# BOLD fMRI: signal source, data acquisition, and interpretation

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# ‘Lecture’ series

- Week 1: Biological basis: where’s the signal coming from?
- **Week 2: Physical basis: what is the signal, how is it measured?**
- Week 3: Imaging basics: image formation, noise, and artifacts.
- Week 4: The specific case of BOLD fMRI.
- Week 5: BOLD analysis: what’s significant and what’s not?
- Week 6: Spikes vs. BOLD: neural activity in visual areas

# Spin Physics

- Topics
  - NMR
  - NMR in biological tissues
  - Basic pulse sequences
  - Contrast in images
- Goal: familiarity with …

  … $T_1$ and $T_2$ decay (and the famous $T_2^*$)

  … Spin echo and gradient echo

  … $T_1$ (inversion recovery) and $T_2$-weighted images

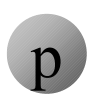
# Terms

- NMR: nuclear magnetic resonance
- $\gamma$: gyromagnetic ratio
- $T_1$: $1/R_1$, the longitudinal relaxation rate
- $T_2$: $1/R_2$, the transverse relaxation rate
- $T_2^*$: $1/R_2^*$, the effective transverse relaxation rate in the presence of magnetic field inhomogeneities
- TE: echo time
- TI: inversion time (between inversion pulse and measurement pulse)
- TR: repetition time

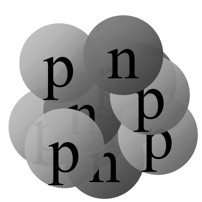
# Nuclear magnetic spin

Nobel prizes:
- Stern (Physics, 1943): magnetic moment of proton (1933)
- Rabi (Physics, 1944): nuclear magnetic resonance (1937)
- Bloch and Purcell (Physics, 1952): NMR measurements (1946)
- Ernst (Chemistry, 1991): high resolution and multi-dimensional NMR

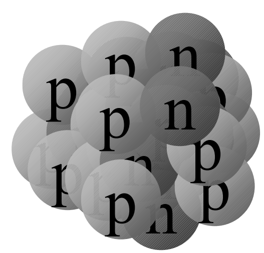
Imaging:
- Lauterbur (1973), Mansfield, Damadian



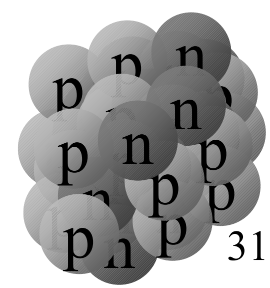

$^{1}H$



$^{13}C$



$^{23}Na$

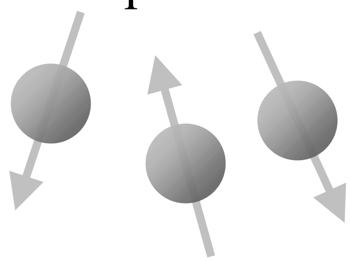


$^{31}P$

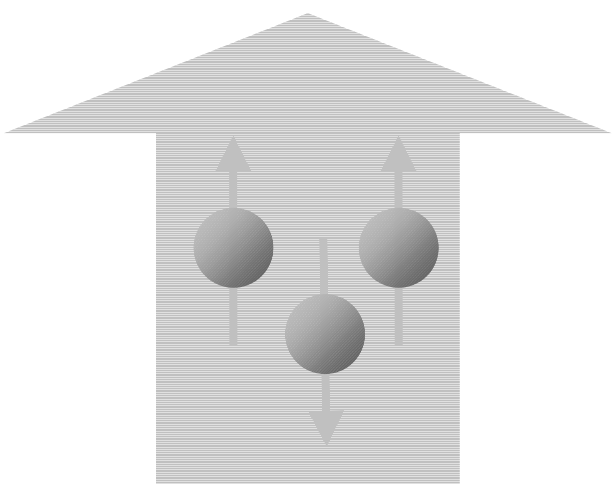
Nuclei with an odd number of protons and neutrons have a nuclear spin

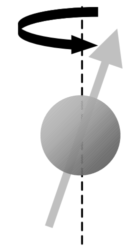
# Nuclear magnetic resonance

Classical picture: in free space, these spins have no preferred orientation,



but in a magnetic field, they like to line up either parallel or anti-parallel.



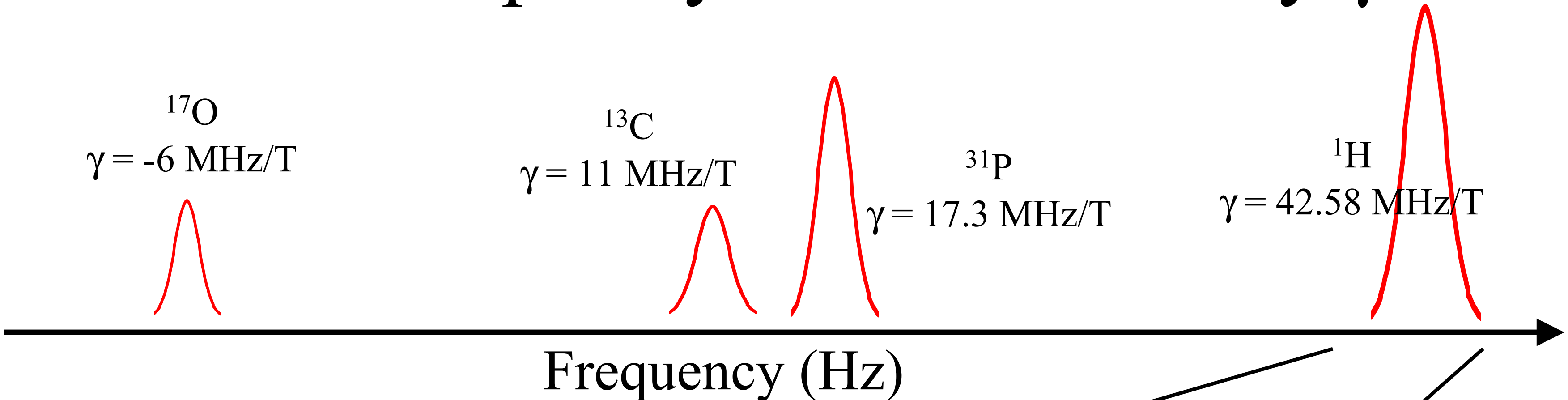


When they're 'aligned', they actually *precess* with a frequency determined by $\gamma$, the gyromagnetic ratio, and $B_0$, the field strength:

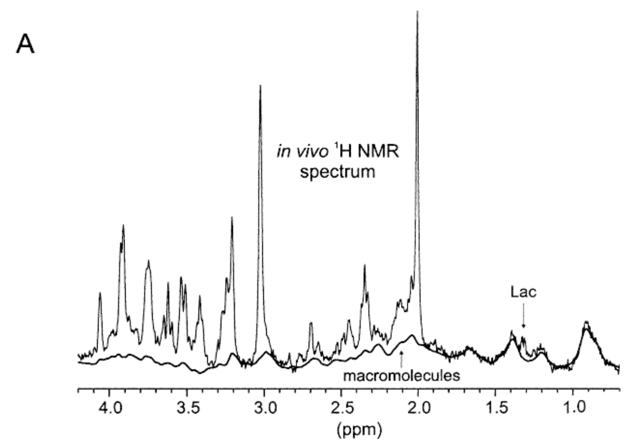
$$\omega_0 = \gamma B_0.$$

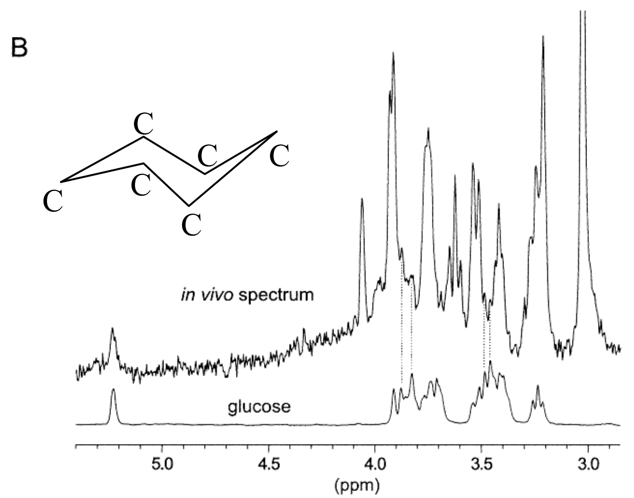
So $\omega$ carries information about the local field (frequency encoding in imaging; spectroscopy).

# Resonant frequency is determined by γ …




…and by chemical environment.

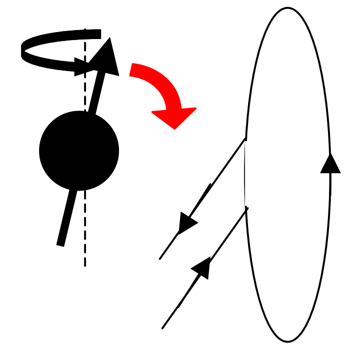


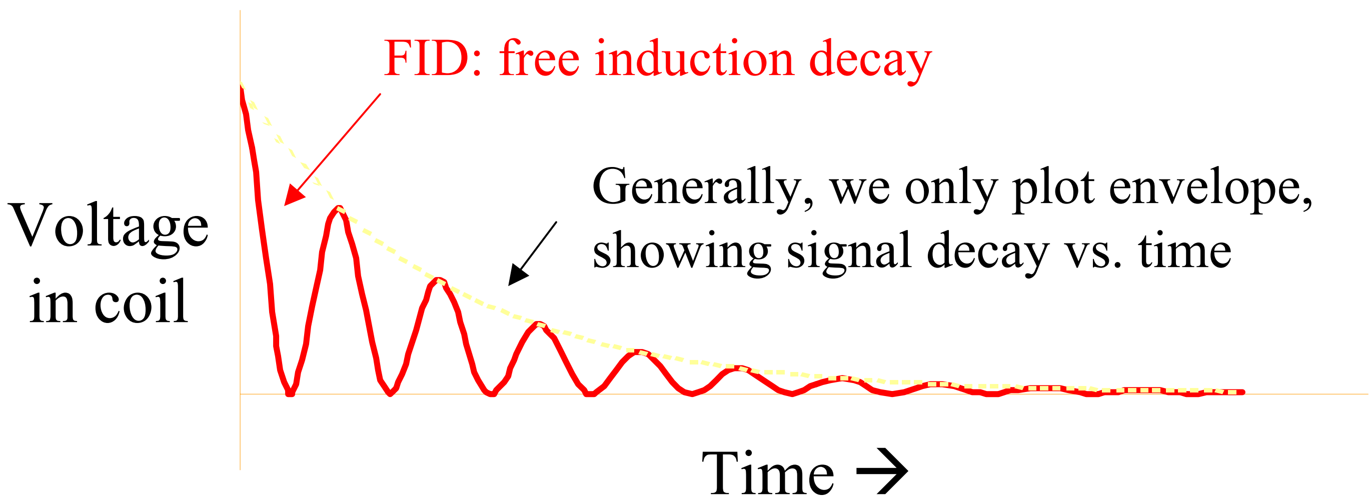

Pfeuffer J, Tkac I, Gruetter R (2000). J Cereb Blood Flow Metab 20, 736-46.

# Excitation of nuclei with RF pulses

1) excite precessing spins with a RF coil
- nuclei absorb and emit energy at their resonant frequency, ω.



2) 'listen' with the same coil as the nuclei give back the energy:

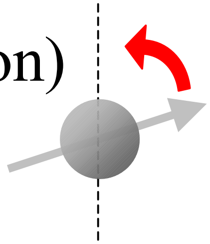


# The importance of coil design

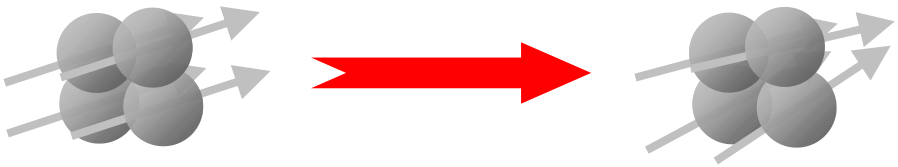
- Many different kinds
  - Surface (single coil, quadrature coil …)
  - Volume coil (birdcage, TEM …)
- High demand on electronics
  - signals going into the sample and coming out of sample are ~10 orders of magnitude different (kilowatts in; microwatts out).
- Geometry
  - $B_1$ profile determines field of view and uniformity
  - which in turn determines homogeneity of excitation
- The higher the field, the harder to get a uniform $B_1$

# Why does the signal decay?

- The protons give back energy to return to equilibrium (alignment with $B_0$)
- Two time scales:
  - Spin-lattice relaxation (a.k.a. longitudinal relaxation)
    - Time constant $T_1$
    - Transverse magnetization is converted into longitudinal



  - Spin-spin relaxation (a.k.a. transverse relaxation)
    - Time constant $T_2$
    - Summed signal decays as spins precess at slightly different frequencies due to *local* field differences, and are no longer in phase

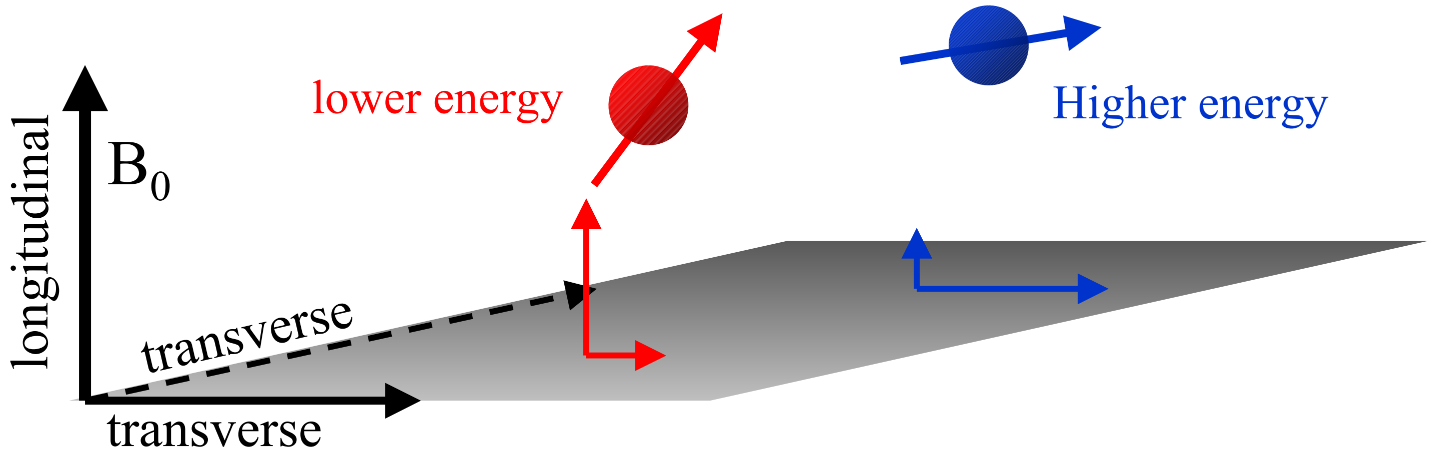


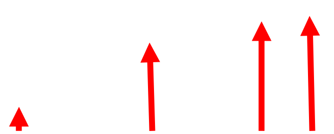
# More on $T_1$ and $T_2$

Each spin is described by two components:

one parallel to $B_0$, relaxing with $T_1$

one perpendicular to $B_0$, relaxing with $T_2$

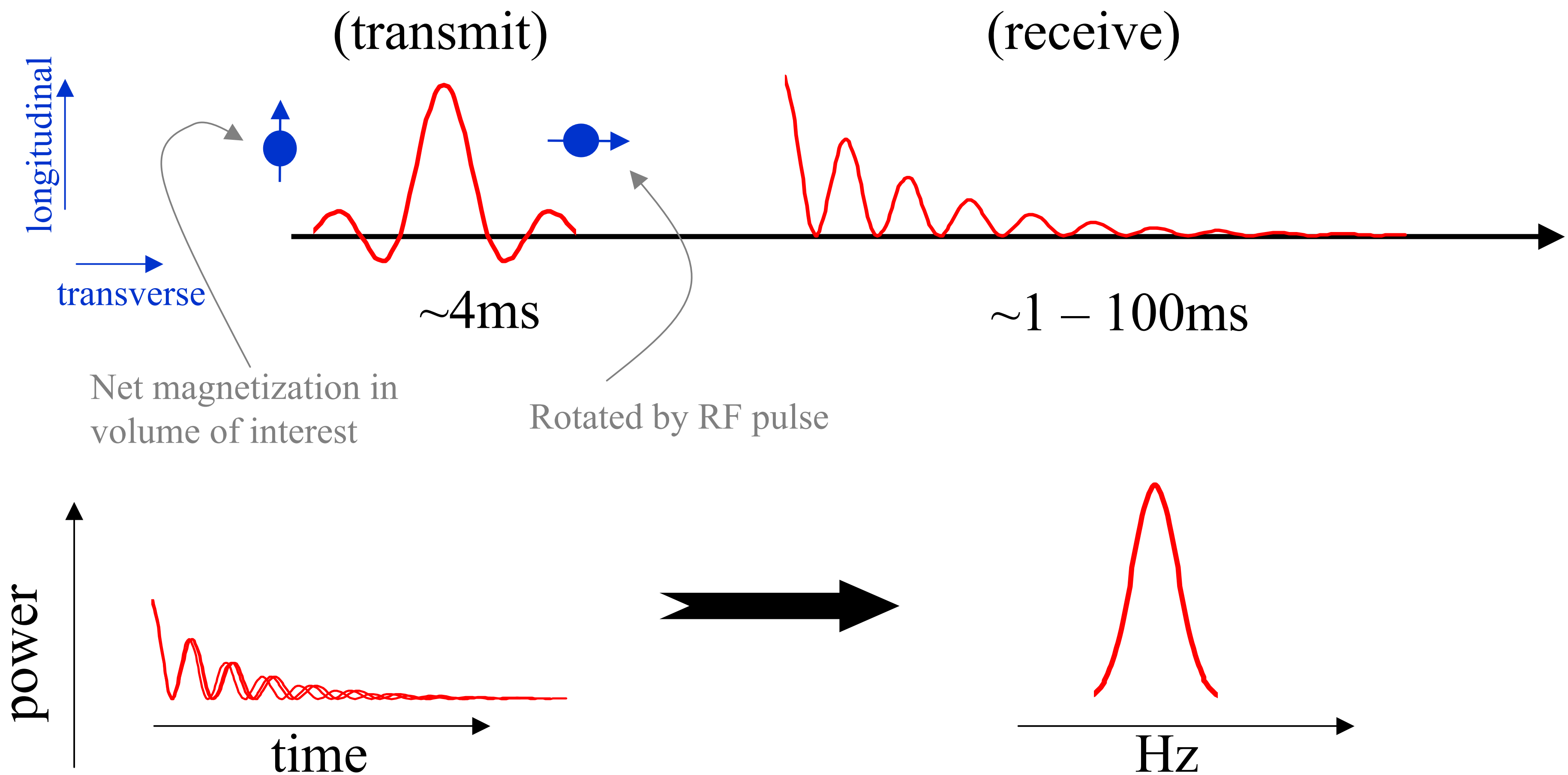


$T_1$ :  1s to 4s, depending on field strength

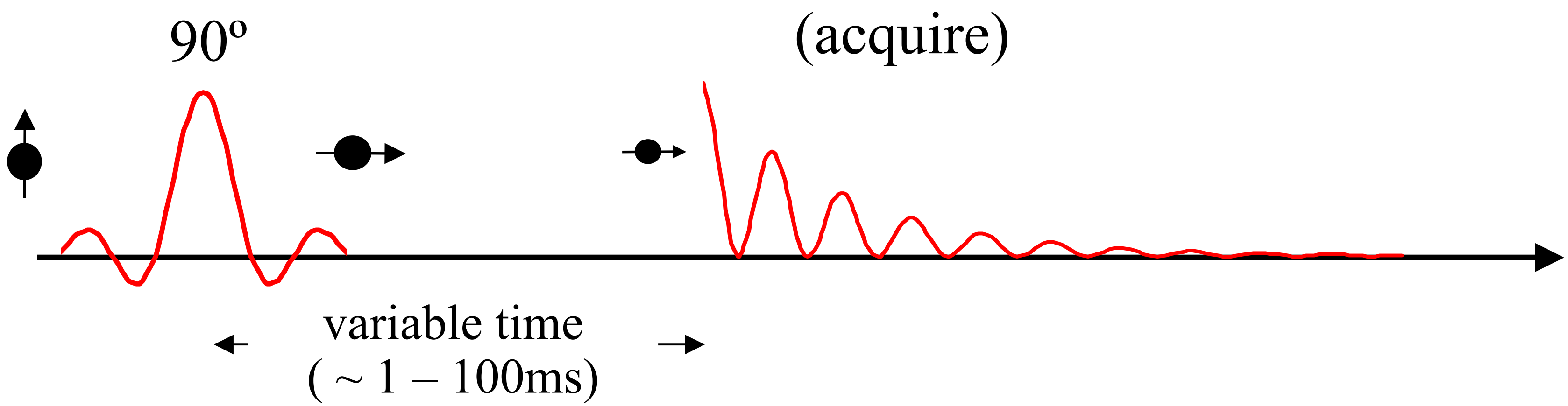
$T_2$ :  50ms to 20ms (**population of spins**)

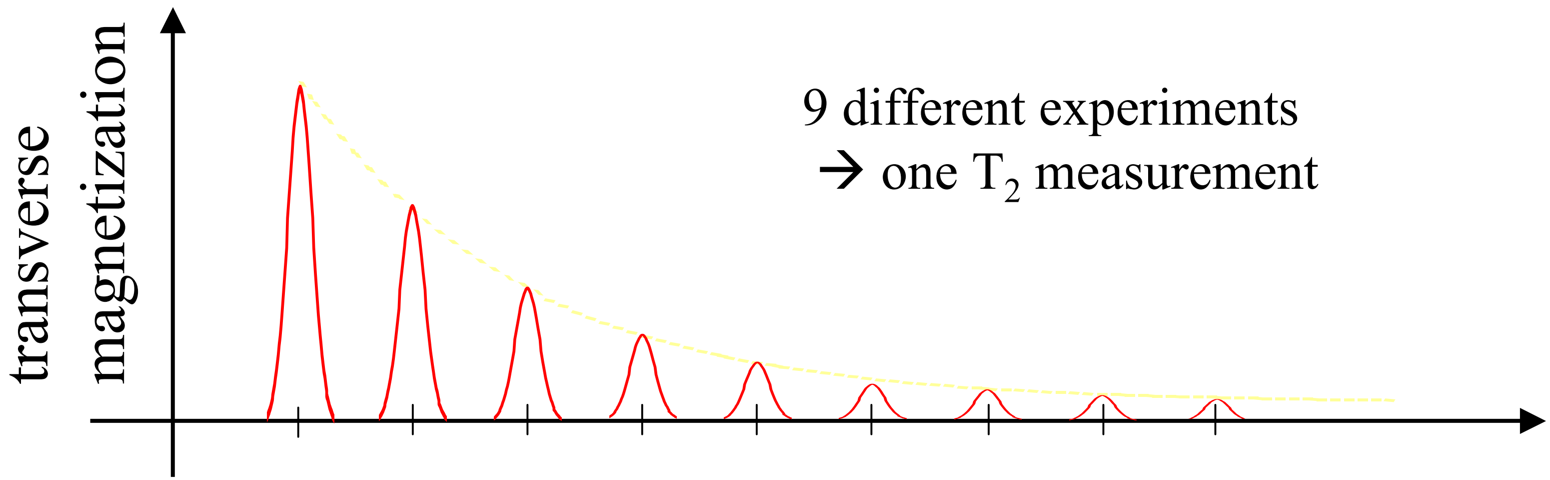
# Basic RF pulse sequence: pulse and acquire



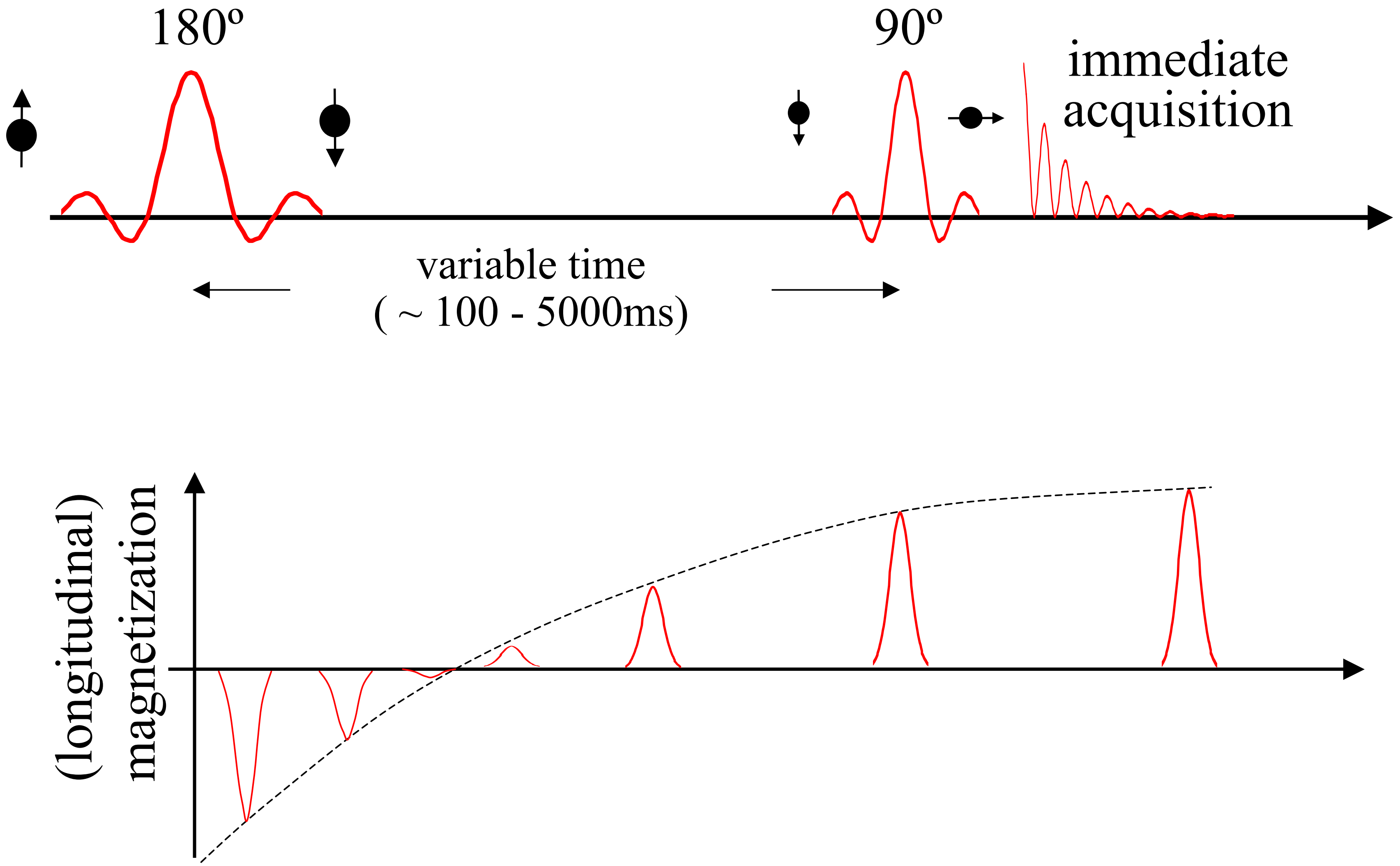

Signal acquired in time domain is transformed to frequency domain

# Pulse and acquire: $T_2$ measurement

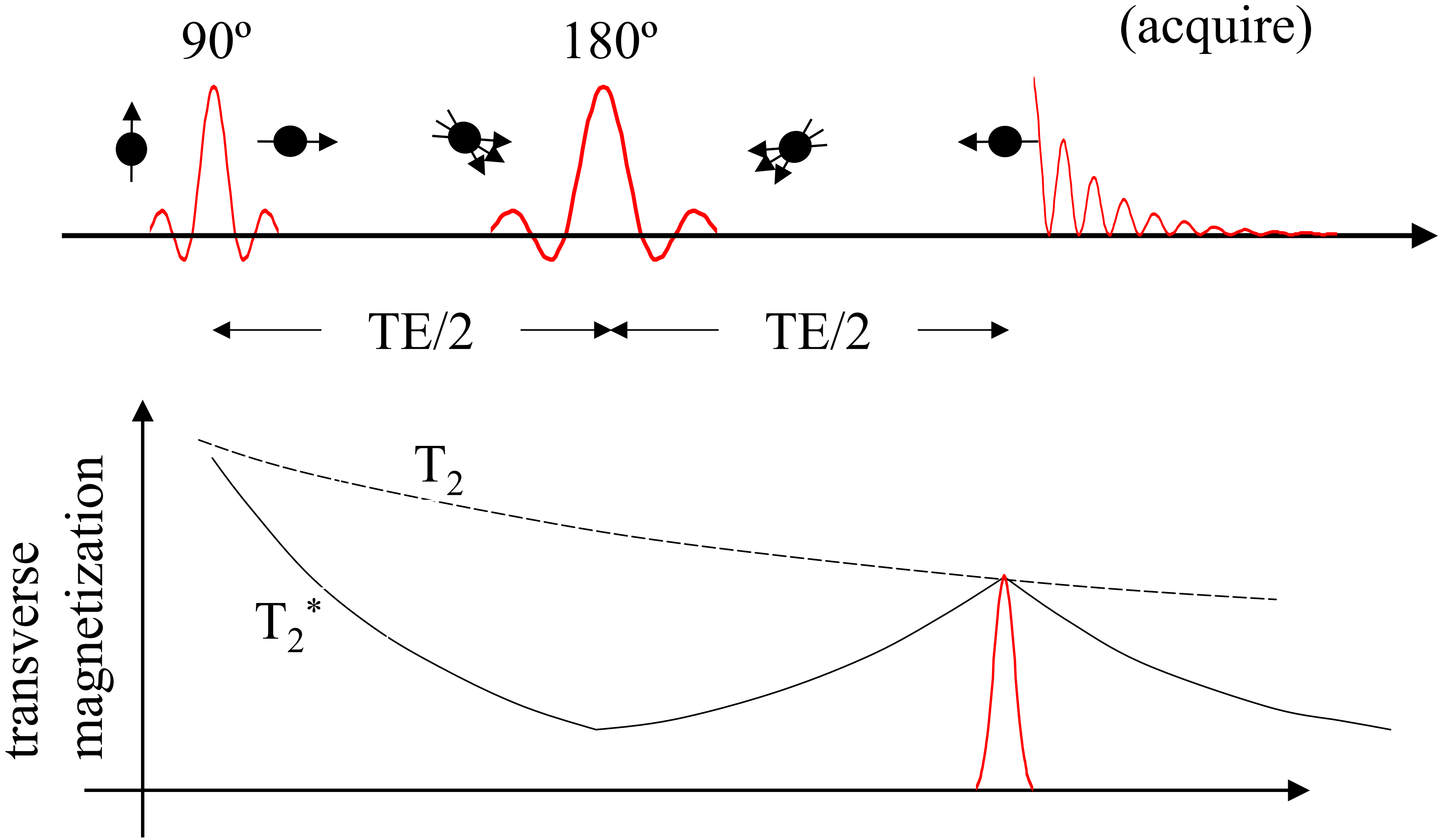


# $T_1$ measurement (inversion recovery)



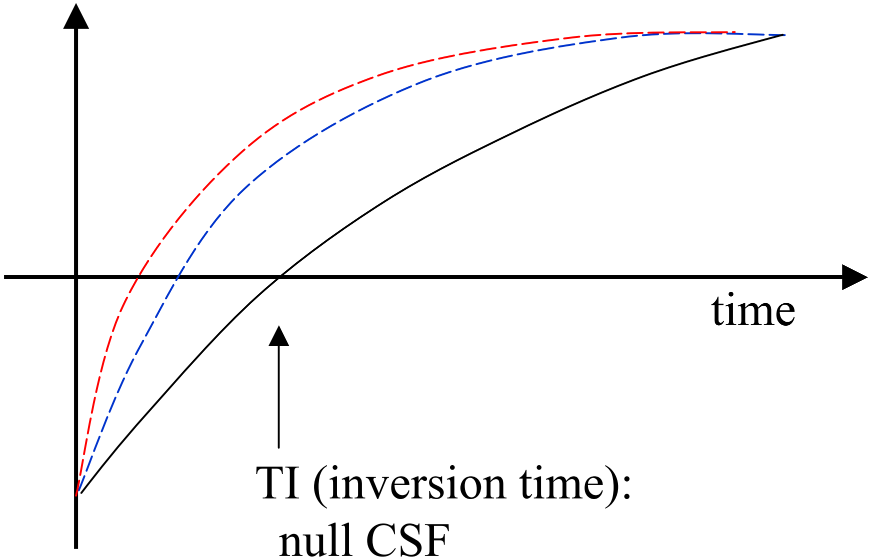
# Spin Echo: true $T_2$ measurement



# Spin Echo vs. Gradient Echo summary

| | **Spin Echo** | **Gradient Echo** |
|---|---|---|
| Magnetization measured | transverse | transverse |
| Weighting | $T_2$ | $T_2^*$ |
| Echo time | Relatively long | Very short |
| Sensitivity | Capillaries (static dephasing) | Capillaries and venuoles (dynamic dephasing) |
| Signal strength | low | high |

# T1-weighted images: inversion recovery

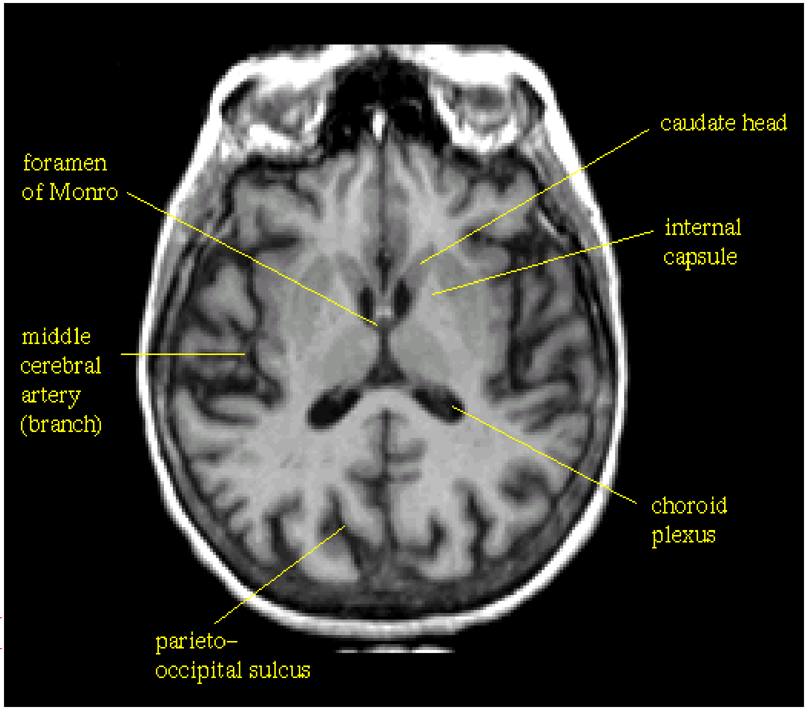



TI (inversion time):

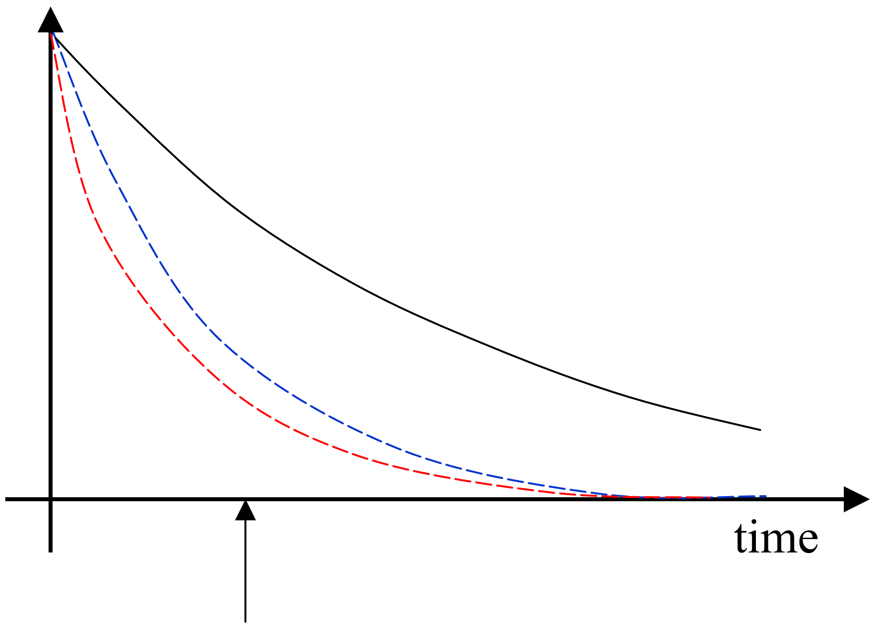
null CSF

signal has recovered more in WM

GM has longer T1 than WM



# $T_2$-weighted images




TE:

CSF has lots of signal

signal has decayed more in WM

GM has longer T1 than WM