Stanford University
Winter 2012 -2013

Signal Processing and Linear Systems I

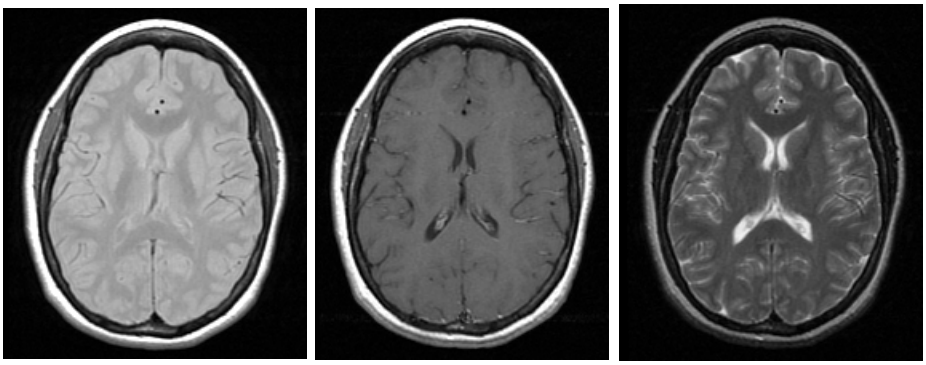
Applications 3: Magnetic Resonance Imaging

Feb 8, 2013

Magnetic Resonance Imaging (MRI)

- MRI has revolutionized medicine
  - Directly visualize soft tissues
  - No ionizing radiation
- Wide range of contrast mechanisms
  - Tissue character (solid, soft, liquid, fat)
  - Diffusion, temperature, flow, velocity
  - Oxygen saturation, metabolic imaging
  - Real-time imaging, functional imaging (fMRI)
- Based directly on Fourier transform

Neuro examples



- Many different contrasts available

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Body Examples

Abdominal Blood Vessels

Knee

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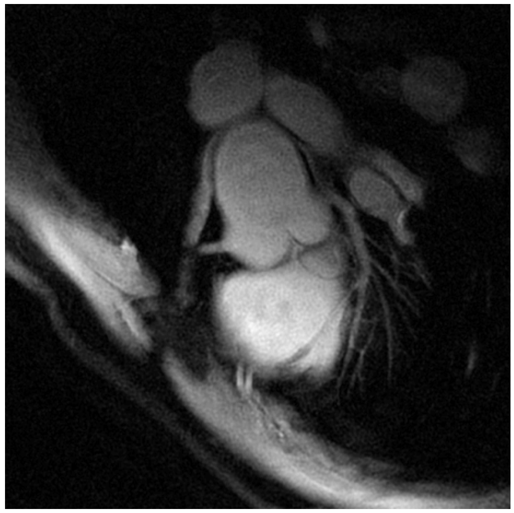
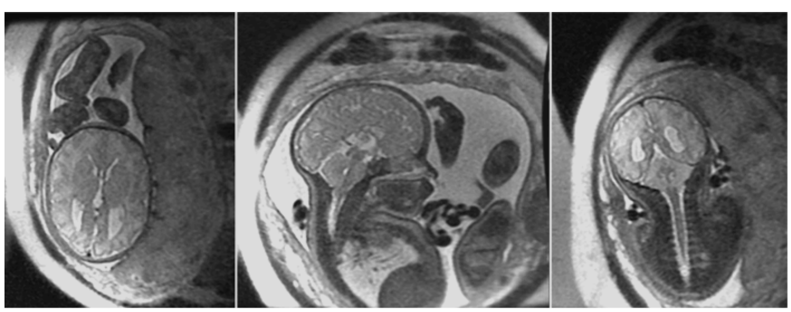
Coronary Arteries



C. Meyer, UVA

Fetal MRI



35 week old fetus with nodularity along ventricles
and failure of development of the corpus callosum

Reed Busse, PhD, GE ASL West

Reed Busse, PhD, GE ASL West

History

- **1946** - Felix Bloch (Stanford) Edward Purcell (Harvard) independently discovered NMR. Certain nuclei absorb RF energy when placed in a magnetic field. Nobel Prize (Physics) in 1952.
- **1971** - Raymond Damadian showed changes in MR parameters (T1 and T2) in cancer. People started thinking about medical NMR applications.
- **1972 –** Invention of CT by Hounsfield and Cormack. Nobel Prize (Medicine) in 1979.
- **1973** - Lauterbur described MRI using spatial magnetic field gradients and backprojection.

History

- **1975** - Ernst proposed frequency and phase encoding (combined with the FT). Nobel prize (chemistry) 1991.
- **1970's** - Mansfield contributes key ideas (slice selection, EPI).
- **1982** - Widespread clinical MRI begins.
- **2003** - Lauterbur/Mansfield receive Nobel prize (Medicine) for their contributions.

Nobel prize controversy!

- NY Times, November 2003

This Year's Nobel Prize in Medicine

The Shameful Wrong That Must Be Righted

This year the committee that awards The Nobel Prize for Physiology or Medicine did the one thing it has no right to do: it ignored the truth. Eminent scientists, leading medical textbooks and the historical facts are in disagreement with the decision of the committee. So is the U. S. Patent Office. Even Alfred Nobel's will is in disagreement. The committee is attempting to rewrite history.

The Nobel Prize Committee to Physiology or Medicine chose to award the prize, not to the medical doctor/research scientist who made the breakthrough discovery on which all MRI technology is based, but to two scientists who later made technological improvements based on his discovery.

WHAT EMINENT SCIENTISTS AND AUTHORS SAY

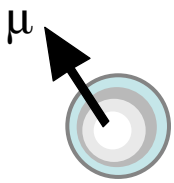
"I was stunned to learn that the Nobel Committee has apparently become so political that it is willing to overlook documented evidence (1971) for the first discovery of the substantial T1 and T2 tissue differences discovered by Damadian, which have become the foundation of all NMR imaging." — John Throck Watson, Ph. D., Professor of Biochemistry and Chemistry, Michigan State University, East Lansing, Michigan

How Does MRI Work?

- Magnetic Polarization
  -- Very strong uniform magnet
- Excitation
  -- Very powerful RF transmitter
- Acquisition
  -- Location is encoded by frequency
  -- Very powerful gradient (audio) amplifiers

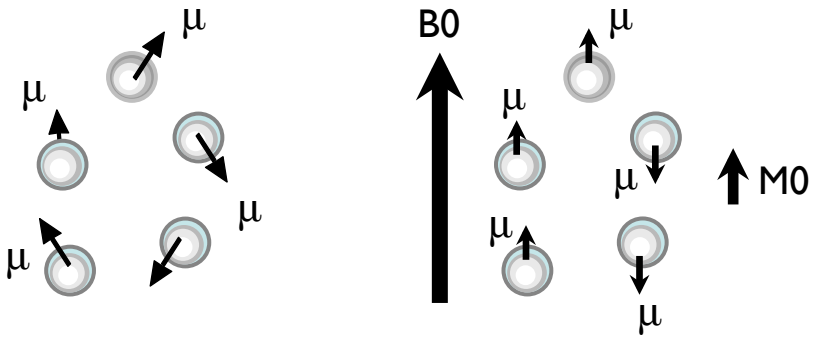
Polarization

- Protons have a magnetic moment
- Mostly the "H" in H_20
- Also "H" in fat, other organic molecules

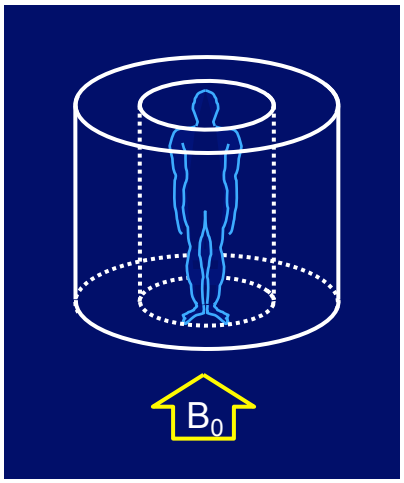


Polarization

- Body has a lot of protons
- In a strong magnetic field B0, slightly more align with B0 giving a net magnetization, M0



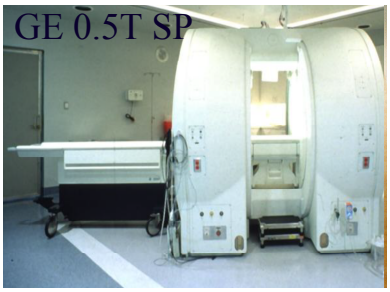
Polarizing Magnet

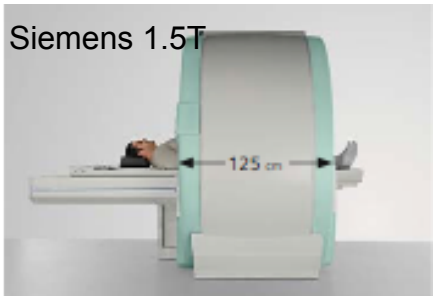


- 0.1 to 12 Tesla
- 0.5 to 3 T common
- 1 T = 10,000 Gauss
- Earth's field ~ 0.5G
- Typically a superconducting magnet, cryogenically cooled (liquid He)

Typical 1.5T MRI System

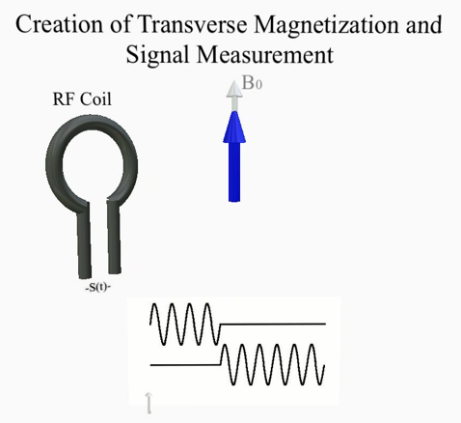
Other systems





The magnet is strong! (And always on!)

Excitation



- Spins absorb energy at characteristic frequency

$$\omega_0 = \gamma B_0$$
$$\gamma = 2\pi * 4.257 \text{ kHz/G}$$

- Magnetization
  - tips away from B0
  - precesses at ω_0

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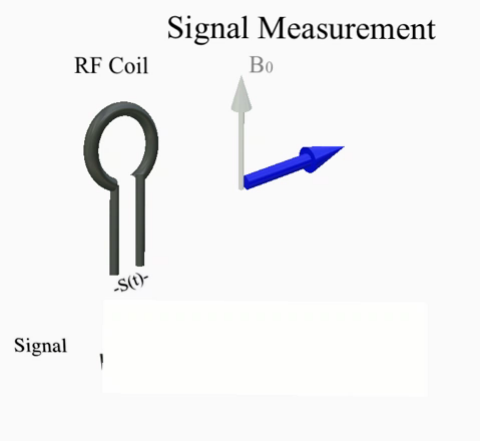
Reception



- Precessing magnetization induces voltage in coil.
- Again

$$\omega_0 = \gamma B_0$$

- Frequency is proportional to B0

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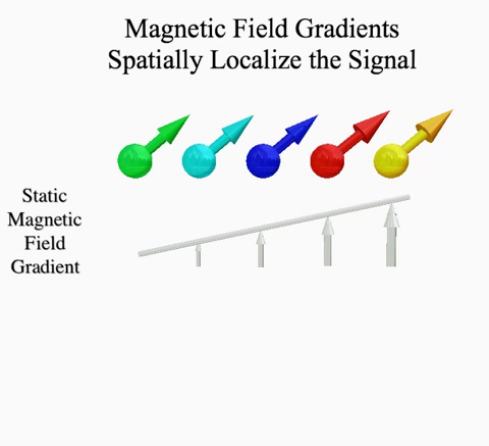
Spatial Encoding



- Add a spatial variation in B0 that is proportional to x

$$\omega(x) = \gamma(Gx + B_0)$$

- Each spin has a unique frequency
- Signal is sum from all spins
- Spectrum tells you where signal came from

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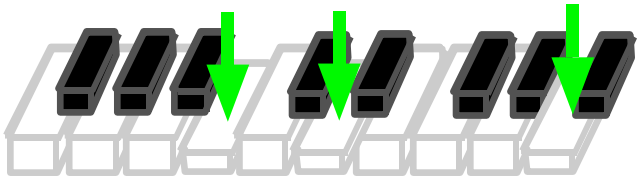
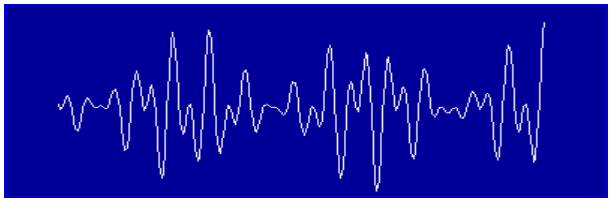
Piano Analogy



Spectrum



Time
Signal

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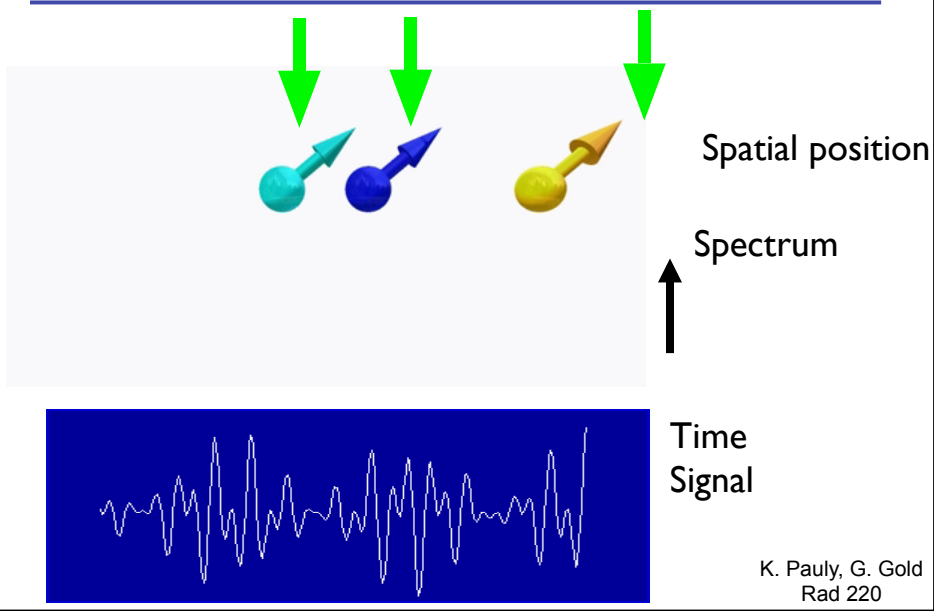
Piano Analogy



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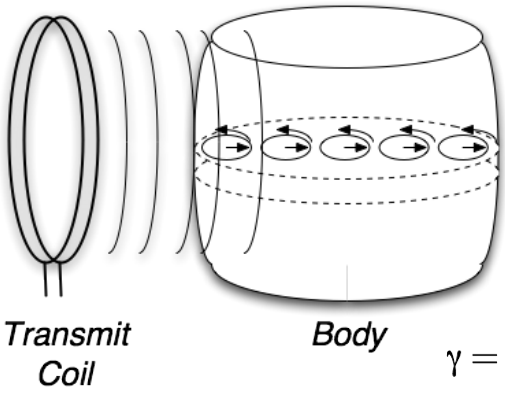
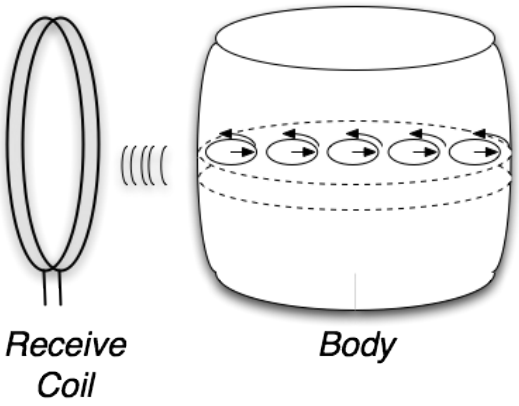
MRI: Excitation



$$\omega_0 = \gamma B_0$$
$$\gamma = 2\pi * 4.257 \text{ kHz/G}$$

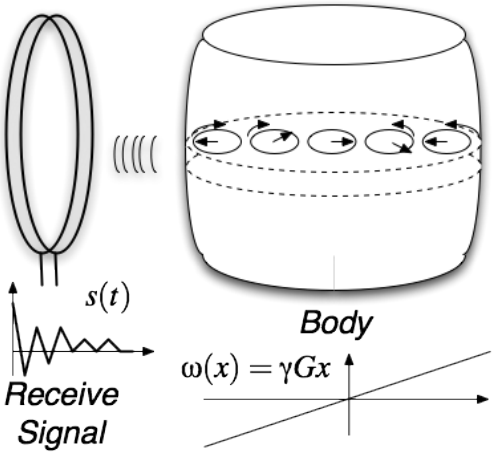
- Spins absorb energy at characteristic frequency ω_0
- Magnetization tips away from B0 and precesses at ω_0

MRI: Reception



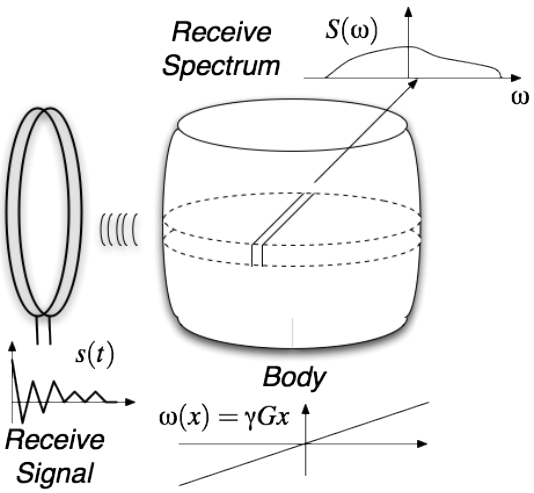
- Spins continue to precess
- Emit small RF signal that can be picked up with receive coil
- Frequency is proportional to field strength

MRI: Spatial Encoding



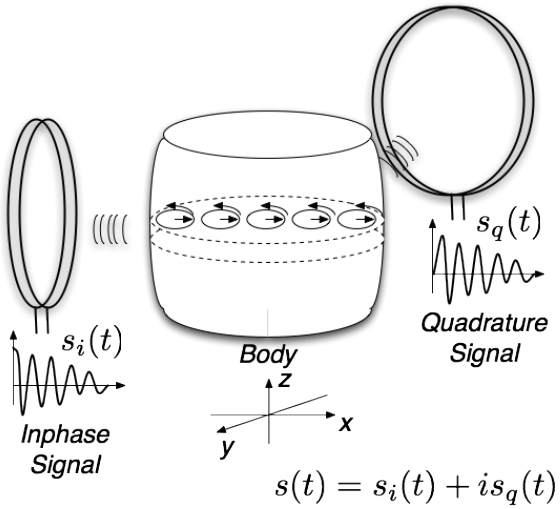
- Linear variation in frequency
- Frequency corresponds to position

MRI: Spatial Encoding



- Spectrum shows how many spins at each position
- Projection of the object
- Many projections would allow reconstruction

Complex Signal



$$s(t) = s_i(t) + i s_q(t)$$

- Receive x and y components
- Consider these as real and imaginary components of complex vector
- Positive and negative frequencies have different physical significance

MR Signal

- Magnetization $m(x)$ is a function of space (1D for now)
- Gradient in x results in frequency

$$\omega(x) = \gamma G x$$

- Spin at position x produces a signal

$$m(x)e^{-i\gamma G x t}$$

- The receive coil sees all of the spins

$$s(t) = \int_X m(x)e^{-i\gamma G x t}dx$$

Spatial Frequency

- The signal can be written as

$$s(t) = \int_X m(x)e^{-i(\gamma G t)x}dx$$

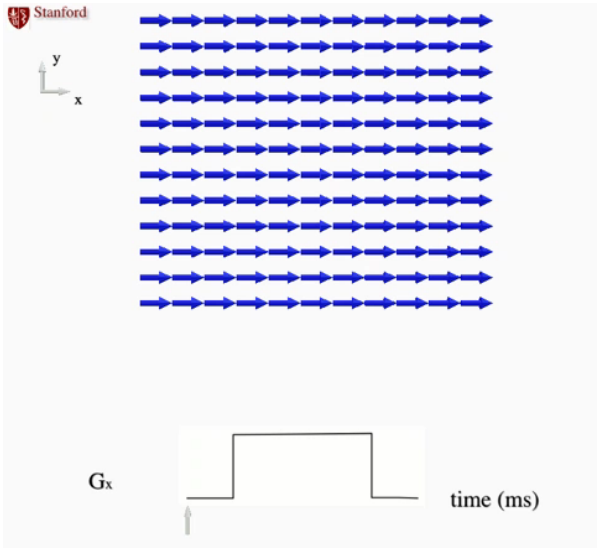
- Compare this to

$$F(j\omega) = \int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt \qquad \begin{array}{r} x \rightarrow t \\ \gamma G t \rightarrow \omega \end{array}$$

- The term $\gamma G t$ is spatial frequency in cycles/cm,

$$k_x(t) = \gamma G t$$

Spatial Frequency



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Spatial Frequency

- Linear variation in frequency produces a complex exponential in space.
- The MR signal is then

$$s(t) = \int_X m(x) e^{-ik_x(t)x} dx$$

- The signal $s(t)$ is the Fourier transform of $m(x)$ evaluated at the spatial frequency $k_x(t)$.

Signal Equation

- Images are multidimensional (2D, 3D, 4D)
- We need to acquire spatial frequencies in all directions

$$s(t) = \int_X \int_Y m(x,y) e^{-i(k_x(t)x + k_y(t)y)} dy\ dx$$

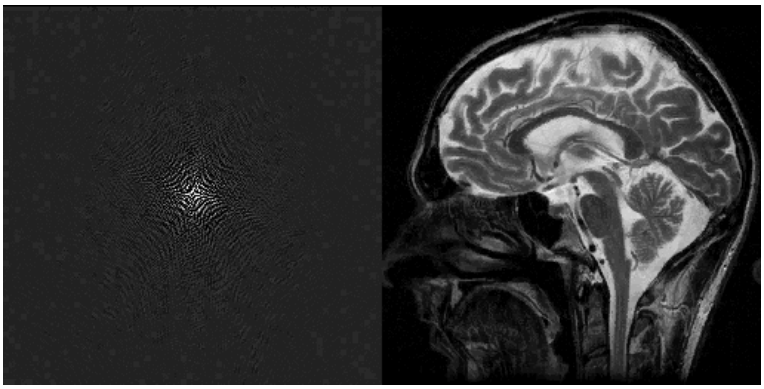
- The 2D Fourier transform is

$$M(k_x, k_y) = \int_X \int_Y m(x,y) e^{-i(k_x x + k_y y)} dy\ dx$$

- The received signal is a sample of the 2D Fourier transform

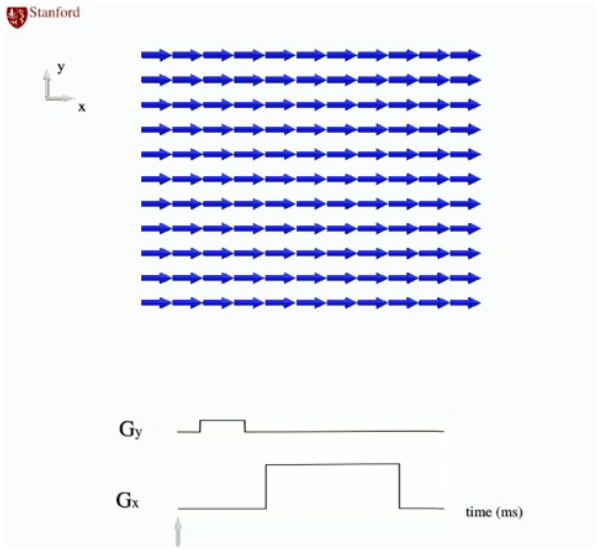
$$s(t) = M(k_x(t), k_y(t))$$

Spatial Frequency Data



Spatial Frequency Image Space

2D Acquisition



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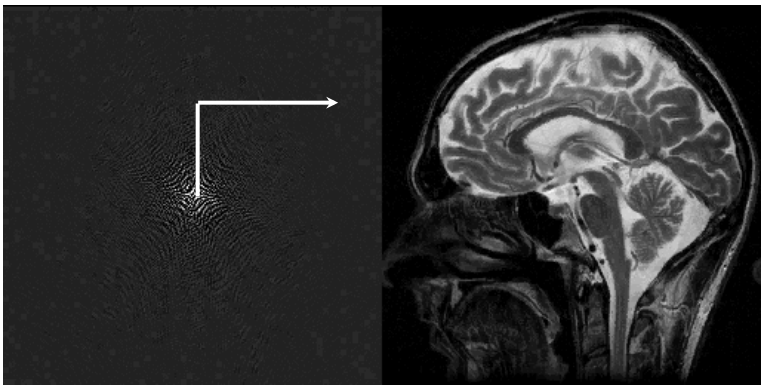
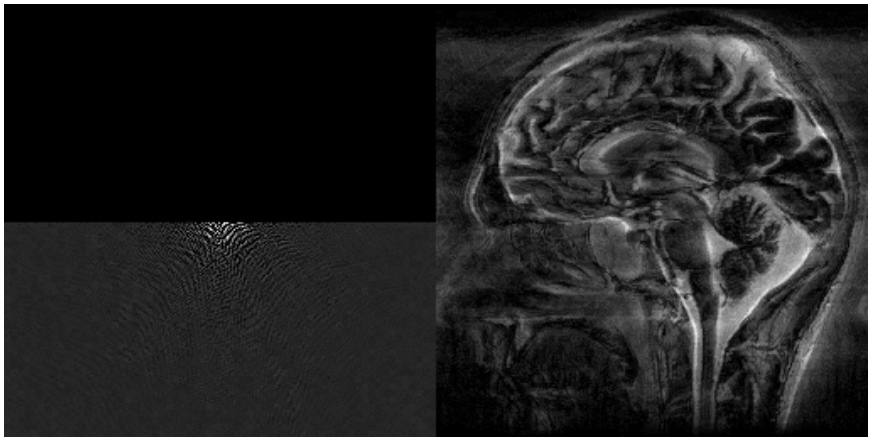
Spatial Frequency Data

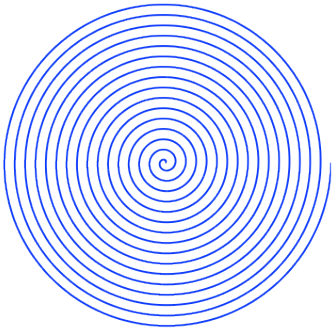


Spatial Frequency Image Space

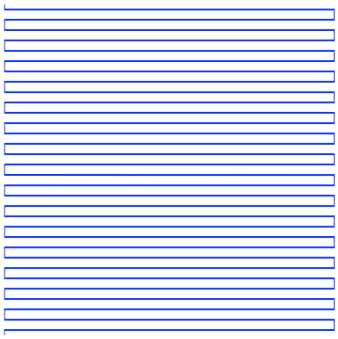
MR Data Acquisition



Other Acquisition Methods

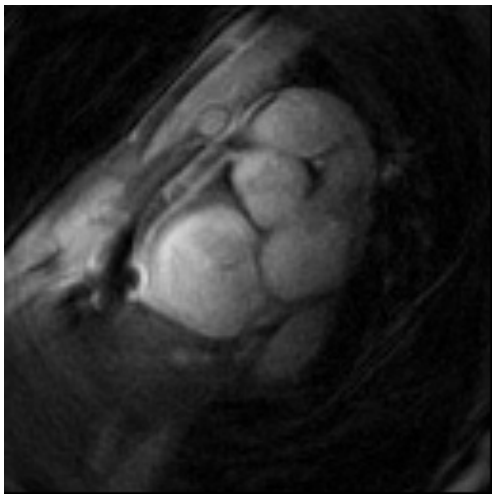


Spiral



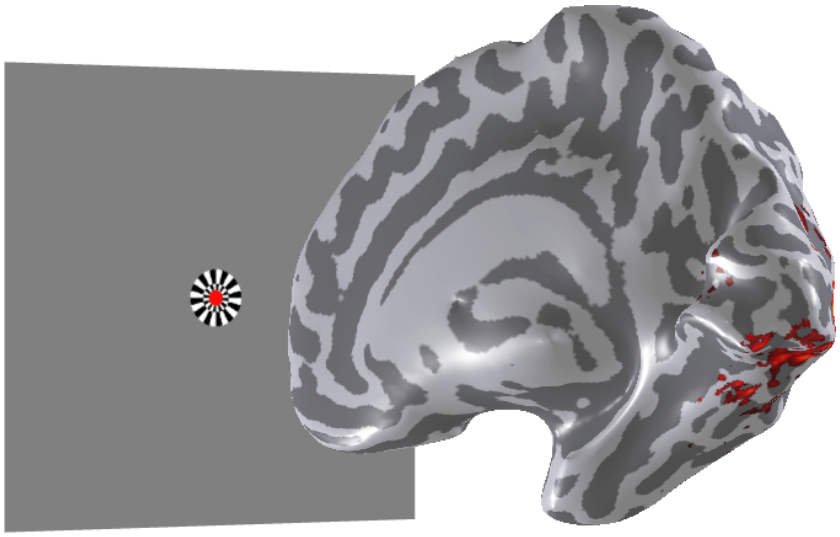
Echo-Planar (EPI)

Real-Time Spiral MRI



- Coronary Artery
- 3T scanner
- 10 images/sec

Visual Field Mapping with fMRI



Jin Hyung Lee, Serge Dumoulin, Stanford

Summary

- MRI makes your body produce a signal that is its own Fourier transform!
- Frequency is proportional to object position
- Signal spectrum is projection of the object
- Reconstruction is a simple inverse Fourier transform