BASICS OF NMR/MRI

Content

Part 1: Basics of NMR/MRI

- History of MRI
- The NMR phenomena
- Basic MR concepts: magnetization, precession, resonance, excitation, relaxation
- Spatial encoding with imaging gradients

History of NMR and MRI

- 1923: Wolfgang Pauli describes the phenomena of nuclear spin.
- 1944: Nobel Prize in Physics: Isidor Isaac Rabi "for his resonance method for recording the magnetic properties of atomic nuclei".
- 1946: The American scientists Felix Bloch and Edward Purcell described, independently, the NMR phenomena.

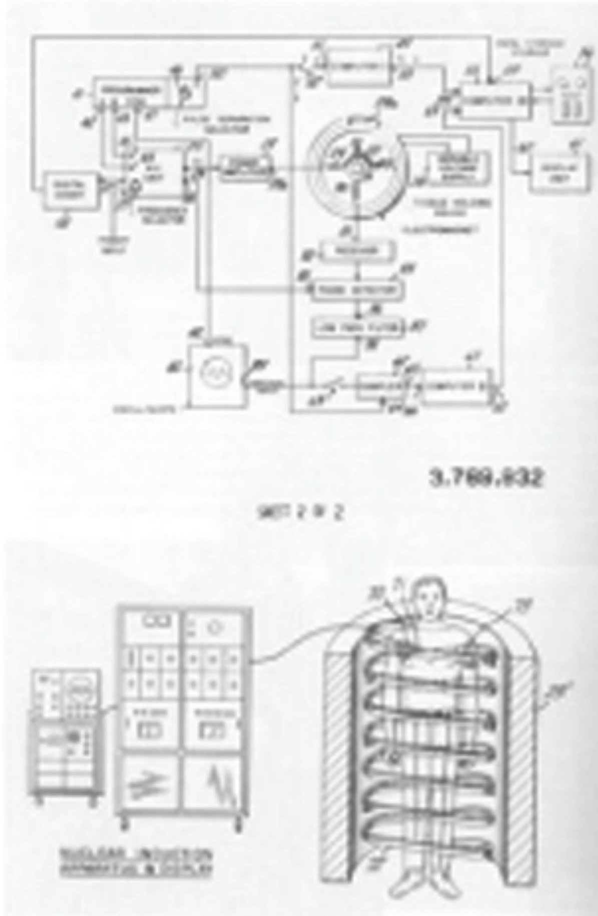
Wolfgang Pauli og Niels Bohr studerer spinn

- 1952: Nobel Prize in Physics: Bloch and Purcell for discovering nuclear magnetic resonance spectroscopy.
- 1972: US Patent 3789832; "Apparatus for detecting Cancer in Tissue". Damadian, March 17, 1972.
- 2003: Nobel Prize in Physiology or Medicine: Paul Lauterbur and Sir Peter Mansfield "for their discoveries concerning magnetic resonance imaging".

History, Cont.

1977: US Patent 3789832; "Apparatus for detecting Cancer in Tissue". Damadian, March 17, 1972.

RIGHT: Although Minkoff was smaller and fit the antenna vest better, he wasn't anxious to risk his health for an experiment that had never been done before. But finally, on July 2, 1977, Minkoff told Damadian that he would go into the machine. That very evening, shortly before midnight, Minkoff took his shirt off and put on the cardboard vest. As soon as the machine was turned on, there was a signal. Four hours and 45 minutes later, after Minkoff had been incrementally moved via the adjustable seat into different positions, the first whole-body human scan showing a cross-section of Minkoff's chest was complete. An ecstatic Damadian noted his jubilant reaction in Goldsmith's notebook (NEXT PAGE).



The "Pioneer Patent" of NMR scanning, U.S. Patent 3,789,832 describing an "Apparatus and Method for Detecting Cancer in Tissue," was the first description ever of a device for scanning the human body by NMR. The patent application was filed by Damadian on March 17, 1972, two days less than one year after Science published his article entitled, "Tumor Detection by Nuclear Magnetic Resonance."

History, Cont.

THIS YEAR'S NOBEL PRIZE IN MEDICINE

30 years of proof that this shameful wrong must be righted

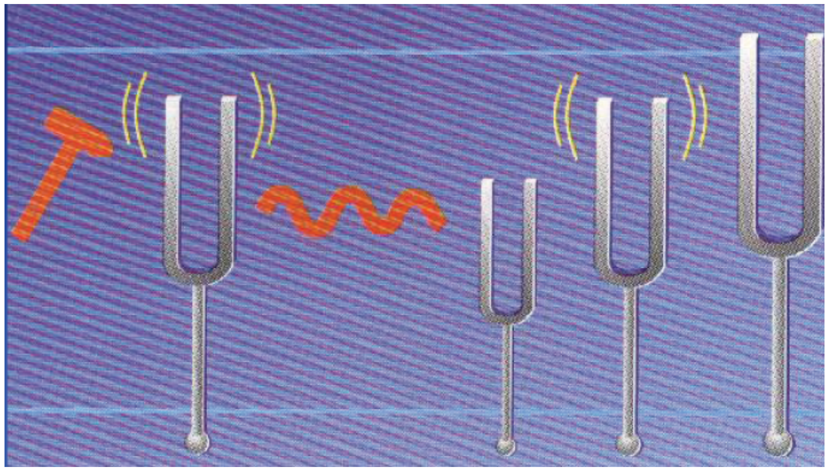
Why the idea of an MRI didn't occur to this year's two winners until *after* a medical doctor made his landmark discoveries

From: http://www.fonar.com/nobel.htm

The NMR Phenomena

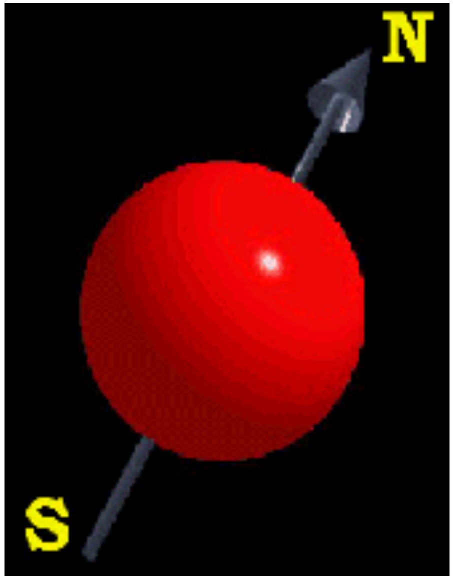
- Bloch and Purcell discovered that if you put protons (or certain nuclei) in a powerful magnetic field and then send *electromagnetic radiation* onto them, they will produce a *signal* in a *coil* placed around the protons.
- The radiation must have a frequency that the protons can "hear" (i.e., they resonate) in order to absorb and then release energy

⇒ **Nuclear Magnetic Resonance or NMR**



The Source of MR Signal

- MR sensitive nuclei have an uneven number of protons or neutrons in their nucleus.
  - Examples: ^{1}H, ^{3}He, ^{13}C, ^{15}N, ^{17}O, ^{19}F, ^{23}Na, ^{31}P, ^{129}Xe
- Such nuclei have a quantum property called **SPIN**
- Spin is a form of **ANGULAR MOMENTUM**



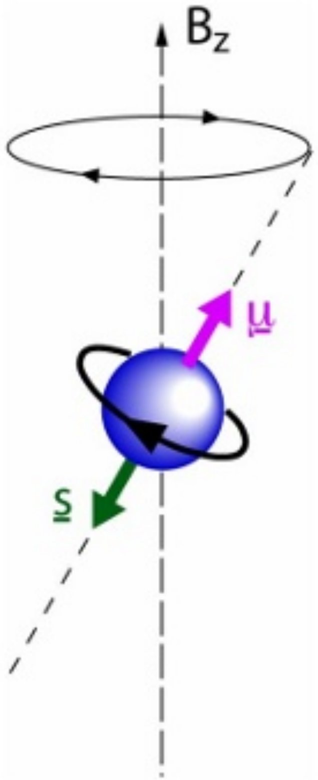
Spin/Spins Interacting with a Magnetic Field

- What happens to a single spin when magnetic field is applied?
  - **RESONANT PRECESSION** around B_0 with a characteristic frequency, which depends on B_0

- What happens to a large number (ensemble) of spins when a magnetic field is applied?
  - **RESONANT PRECESSION** around B_0 with a characteristic frequency
  - Development of a net **MAGNETIZATION**, which also depends on B_0

Resonant Precession

- Spins **PRECESS** (rotate) in the plane perpendicular to the magnetic field axis.
- This phenomena is described, using purely classical mechanics, as a **GYROSCOPE**



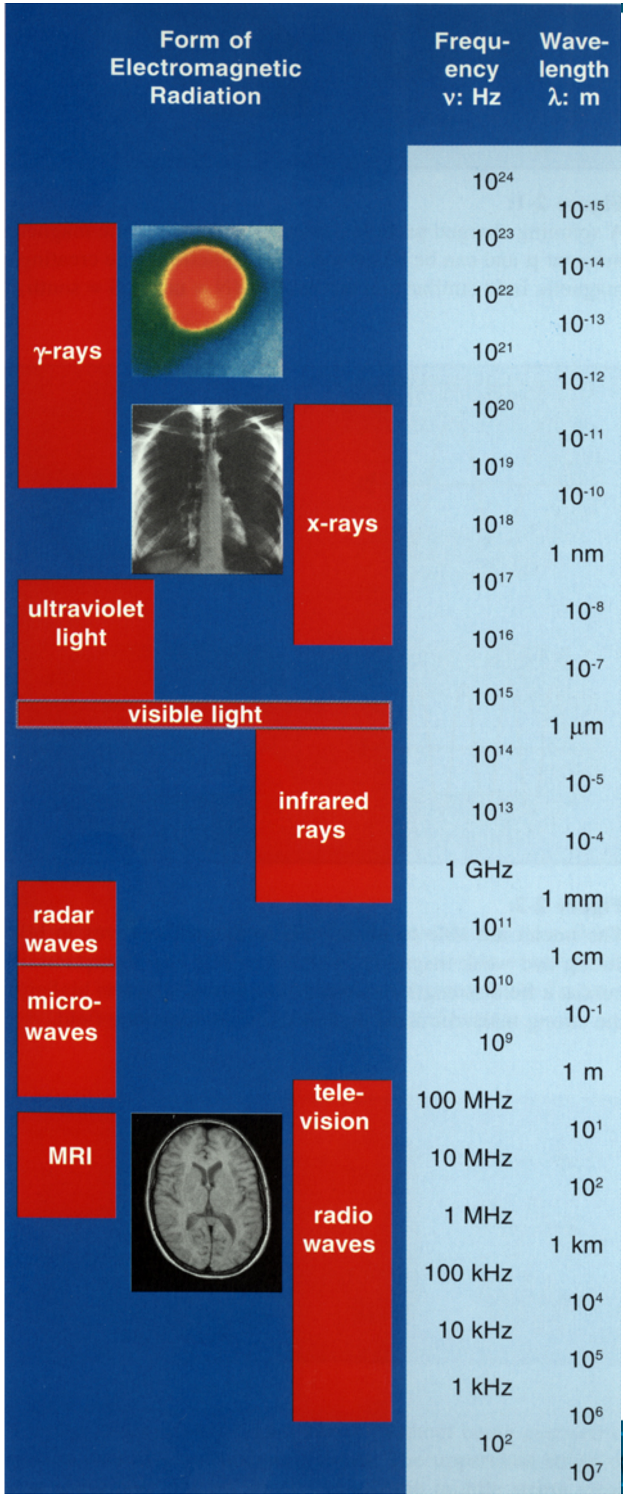
Resonant Precession, Cont.

- The frequency of precession is called **LARMOR FREQUENCY**
- Larmor frequency depends on the:
  - strength of the magnetic field (B_0 provides the torque for this precession)
  - "magneto-rotational" property of each nuclei (ratio between magnetic moment and angular momentum)

=> LARMOR EQUATION: $f_0 = \gamma * B_0$

  - f_0 = Resonant frequency (Larmor frequency, precession frequency, in Hz)
  - γ = Gyromagnetic ratio (constant = 42,58MHz/T for ^{1}H)
  - B_0 = Static magnetic field (7T on "our" MR)

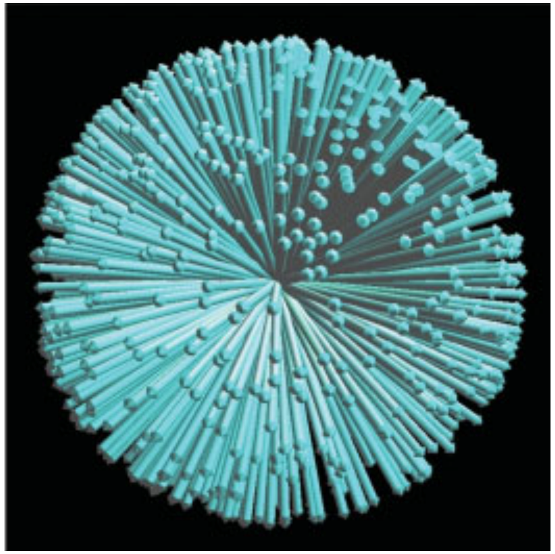
  - Ex1: Clinical MRI machine uses 1.5T => f_0 = 64 MHz
  - Ex2: 7T Pharmascan => f_0 = 300.3MH



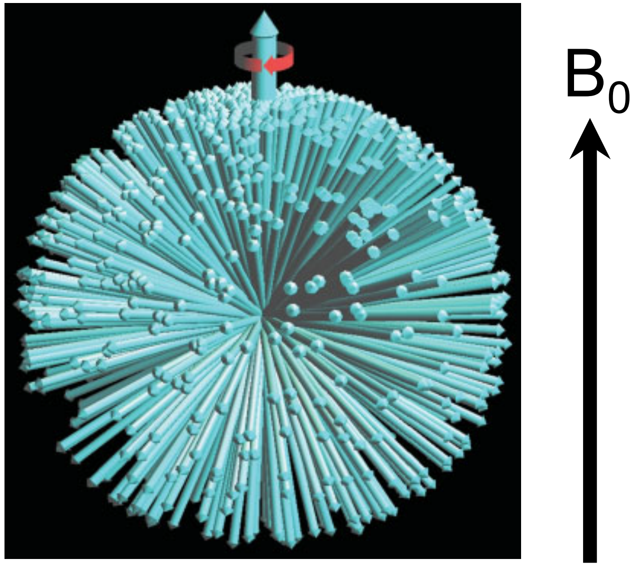
The magnetic field

- Magnetic field strength is measured in Tesla (T) or Gauss (G)
- One Tesla = 10 000 Gauss.
- We use a 7T MR = 140 000 times stronger than the earth´s magnetic field (0.05 mT).

Magnetization



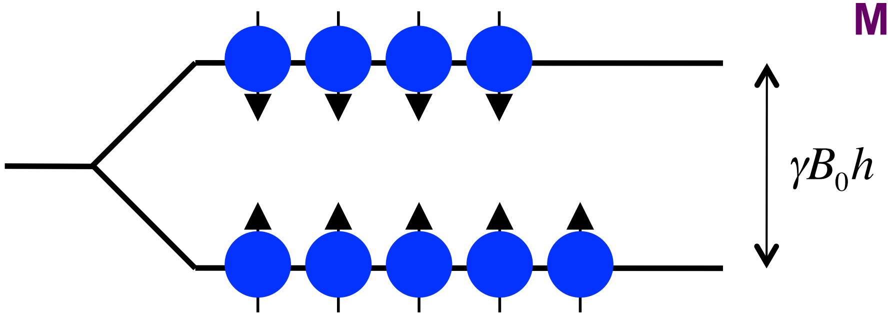
No magnetic field



Magnetic field present

- In the absence of mag. field, spin distribution is randomly oriented in all directions.
- In the presence of mag. field, spin distribution is very slightly skewed towards the magnetic north → **MAGNETIZATION**

Magnetization, an Alternative View



Magnetic energy

$$e^{-\frac{\gamma B_0 \hbar}{k_B T}}$$

Thermal energy

- Spins have two energy eigenstates: spin up (low energy state) and spin down (high energy state).
- At room T, thermal energy >> magnetic energy, so the access of spins in low energy state vs. high energy state is 1 in 1 mill.
- Body is 2/3 water → lots of protons and thus spins → the excess number of spins in the lower energy state becomes big enough to be detected
- This spin excess is called **MAGNETIZATION**

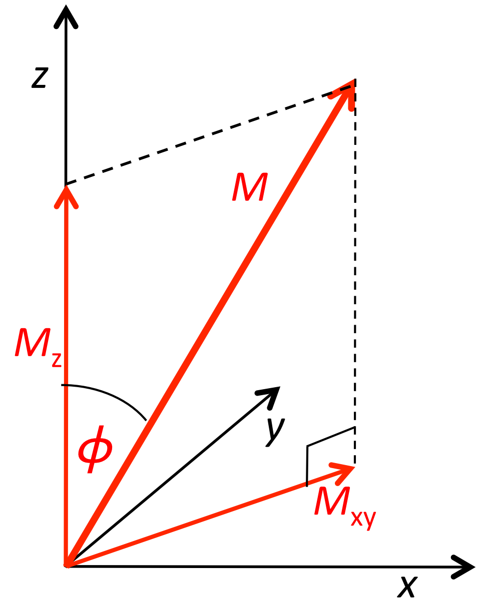
Video: Introduction to Nuclear Magnetic Resonance

Excitation

- From now on we will only be describing the behavior of net magnetization *M* (i.e., ignore the behavior of individual spins).
- ***M* is the source of MR signal and is used to produce MR images**
- In equilibrium, *M* is aligned with B_0 → no precession around B_0 → no emission of EM radiation.
- To produce an MR signal, *M* has to be tipped away from the B_0 field.
- This is achieved with an **RF pulse** which is produced by an **RF coil** whose long axis is oriented perpendicular to the direction of B_0 field.
- RF pulse tips *M* away from B_0 → *M* precesses around B_0 → emission of RF radiation → detection of RF radiation by the RF coil via Faraday´s law of induction (can be the same coil as the one that excited *M*).

Excitation, Cont.

$$\omega_0 = \gamma B_0 \text{ and } \omega_1 = \gamma B_1$$
$$\Rightarrow \frac{d\phi}{dt} = \gamma B_1$$
$$\Rightarrow \Delta\phi = \gamma B_1 \Delta t$$



- Flip angle by which *M* is tipped away from B_0 is proportional to the strength and the length of the B_1 pulse.
- A $\pi/2$ RF pulse flips *M* by a 90° angle, a π RF pulse flips *M* by 180°.
- *M* has now 2 vector components: a longitudinal component, M_z, which is parallel to B_0, and a transverse component, M_{xy}, which is perpendicular to B_0.
- Signal that is detected by the RF coil is called an FID (**Free Induction Decay**).
- FID is precession of M_{xy} (transverse component) around *z-axis*.

Video 1: Precession, Resonance and Excitation

Introductory NMR and MRI
with Paul Callaghan

Video 1
Precession and Resonance

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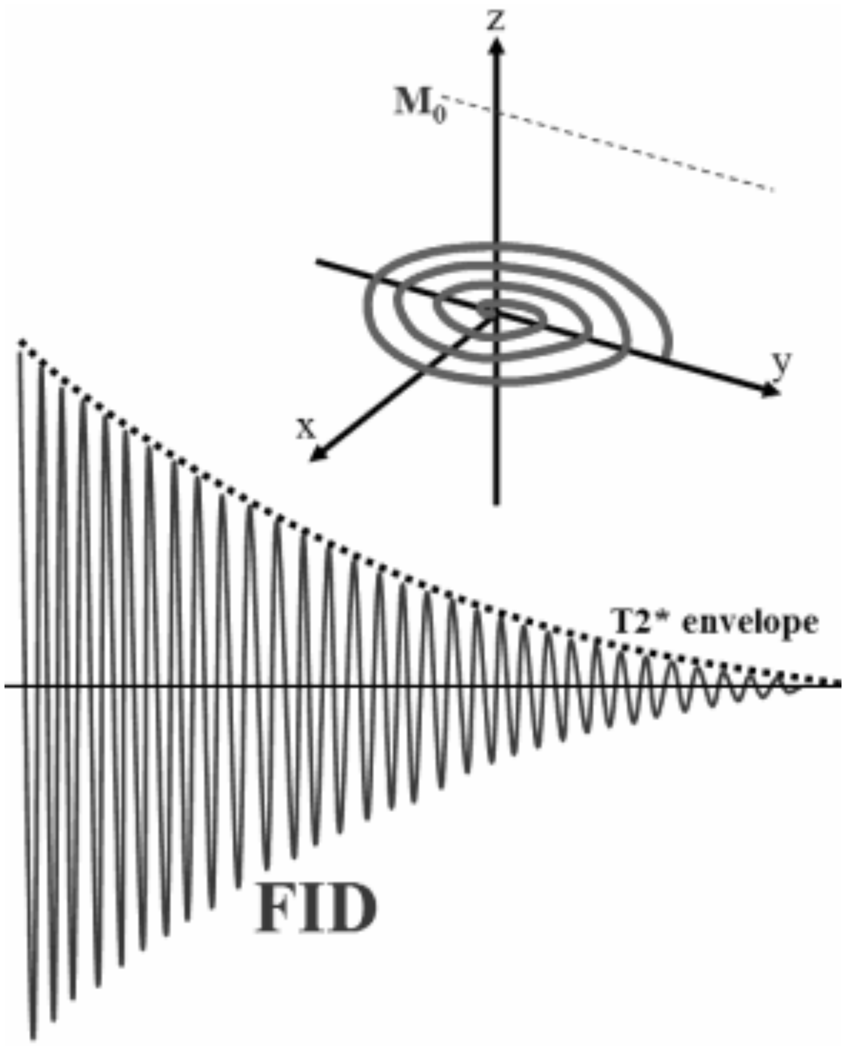
Relaxation

Relaxation

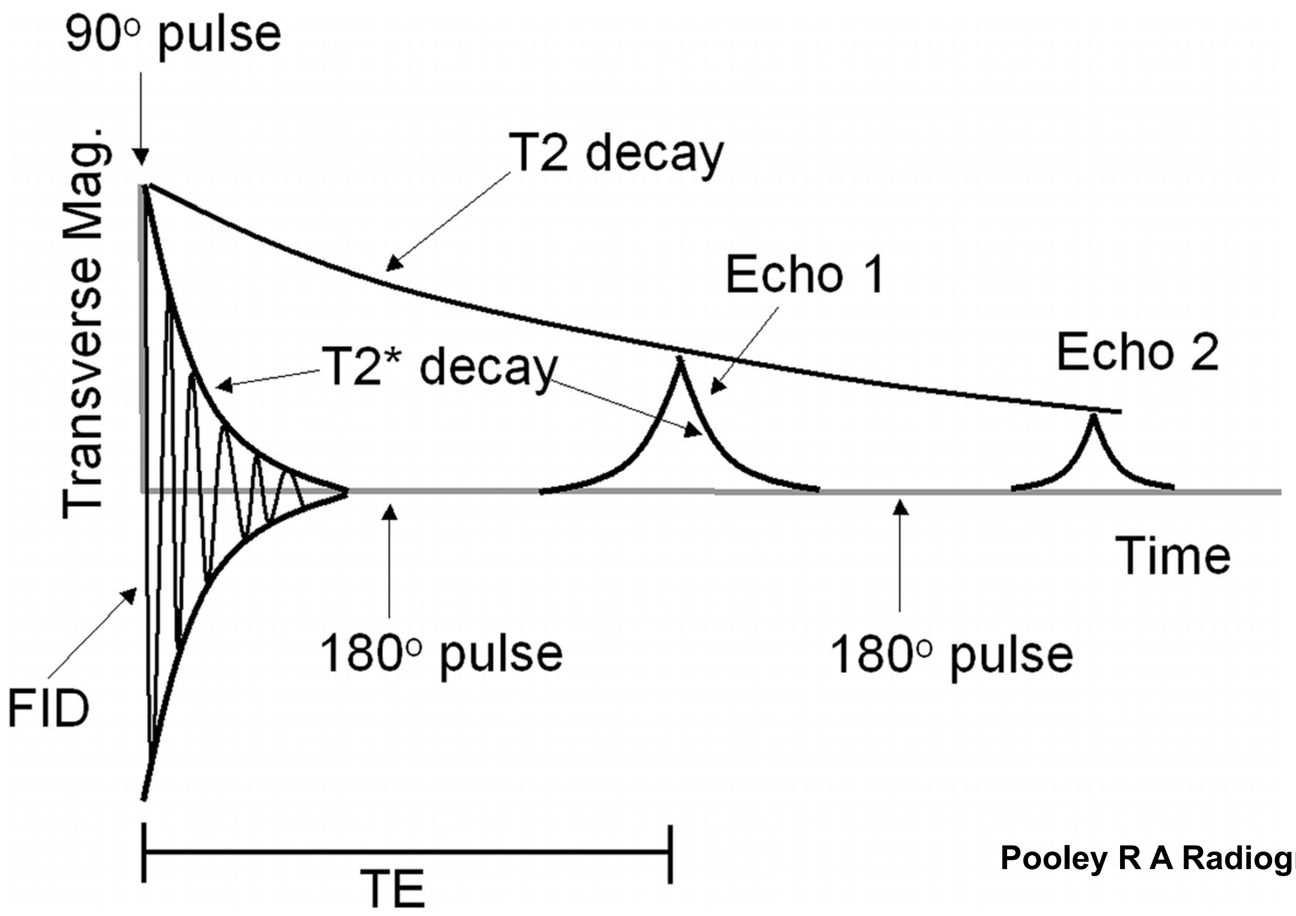
- After RF pulse tips M away from B_0 and is turned off, magnetization relaxes back to its equilibrium state.
- Two main **RELAXATION** processes present:
  - ***T*₂ relaxation** or T_2 decay
  - ***T*₁ relaxation** or T_1 recovery
- These processes occur simultaneously. However:
  - In liquids, $T_1 \approx T_2$
  - In solids, $T_1 >> T_2$

T_2 and T_2* Relaxation: Free Induction Decay



- After the RF pulse, M_{xy} decays due to:
  - SPIN-SPIN INTERACTIONS which cause de-phasing or loss of phase coherence → unrecoverable loss
  - STATIC MAGNETIC FIELD INHOMOGENEITIES present over the sample → recoverable loss
  - MAGNETIC SUSCEPTIBILITIES → recoverable loss
- ***T_2* relaxation*** is due to all causes above
- ***T_2* relaxation** is due to spin-spin relaxation (property of the spin system)

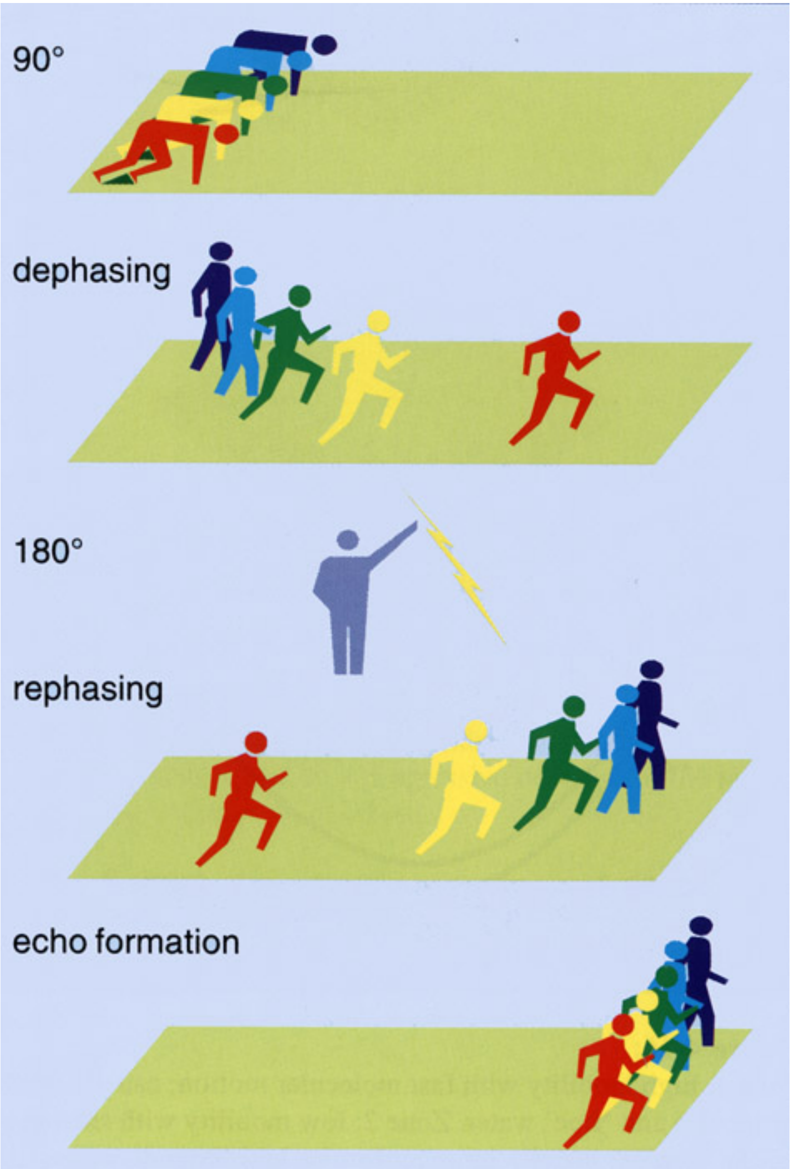
T_2 and T_2* Relaxation: Spin-Echo Train



Pooley R A Radiographics 2005;25:1087-1099

- Spin-echo envelope decays with T_2 **RELAXATION** time constant
- The width of each echo is related to T_2* **RELAXATION** time constant

A Cartoon View of Spin Echoes



At the time of the 90^0 pulse, are runners are lined up at the starting line.

After the 90^0 pulse, the fast runners separate from the slow runners.

At a certain time during the race, the runners are transposed.

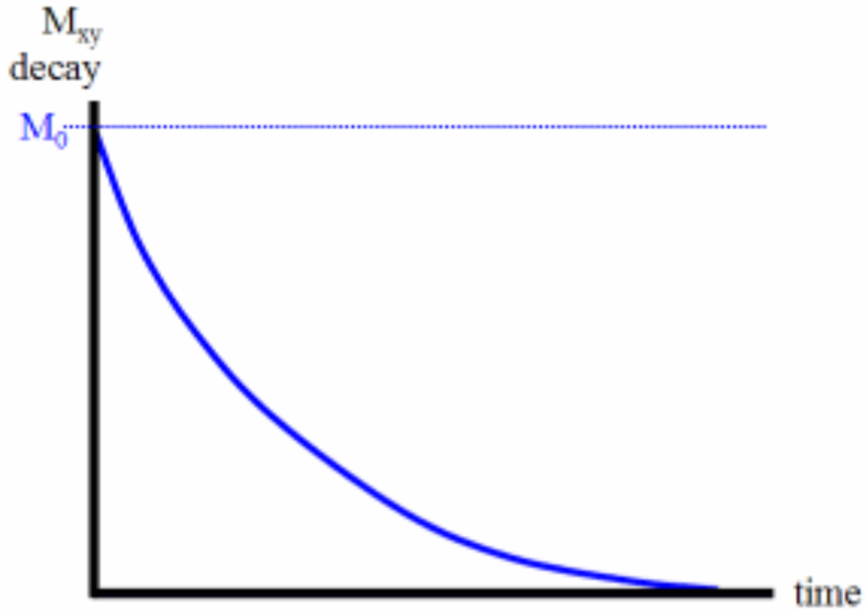
Now the fast runners are behind the slow ones, but the catch up.

T_2 Relaxation: Mathematical Description

$$\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T_2}$$

After a 90° pulse, $M_{xy}(0) = M_0$

$$M_{xy} = M_0 e^{-t/T_2}$$

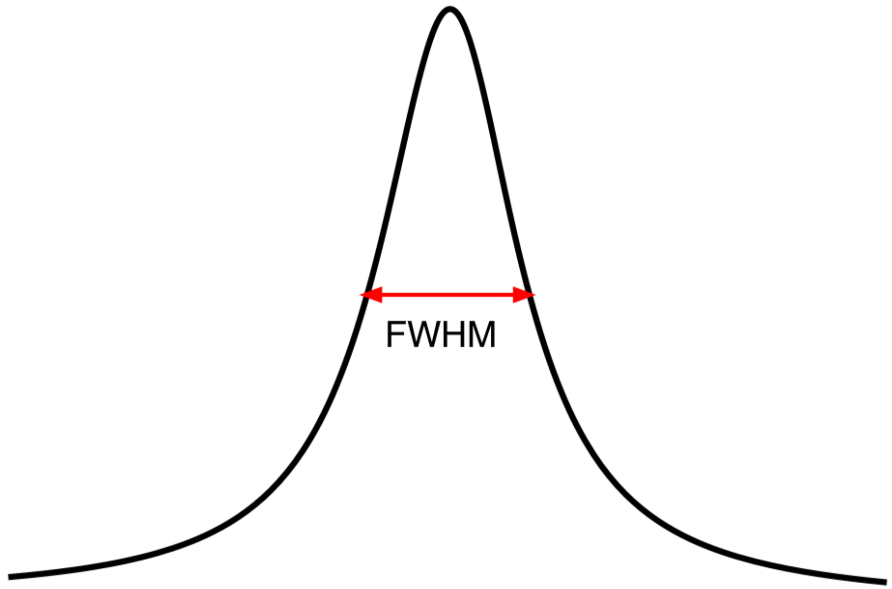


T_2* Relaxation: Mathematical Description

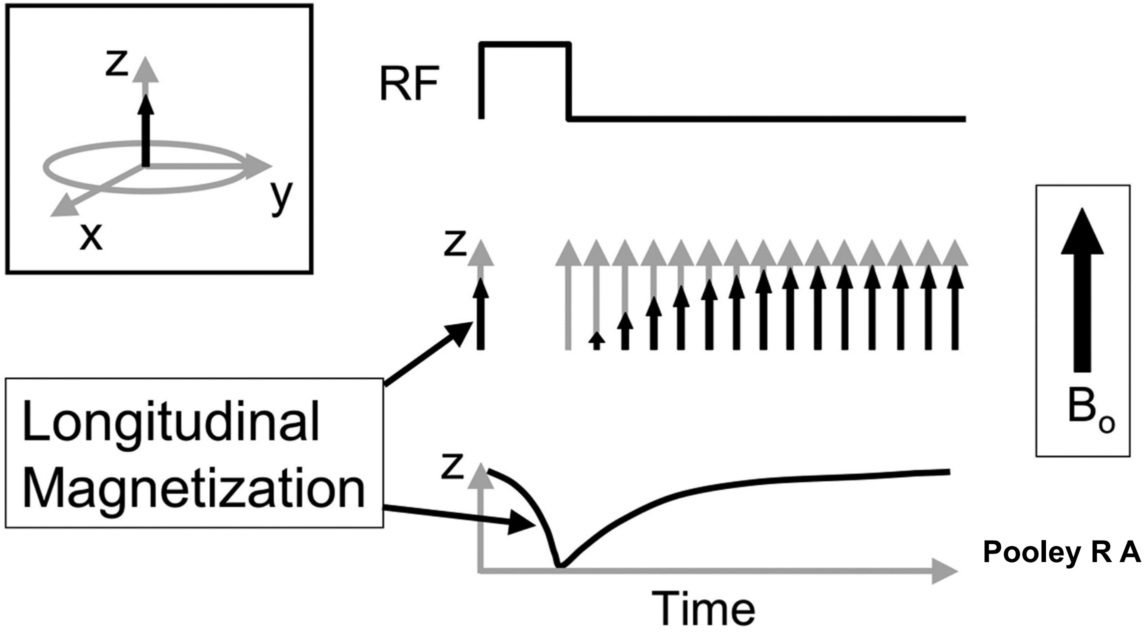
$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{\gamma}{2\pi}\Delta B$$

- T_2* is related to the width of the FT (Fourier Transform) of FID

$$FWHM = \frac{1}{\pi T_2^*}$$



T_1 Relaxation: Recovery of M_z



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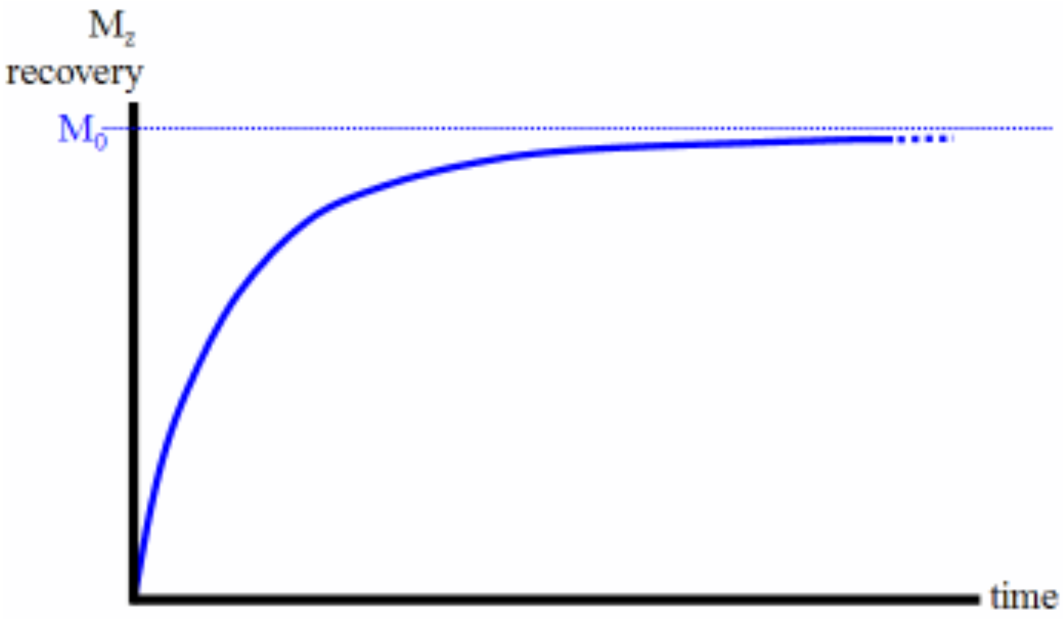
- After the RF pulse, M_z grows back to its equilibrium along *z*-axis
- This process is due to small field fluctuations resulting from moving spins
- The process is independent of T_2 relaxation

T_1 Relaxation: Mathematical Description

$$\frac{dM_z}{dt} = -\frac{M_z - M_0}{T_1}$$

After a 90° pulse, $M_z(0) = 0$

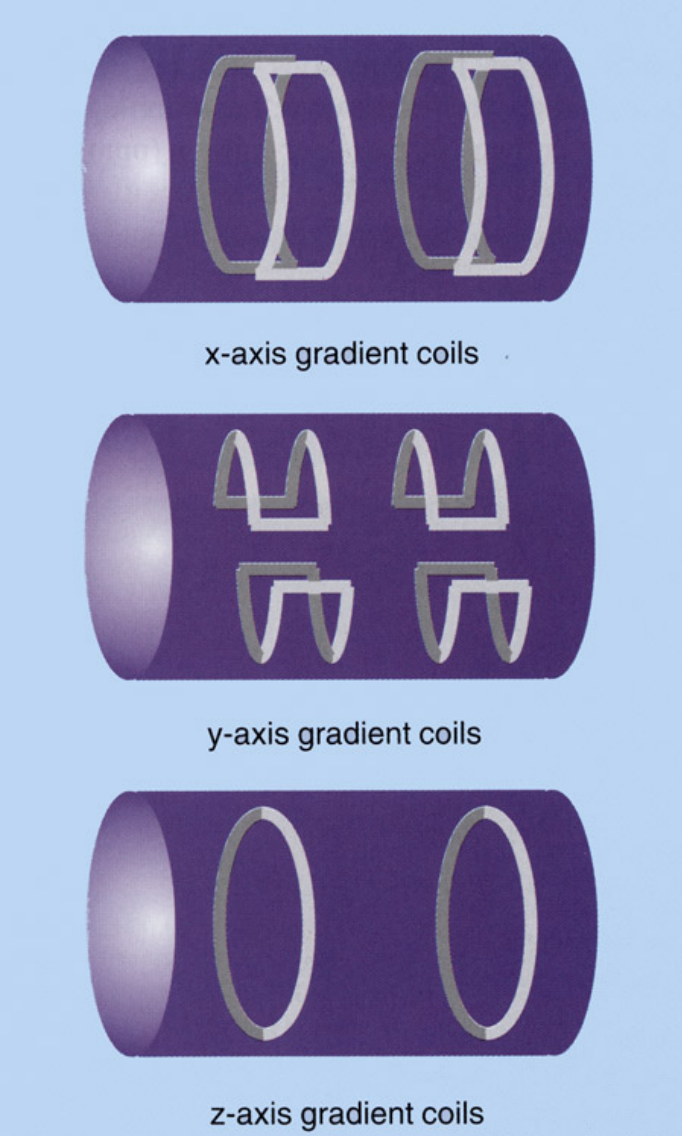
$$M_z = M_0\left(1 - e^{-t/T_1}\right)$$



But, which spins exactly do we image in MRI?

- Generally, in MRI, we detect the resonant precession of protons in Hydrogen (^{1}H).
- The Hydrogen atom is a component of water and fat → We image both water and fat (unless we suppress signal from fat)
- Body consists of 2/3 water → a lot of spins → large magnetization → large potential signal
- An RF coil placed near the body will detect the precession of this magnetization, however, this will be a net signal from the entire body (or coil sensitive region)
- **QUESTION: how do we distinguish signals from different parts of the body?**

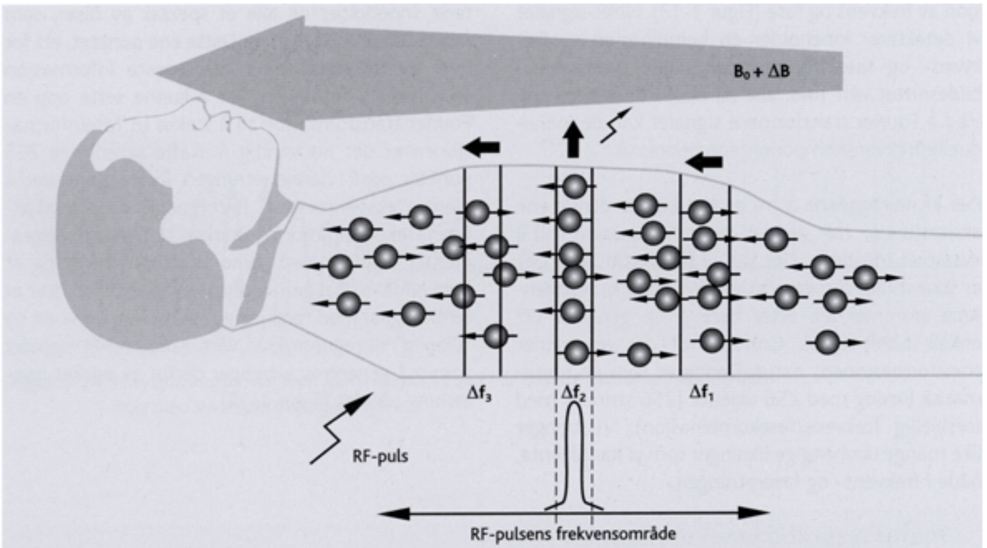
Imaging Gradients



- There are coils which produce the main magnetic field (B_0 = 7T in our case).
- In addition, there are several other coils making small, additional magnetic fields which vary linearly in space. These are called **gradient coils**.
- These small additional magnetic fields are present in X, Y and Z direction. Without them, we can not say where in the tissue the signals come from.

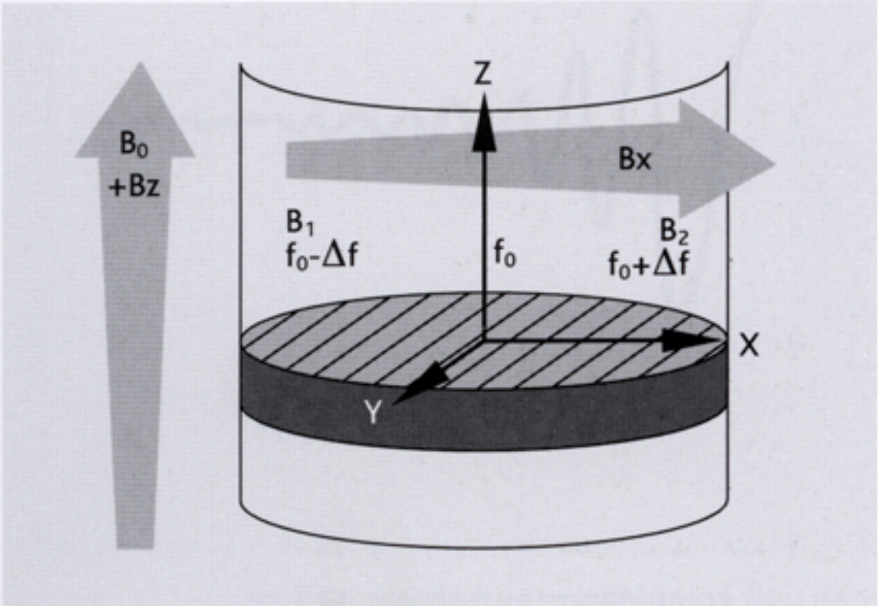
Slice Selection

- Slice selective gradients, G_z, are put ”on top” of the static magnetic field, in order to change the Larmor frequency along slice direction => *f*(z).
- A specially designed RF excitation pulse is applied at the same time as the gradient. This RF pulse contains a narrow range of RF frequencies, centered about the Larmor frequency.
- RF only excites the spins which are on-resonance with the RF pulse => **SLICE SELECTION**.
- You cut salami into small slices!



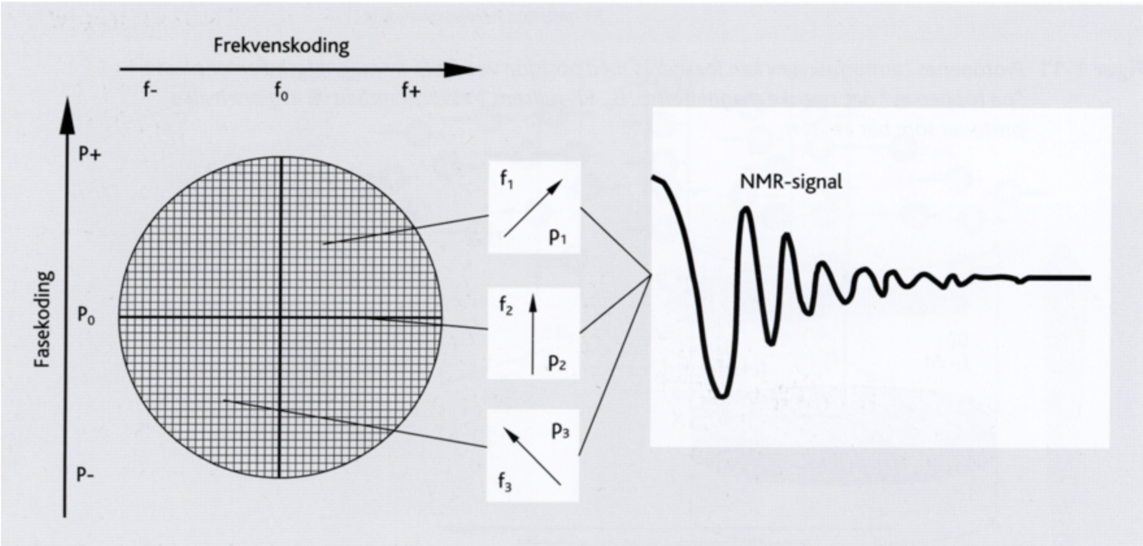
Frequency Encoding

- A constant gradient (usually along *x*-axis), G_{FE} or G_{read}, is applied continuously during readout of the MR signal.
- Signals which are sampled at different time-points during the readout will have different spatial frequency => **FREQUENCY ENCODING**
- Applying FT (Fourier Transform) along this direction will produce a 1D projection of the object
- You cut the salami slice into thin strips!



Phase Encoding

- A gradient (usually along *y*-axis), G_{PE}, is applied for a certain period of time after RF excitation and before signal readout/detection.
- Spins will dephase (acquire phase difference in relation to each other) depending on the position along the gradient. This happens because the Y gradient gives different spins different Larmor frequency.
- When the gradient is turned off, the frequency will go back to the original value, but the phase difference will be kept => **PHASE ENCODING.**
- This process has to be repeated for many different G_{PE} values in order to sample the entire range of spatial frequencies



Gradient Summary

- Z direction: Slice selection. Gradient ON at the same time as the RF excitation.
- X direction: Frequency encoding. Gradient ON at the same time as the readout.
- Y direction: Phase encoding. Gradient ON for a specific duration before readout.

Video 2: Introduction to k-space

Introductory NMR and MRI
with Paul Callaghan

Video 9
Part I: Introduction to k-space

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System components

- A powerful magnet: 7T(ours) or 1.5-3T (clinical)
  - The magnet is supraconductive: IT IS ALWAYS ON
- Gradient coils
- Radio transmitter and radio receiver
- Powerful computer to reconstruct images
- A storage utility (images take space)

Section Summary

- Spin angular momentum
- Resonant precession and Larmor frequency
- Magnetization
- Excitation
- Relaxation
- Imaging gradients
- Hardware