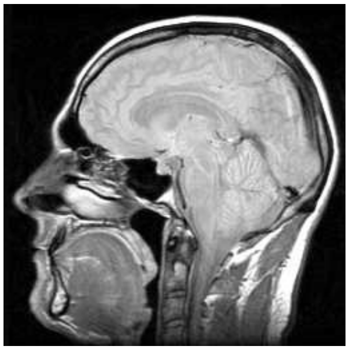
MRI Physics

(Magnetic Resonance Imaging)

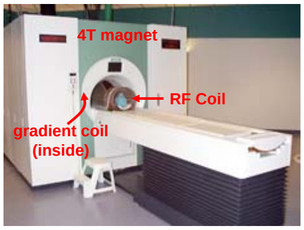
http://www.williamoslerhc.on.ca/Patient_Services/di.htm

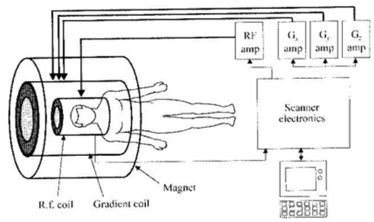
What is MRI good at?

Among other things (to be discussed later),
TISSUE CONTRAST!

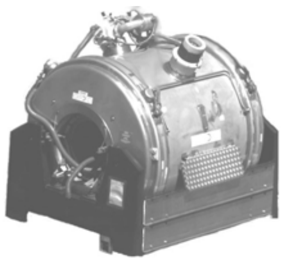


Necessary Equipment



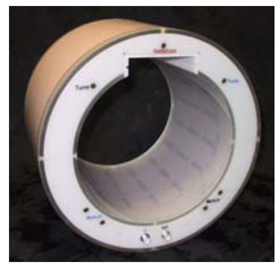


Magnet



Gradient Coil

RF Coil



Source: Joe Gati, photos

Dipole Spin

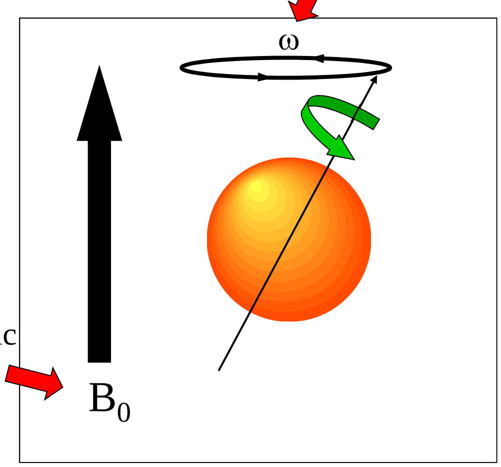
Larmour Frequency

Magnetic moment

$$\frac{d\vec{\mu}}{dt} = \gamma\vec{\mu} \times \vec{B}_0$$

$$\Rightarrow \quad \omega = \gamma B_0$$

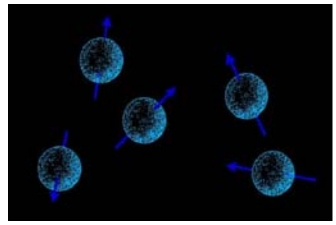
Magnetic field

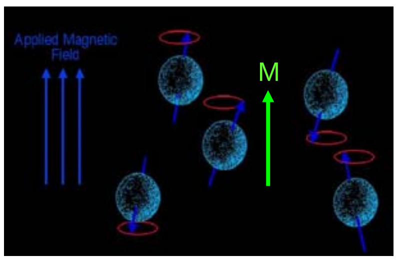


http://www.youtube.com/watch?v=IEwAry0GARw
http://www.youtube.com/watch?v=MOrk9ZQy1Dw&feature=share&list=ULMOrk9ZQy1Dw

Net Magnetization Vector

Spins orient themselves randomly.



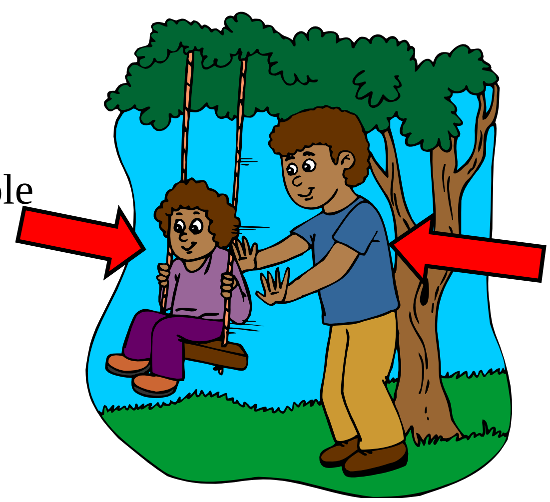


Source: Mark Cohen's web slides

But in a magnetic field, they orient either “spin-up” or “spin-down”, and result in a net magnetization in a given neighbourhood.

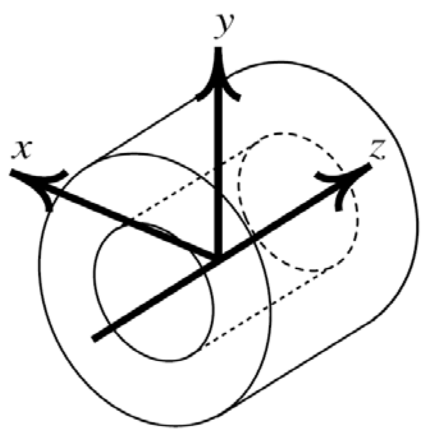
Nuclear Magnetic Resonance (NMR)

Dipole



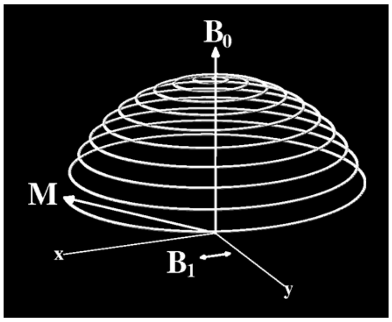
RF Pulse

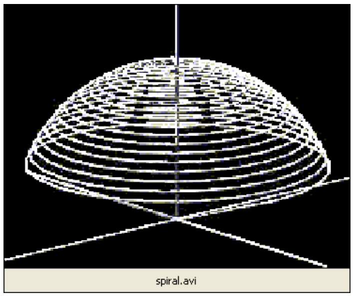
Scanner Coordinate System



Nuclear Magnetic Resonance (NMR)

By pulsing a magnetic field perpendicular to $\boldsymbol{B}_0$, we can move $\boldsymbol{M}$ out of alignment with $\boldsymbol{B}_0$. This pulsing magnetic field is called the RF (radiofrequency) pulse, and pulses at the Larmour frequency





Source: Robert Cox's web slides

http://www.youtube.com/watch?v=1KUDkeZW44Y&feature=mfu_in_order&list=UL

http://www.youtube.com/watch?v=sWP6IcmUDZs&feature=mfu_in_order&list=UL

Relaxation

$$\frac{d\vec{M}}{dt} = \gamma\vec{M} \times \vec{B}_0 - \frac{1}{T_2}\left(M_x\vec{i} + M_y\vec{j}\right) - \frac{1}{T_1}\left(M_z - M_0\right)\vec{k}$$

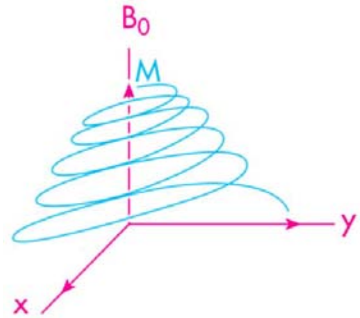
Transverse component spirals down to nothing.

$$M_{xy}(x,y,t) = ce^{-i\gamma B_0 t}e^{\frac{-t}{T_2}}e^{-i(k_x x + k_y y)}$$

Longitudinal component relaxes back to the steady state $\boldsymbol{M}_0$.

$$M_z(t) = M_0\left(1 - c_1 e^{-\frac{t}{T_1}}\right)$$

http://www.youtube.com/watch?v=A0dl4_wxr1c&feature=mfu_in_order&list=UL

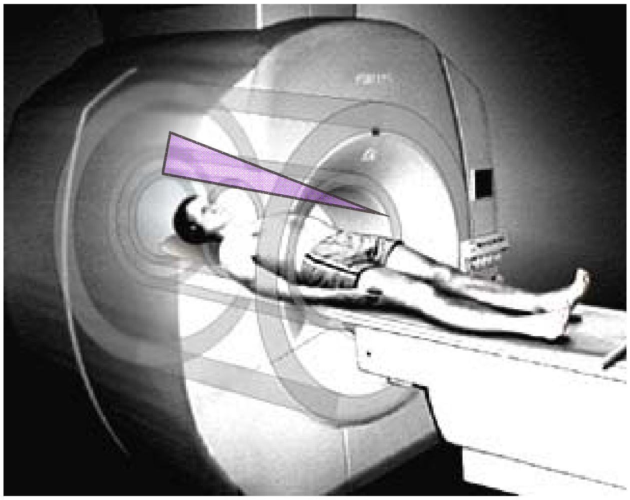


Source: Mike Noseworthy, McMaseter University

MR Imaging

(Magnetic Resonance Imaging)

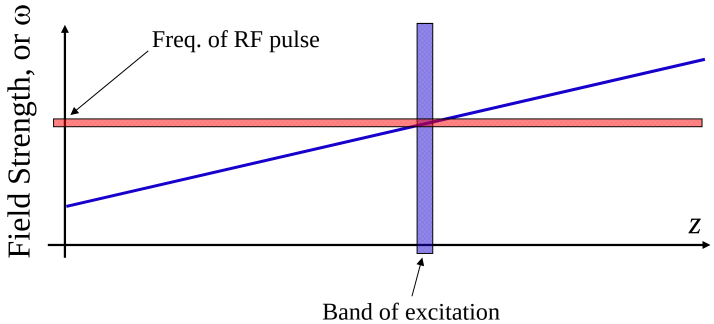
http://www.williamoslerhc.on.ca/Patient_Services/di.htm



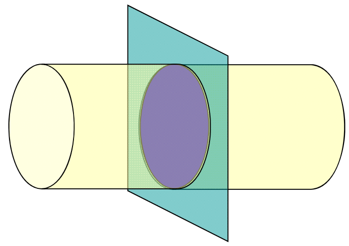
http://nobelprize.org/nobel_prizes/medicine/laureates/2003/press.html
Paul C Lauterbur and **Peter Mansfield, Nobel Prize 2003 in Physiology or Medicine**

Slice Selection

Adding a gradient to the magnetic field causes a gradient in Larmour frequency. The frequency of the RF pulse will only excite a thin band of matter.

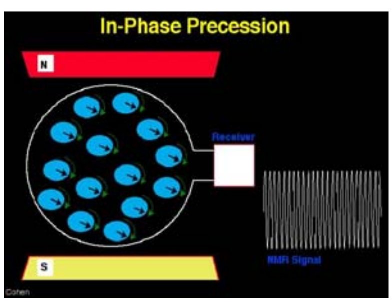


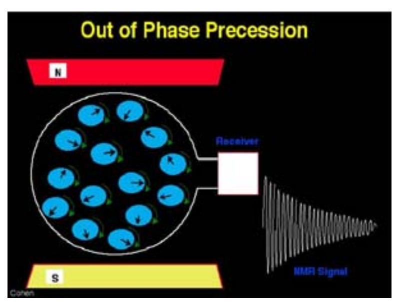
Slice Selection



Once a slice is excited, the magnetization vectors in that slice are coherent (synchronized) and create a signal.

T_2^* Decay





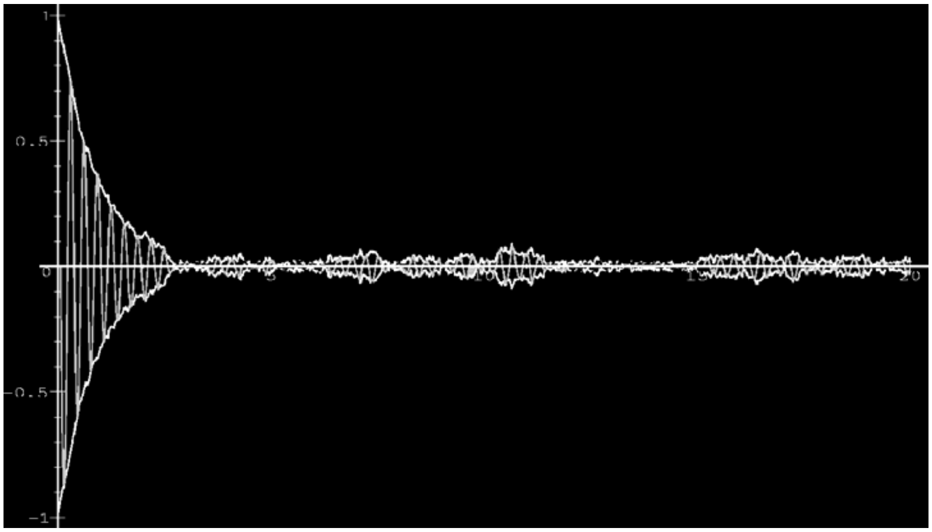
- protons precess at slightly different frequencies because of
  (1) random fluctuations in the local field at the molecular scale (T2) and
  (2) larger scale variations in the magnetic field (T2*).
- over time, the frequency differences lead to different phases between the net magnetization vectors (think of a bunch of clocks running at different rates – at first they are synchronized, but over time, they get more and more out of sync until they are random)
- as the protons get out of phase, the transverse magnetization decays

http://www.youtube.com/watch?v=YUSZoLBgSuA&feature=mfu_in_order&list=UL

http://www.youtube.com/watch?v=7K-Dg5jmV-8&feature=mfu_in_order&list=UL

Source: Mark Cohen's web slides

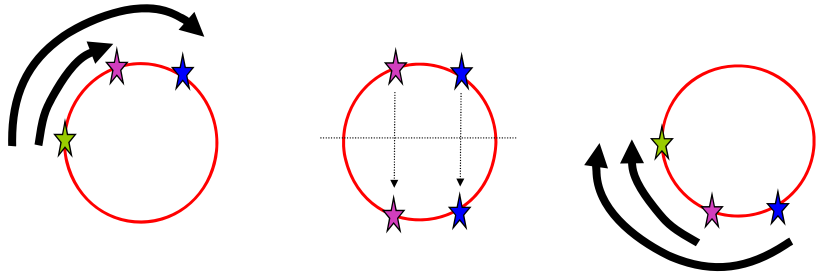
Sum of 500 cosines with random frequencies



Source: Robert Cox's web slides (http://intramural.nimh.nih.gov/research/clinicians/sc_cox_r.html)

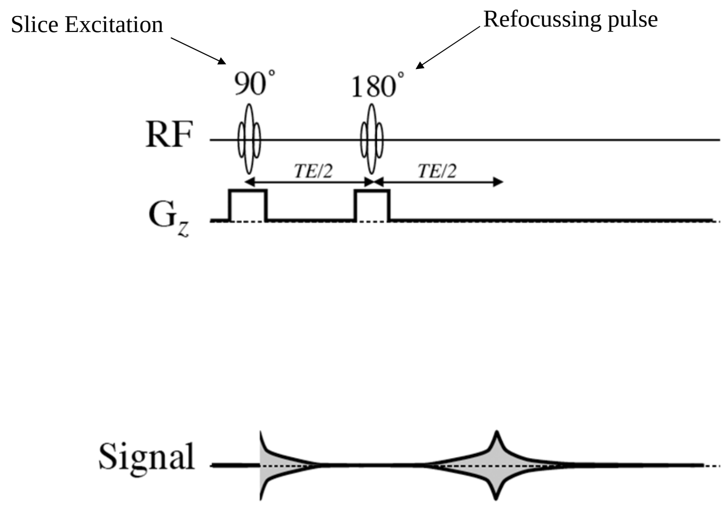
Hahn Spin Echo: Retrieving Lost Signal

- Problem: $\boldsymbol{M}_{xy}$ rotates at different rates in different spots
- Solution: take all the $\boldsymbol{M}_{xy}$'s that are ahead and make them get behind (in phase) the slow ones
  - After a while, fast ones catch up to slow ones ⇒ re-phased!

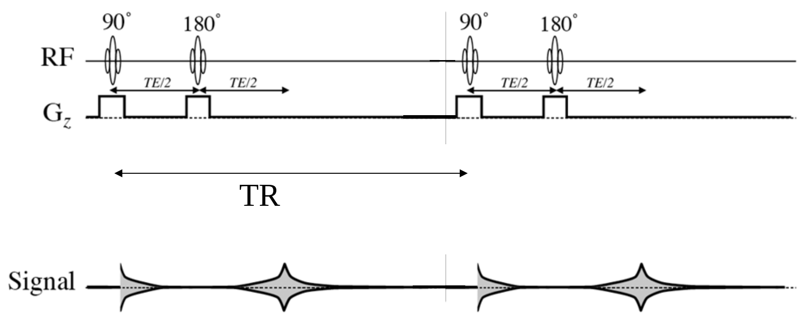


http://www.youtube.com/watch?v=vMh11VtUA5o&feature=mfu_in_order&list=UL   *Source: Robert Cox's web slides*

Spin-Echo Imaging



Spin-Echo Imaging



T1 Decay

- Thermal jostling of molecules disperses energy. In the presence of heavy molecules such as large protein molecules, this energy dispersal is quite rapid. For this reason, tissues such as fat, and those found in organs like the liver and kidneys, have short T1 times. Dipoles in light, mobile molecules tend to hang onto this energy longer. Materials such as cerebrospinal fluid (CSF) and water have relatively long T1 times.

T2 Decay

- The decay of the transverse component is mostly dependent on local magnetic field inhomogeneities. Dipoles precessing at slightly different frequencies interfere with each other, and can exchange energy. The spins quickly become dephased. If the molecules can move around, like in water, the net magnetic field that a particular molecule experiences is averaged and therefore the magnetic field inhomogeneities are somewhat smoothed out. For this reason, the T2 time of aqueous materials is longer than that of fixed or elastic tissues.

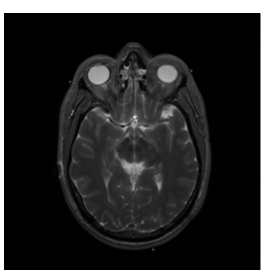
Tissue Decay Constants at 1.5 Tesla

Tissue	T_1 (msec)	T_2 (msec)
CSF	2400	160
White Matter	780	90
Gray Matter	900	100
Muscle	870	45
Liver	500	40
Fat	260	80

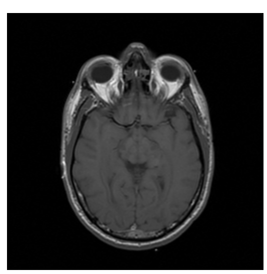
TE = Echo Time

When TE is long, dipoles in tissues with long T2 decay times (eg. CSF) don't decay as much as dipoles in tissues with short T2 decay times (eg. muscle).

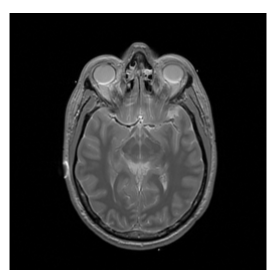
T2-weighted



T1-weighted



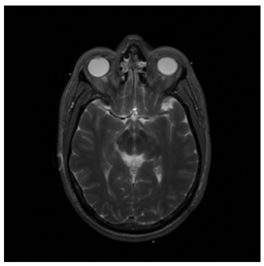
PD-weighted



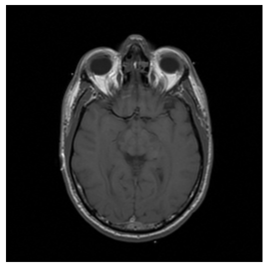
TR = Repetition Time

When TR is short, the dipoles in tissue with long T1 times (eg. liquids) don't have a chance to relax to the full length of M_0. This makes those tissues darker in the corresponding images, called "T1-weighted" images.

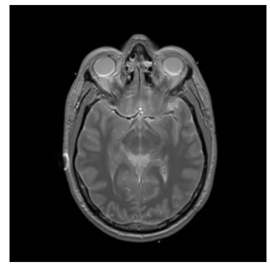
T2-weighted



T1-weighted



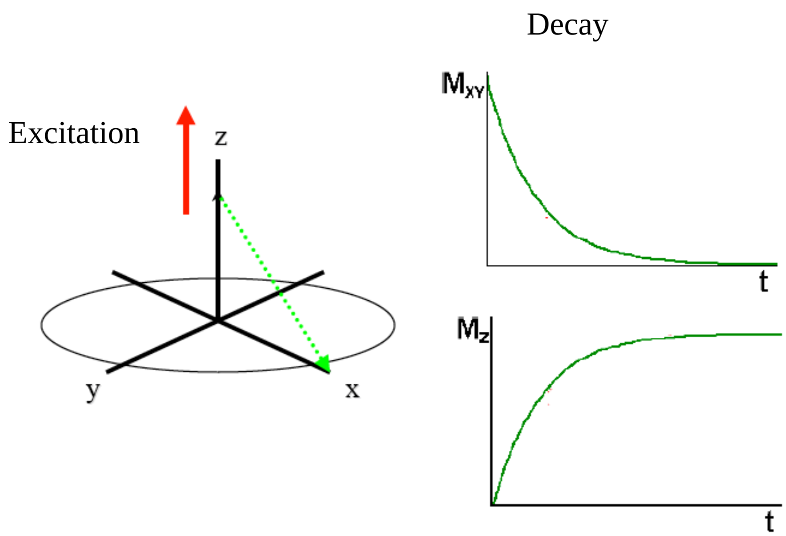
PD-weighted



MRI Properties

http://www.williamoslerhc.on.ca/Patient_Services/di.htm

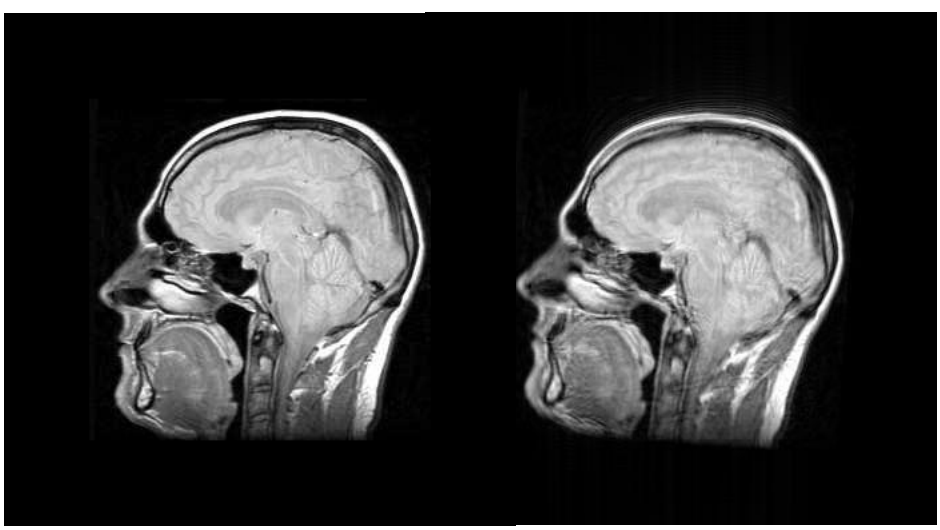
Magnetic Decay



Courtesy of Mike Noseworthy, McMaster University

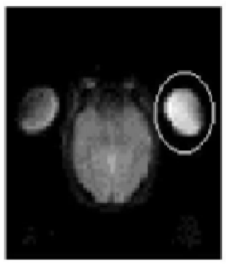
MRI Artifacts

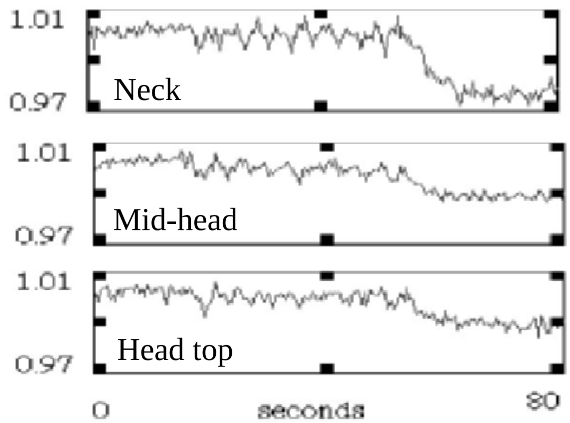
Intra-scan Motion



Physiological Artifacts

Breathing motion of a patient's chest affects the magnetic field, and changes the signal measured in a water-bottle beside the patient's head.

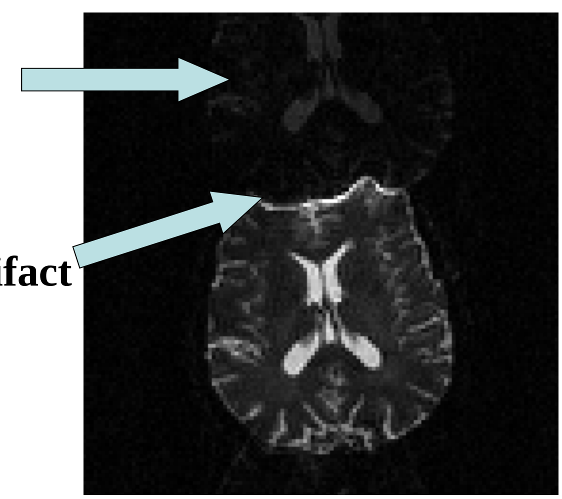




Raj, *ISMRM* (2001).

Ghosting

Imperfect acquisition timing can lead to ghosting, a low-intensity repetition of the main image.



Susceptibility Artifact

Objects in the MR scanner disrupt the B_0 magnetic field, especially when tissue right next to air (eg. Sinus cavities, or metal objects).

http://www.mritutor.org/mritutor/suscept.htm

Speed of MRI

It takes time to collect all that data. It takes a finite amount of time for the dipoles to relax close to their steady states.

A typical 256x256x128 T1-weighted dataset takes over 5 minutes to collect. Hence, motion is a BIG problem in MRI.

Resolution

A typical MRI is multiple slices of 256x256 pixels. For a head scan, voxels are often ~1mm.

Trade-Offs

Like many imaging modalities, MRI involves a tradeoff between imaging time, image resolution, and signal-to-noise ratio.

Dangers of MRI

- Ballistic metal objects (ie. Wrench, O_2 tank)
- Internal (loose) metal objects (iron shavings, IUD) could move and cause internal bleeding
- Burning from
  - Induction loop in anatomy (ie. Touching leg)
  - Radio waves from RF pulses (heating just like a microwave oven)
- Interference with implanted devices (eg. pacemaker, hydrocephalus shunt)

Other uses of MRI

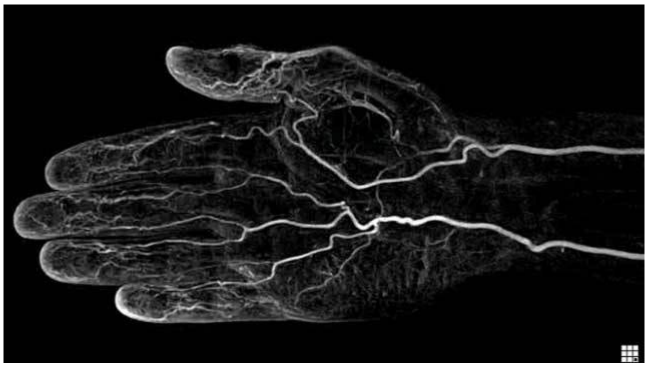
- **Elastography** (similar to diffusion, but done while the tissue is vibrated)
- **Spin Tagging**: encode stripes into tissue, let the tissue move, THEN acquire the image.
- **MR Spectroscopy**: analyzing the signal of a single voxel to determine different chemicals
- **Angiography**: excite the blood in a slice, and then acquire a slice downstream… only blood is bright.
- **Contrast Agents** for viewing blood
- **Functional MRI**: Detecting neurological activity
- **Diffusion Imaging**: Detecting preferential motion of water

Spin Tagging

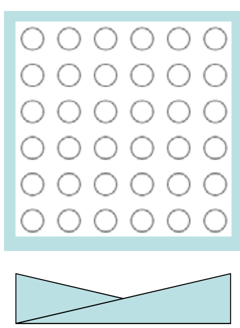
- Excite stripes of tissue and image as usual.

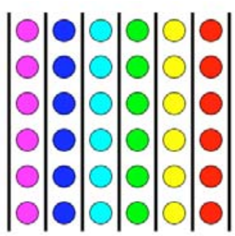
Angiography (imaging blood vessels)

- Inject contrast agent, or use spin labeling.

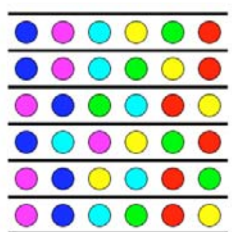


Diffusion Imaging

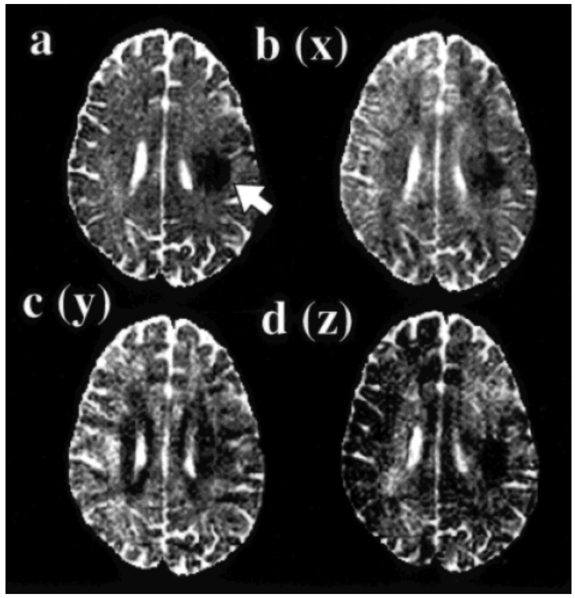




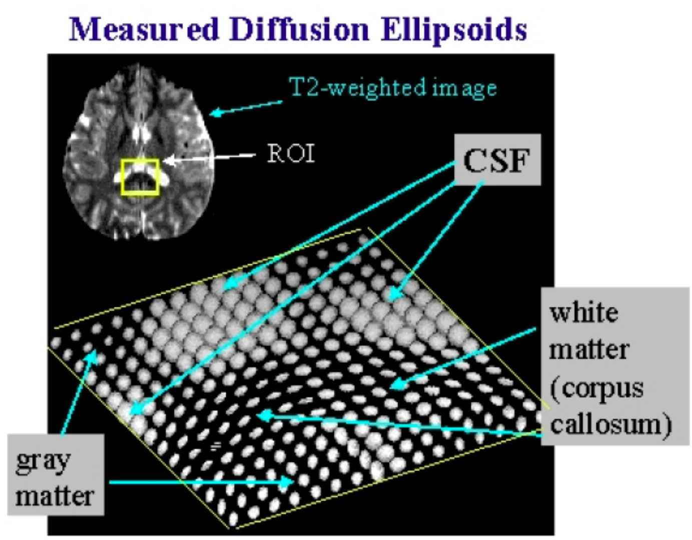
Constrained along
x-direction



Constrained along
y-direction



From Ulug et al., *Stroke*, 1997



Pierpaoli et al, **Radiology** 1996; 201: 637-648.

Courtesy of Mike Noseworthy, McMaster University

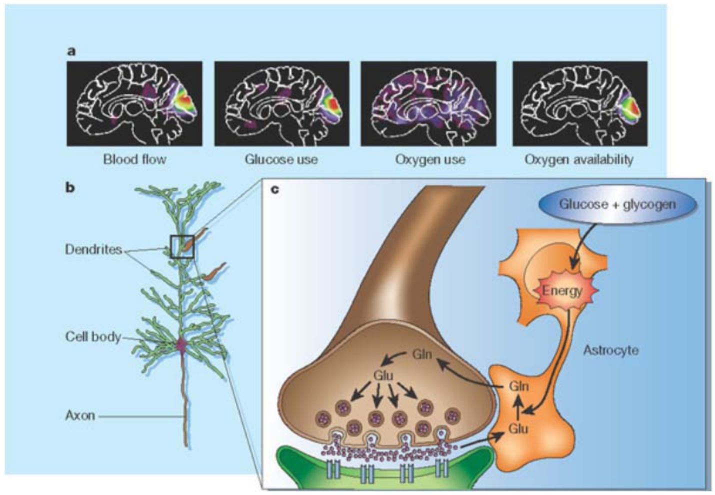
Tractography (follow diffusion tracks)

Courtesy of Mike Noseworthy, McMaster University
http://www.ece.mcmaster.ca/~mikenose/web/HOME.html

Functional MRI

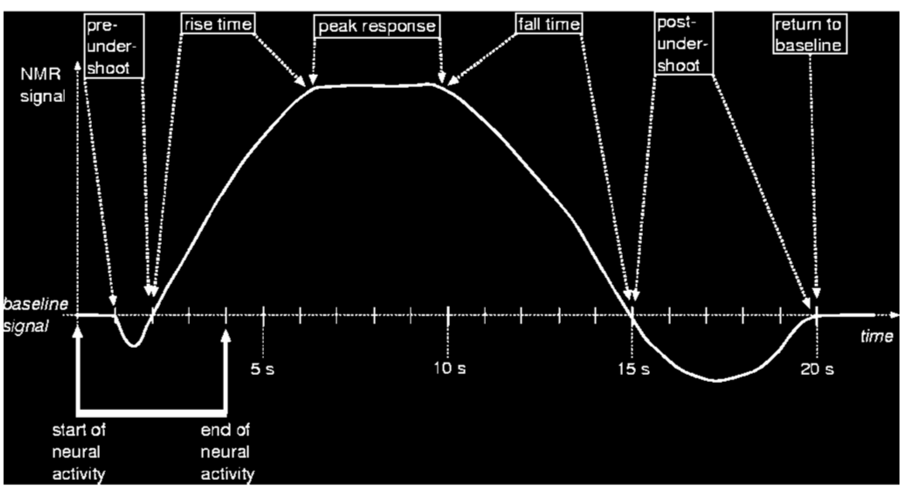
Cognitive stimulus is turned on and off while snapshots are acquired.

Neurological activity needs blood glucose, but not oxygen. Blood flow increases to supply glucose, resulting in a local increase in oxygenated hemoglobin, which affects the MR signal.

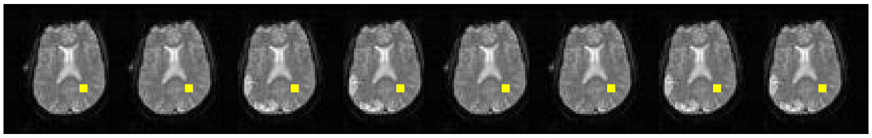


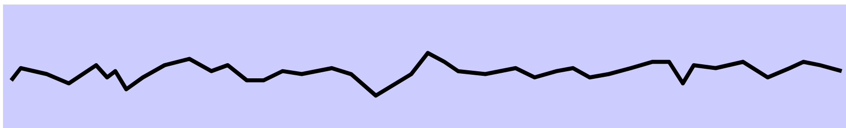
Logothetis, *Nature* (July 2001)   Raichle, *Nature* (July 2001)

Blood Oxygen Level Dependent (BOLD) Signal

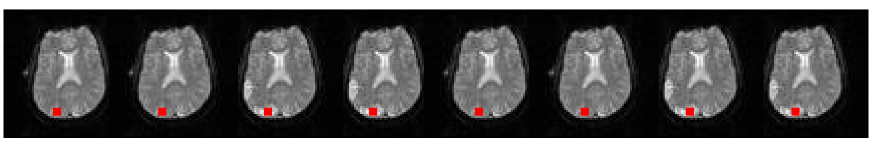


Voxel Time-Series: Inactive

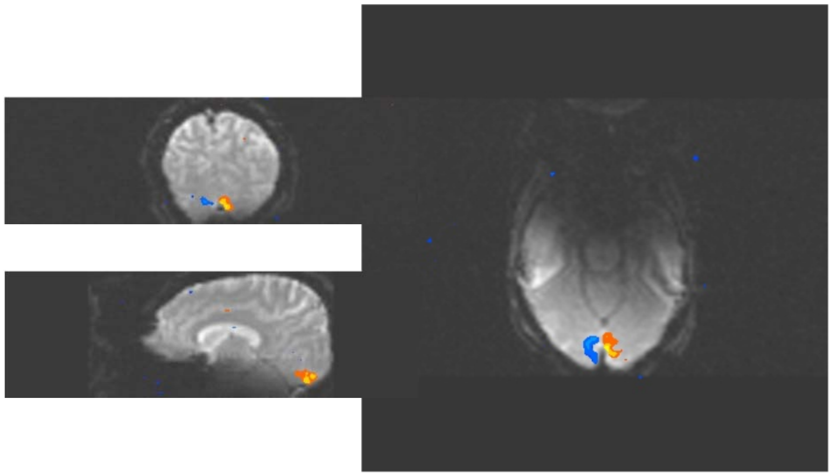




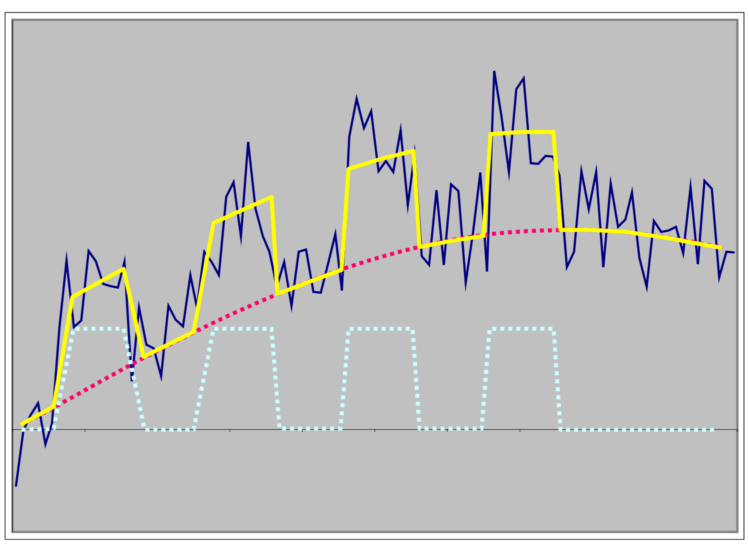
Voxel Time-Series: Active



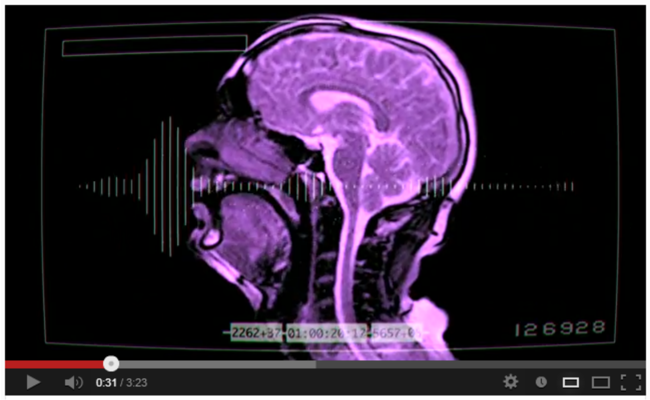
Visual Stimulus (primary visual cortex)



General Linear Model



MRI Fun



http://youtu.be/_964dqQxQwY