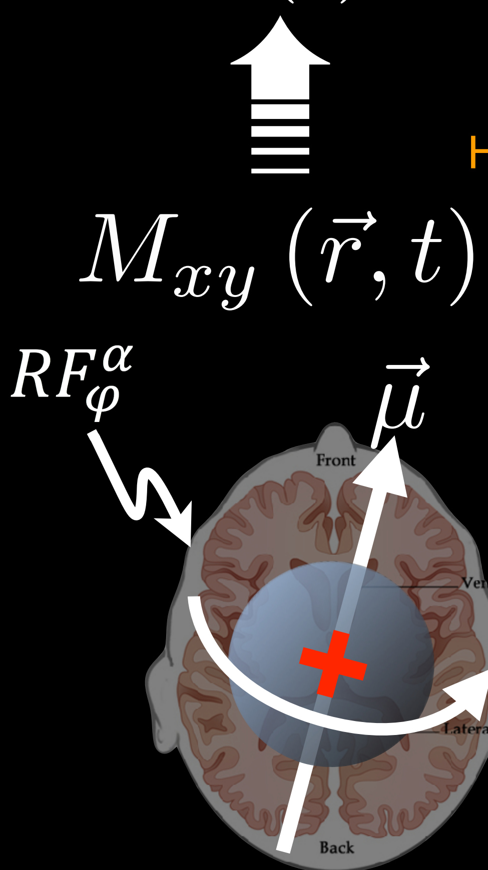
Signals in MRI

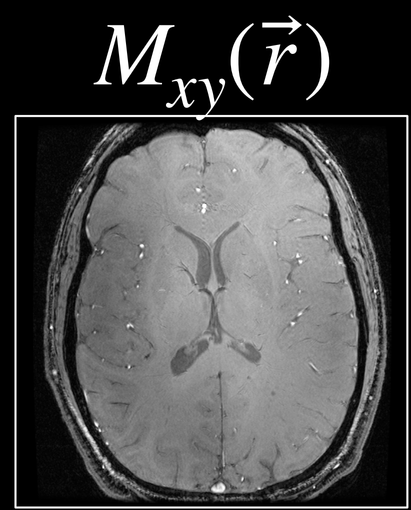


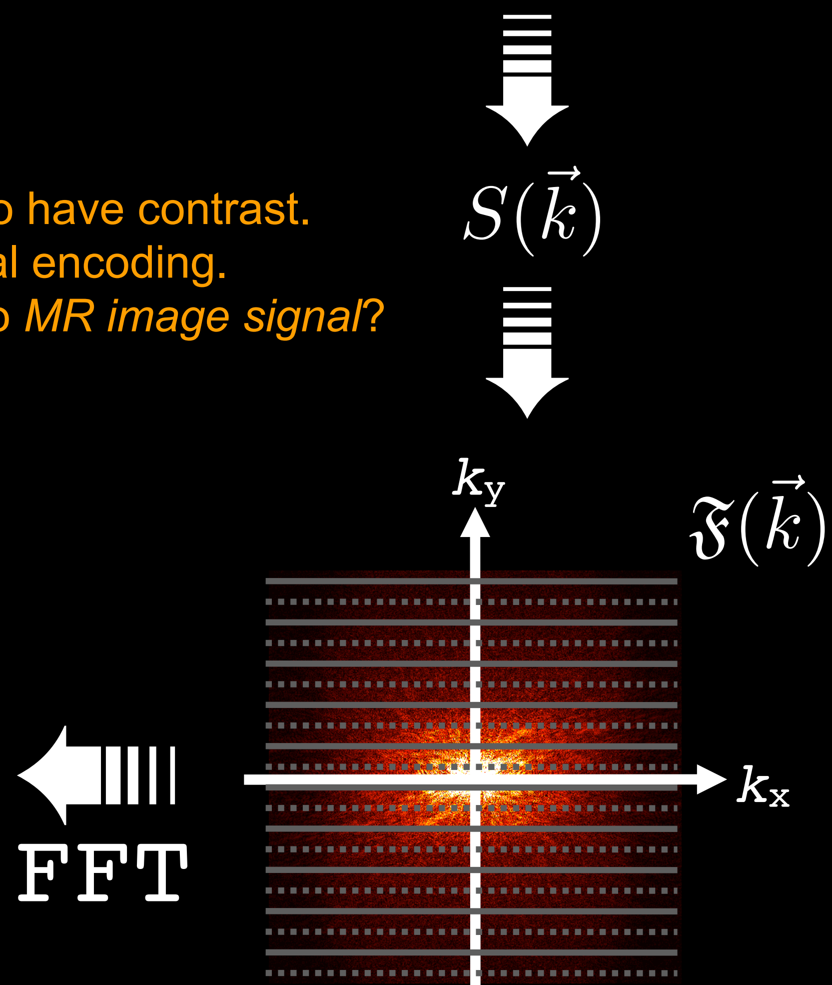
$$k_x(t) = \frac{\gamma}{2\pi}\int_0^t G_x(\tau)d\tau$$

$$k_y(t) = \frac{\gamma}{2\pi}\int_0^t G_y(\tau)d\tau$$

We know how to prepare M_{xy} to have contrast.
We know a bit about spatial encoding.
How does Mxy(r,t) get converted to *MR image signal*?

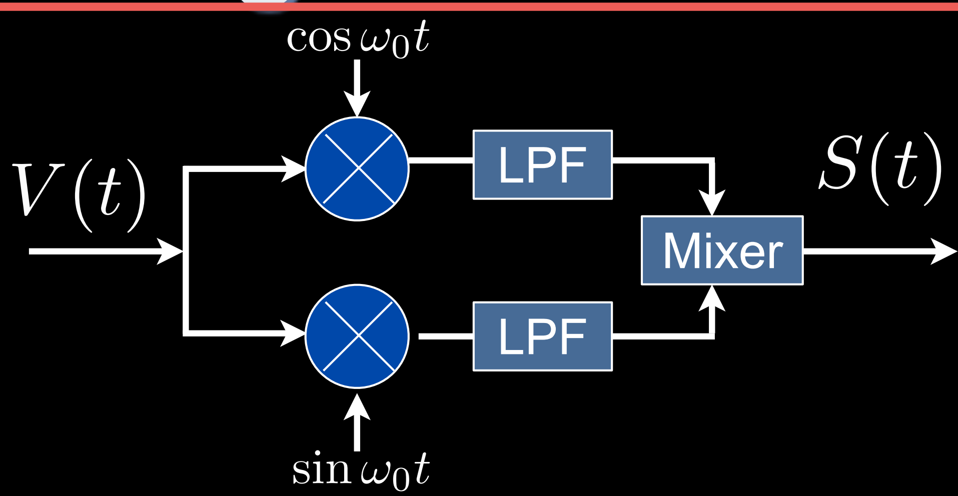






Signals in MRI

$V(t)$



$$k_x(t) = \frac{\gamma}{2\pi}\int_0^t G_x(\tau)d\tau$$

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$S(\vec{k})$

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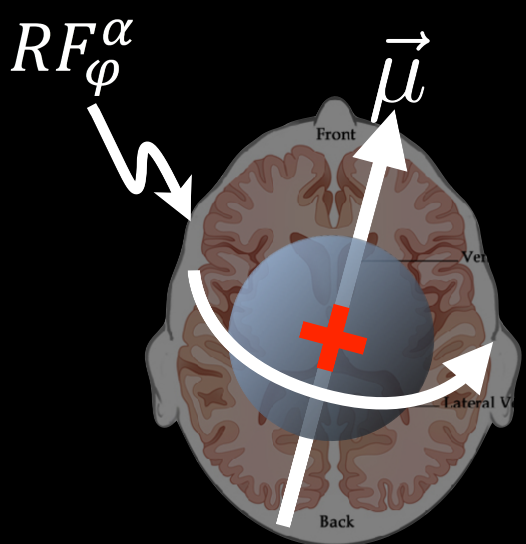
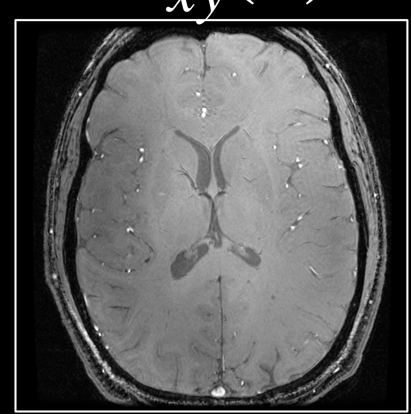
$M_{xy}(\vec{r}, t)$

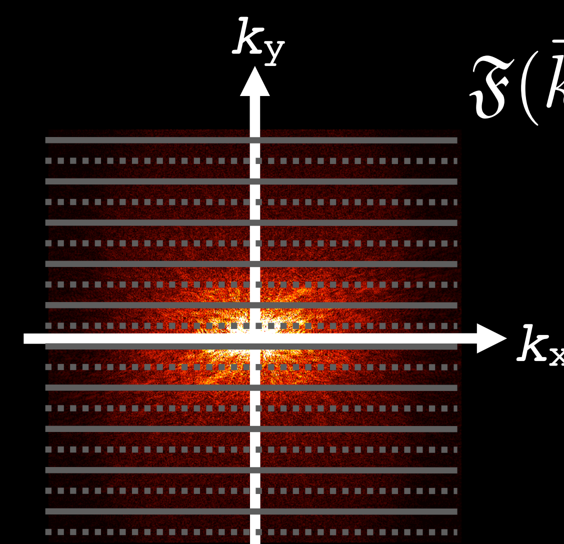


$M_{xy}(\vec{r})$



FFT

$\mathfrak{F}(\vec{k})$



To the Board

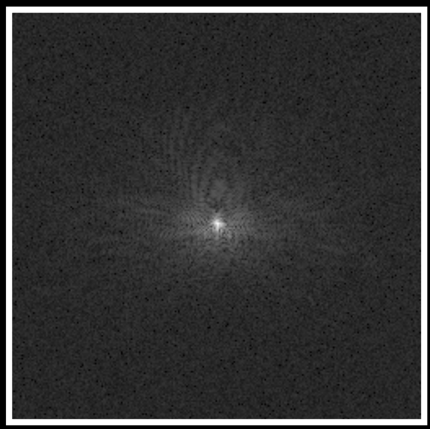
MR Signal Equation

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

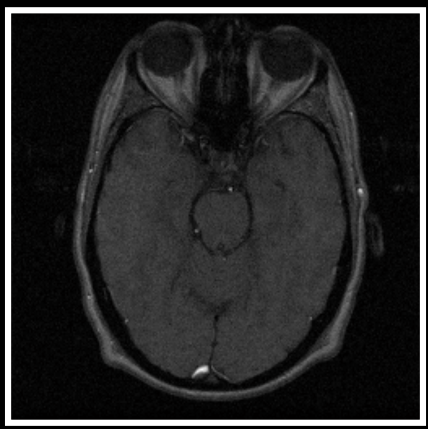
$$k_x(t) = \frac{\gamma}{2\pi}\int_0^t G_x(\tau)d\tau \quad k_y(t) = \frac{\gamma}{2\pi}\int_0^t G_y(\tau)d\tau$$

$$s(t) = m(k_x(t), k_y(t))$$

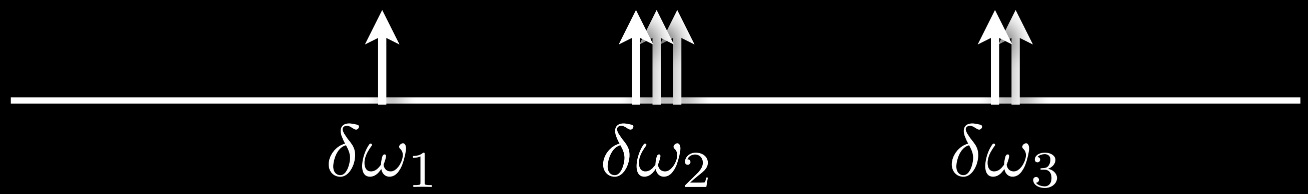
$$m = \mathcal{FT}(\, M(x,y)\,)$$



FT ⟷



1D Imaging



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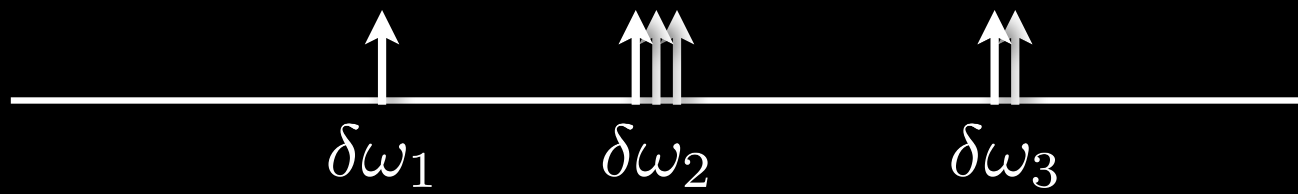
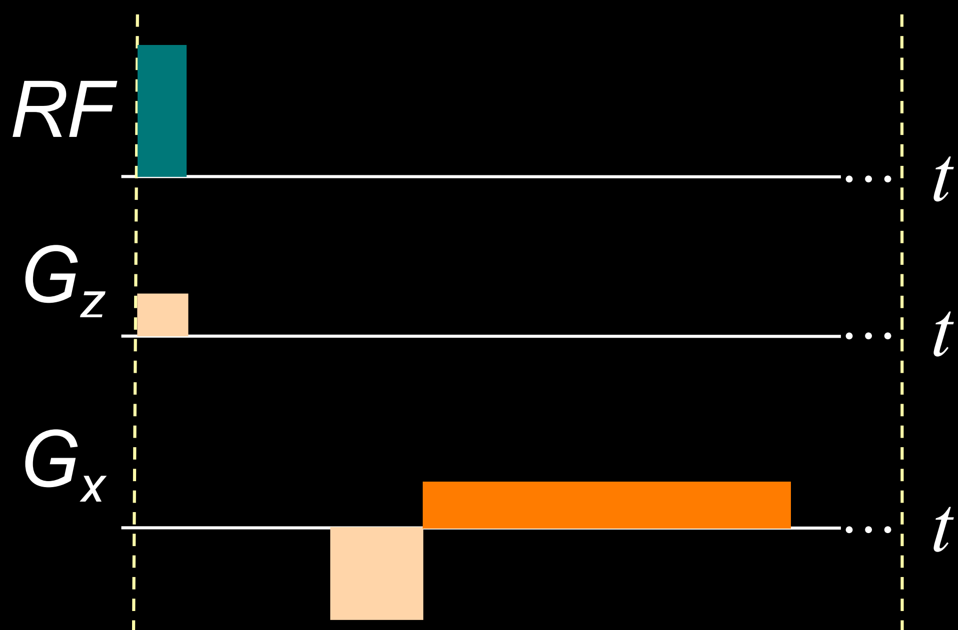
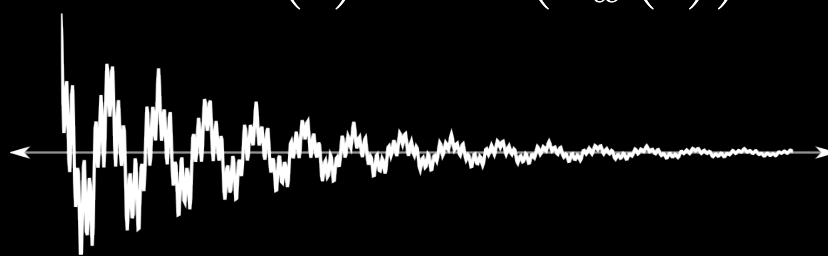


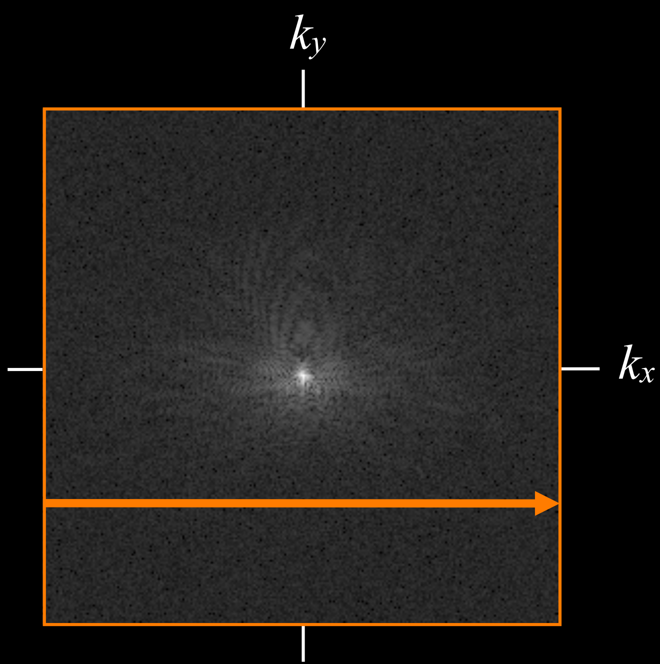
Pulse Sequence Diagram



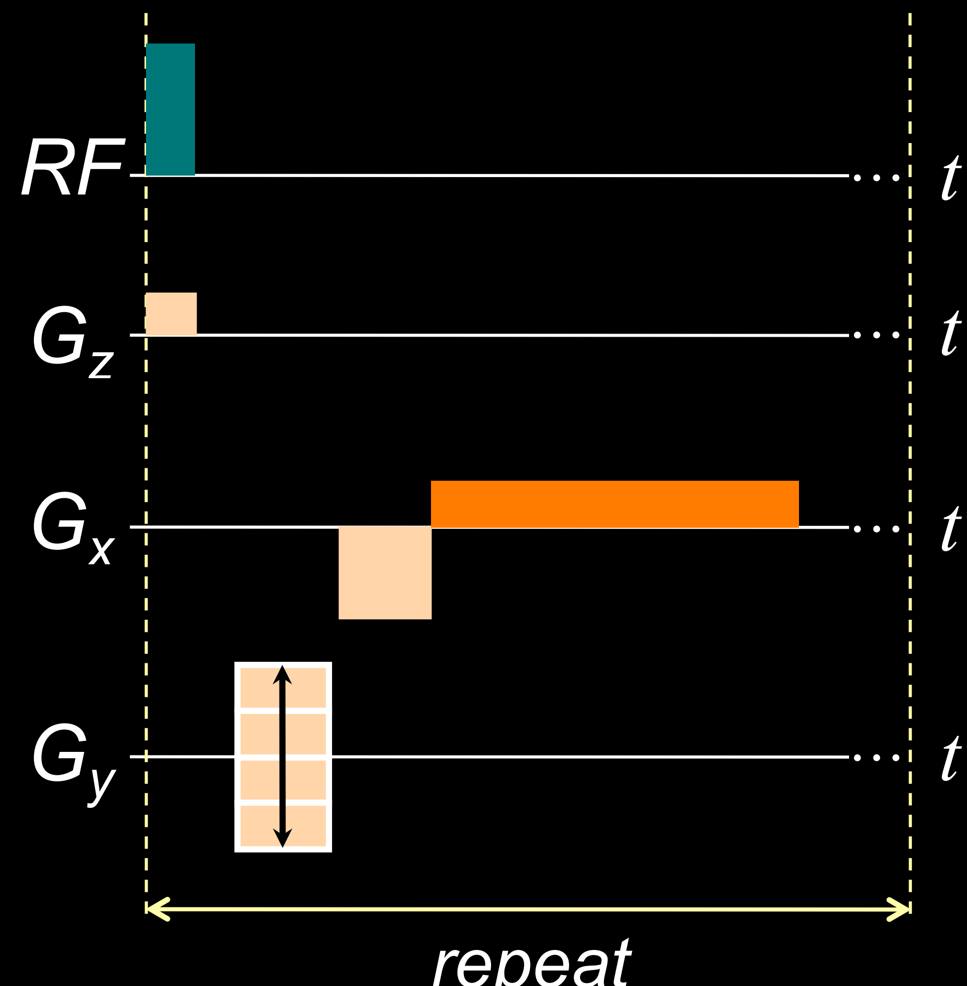
$$s(t) = m(k_x(t))$$



2D Imaging



$$s(t) = m(\, k_x(t), k_y(t) \,)$$



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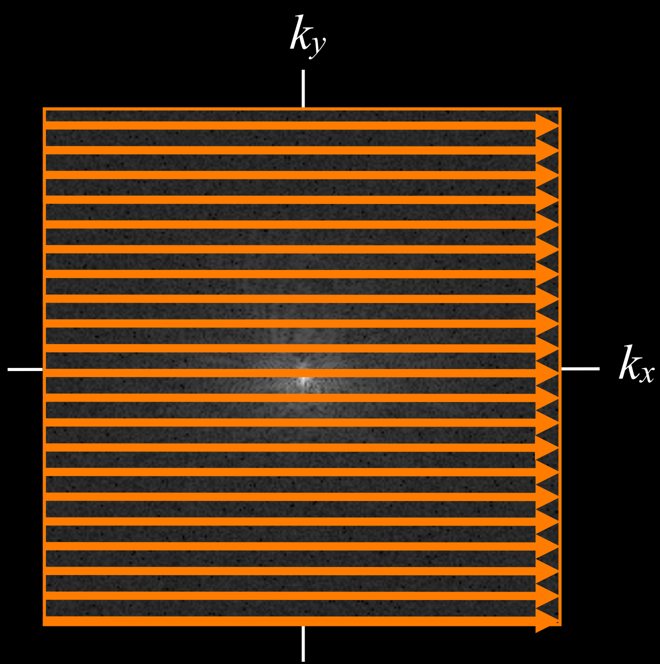

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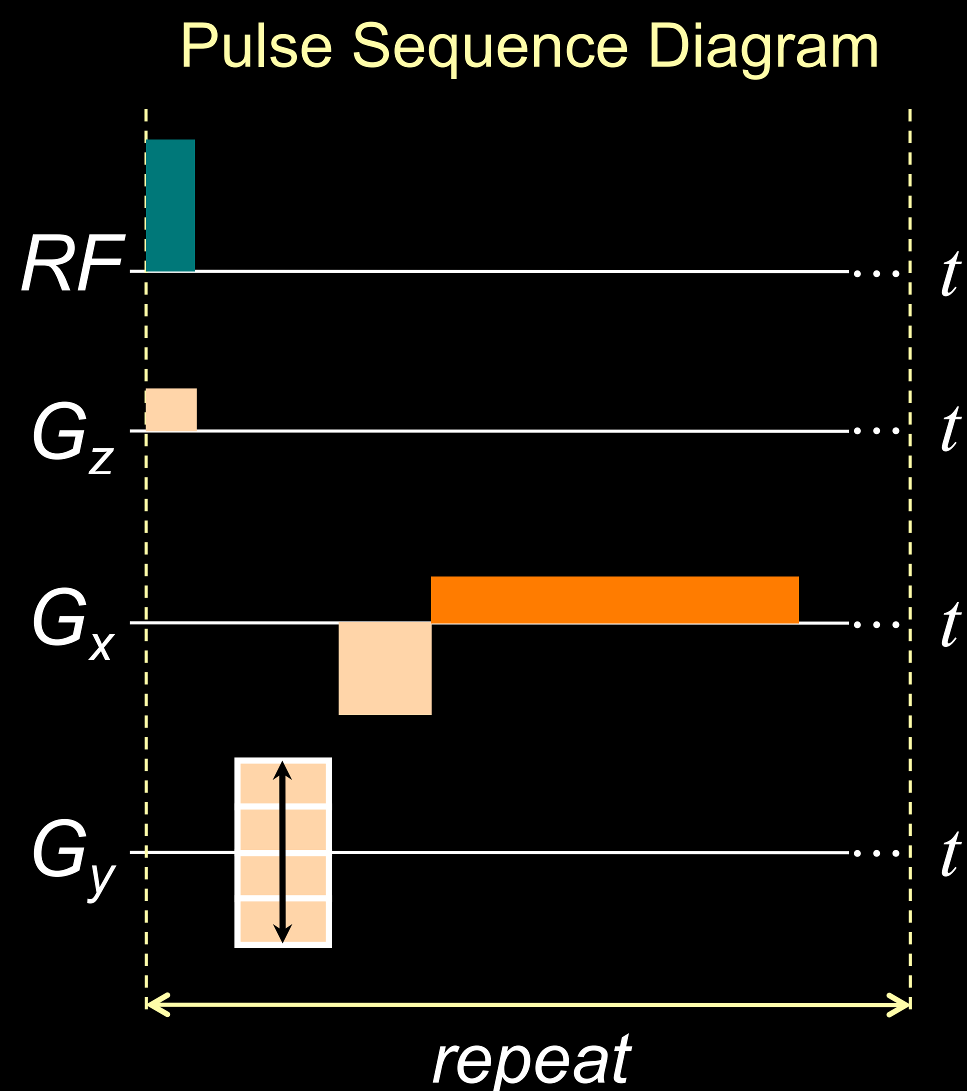

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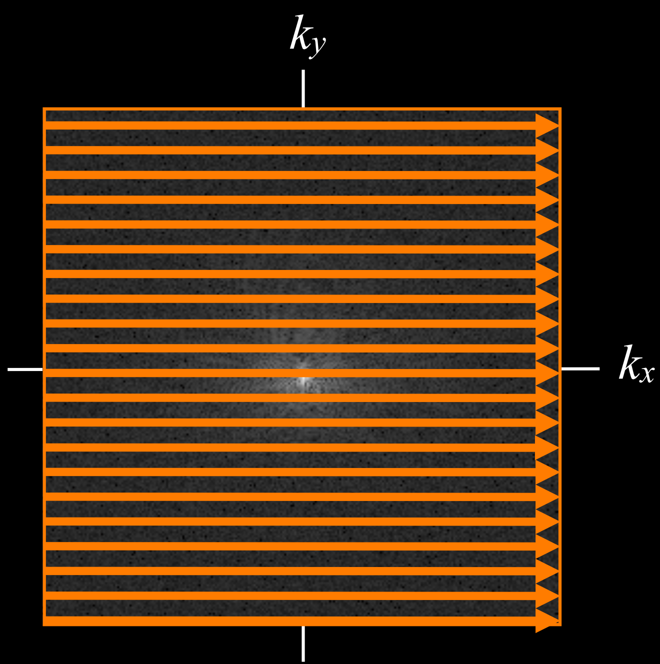
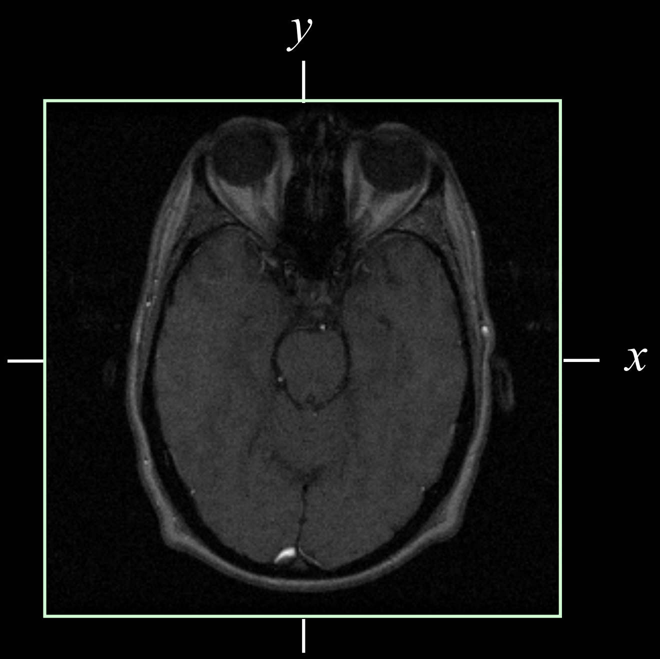
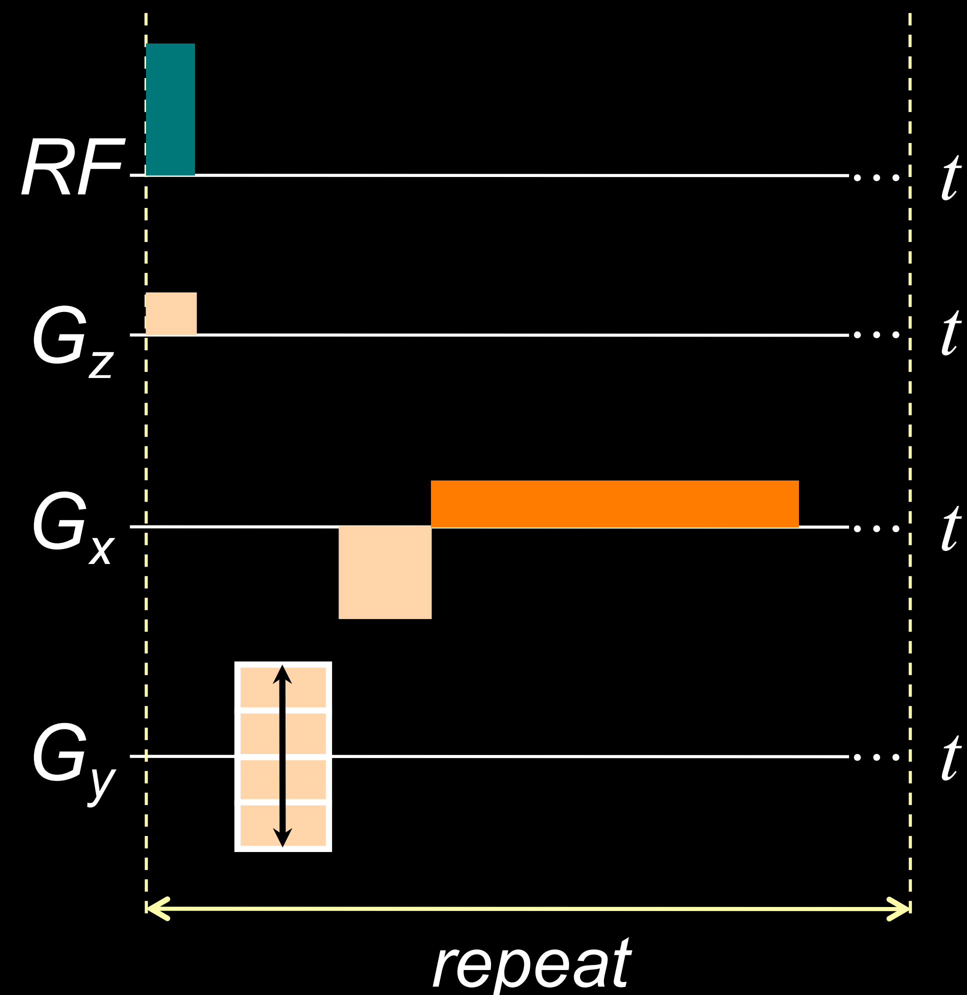


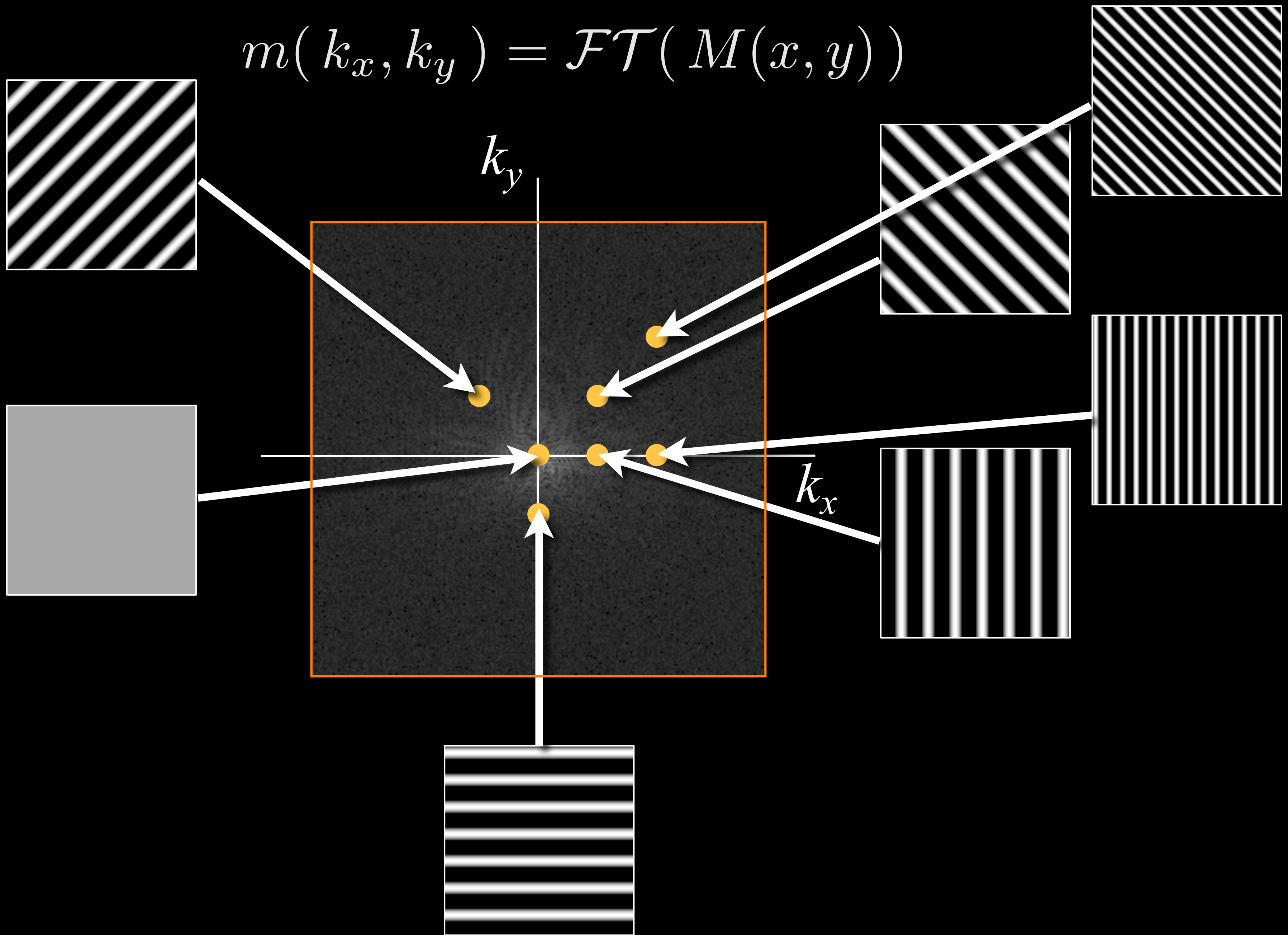


Pulse Sequence Diagram



2D k-Space: MRI Data

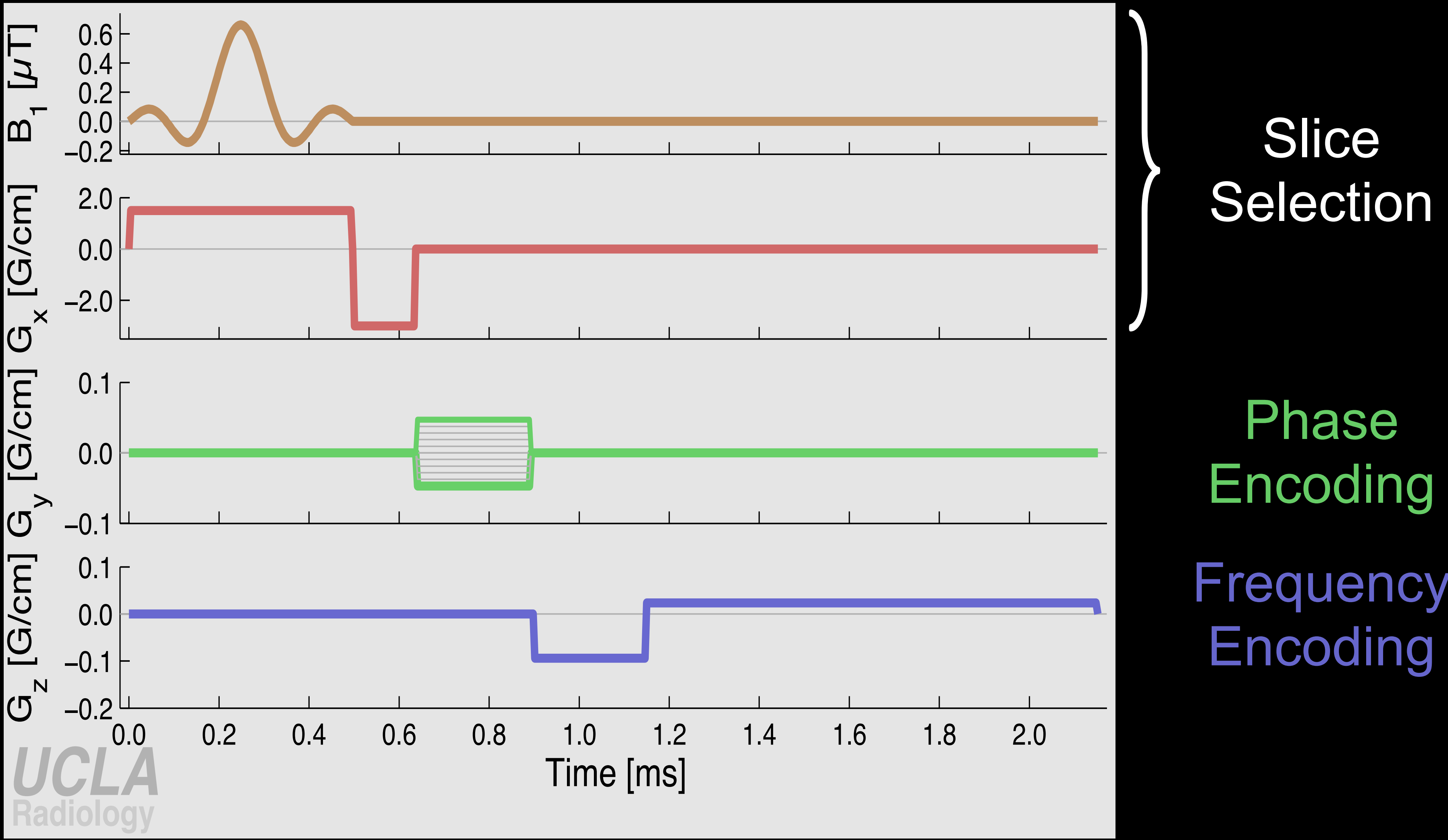
$$m(k_x, k_y) = \mathcal{FT}(M(x,y))$$



Spatial Encoding

- **Three key steps:**
  - **Slice selection**
    - You have to pick slice!
  - **Phase Encoding**
    - You have to encode 1 of 2 dimensions within the slice.
  - **Frequency Encoding (aka *readout*)**
    - You have to encode the other dimension within the slice.

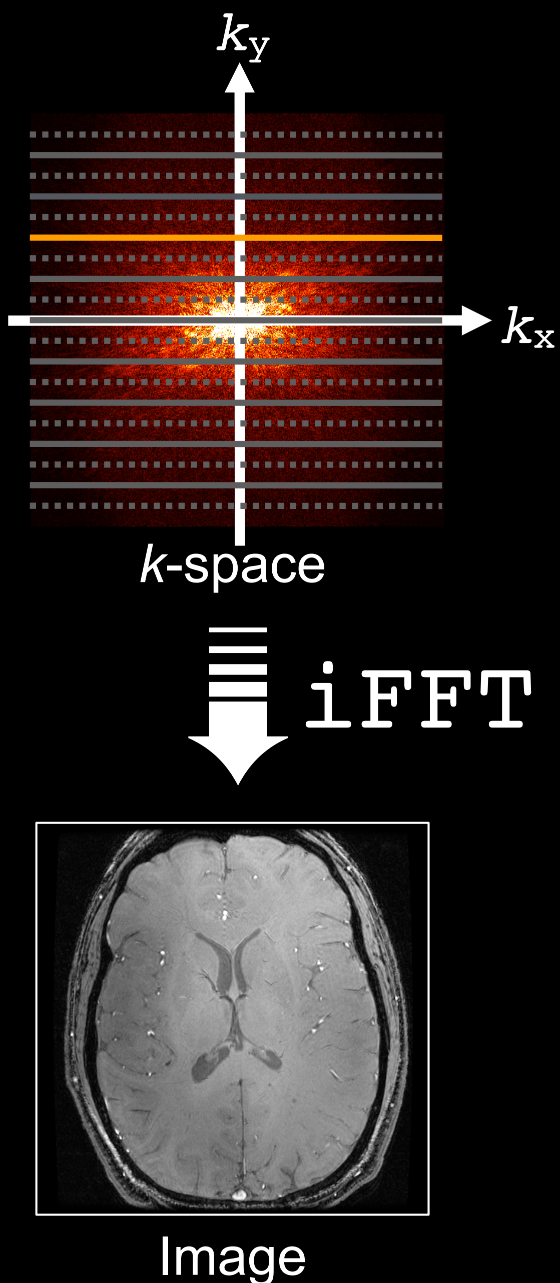
3 Steps for Spatial Localization

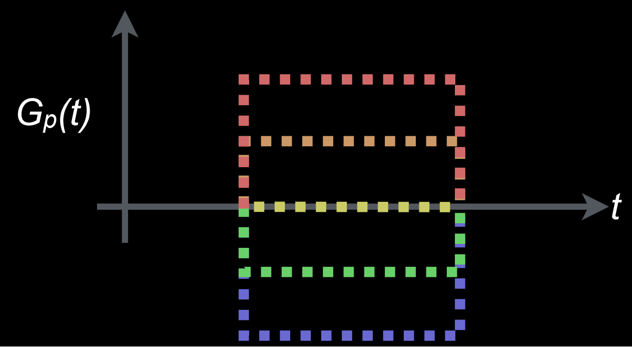


Pulse Sequence Diagram - Timing diagram of the RF and gradient events that comprise an MRI pulse sequence.

Phase Encoding

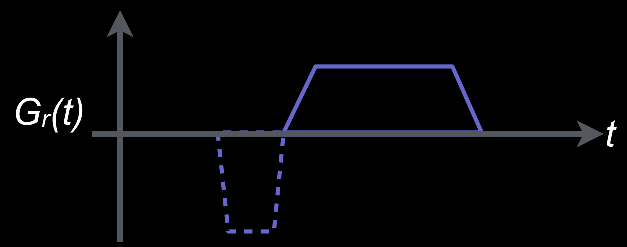
- **Consists of:**
  - **Phase encoding gradient**
    - **Magnitude changes with each TR**
    - **Can be played with other gradients**
      - **Crushers, Slice-selection rephaser, readout dephasing**
- **Used with Cartesian imaging**
- **After excitation, before readout**
- **Adds linear spatial variation of phase**
- **Phase encode in**
  - **one direction for 2D imaging**
  - **two directions for 3D imaging**
- **Only one PE step per echo**



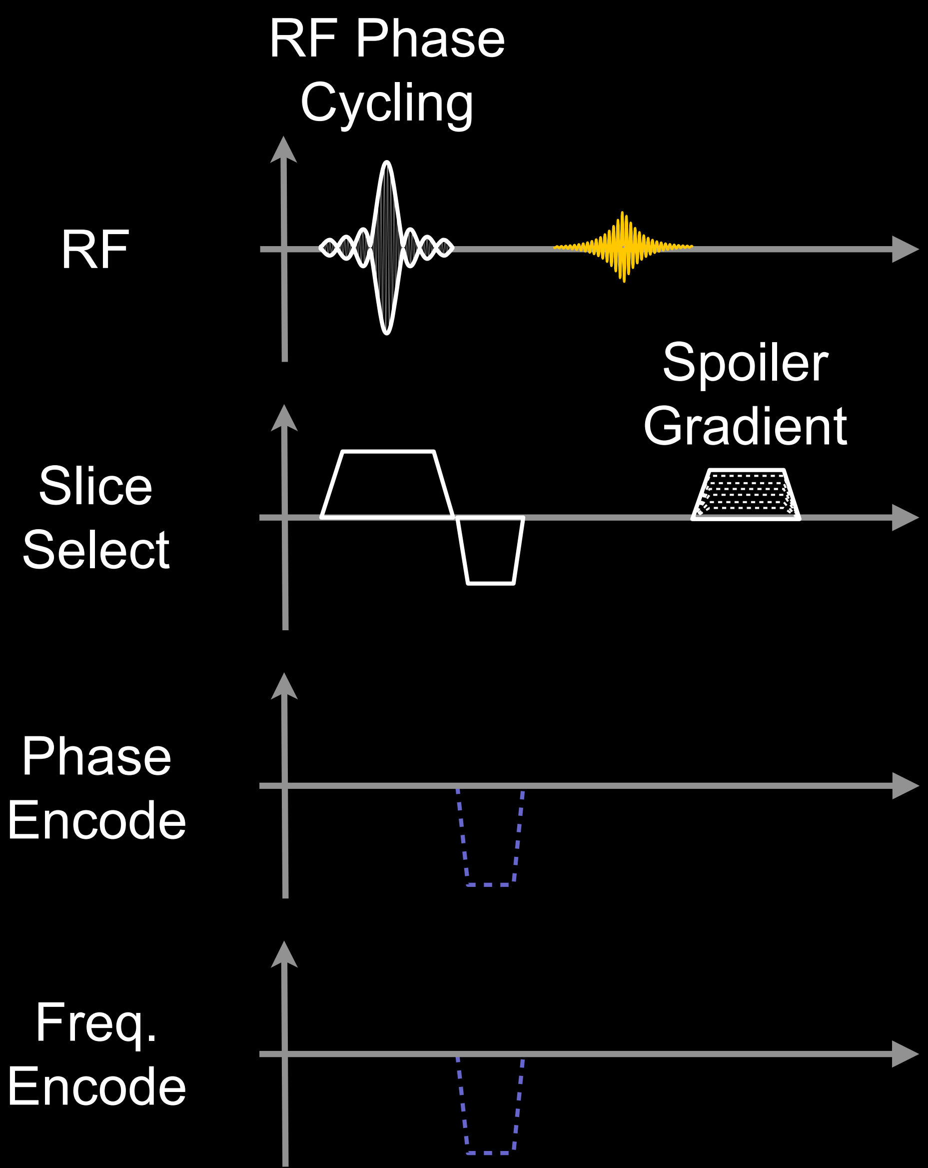


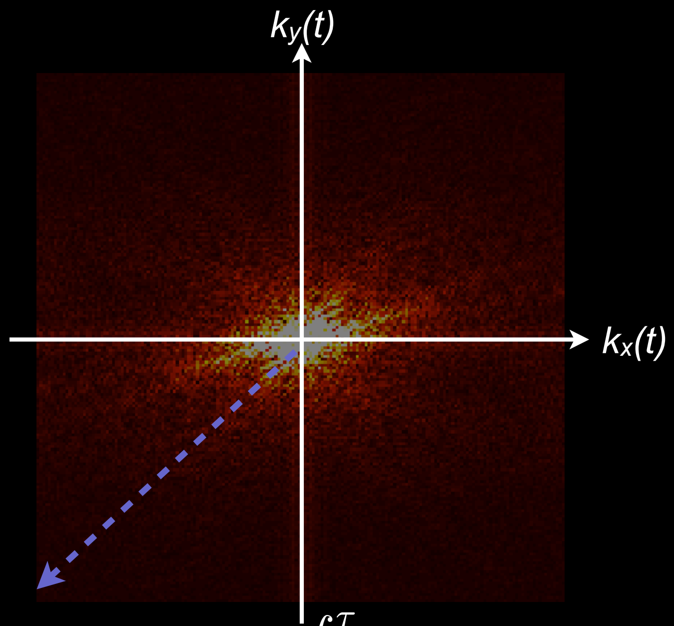
Frequency Encoding

- **Consists of:**
  - **Frequency encoding gradient**
    - **Constant magnitude for Cartesian imaging**
  - **No simultaneous**
    - **RF (B_1)**
    - **Other gradients**
      - **phase encoding, slice encoding, crushers**
  - **Readout pre-phasing gradient**
    - **Prepares spin phase so peak echo amplitude occurs at middle of readout (TE)**
    - **AKA "readout de-phasing gradient"**
- **Adds linear spatial variation of frequency**
- **Helps form an *echo***

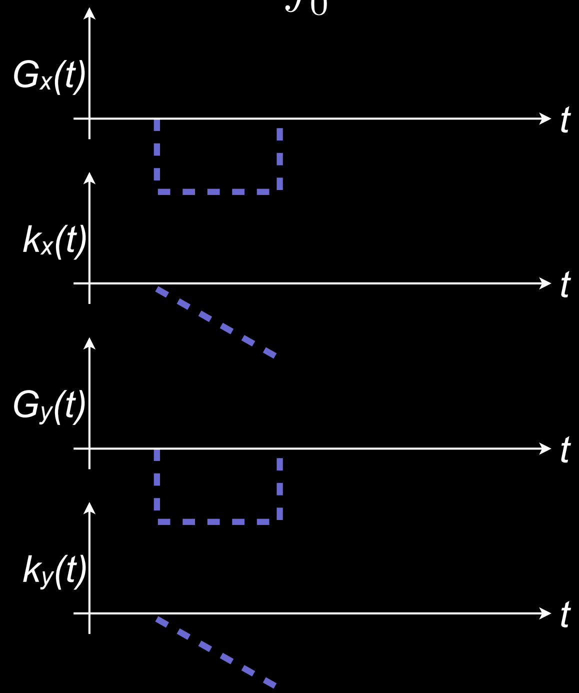


Where am I in *k*-space?





$$\vec{k}(t) = \frac{\gamma}{2\pi} \int_0^{\tau} \vec{G}(t)\, d\tau$$



One phase encoded echo is acquired per TR.

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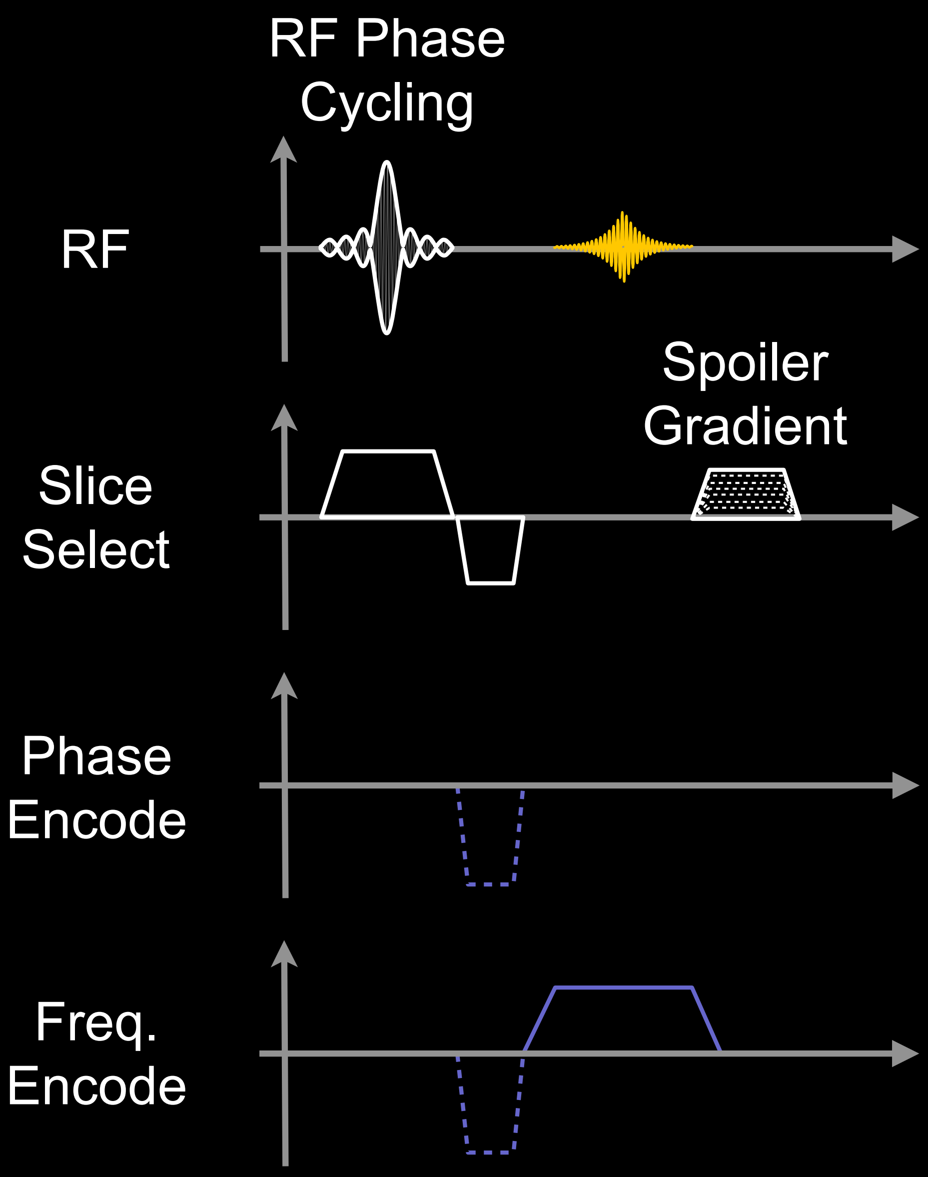

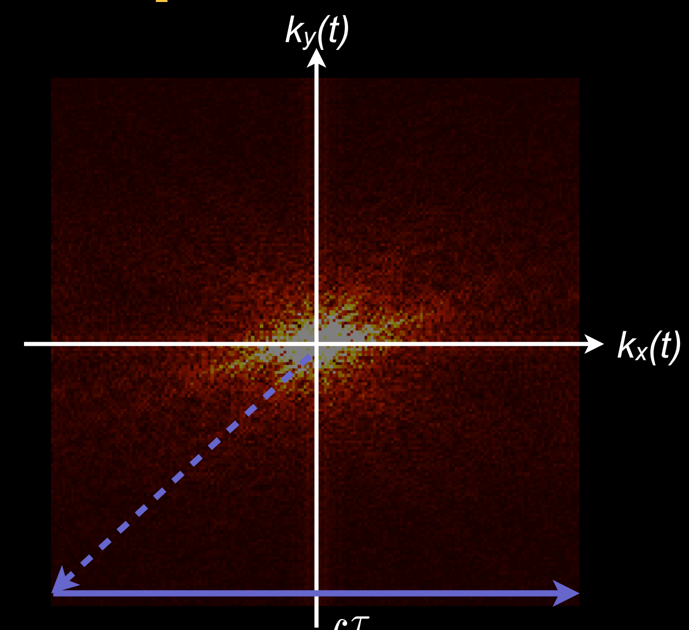

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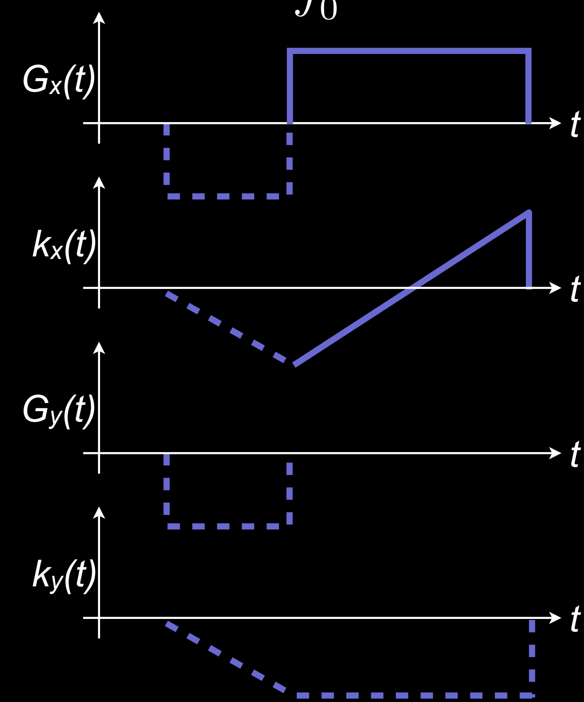

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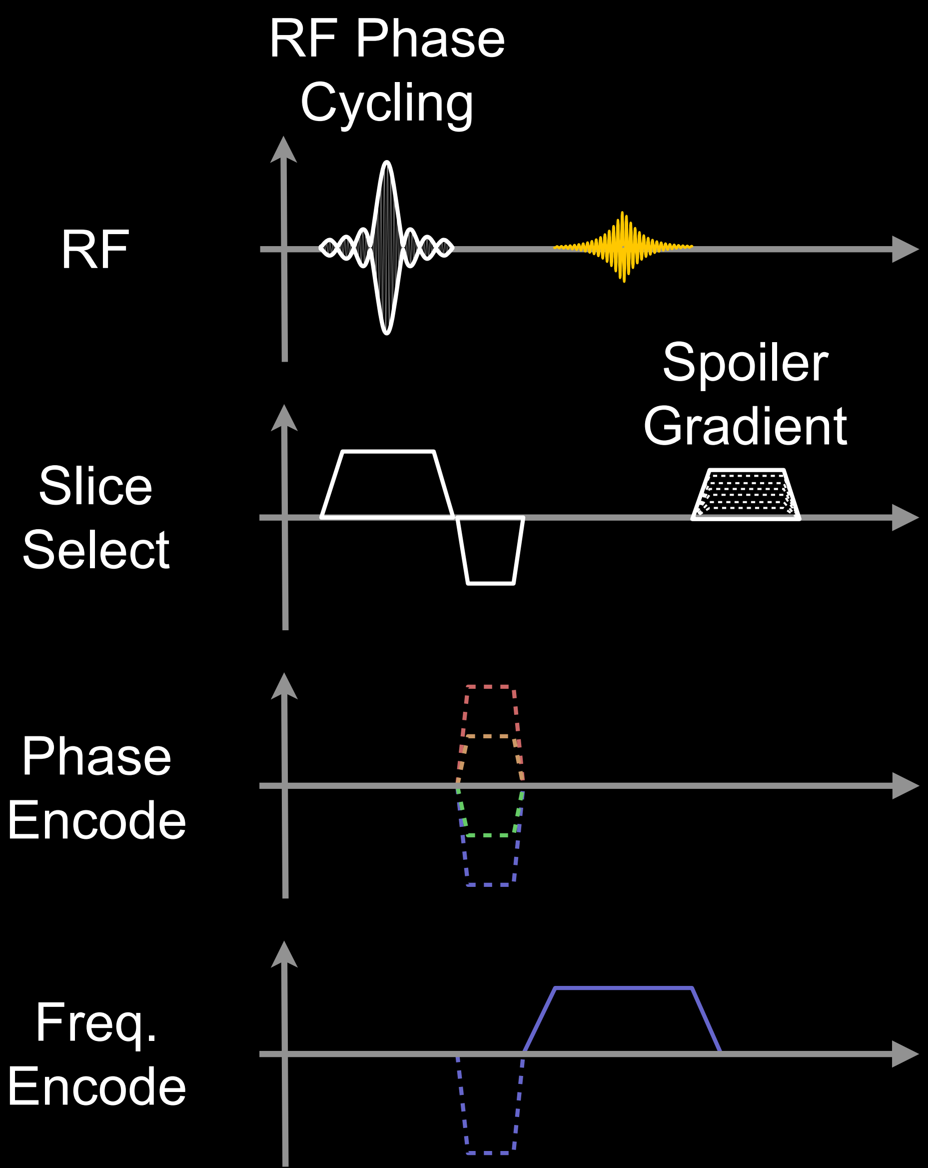

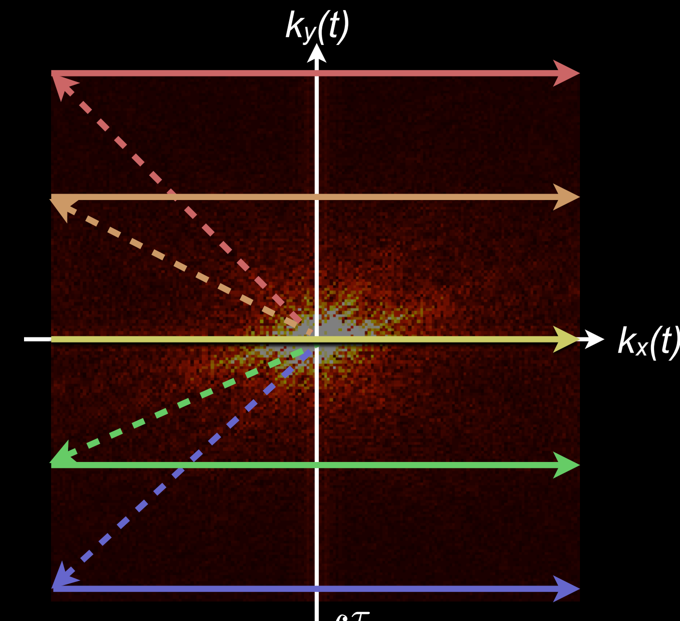

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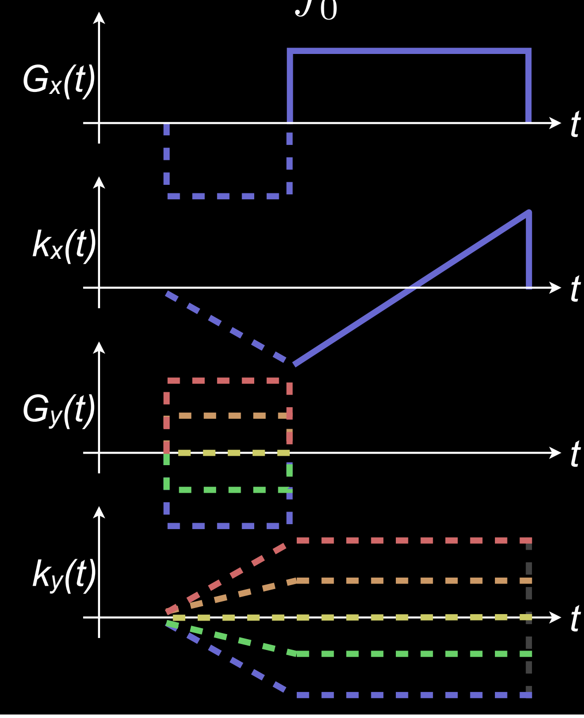

One phase encoded echo is acquired per TR.

Questions?

- Related reading materials
  - Nishimura - Chap 5

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http://mrrl.ucla.edu/sunglab