Advanced MRI and fMRI Acquisition Methods

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Functional MRI Facility

National Institutes of Health

National Institute of Mental Health

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Outline

- NMR: Review of physics basics
- MR Imaging: tools and techniques
- K-space trajectories
- Controlling the image contrast
- Other stuff ...

Outline

- NMR: Review of physics basics
  - Classical view of NMR
  - Excitation and reception of MR signals
  - Relaxation: M_0, T_1, T_2. Bloch Equations.
  - Modes of NMR evolution: FID, spin-echo
- MR Imaging: tools and techniques
- K-space trajectories
- Controlling the image contrast
- Other stuff...

NMR: Classical view

NMR: Nuclear Magnetic Resonance

- Effect is due to intrinsic spin of positively charged atomic nuclei of atoms.
- In the presence of an external magnetic field the nuclei absorb and re-emit electromagnetic radiation
- The radiation at a specific resonance frequency

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- The radiation at a specific resonance frequency

$$\omega = \gamma B$$

- ω : angular frequency. $\omega = 2\pi\nu$
- γ : gyromagnetic ratio
- B : strength of the external magnetic field

NMR: Classical view

NMR: Nuclear Magnetic Resonance

- $\omega = \gamma B$
- For ^{1}H (aka protons): $\bar{\gamma} = 42.58$ MHz / T
  where $\bar{\gamma} = \gamma / 2\pi$
- Magnetization is a vector:

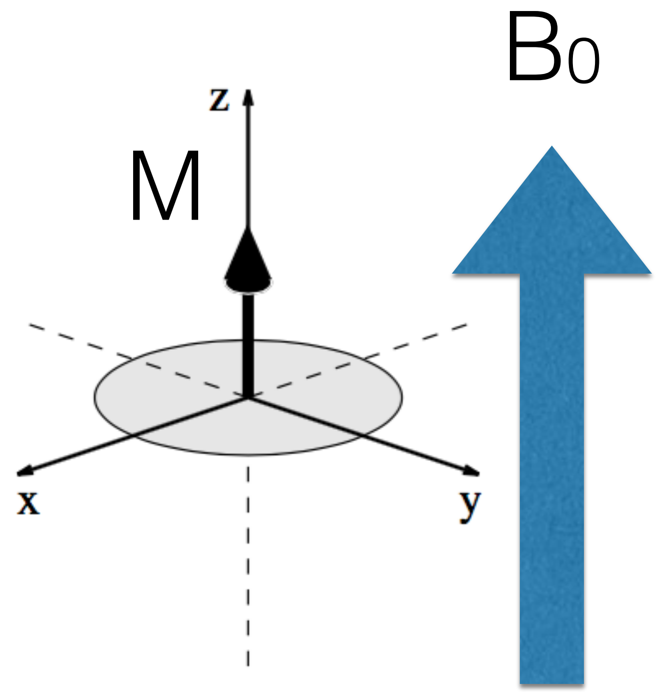
$$\mathbf{M} = (M_x, M_y, M_z)^T$$

- At equilibrium:

$$\mathbf{M} = (0, 0, M_0)^T$$

where

$$\frac{M_0 = N\gamma\hbar^2 I_z(I_z + 1)B_0}{3kT}$$



NMR: Classical view

NMR: Nuclear Magnetic Resonance

1.5T: 63MHz
3.0T: 127MHz
7.0T: 298MHz

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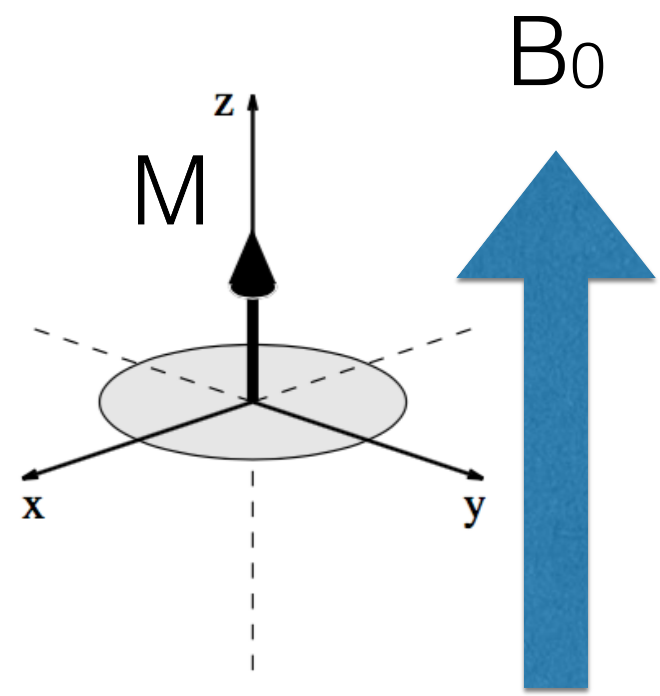
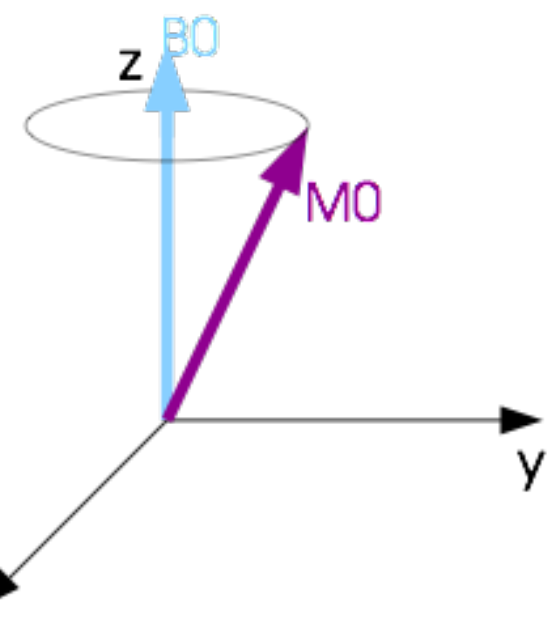


NMR: Classical view

Excitation, Precession and the Rotating Frame

- Excitation is the process of tipping the magnetization away from the direction of the main magnetic field.
- Once excited, the magnetization precesses around the magnetic field with angular frequency

$$\omega = \gamma B$$



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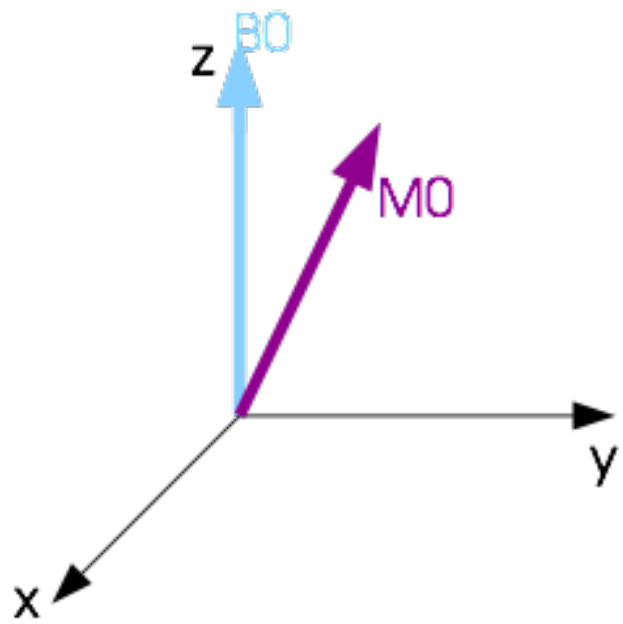
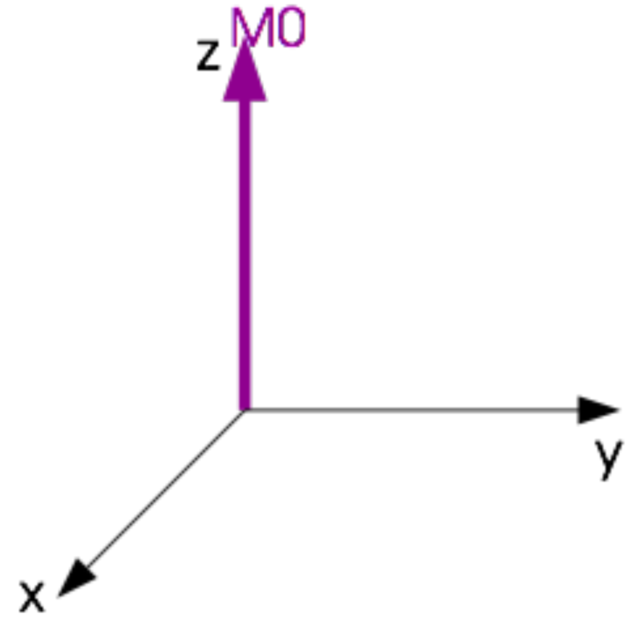
- It is convenient to work in a frame of reference rotating at $\omega = \gamma B$



NMR: Classical view

Excitation, Precession and the Rotating Frame

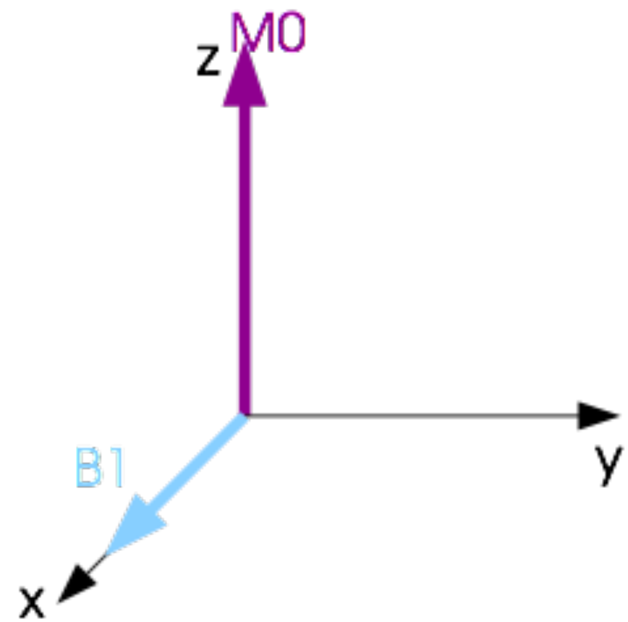
- In rotating frame at equilibrium



NMR: Classical view

Excitation, Precession and the Rotating Frame

- In rotating frame at equilibrium
- Apply B_1 magnetic field along (rotating frame) x-axis



NMR: Classical view

Excitation, Precession and the Rotating Frame

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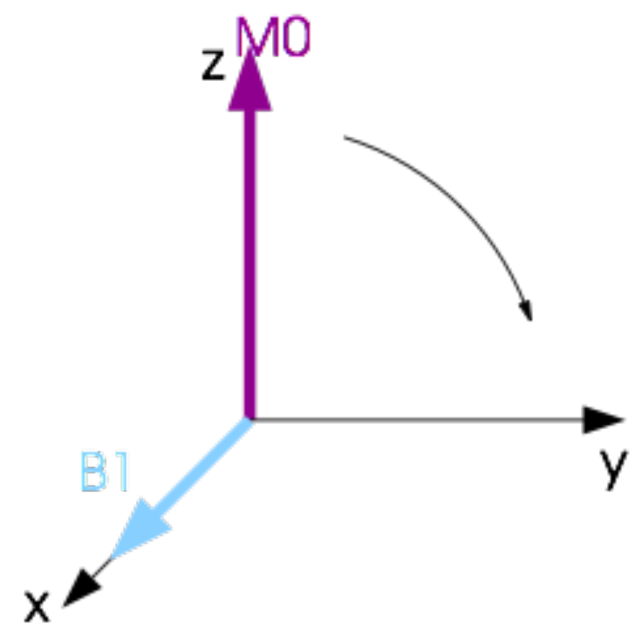
- $\omega_1 = \gamma B_1$
- Magnetization rotates towards (rotating-frame) y-axis



NMR: Classical view

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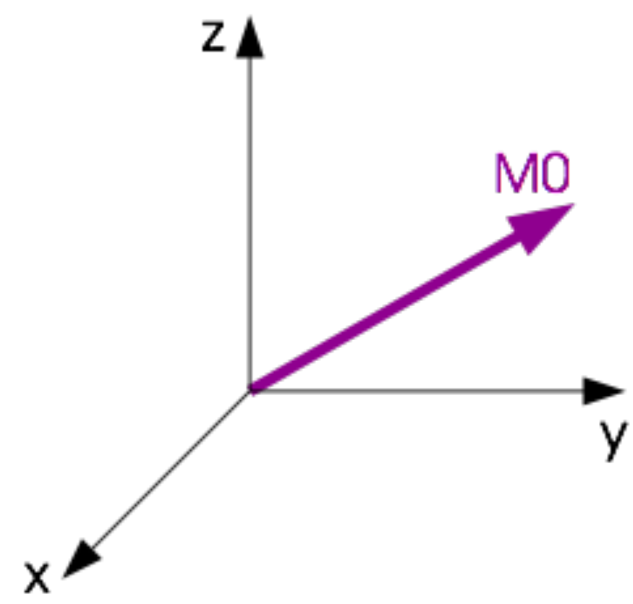
- Turn off B1 field when magnetization reaches the appropriate flip angle with respect to the z-axis



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- $\omega_1 = \gamma B_1$
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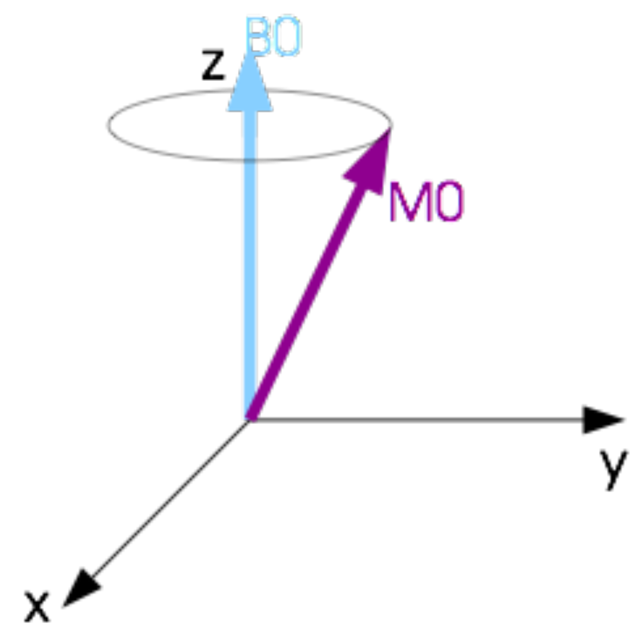
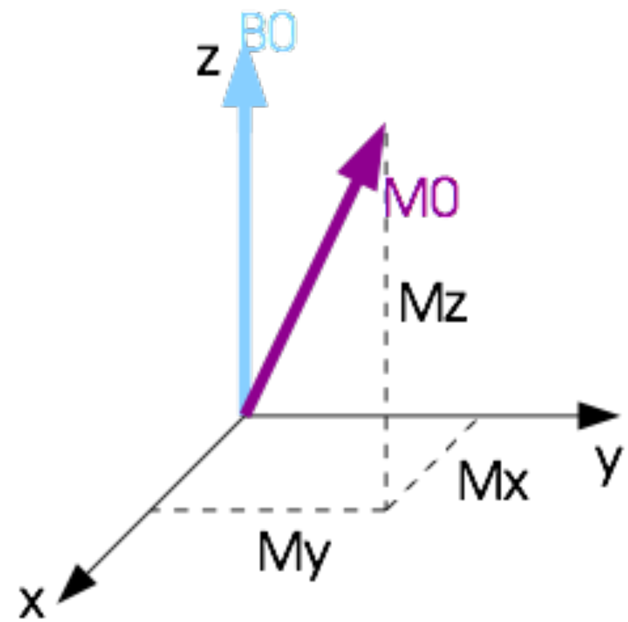
- Turn off B1 field when magnetization reaches the appropriate flip angle with respect to the z-axis
- Magnetization precesses and relaxes back to equilibrium



NMR: Classical view

MR signal

- $\mathbf{M} = (M_x, M_y, M_z)^T$
- M_z is the longitudinal component
- M_x, M_y are transverse components



NMR: Classical view

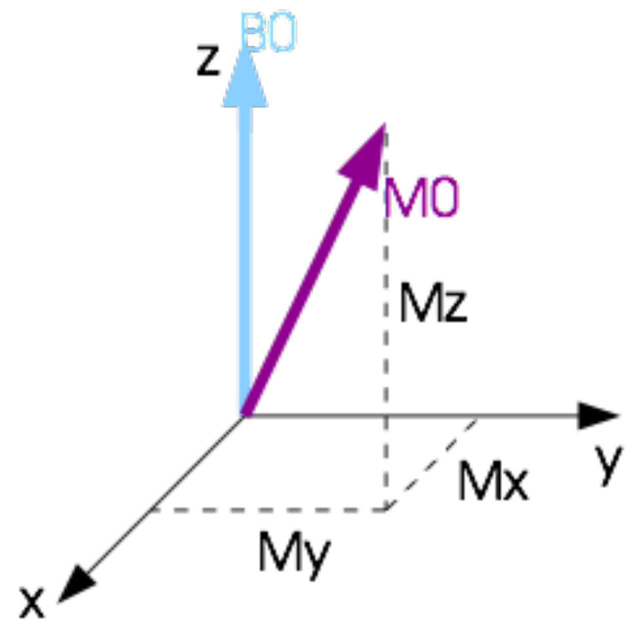
MR signal

- **M** = $(M_x, M_y, M_z)^T$
- M_z is the longitudinal component
- M_x, M_y are transverse components

- NMR signal is proportional to M_{xy} where:

$$M_{xy} = M_x + iM_y$$

- M_{xy} is considered to be a complex-valued signal induced in the receiver coil



NMR: Classical view

MR relaxation

- M_z is the longitudinal component of **M**
- After excitation M_z relaxes back to M_0 by T_1 relaxation

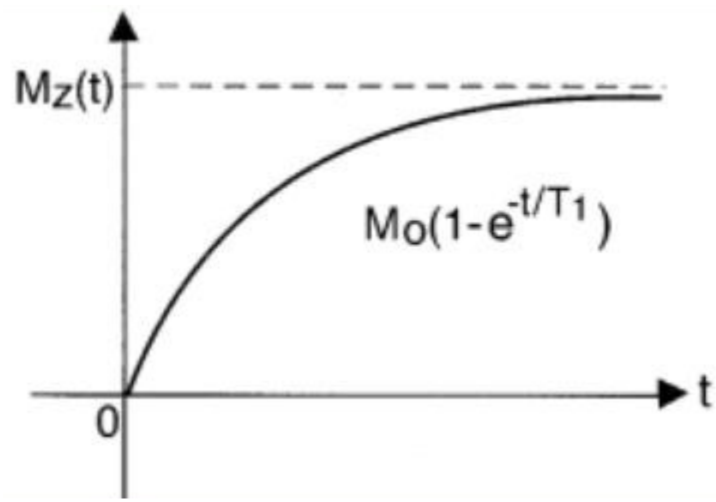
$$\frac{dM_z}{dt} = \frac{(M_0 - M_z)}{T_1}$$

- So that:

$$M_z(t) = M_0 + (M_z(0) - M_0)e^{-t/T1}$$

- or, equivalently

$$M_z(t) = M_z(0)e^{-t/T1} + M_0(1 - e^{-t/T1})$$



NMR: Classical view

MR relaxation

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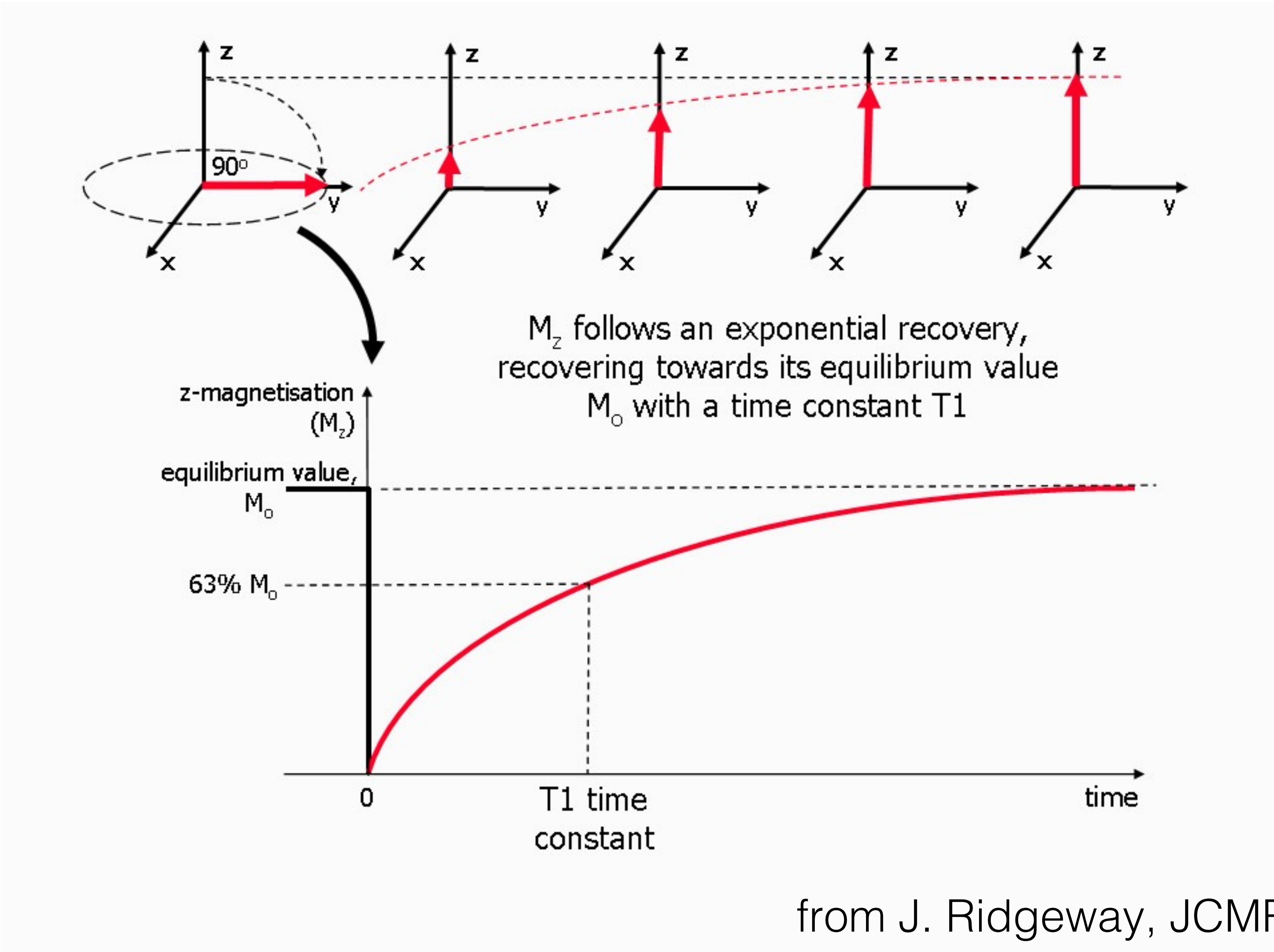


from J. Ridgeway, JCMR, **12**:71, 2010

NMR: Classical view

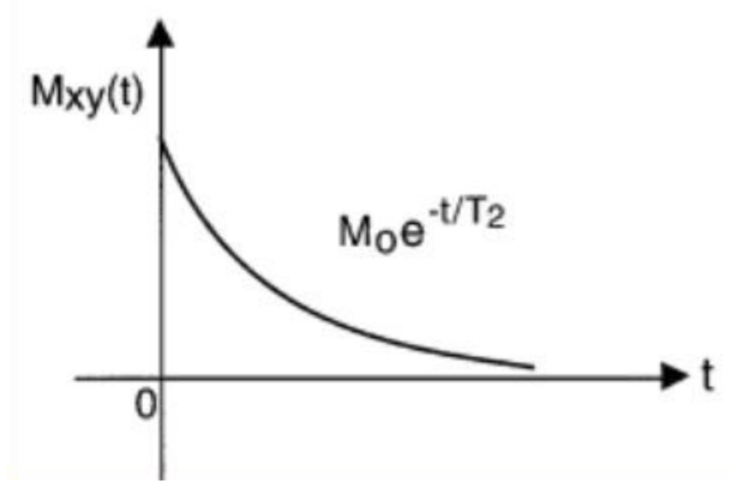
MR relaxation

- M_{xy} is the transverse component of **M**
- After excitation M_{xy} relaxes back to zero by T_2 relaxation

$$\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T_2}$$

- So that:

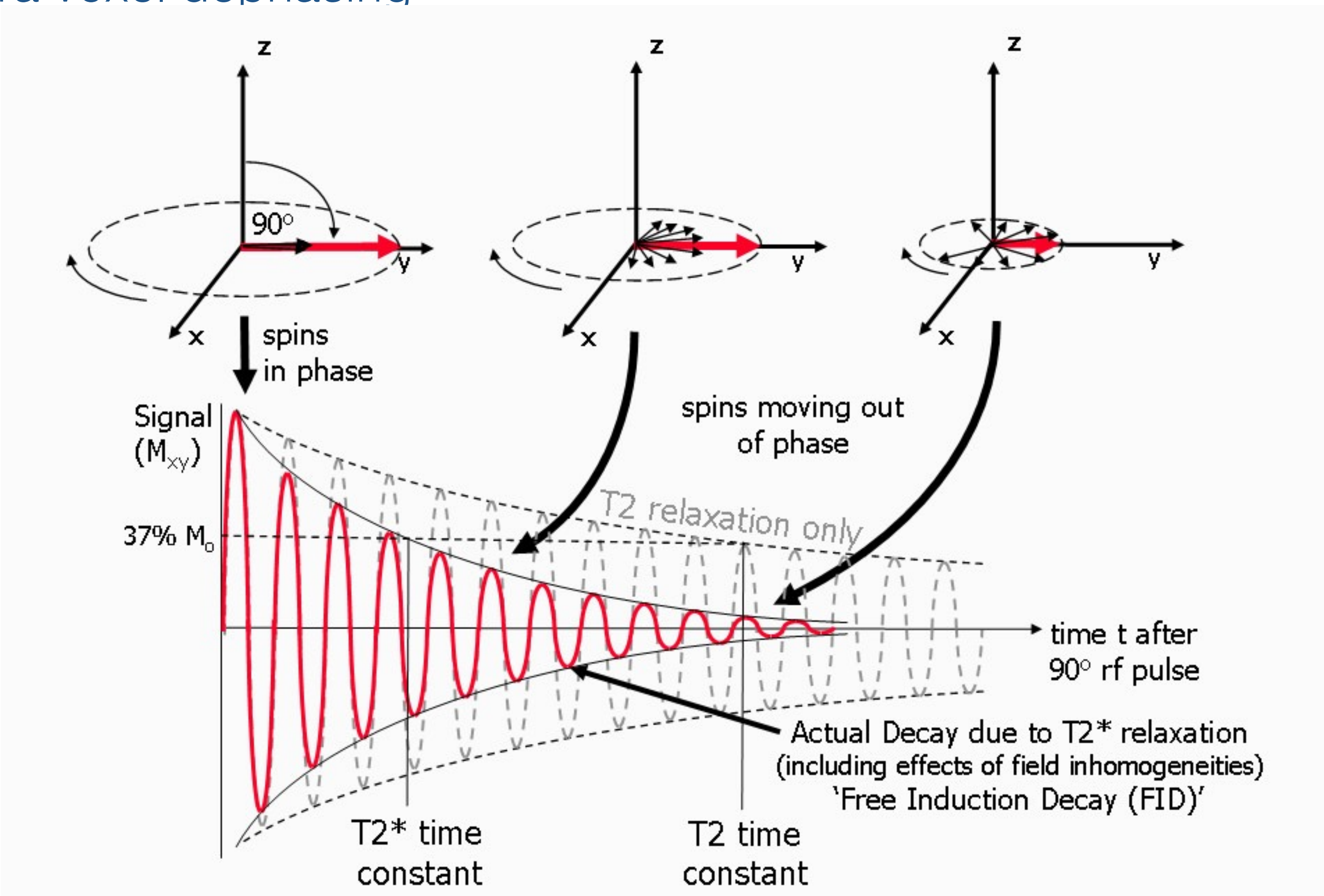
$$M_{xy}(t) = M_{xy}(0)e^{-t/T_2}$$



- Note that $T_2 <= T_1$ so that the MR signal generally dies faster than Mz regrows.

NMR: Classical view

Intra voxel dephasing



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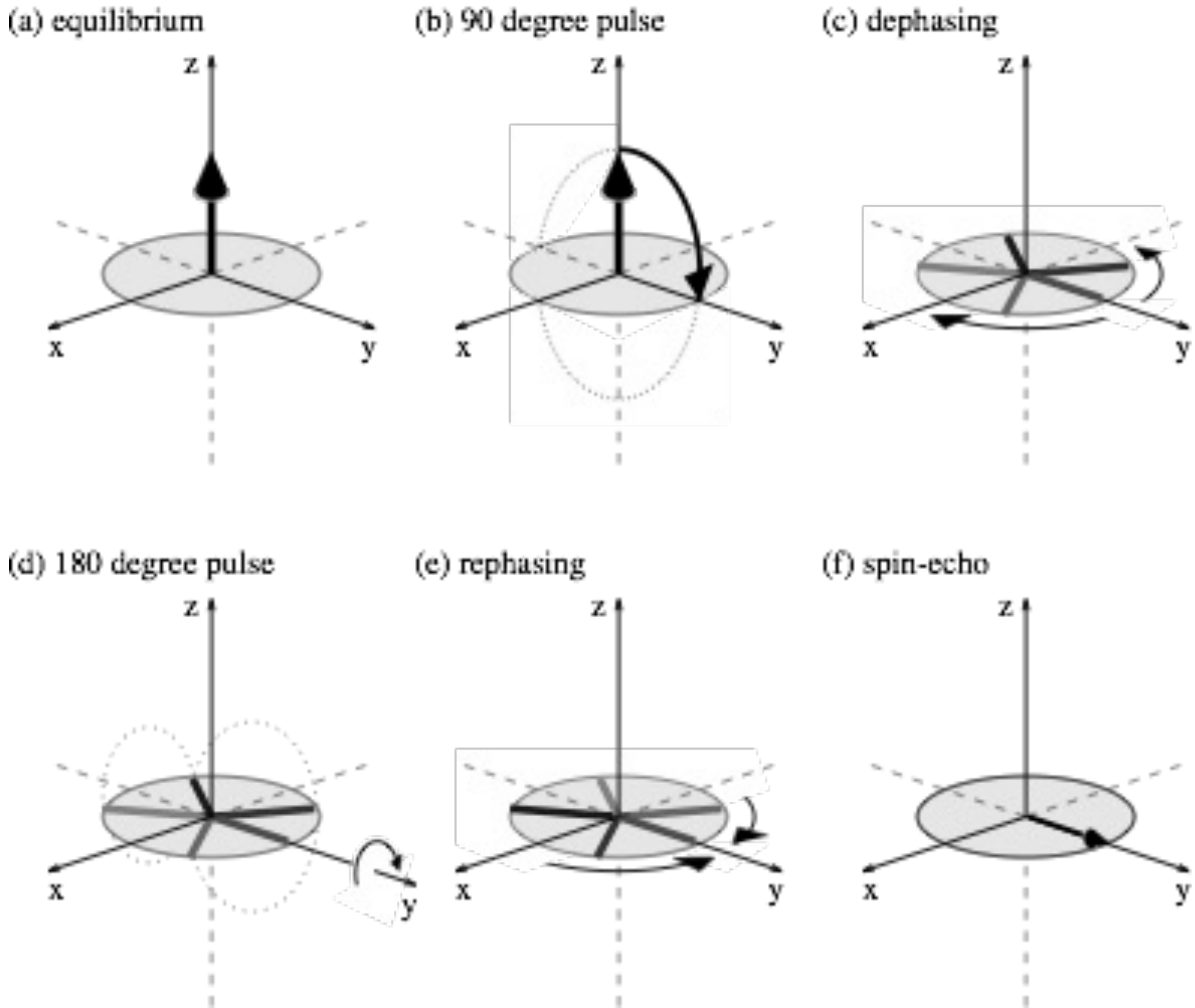
NMR: Classical view

Spin-echo



Outline

- NMR: Review of physics basics
- MR Imaging: tools and techniques
  - Gradients
  - Selective excitation
  - Gradient echo
- K-space trajectories
- Controlling the image contrast
- Other stuff

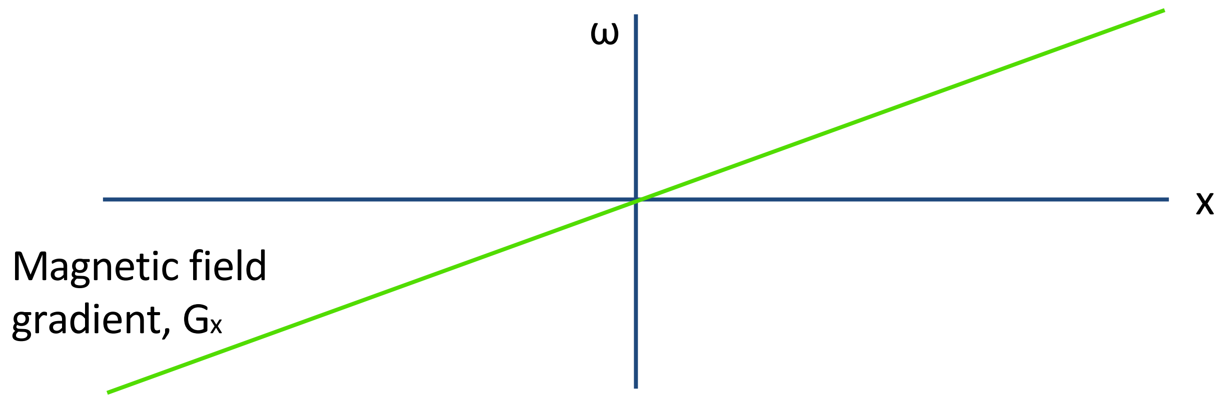
Gradients

- MR image formation is based on the equation: $\omega = \gamma B$
- In the main magnetic field, B_0, we have: $\omega_0 = \gamma B_0$
- Superimpose a spatial magnetic field gradient,

$$\mathbf{G} = (G_x\ ,\ G_z\ ,\ G_z\ )^T$$

then:

$$\omega = \gamma(G_x x + G_z y + G_z z) = \mathbf{G.r}$$



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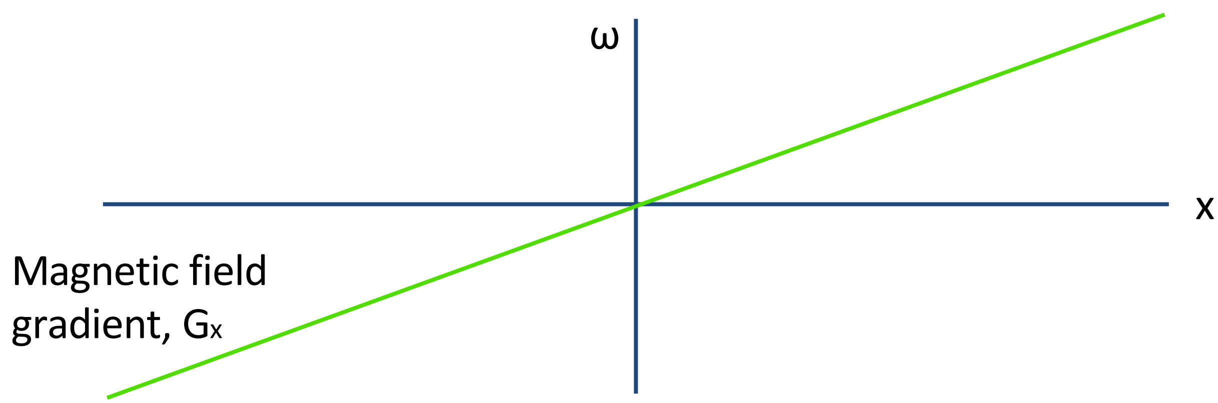
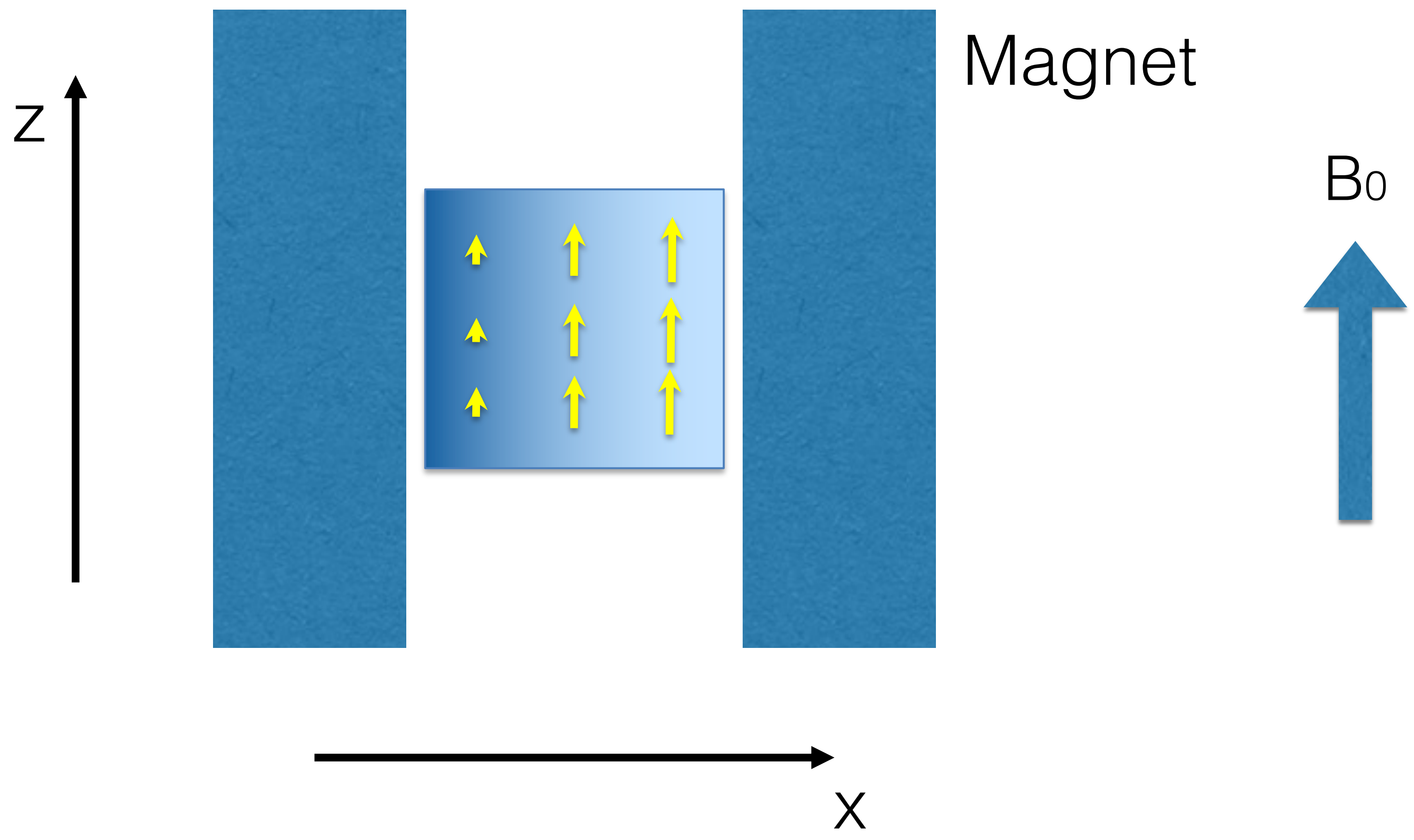


- Typical gradient fields are G = 30mT/m.
  i.e. +/-3mT at 10cm from isocenter.
- 1000 times smaller than B_0

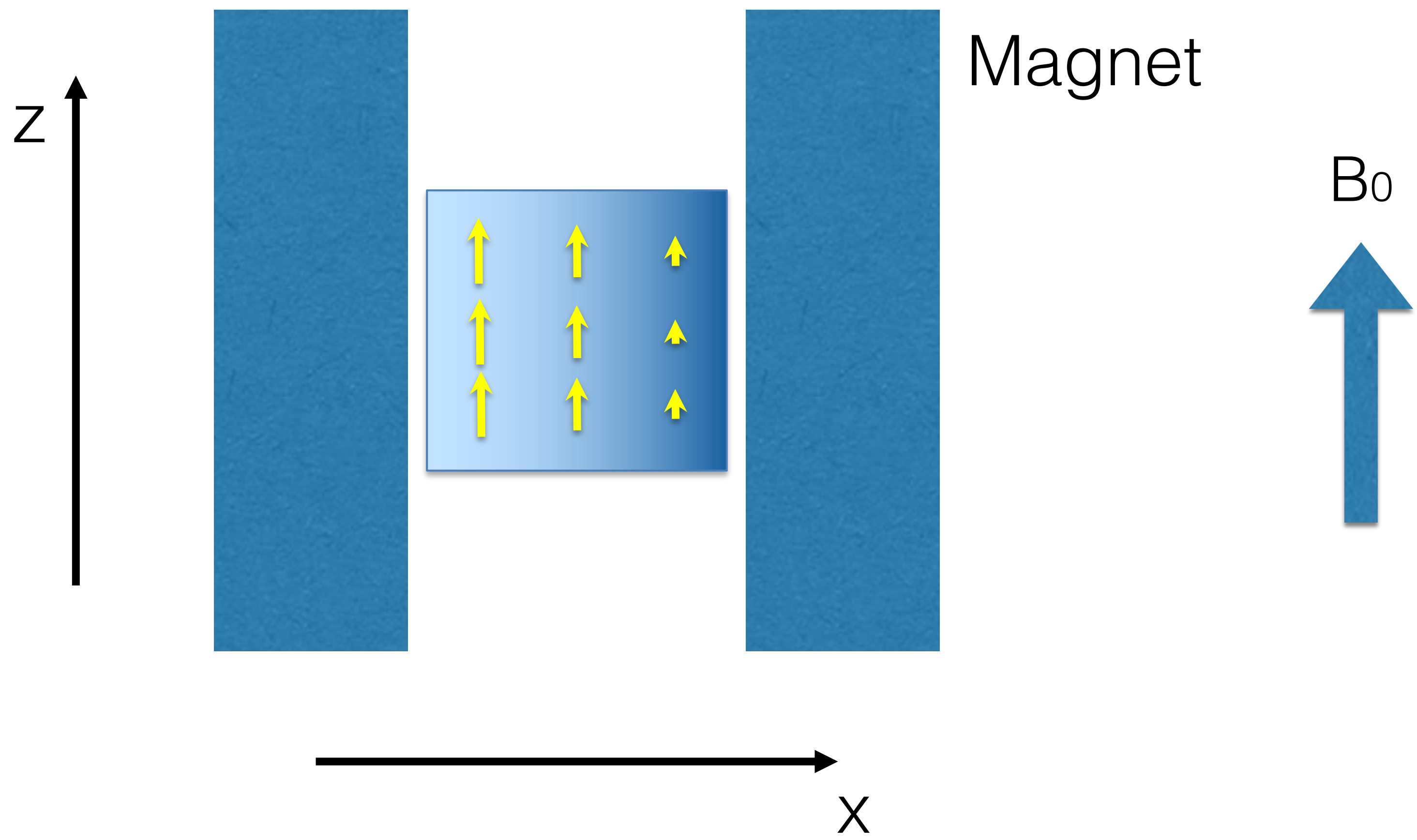
Gradients

- Gradient in +X



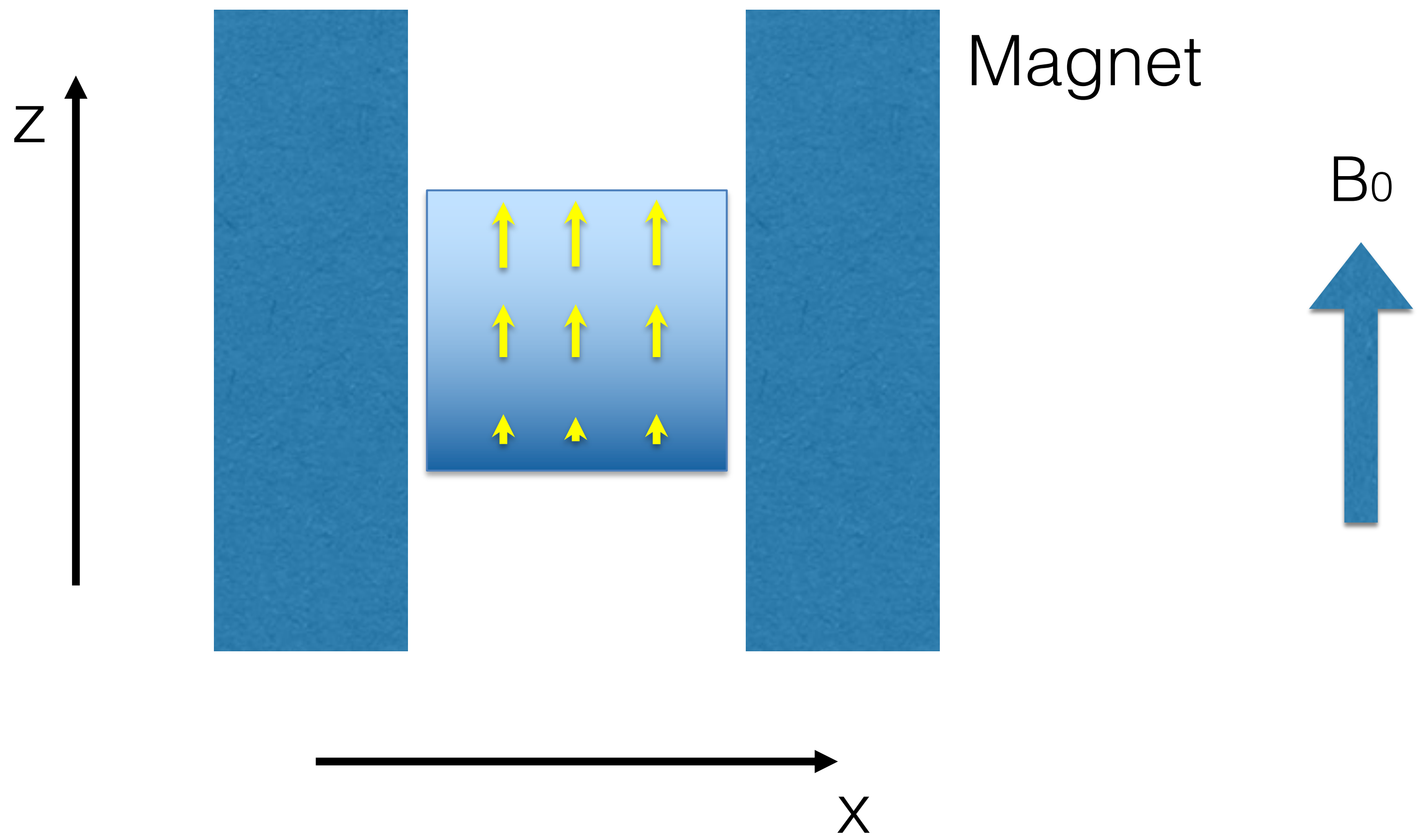
Gradients

- Gradient in -X



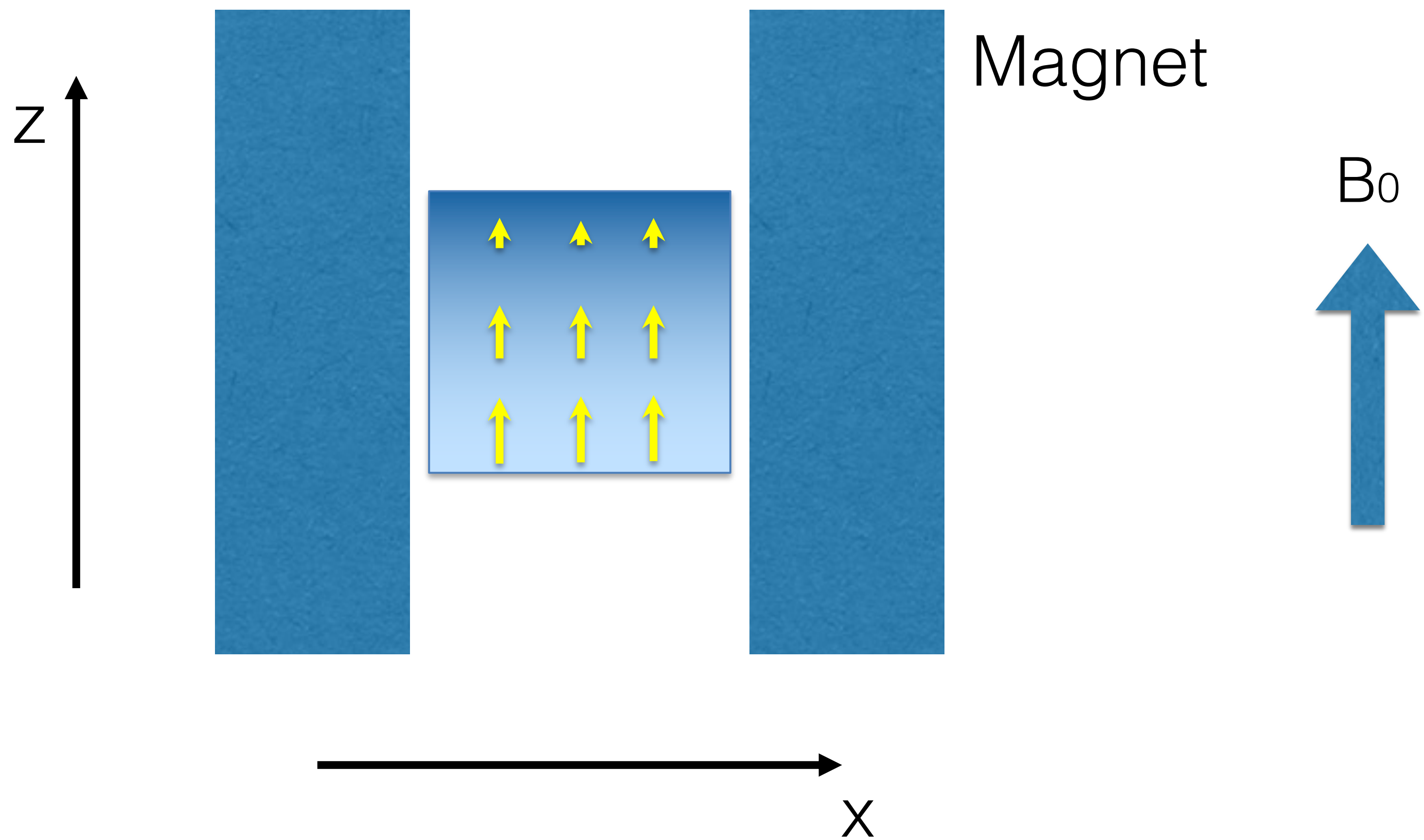
Gradients

- Gradient in +Z



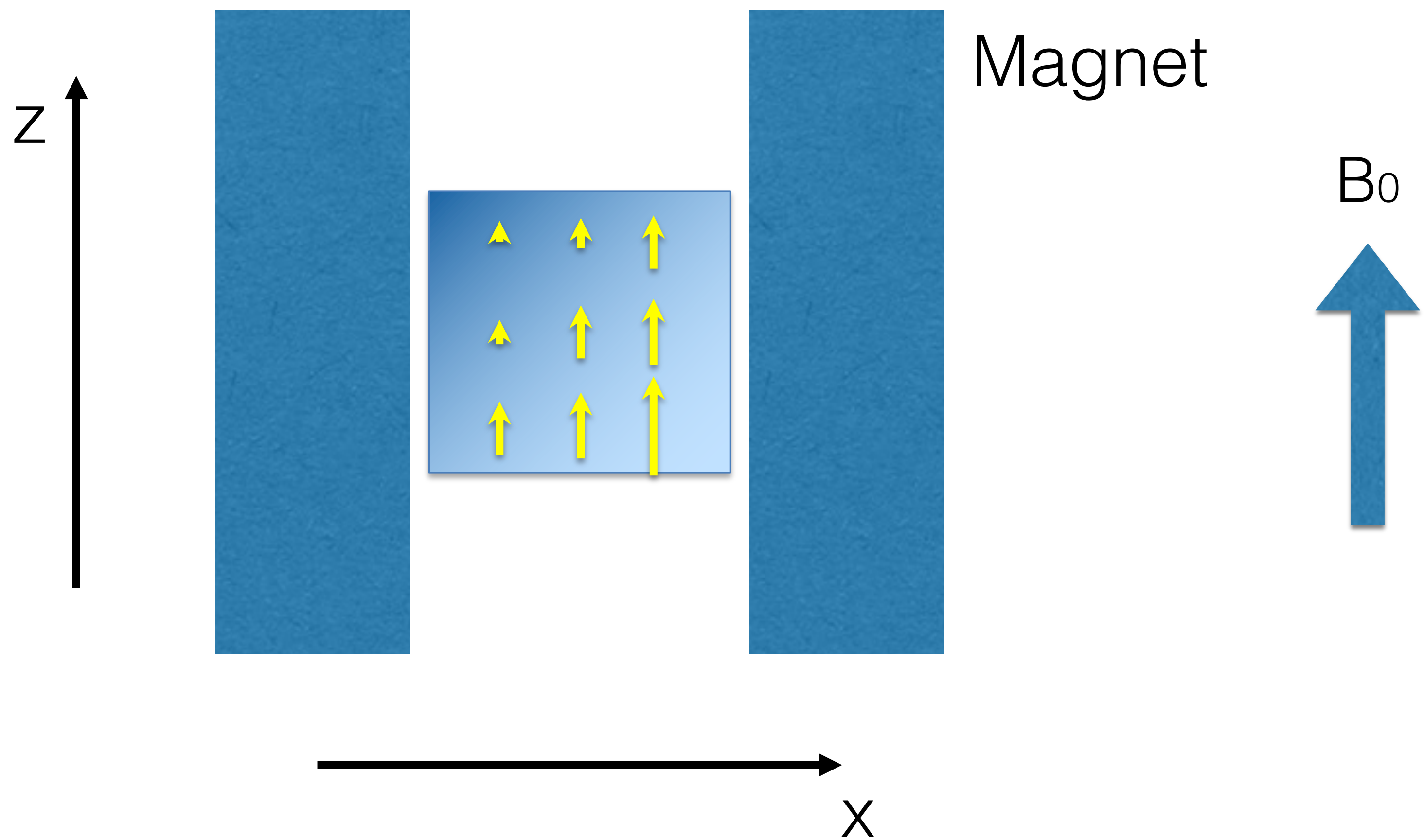
Gradients

- Gradient in -Z



Gradients

- Gradients in both X and -Z

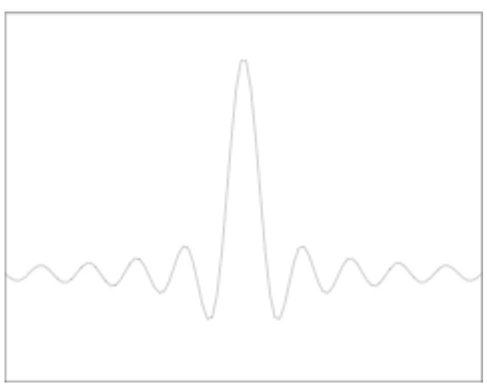


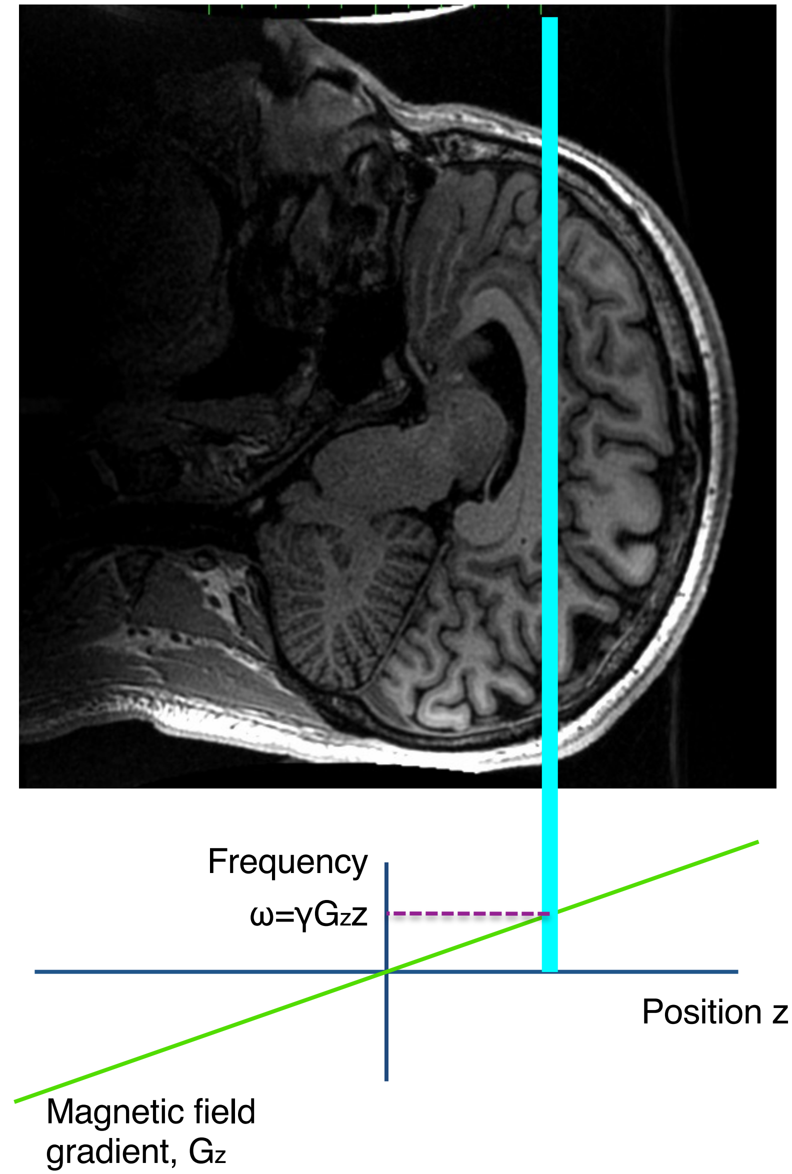
Slice selection

- Consider the slice of tissue at position z
- In the presence of gradient G_z, the local slice frequency is given by:

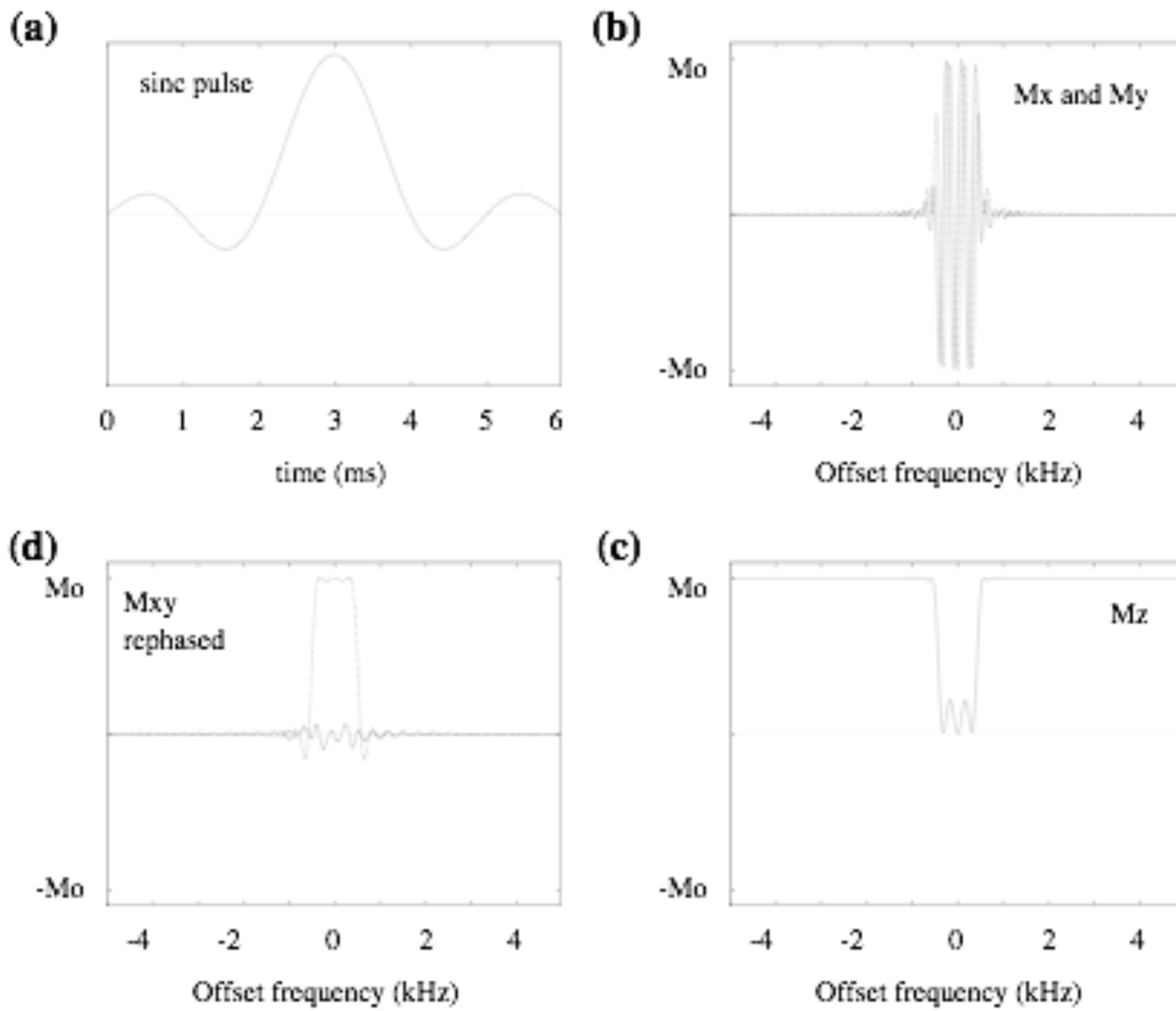
$$\delta\omega = \gamma G_z z$$

- Excite with frequency $\omega_0+\delta\omega$ to move slice from isocenter to position of interest.
- Excite with a band of frequencies to define a particular slice width.
- Sinc pulse:

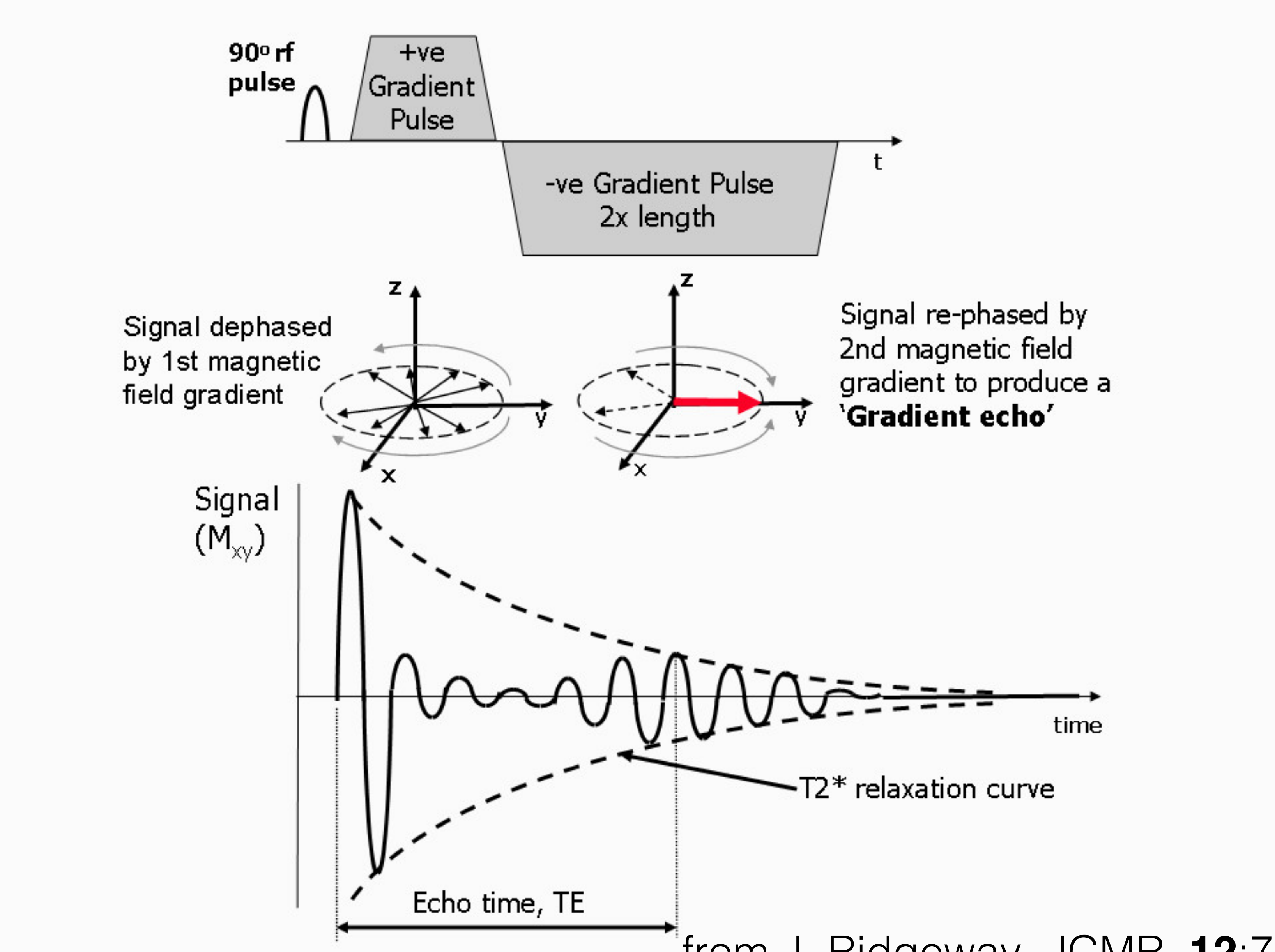




Selective excitation



Gradient echo



from J. Ridgeway, JCMR, **12**:71, 2010

Outline

- NMR: Review of physics basics
- MR Imaging: tools and techniques
- K-space trajectories
  - Theory: MR signal and reconstruction equations
  - Fourier Imaging: readout and phase encoding
  - Echo planar imaging
  - Spiral Imaging
- Controlling the image contrast
- Other stuff...

Effect of imaging gradient

- MR image formation is based on the equation: $\omega = \gamma B$
- In the main magnetic field, B_0, we have: $\omega_0 = \gamma B_0$
- Superimpose a spatial magnetic field gradient,

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then:

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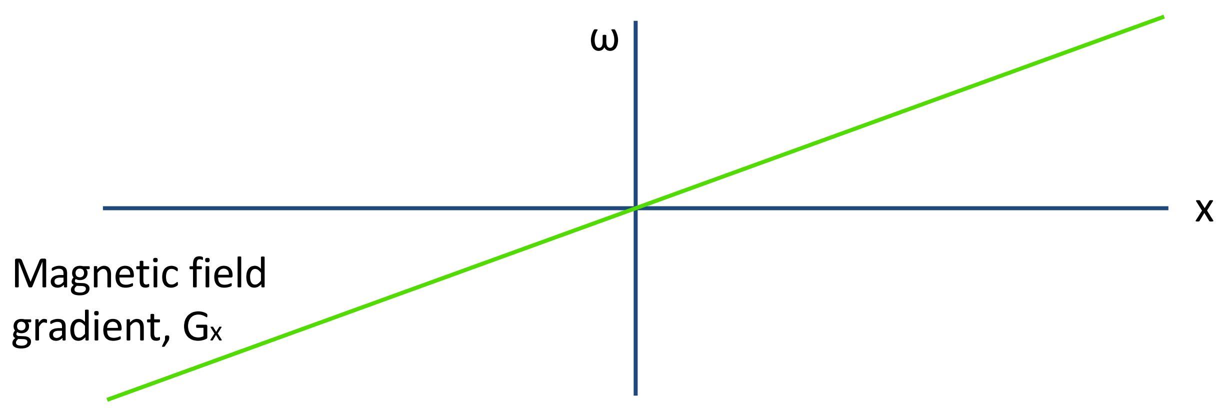
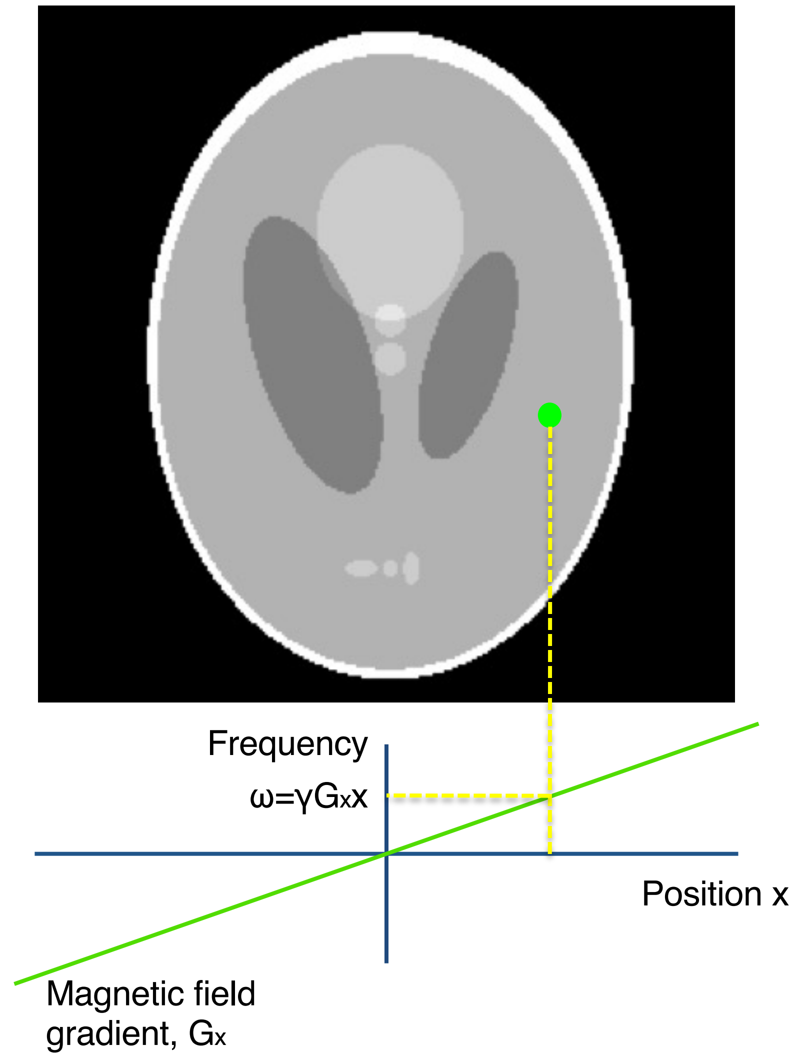


MR Imaging Theory

- Consider the green blob of tissue...
- The frequency is given by: $\delta\omega = \gamma \mathbf{G}(t) \cdot \mathbf{r}(t)$



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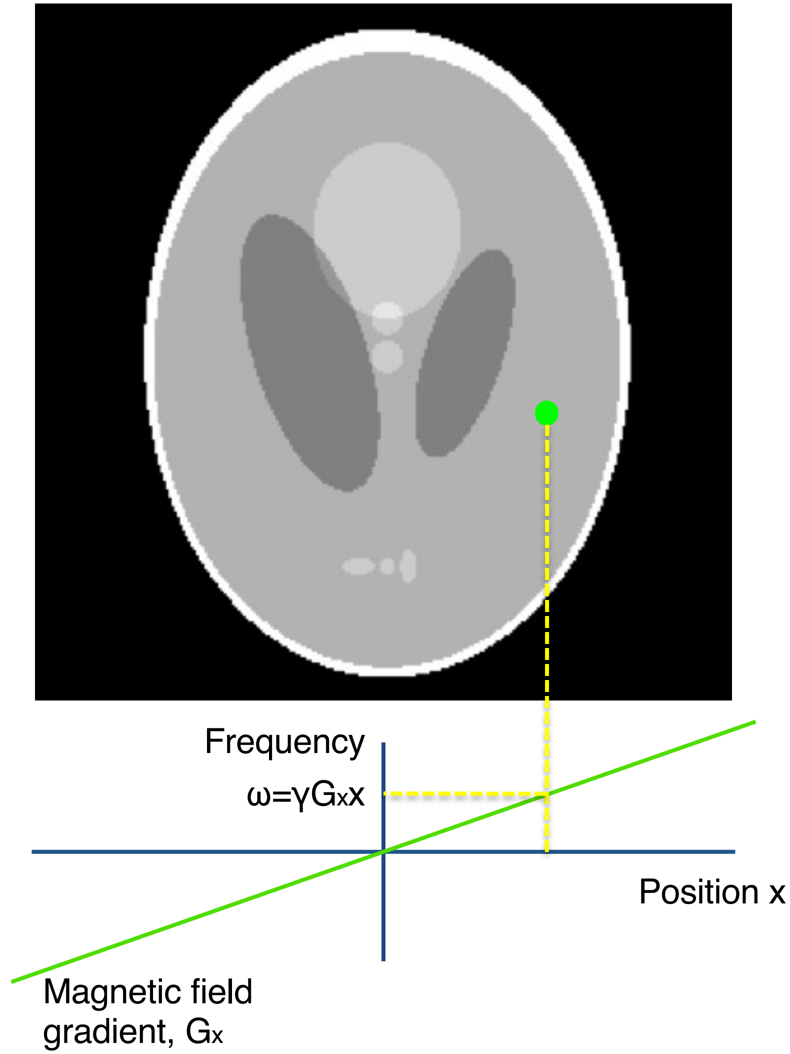
- Over time, phase accumulates as: $$\delta\theta = \gamma \int_0^t \mathbf{G}(t')dt' \cdot \mathbf{r}(t)$$



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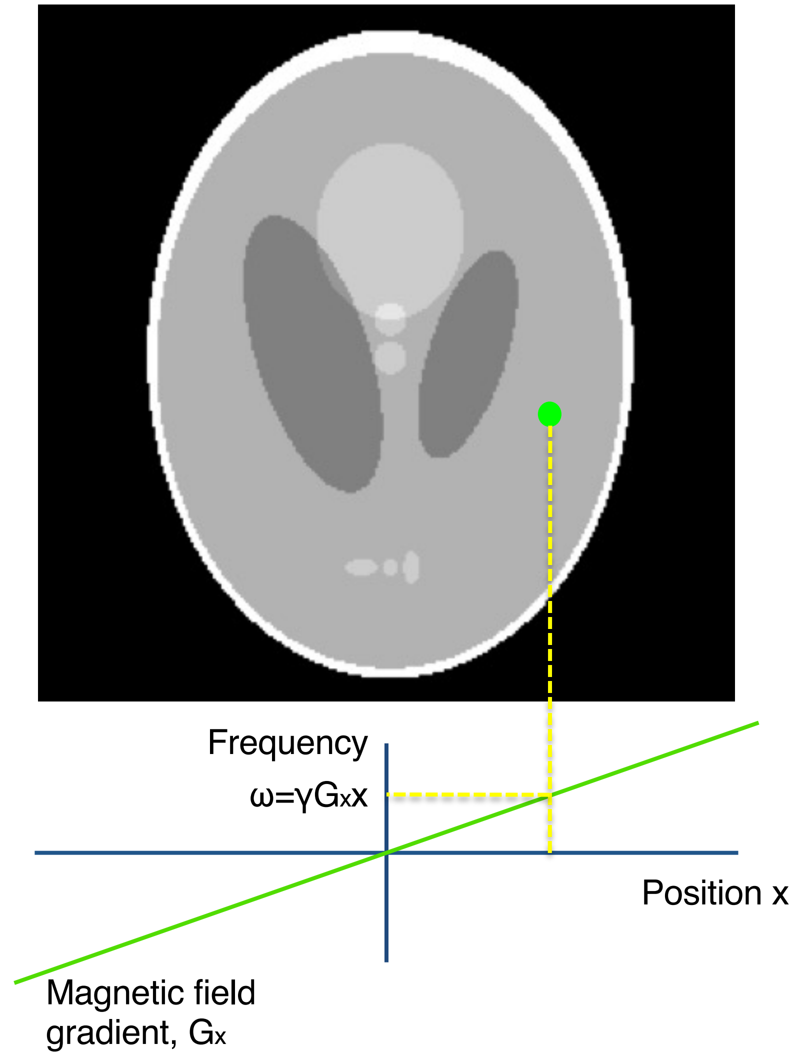
- Signal from the whole slice is given by:

$$S(G,t) = A \int_V \rho(\mathbf{r}) \exp\left[i\gamma \int_0^t \mathbf{G}(t')dt' \cdot \mathbf{r} \right] d^3\mathbf{r}$$



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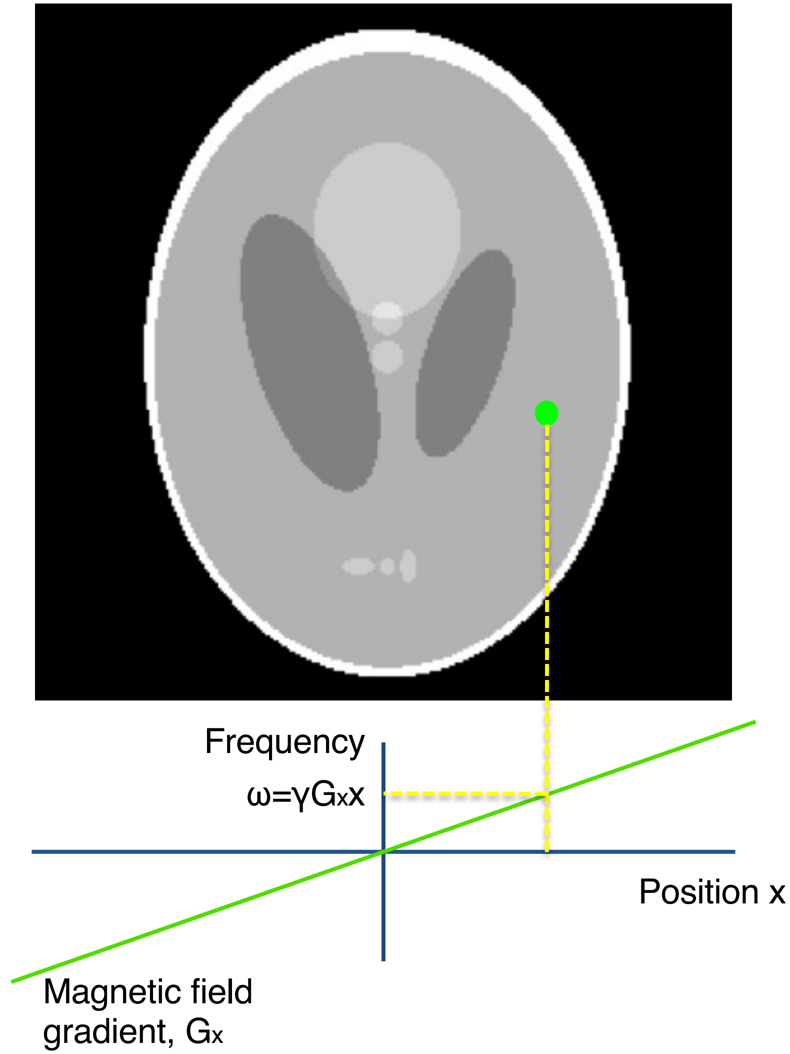
- Write:

$$\mathbf{k}(t) = \frac{\gamma}{2\pi} \int_{0}^{t} \mathbf{G}(t')dt'$$



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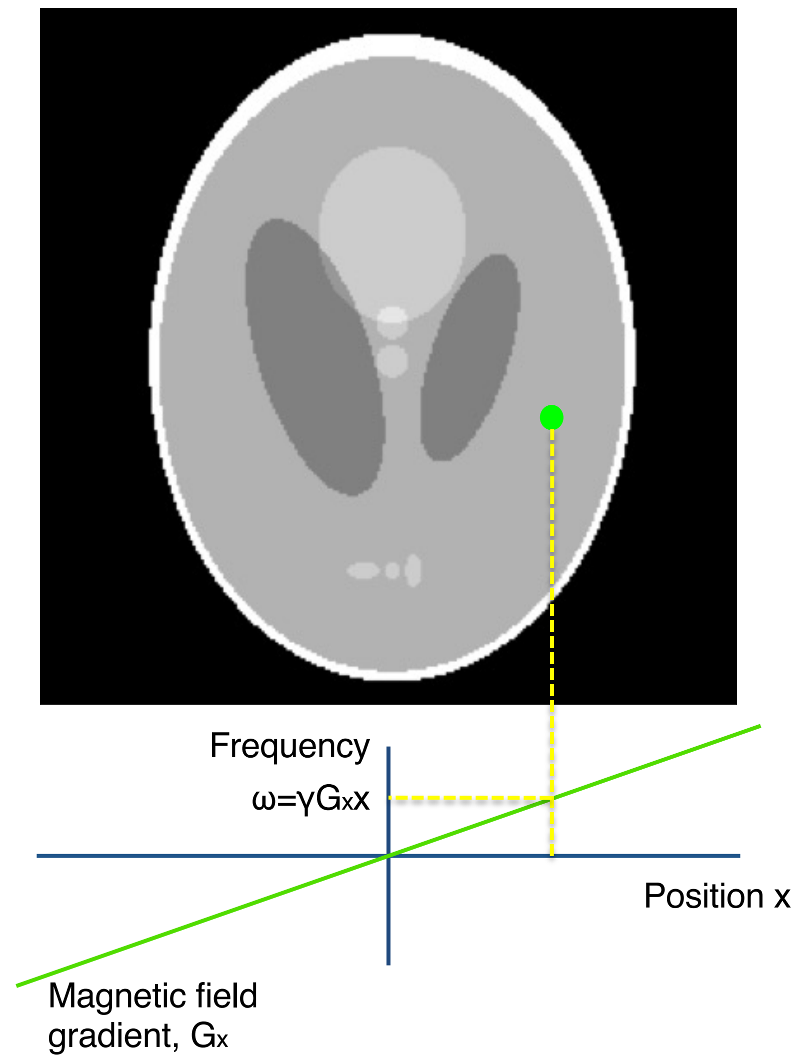
- Signal from the whole slice is given by
- Write:

$$\mathbf{k}(t) = \frac{\gamma}{2\pi} \int_{0}^{t} \mathbf{G}(t')dt'$$

- Then:

$$S(\mathbf{k}) = \int_{V} \rho(\mathbf{r}) \exp(i2\pi\mathbf{k}\cdot\mathbf{r})\, d^3\mathbf{r}$$

$$\rho(\mathbf{r}) = \int_{\mathbb{R}^3} S(\mathbf{k}) \exp(-i2\pi\mathbf{k}\cdot\mathbf{r})\, d^3\mathbf{k}$$



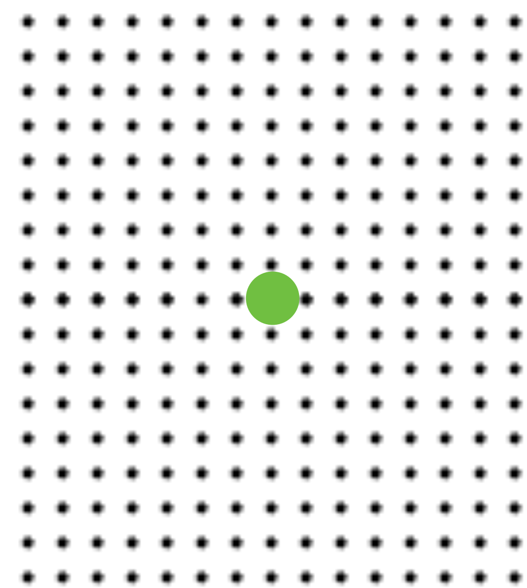
Encoding strategies

k-space trajectories

$$\mathbf{k}(t) = \frac{\gamma}{2\pi} \int_0^t \mathbf{G}(t')dt'$$

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r}) \exp(i2\pi \mathbf{k} \cdot \mathbf{r})\, d^3\mathbf{r}$$

- Sample all points in k-space to acquire sufficient data for image reconstruction.
- Initial position: origin
- **k**(t) is the sampling position
- **G**(t) is the velocity through k-space
- Sample spacing: δ**k** = 1/FOV
- Sampling extent: Δ**k** = 1/pixelsize

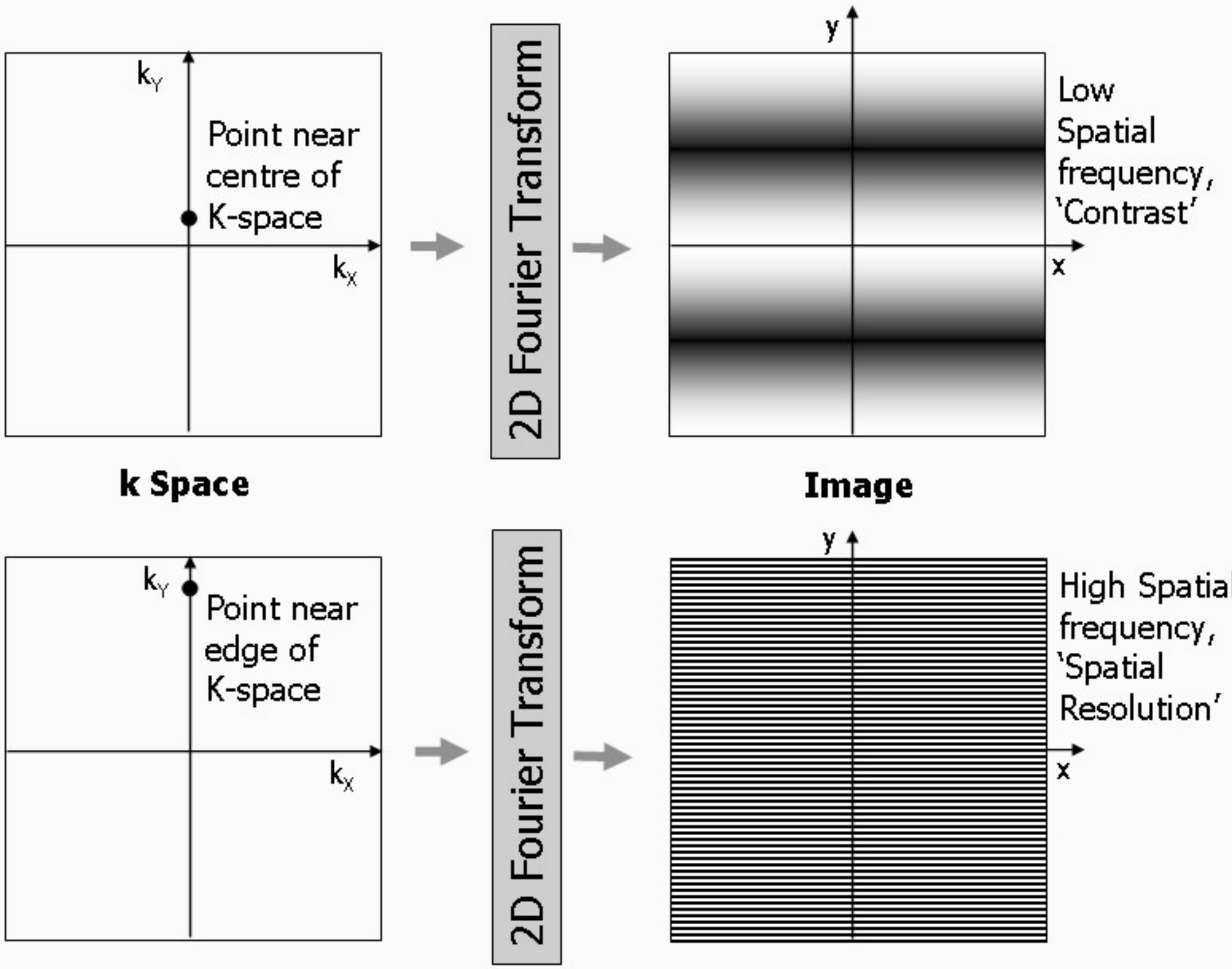


K-space

Spatial frequencies

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r}) \exp(i2\pi\mathbf{k}\cdot\mathbf{r})\, d^3\mathbf{r}$$



from J. Ridgeway, JCMR, **12**:71, 2010

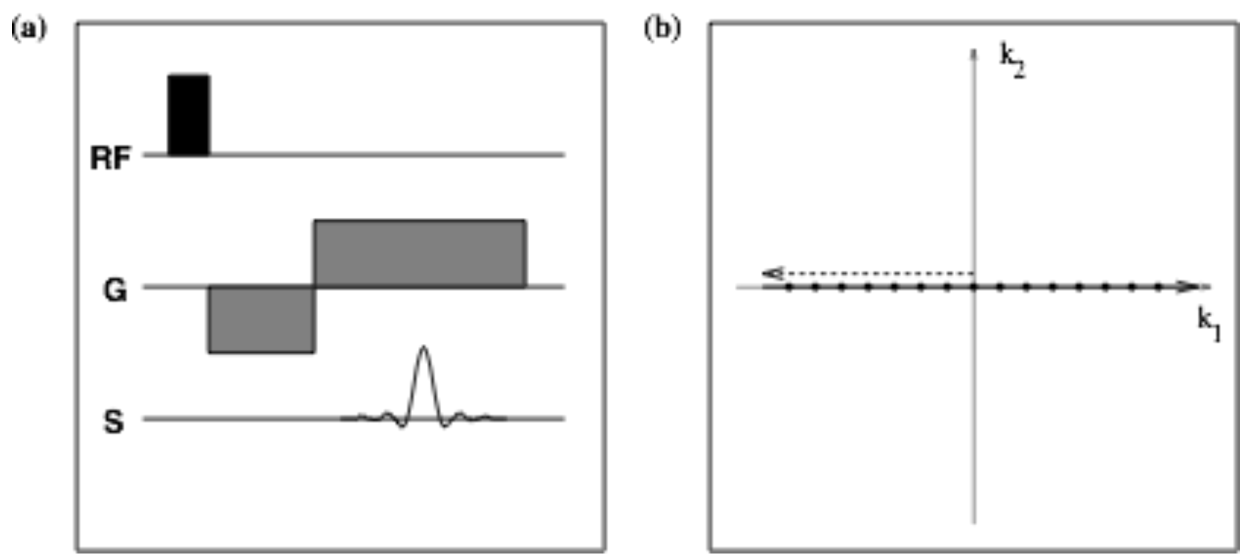
Encoding strategies

Gradient echo

- Forms echo signal with spatial encoding in the gradient direction

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r})\exp(i2\pi\mathbf{k}\cdot\mathbf{r})\,d^3\mathbf{r}$$



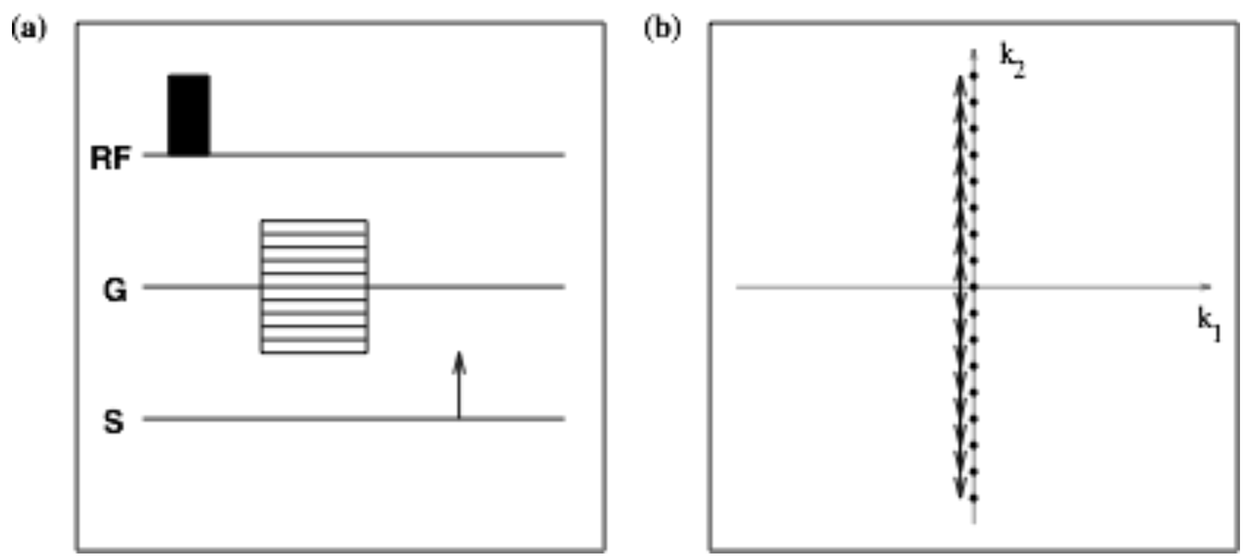
Encoding strategies

Phase encoding

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

- Offsets each acquisition in an orthogonal direction

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r})\exp(i2\pi\mathbf{k}\cdot\mathbf{r})\,d^3\mathbf{r}$$



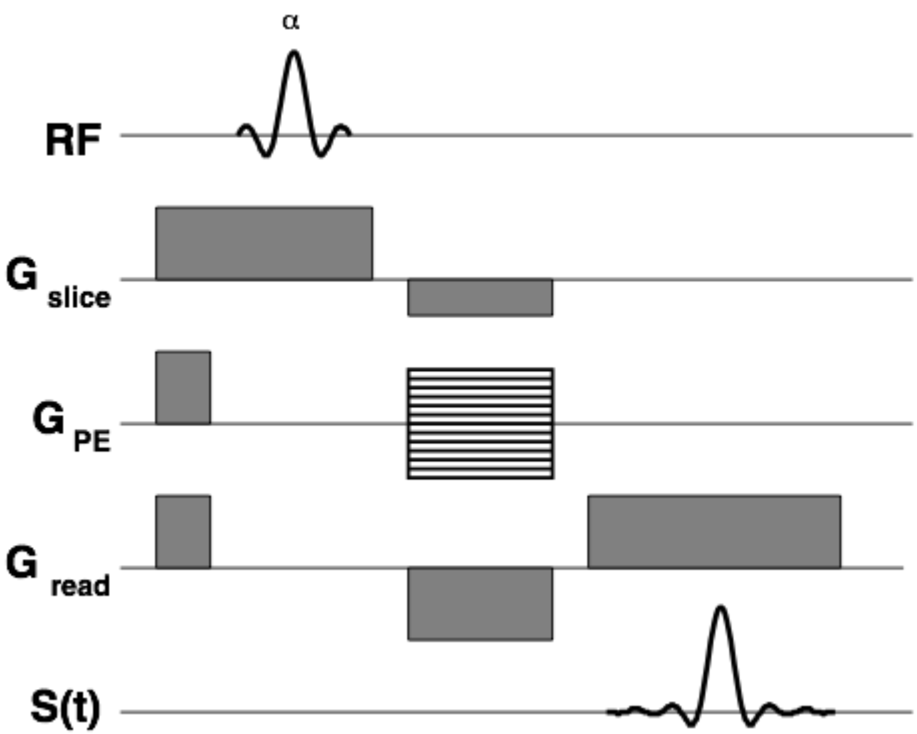
Encoding strategies

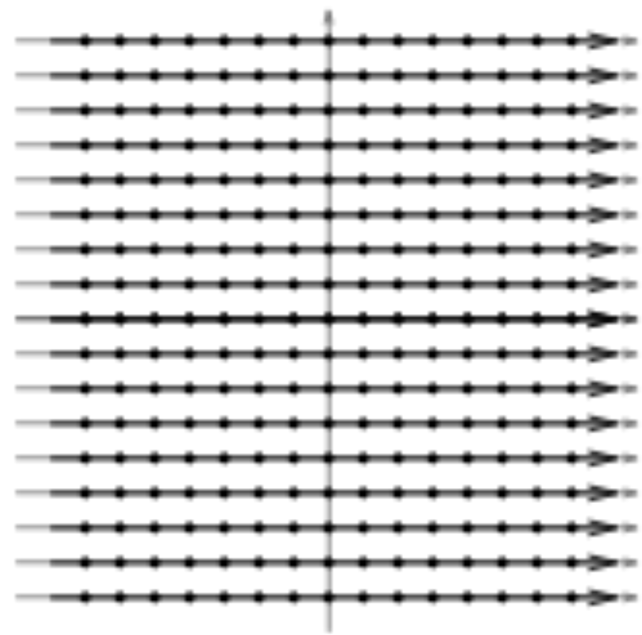
2D Gradient echo imaging

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r}) \exp(i2\pi\mathbf{k}\cdot\mathbf{r})\, d^3\mathbf{r}$$

- Slice selective excitation combined with gradient echo in one direction and phase encoding in the other





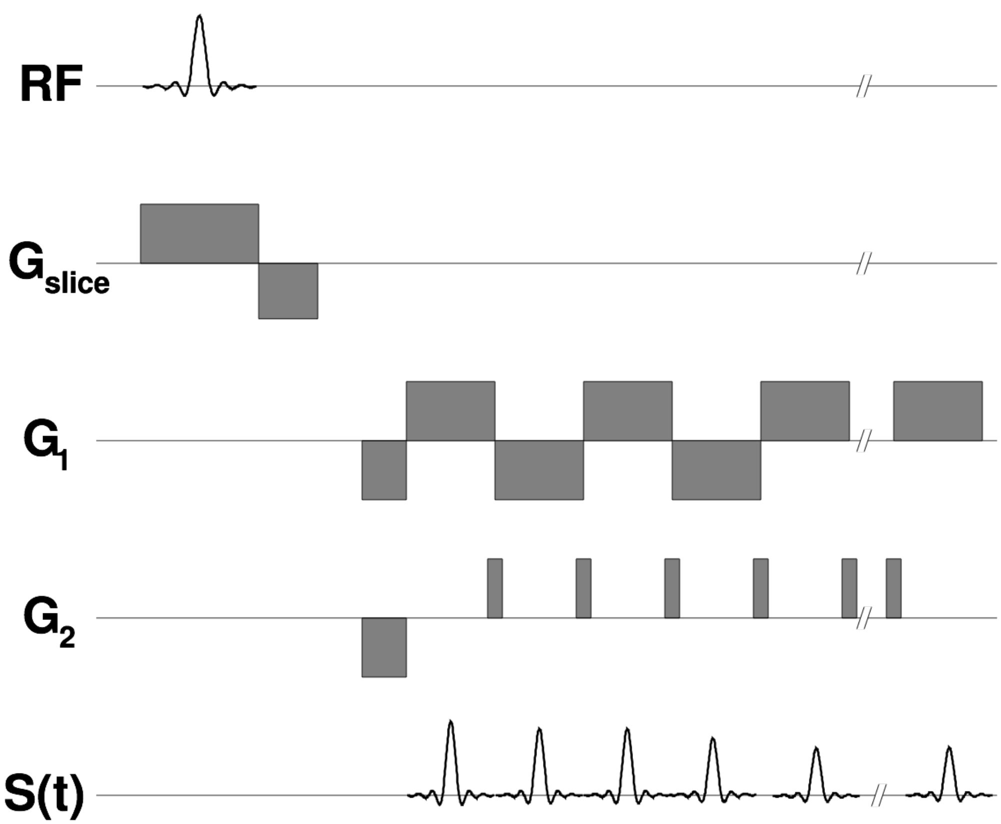
Encoding strategies

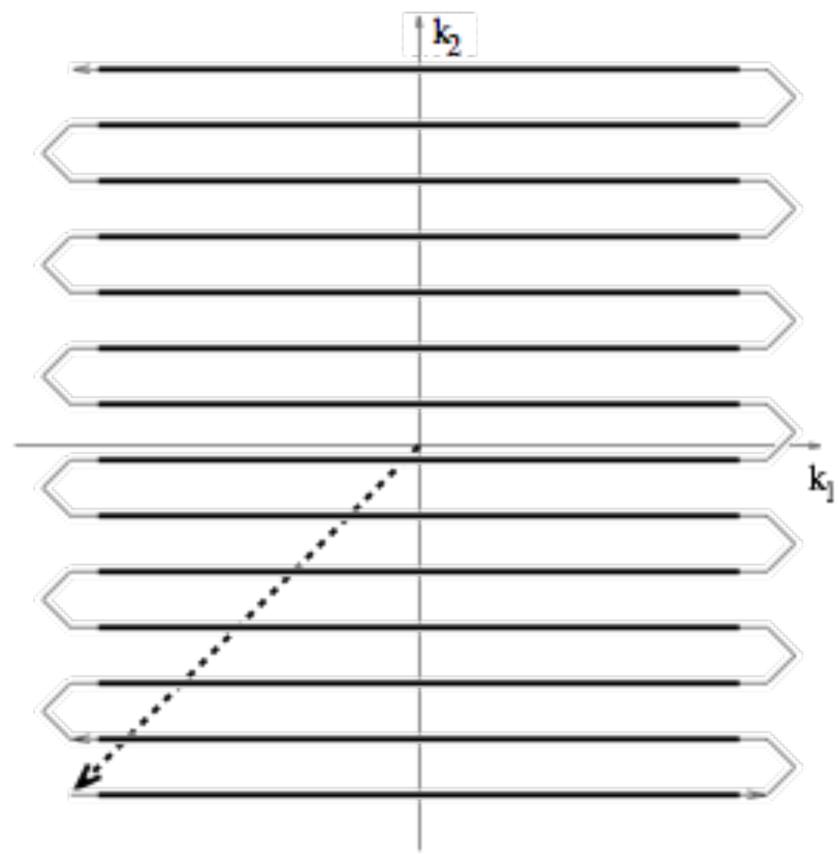
$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

Echo planar Imaging

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r}) \exp(i2\pi\mathbf{k}\cdot\mathbf{r})\, d^3\mathbf{r}$$

- Acquire the whole 2D k-space after excitation
- Time varying gradients during the acquisition
- Boustrophedonic trajectory



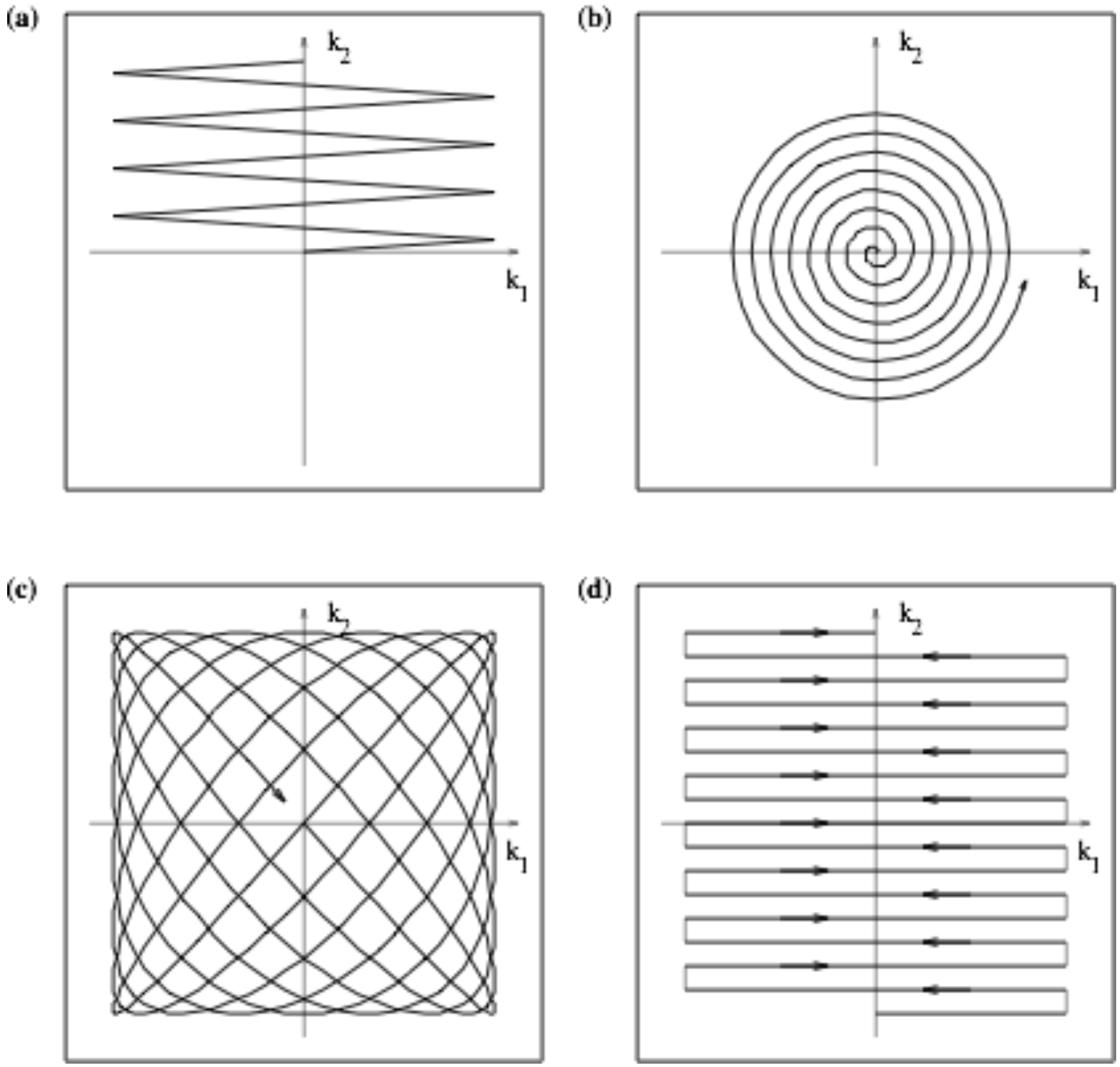


Encoding strategies

Spirals etc...

$$\mathbf{k}(t) = \frac{\gamma}{2\pi}\int_0^t \mathbf{G}(t')dt'$$

$$S(\mathbf{k}) = \int_V \rho(\mathbf{r}) \exp{(i2\pi\mathbf{k}\cdot\mathbf{r})}\, d^3\mathbf{r}$$

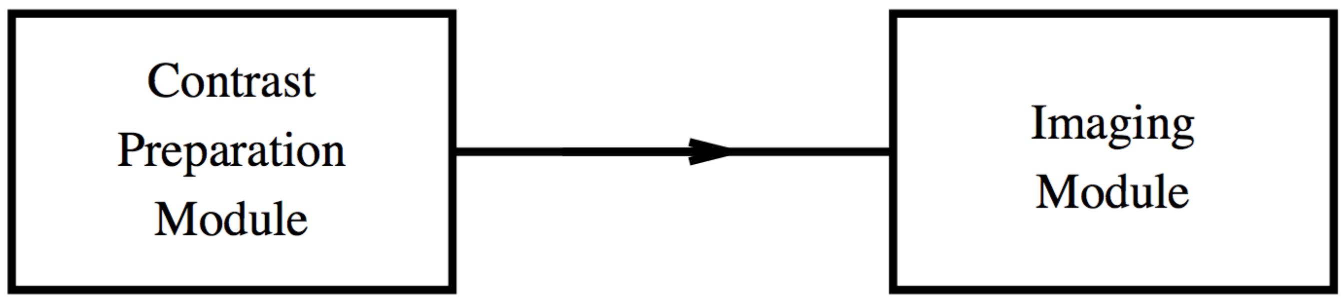


Outline

- NMR: Review of physics basics
- MR Imaging: tools and techniques
- K-space trajectories
- Controlling the image contrast
  - Intrinsic contrast of the pulse sequence
    - Gradient-echo and spin-echo sequences
    - Effects of TE and TR
  - Fat saturation
  - Magnetization Preparation methods
    - Flow preparation
    - Diffusion preparation
- Other stuff

Controlling image contrast

- Intrinsic contrast of the pulse sequence
  - Gradient-echo and spin-echo sequences
  - Effects of TE and TR



- Magnetization Preparation methods (examples)
  - Fat saturation
  - Flow preparation
  - Diffusion preparation

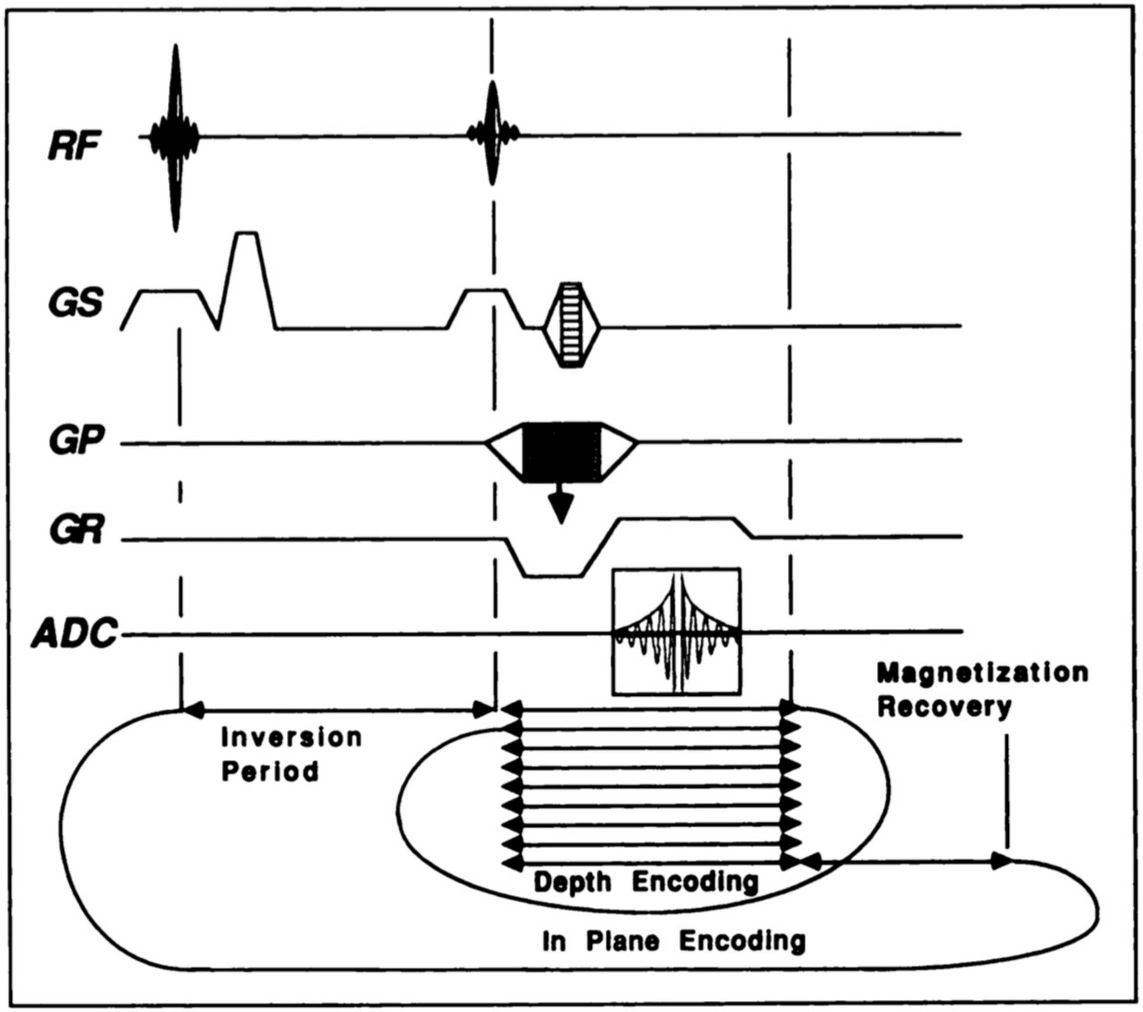
MP-RAGE

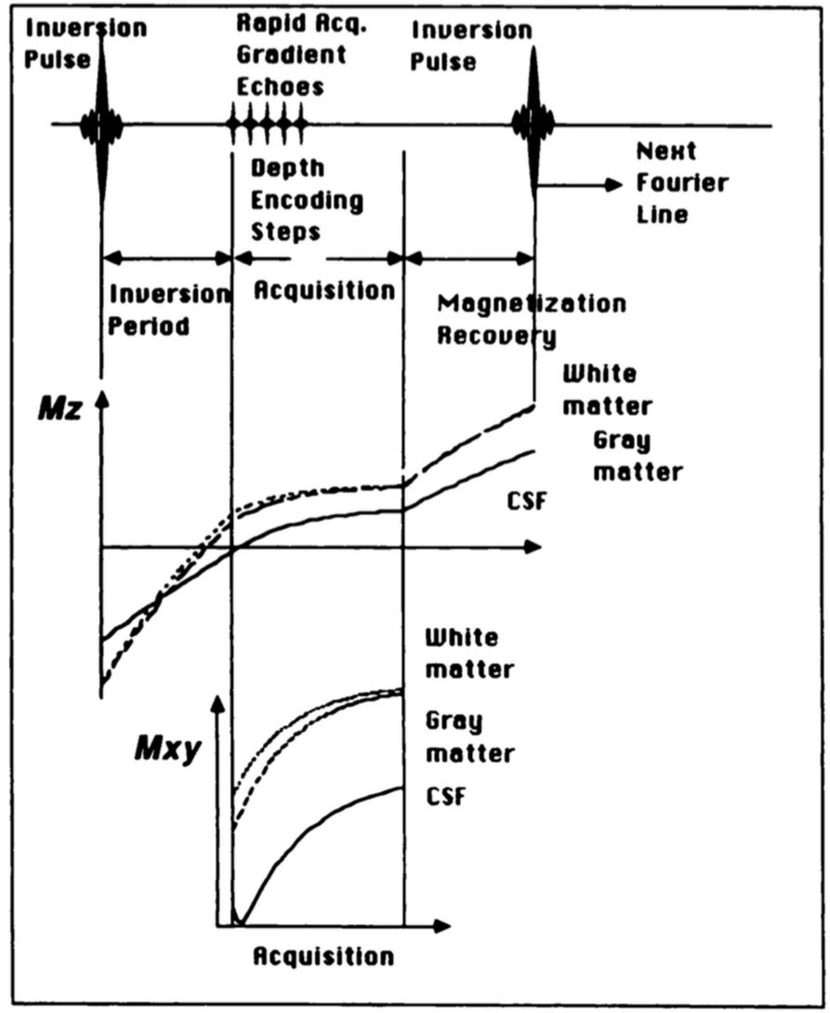
Magnetization Prepared Rapid Acquisition with Gradient Echoes

- 3D anatomical scan with white/grey matter contrast
- Typically:
  - 0.8-1.25mm isotropic resolution
  - 6 -12 minutes scan time
- Inversion recovery preparation pulse
- Multiple imaging readouts (slice direction phase encoding)

MP-RAGE

Magnetization Prepared Rapid Acquisition with Gradient Echoes





Outline

- NMR: Review of physics basics
- MR Imaging: tools and techniques
- K-space trajectories
- Controlling the image contrast
- Other stuff...

Other stuff

Not covered in this talk

- Parallel Imaging
  - Sparse sampling of k-space
  - Use multiple receiver coils for spatial encoding (in addition to the image gradients)
- Motion monitoring/suppression
- Diffusion imaging
- Anything involving deeper NMR phenomena
- System engineering

Thanks for your attention

National Institute of Mental Health
Functional MRI Facility