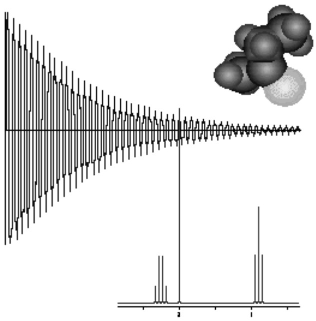
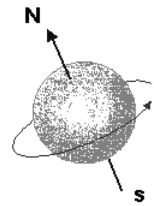


MRI Physics



Overview

- Magnetic properties of protons
- Larmor frequency
- NMR signal
- T1 & T2 relaxation
- Spin echo formation
- Contrast mechanisms

Magnetic Resonance Imaging (MRI)

- A way of obtaining diagnostic images of the body
- Uses electromagnetic radiation
- Does not use ionising radiation
- Very versatile
- Excellent tissue contrast and resolution – anatomy and pathology

MRI

- A typical image
- Shows Lumbar spine and cord

Tissue Contrast

- MRI allows for different types of tissue contrast
- Provides lots of information
  - Anatomy
  - Pathology
  - Blood flow etc.

What Does a Scanner Look Like?

- Usually one of two configurations

Closed Bore (tunnel) magnet

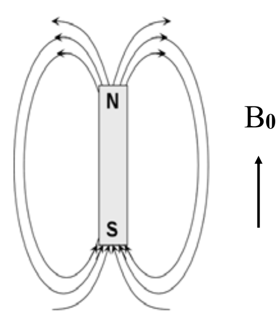
Open magnet

The MRI Scanner consists of:

- Powerful magnet
- Patient table
- Magnetic gradients (for localising the signal)
- Radio-frequency (RF) coils that transmit RF into the patient and receive the signal
- Computer
- VDU

Magnetic Fields

- A field is a quantity that varies over a spatial region:
- Magnetic field exerts torque to line magnets up in a given direction
  - Direction of alignment is direction of magnetic field B_0
  - Torque proportional to size of B_0



Magnetic Field Strength

- S.I. Units = Tesla (T)
- Old units = Gauss (G)
- 1.0T = 10,000G
- Earths magnetic field ~ 0.7×10^{-4}T
- Fridge magnet ~ 5×10^{-3}T
- Clinical MRI typically between 0.2T and 1.5T. *It's very strong!*

Types of Magnet

Superconducting

- Electromagnet
- Immersed in liquid helium
  - Windings lose electrical resistance and become superconducting
- High field strengths
- Permanently on unless ramped down or "quenched" when helium allowed to boil off
- Expensive

Resistive

- Normal electromagnet
- Can be switched on and off
- Windings have resistance – limits amount of current and therefore field strength
- Uses loads of electricity
- Expensive

Permanent

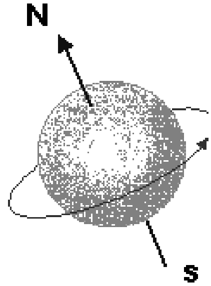
- Magnetised iron core (like a horseshoe magnet)
- Permanently on
- Very heavy pieces of kit
- Field strength limited by weight of magnet

How Does it Work?

Faraday’s Law of Induction

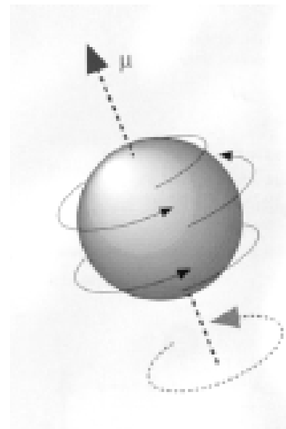
- A moving electric charge produces a magnetic field.
- The faster it moves or the larger the charge, the larger the magnetic field it produces.
- A moving magnetic field produces an electrical charge

Proton Spin and Magnetic Moment



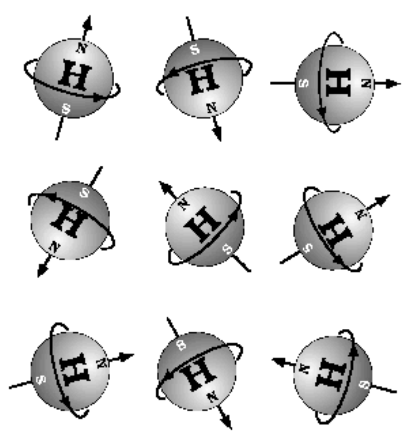
The Basic Properties of a Proton

- Mass
- A positive electric charge (very small)
- Spin (very fast)
- Produces a small, but noticeable, magnetic field.



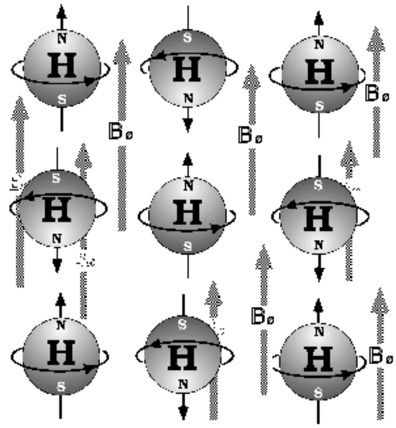
Spinning Protons Act Like Little Magnets

- Water is the biggest source of protons in the body, followed by fat (how closely followed depends upon what shape you're in!)
- Normally, the direction that these tiny magnets point in is randomly distributed



Spins Align With an External Magnetic Field (B_0)

- Like a compass aligns with the earth's magnetic field
- Some protons align with the field & some align against the field cancelling each other out.
- A slight excess will align with the field

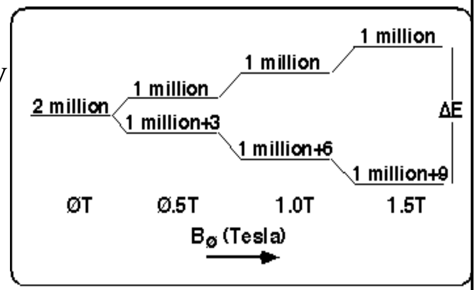


The Quantum Physics Bit

- Both alignments are possible
- The one with the external field is a lower energy state.
- The protons are continually oscillating back and forth between the two states

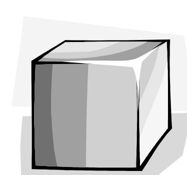
The Quantum Physics Bit

- At any given instant there will be a very slight majority aligned with the field.
- The larger the external B_0 field,
  - The greater the difference in energy levels
  - The larger the excess number aligned with the field



How many *excess* protons are there in a single *voxel* at 1.5T?

- Assume a voxel is 2 x 2 x 5 mm = .02 ml
- Avagadro's number = 6.02 x 10^{23} molecules per mole
- 1 mole of water:
  - Weighs 18 grams (o^{16} + $2h^{1}$)
  - Has 2 molecules of hydrogen
  - Fills 18 ml, so.....



How many *excess* protons are there in a single *voxel* at 1.5T?

- 1 voxel of water has $2 \times 6.02 \times 10^{23} \times 0.02 / 18 = 1.338 \times 10^{21}$ **total** protons

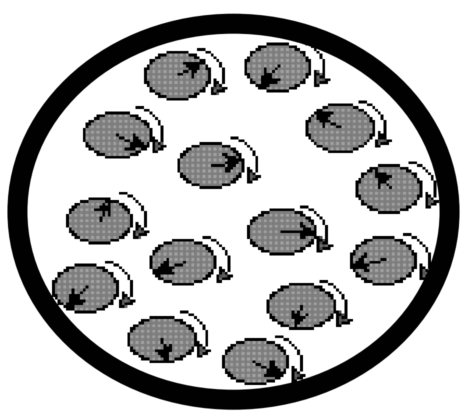
- The total number of **excess** protons =

$$(1.338 \times 10^{21}) \times \frac{9}{2 \times 10^{6}} = \mathbf{6.02 \times 10^{15}}$$

•***Or.... 6 million billion !***

Phase

- At this point, all the protons are spinning around B_o out of phase with each other

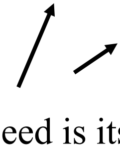


The Net Magnetic Vector

- The total magnetic field of the excess protons forms a vector
- This is called The Net Magnetic Vector (M_0)

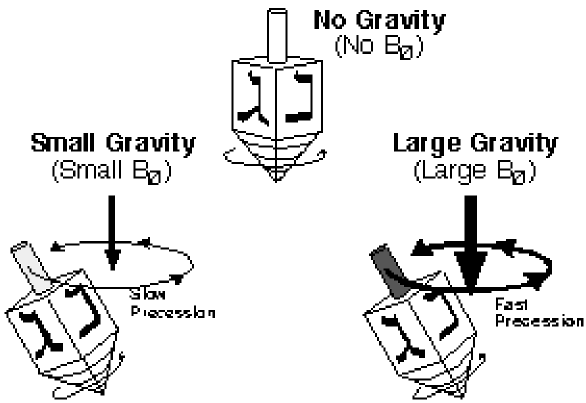
Vectors

- Magnetic field B_0 and magnetization M_0 are *vectors*:
  - Quantities with direction as well as size
  - Drawn as arrows
  - Another example: velocity is a vector (speed is its size)



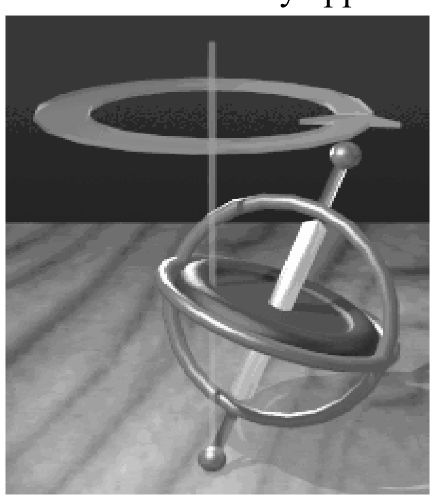
When Is A Proton Just Like a Spinning Top?

- When it wobbles. (or precesses)



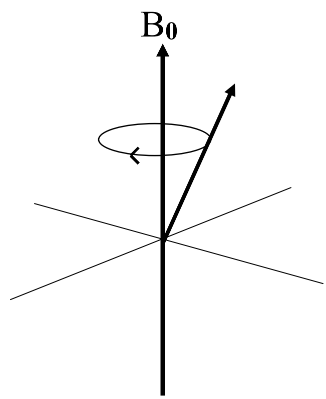
A Mechanical Analogy

- A gyroscope in the Earth's gravitational field is like magnetization in an externally applied magnetic field



The Larmor Equation

- Just as a spinning top wobbles about its axis so do spinning protons wobble, or precess, about the axis of the external B_0 field.



The Larmor Equation

- The frequency of the precession is directly proportional to the strength of the magnetic field and is defined by the Larmor equation

$$\omega_0 = \gamma B_0$$

ω_0 = The Procession frequency

γ = The Gyromagnetic ratio

B_0 = The External magnetic field strength

The Larmor Equation

For Hydrogen protons the procession frequency =

$42.6 MHzT^{-1}$

I.e. at 1.0 T the protons spin at approx. 42 *million* times a second

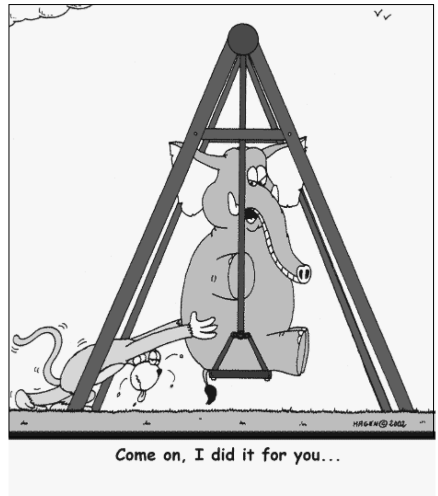
At 1.5T, they spin at approx. 63 million times a second

Apply an RF Pulse

- If an electromagnetic radio frequency (RF) pulse is applied at the resonance frequency, then the protons can absorb that energy. At the quantum level, a single proton jumps to a higher energy state.

A Mechanical Analogy: A Swing

- Person sitting on swing at rest is “aligned” with externally imposed force field (gravity)
- Push back and forth with a tiny force, synchronously with the natural oscillations of the swing



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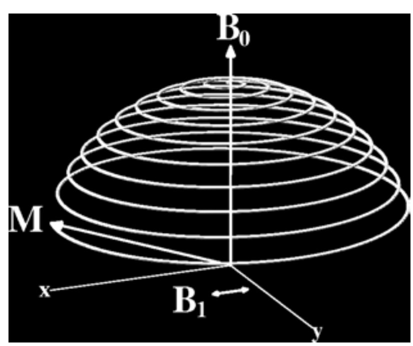
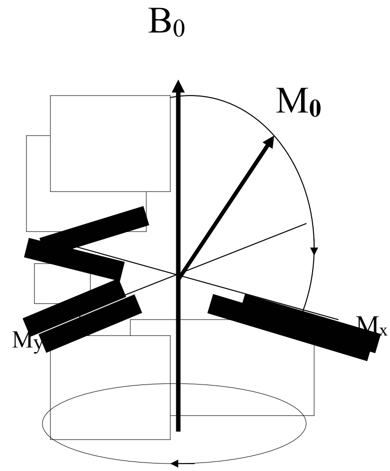
Laboratory Frame of Reference

- The viewpoint of an observer in the surrounding laboratory
- The laboratory is stationary
- The protons are spinning
- M_0 will spiral down to the XY plane (or even to the -Z axis)

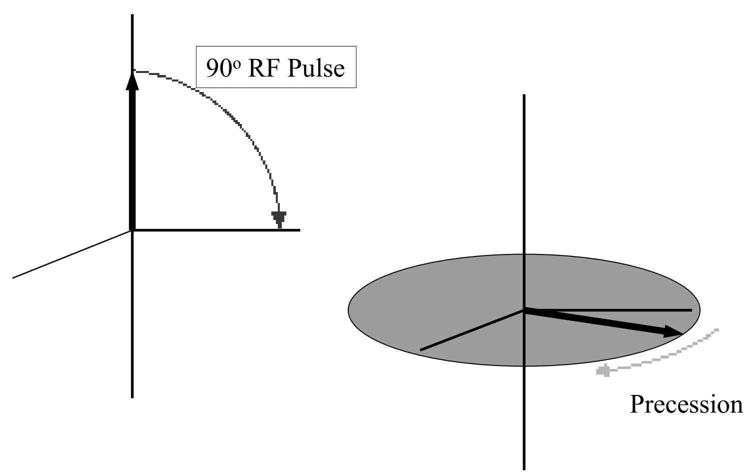


Rotating Frame of Reference

- An observer riding along with the protons (the M_0 vector)
- Sees the external world rotating about him.
- M_0 then seems to tip towards the M_{xy} plane

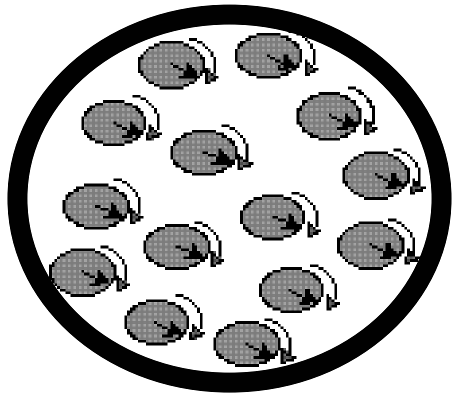


An RF Pulse Converts Longitudinal Magnetisation into Signal



In Phase Procession

- As the spins absorb the RF energy, they come into phase with each other



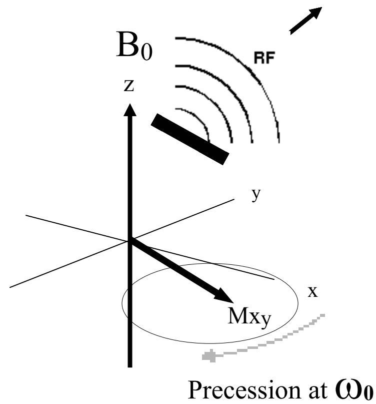
Turn Off the Transmitter What Happens?

Once the RF transmitter is turned off three things begin to happen simultaneously

- The absorbed RF energy is retransmitted
- The excited spins begin to return to the original Mz orientation. T1 recovery
- Initially in phase, the excited protons begin to dephase T2 and T2* relaxation

The Absorbed RF Energy is Retransmitted

- NMV precesses around B_0 at ω_0
- A rotating magnetic field produces EM radiation.
- Since ω_0 is in the RF portion of the electromagnetic spectrum the rotating vector is said to give off RF waves.
- Absorbed RF energy is retransmitted, thereby producing the NMR signal.



T1 Relaxation

TI Relaxation

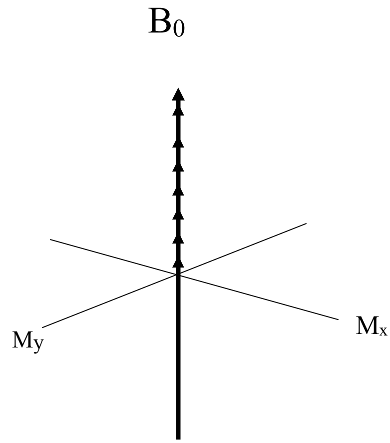
- The process of giving off RF energy occurs as the spins go from a high energy state to a low energy state, realigning with B_0
- The RF emission is the net result of the Z component (Mz) of the magnetization recovering back to M_0.
- Not all of the energy given off is detectable as an RF pulse.

Spin Lattice Interaction

- Some energy goes to heating up the surrounding tissue the lattice.
- Spin-lattice interaction is the process whereby energy absorbed by the excited protons or spins is released back into the surrounding lattice, re-establishing thermal equilibrium.

T1 Relaxation

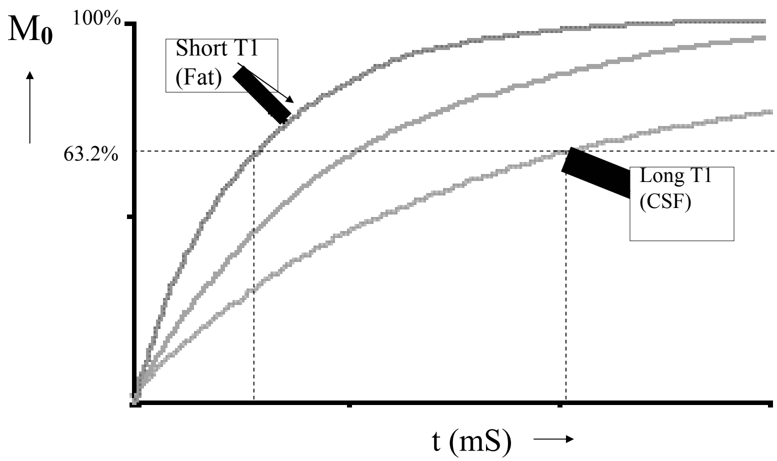
- The exponential recovery of longitudinal (aligned with B_0) magnetization.
- M_z returns to M_0



T1 Recovery Curve

- The recovery time is mathematically described by an exponential curve.
- Recovery rate is characterized by time constant T1
  - Every tissue has a unique T1 value.
  - This uniqueness in Mz recovery rates is what enables MRI to differentiate between different types of tissue
  - T1 varies with field strength
- At a time t=T1 after the excitation pulse, 63.2% of the magnetization has recovered alignment with B_0

T1 Recovery Curve



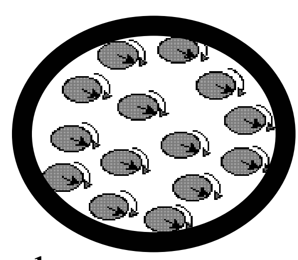
Common T1 Values at 1.5T

Tissue	T1 Value (mS)
Blood	1200
CSF	3000
Fat	259
Grey Matter	921
White Matter	786

T2 and T2* Relaxation

T2 Decay & Loss of Phase

- After RF pulse, the spins are all *in phase*.
- When RF pulse switched off, spins start to dephase
- Spin-spin interaction



- Loss of phase = loss of signal

T2 Decay & Loss of Phase

- How fast a proton precesses depends on the magnetic field that it ***experiences***.
- An isolated proton only experiences B_0, therefore has a constant rate of spin
- As protons move together (due to random Brownian motion), their magnetic fields begin to interact.

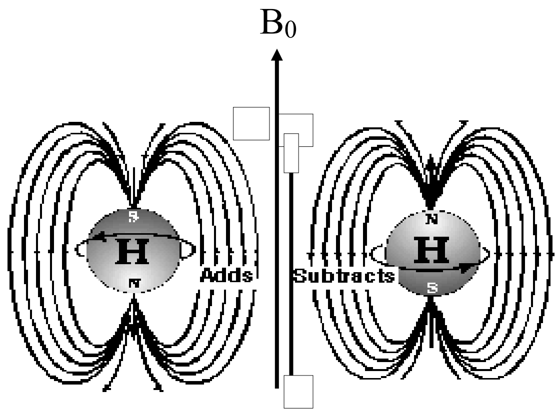
T2 Decay & Loss of Phase

- If the field from one proton increases the field that the second proton feels then the second proton will speed up
- If the first field opposes the second field then the second proton will precess more slowly.
- As soon as the spins move farther apart their fields no longer interact and they both return to the original frequency but at *different phases*!

T2 Decay & Loss of Phase

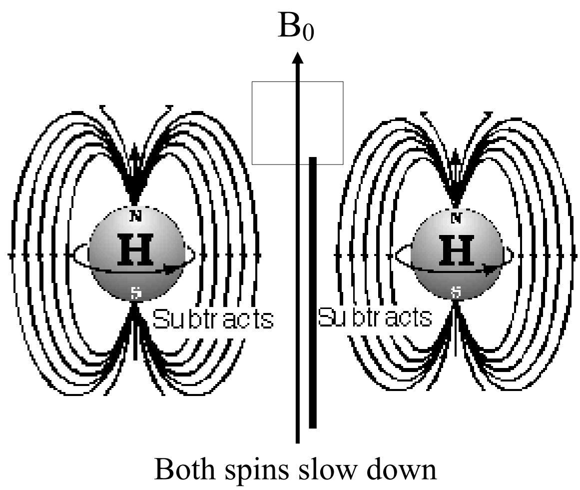
- This type of interaction is called spin-spin interaction.
- These temporary, random interactions cause a cumulative loss of phase across the excited spins
- Results in an overall loss of signal

Spin Spin Interaction



Spin speeds up　　Spin slows down

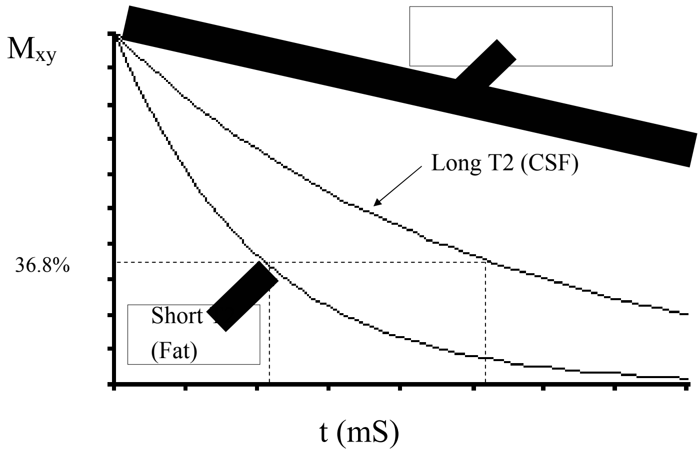
Spin Spin Interaction



T2 Decay Curve

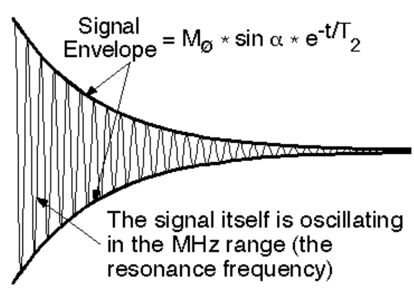
- The signal decay resulting from spin-spin relaxation is described mathematically by an exponential curve
- The value **T2** is the time after excitation when the signal amplitude has been reduced **to** 36.8% of its original value
- The value of T2 is unique for every kind of tissue and is determined primarily by its chemical environment with little relation to field strength.

T2 Decay Curve



Free Induction Decay (FID)

- **FID:** Free Induction Decay. An NMR Signal in the absence of any magnetic gradients.
- An FID decays exponentially.
  At t = T2, 63.2% of the signal has been lost.
- The decay curve is the signal envelope. The actual signal is oscillating at the resonance frequency in the MHz range.



Free Induction Decay (FID)

- The initial amplitude of the signal is determined by the portion of the NMV that has been tipped onto the XY plane.
- This, in turn, is determined by the sine of the flip angle, a. The maximum signal is obtained when the flip angle is 90°. (Remember, sin(0°) = 0, sin(90°) = 1.0)

T2* Decay

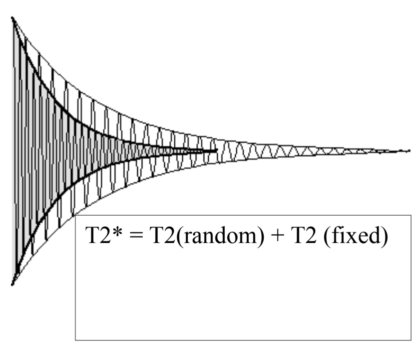
- T2 decay is a function of completely random interactions between spins.
- The assumption is that the main external field is *absolutely* homogeneous.
- In reality, there are many factors creating imperfections in the homogeneity of a magnetic field.

An Imperfect World

- The main magnet itself will have flaws in its manufacture.
- Every tissue has a different magnetic susceptibility which distorts the field at tissue borders, particularly at air/tissue interfaces.
- Patients may have some type of metal on or in them (dental work, clips, staples, etc.).

T2* Decay

- The sum total of all of these random and fixed effects is called T2*
- Causes signal to drop off even quicker

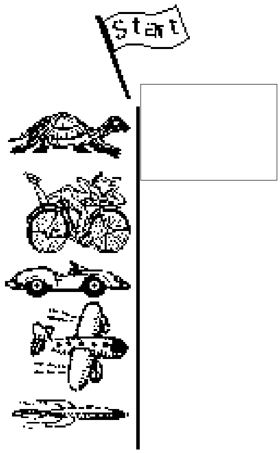


Spin Echo

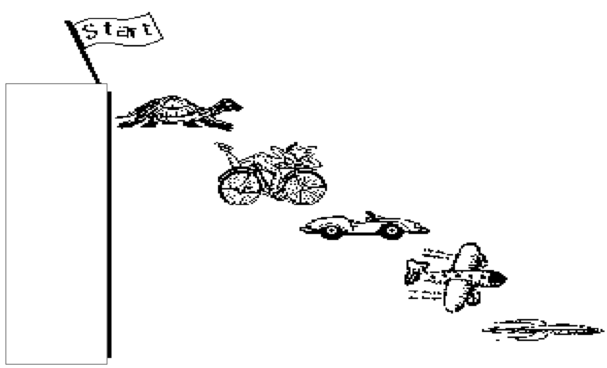
Spin Echo

- The NMR signal decays due to:
  - Random effects
  - Fixed effects
- The fixed effects can be compensated for using spin echo

Consider this Lineup

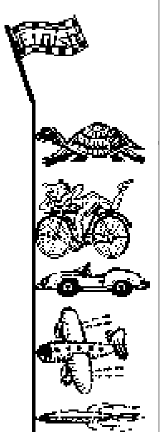


The race begins



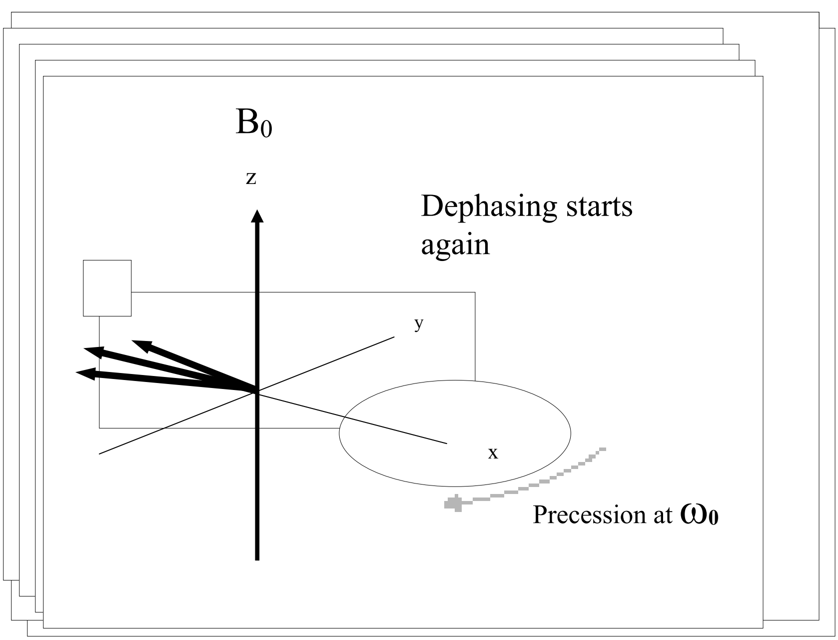
Turn Around

The Race Ends



The principle of Spin Echo

- **TE = Time to Echo**
- M_0 is flipped by a 90° RF pulse into the xy plane
- A time of TE/2 is allowed to elapse while the spins dephase (T2* mechanisms).
- At t = TE/2, a 180° RF pulse is given which flips the dephased vectors
- Another TE/2 time is allowed to pass while the vectors rephase.
- At t = TE, the vectors have rephased and a signal (echo) forms.



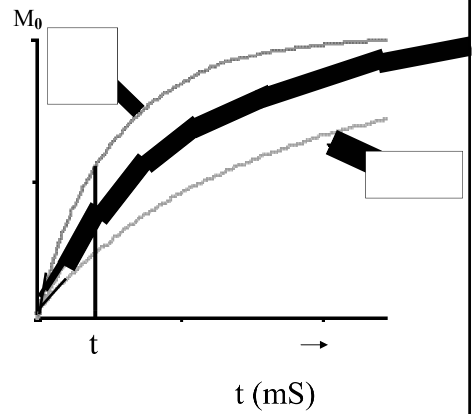
Basic Contrast

T1 Contrast

- Uses T1 relaxation as a contrast mechanism
- TR = Repetition Time for 90^o RF Pulse
- Shows
  - fat as bright in the image
  - Fluid as dark in the image
- Good for anatomy

T1 Contrast Mechanism

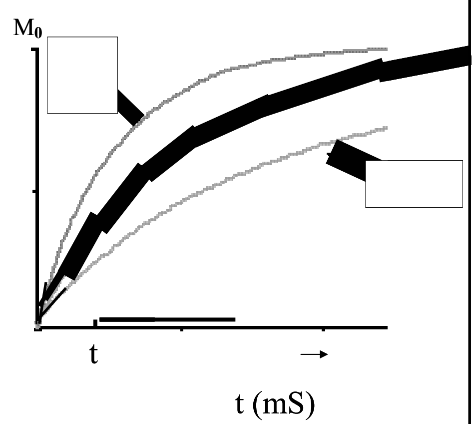
- 90^o RF pulse applied and Mo allowed to start to recover
- After a short time “t”
  - –This much fat will have recovered
  - –This much fluid will have recovered



T1 Contrast Mechanism

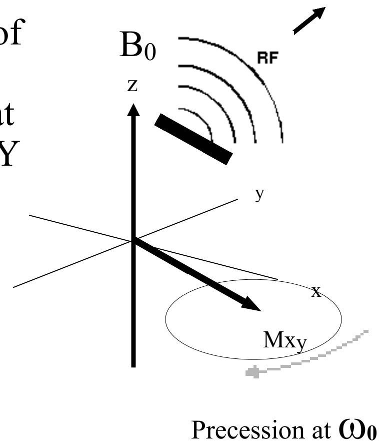
- Another 90^o RF pulse is applied at time t
- This is the repetition time or **TR**

The NVM is flipped into the xy plane again



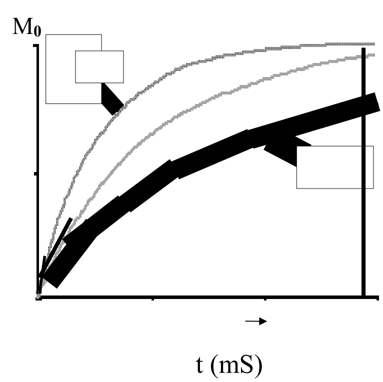
T1 Contrast Mechanism

- Remember, the amplitude of the signal is determined by the portion of the NMV that has been tipped onto the XY plane.
- So:
  - High signal from fat
  - Fat will be bright on image
  - Low signal from fluid
  - Fluid will be dark on image



T1 Contrast Mechanism

- If the TR is set for a long value of t,
- Most of Mo will have recovered for all tissues
- There will not be any T1 contrast

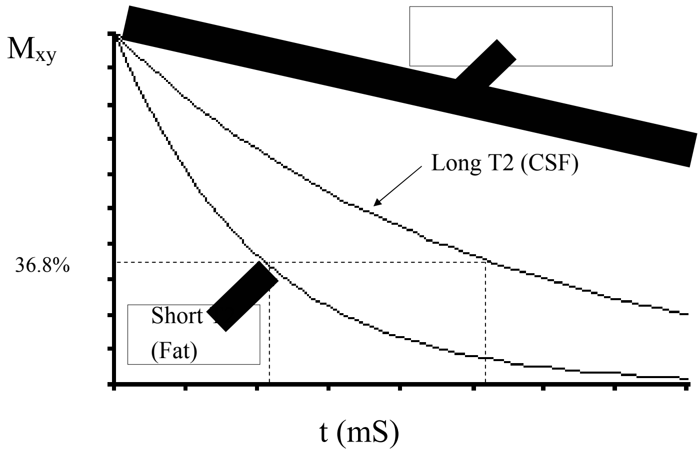


T2 Contrast

T2 Contrast

- Uses T2* relaxation as a contrast mechanism
- The TE (echo time) determines the contrast
- Shows:
  - Fluid Bright
  - Fat Dark
- Good for pathology

T2 Decay Curve

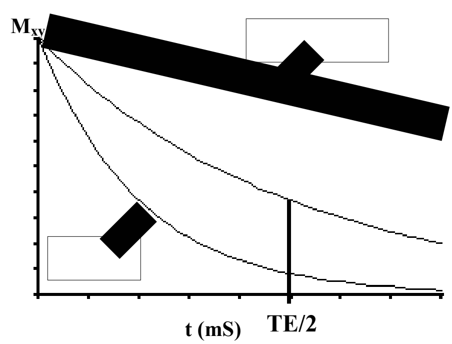


T2 Contrast Mechanism

- A long echo time (TE) is set
- At TE/2 the 180^{o} pulse is applied

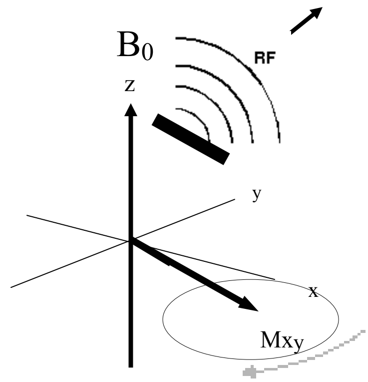
CSF will contribute this much to Mxy

Fat will contribute this much to Mxy



T2 Contrast

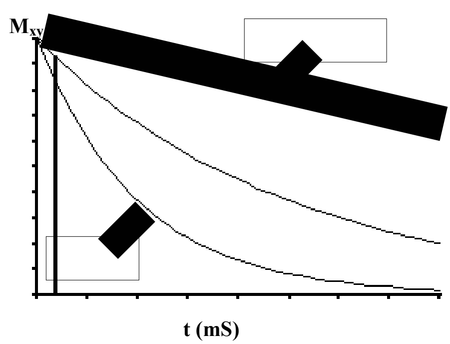
- CSF will give a high signal in the echo
- Bright on image
- Fat will give a low signal in the echo
- Dark on image



Precession at ω_0

T2 Contrast Mechanism

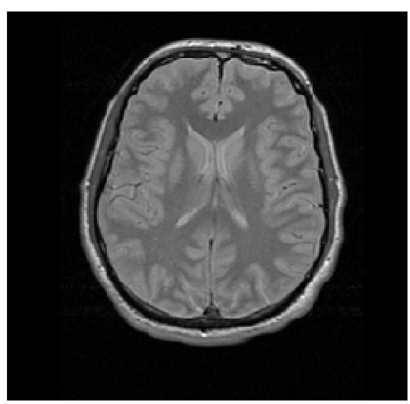
- If TE is short
- Insufficient time will have elapsed for relaxation rates of different tissues to become significant
- No discernable contrast



Proton Density

Proton Density

- Contrast factor present in all MR Images
- Product of the number of protons in a given volume of tissue
  - High density = high signal
  - Low density = low signal



Putting it all Together

T1 Weighted image

Demonstrates anatomy

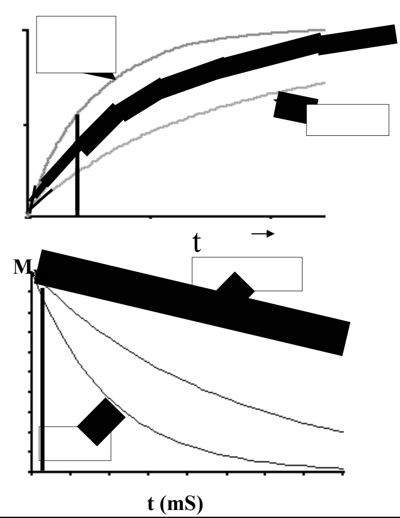
Bright Fat

Dark Fluid

Short TR needed (400ms)

Do not want any T2 contrast

Short TE needed (20mS)

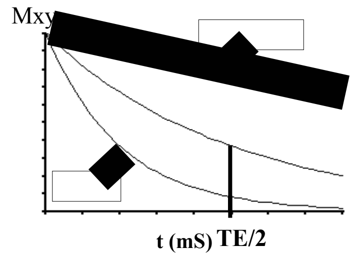


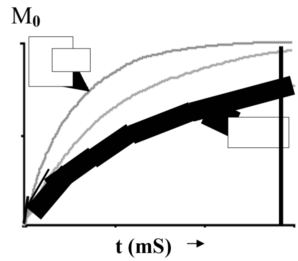
T2 Weighted Image

Demonstrates pathology
Fluid Bright
Fat Dark
Long TE needed (120ms)

Do not want any T1 contrast

Long TR needed (4000ms)



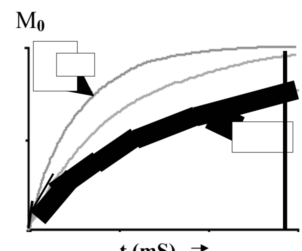


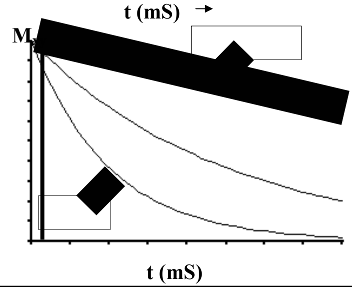
Proton Density Weighted Image

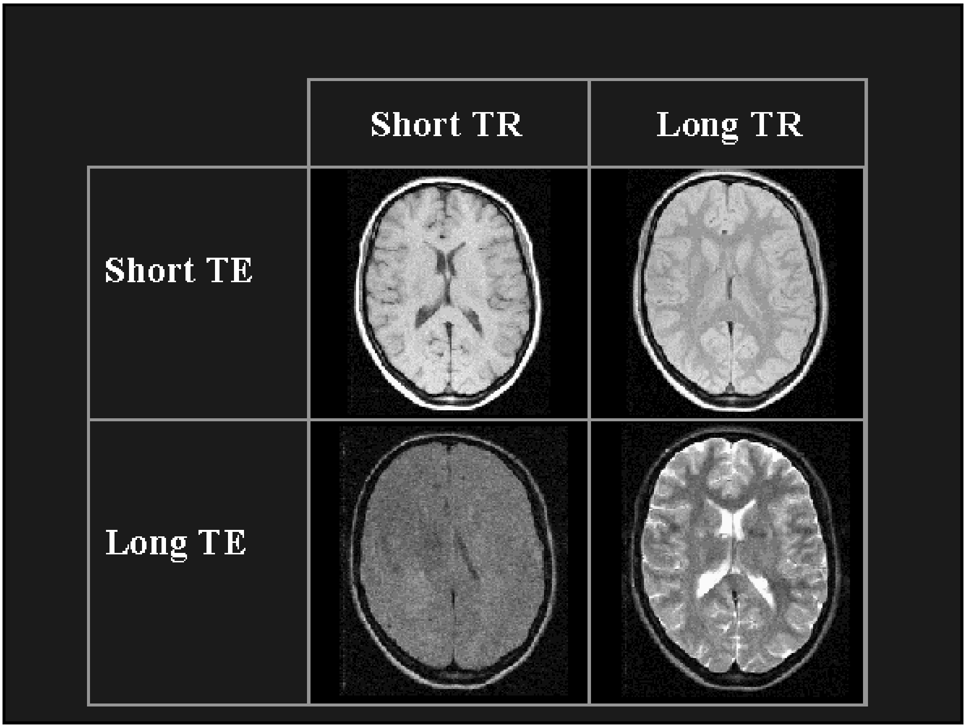
Useful for anatomy
Some Pathology
Do not want T1 contrast
Long TR

Do not want T2 contrast

Short TE






Short TR
Long TR
Short TE
Long TE