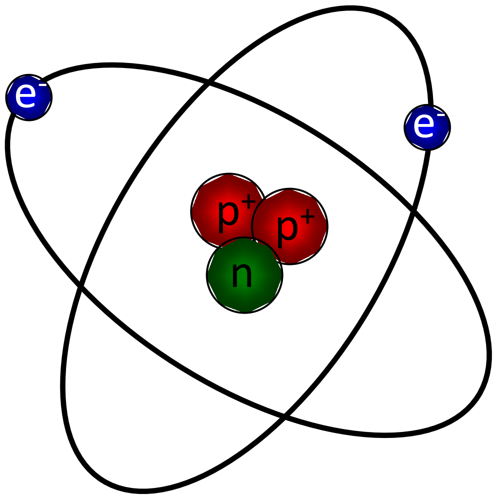
Introduction to Magnetic Resonance

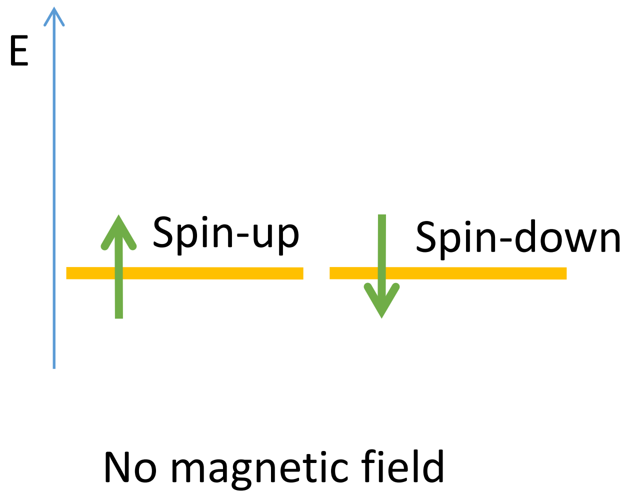
- a general overview

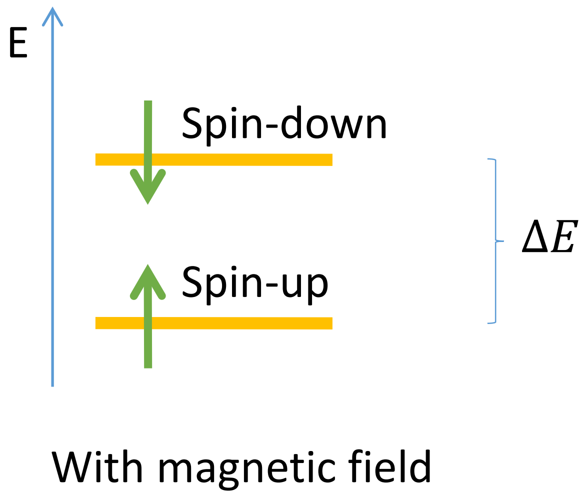
Steffen Ringgaard

Nuclear spin

- Spin: basic property of particles
  - Angular momentum and magnetic dipole moment
- Discrete quantum states
- In MR, spins are flipped between the two states
- Photons with frequency proportional to ΔE will be emitted





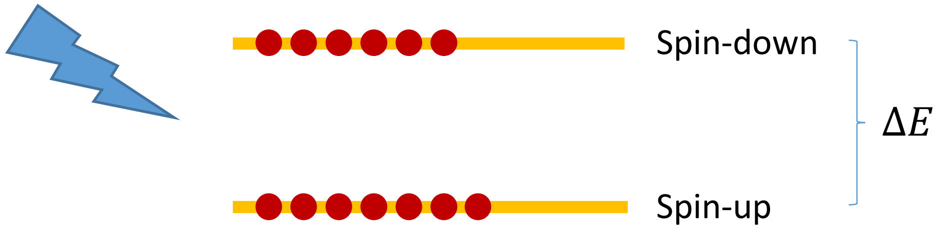


Equilibrium, excitation, signal

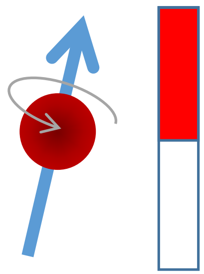
- In equilibrium, distribution of spins given by the Boltzmann equation

$$\frac{N_{down}}{N_{up}} = e^{-\frac{\Delta E}{k_B T}}$$

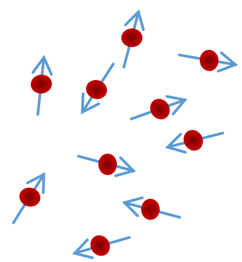
- At 3T: $\frac{\Delta N}{N_{up}+N_{down}} = 10 \text{ ppm}$
- RF fields can flip spins between the two states
- After excitation, magnetization will oscillate and can induce current in receive coil

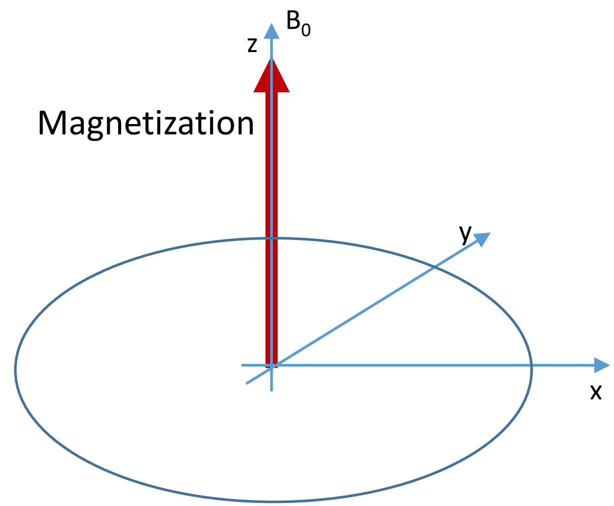


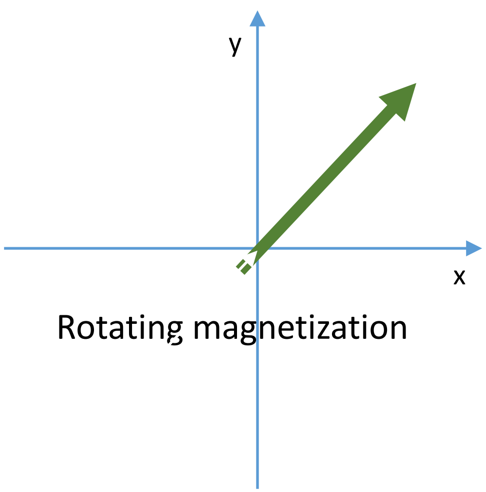
Description with classical physics

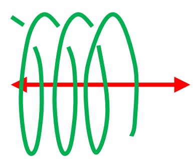


Magnetic dipole

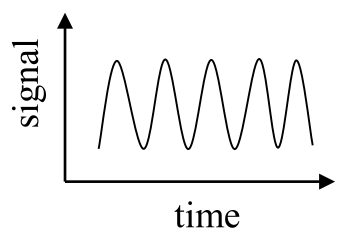


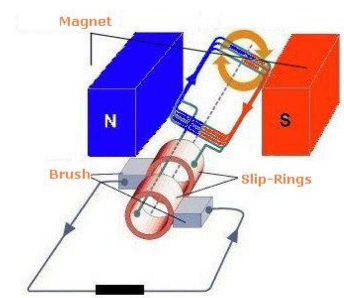






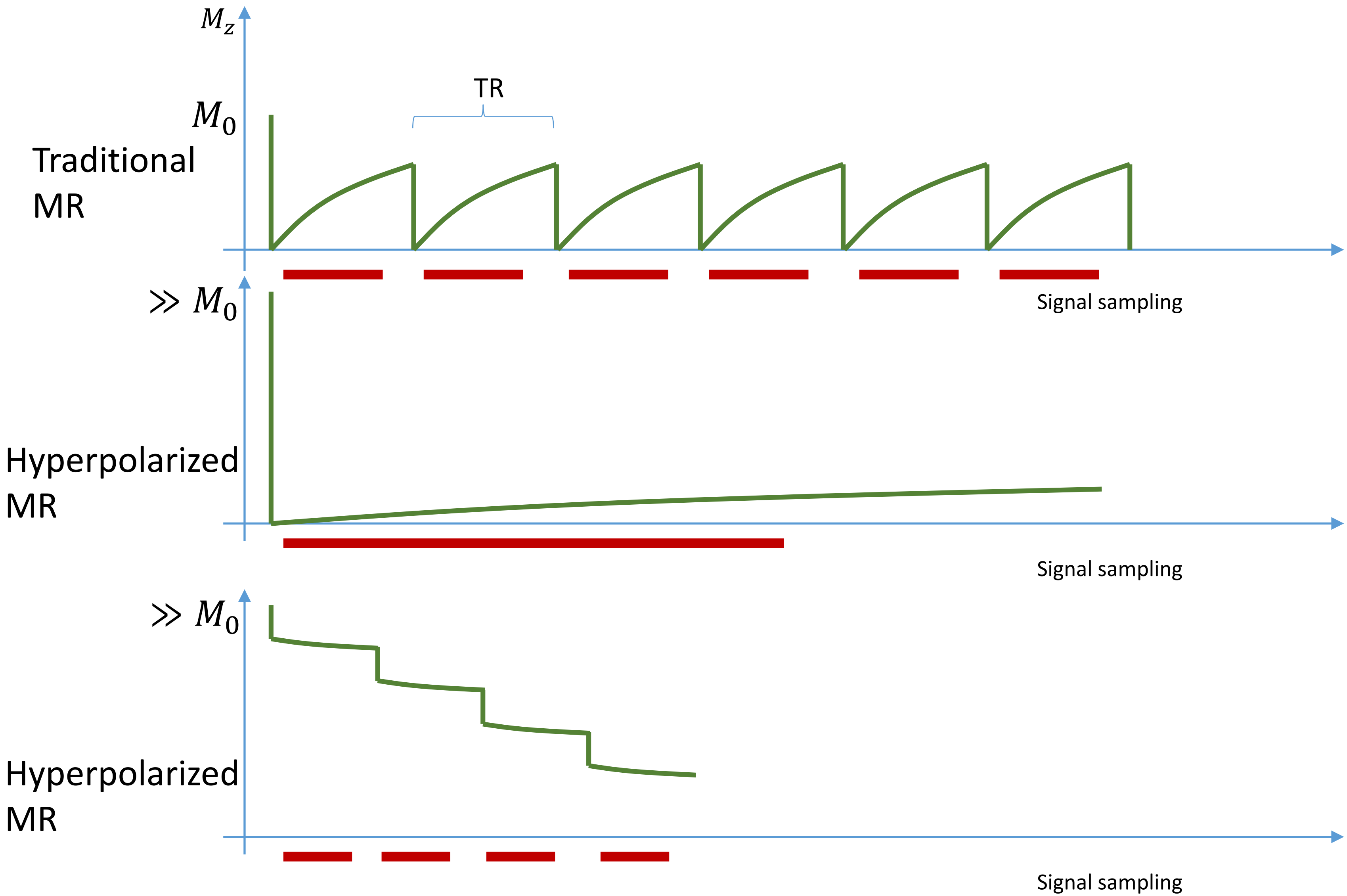
Receive coil



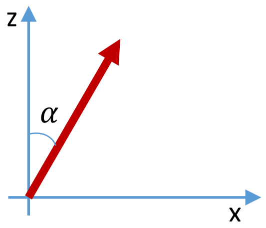


Repeated vs single excitation

Magnetization: sum of all magnetic dipoles

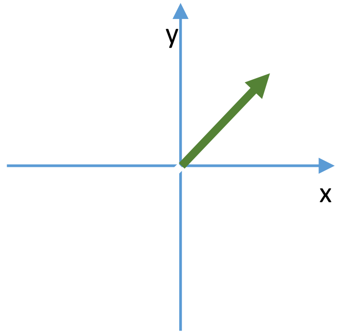


Precession frequency and angles

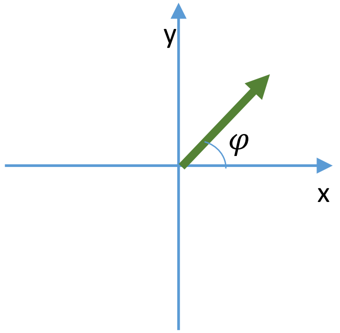


Signal $= sin(\alpha)$

Remaining $M_z = cos(\alpha)$



Precession frequency $f = \frac{\gamma}{2\pi} B_0$

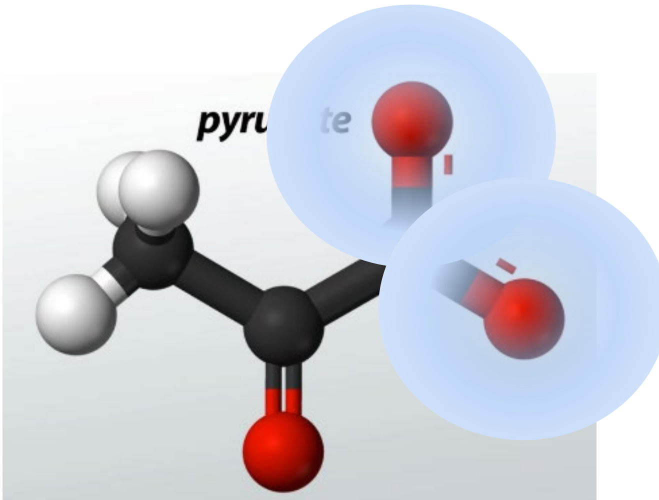


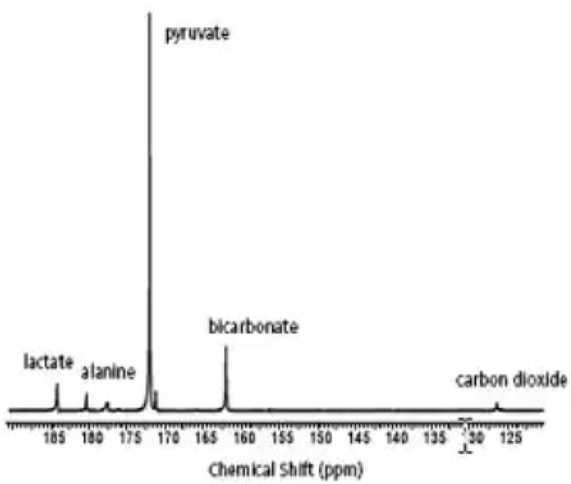
Precession phase: given by f duration and RF phase

$$\varphi = \varphi_0 + f \cdot t$$

Often both *x*- and *y*-projections are sampled

Spectroscopy





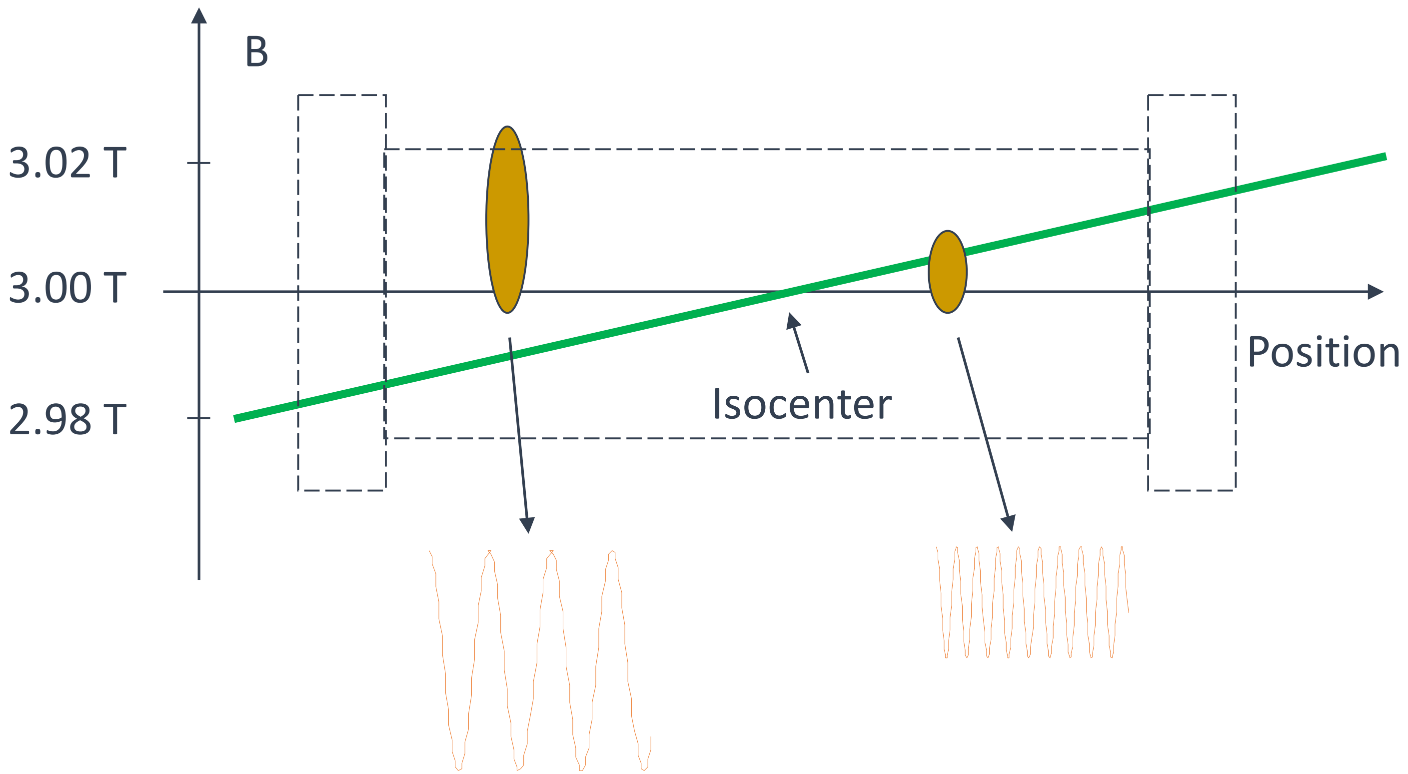
- Electrons shields nuclei slightly
  - Chemical shielding
- Frequency at nuclei determined by specific electronic structure
- Larmor relation

$$f = \frac{\gamma}{2\pi} B_0$$

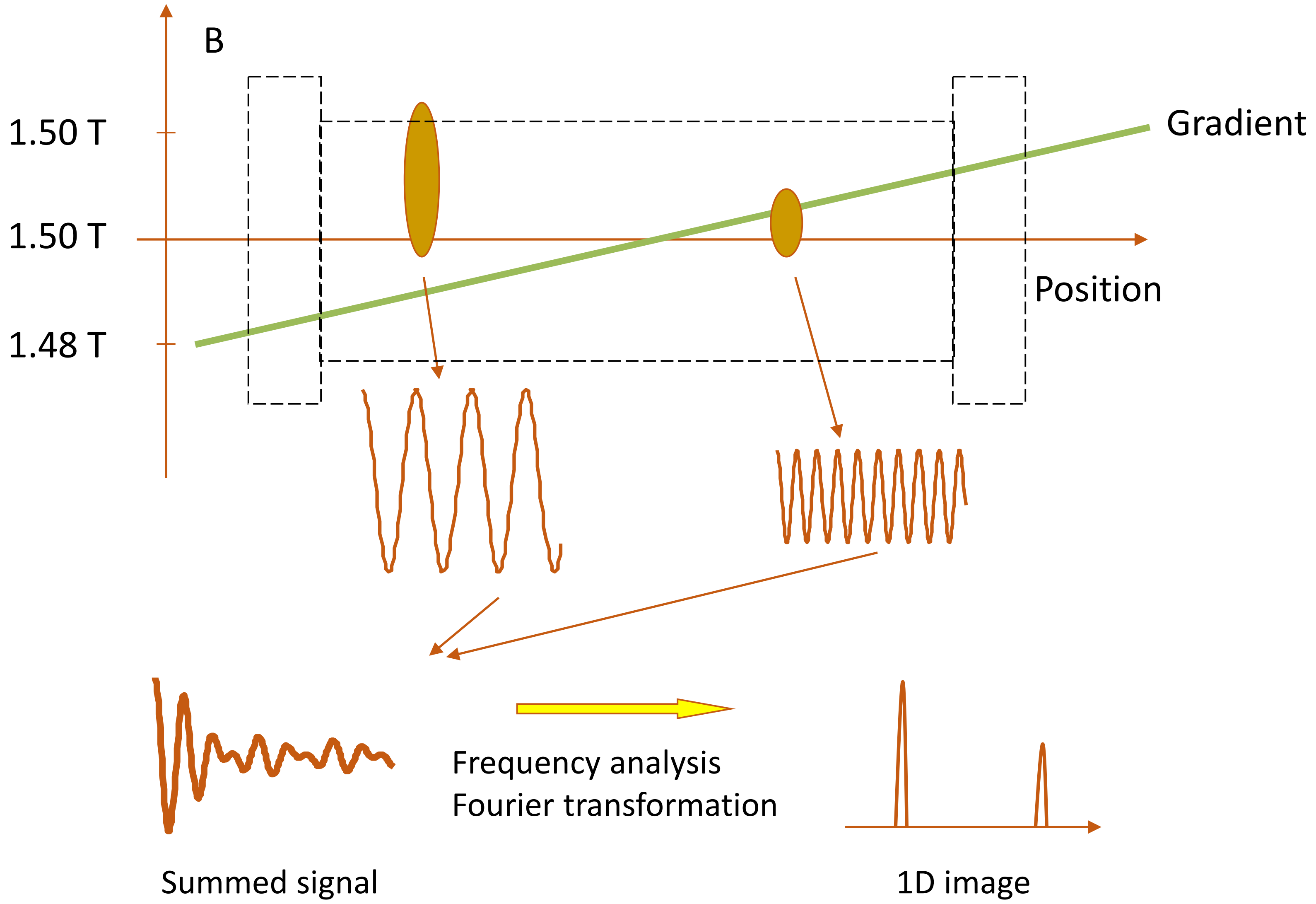
- Sampling of temporal signal variation
  - Fourier Transformation
  - Signal on frequency axis
- Signal amplitude given by molecular concentration

Principles of MR imaging

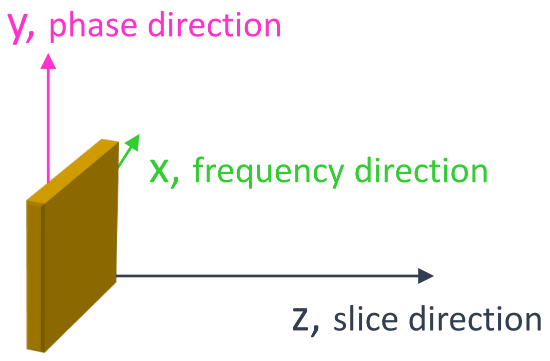
- Encoding spatial information in MR signal



Frequency encoding

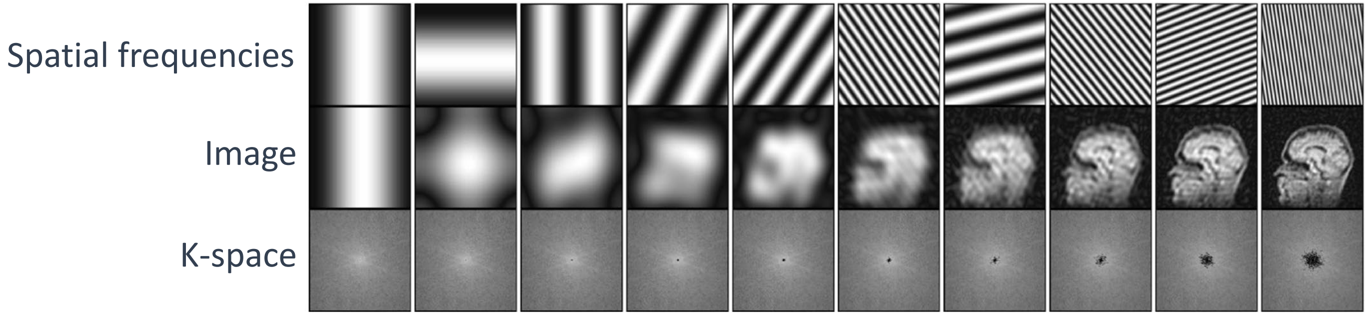


3 dimensions and k-space

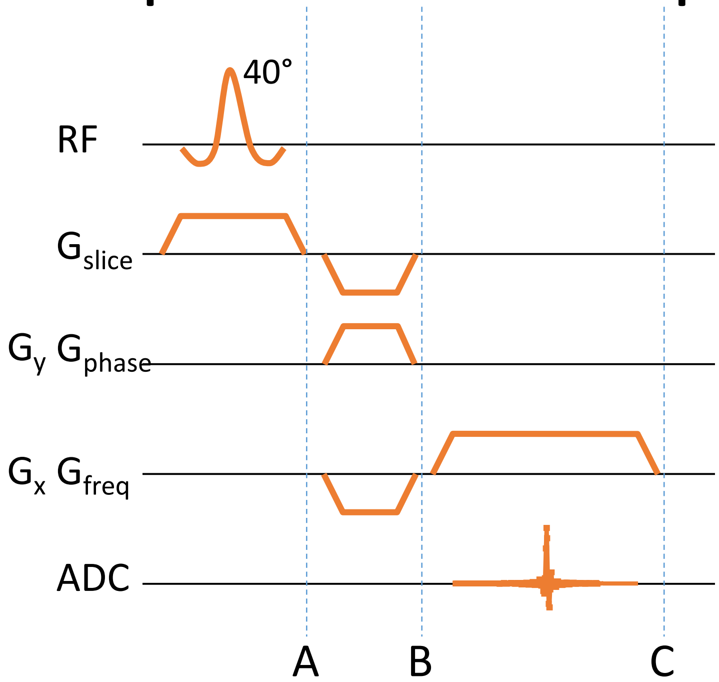


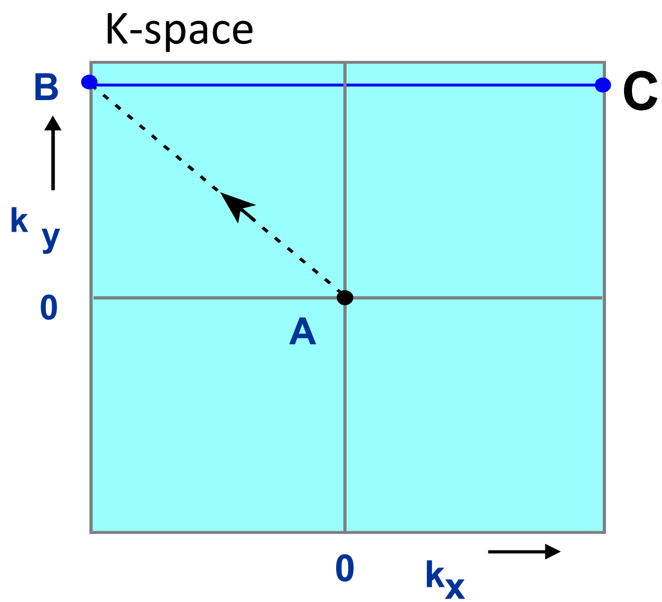
K-space

- Fourier inverse to normal space
- Images can be decomposed to weighted sum of spatial frequencies
- Each spatial frequency symbolized by point in k-space
- In MR, the amplitude of spatial frequencies are sampled
  - Spatially dephased magnetization corresponds to one spatial frequency



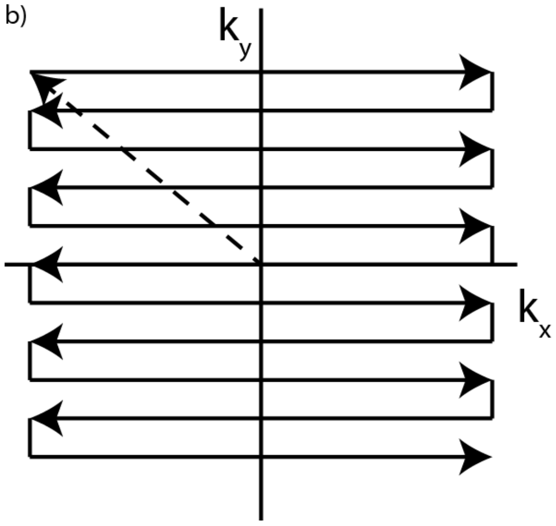
K space description



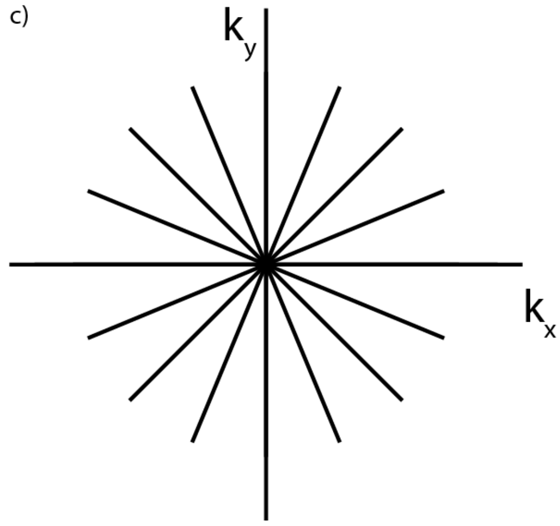


- Signal is sampled in k-space
- Using gradients to move around in k-space
- After having sampled the entire k-space, images can be reconstructed by 2D inverse Fourier Transformation

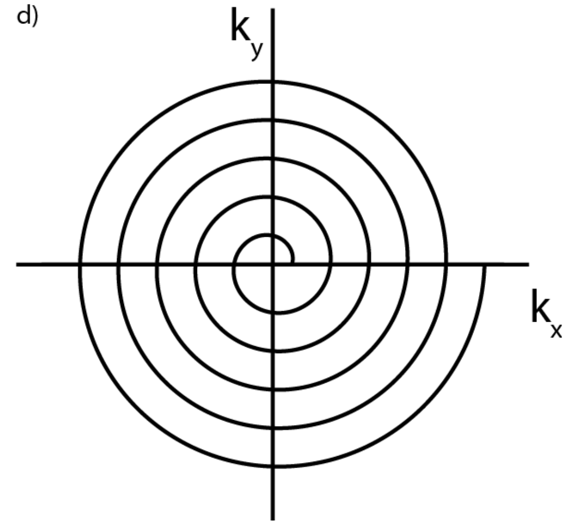
Different ways to sample k-space



EPI

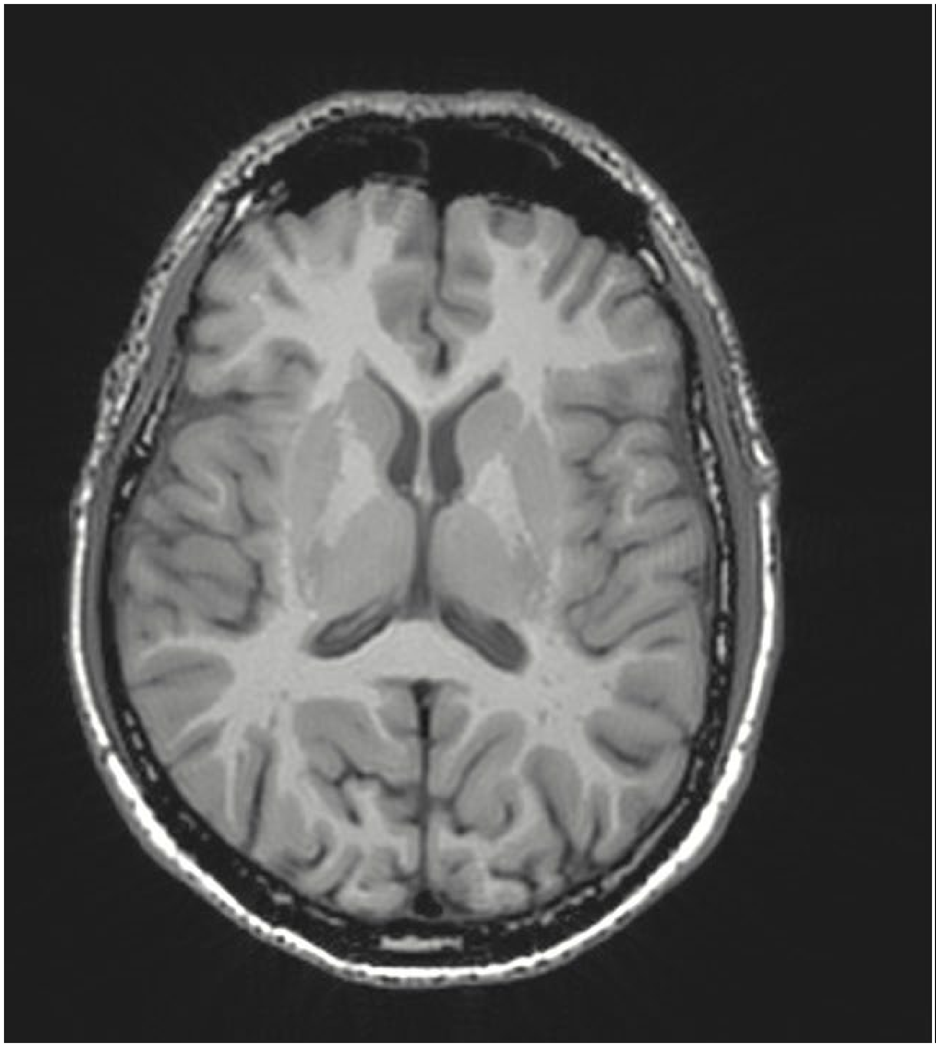


radial

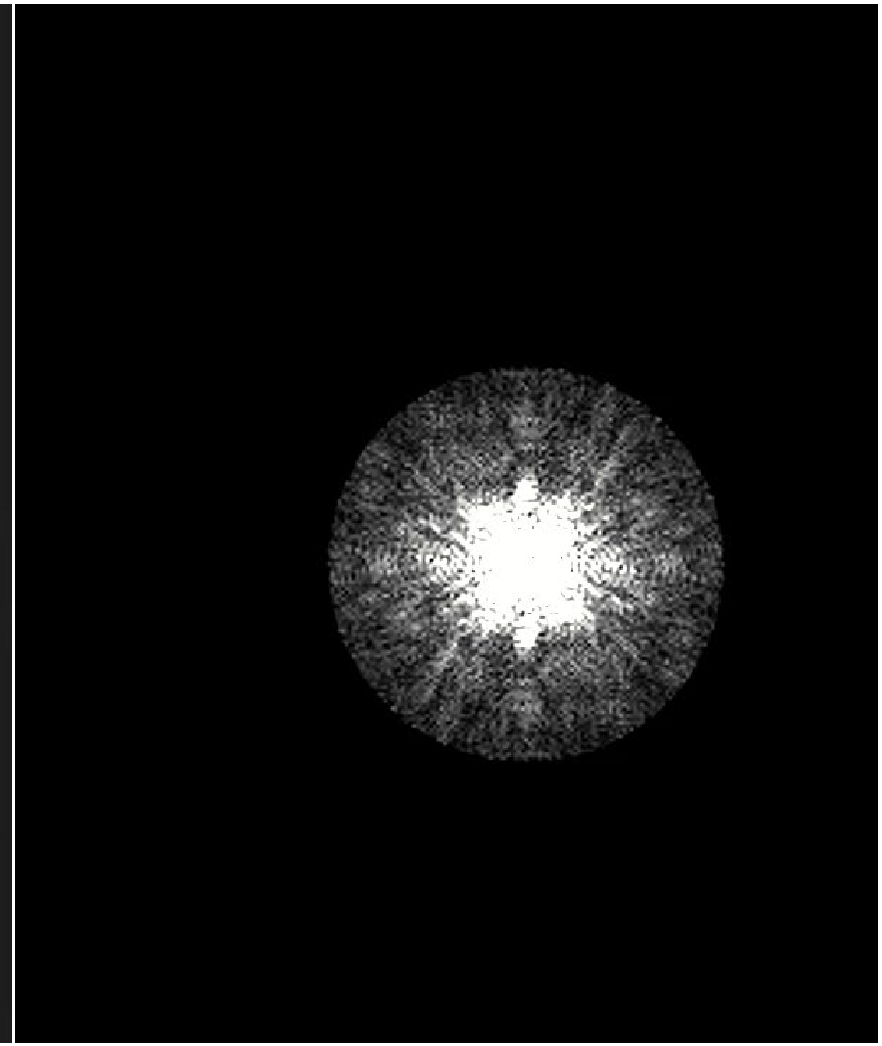


spiral

K-space filtering

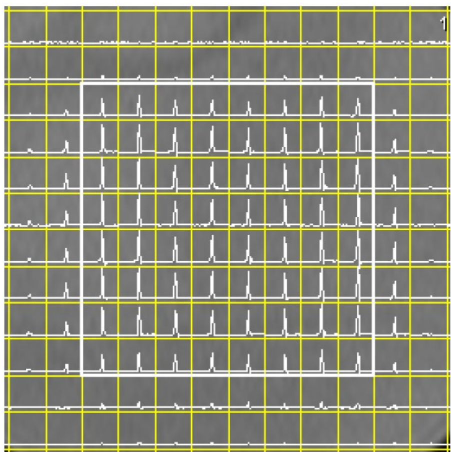


Image

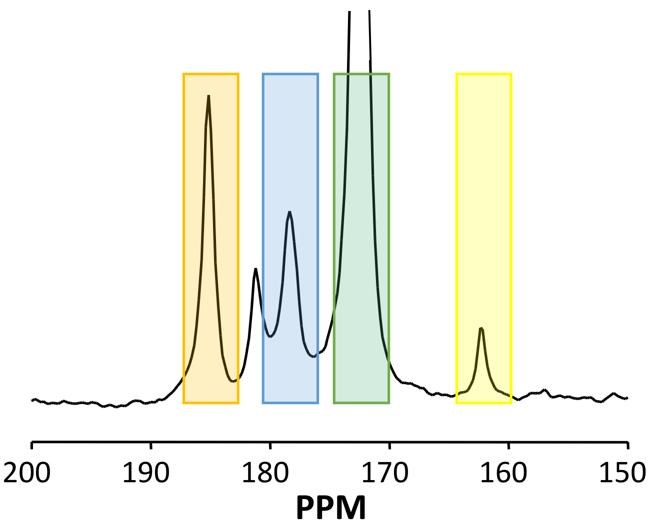


K-space

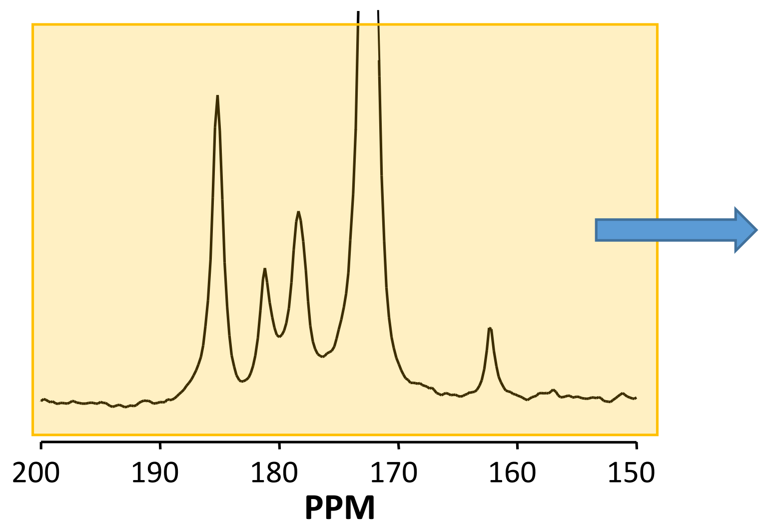
Frequency + spatial information



- Frequency adds one extra information dimension
  - Time consuming
  - Lower spatial resolution



Sequential excitations



Simultaneous excitation

Spectral decomposition

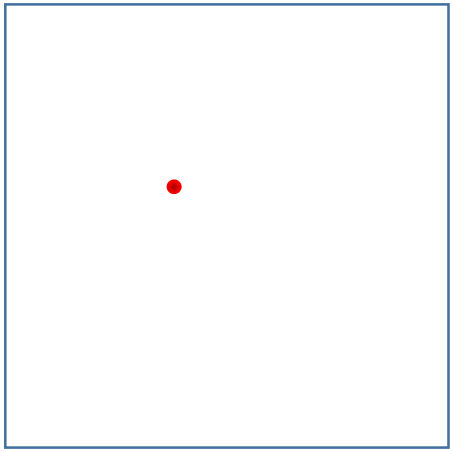
Signal amplitude and noise

- Signal amplitude given by
  - Density of nuclei
    - Proton density is high
  - Gyromagnetic ratio γ
    - Signal $\propto \gamma^3$
  - Polarization
    - For standard MR around 10 ppm
- Noise
  - Mainly from patient
- $SNR = \frac{signal}{noise}$
- Signal on scanner is not absolute

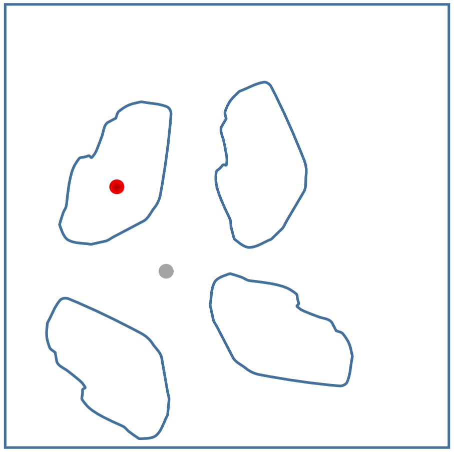
Functional MR methods

- Static or dynamic imaging
  - Various contrast choices: T1w, T2w, T2*w, etc
- Functional MRI methods
  - Diffusion weighted MRI
  - Blood perfusion measurements
  - Phase contrast flow measurements
  - BOLD based fMRI
  - Cell metabolism with hyperpolarized bioprobes

Diffusion weighted MRI

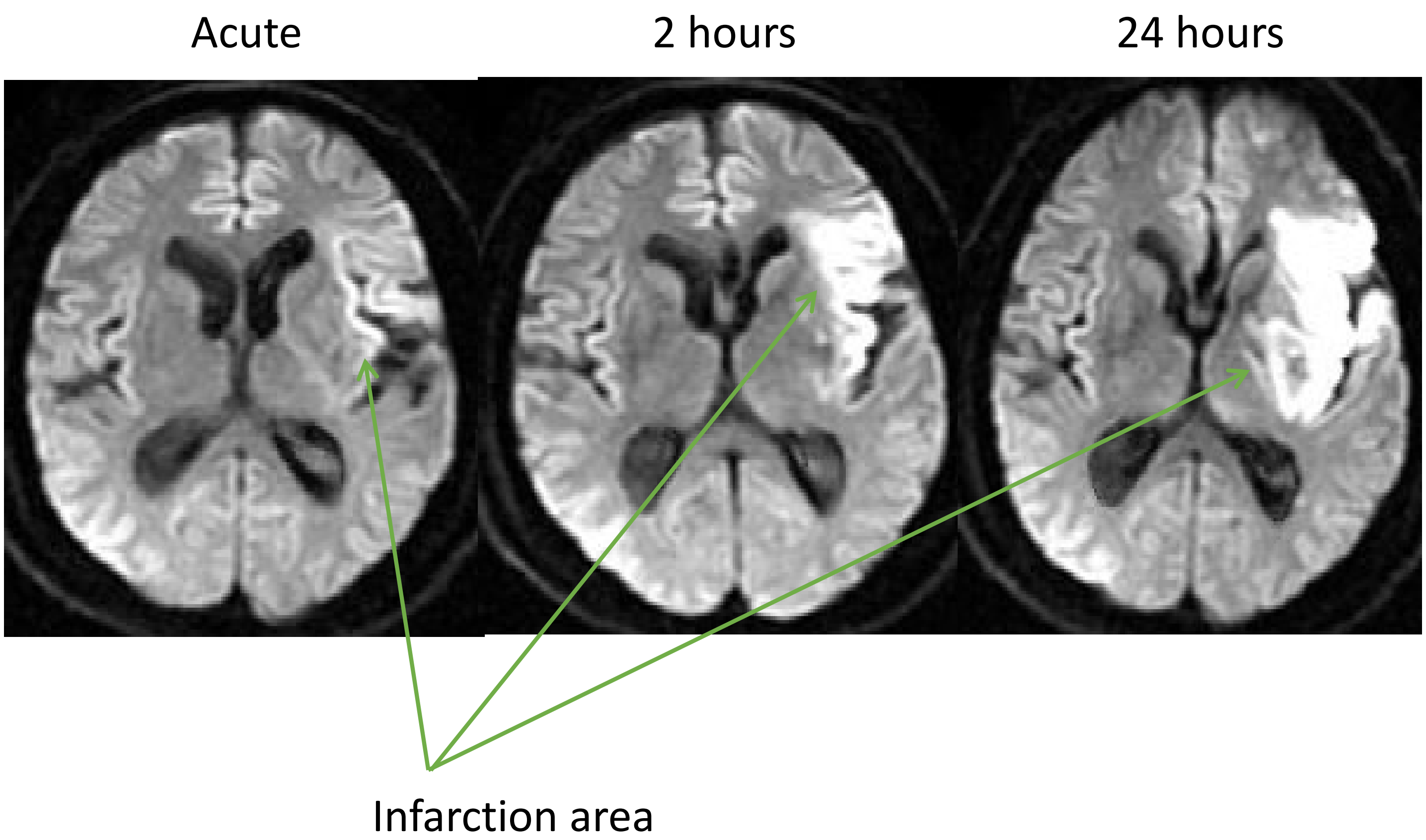


Free diffusion:
Water molecular motion only limited by collision with each other

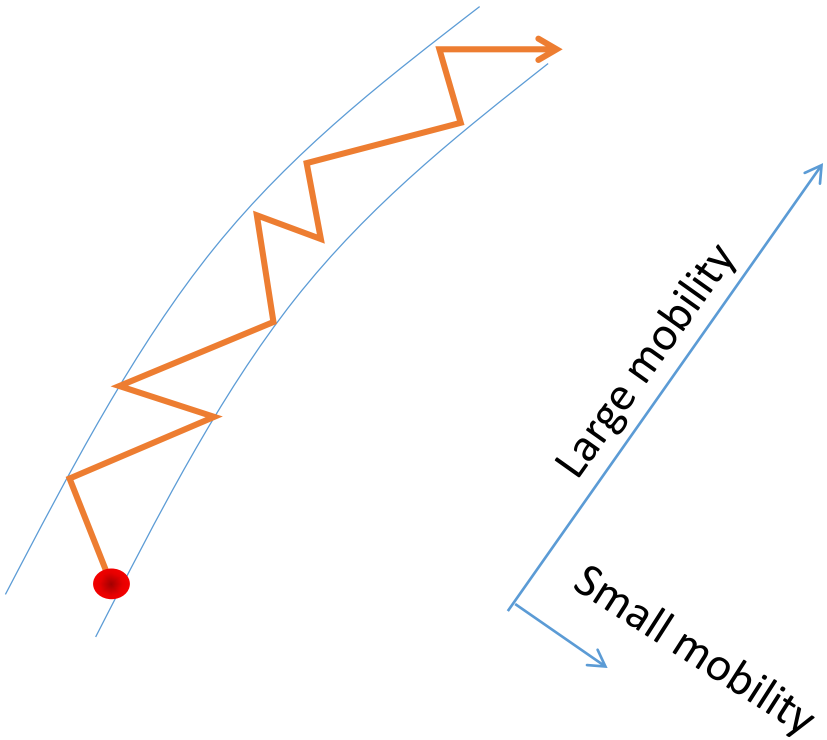


Restricted diffusion:
In biological tissue. Water molecular motion limited by collisions with cells and macromolecules

Diffusion measurement in stroke

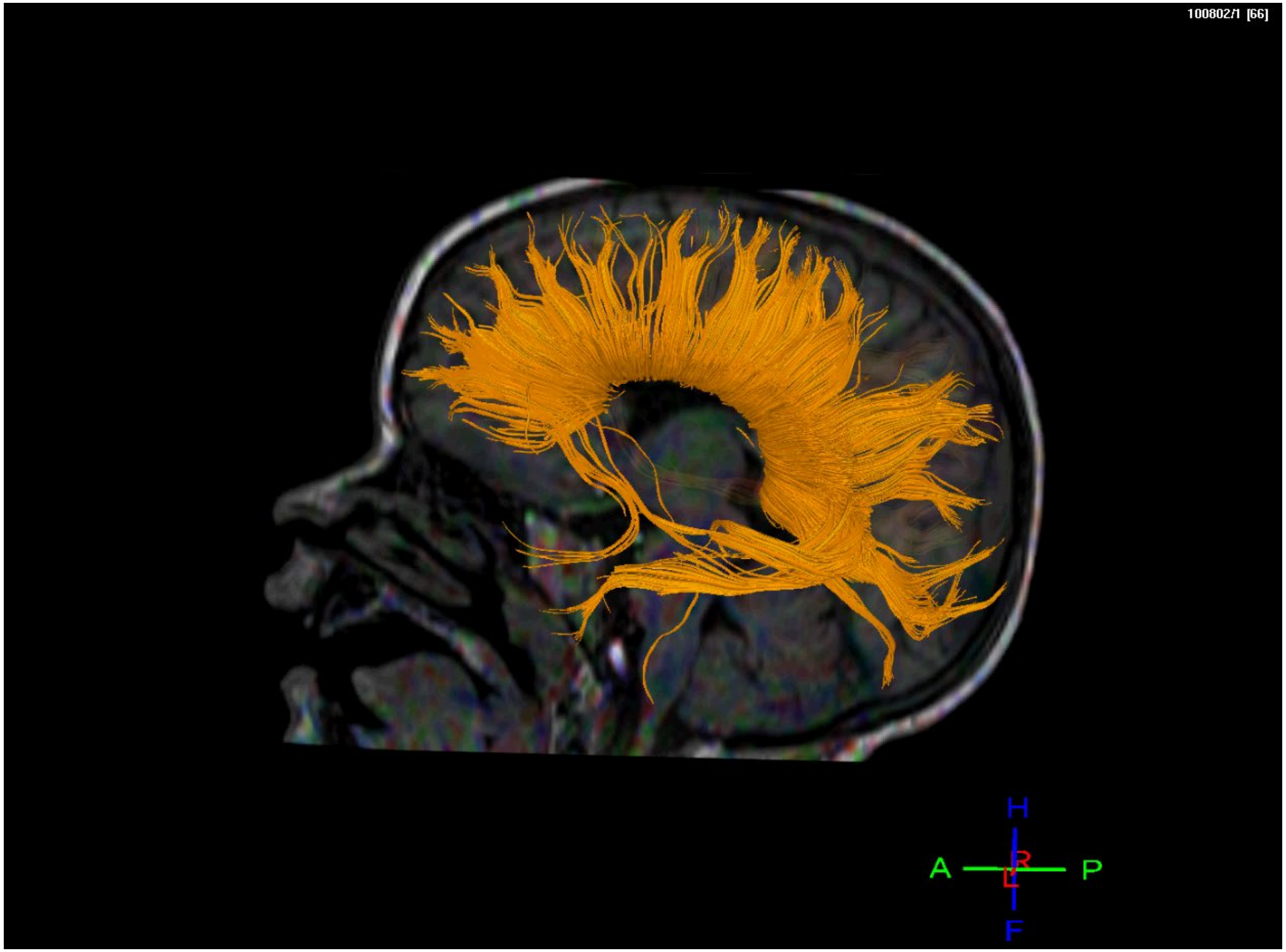


Assessment of anisotropic diffusion

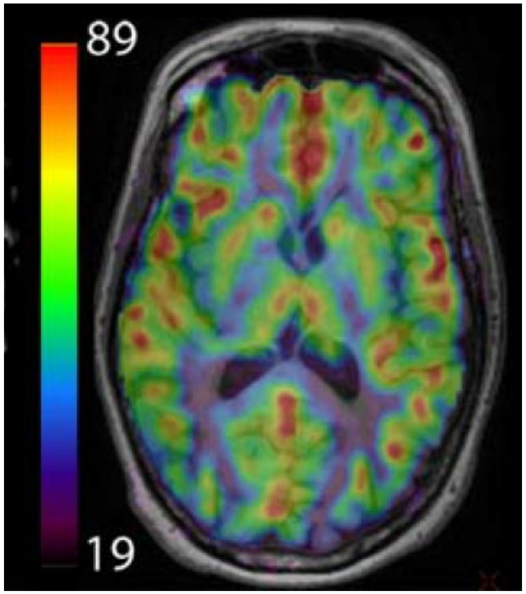


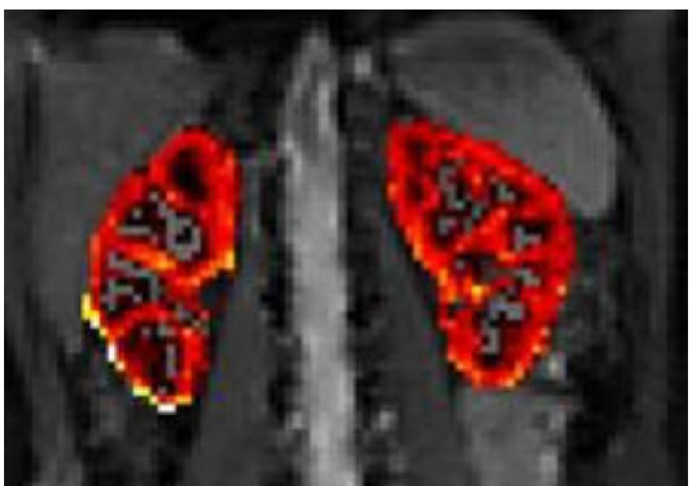
- Can also use more advanced models
  - Neurite density
  - Neurite orientation dispersion index
  - Kurtosis
  - IVIM

White matter tractography example



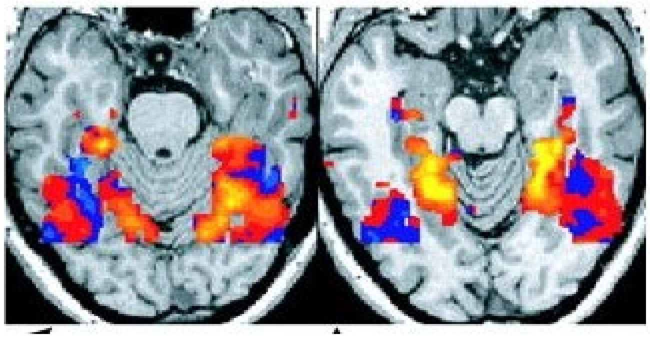
Blood perfusion measurements





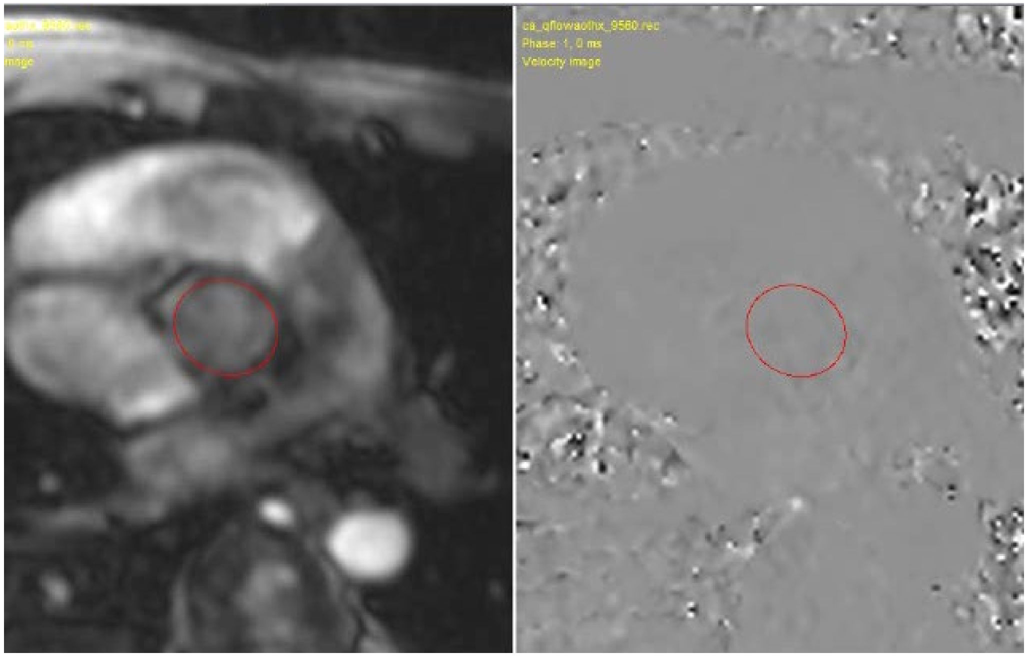
- Injection of contrast agent
  - DSC, DCE
- Labelling arterial blood
  - ASL
- Quantitative parameters obtained using models
- Hyperpolarized MR
  - Urea, pyruvate

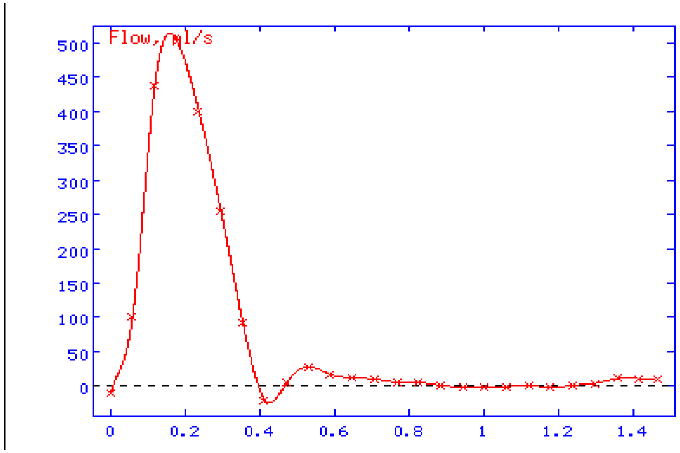
fMRI



- Mapping of brain activity
- Based on blood flow variations
- BOLD: differences in T2* of oxy- and de-oxy blood
- Activation or resting state based
- Low signal differences
  - Multiple averages and statistical measures needed

Phase contrast, vessel blood flow





- Blood flow in vessels
- Measuring global cardiac function
- Assessing heart valve integrity and vessel stenoses

$$Mean\ flow_{vessel} = \frac{\sum_{frames} Flow_{vessel}}{N_{frames}}$$

$$Stroke\ vol = \frac{Mean\ flow}{Cycle\ time}$$

Hyperpolarized MR - MR molecular imaging

- In vivo study of various metabolic pathways
- [1-^{13}C] pyruvate
  - Glycolysis, aerobic vs an-aerobic metabolism, pH
  - Cancer probe, monitor of therapy response
- [2-^{13}C] pyruvate
  - Study of TCA cycle pathways
- [1,4-$^{13}C_2$] Fumarate
  - Detection of cell necrosis
- ^{129}Xe Xenon gas
  - Assessment of lung function

History of MR

- ~1943: Spin and interaction with radiofrequency fields discovered
- ~1973: Paul Lauterbur made the first MR images
- 1980 ->: MR being used for clinical non-invasive imaging
- 1953: Overhauser predicted the possible manipulation of nuclear Boltzmann distribution transferring polarization from electrons
  - Initially doubted by Bloch, Rabi, Ramsey etc
- 1953: Experimental verification by Carver and Slichter
- 1994: Hyperpolarized Helium and Xenon introduced for lung imaging
- 2013: Ardenkjær introduces dDNP and showed a factor >10000 signal enhancement for ^{13}C

Summary

- Traditional MR
  - Frequency of signal: information about chemical structure
  - Spatial information: enables imaging
  - Allows measurements with different contrasts and functional measurements
  - Signal is low: some methods on the edge of useful sensitivity
- Hyperpolarization
  - 10000 to 50000 fold signal enhancement
  - Enables new measures of metabolism
  - Much larger signal but sensitivity still an issue