Northeastern University
College *of* Engineering

Optical Science Northeastern University Laboratory

Biomedical Imaging
Magnetic Resonance Imaging

Charles A. DiMarzio & Eric Kercher
EECE–4649
Northeastern University

May 2018

Background and History

- Measurement of Nuclear Spins
  - Widely used in physics/chemistry labs (Absorption)
  - First Medical applications in the 1980s (Wiggles)
  - Improvement over Decades with Computer Technology
- NMR = Nuclear Magnetic Resonance
  - But you can't say "Nuclear" to Patients!
  - Not about ionization
  - Not about bombs
- Marketable name: Magnetic Resonance Imaging

Larmor Precession

- An object with magnetic moment μ is placed in an external magnetic field $\mathbf{B}$. Torque τ is applied on the object:

$$\tau = \mu \times \mathbf{B} \tag{1}$$

- Torque causes the object to rotate at a frequency proportional to the applied field, i.e., the Larmor frequency

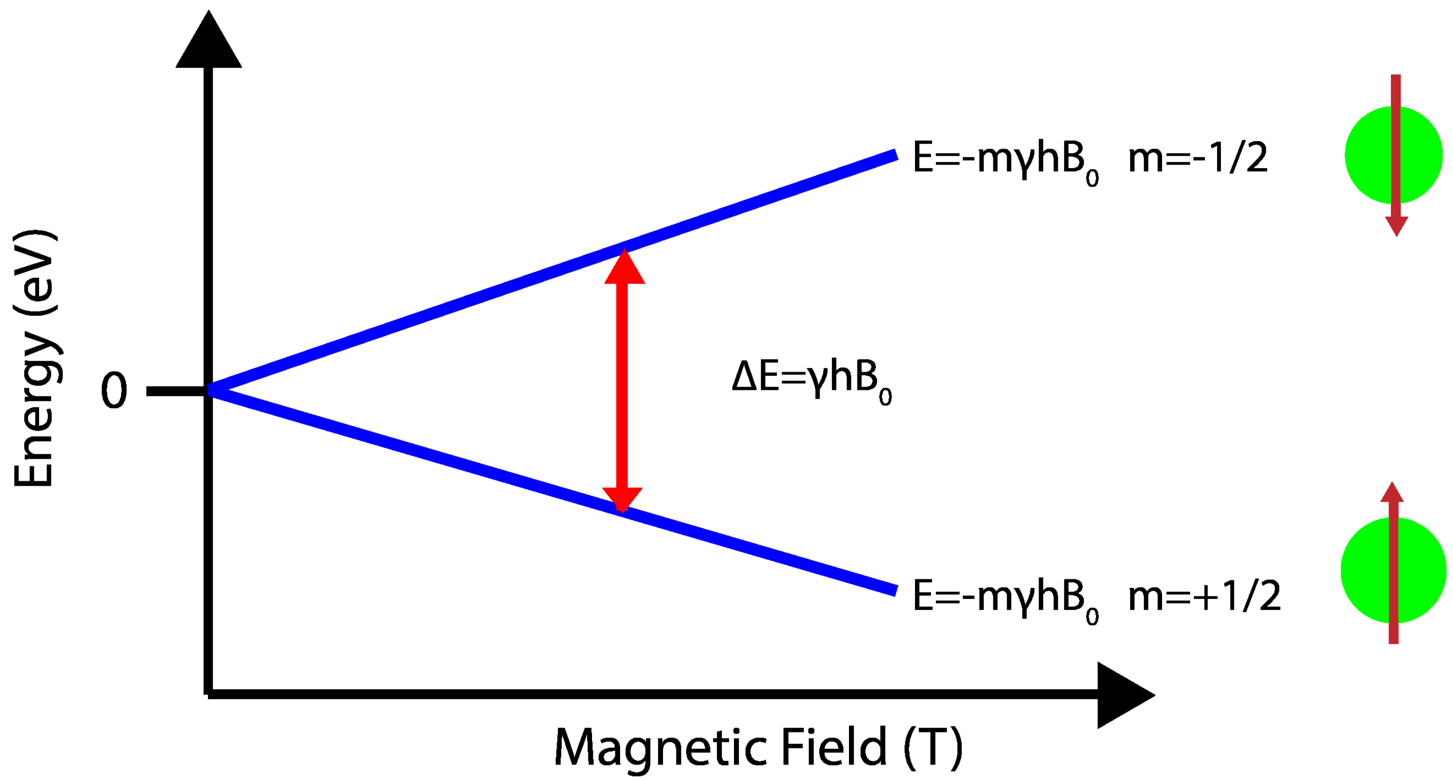
$$\omega = \gamma B \tag{2}$$

- γ is the gyromagnetic ratio, which depends on the properties of the object

$$\gamma = \frac{|e|}{2m} g \tag{3}$$

Zeeman Effect

- Spin-state energy levels "split" under an applied magnetic field



Magnetization

- Convenient to talk about bulk material properties.

- Imagine a material with many objects "spinning" in random directions...

- Result of a external magnetic field is two-fold:
  - Torque causes precession at $\omega = \gamma B$ around the B field.
  - Two spin states "appear"; spin up $(+1/2)$ and spin down $(-1/2)$. These are also aligned with the B field.

- The material now has a net magnetization $\mathbf{M} = \sum_i m_i$.

Population Difference

- Spin states populated in a Boltzmann distribution. Most spins will align with B field (low energy state), but some will be anti-aligned!

- Fields in a few Teslas, Larmor frequencies in Tens of MHz.

- Photon Energies $\approx 10^{-26}$ Joules
  (Below μEv)

$$N_{upper}/N_{lower} \approx e^{-hf/kT} = 10^{-5}$$

- but $N \approx N_A/$ cm^3

$$N_{upper} - N_{lower} \approx 10^{-18}/\ \text{cm}^3$$

MRI Imaging

- "Excite" spins into the higher energy state.
  - Use RF pulses to "Flip" $\mathbf{M}$
  - If half the spins flip $\rightarrow \mathbf{M}$ rotates 90 degrees
  - If most of the spins flip $\rightarrow \mathbf{M}$ rotates 180 degrees
- Let spins relax back to equilibrium. $\mathbf{M(x,y,z,t)}$ is 4D!
  - M_z: Longitudinal relaxation
  - M_x, M_y: Transverse relaxation
- Reconstruct image from collected signals.

Bloch Equations

$$\frac{dM_{x'}}{dt} = (\omega_0 - \omega)\, M_{y'} - \frac{M_{x'}}{T_2}$$

$$\frac{dM_{y'}}{dt} = -(\omega_0 - \omega)\, M_{x'} - \frac{M_{y'}}{T_2} + 2\pi\gamma B_1 M_z$$

$$\frac{dM_z}{dt} = -\frac{M_z - M_{z0}}{T_1} - 2\pi\gamma B_1 M_y$$

Green Terms are Rotation "Error"

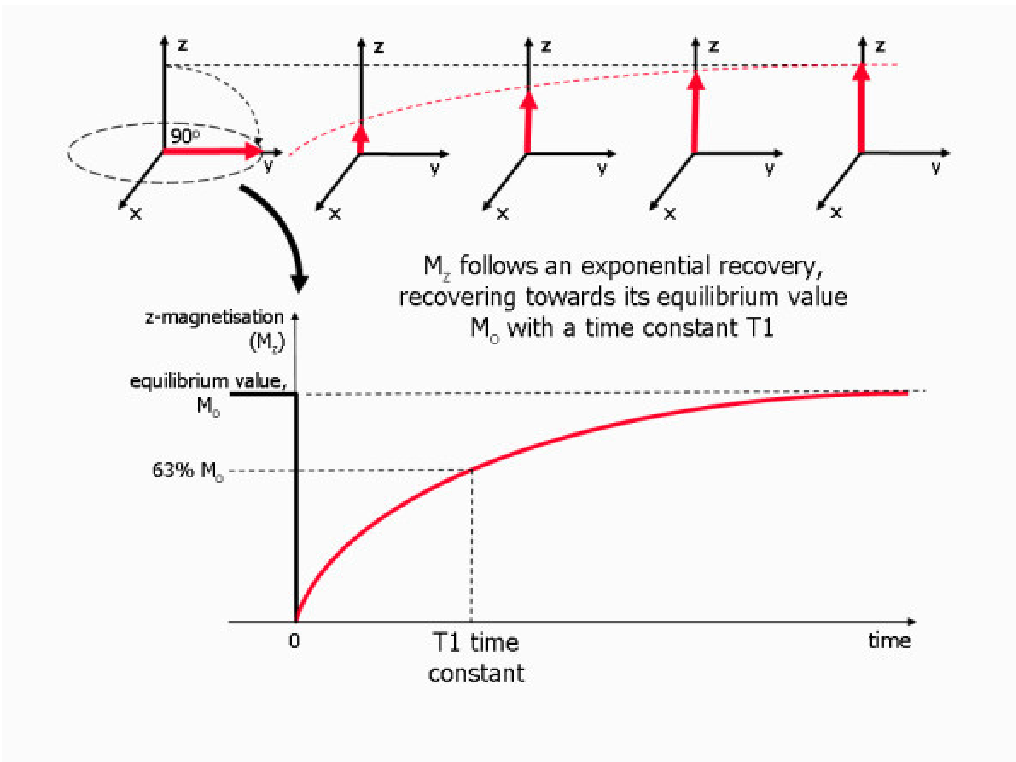
Red Term is Decay

B_1 is RF field parallel to $\hat{x}$

Blue Terms are Dephasing

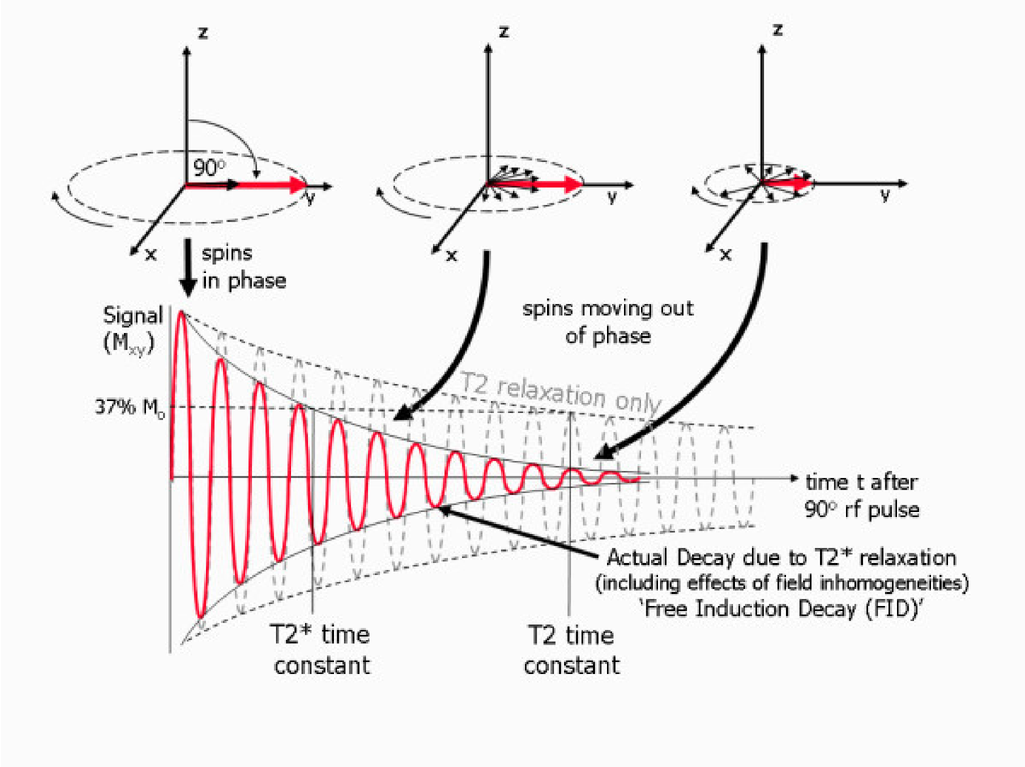
Longitudinal Relaxation - T1

- AKA Spin-Lattice relaxation, applies to the z-component of $\mathbf{M}$. Natural decay from spins flipping back to low energy state (thermal decay).



Transverse Relaxation - T2

- AKA Spin-Spin relaxation, applies to the xy-components of $\mathbf{M}$. Spins in phase create coherent M_{xy} vector (rotating at ω). Signal decays as spins de-phase. Local field imhomogeneities cause faster-than-expected decay $\rightarrow$ T2*.



Decay Times

- T1 and T2 decay happen simultaneously. Put together:

$$S = k\rho\left(1 - e^{-T_R/T_1}\right)e^{-T_E/T_2}$$

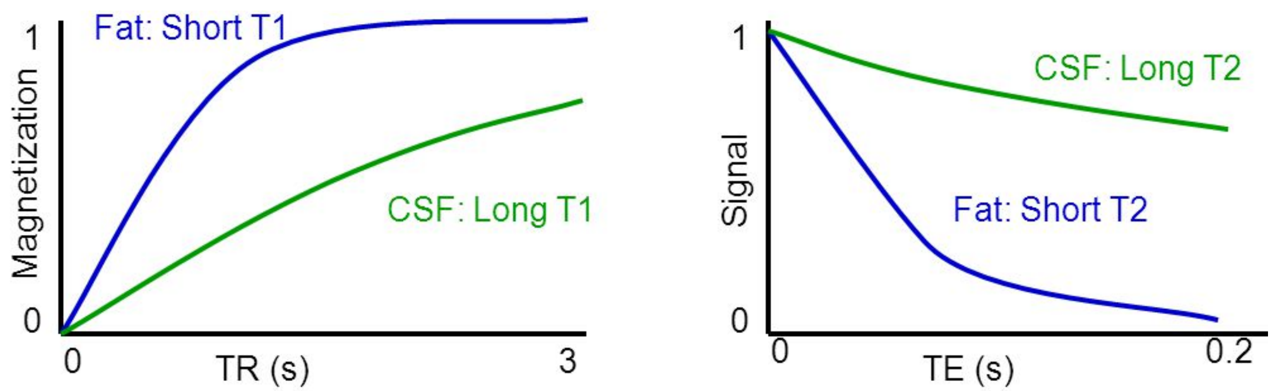
- Rule: $T_1 > T_2$.

Parameter to Which Signal is Sensitive

	T_R Long	T_R Med	T_R Short
T_E Long	0	0	0
T_E Med	T_2		0
T_E Short	ρ	T_1	0

Contrast

- Endogenous contrast comes from differences in bulk tissue properties:
  - Water, fat: Lots of $^1H \rightarrow$ High signal (Most of body)
  - Bone: Not as much signal
- Tissues have varying T1 and T2. Compare Fat and CSF:

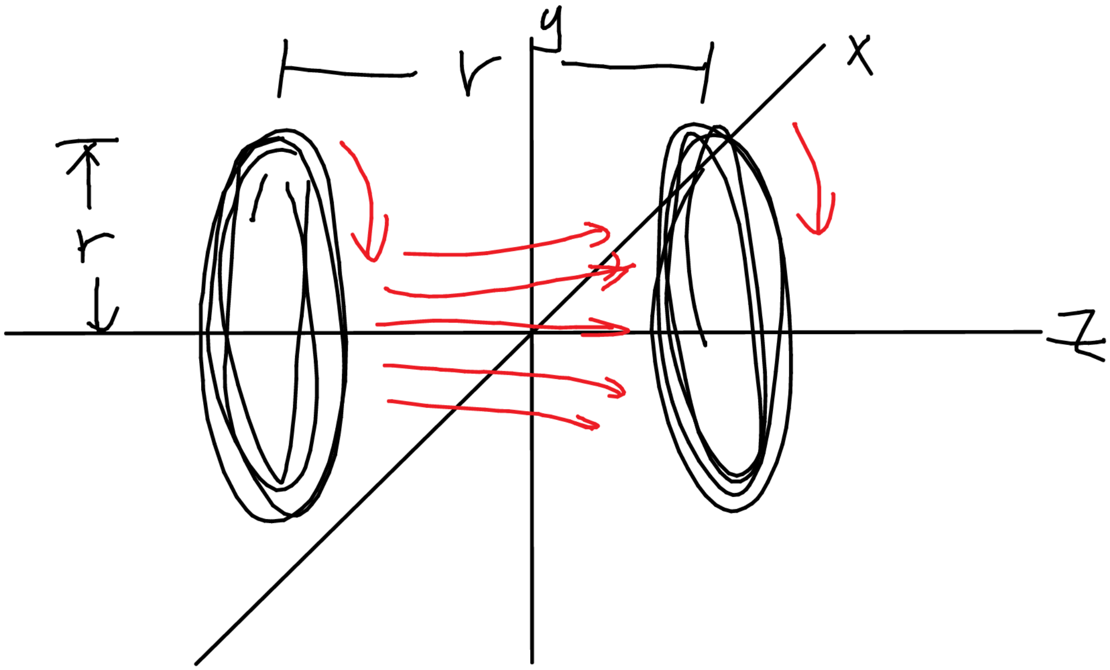


Contrast Agents

- Exogenous contrast alters T1 and T2 to boost contrast
- Gadolinium
  -
  -
- Iron Oixide Nanoparticles (Ferumoxytol)
  -
  -

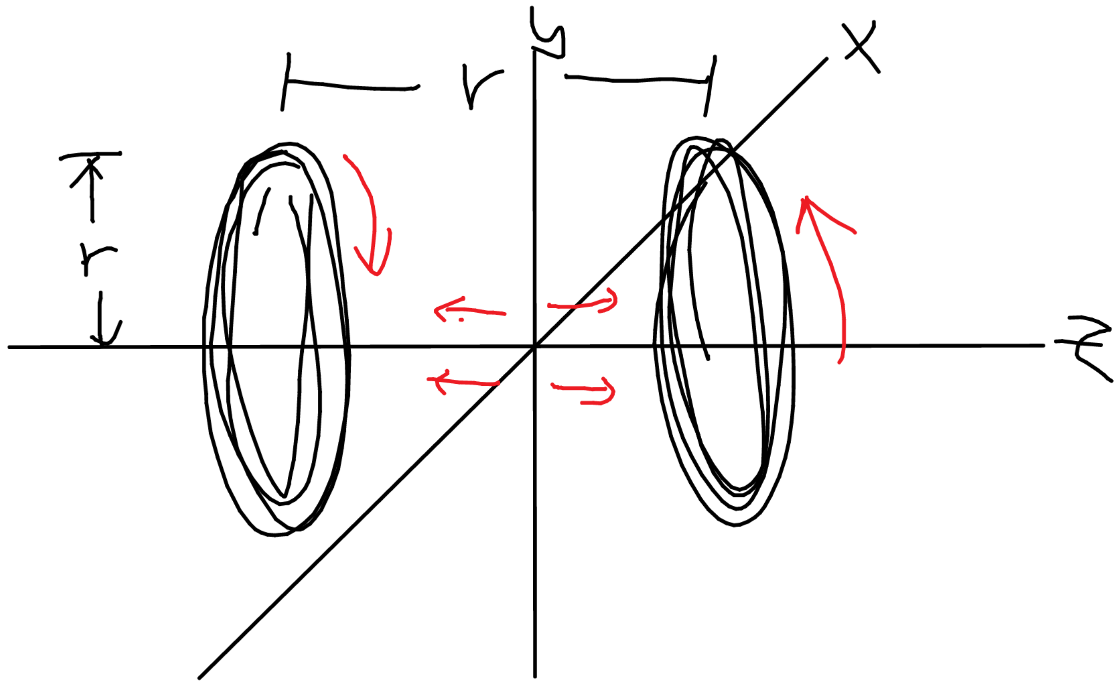
Helmholtz Coils

Large, Uniform, DC Magnetic Field



Anti–Helmholtz Coils

Moderate Field Gradient (More is Better)



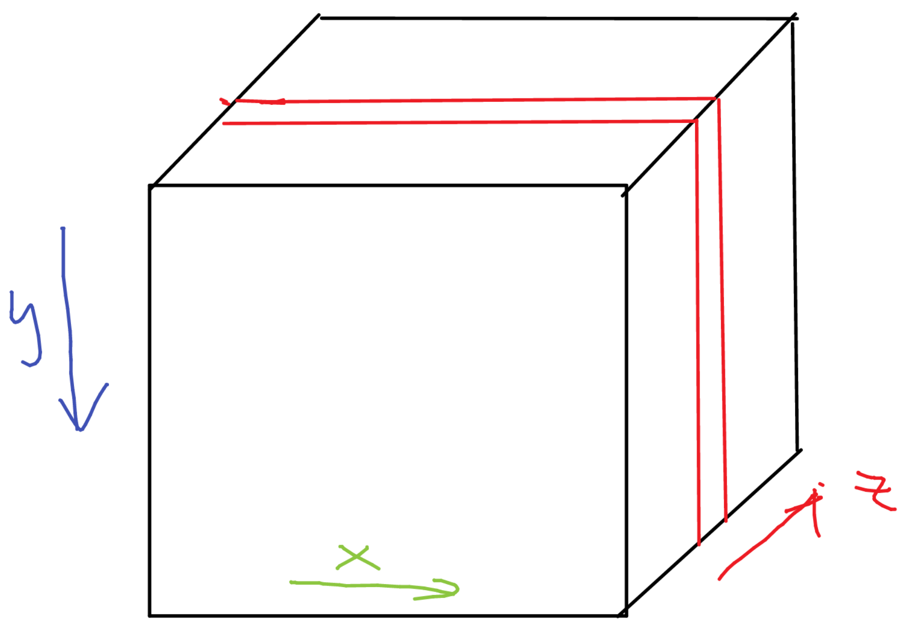
Big Fields: Big Problems

- Large Coils for Uniform Field
- High Current for High Field
- Superconductors
- Liquid Helium
- High Cost
- B Field Hazards $\rightarrow$
- dB/dt: Loud Noise
- Start/Stop Challenges

Slice Selection

Excite with Narrow–Band RF Signal, $B = B_0 + G_z z$

$$\omega = \gamma B_0 + \gamma G_z z$$



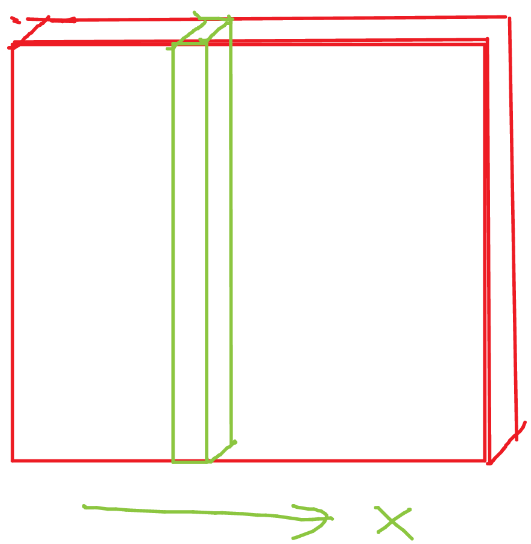
Slice Selection

Match the Resonant Frequency

Column Measurement

Sort Detected Signal by Frequency, $B = B_0 + G_x x$

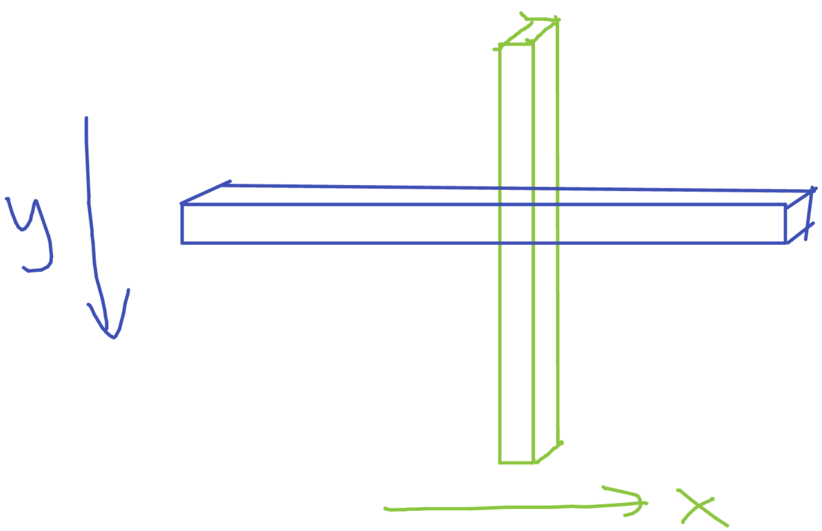
$$\omega = \gamma B_0 + \gamma G_x x$$



Row Measurement

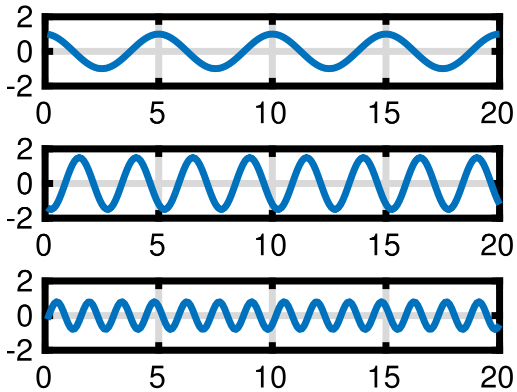
Sort Detected Signal by Phase, $B = B_0 + G_y y$

$$\omega = \gamma B_0 + \gamma G_y y$$

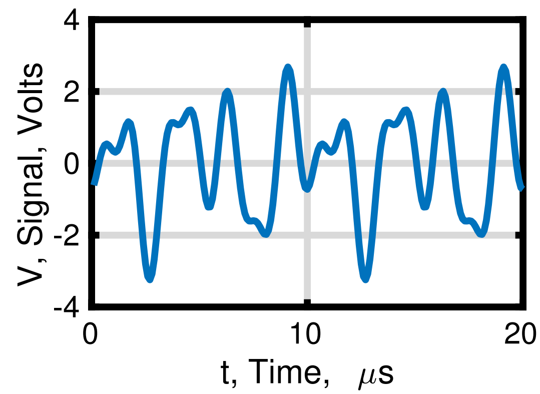


Fourier Transforms

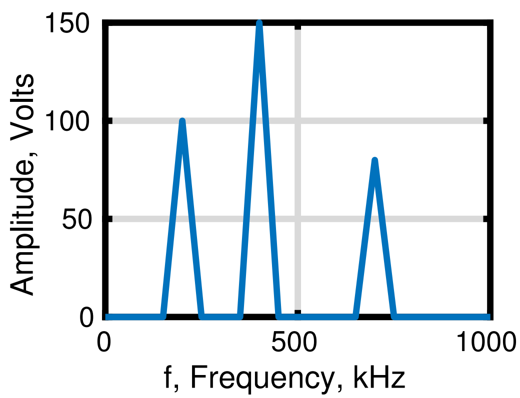
Signals *vs.* Time



Fourier Transform of Sum (Amplitude)



Sum Signal *vs.* Time



Fourier Transform of Sum (Phase)