MRI Physics I: Spins, Excitation, Relaxation

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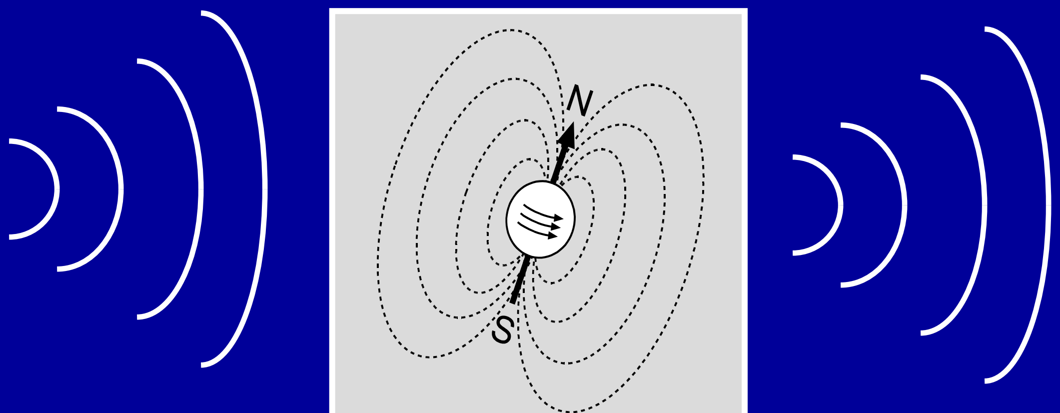
Outline

- Introduction to Nuclear Magnetic Resonance Imaging
  - NMR Spins
  - Excitation
  - Relaxation
  - Contrast in images

MR Principle

Magnetic resonance is based on the emission and absorption of energy in the radio frequency range of the electromagnetic spectrum by nuclear spins



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Historical Notes

- In 1946, MR was discovered independently by Felix Bloch and Edward Purcell
- Initially used in chemistry and physics for studying molecular structure (spectrometry) and diffusion
- In 1973 Paul Lauterbur obtained the 1st MR image using linear gradients
- 1980's: MRI was widely commercialized for clinical
- 1990's: fMRI spread rapidly
- 2000's: era of new fast imaging methods
- 2010's: tech advances, high field, standardization
- 2020's: machine learning, low field?

Important Events in the History of MRI

- 1946 MR phenomenon - Bloch & Purcell
- 1950 Spin echo signal discovered - Erwin Hahn
- 1952 Nobel Prize - Bloch & Purcell
- 1950 - 1970 NMR developed as analytical tool
- 1963 Doug Noll born
- 1972 Computerized Tomography
- 1973 Backprojection MRI - Lauterbur
- 1975 Fourier Imaging - Ernst (phase and frequency encoding)
- 1977 MRI of the whole body - Raymond Damadian
  Echo-planar imaging (EPI) technique - Peter Mansfield
- 1980 Spin-warp MRI demonstrated - Edelstein
- 1986 Gradient Echo Imaging NMR Microscope
- 1988 Angiography – O'Donnell & Dumoulin
- 1989 Echo-Planar Imaging (images at video rates = 30 ms / image)
- 1991 Nobel Prize - Ernst
- 1992 BOLD Functional MRI (fMRI)
- 1994 Hyperpolarized ^{129}Xe Imaging
- 1997 Parallel MRI
- 2003 Nobel Prize – Lauterbur & Mansfield
- 2007 Sparse sampling/compressed sensing
- 2010 Multiband (simultaneous multislice) MRI
- 2017 FDA approval of 7T, the machine learning craze

MR Physics

- Based on the quantum mechanical properties of nuclear spins

- Q. What is SPIN?
- A. Spin is a fundamental property of nature like electron charge or mass. Spin comes in multiples of 1/2 and can be + or –.

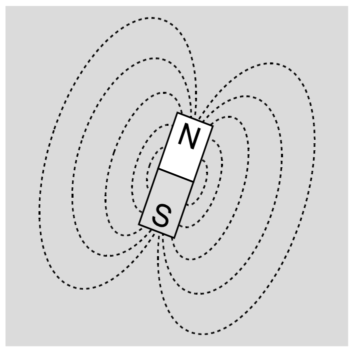
Properties of Nuclear Spin

Nuclei with:

- Odd number of Protons
- Odd number of Neutrons
- Odd number of both

exhibit a net MAGNETIC MOMENT

(e.g. ^{1}H, ^{3}He, ^{31}P, ^{23}Na, ^{17}O, ^{13}C, ^{19}F)



Pairs of spins take opposing states, cancelling the observable effects.

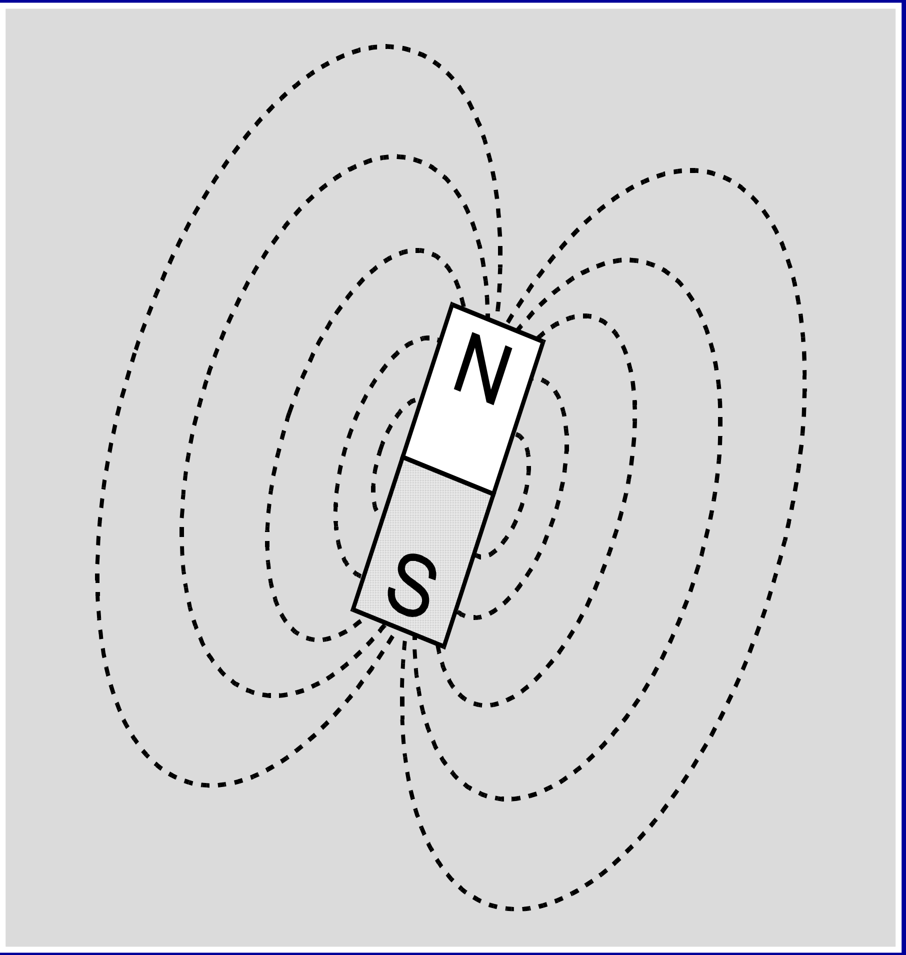
(e.g. ^{16}O, ^{12}C)

Common NMR Active Nuclei

Isotope	Spin *I*	% natural abundance of isotope	γ MHz/T	elemental abundance in body
^{1}H	1/2	99.985%	42.575	63%
^{2}H	1	0.015%	6.53	63%
^{13}C	1/2	1.108%	10.71	9.4%
^{14}N	1	99.63%	3.078	1.5%
^{15}N	1/2	0.37%	4.32	1.5%
^{17}O	5/2	0.037%	5.77	26%
^{19}F	1/2	100%	40.08	0%
^{23}Na	3/2	100%	11.27	0.041%
^{31}P	1/2	100%	17.25	0.24%

Bar Magnet

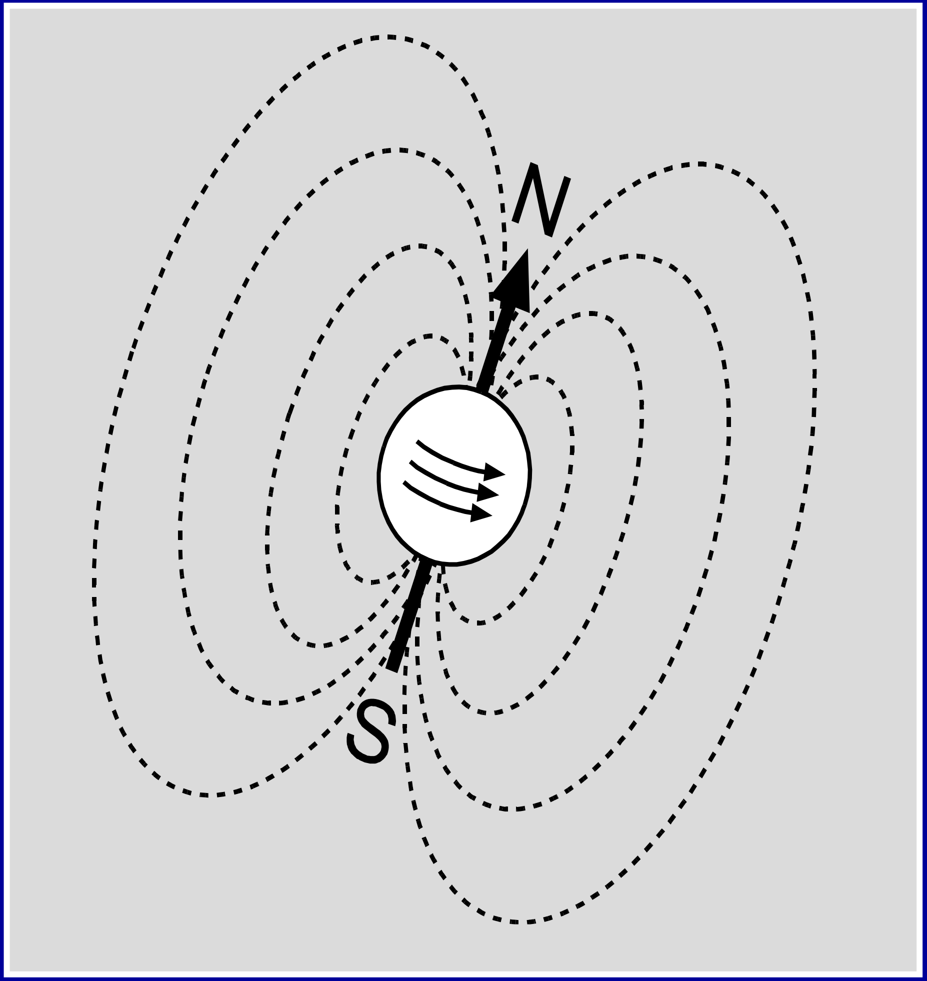
Bar Magnets "North" and "South" poles



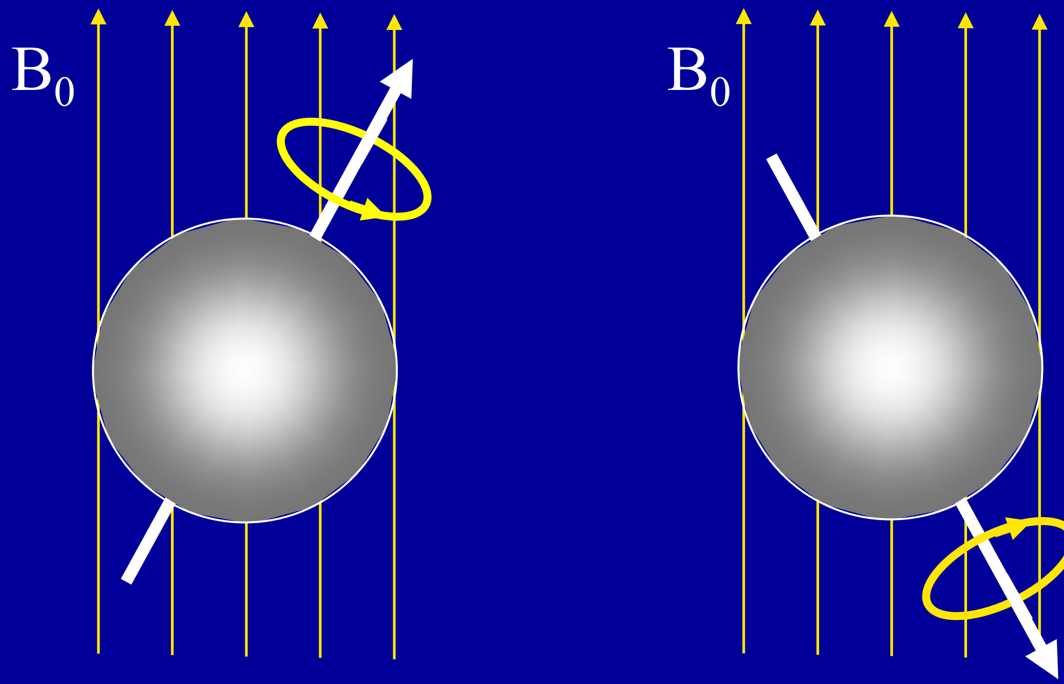
A “Spinning” Proton

A “spinning” proton generates a tiny magnetic field

Like a little magnet
+
angular momentum



NMR Spins



In a magnetic field, spins can either align with or against the direction of the field

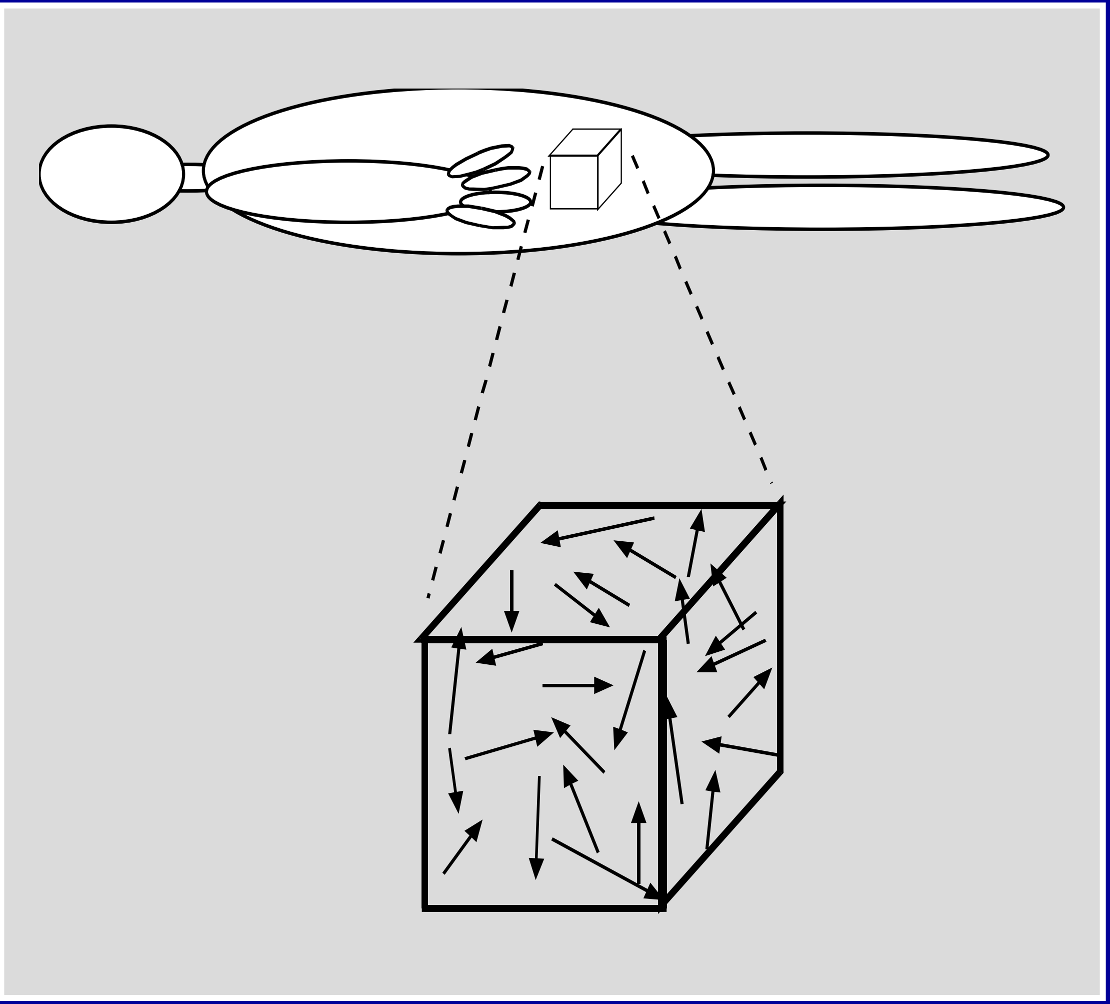
Protons in the Human Body

- The human body is made up of many individual protons.
- Individual protons are found in every hydrogen nucleus.
- The body is mostly water, and each water molecule has 2 hydrogen nuclei.
- 1 gram of your body has ~ 6×10^{22} protons

Spinning Protons in the Body

Spinning protons are randomly oriented.

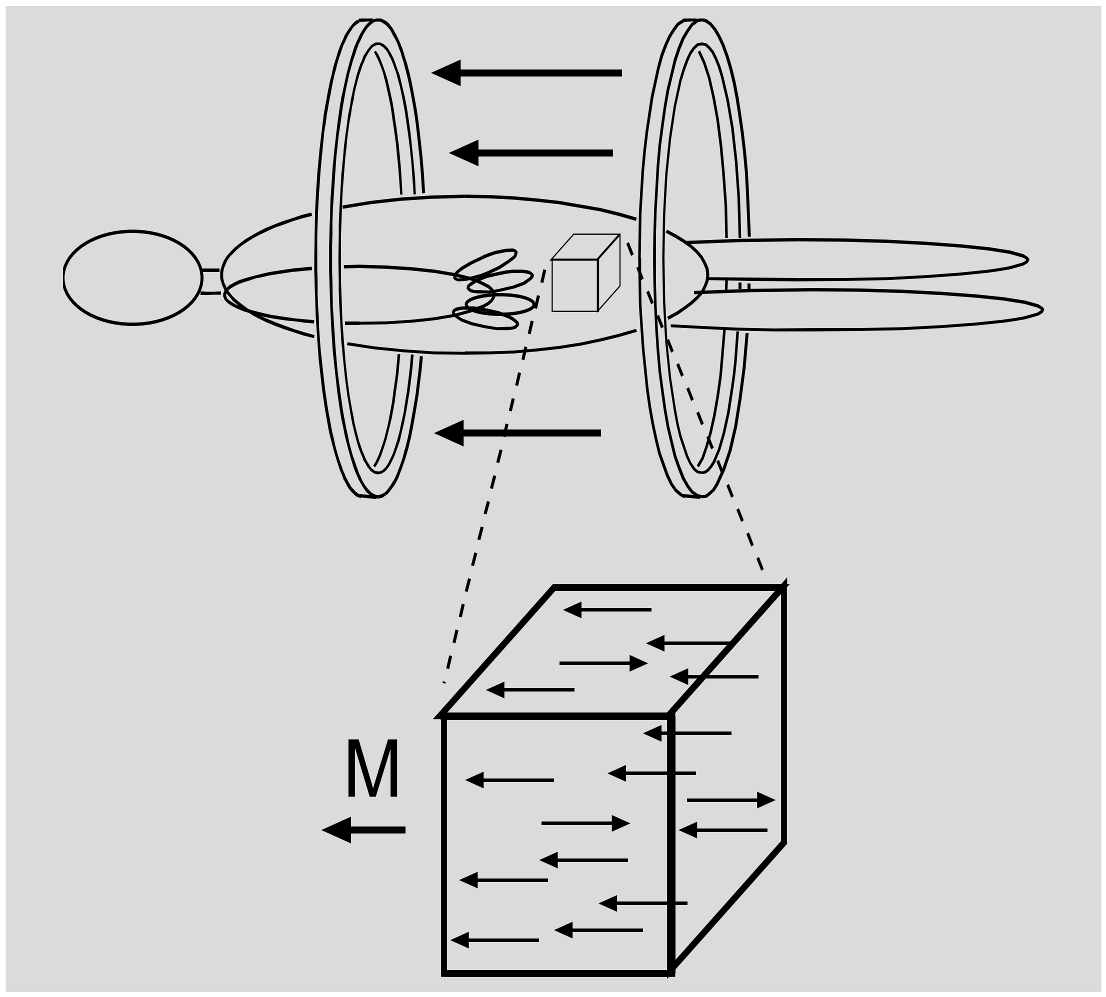
No magnetic field - no net effect



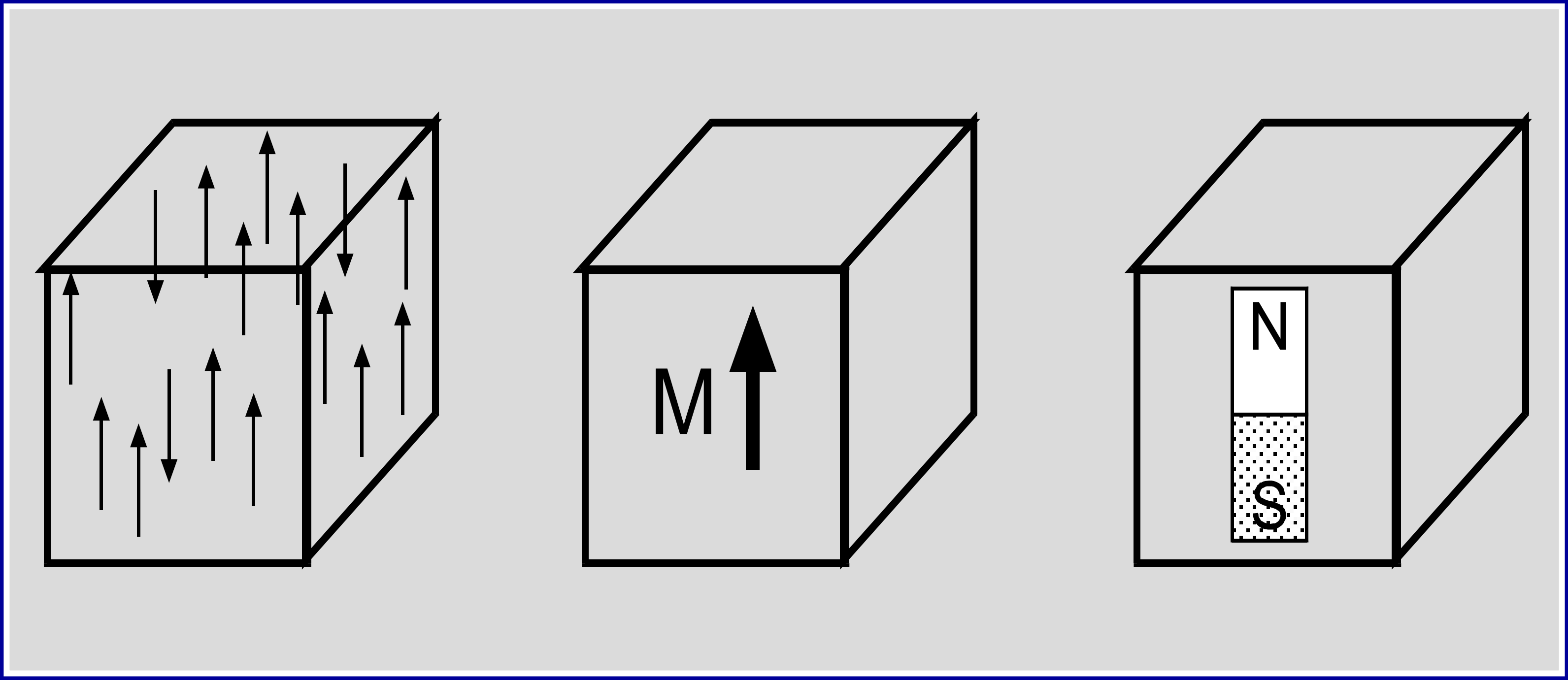
Protons in a Magnetic Field

Spinning protons become aligned to the magnetic field.

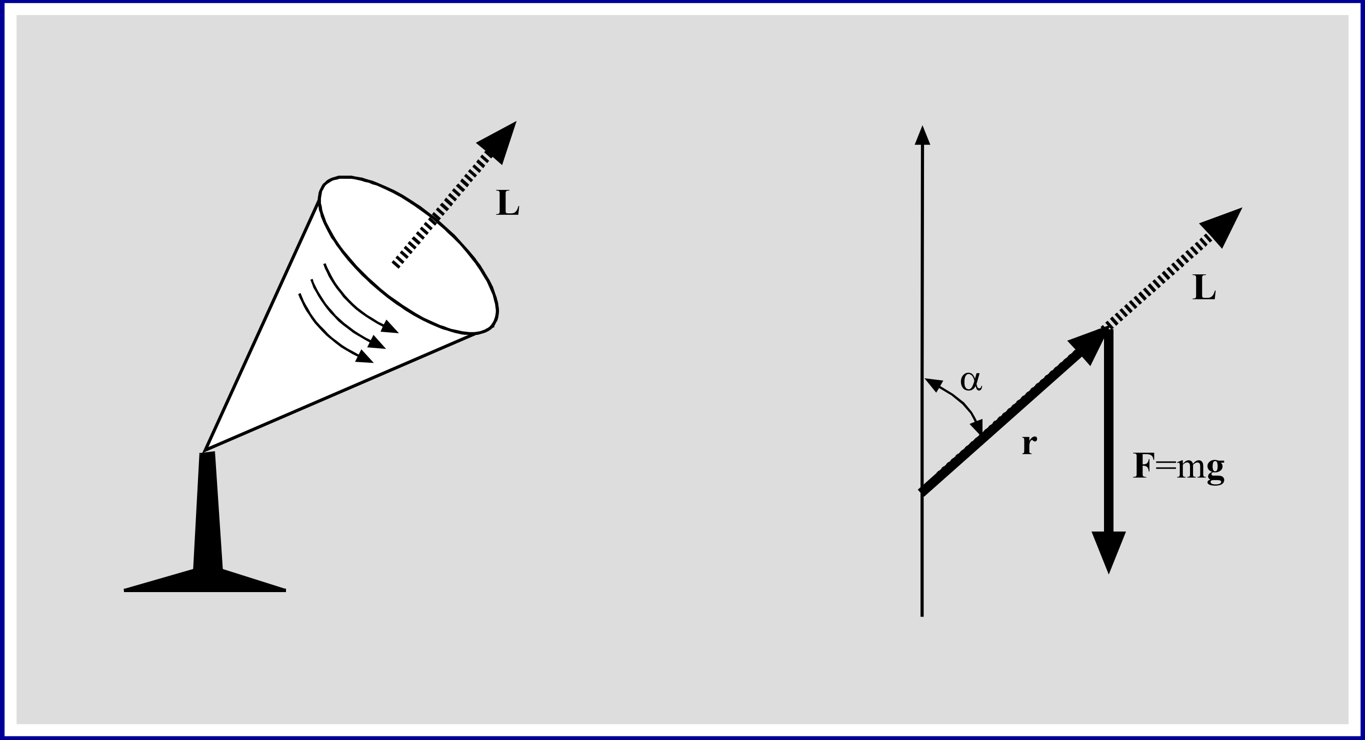
On average - body become magnetized.



Magnetization of Tissue

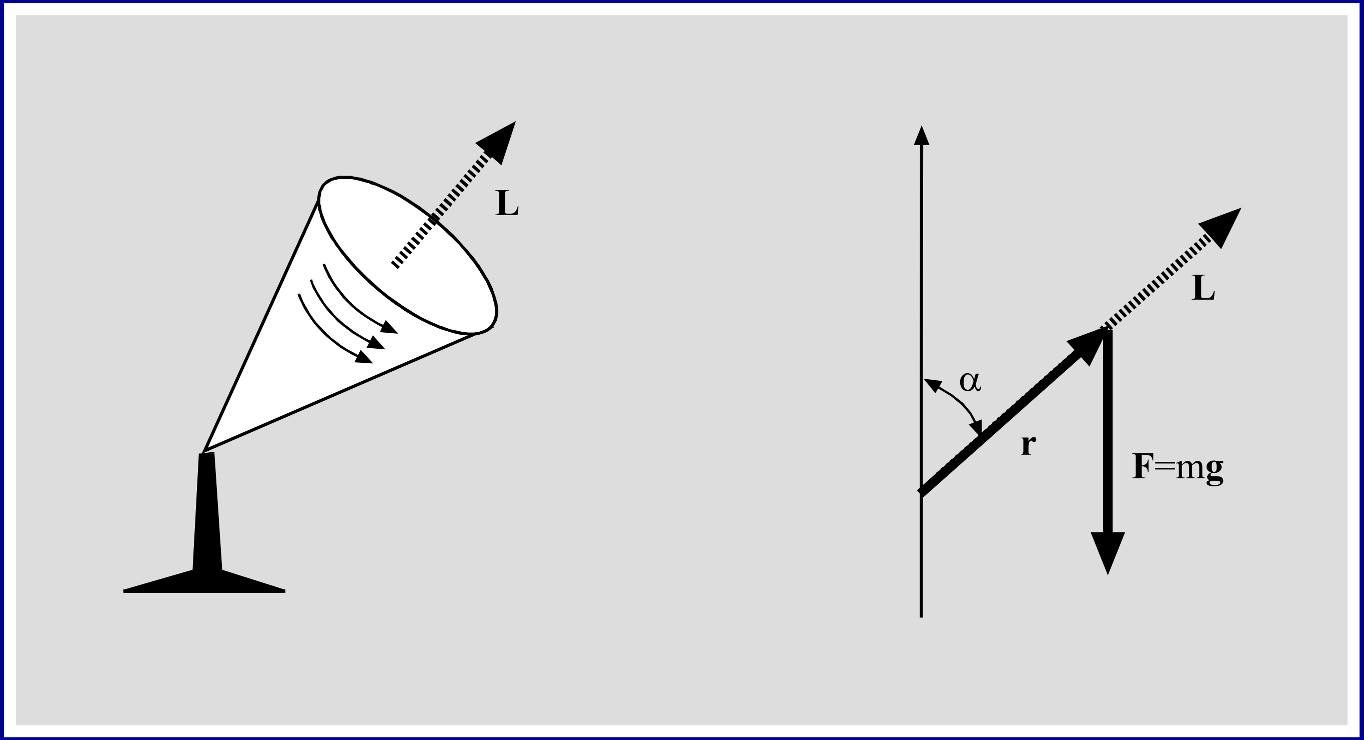


A Top in a Gravitational Field



A spinning top in a gravitational field is similar to a nuclear spin in a magnetic field (classical description)

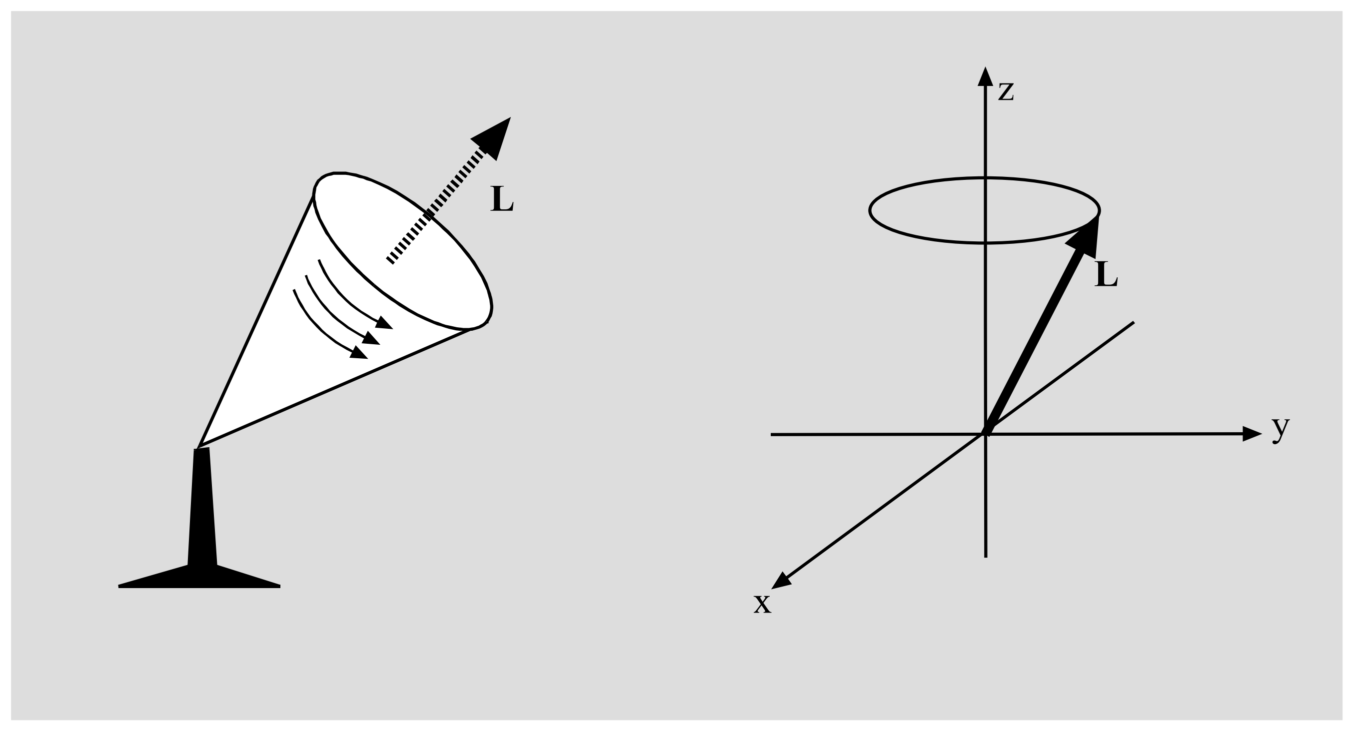
A Top in a Gravitational Field



Gravity exerts a force on top that leads to a Torque (**T**):

$$\mathbf{T} = \frac{d\mathbf{L}}{dt} = \mathbf{L} \times \left(\frac{rm}{L} \right) \mathbf{g}$$

A Top in a Gravitational Field



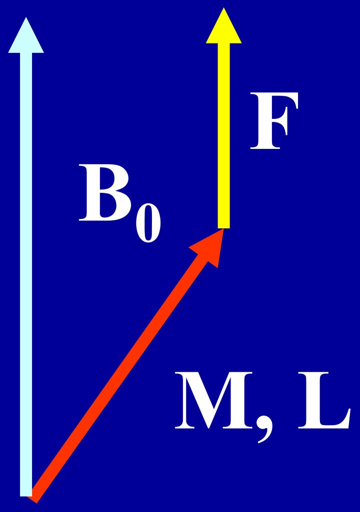
This causes the top to *precess* around **g** at frequency:

$$\Omega = \frac{r\,g\,m}{L}$$

Spins in a Magnetic Field

Spins have both magnetization (**M**) and angular momemtum (**L**):

$$\mathbf{M} = \gamma \, \mathbf{L}$$



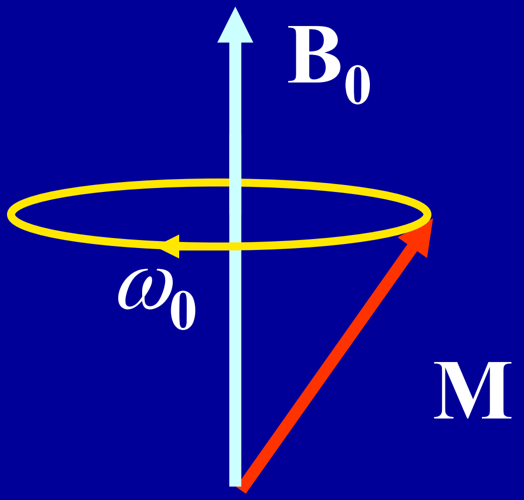
Applied magnetic field ($\mathbf{B}_0$) exerts a force on the magnetization that leads to a torque:

$$\mathbf{T} = \frac{d\mathbf{L}}{dt} = \mathbf{M} \times \mathbf{B}_0$$

Spins in a Magnetic Field

This can be rewritten to yield the famous Bloch Equation:

$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma\, \mathbf{B}_0$$



which says that the magnetization will *precess* around the applied magnetic field at frequency:

$$\omega_0 = \gamma B_0$$

"Larmor Frequency"

Common NMR Active Nuclei

Isotope	Spin I	% natural abundance of isotope	γ MHz/T	elemental abundance in body
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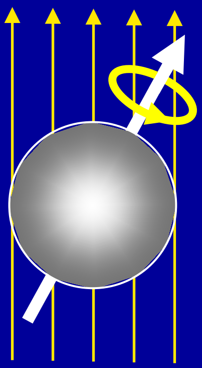
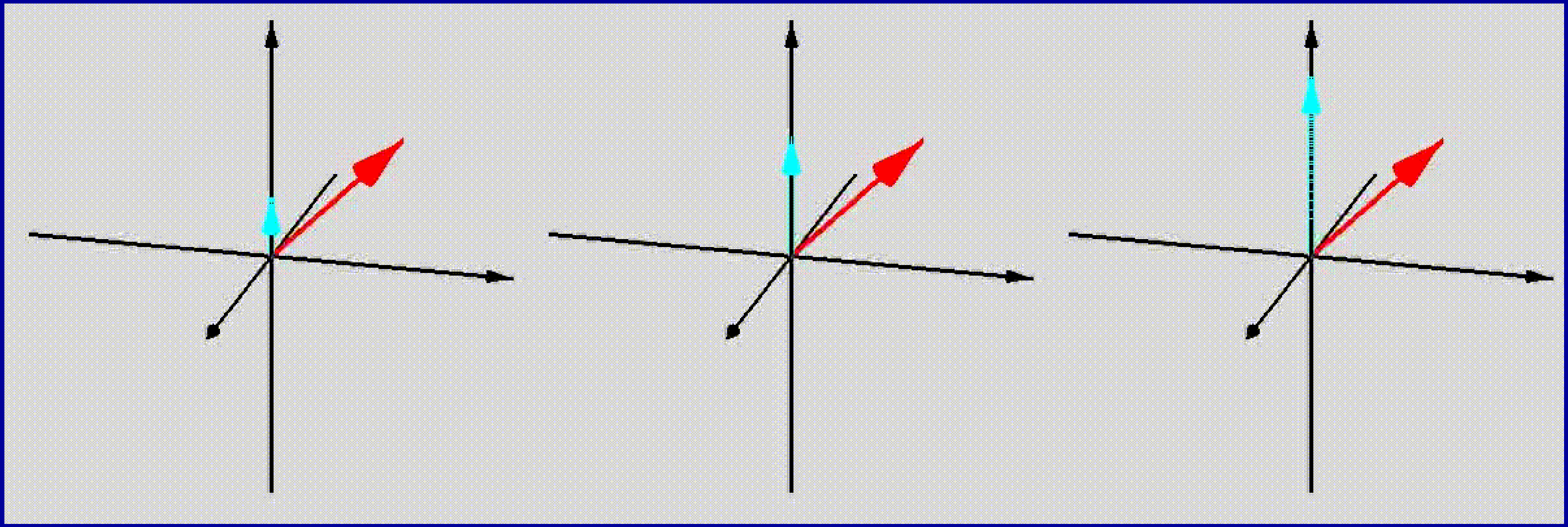
So far …



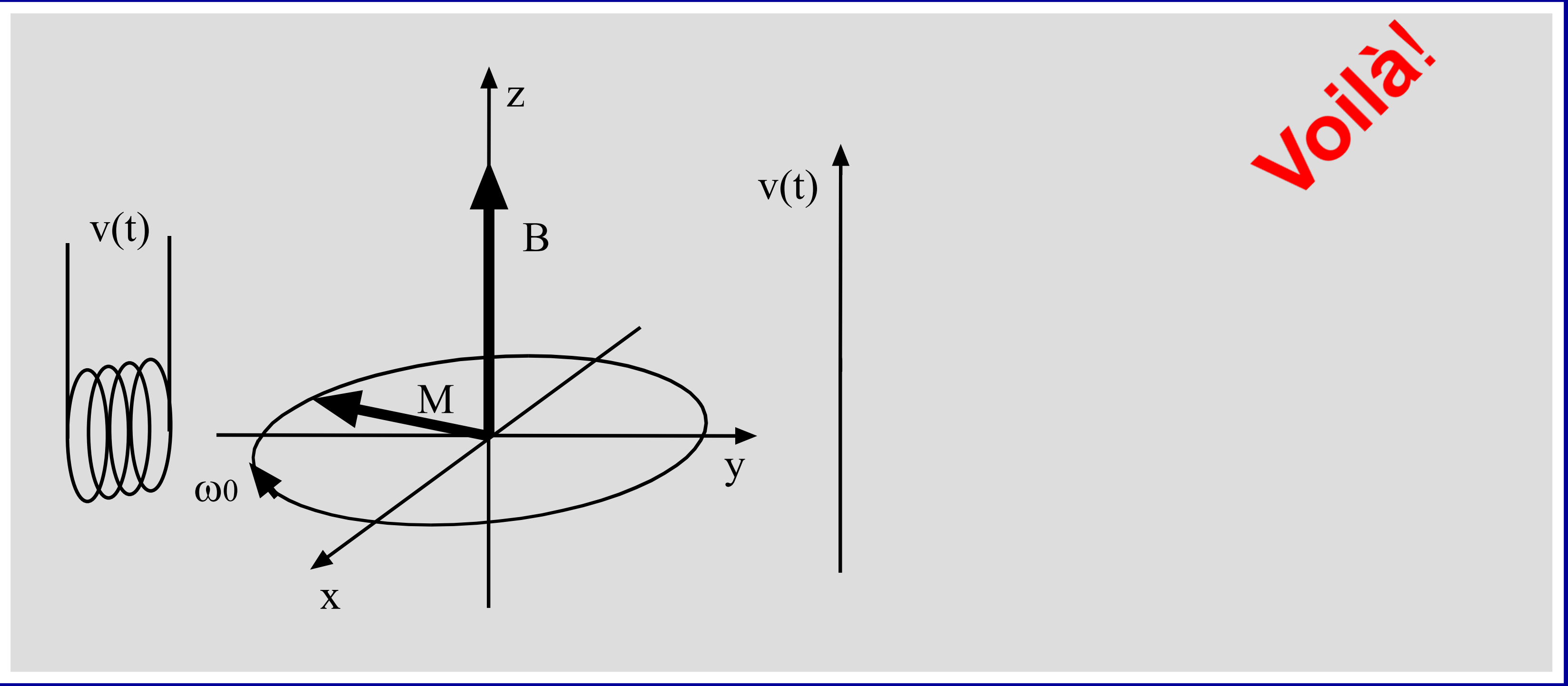
- At the microscopic (quantum) level: spins have angular momentum and magnetization
  - We use spin, proton, hydrogen nucleus interchangeably
- The magnetization of particles is affected by magnetic fields: torque, precession
- At the macroscopic level: They can be treated as a single magnetization vector (makes life a lot easier)
- Next: NMR uses the precessing magnetization of water protons to obtain a signal

Spins in a Magnetic Field



Three “spins” with different applied magnetic fields.

The NMR Signal



The precessing magnetization generates the signal in a coil we receive in MRI, $v(t)$

Frequency of Precession

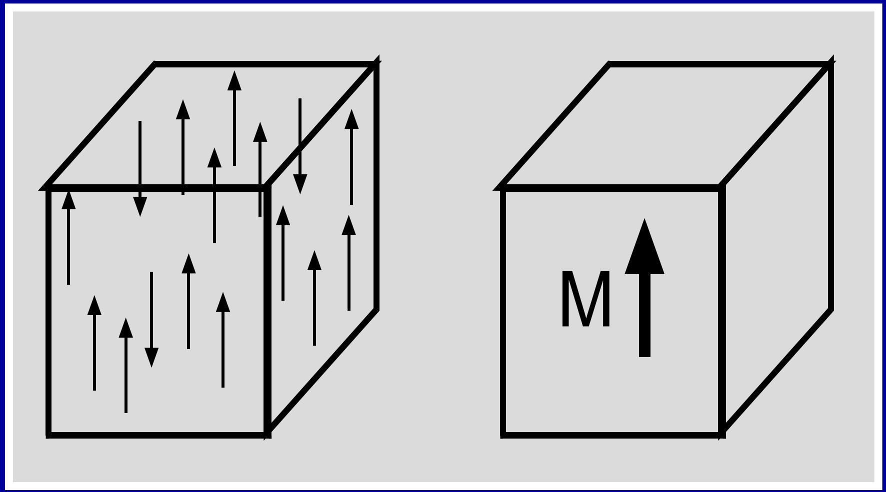
- For ^1H, the frequency of precession is:
  - 63.8 MHz @ 1.5 T (B_0 = 1.5 Tesla)
  - 127.6 MHz @ 3 T
  - 300 MHz @ 7 T

$$\omega_0 = \gamma B_0$$

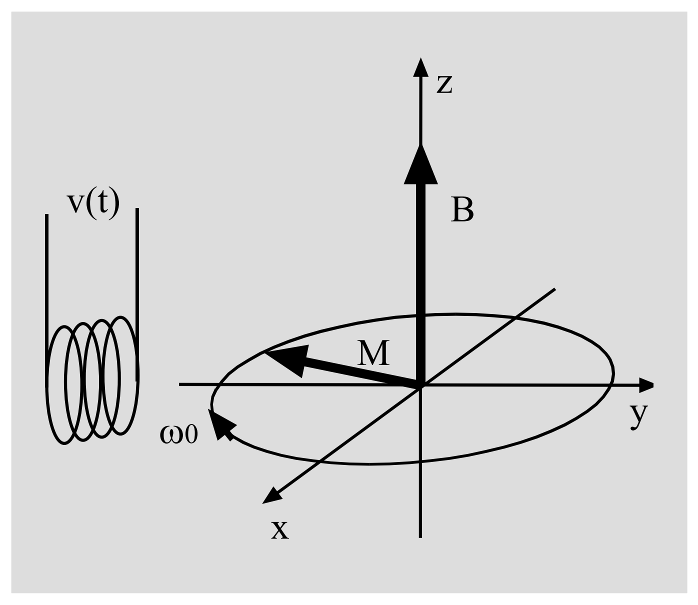
"Larmor Frequency"

Excitation

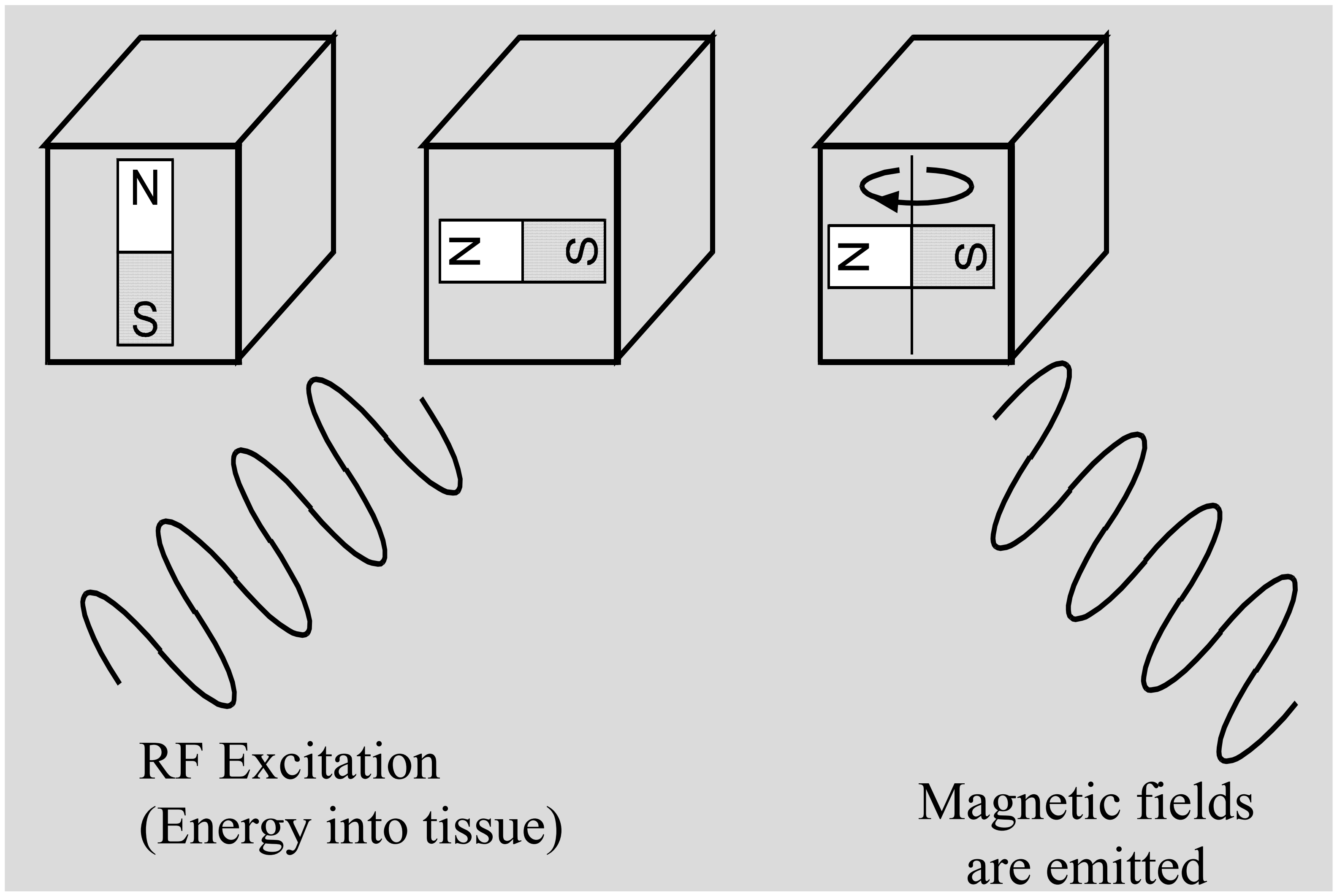
- The magnetization is initially parallel to B_0



- But, we need it perpendicular in order to generate a signal



The Solution: Excitation



Excitation

- Concept 1: Spin system will absorb energy at ΔE corresponding difference in energy states
  - Apply energy at $\omega_0 = \gamma \mathbf{B}_0$ (RF frequencies)

- Concept 2: Spins precess around a magnetic field.
  - Apply magnetic fields in plane perpendicular to $\mathbf{B}_0$.

Resonance Phenomena

- Excitation in MRI works when you apply magnetic fields at the "resonance" frequency.

- Conversely, excitation does not work when you excite at the incorrect frequency.

Resonance Phenomena

- Wine Glass
- http://www.youtube.com/watch?v=JiM6AtNLXX4

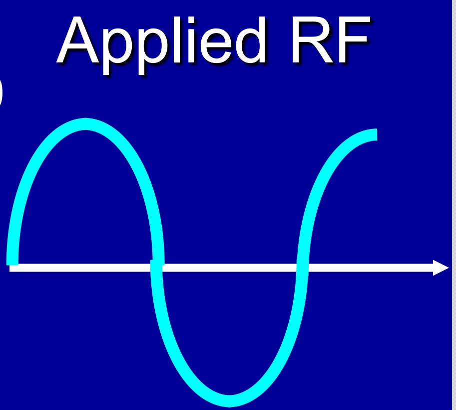
- Air Track
- http://www.youtube.com/watch?v=wASkwB8DJpo

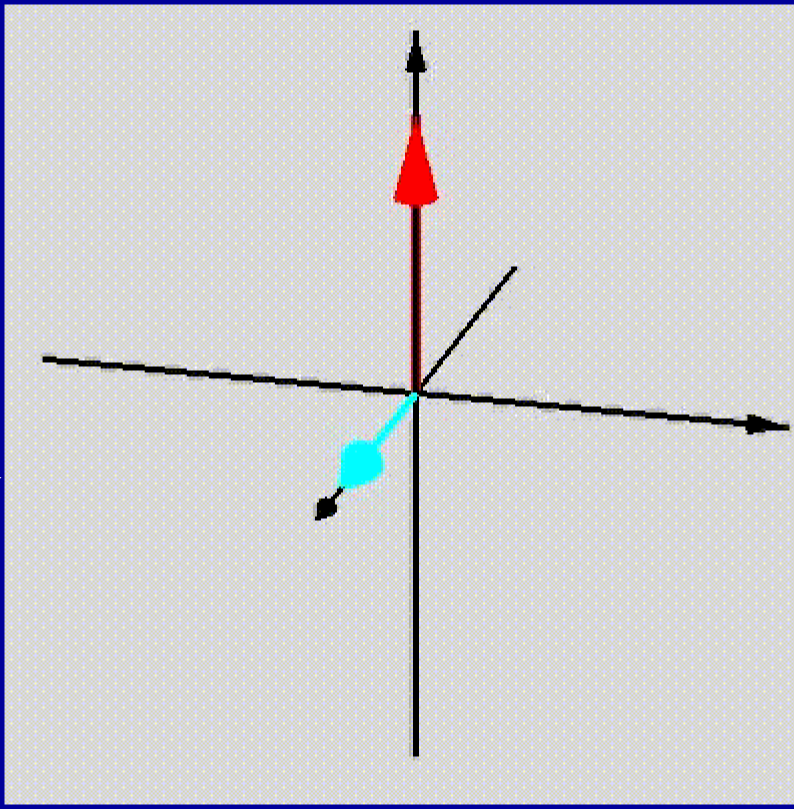
Excitation

Try this: Apply a magnetic field ($\mathbf{B}_1$) rotating at $\omega_0 = \gamma \mathbf{B}_0$ in the plane perpendicular to $\mathbf{B}_0$

→

Magnetization will tip into transverse plane





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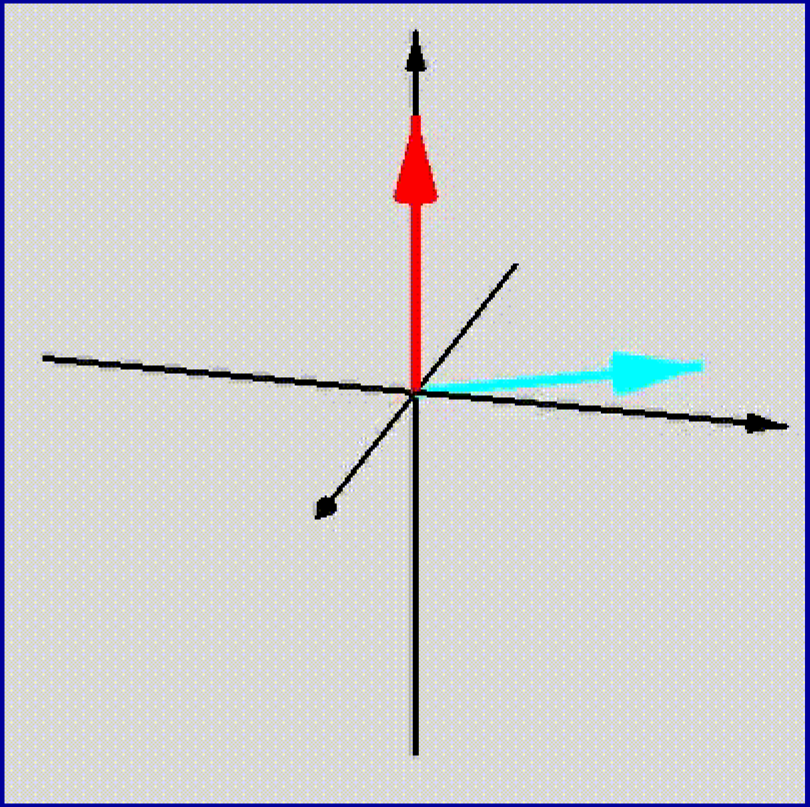
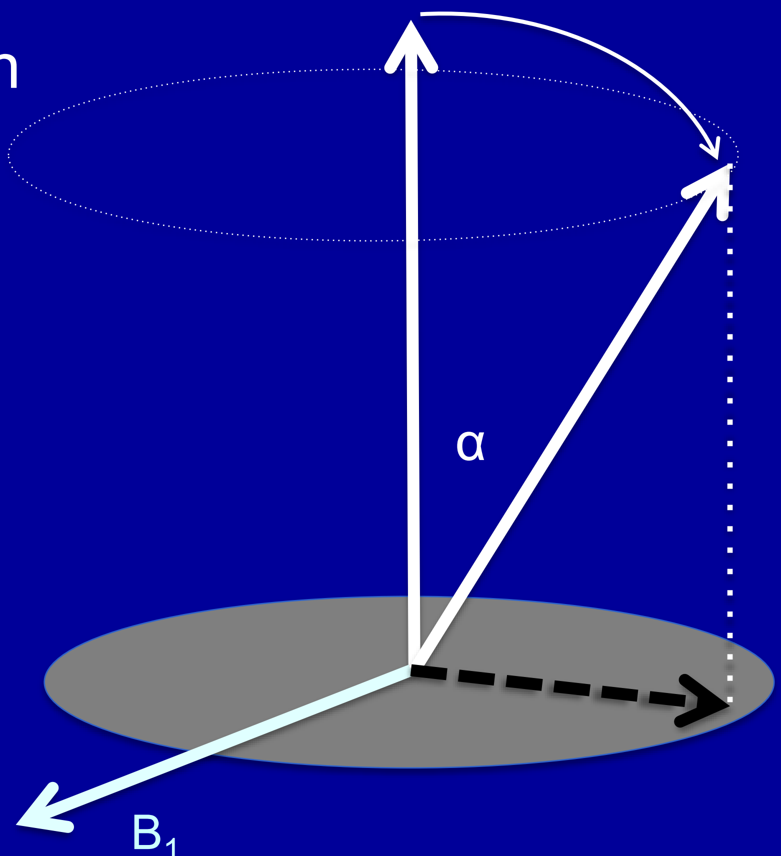
Off-Resonance Excitation

- Excitation only works when $\mathbf{B}_1$ field is applied at $\omega_0 = \gamma \mathbf{B}_0$ (wrong ΔE)
- We will see that this allows us the select particular groups of spins to excite (e.g. slices, water or fat)



Flip Angle

- Excitation stops when the magnetization is tipped enough into the transverse plane
- We can only detect the transverse component: sin(alpha)
- 90 degree flip angle will give most signal (ideal case)

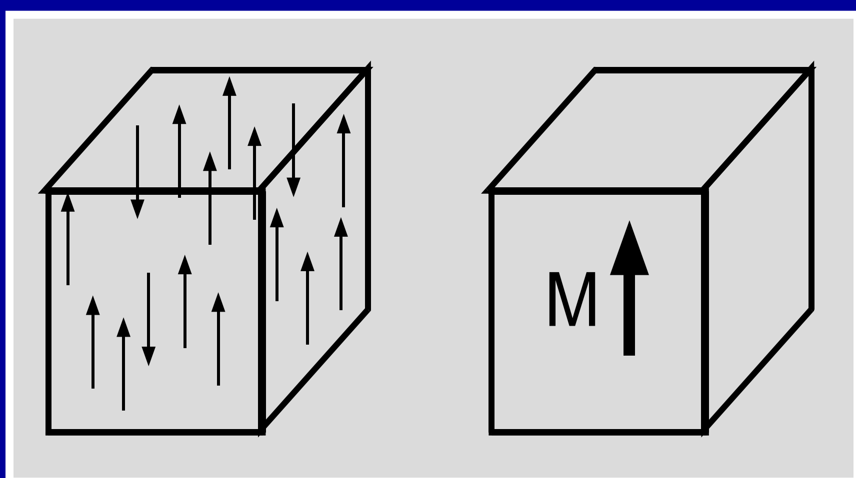


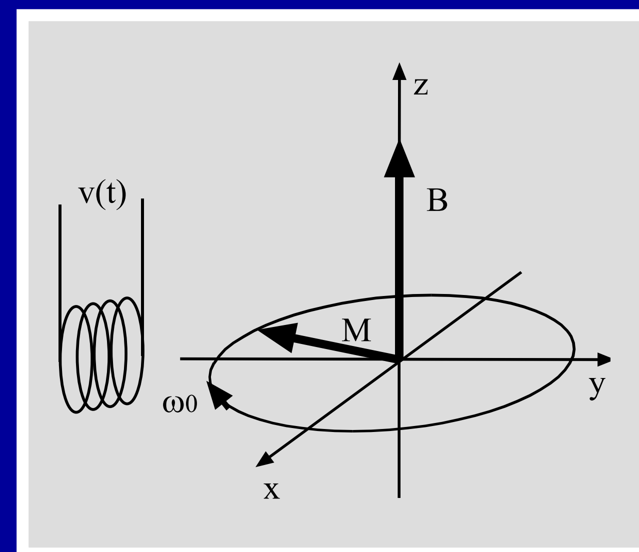
- Typical strength is $B_1 = 1\text{-}2 \times 10^{-5}$ T
- 90 degree tip takes about 300-600 μs

Courtesy Luis Hernandez

What next? → Relaxation

Excitation





Spins “relax” back to their equilibrium state

Relaxation

- The system goes back to its equilibrium state

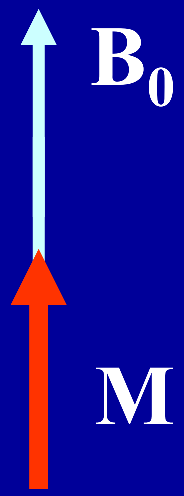
- Two main processes:
  - Decay of traverse (observable) component
  - Recovery of parallel component

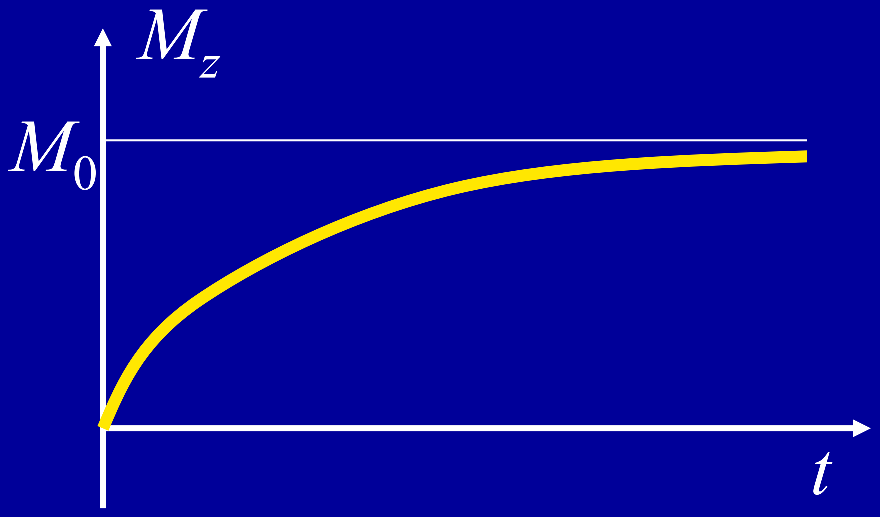
T_1 - relaxation

- Longitudinal magnetization (M_z) returns to steady state (M_0) with time constant T_1
- Spin gives up energy into the surrounding molecular matrix as heat
- Factors
  - Viscosity
  - Temperature
  - State (solid, liquid, gas)
  - Ionic content
  - Bo
  - Diffusion
  - etc.

T1 Recovery

- Tissue property (typically 1-3 seconds)
- Spins give up energy into molecular matrix
- Differential Equation: $\frac{dM_z}{dt} = -\frac{(M_z - M_0)}{T1}$



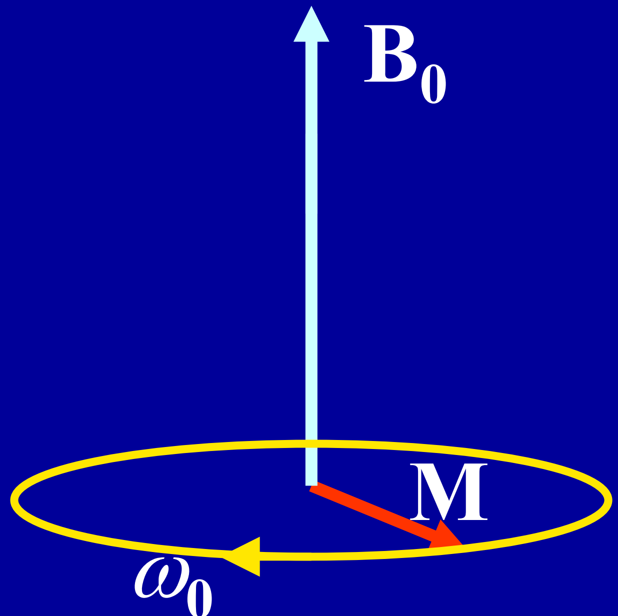


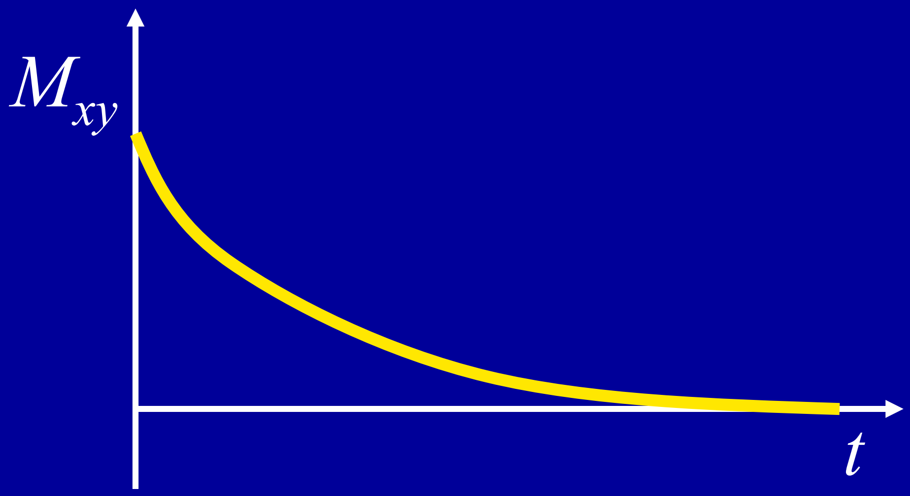
T_2 - relaxation

- Transverse magnetization (M_{xy}) decay towards 0 with time constant T_2
- Factors
  - T_1 ($T_2 \leq T_1$)
  - Phase incoherence
    - » Random field fluctuations
    - » Magnetic susceptibility
    - » Magnetic field inhomogeneities (RF, B_0, Gradients)
    - » Chemical shift
    - » Etc.

T2 Decay

- Tissue property (typically 10's of ms)
- Spins dephase relative to other spins
- Differential Equation: $\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T2}$

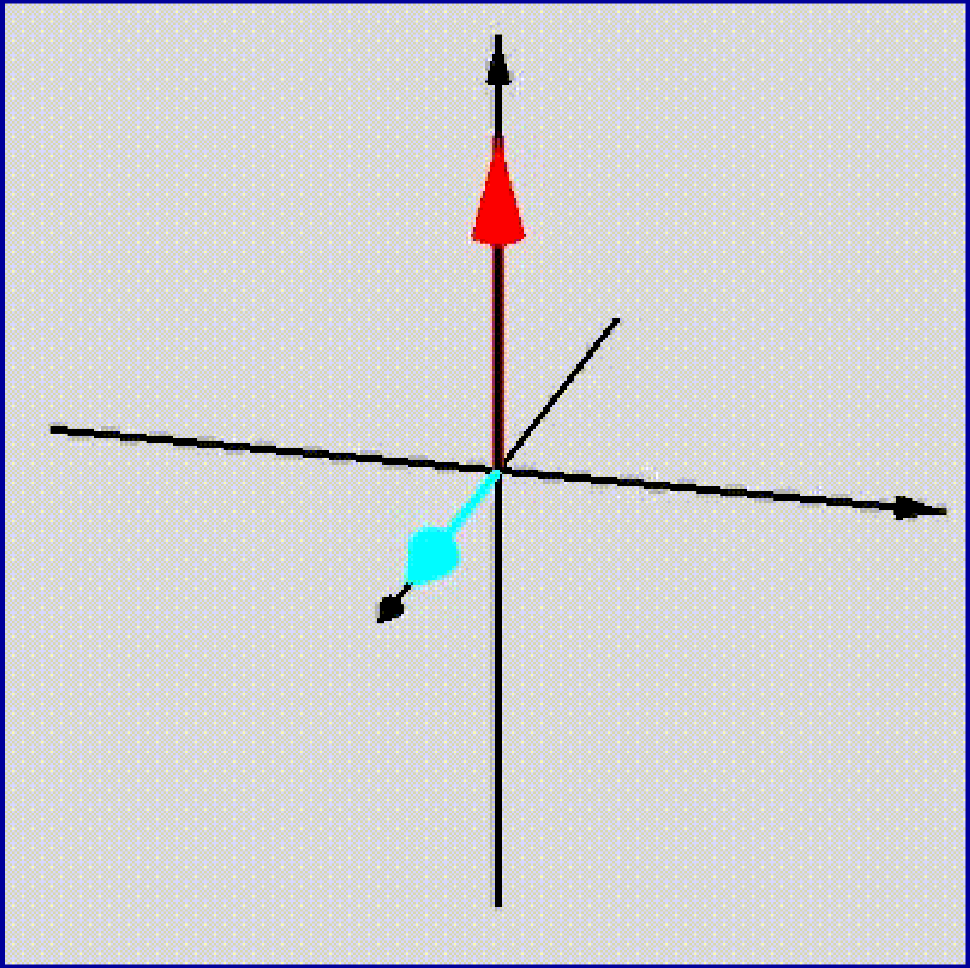




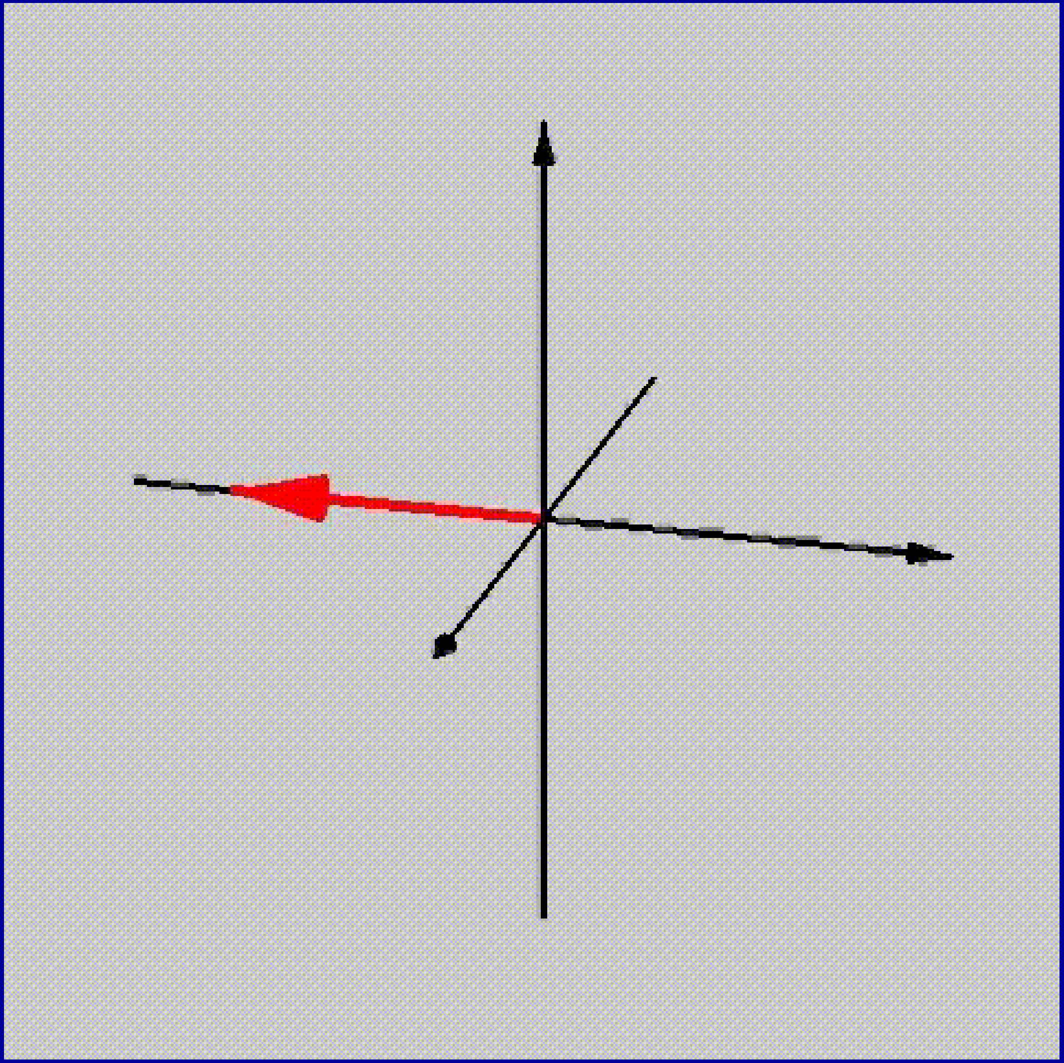
Steps in an MRI Experiment

0. Object goes into B_0
1. Excitation
2a. T_2 Relaxation (faster)
2b. T_1 Relaxation (slower)
3. Back to 1.

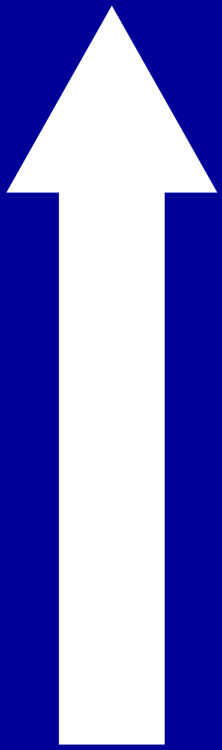
Excitation



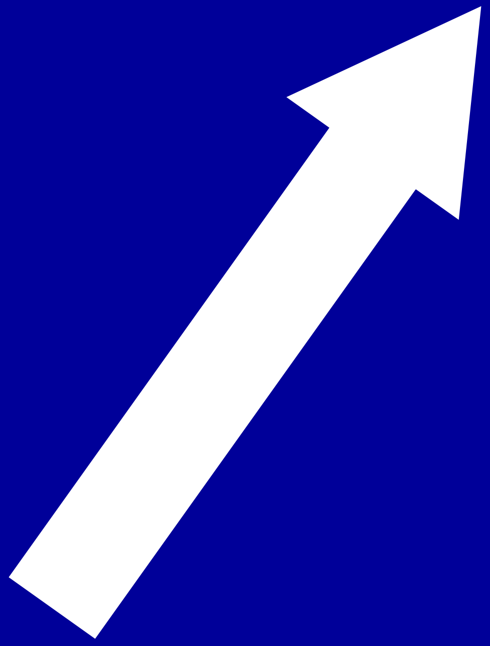
Relaxation



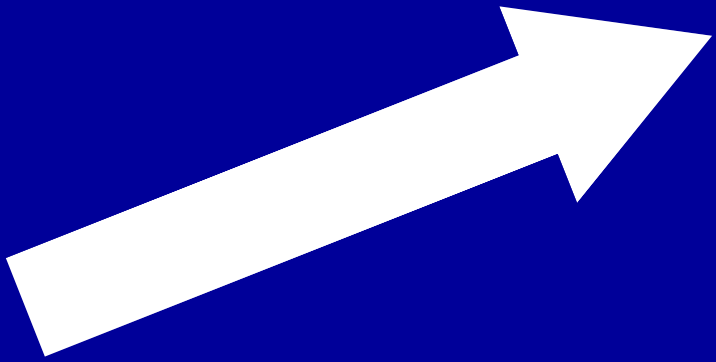
Resting State



Excitation

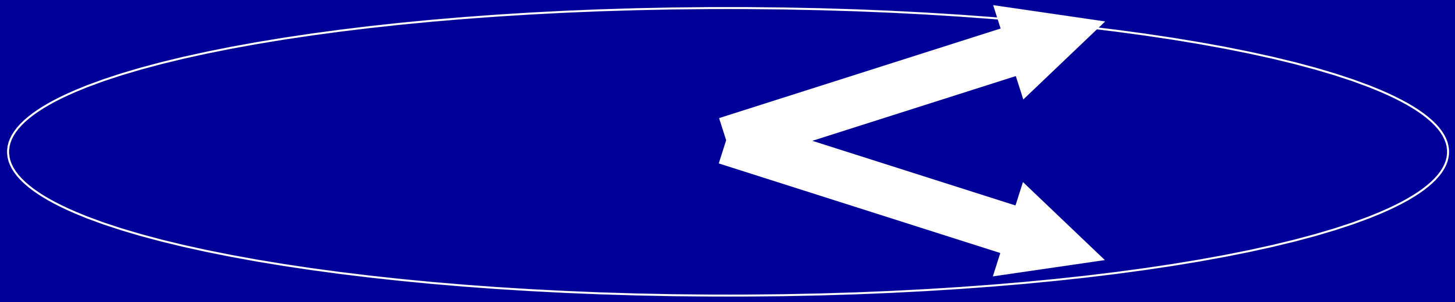


Excitation

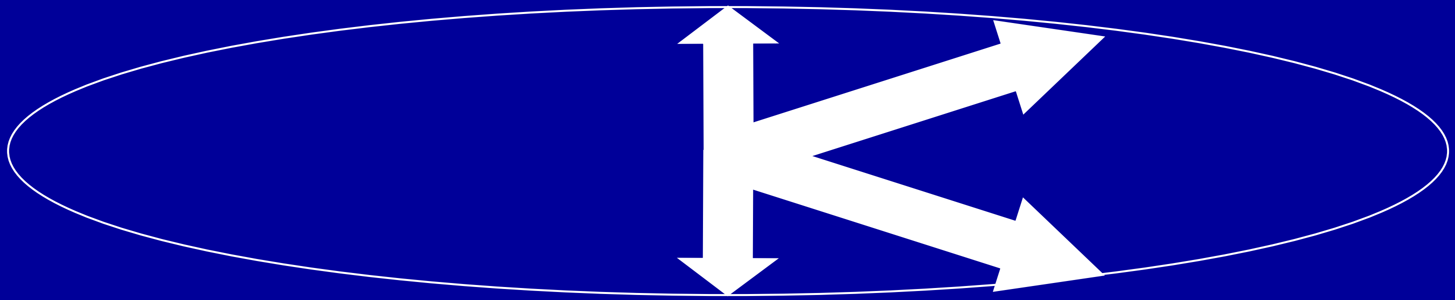


Excitation

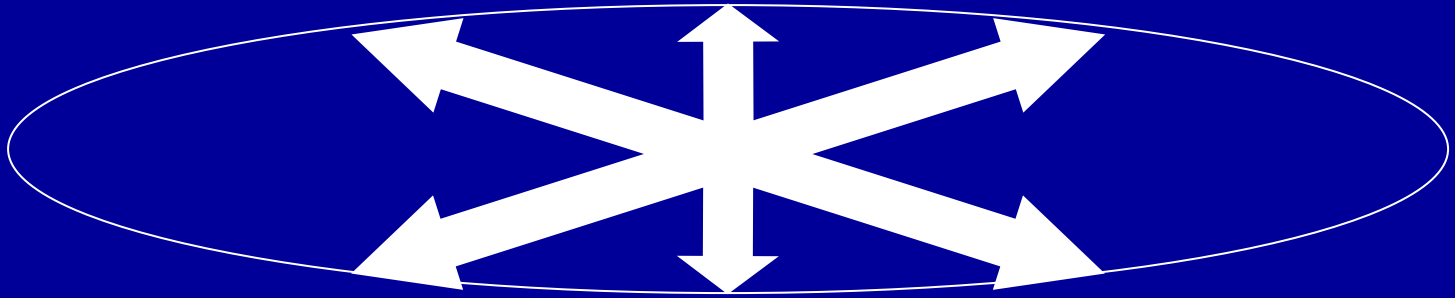
T_2 Relaxation



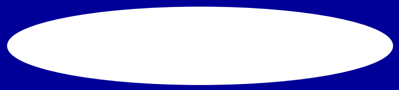
T_2 Relaxation



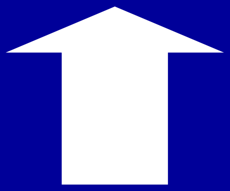
T_2 Relaxation



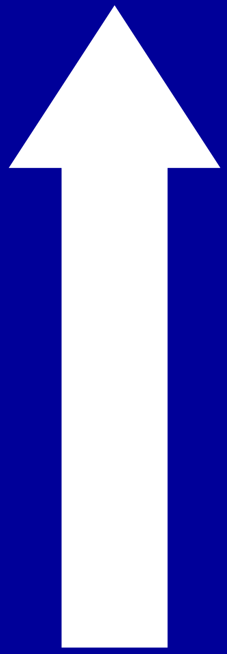
T_2 Relaxation



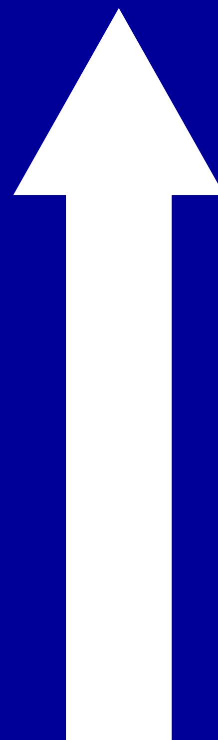
T_1 Relaxation



T_1 Relaxation



T_1 Relaxation



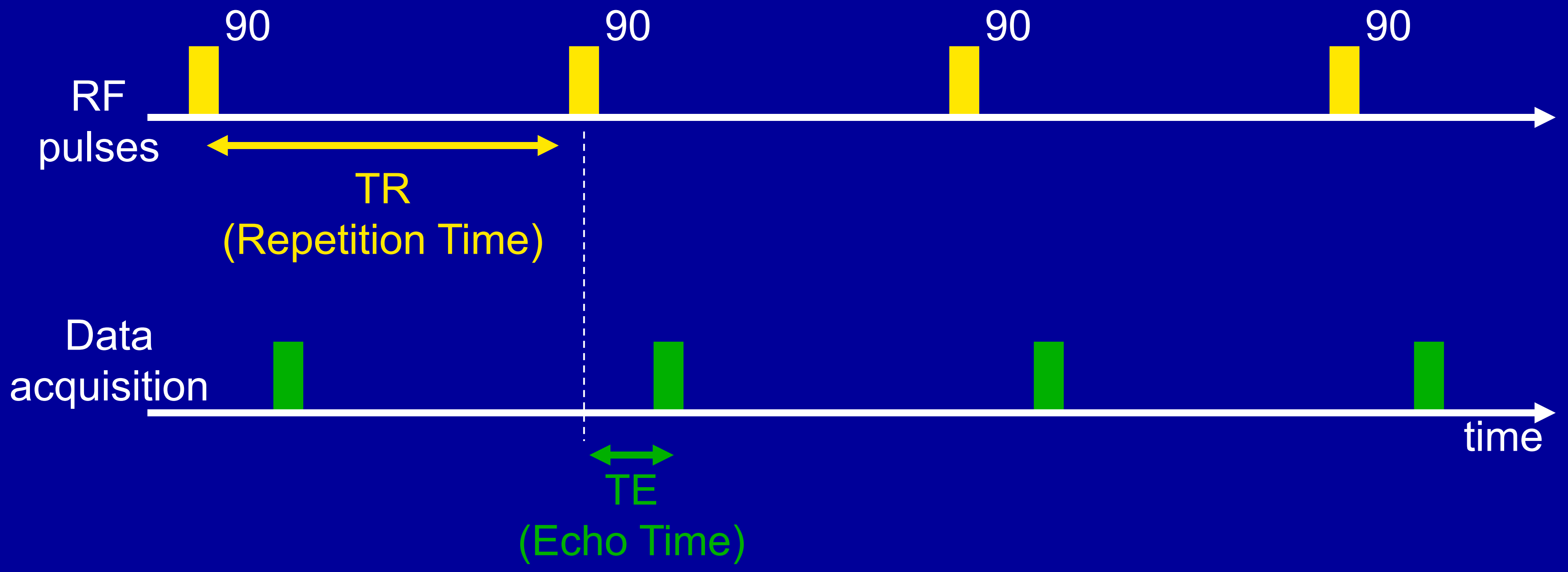
Typical T_1's, T_2's, and Relative "Spin Density" for Brain Tissue at 3.0 T

	T_1 (ms)	T_2 (ms)	ρ_R
Water	4000	2000	1
CSF	4000	500	1
Gray matter	1330	110	0.95
White matter	830	80	0.8
Fat	380	45	1

Several refs: Wansapura et al., JMRI, 1999; Bojoquez et al. MRI, 2017, and others.
Note: Large variability based on technique, individual, area of brain, etc.

The Pulsed MR Experiment

- MRI uses a repeated excitation pulse experimental strategy

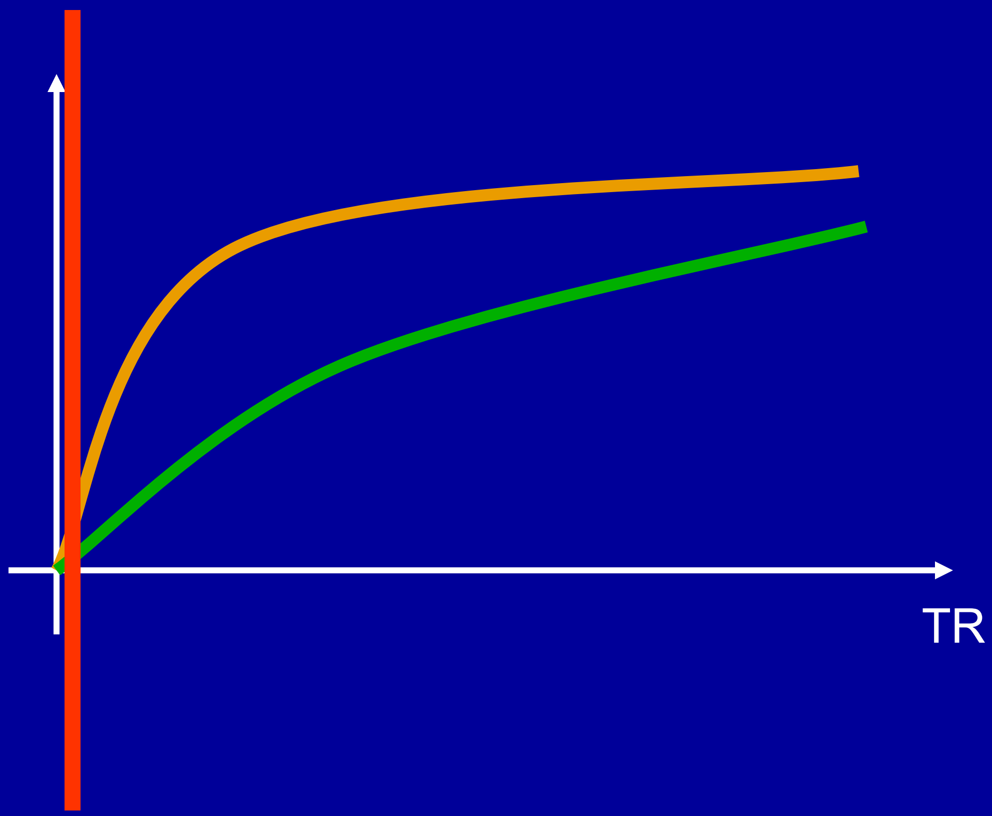


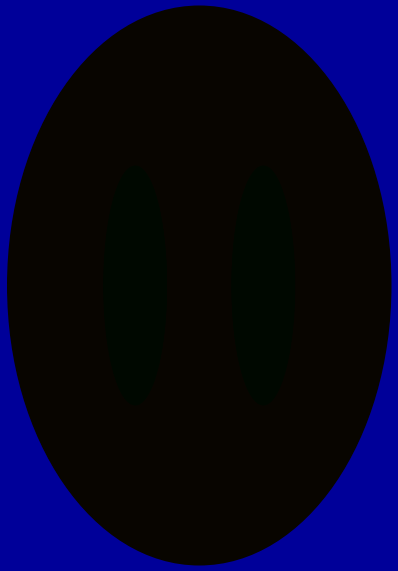
Contrast

- TR mainly controls T1 contrast
  – Excitation or flip angle also contributes

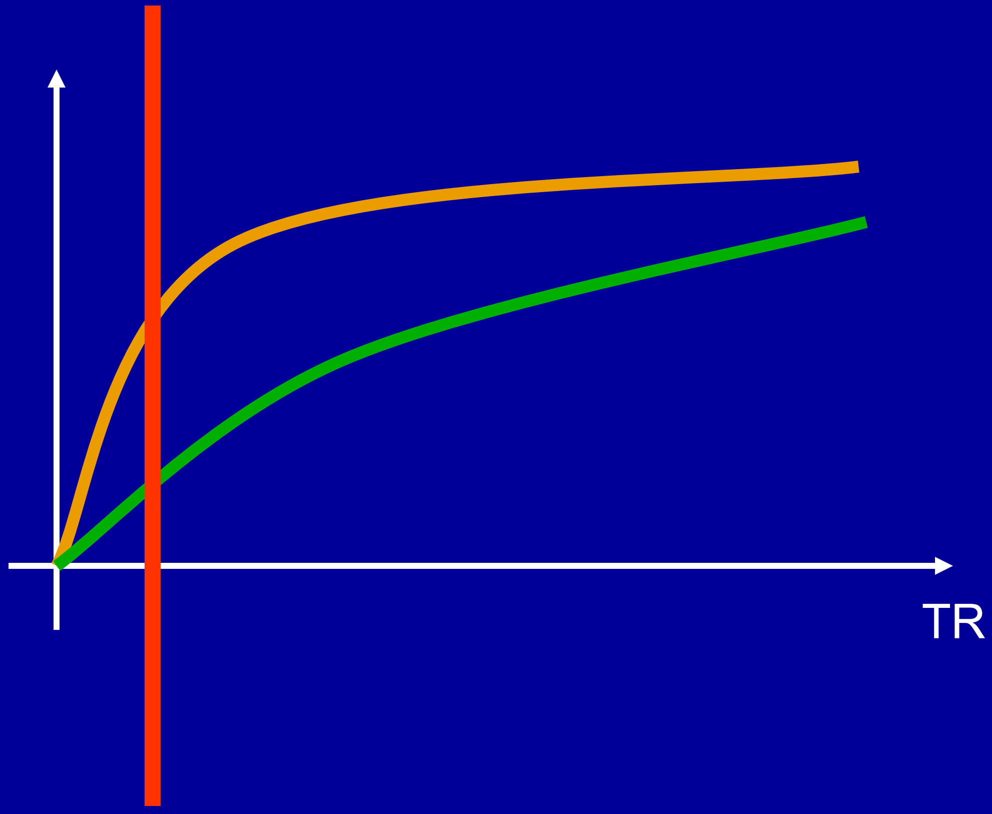
- TE mainly controls T2 contrast

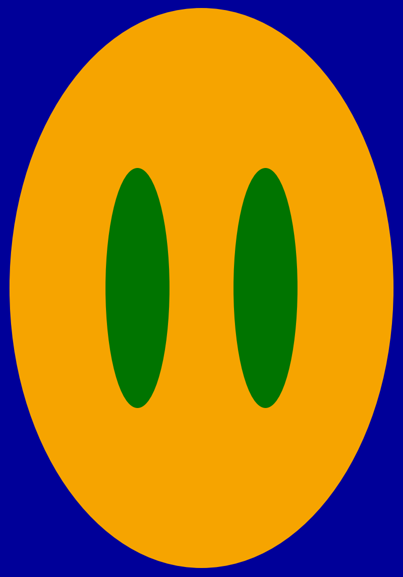
T1 Contrast and TR



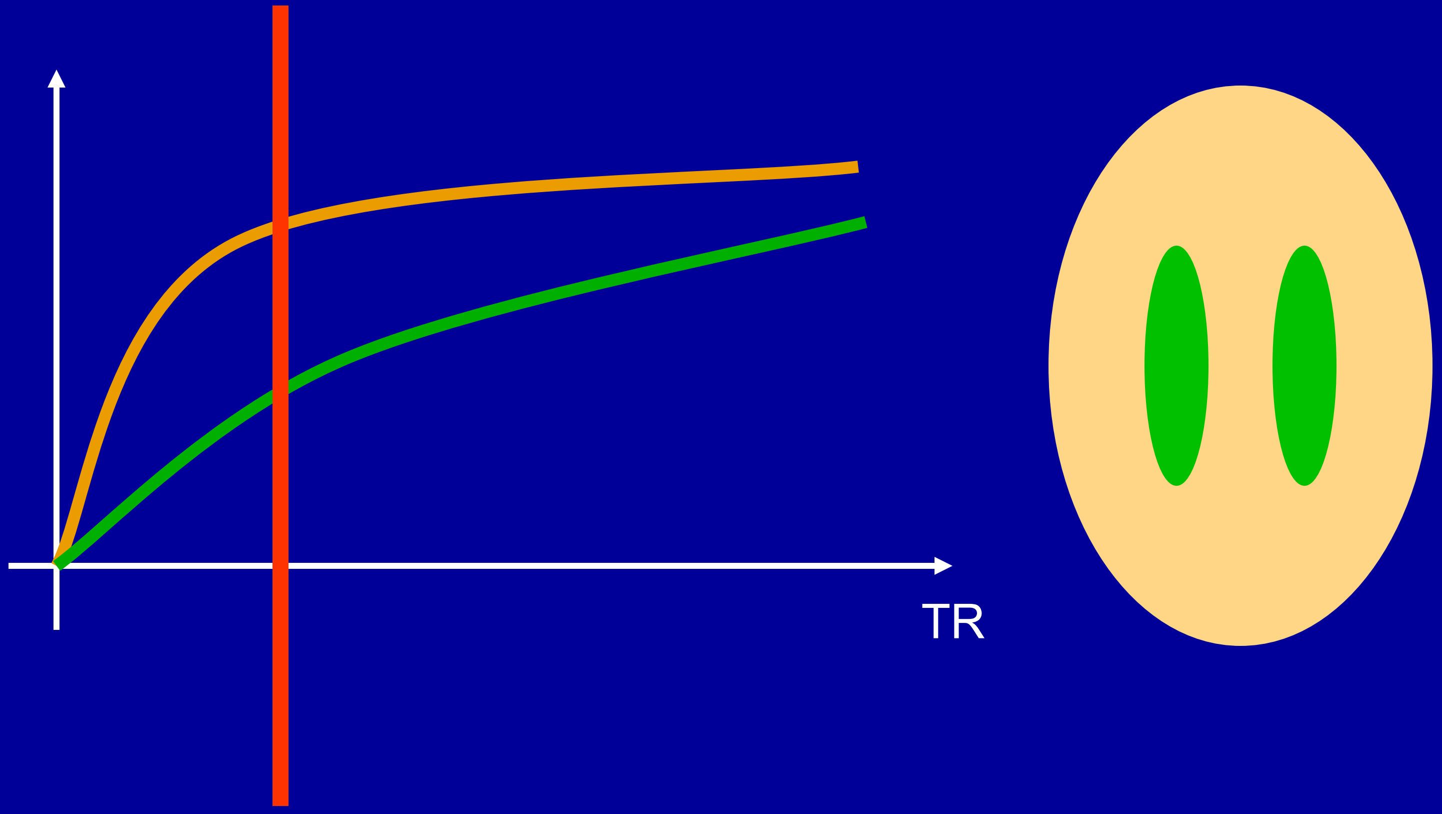


T1 Contrast and TR





T1 Contrast and TR



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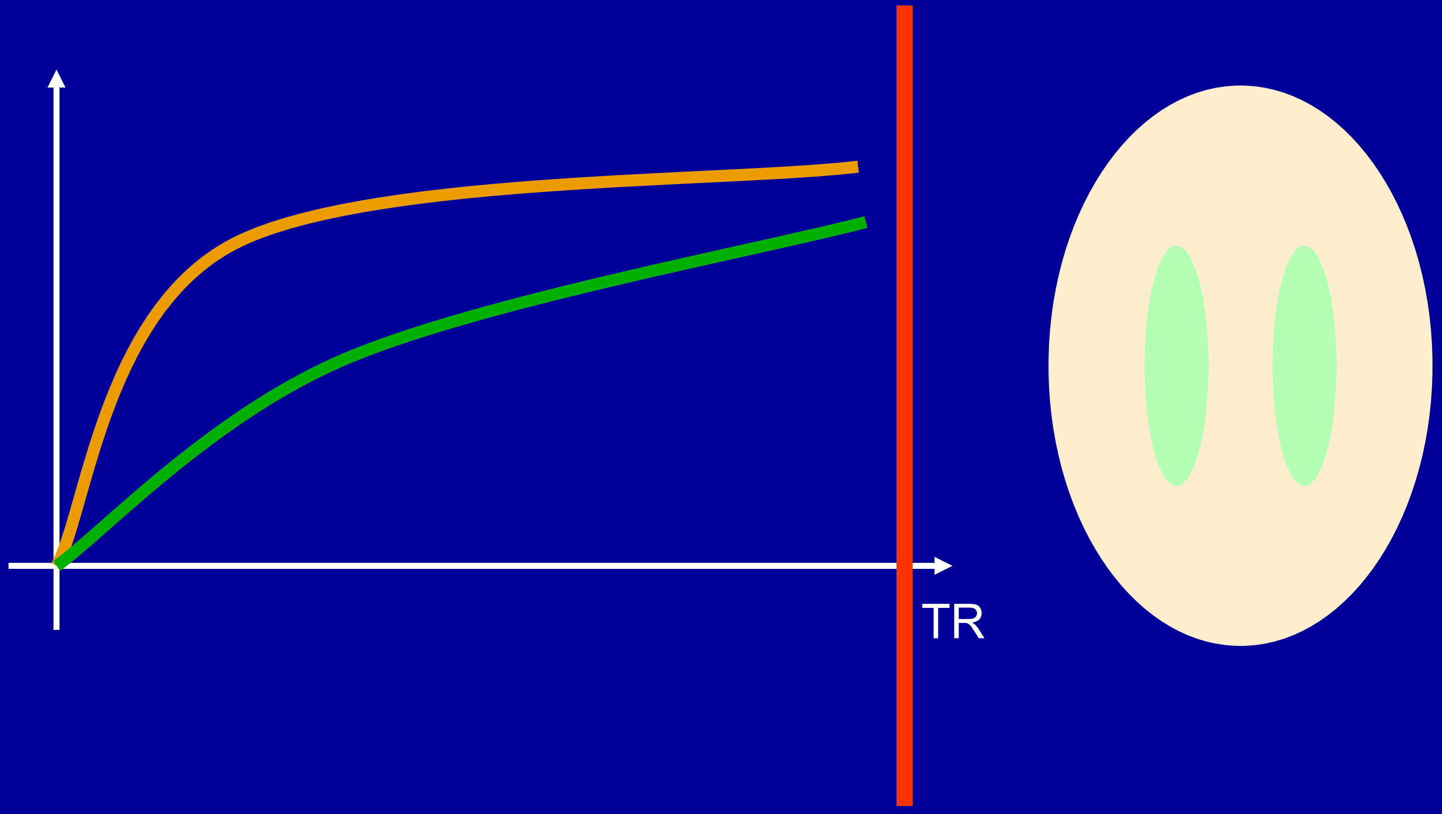
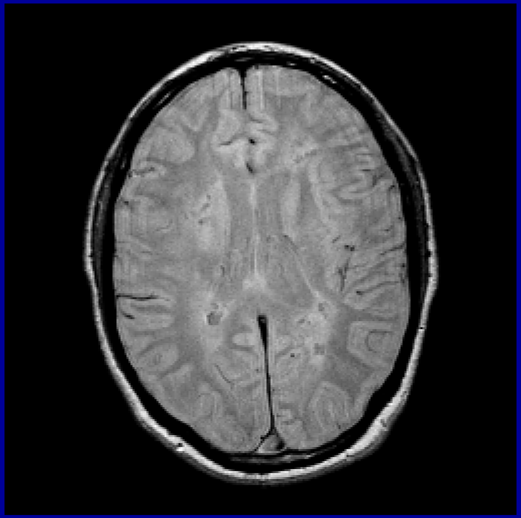
T1 Contrast and TR



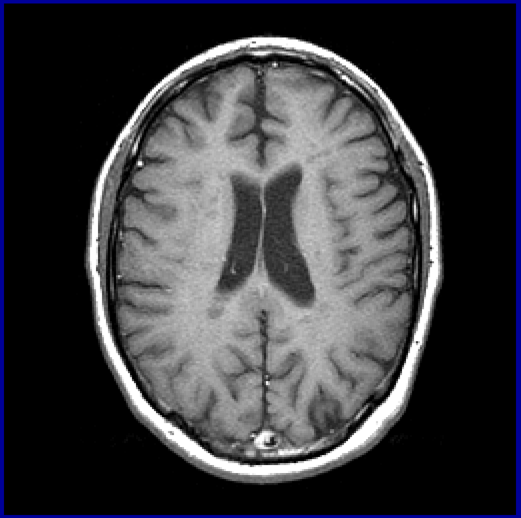
T1 Contrast

- For short TR imaging, tissues with short T1's (rapidly recovering) are brightest
  - Fat > brain tissue
  - White Matter > Grey Matter
  - Gray Matter > CSF

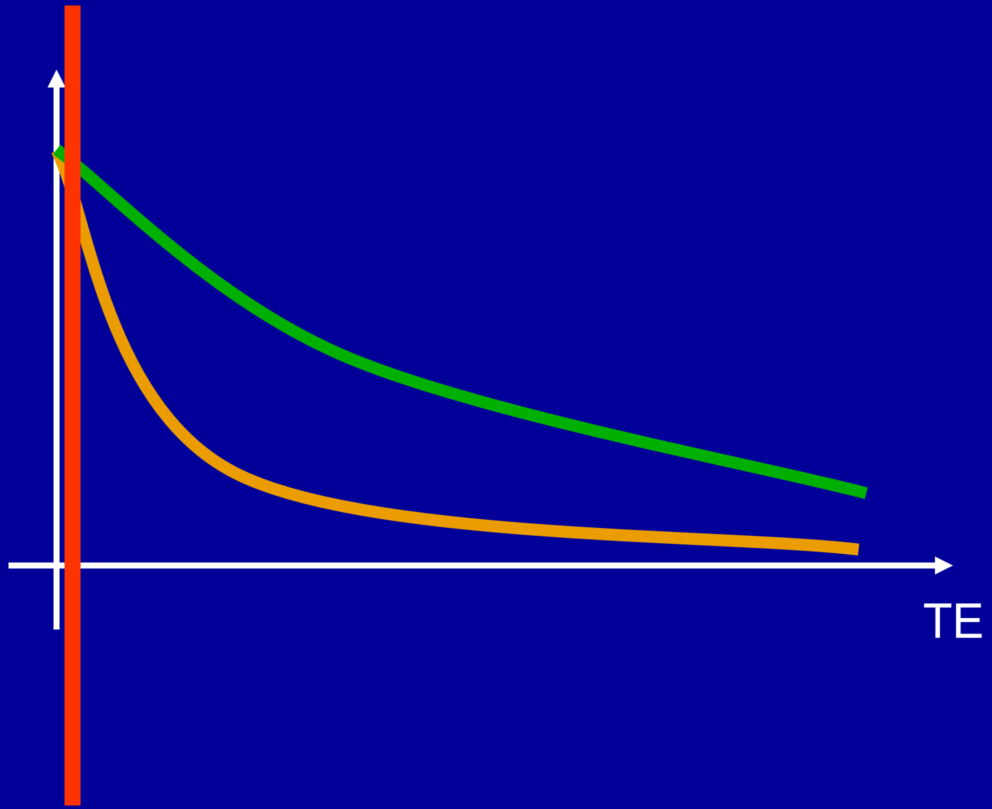
Spin Density

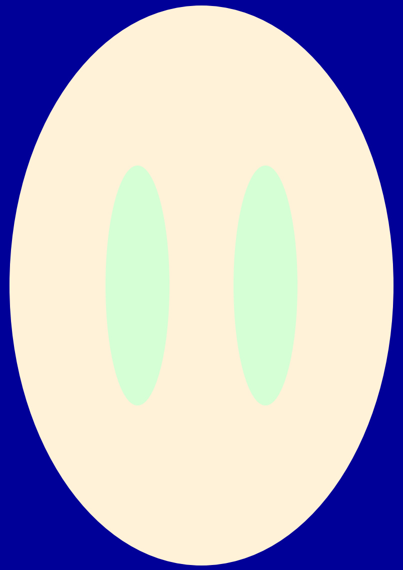


T1 Weighting

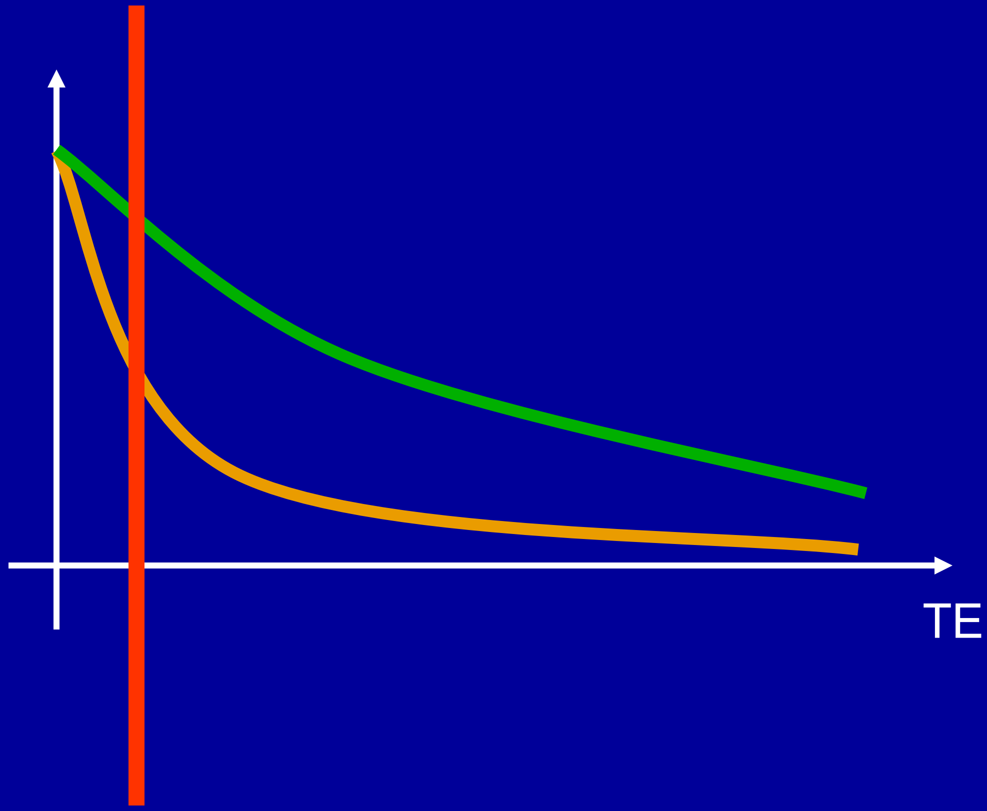


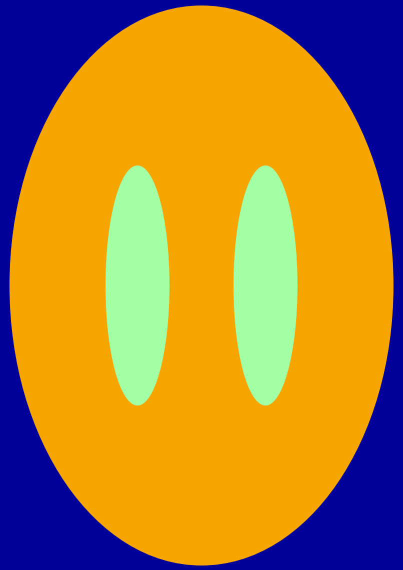
T2 Contrast and TE



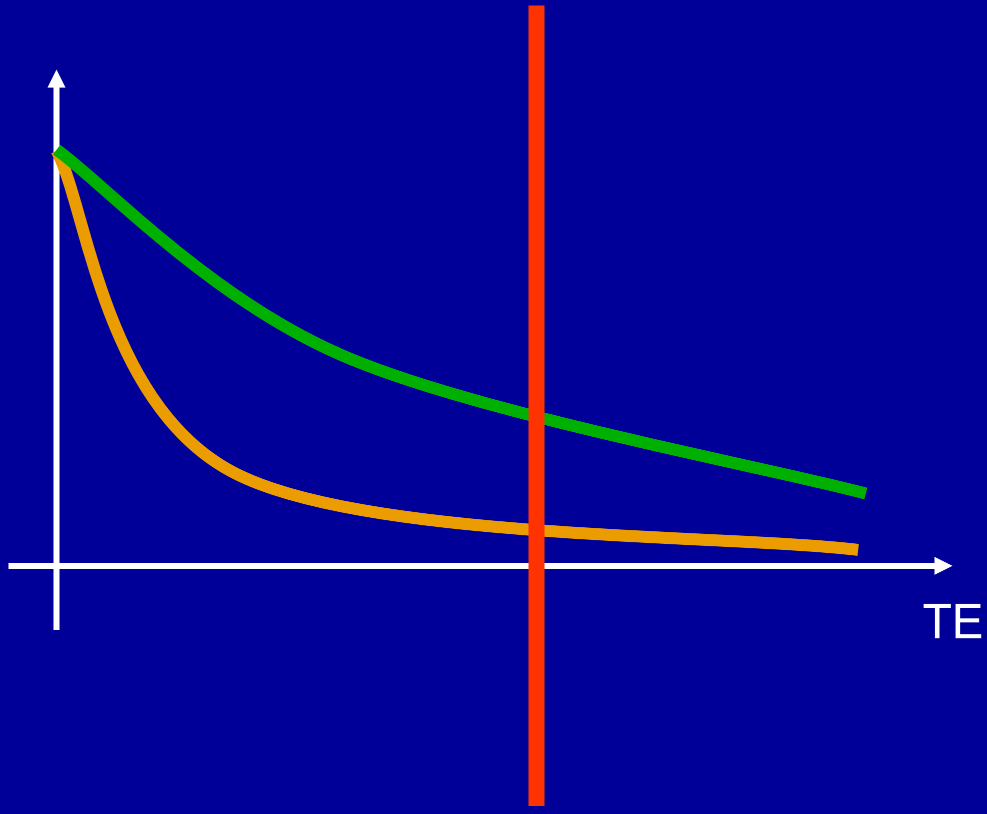


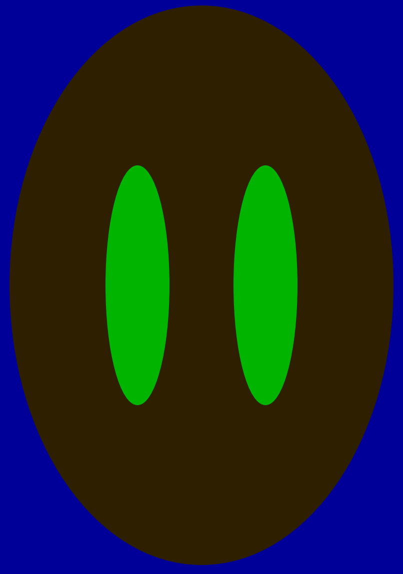
T2 Contrast and TE



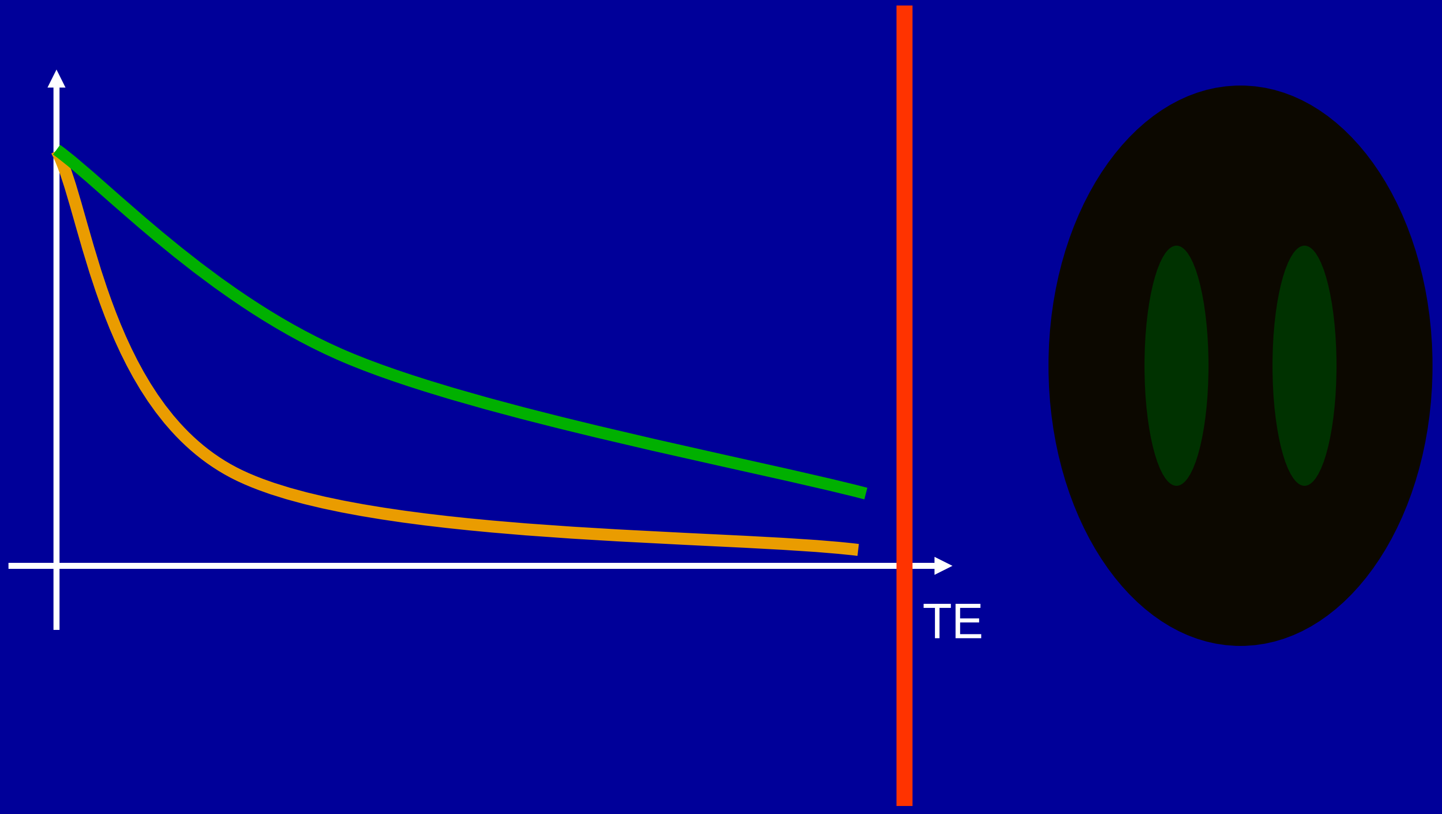


T2 Contrast and TE





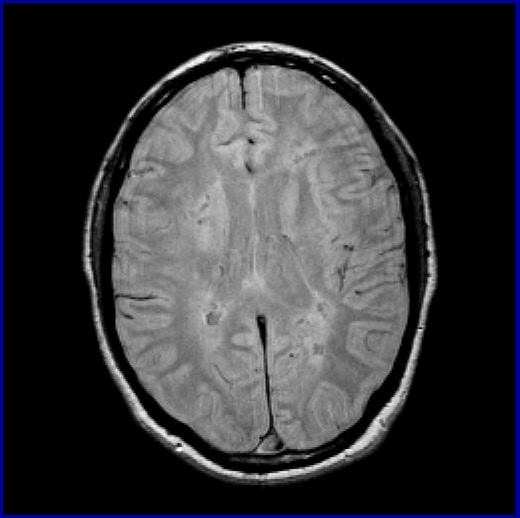
T2 Contrast and TE



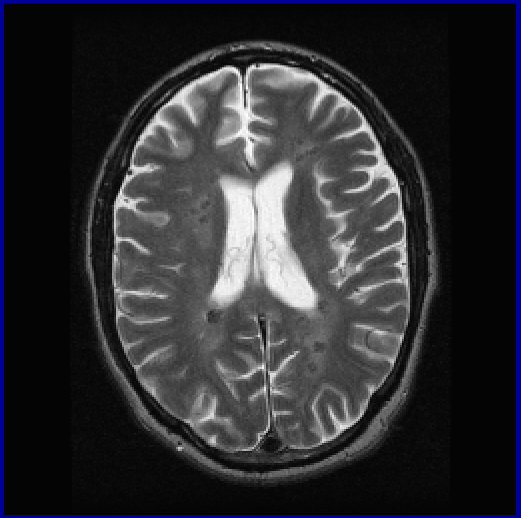
T2 Contrast

- For long TE imaging, tissues with short T2's (rapidly recovering) are darkest
  - Fat < brain tissue
  - White Matter < Grey Matter
  - Gray Matter < CSF

Spin Density



T2 Weighting



Contrast Equation

- For a 90 degree flip angle, the contrast equation is:

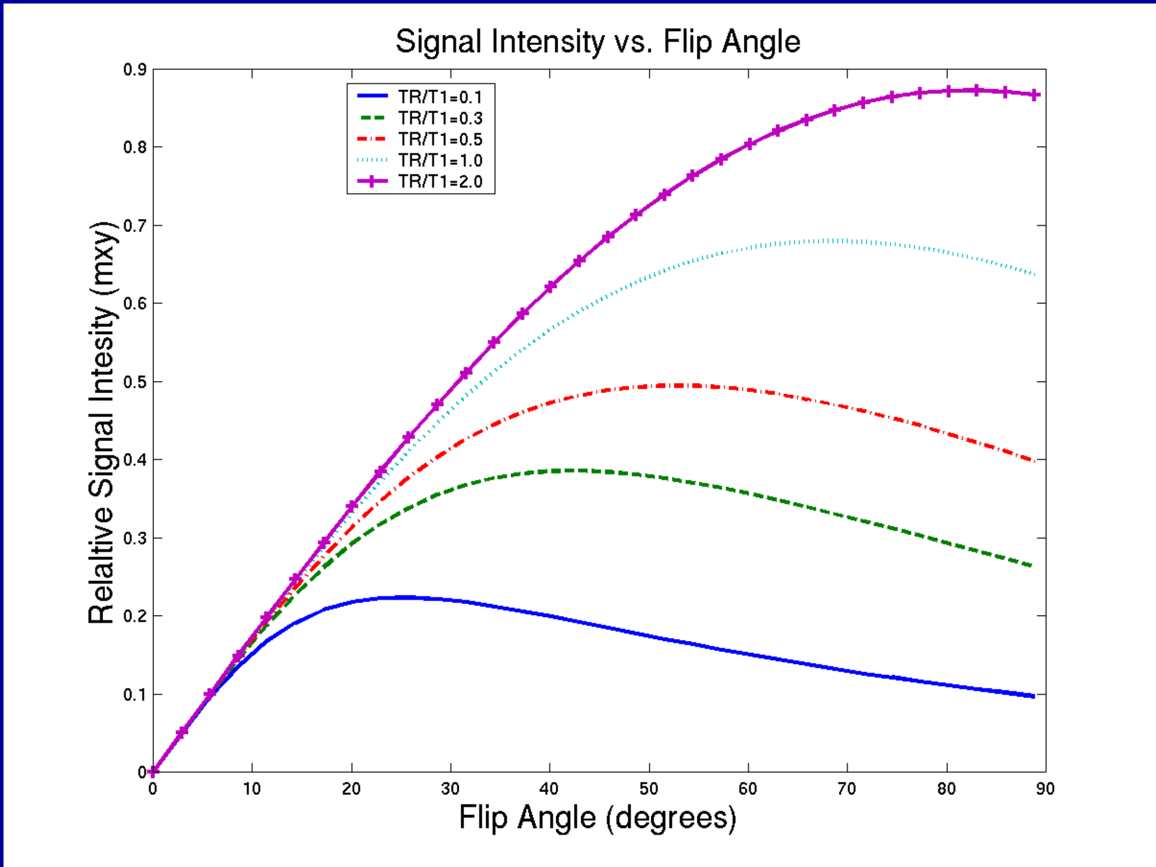
$$\text{Signal} \propto \rho(1 - e^{-TR/T1})e^{-TE/T2}$$

Spin Density — T1-weighting — T2-weighting

Can the flip angle be less than 90?

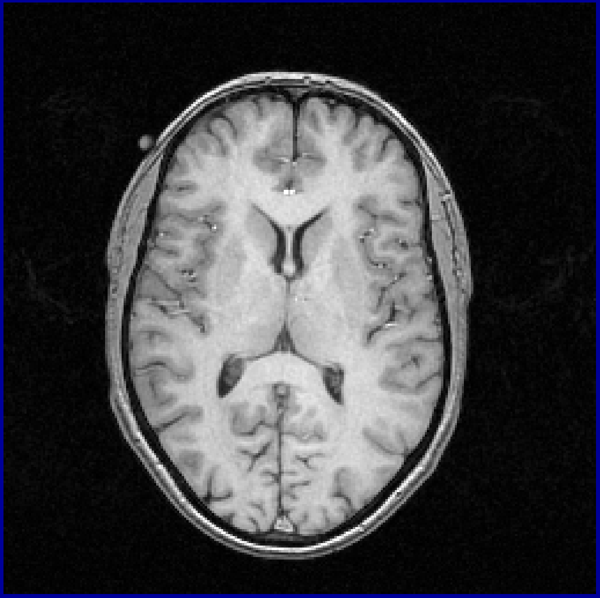
- Of course, but the contrast equation is more complicated.
- Flip angle can be chose to maximize signal strength:

  Ernst Angle



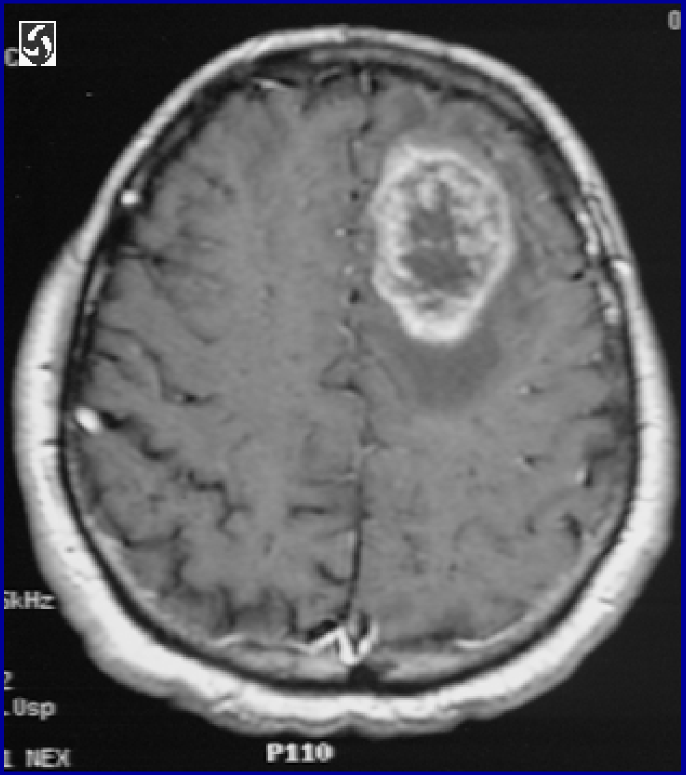
Next Step

Making an image!!

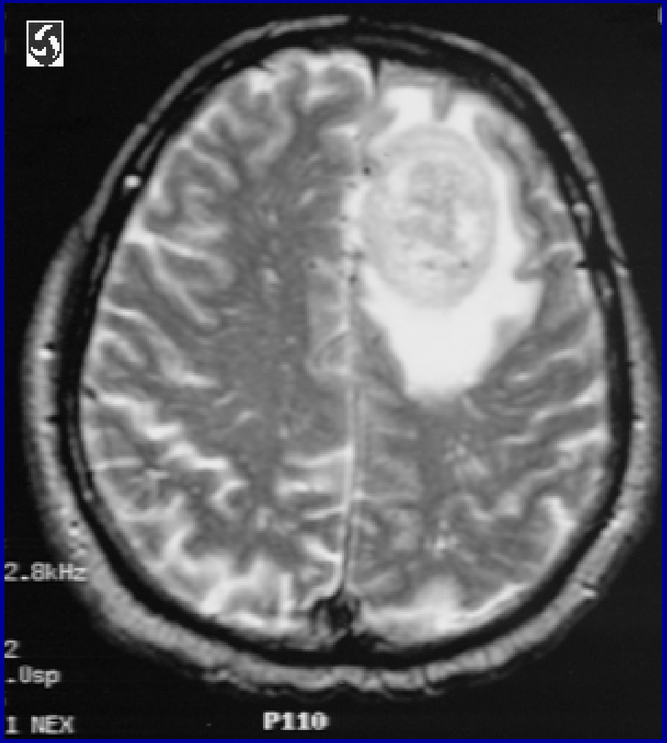


First – some examples of MR Images and Contrast

Supratentorial Brain Neoplasm



T1-weighted image
with contrast

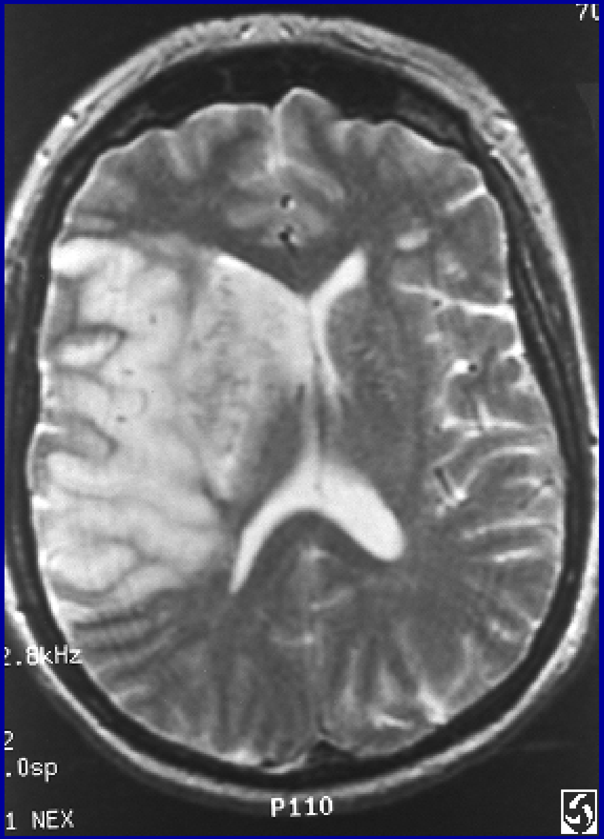


T2-weighted image

Brigham and Women's Hospital Teaching Files

Cerebral Infarction

MR Angiogram



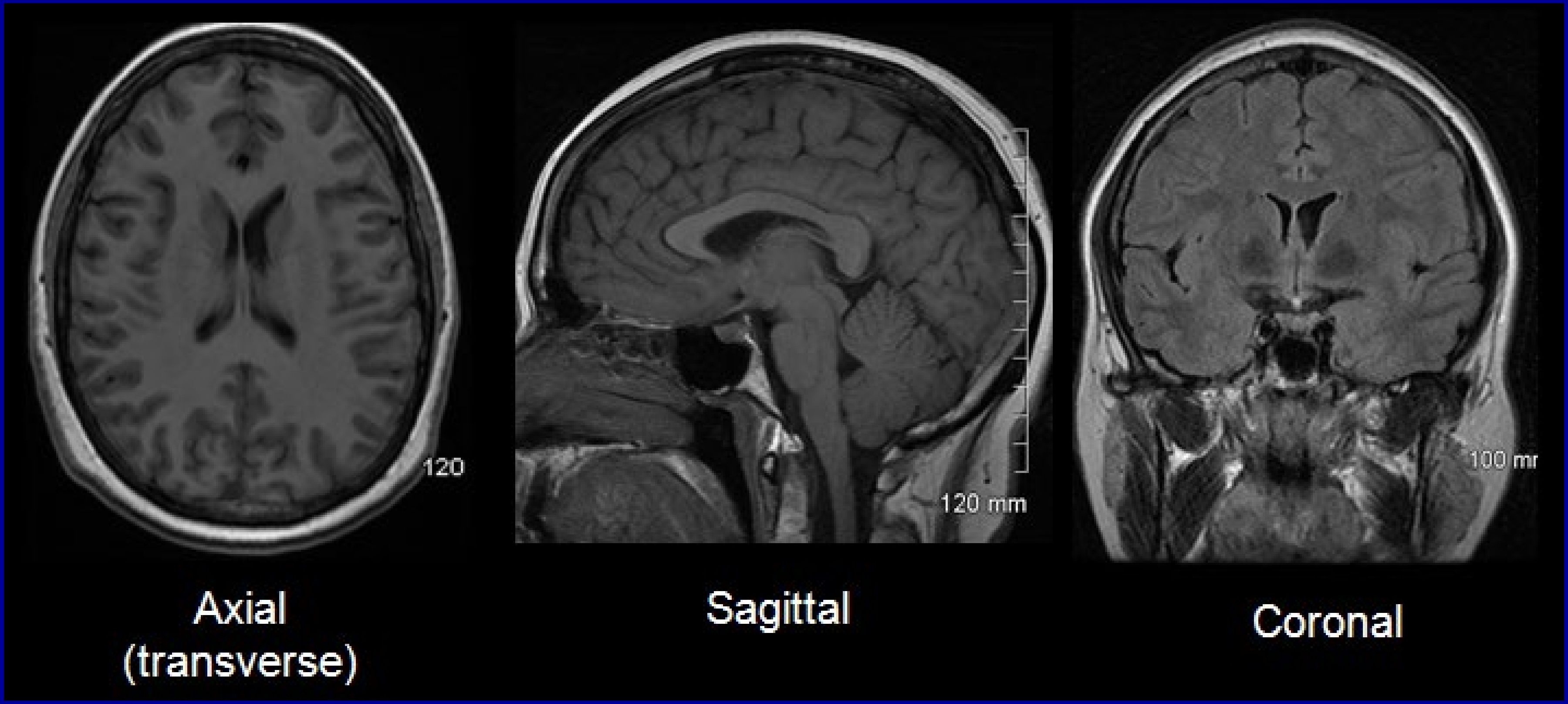
T2-weighted image

Brigham and Women’s Hospital Teaching Files

Imaging Breast Cancer

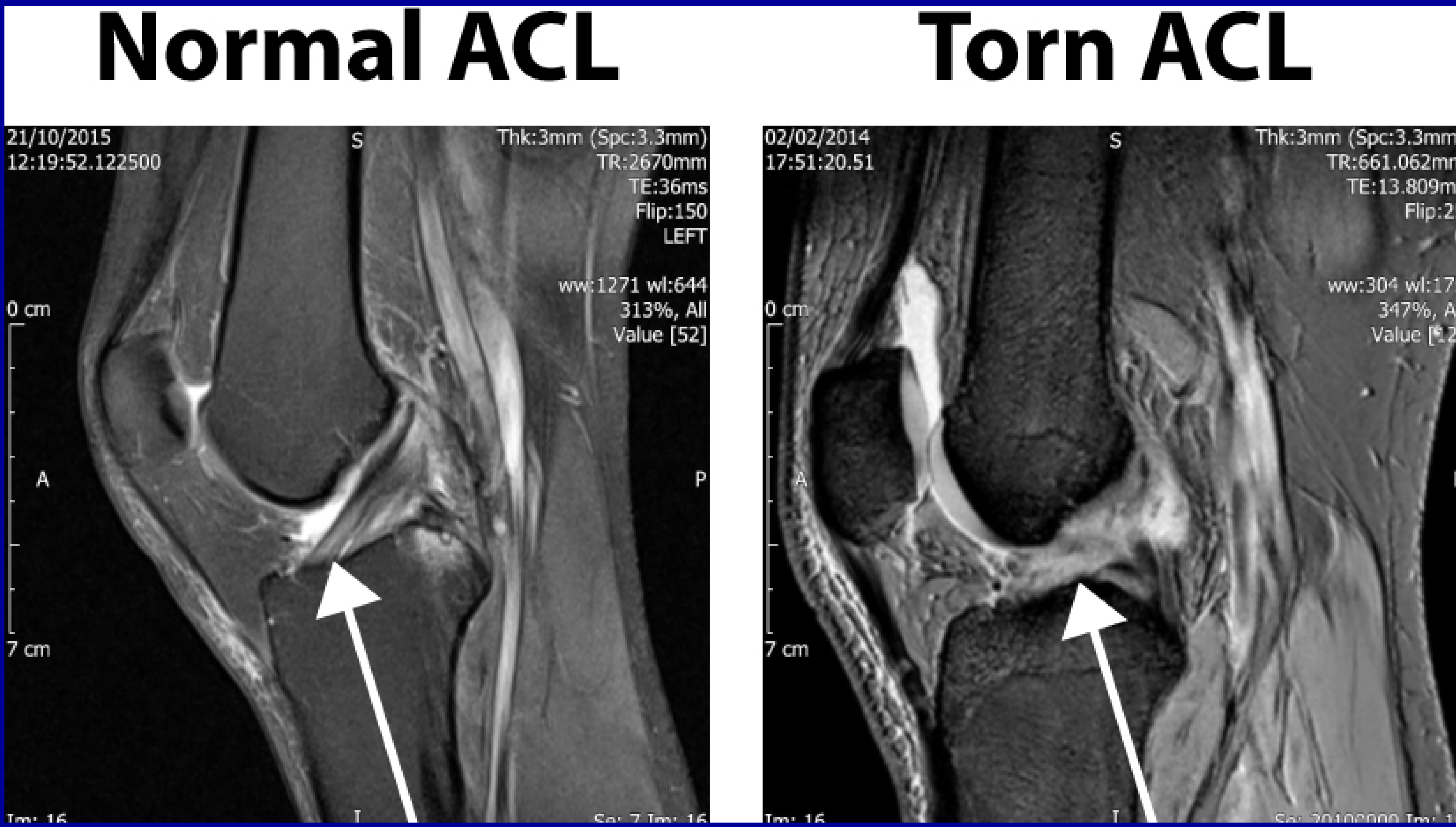
http://tristans.com/services/breast-mri/

Imaging any Orientation



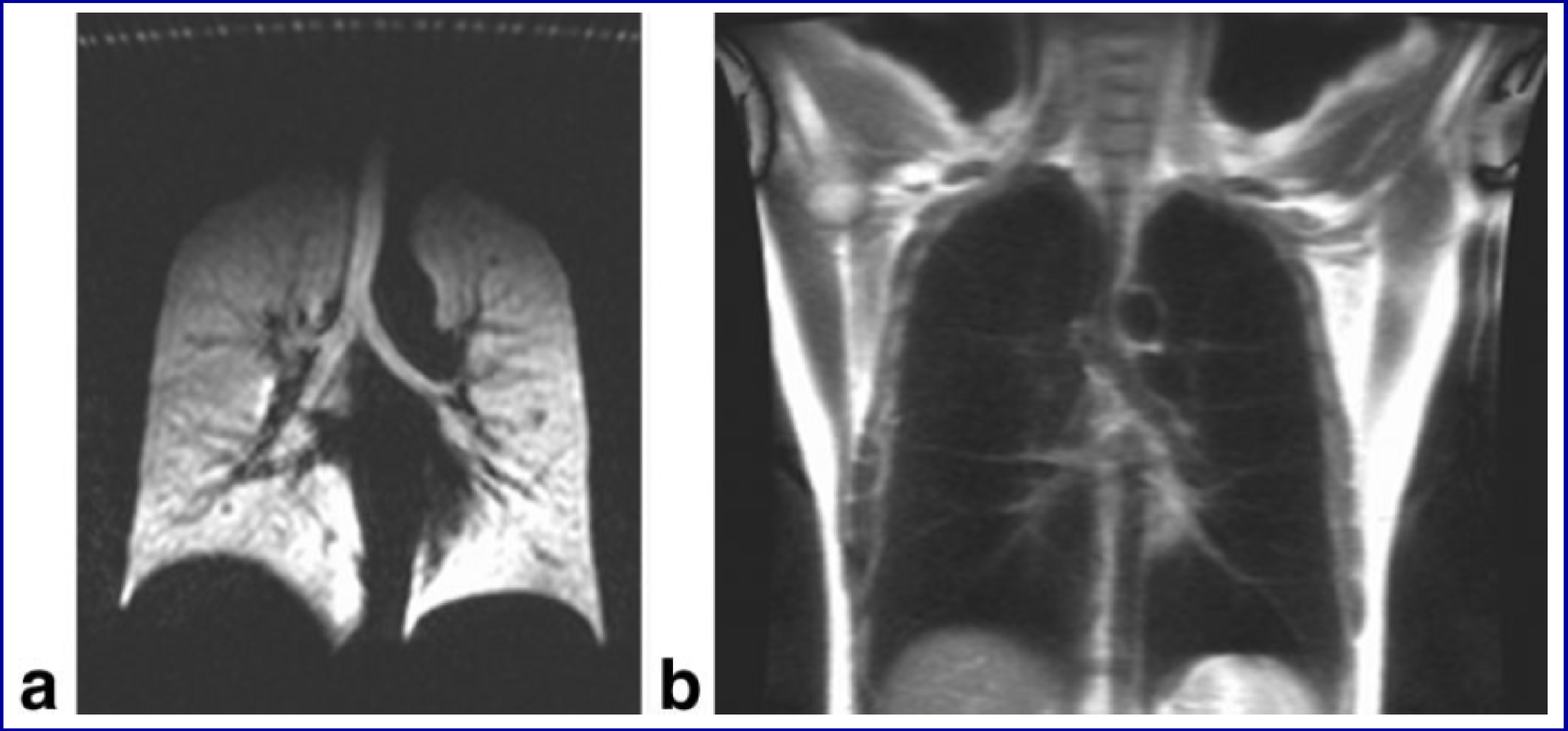
https://sites.google.com/a/wisc.edu/neuroradiology/image-acquisition/the-basics

Imaging Joints



Noll http://wolverhamptonhipandkneeclinic.co.uk/services-view/anterior-cruciate-ligament-acl-surgery/

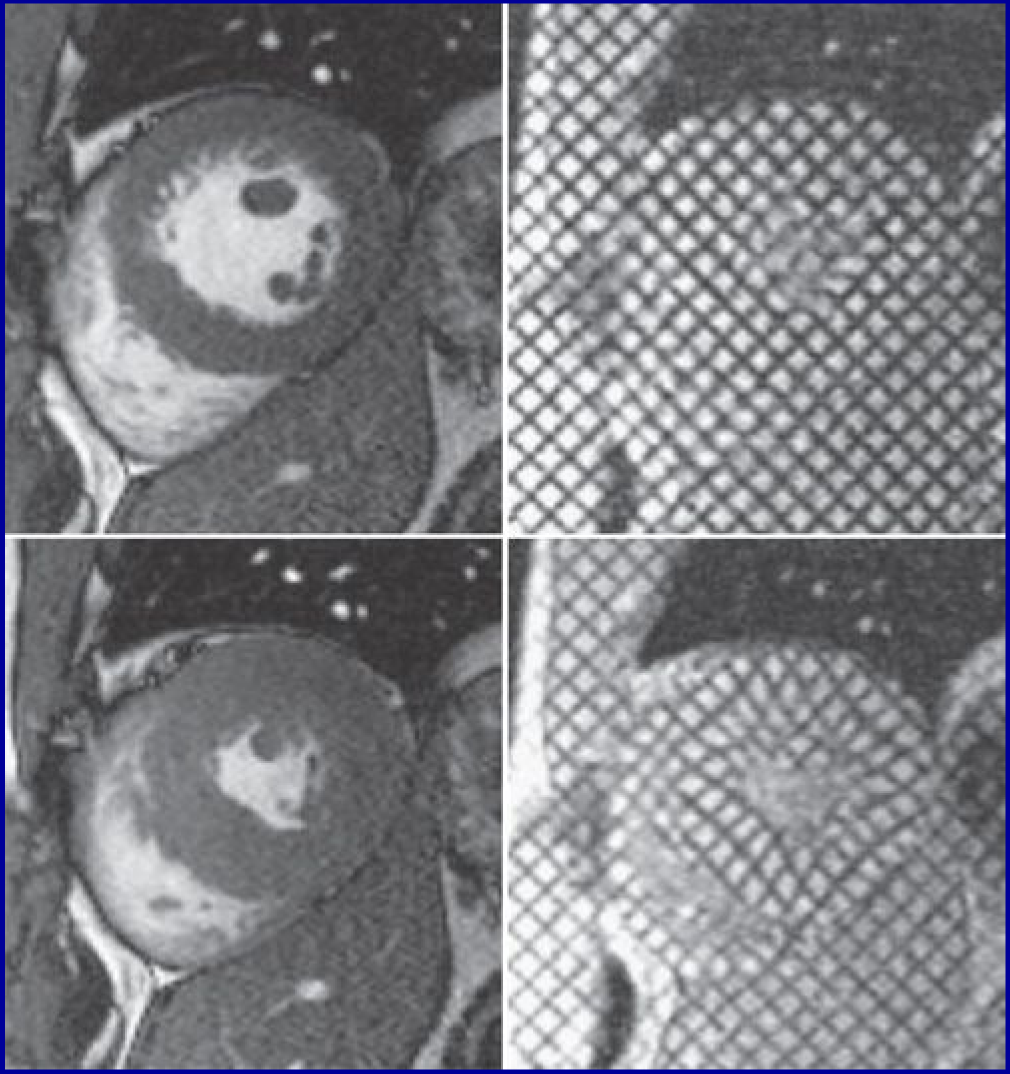
Imaging Air Passages



Noll

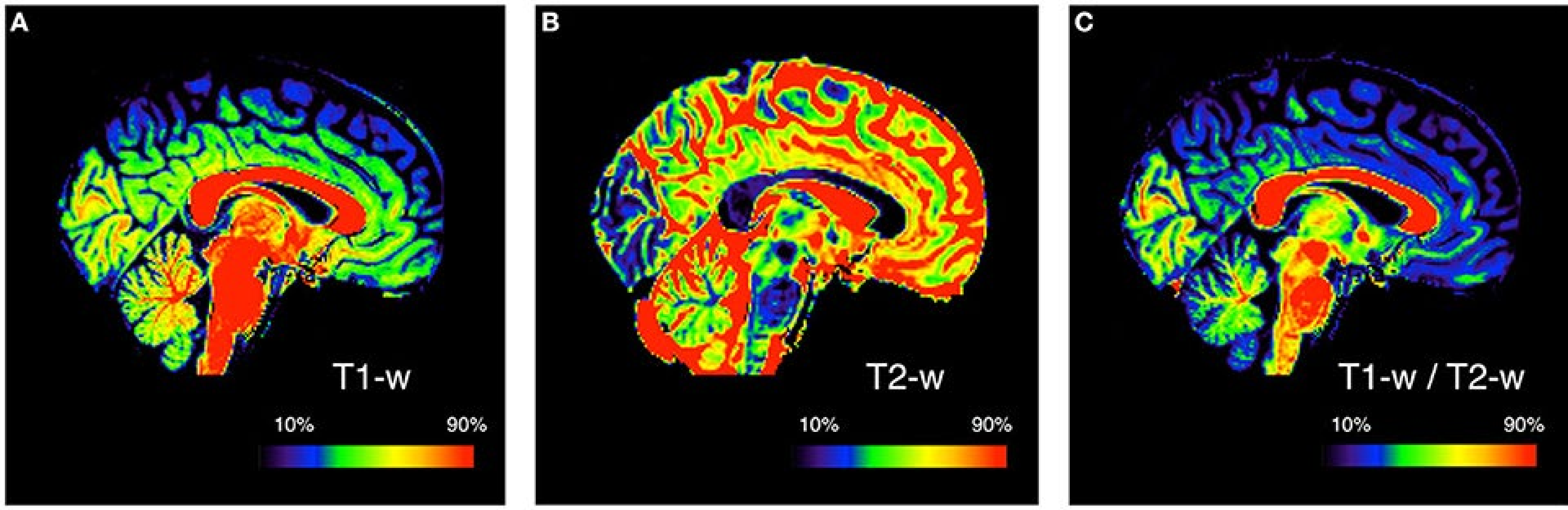
Fain et al. J. Magn. Reson. Imaging 2007;25:910–923.

Tagging Cardiac Motion



https://www.nature.com/articles/nrcardio.2009.189

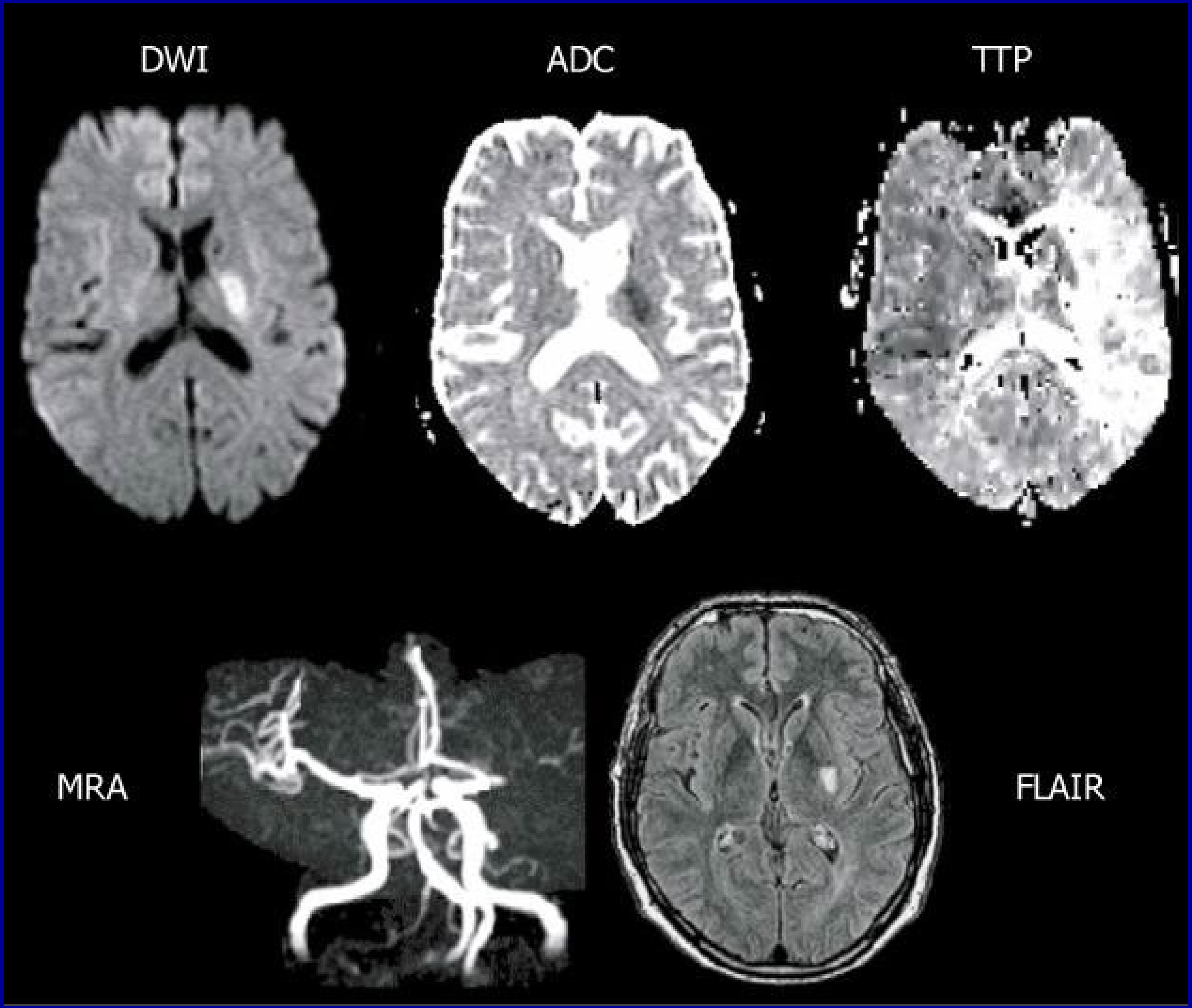
Calculated Images



Noll

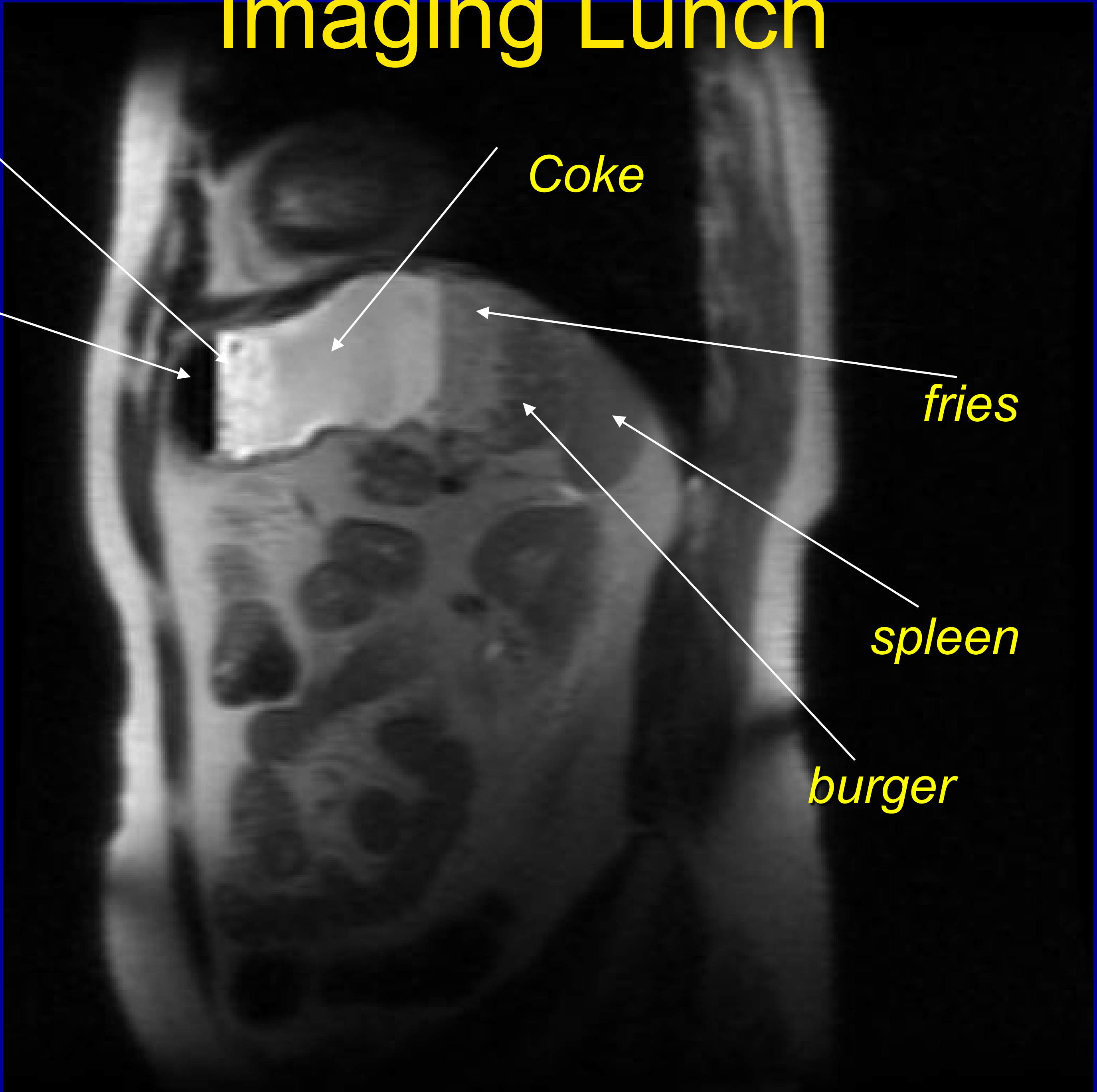
Ganzetti M, Wenderoth N and Mantini D (2014) Whole brain myelin mapping using T1- and T2-weighted MR imaging data. *Front. Hum. Neurosci*. **8**:671. doi: 10.3389/fnhum.2014.00671

Diffusion and Perfusion Weighted MRI



https://www.wjgnet.com/1949-8470/full/v4/i3/WJR-4-63-g002.htm

Imaging Lunch



Courtesy Vikas Gulani