Medical Image Processing

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Magnetic Resonance Imaging

- Magnetic resonance imaging (MRI) is an imaging technique used primarily in medical settings to produce high quality images of the soft tissues of the human body.

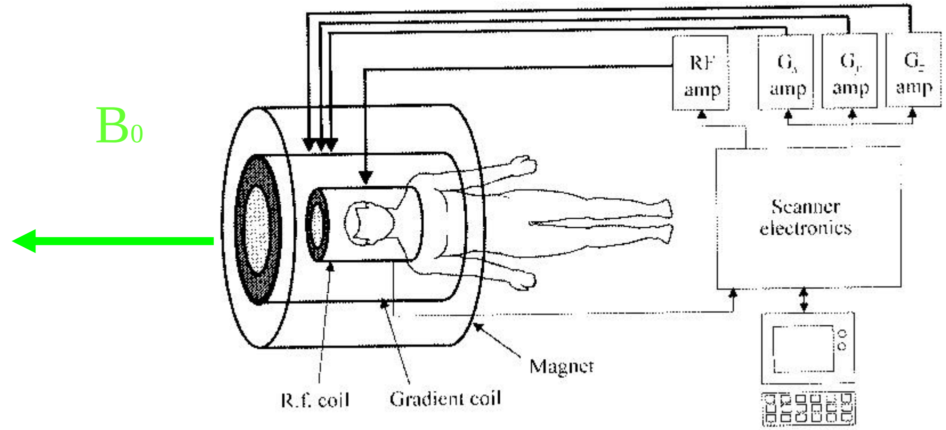
- It is based on the principles of nuclear magnetic resonance (NMR), a spectroscopic technique to obtain microscopic chemical and physical information about molecules

- MRI has advanced beyond a tomographic imaging technique to a volume imaging technique

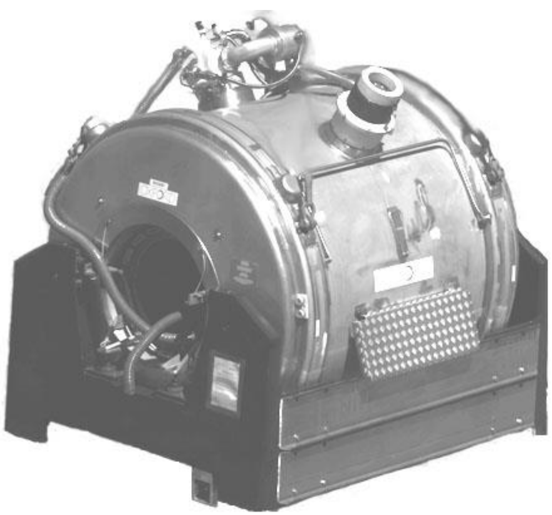
Components of a Scanner

- Static Magnetic Field Coils
- Gradient Magnetic Field Coils
- Magnetic shim coils
- Radiofrequency Coil
- Subsystem control computer
- Data transfer and storage computers
- Physiological monitoring, stimulus display, and behavioral recording hardware

MRI Hardware

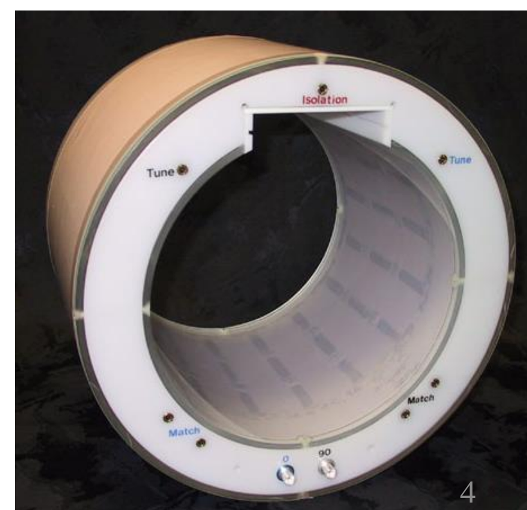


Magnet

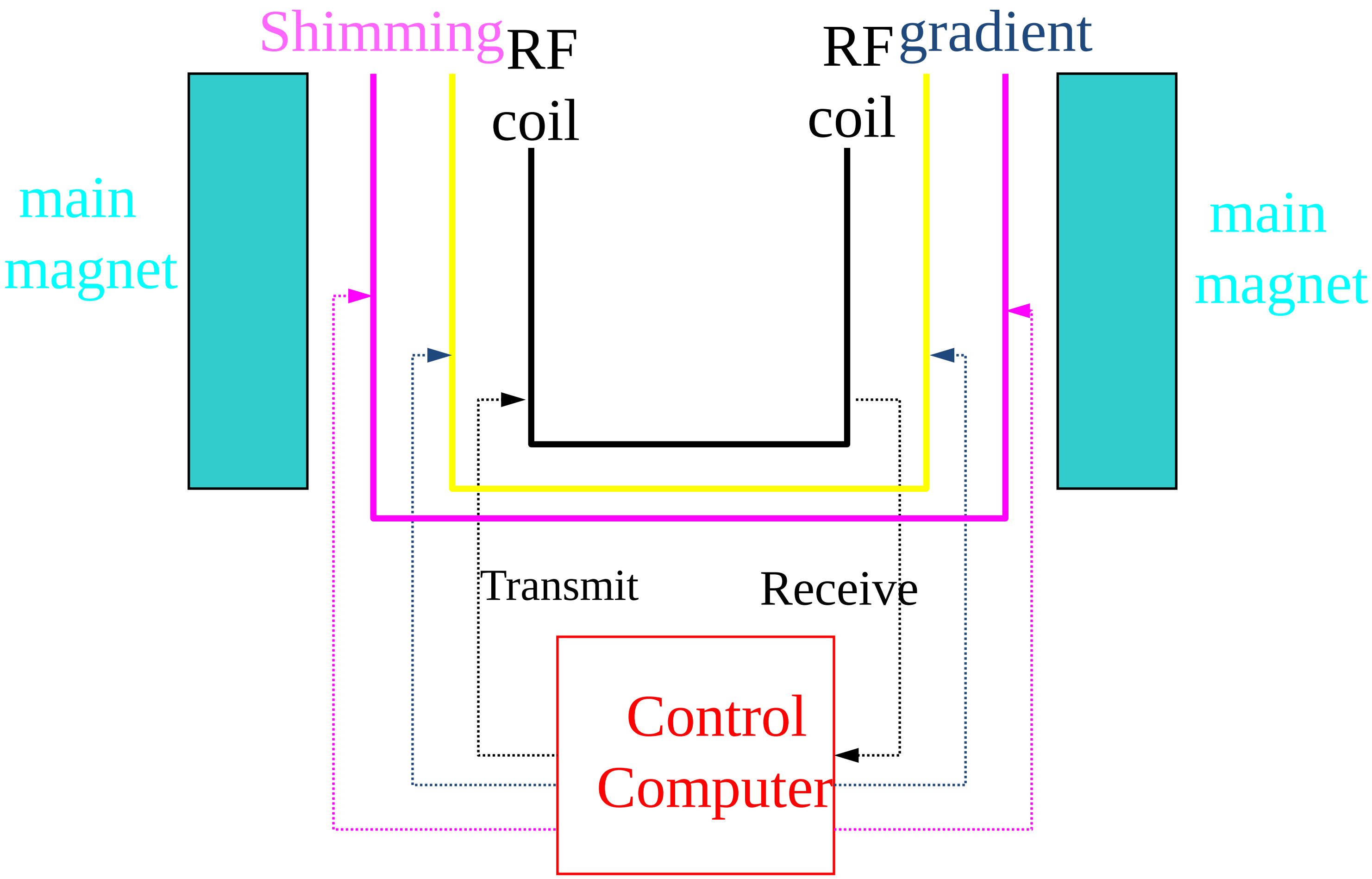


Gradient Coil

RF Coil

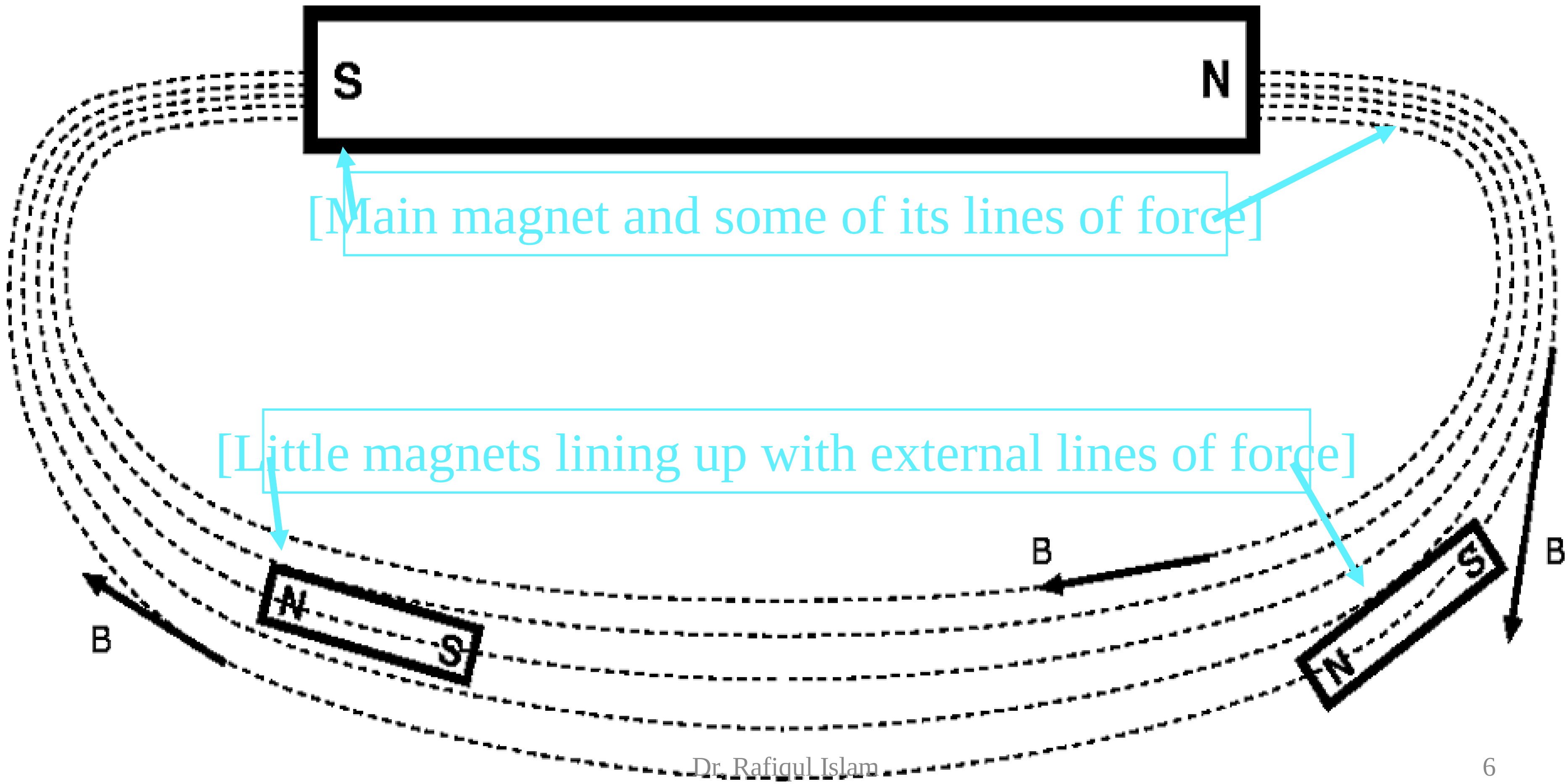


MRI Component



Main Magnet Field

- Purpose is to align H protons in H_2O (little magnets)

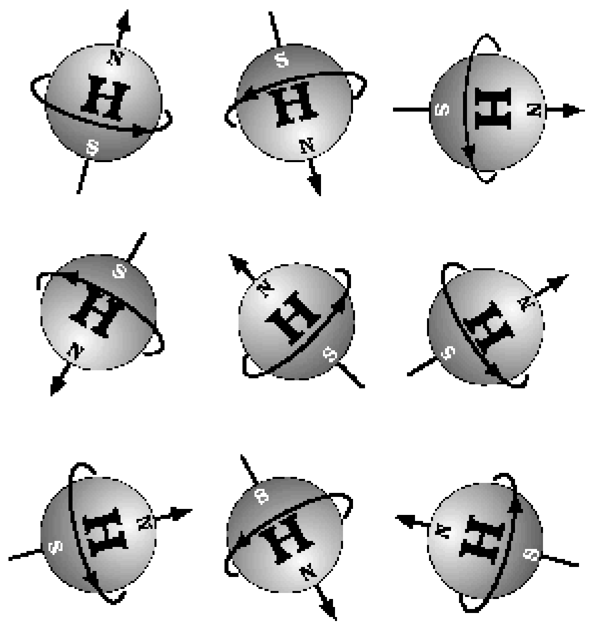


MRI Basics

- Nuclear Magnetic Resonance (NMR) (or Magnetic Resonance Imaging - MRI)
- most detailed anatomical information
- high-energy radiation is not used, i.e. “save”
- based on the principle of nuclear resonance
- (medicine) uses resonance properties of protons

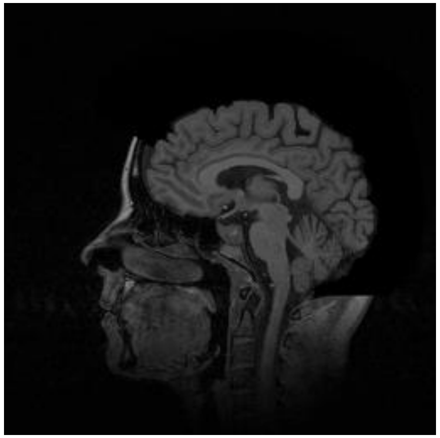
MRI Basics: polarized

- all atoms (core) with an odd number of protons have a 'spin', which leads to a magnetic behavior
- Hydrogen (H) - very common in human body + very well magnetizing
- Stimulate to form a macroscopically measurable magnetic field



MRI Basics: Signal to Noise Ratio

- proton density pictures - measures H
  MRI is good for tissues, but not for bone
- signal recorded in Frequency domain!!
- Noise - the more protons per volume unit, the more accurate the measurements - better SNR through decreased resolution
- MR signal-→ image



MRI Principles

- The composition of the human body is primarily fat and water
- Fat and water have many hydrogen atoms
- 63% of human body is hydrogen atoms
- Hydrogen nuclei have an NMR signal
- MRI uses hydrogen because it has only one proton and it aligns easily with the MRI magnet.
- The hydrogen atom’s proton, possesses a property called spin
  - A small magnetic field
  - Will cause the nucleus to produce an NMR signal

MRI Principles

- The spinning hydrogen protons act like small , weak magnets.
- They align with an external magnetic field (Bø).
- There is a slight excess of protons aligned with the field. (for 2 million , 9 excess)

  ~6 million billion/voxel at 1.5T
- The # of protons that align with the field is so very large that we can pretty much ignore quantum mechanics and focus on classical mechanics.

More MRI Principles

- The spinning protons wobble or "precess" about that axis of the external Bø field at the precessional, Larmor or resonance frequency.
- Magnetic resonance imaging frequency

$$\nu = \gamma B_o$$

where γ is the gyromagnetic ratio

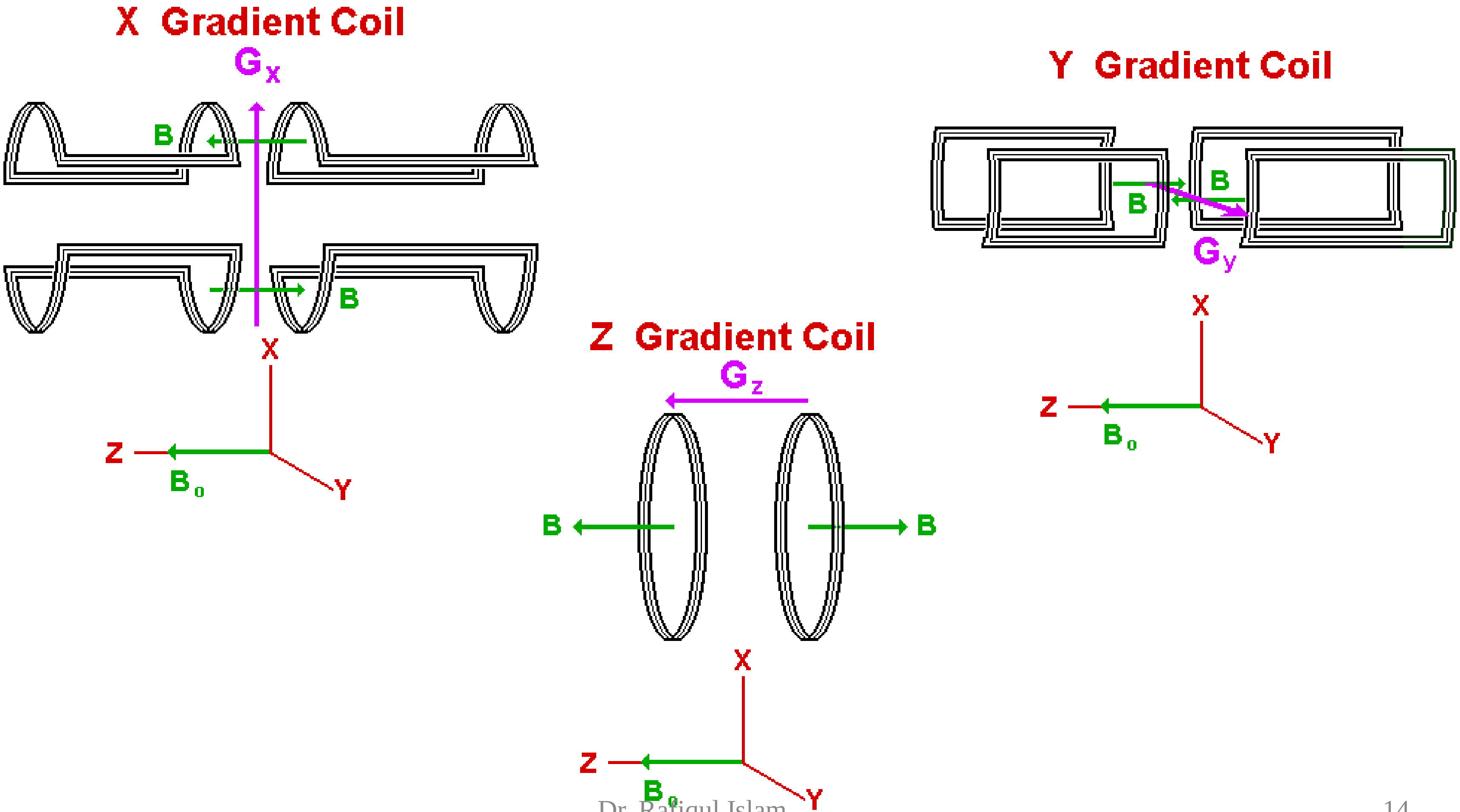
The resonance frequency ν of a spin is proportional to the magnetic field, B_o.

More MRI Principles

- Now if an electromagnetic radio frequency (RF) pulse is applied at the resonance (Larmor, precession, wobble) frequency, then the protons can absorb that energy, and (at the quantum level) jump to a higher energy state.

- At the macro level, the magnetization vector, Mø, (6 million billion protons) spirals down towards the XY plane.

MRI Details: Gradient Coils



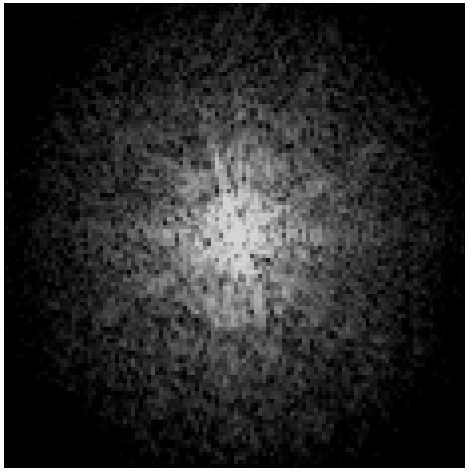
Gradient Coils Principles

- These are room temperature coils
- A gradient in Bo in the Z direction is achieved with an anti-helmholtz type of coil.
- Current in the two coils flow in opposite directions creating a magnetic field gradient between the two coils.
- The B field at one coil adds to the Bo field while the B field at the center of the other coil subtracts from the Bo field
- The X and Y gradients in the Bo field are created by a pair of figure-8 coils. The X axis figure-8 coils create a gradient in Bo in the X direction due to the direction of the current through the coils.
- The Y axis figure-8 coils provides a similar gradient in Bo along the Y axis.

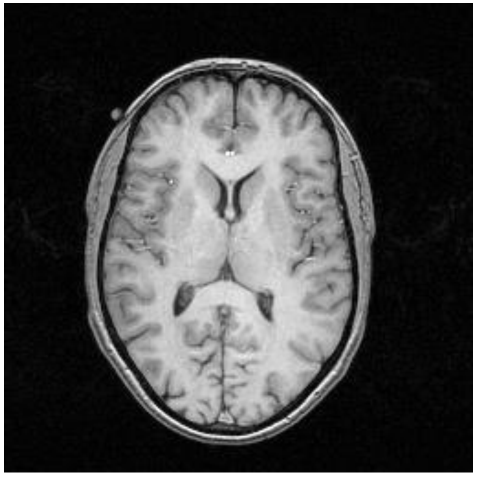
RF Coils

- RF coils create the B1 field which rotates the net magnetization in a pulse sequence.
- RF coils can be divided into three general categories
  - transmit and receive coils
  - receive only coils
  - transmit only coils

MRI Image Formation



K-space data



MRI Image

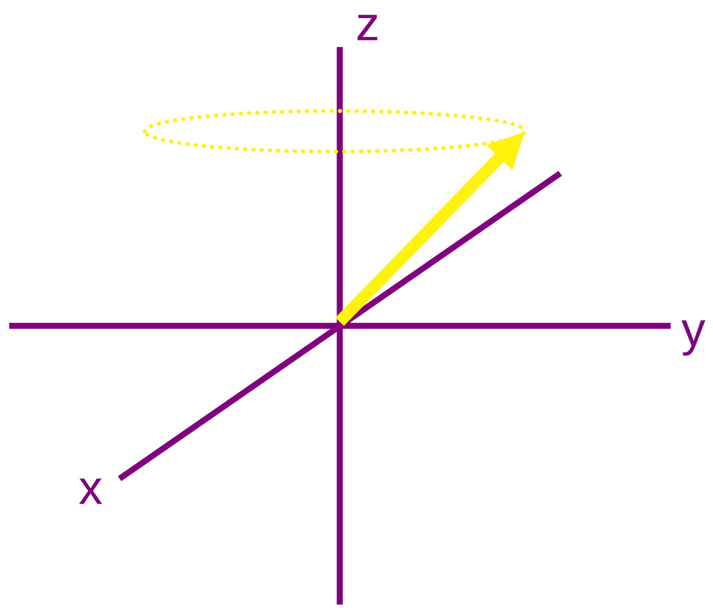
MR Machine → K-space Data (MR Signal) → IFT → MRI Image

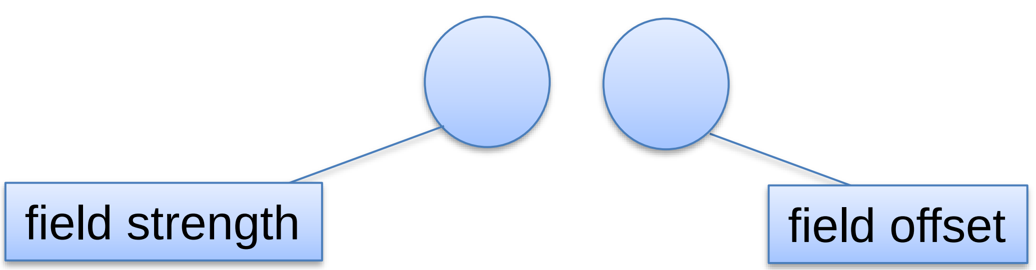
Image (2D) → Fourier Transform → 2D Signal (Frequency Domain)

MRI Image Formation

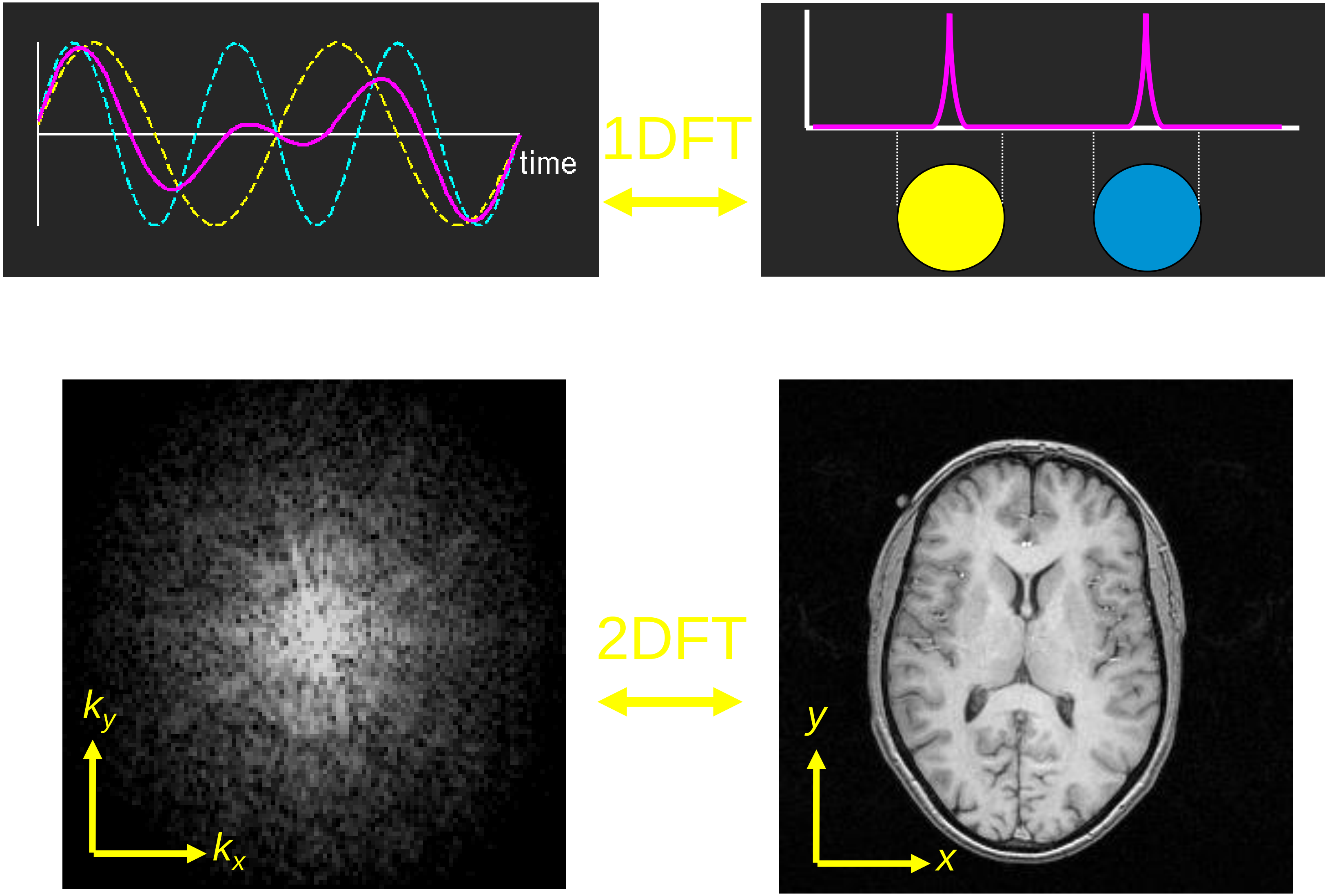
- Gradients and spatial encoding
- Sampling k-space
- Trajectories and acquisition strategies
- Fast imaging
- Acquiring multiple slices
- Image reconstruction and artifacts

MR imaging is based on precession





2D Imaging via 2D Fourier Transform

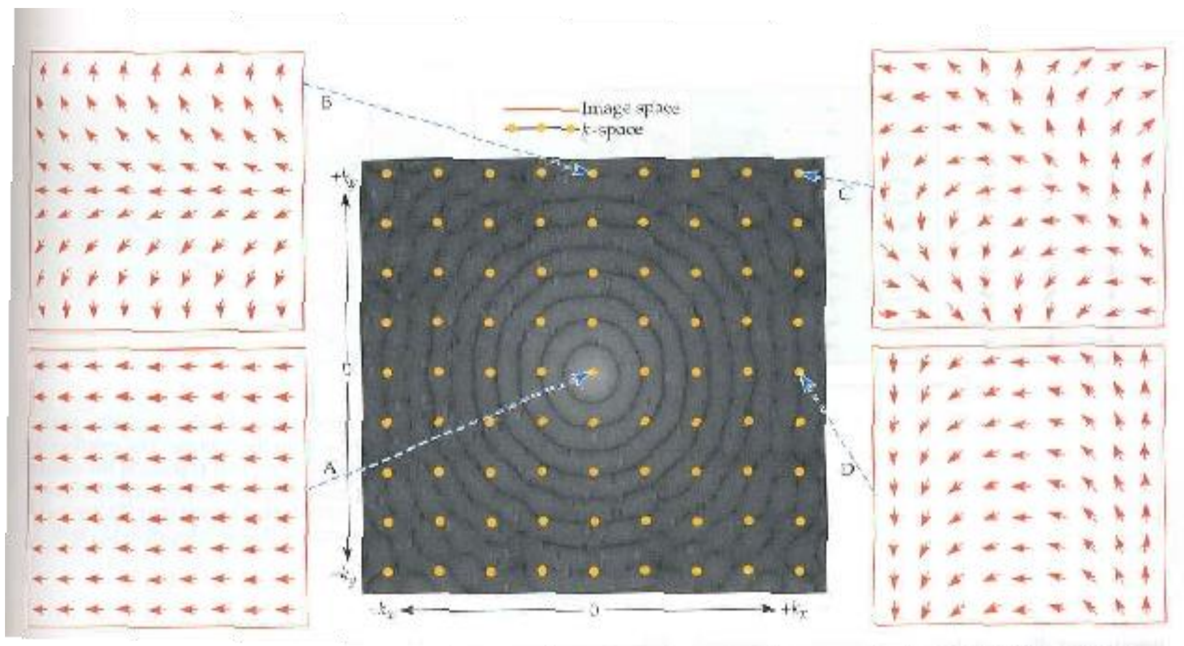


K-space (raw data) ⟷ Image space
(spatial frequency domain) FT

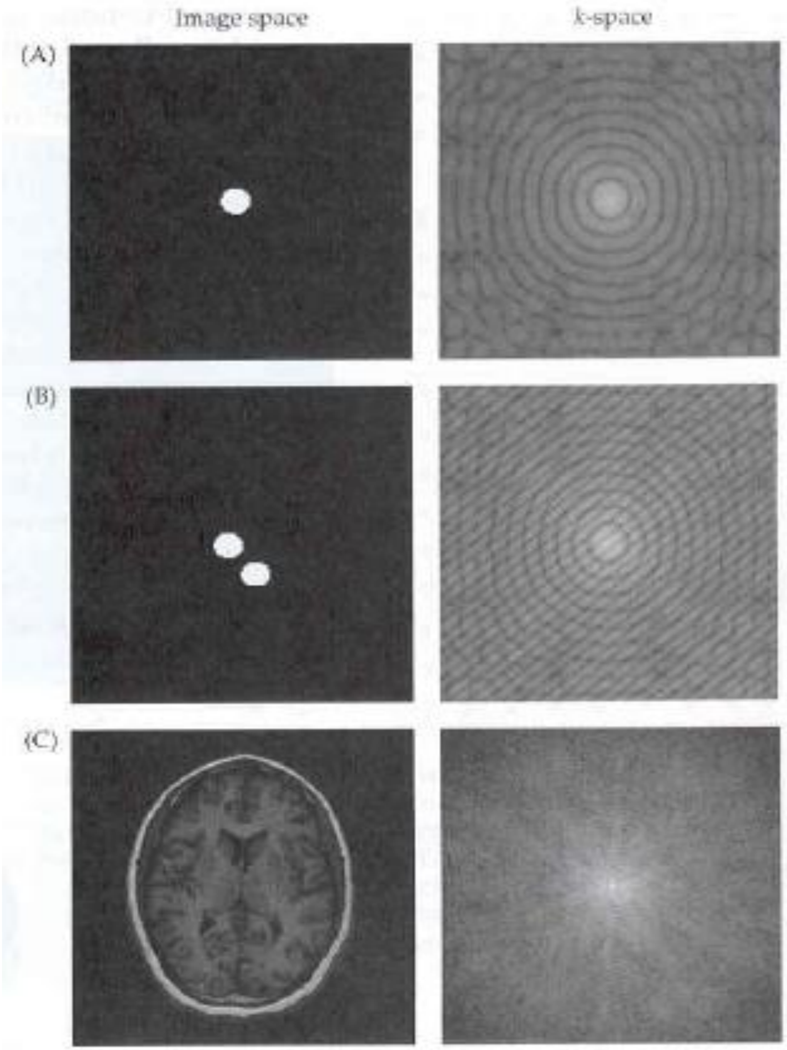
Measured MRI signal (k-space)

$$S(k_x(t), k_y(t)) = \iint M(x,y)\, e^{i2\pi k_x(t)x}\, e^{i2\pi k_y(t)y}\, dx\, dy$$

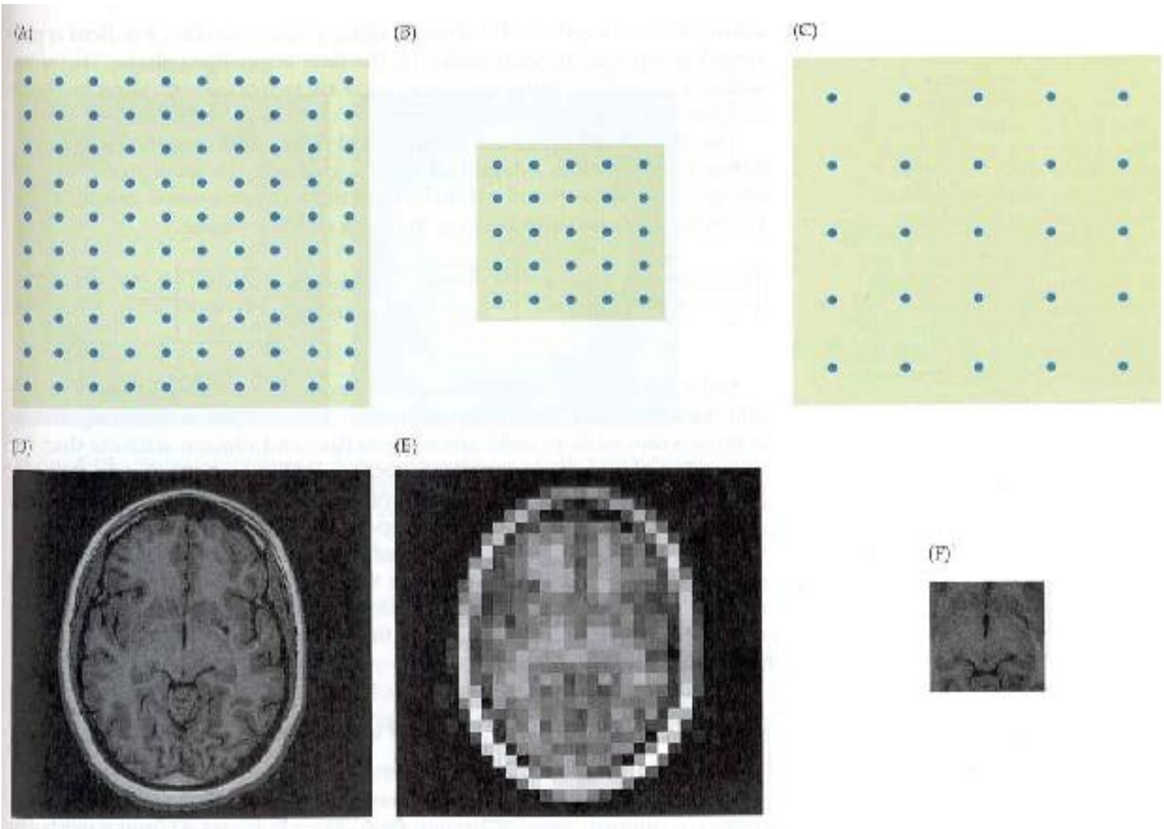
Magnetization at each voxel (= image): $M(x,y) = \int M_{xy0}(x,y,z)\, dz$



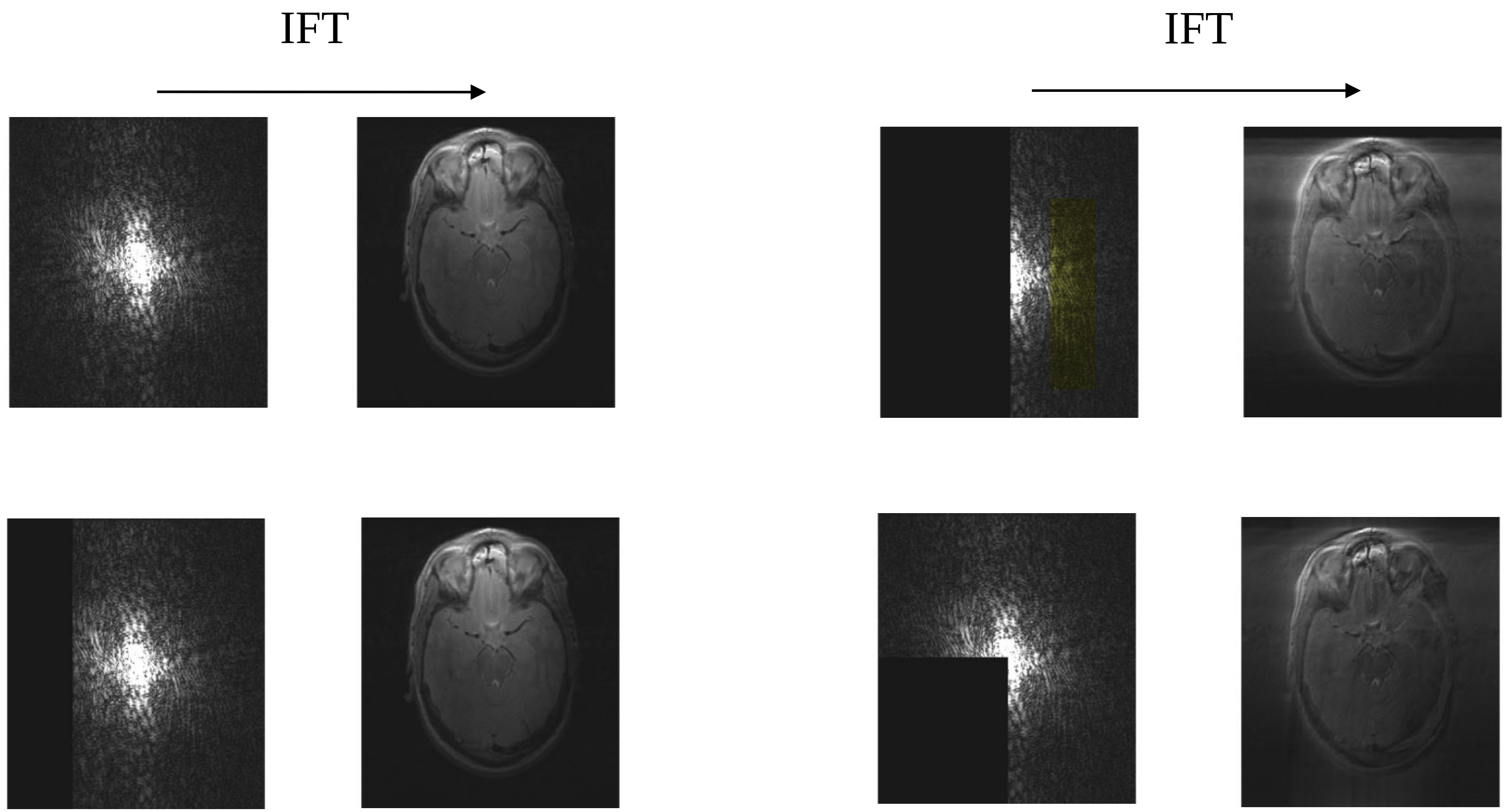
MRI Reconstruction Examples



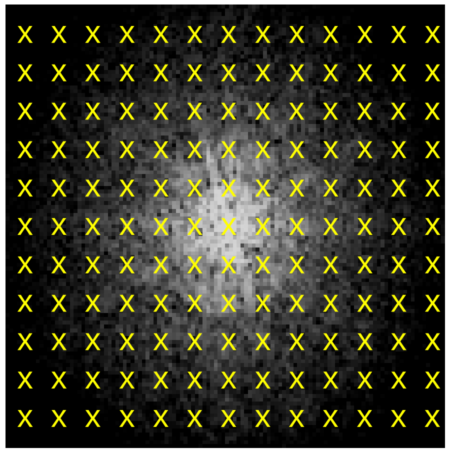
Effects of Sampling the K-space

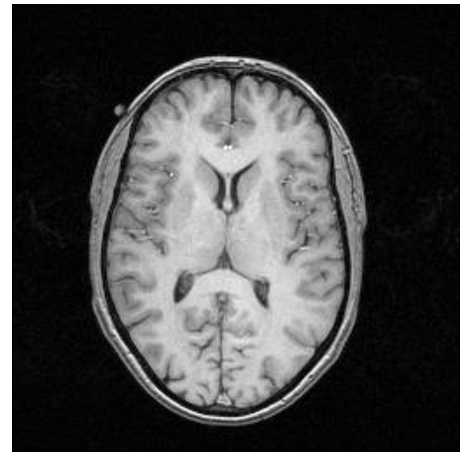


Partial k-space coverage



Sampling k-space



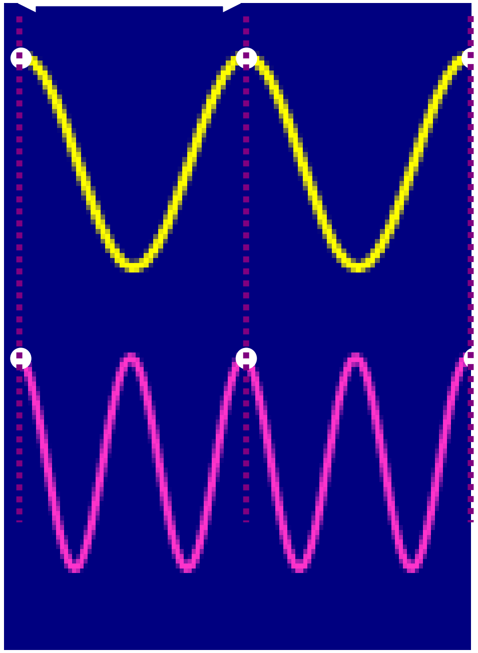


- Perfect reconstruction of an object would require measurement of *all* locations in *k*-space (infinite!)
- Data is acquired point-by-point in *k*-space (sampling)

Nyquist Sampling Theorem

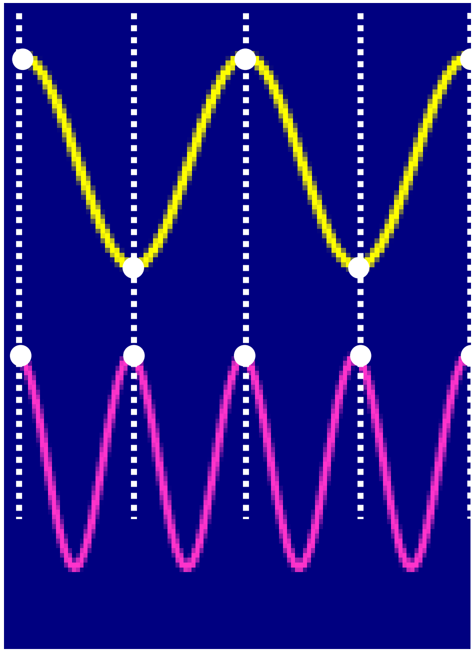
- A given frequency must be sampled at least twice per cycle in order to reproduce it accurately

1 samp/cyc



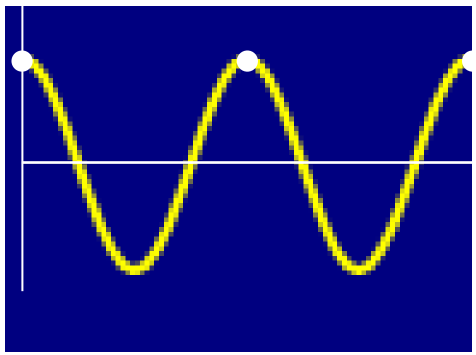
Cannot distinguish between waveforms

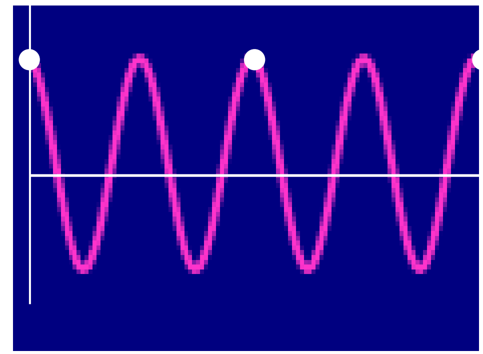
2 samp/cyc

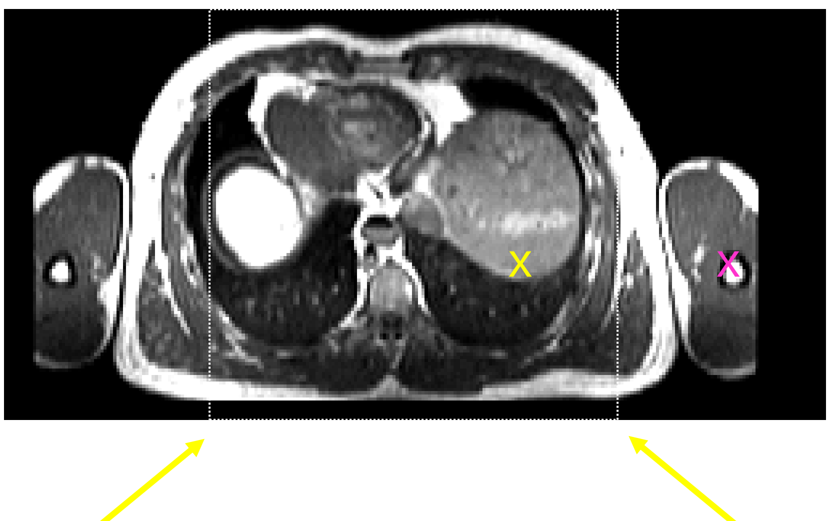


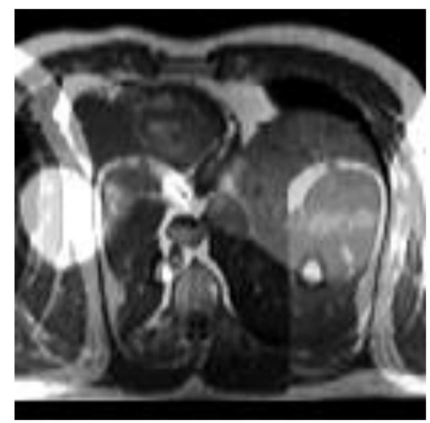
Upper waveform is resolved!

Aliasing (ghosting): inability to differentiate between 2 frequencies makes them appear to be at same location



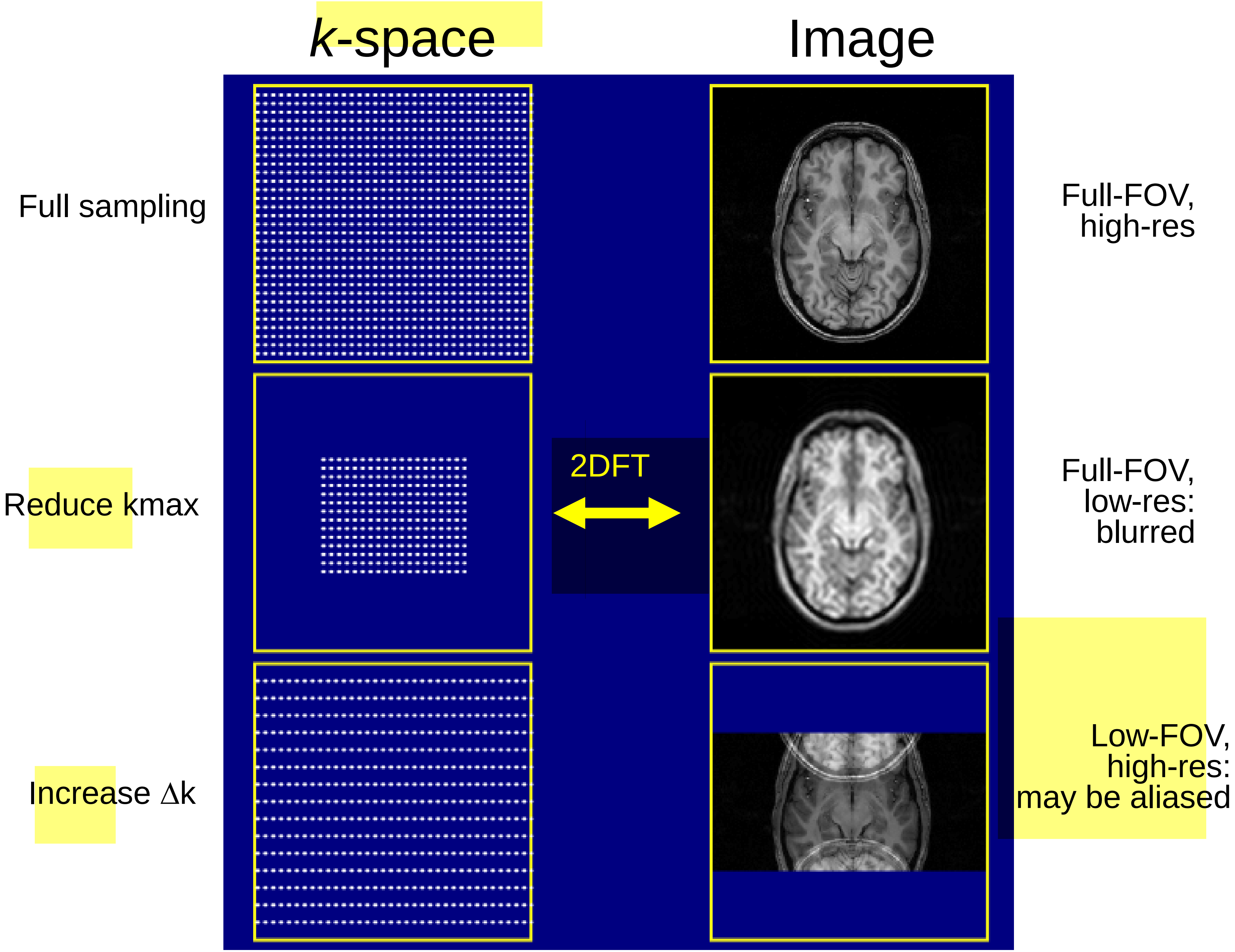




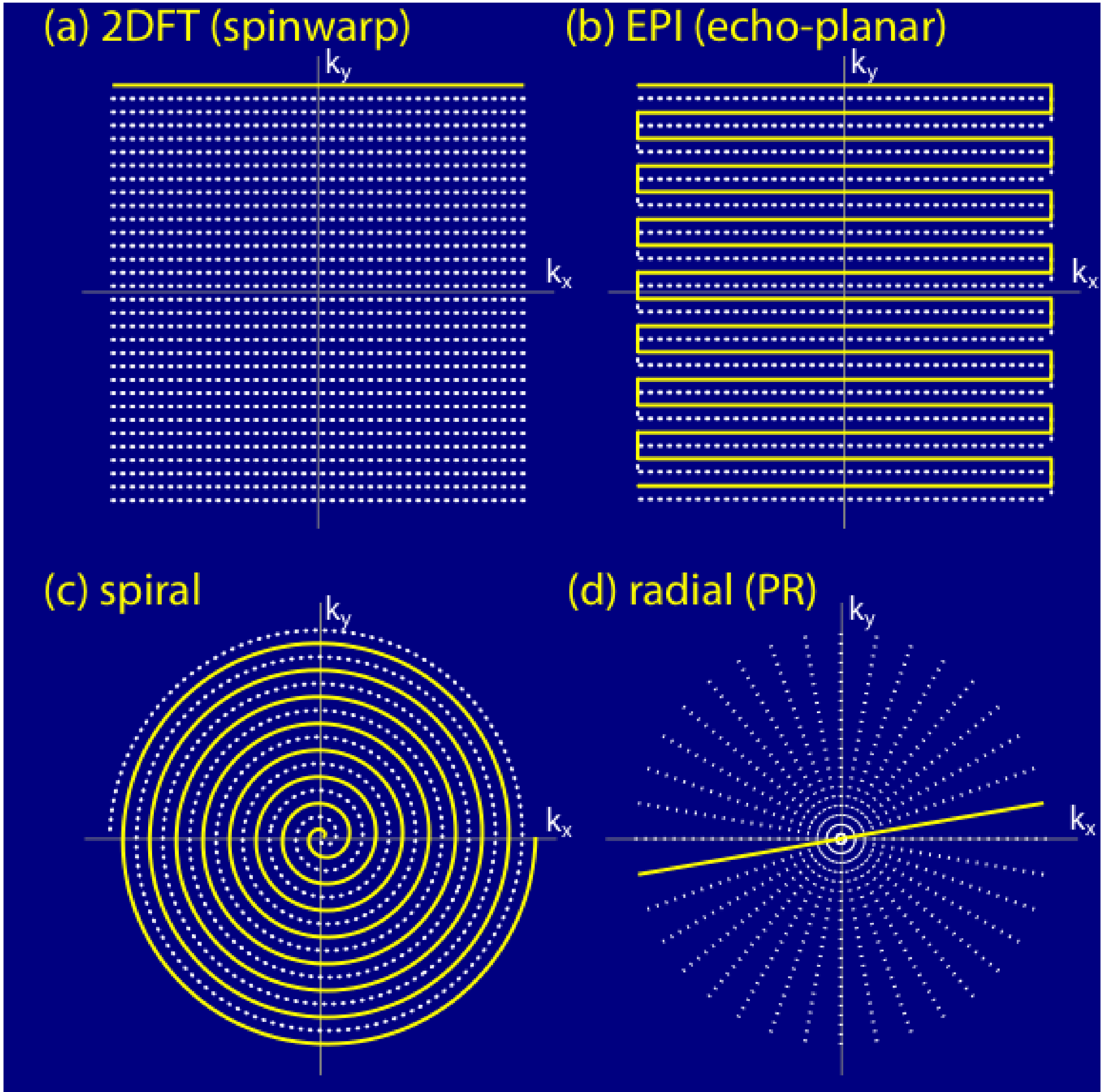


max □ive frequency

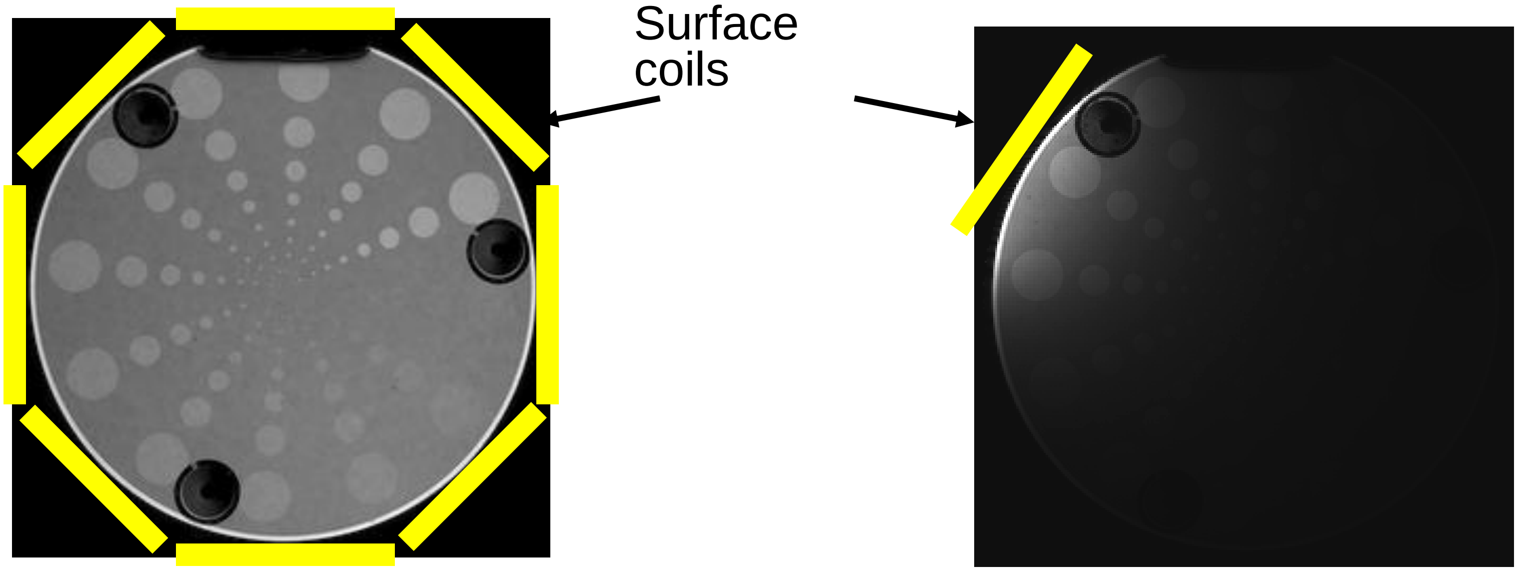
max □ive frequency


k-space
Image
Full sampling
Reduce kmax
Increase Δk
2DFT
Full-FOV,
high-res
Full-FOV,
low-res:
blurred
Low-FOV,
high-res:
may be aliased

Many possible trajectories through *k*-space…

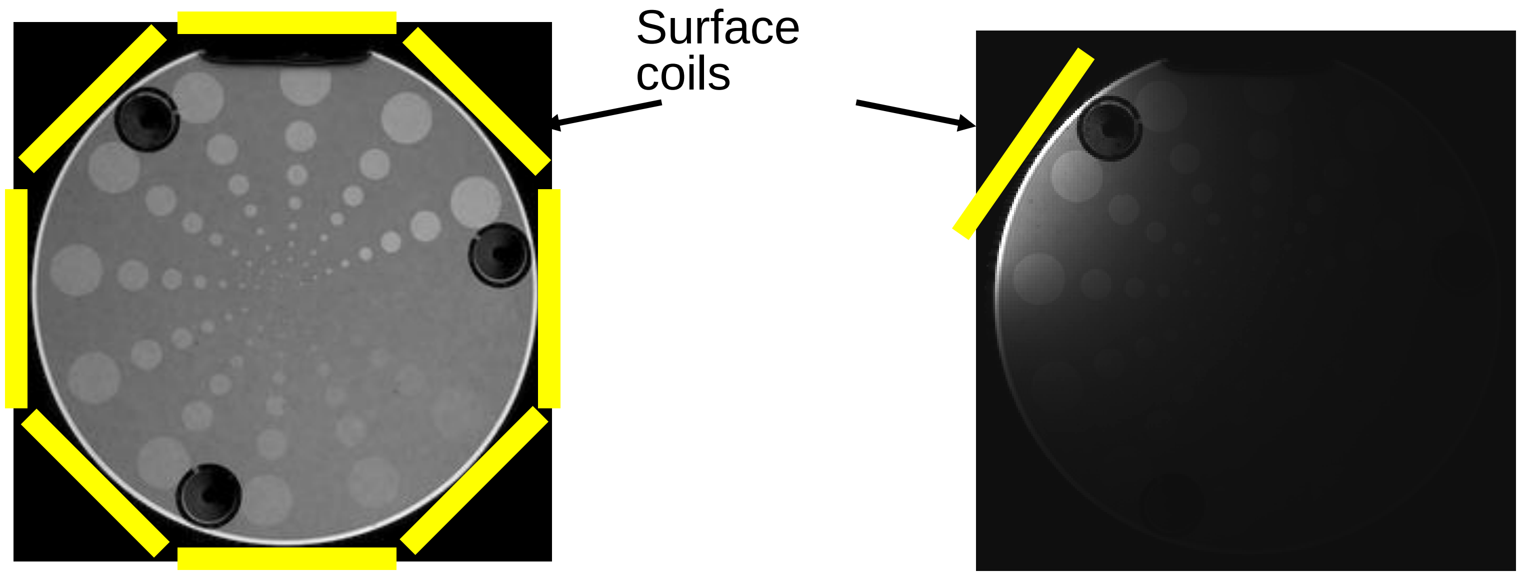


Parallel imaging
(SENSE, GRAPPA, SPIRiT, etc)



Multi-channel coils: Array of RF receive coils
Each coil is sensitive to a subset of the object

Parallel imaging
(SENSE, GRAPPA, SPiRT, etc)

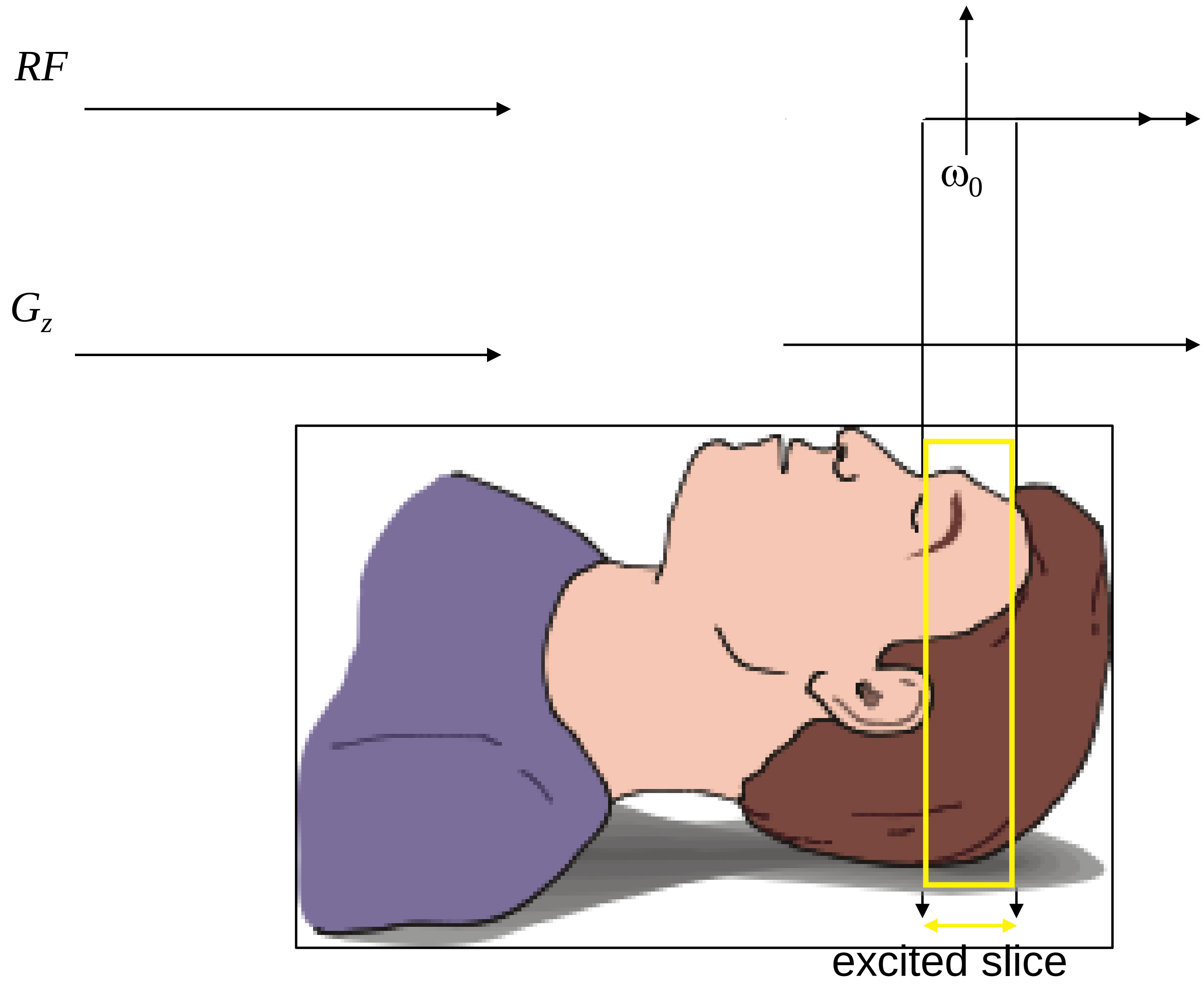


Coil sensitivity to encode additional information

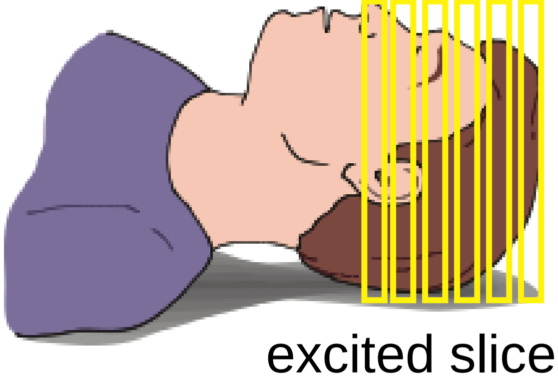
Can “leave out” large parts of k-space (more than 1/2!)

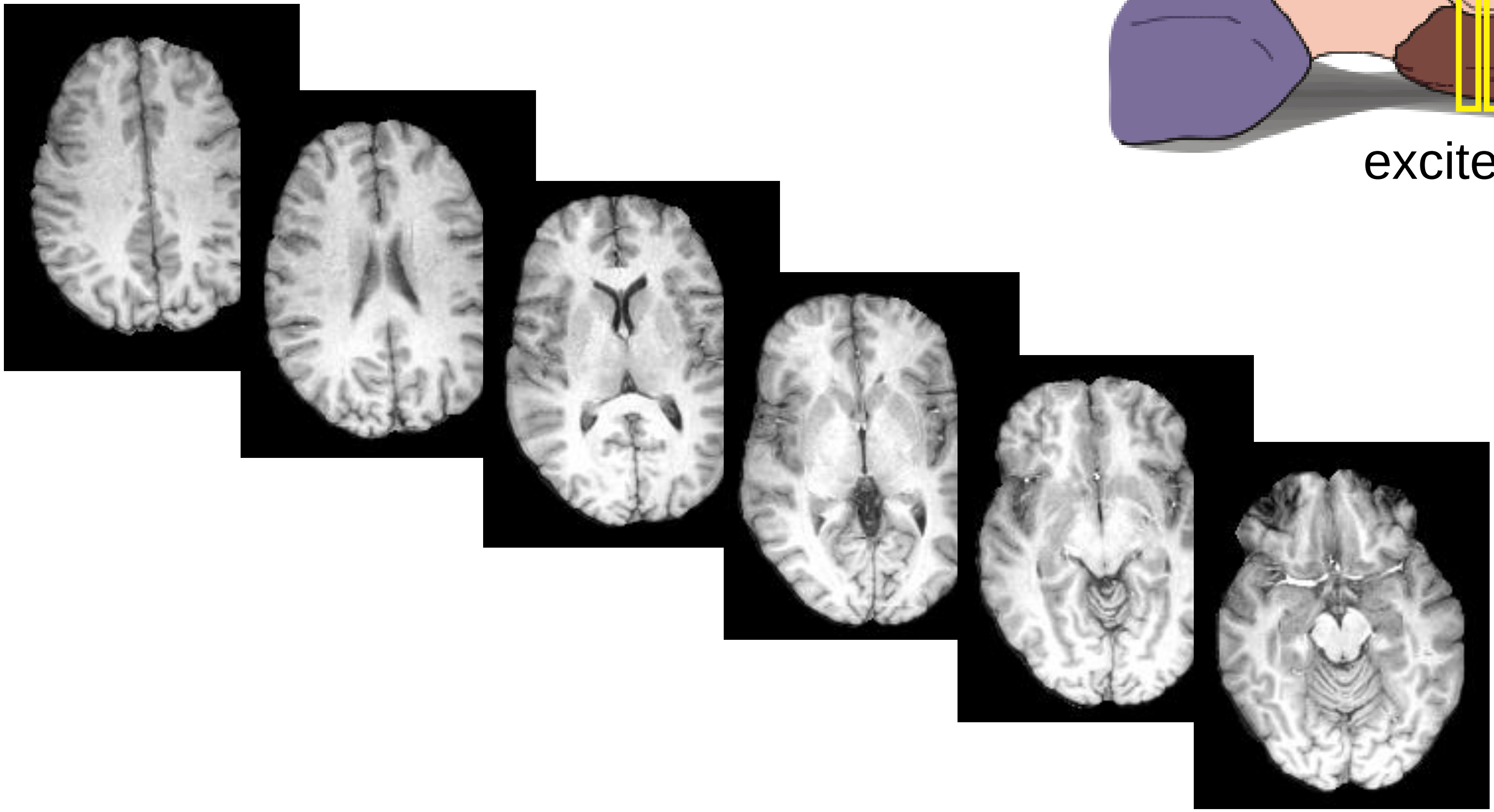
Similar uses to partial k-space (faster imaging, reduced distortion, etc),
but can go farther

Slice Selection



2D Multi-slice Imaging

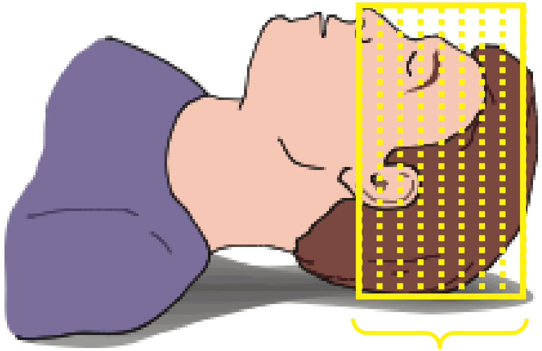




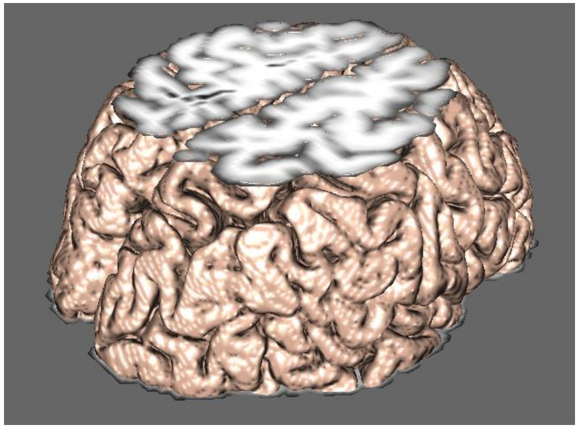
All slices excited and acquired sequentially (separately)

Most scans acquired this way (including FMRI, DTI)

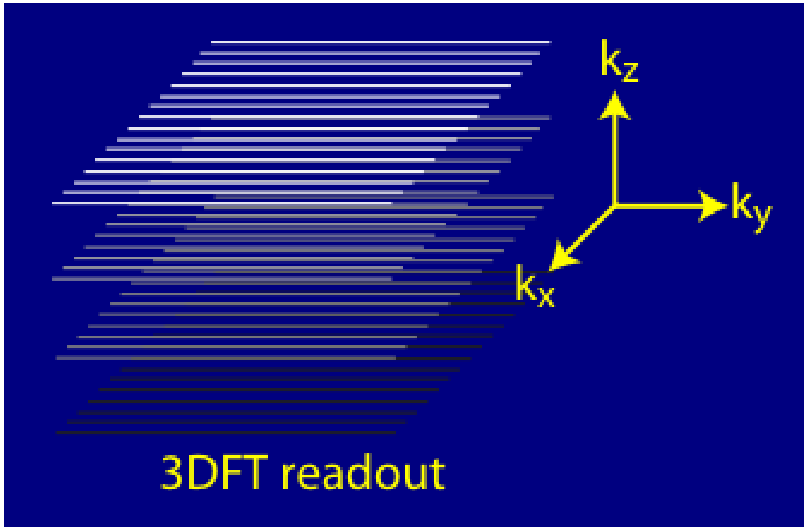
"True" 3D imaging



excited volume



excited volume



- Repeatedly excite all slices simultaneously, *k*-space acquisition extended from 2D to 3D
- Higher SNR than multi-slice, but *may* take longer
- Typically used in structural scans

Sampling Theory

- https://people.eecs.berkeley.edu/~mlustig/CS.html