

Introduction to Magnetic Resonance

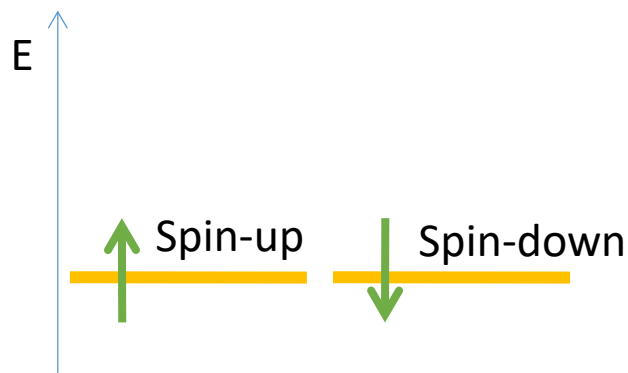
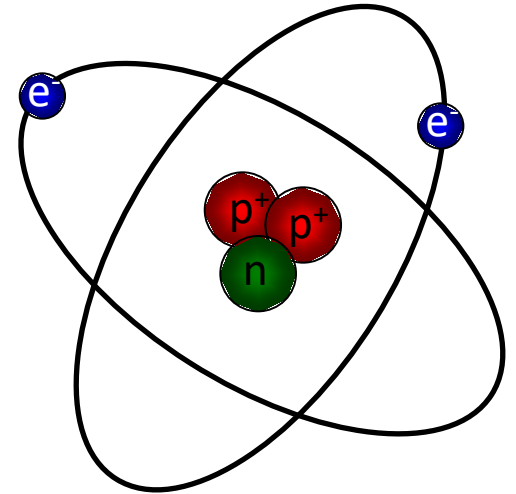
- a general overview

Steffen Ringgaard

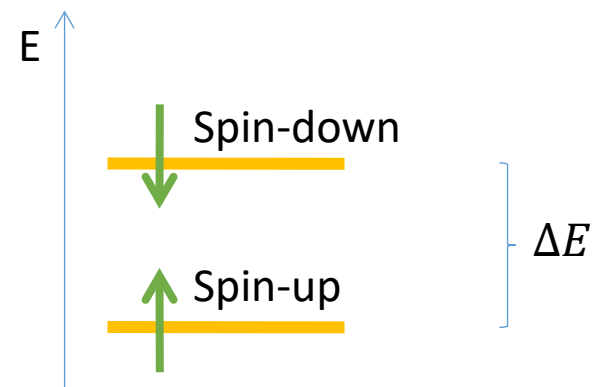


Nuclear spin

- 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



No magnetic field



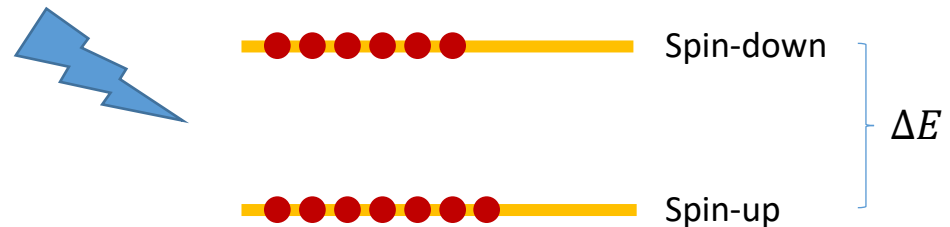
With magnetic field

Equilibrium, excitation, signal

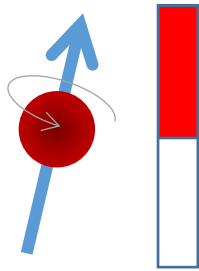
- In equilibrium, distribution of spins given by the Boltzmann equation

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

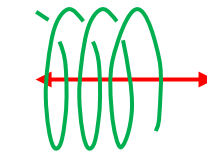
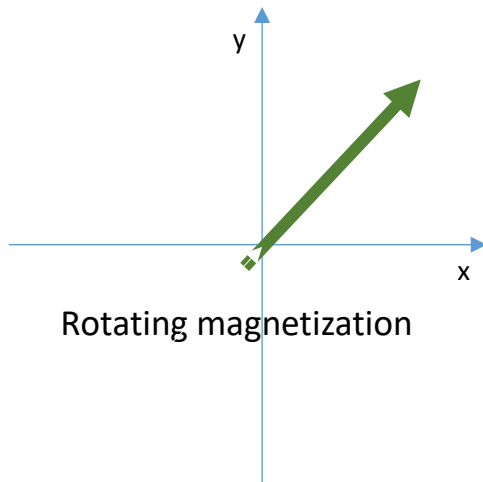
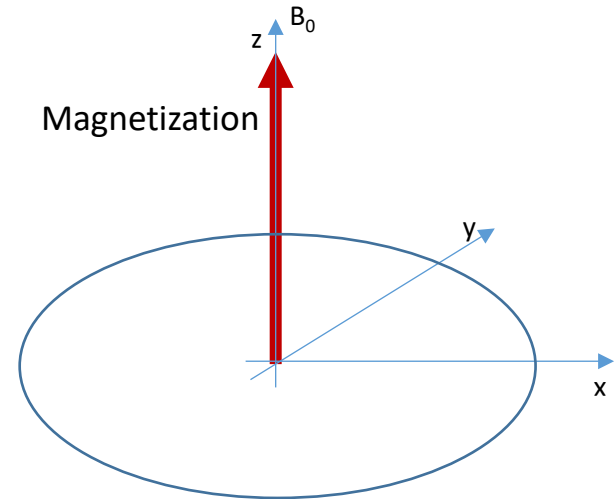
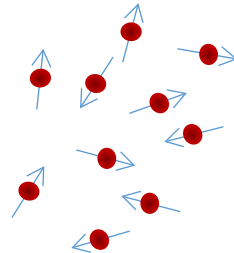
- At 3T: $\frac{\Delta N}{N_{up} + N_{down}} = 10 \text{ ppm}$
- RF fields can flip spins between the two states
- After excitation, magnetization will oscillate and can induce current in receive coil



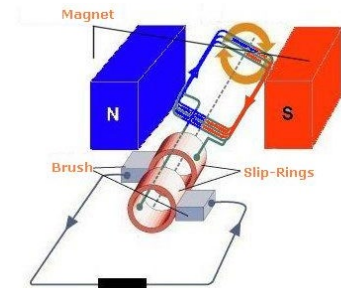
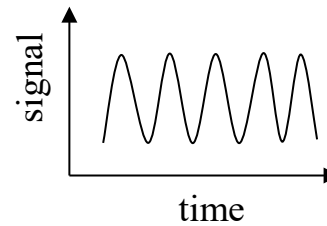
Description with classical physics



Magnetic dipole

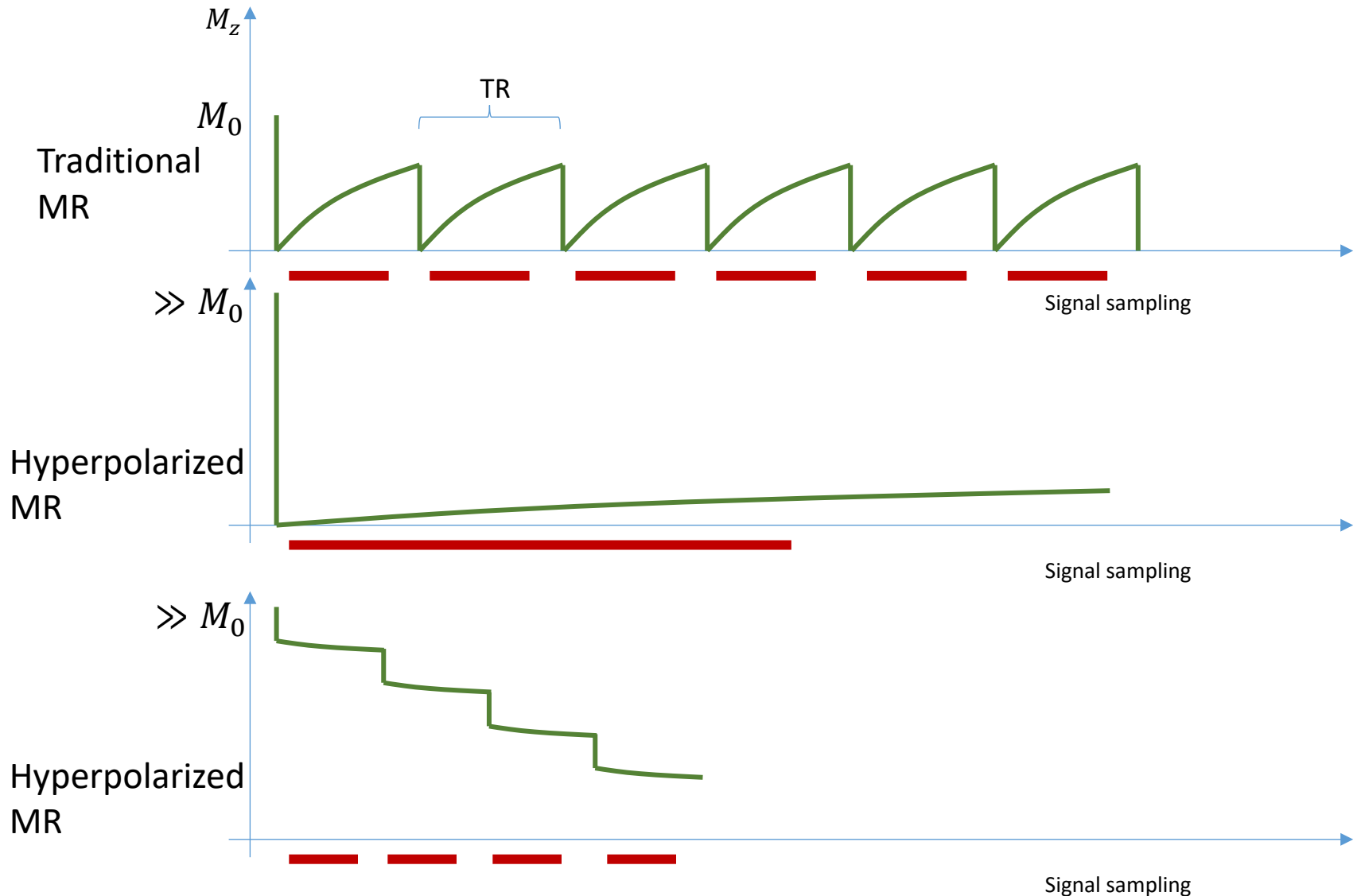


Receive coil

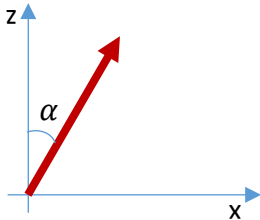


Repeated vs single excitation

Magnetization: sum of all magnetic dipoles

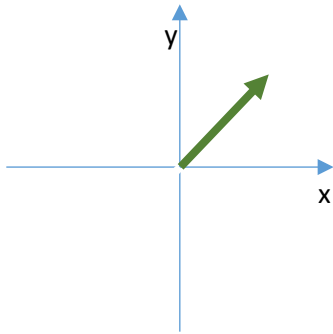


Precession frequency and angles



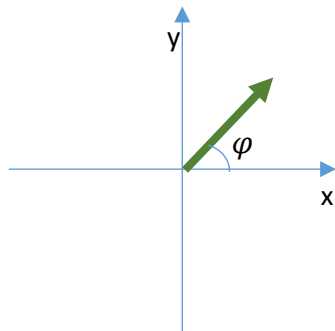
$$\text{Signal} = M_0 \sin(\alpha)$$

$$\text{Remaining } M_z = M_0 \cos(\alpha)$$



Larmor equation

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

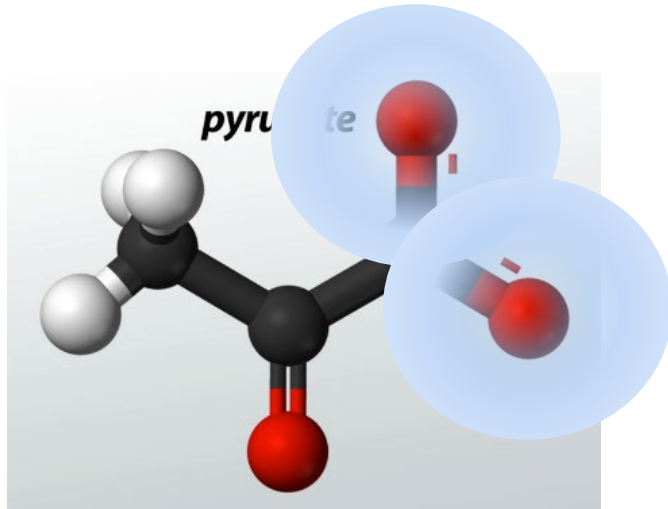


Precession phase: given
by f , duration and RF
phase

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

Often both x- and y-projections are sampled

Spectroscopy



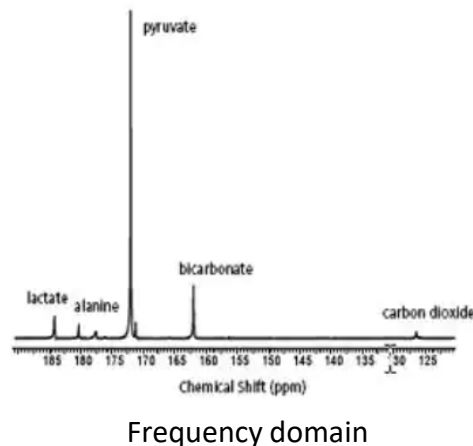
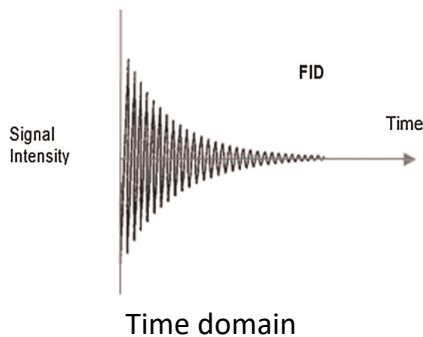
- Electrons shields nuclei slightly
 - Chemical shielding
- Frequency at nuclei determined by specific electronic structure

- Larmor relation

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

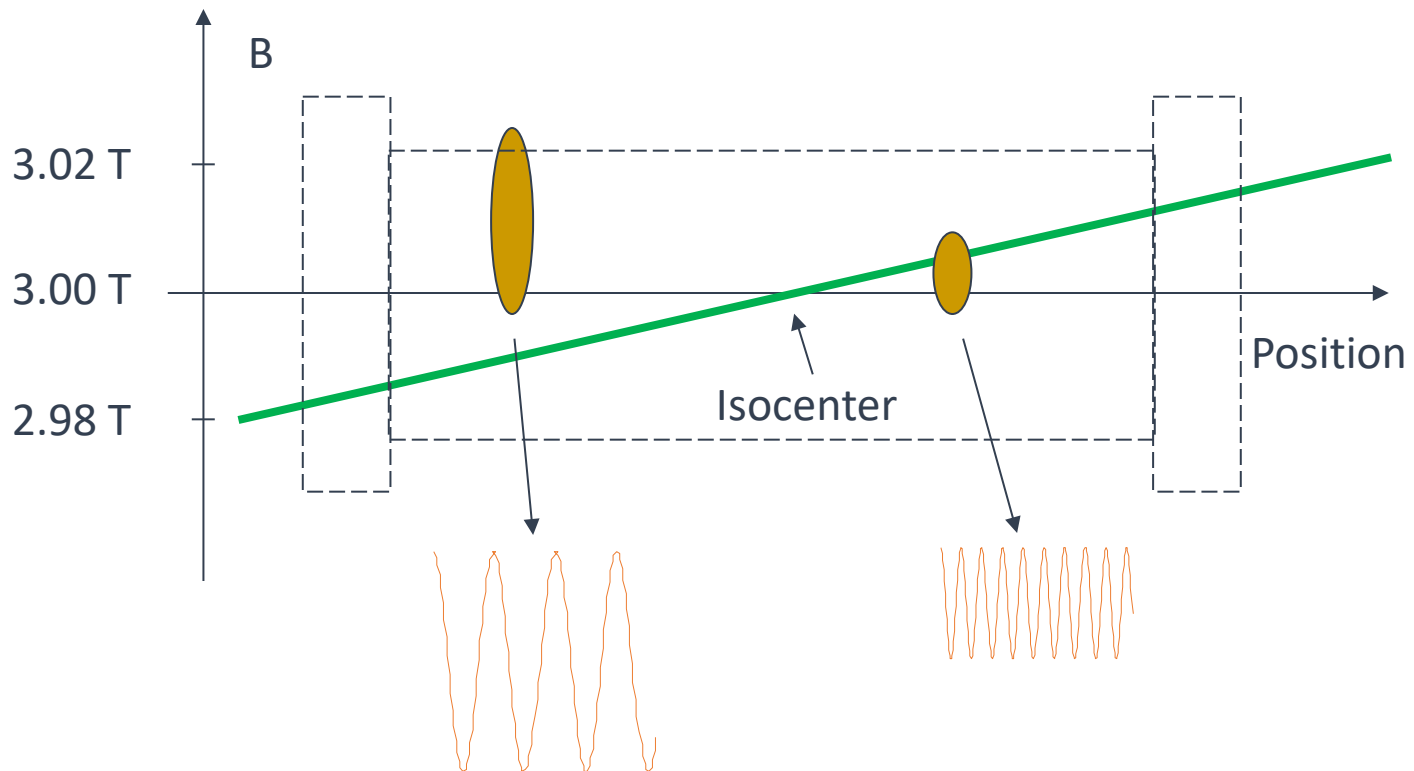
- Sampling of temporal signal variation
 - Fourier Transformation
 - Signal on frequency axis

- Signal amplitude given by molecular concentration

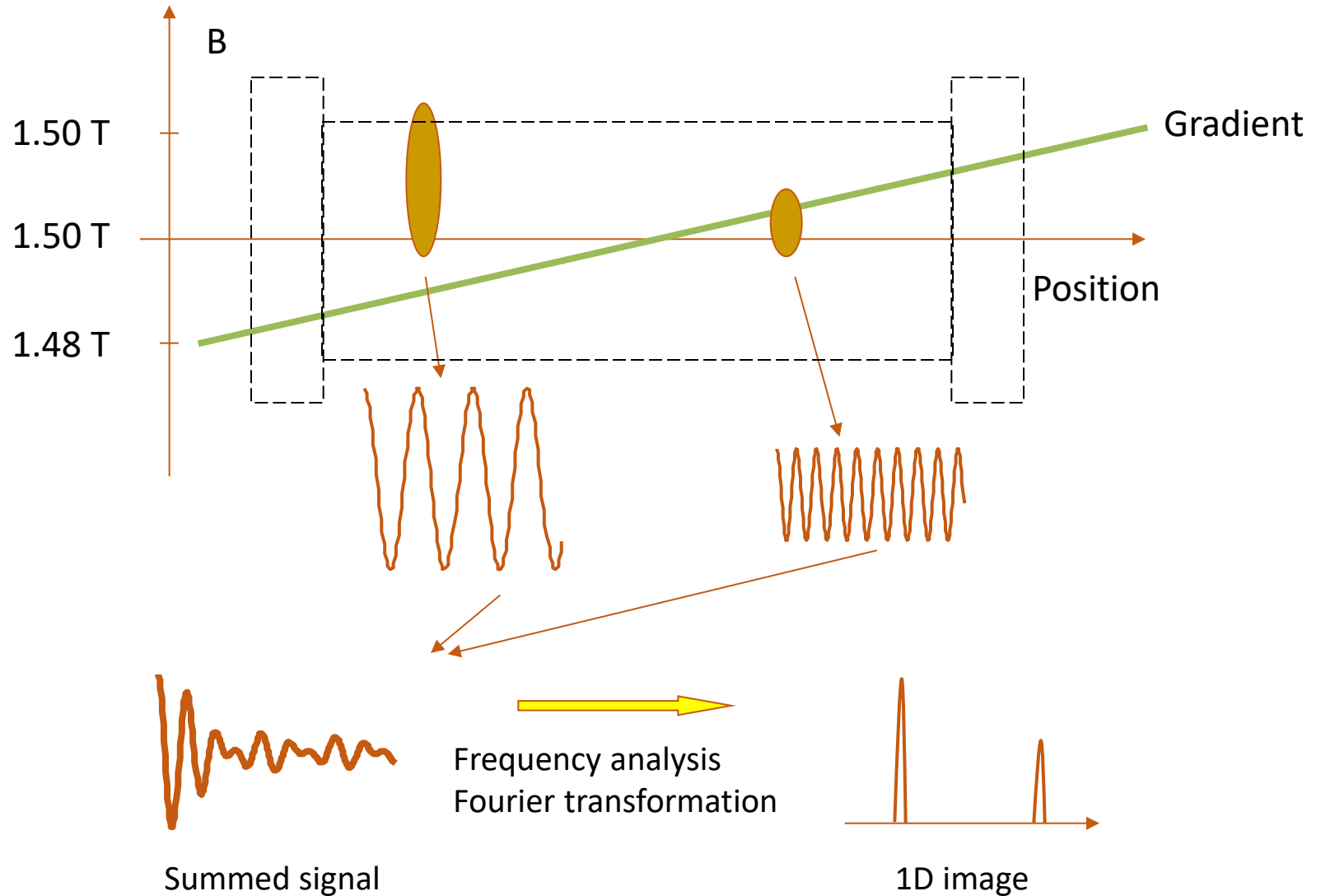


Principles of MR imaging

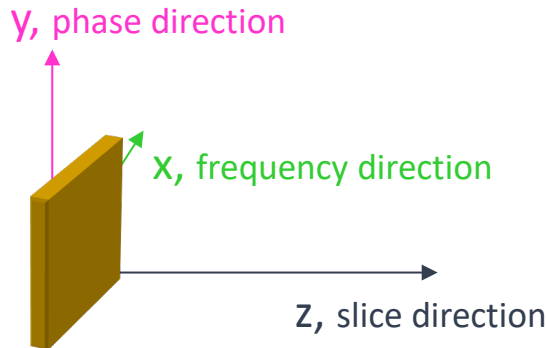
- Encoding spatial information in MR signal



Frequency encoding

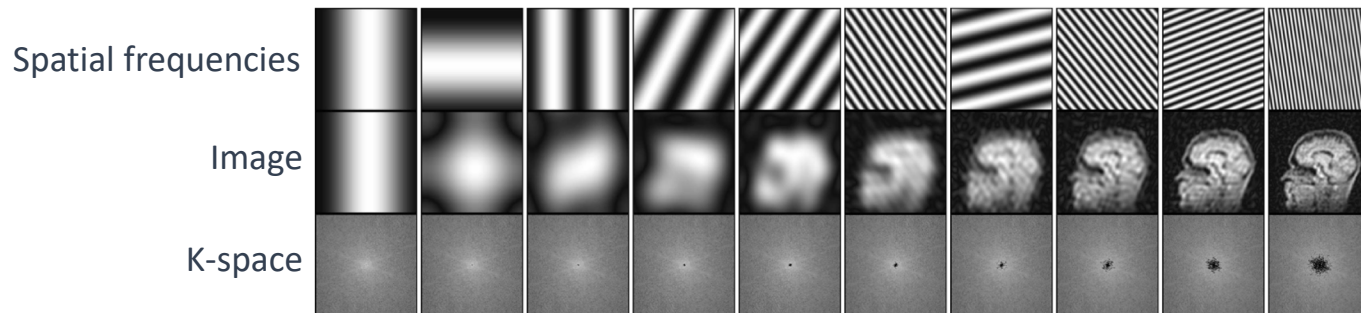


3 dimensions and k-space

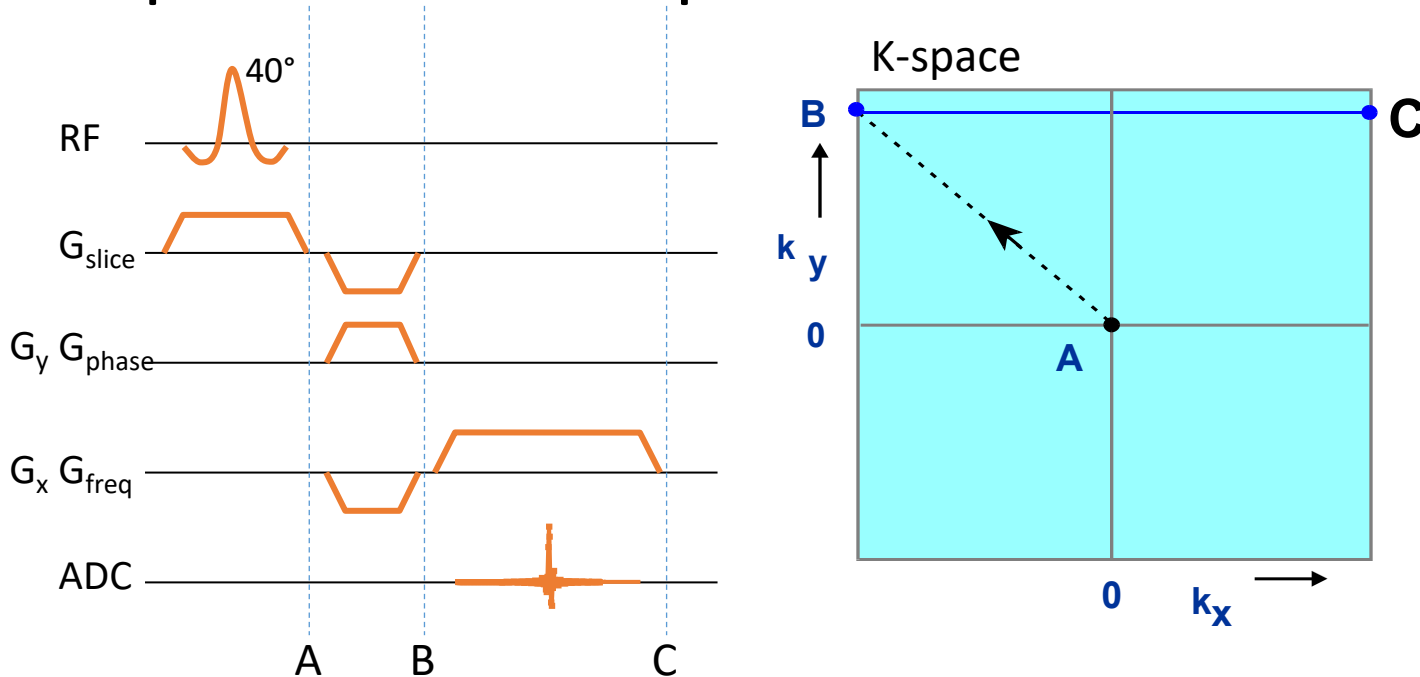


K-space

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

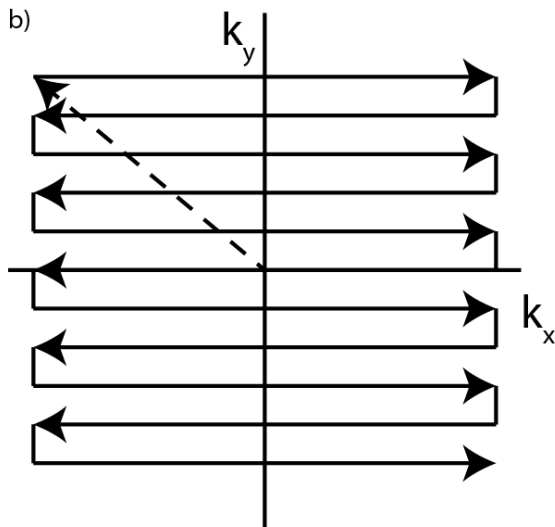


K space description

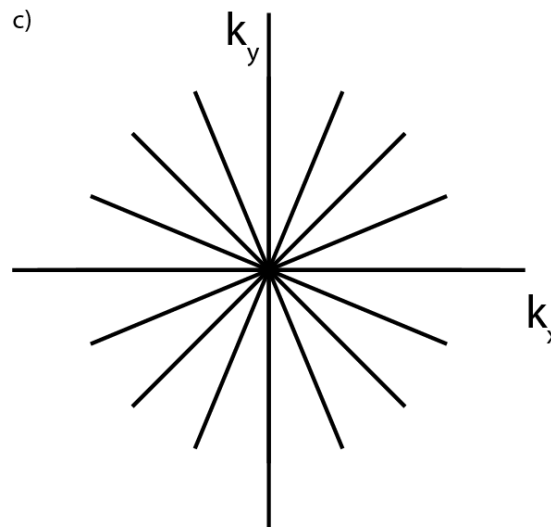


- Signal is sampled in k-space
- Using gradients to move around in k-space
- After having sampled the entire k-space, images can be reconstructed by 2D inverse Fourier Transformation

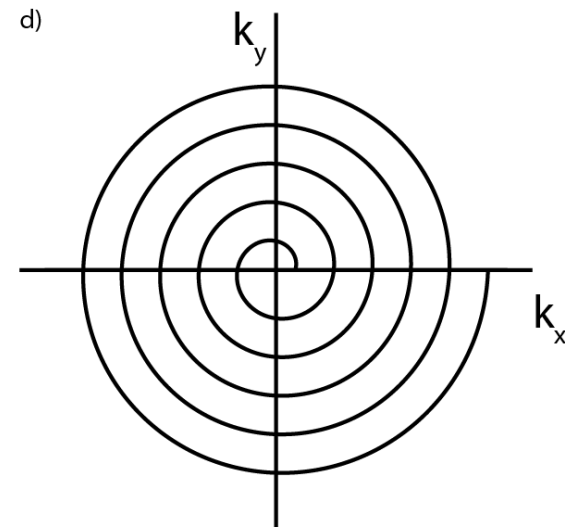
Different ways to sample k-space



EPI

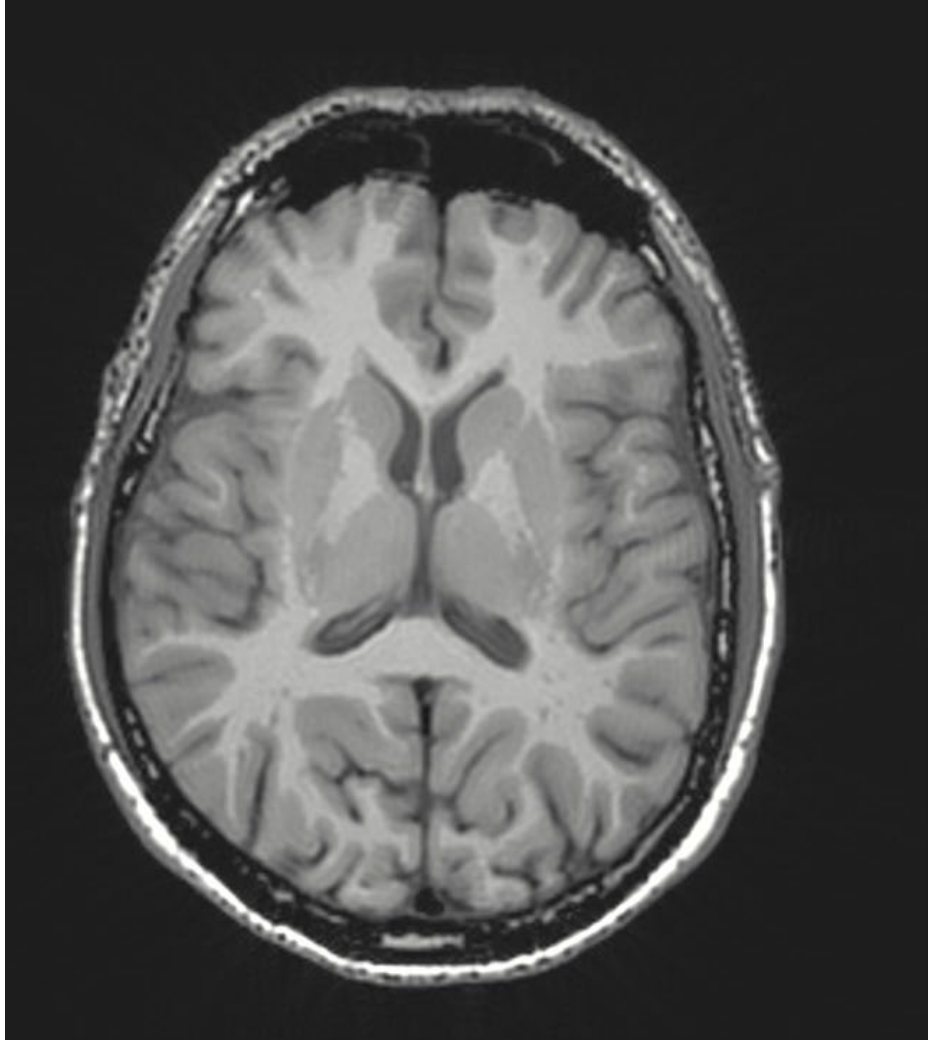


radial

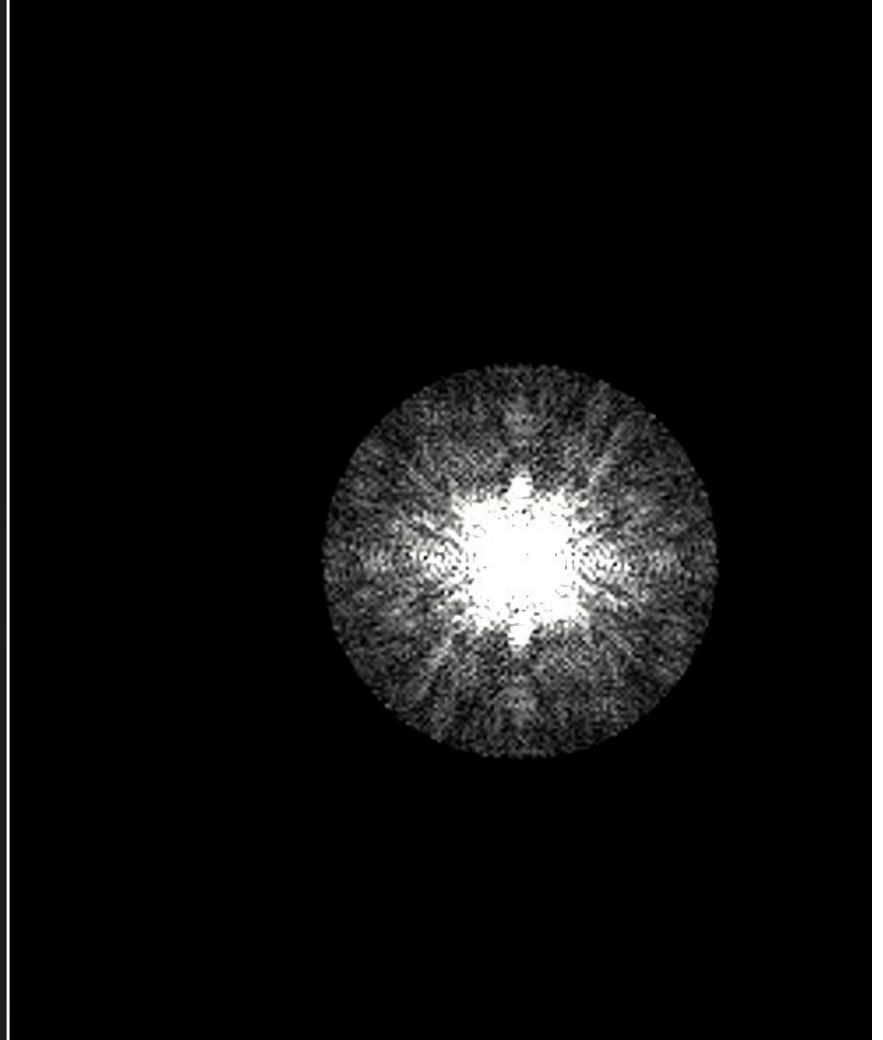


spiral

K-space filtering

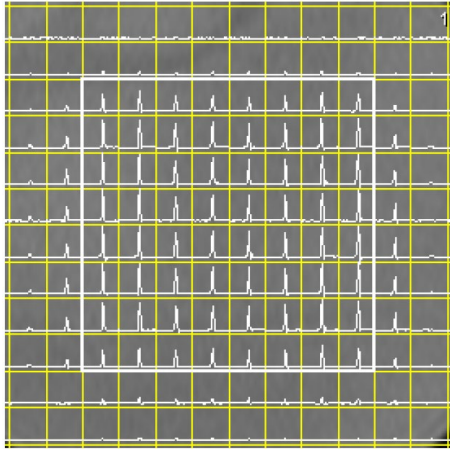


Image

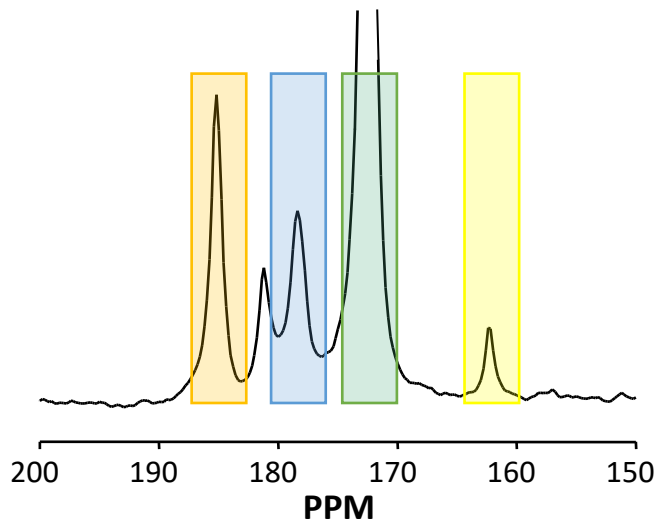


K-space

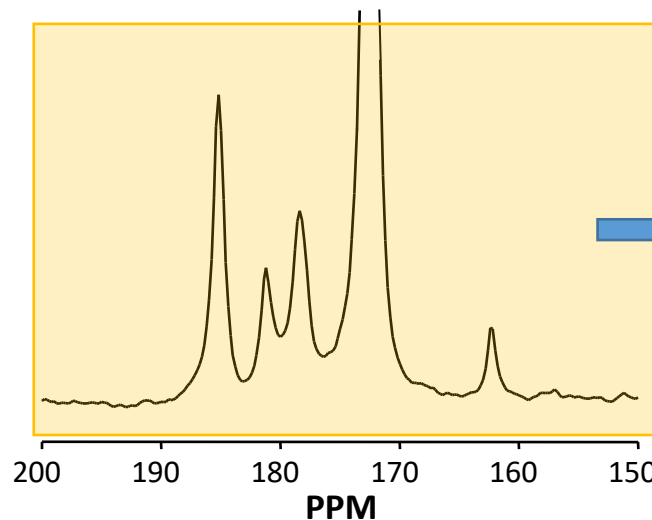
Frequency + spatial information



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



Sequential excitations



Simultaneous excitation

→ Spectral decomposition

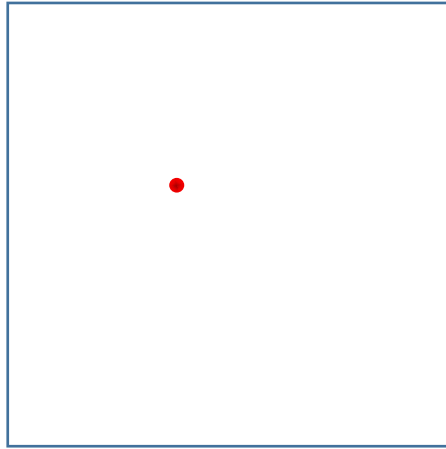
Signal amplitude and noise

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

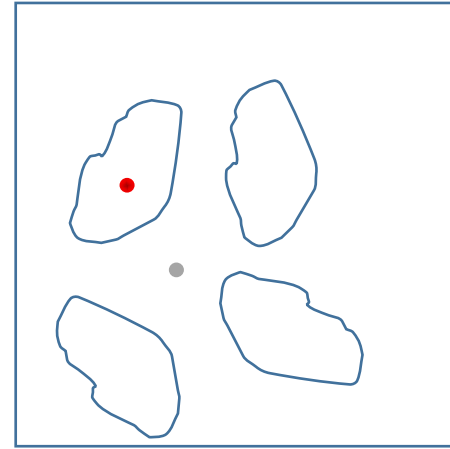
Functional MR methods

- 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

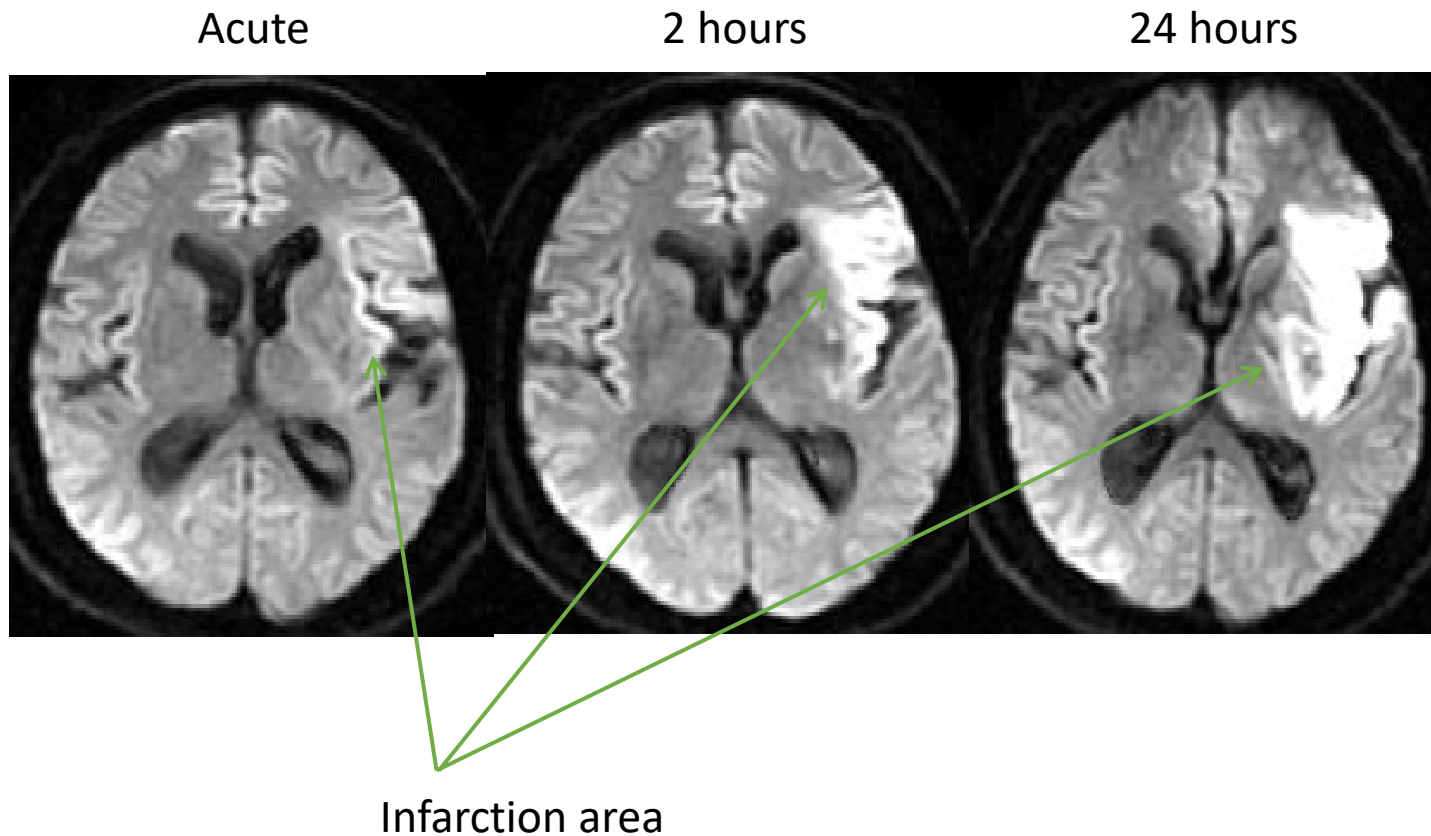


Free diffusion:
Water molecular
motion only limited
by collision with each
other

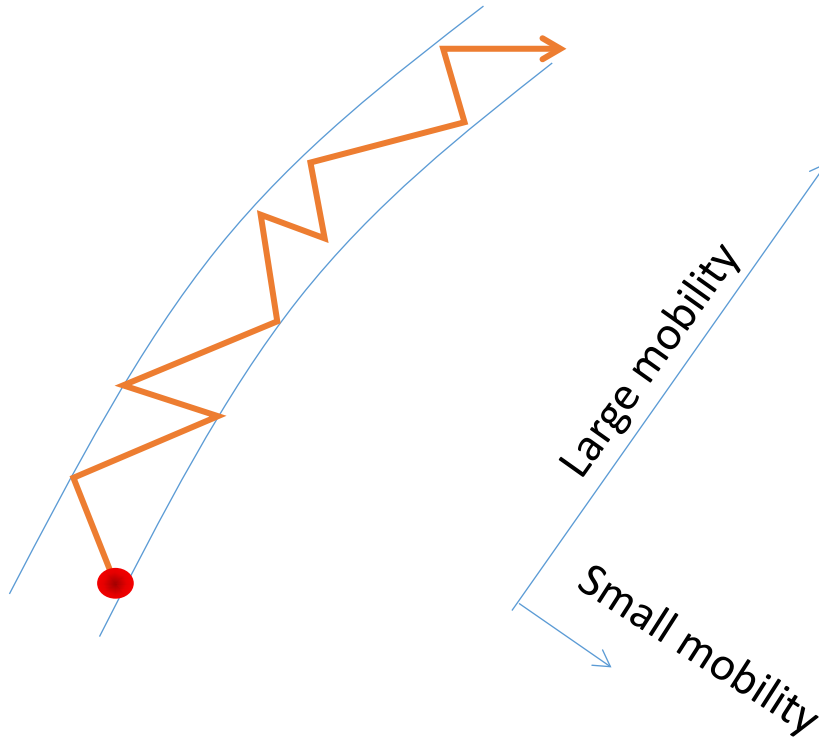


Restricted diffusion:
In biological tissue. Water
molecular motion limited by
collisions with cells and
macromolecules

Diffusion measurement in stroke

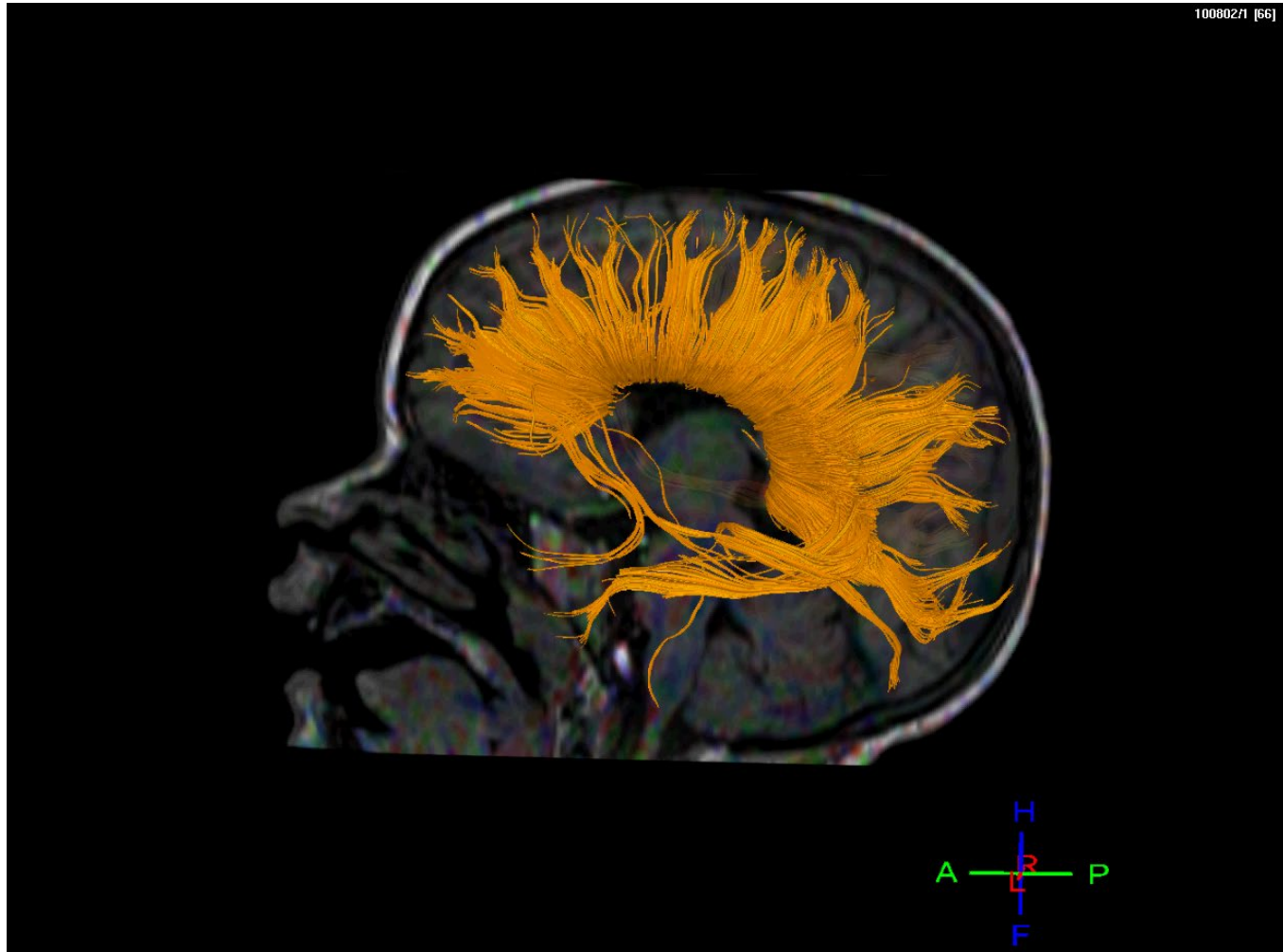


Assessment of anisotropic diffusion

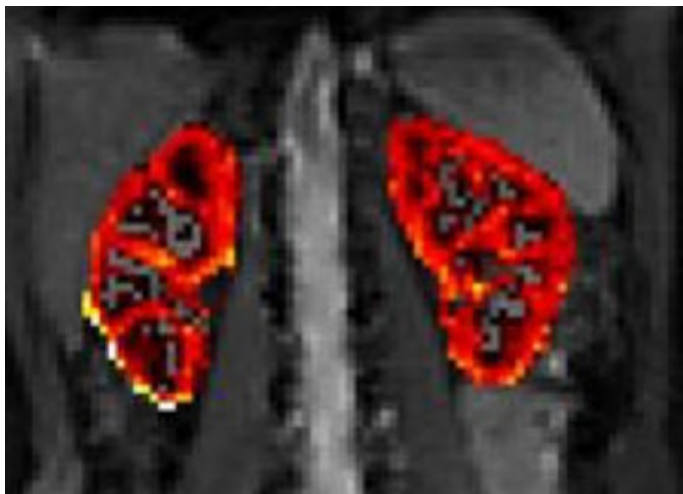
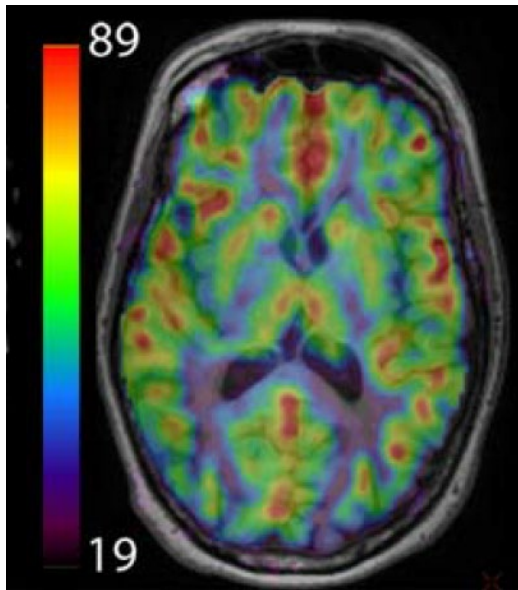


- Can also use more advanced models
 - Neurite density
 - Neurite orientation dispersion index
 - Kurtosis
 - IVIM

White matter tractography example

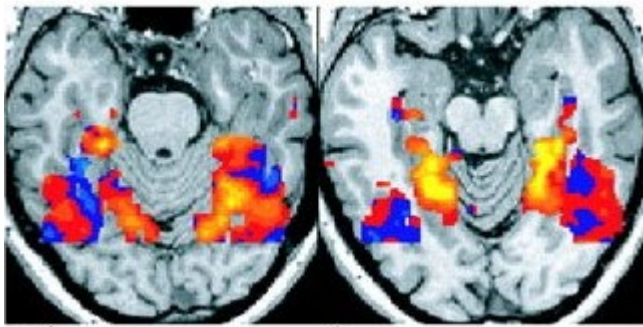


Blood perfusion measurements



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

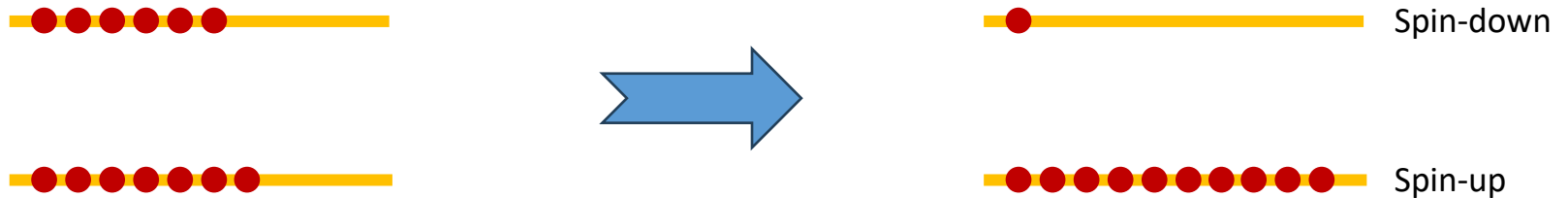
fMRI



- 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

Hyperpolarization, principles

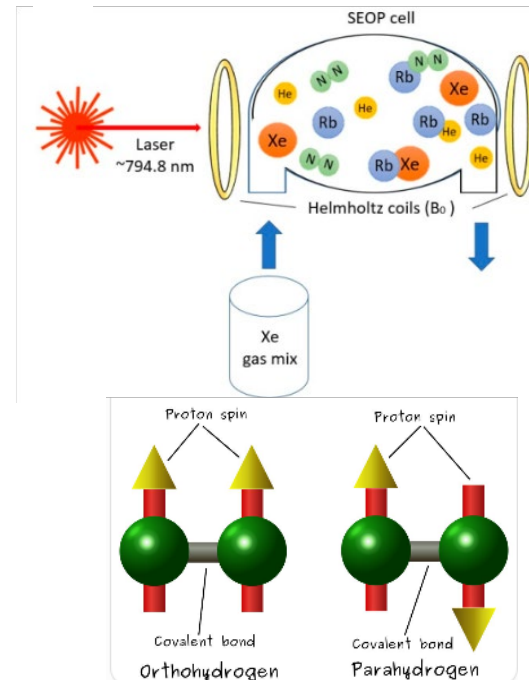
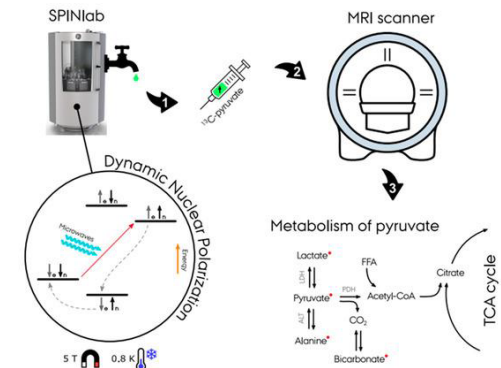
- Manipulation of Boltzmann distribution



- Violation of 2. law of thermodynamics ??
 - Initially doubted by Bloch, Rabi, Ramsey, etc
- Polarization generated in quite different ways

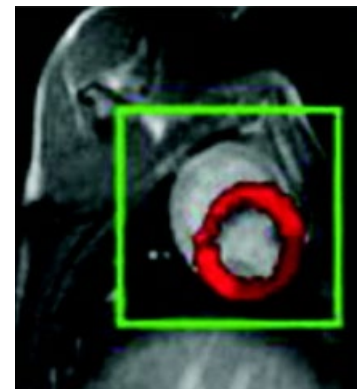
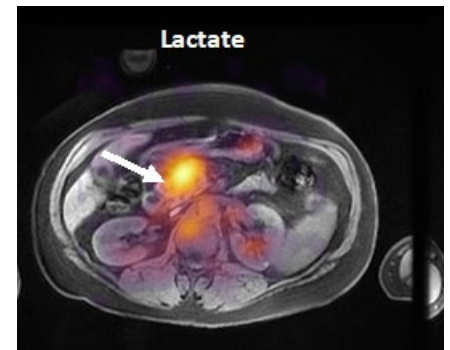
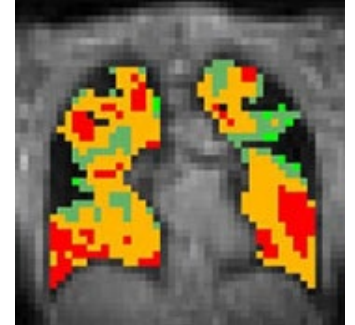
Hyperpolarization methods

- Brute force
 - Polarization given directly by Boltzmann equation
 - Requires very low temperature and high fields
- Dynamic Nuclear Polarization (DNP)
 - Transfer of electron polarization by microwaves
 - ^{13}C -labeled molecules
- Spin-exchange Optical Polarization (SEOP)
 - Transfer of photon angular momentum using laser and optical pumping
 - Polarization of Xenon-129
- Parahydrogen induced polarization (PHIP)
 - Transfer of non-equilibrium spin order to ^{13}C molecules
 - Rapid polarization



Use of hyperpolarization in clinical research

- Lung function
 - Assessment of ventilation, gas uptake and aveolar microstructure
- Cancer tissue
 - Cancer cell detection and characterization
 - Pyruvate-to-lactate conversion rates
 - Warburg effect: cancer cells produce unusual amount of lactate
- Myocardial function
 - Oxidative and glycolytic metabolism
 - Viability, ischemia



Limitations

- Short duration of hyperpolarized probes
 - Very fast scanning is needed
- Limited sensitivity
- MR in general prone to artifact
- Expensive
- Complex

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
- 1953: Experimental verification by Carver and Slichter
- 1994: Hyperpolarized Helium and Xenon introduced for lung imaging
- 2003: 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
- Course content
 - Physical principles of hyperpolarization
 - Practical sessions to see how it is done
 - Medical applications of hyperpolarized agents