Basics of CMR: How Does It Work?

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Why MRI?

- The principle advantage of MRI is its **excellent contrast resolution**.
- By manipulating the MR parameters one can optimize pulse sequences for different pathologies.
- Another advantage of MRI is the possibility to make images in every imaginable plane.

Hardware – Magnets

- MRI scanners come in many varieties.

- Magnet types
  - Permanent magnets
  - Resistive magnets

  } Usually Very low field strength ~ 0.3T
  - Superconducting magnets – most commonly used

Hardware – Radio Frequency coils

- RF coils are needed to transmit and receive radio-frequency waves used in MRI scanners.
- RF coils are one of the most important components that affect image quality.
- Current MRI scanners have a range of RF coils suitable to acquire images of all body parts.
- There are two types of RF coils:
  - Volume coils
  - Surface coils

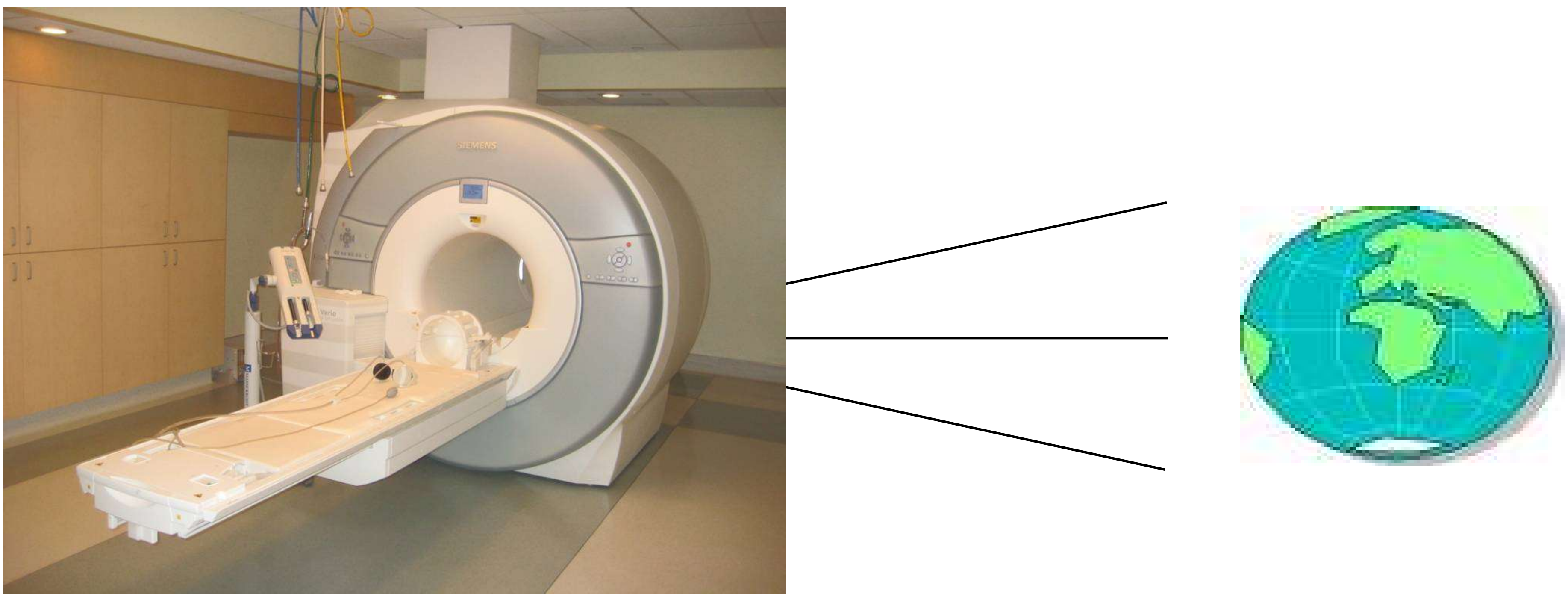
Lets Talk Physics!

- From physics lessons in high school you may remember that a **rotating electrical charge creates a magnetic field**.

- The earth is a giant charged rotating ball – which means it has a magnetic field (field strength of the earth is rather small: 30 μT at the poles and 70 μT at the equator – T is for Tesla, the unit we use to measure magnetic field strength)

Static magnetic field

Measured in Gauss or Tesla (1 T = 10,000 G)



1.5 T is 30,000 x the strength of earth's magnetic field

We too are magnets!

- Humans are made of tiny little balls, which rotate around their own axes and also have an electrical charge.
- Human body is built of 26 elements.
- Oxygen, hydrogen, carbon, nitrogen elements constitute 96 % of human body mass.
- Oxygen is 65 % of body mass; carbon is 18.5 %, hydrogen 9.5 %, nitrogen 3.2 %.

Nuclei with NMR properties

- Criteria: Must have ODD number of protons or ODD number of neutrons.

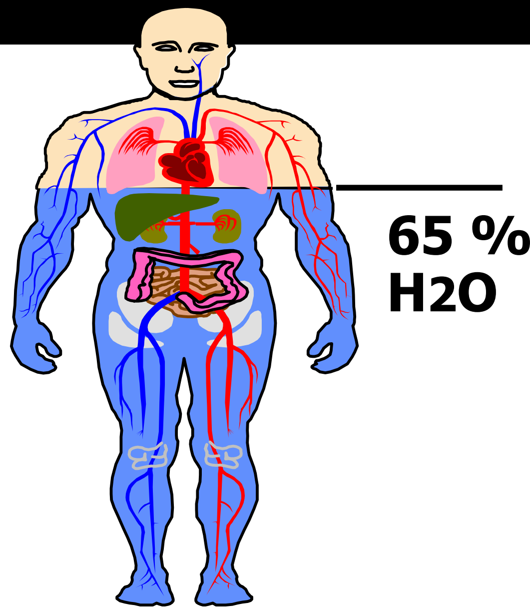
- Reason:
  - It is impossible to arrange these nuclei so that a zero net angular momentum is achieved.

  - Thus, these nuclei will display a magnetic moment and angular momentum necessary for NMR.

- Examples:
  - 1H, 13C, 19F, 23N, and 31P

- Let us ignore all elements but Hydrogen.

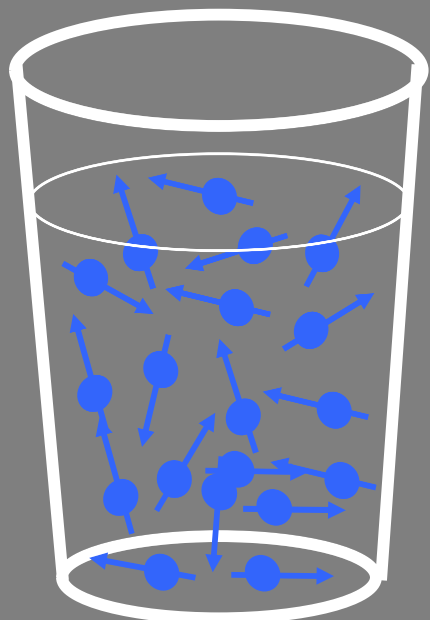
Why hydrogen?

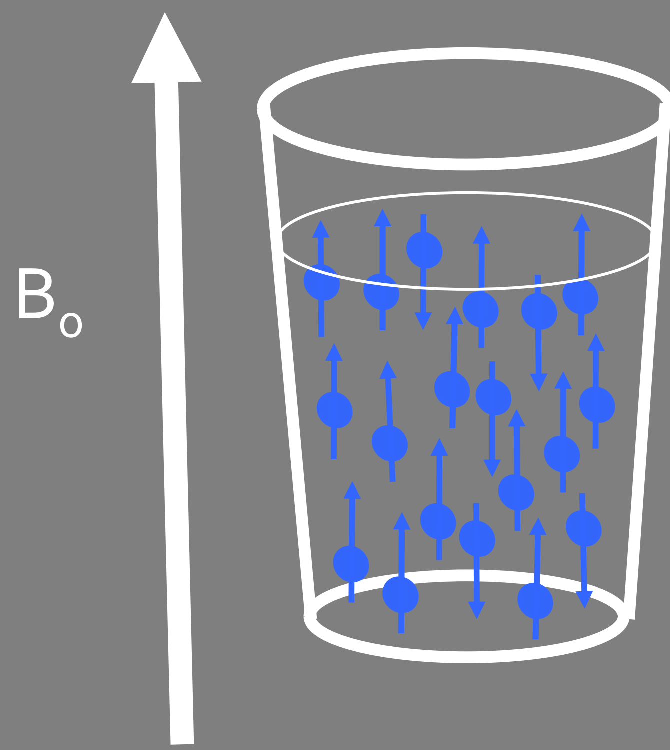


- Our body consists of 65% water (H_2O).
- 4.7×10^{27} Hydrogen atoms in adult (~70 kg).
- Simplest element with one proton.
- Proton is not only positively charged, but also has magnetic spin (wobble)!
- MRI utilizes this magnetic spin property of protons of hydrogen to obtain images!
- We are magnets!!

Randomly oriented protons

Protons aligned with a strong magnetic field

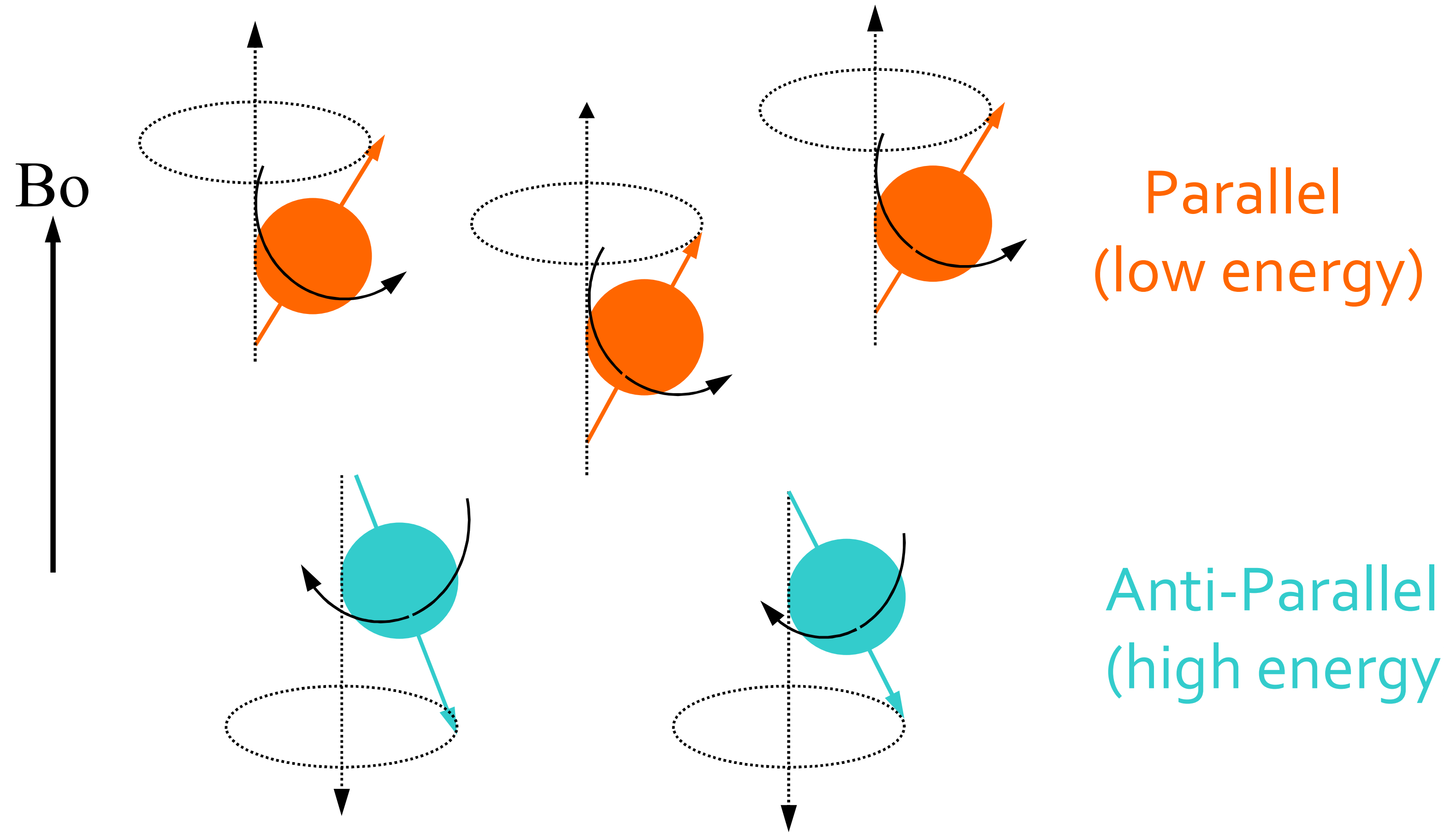




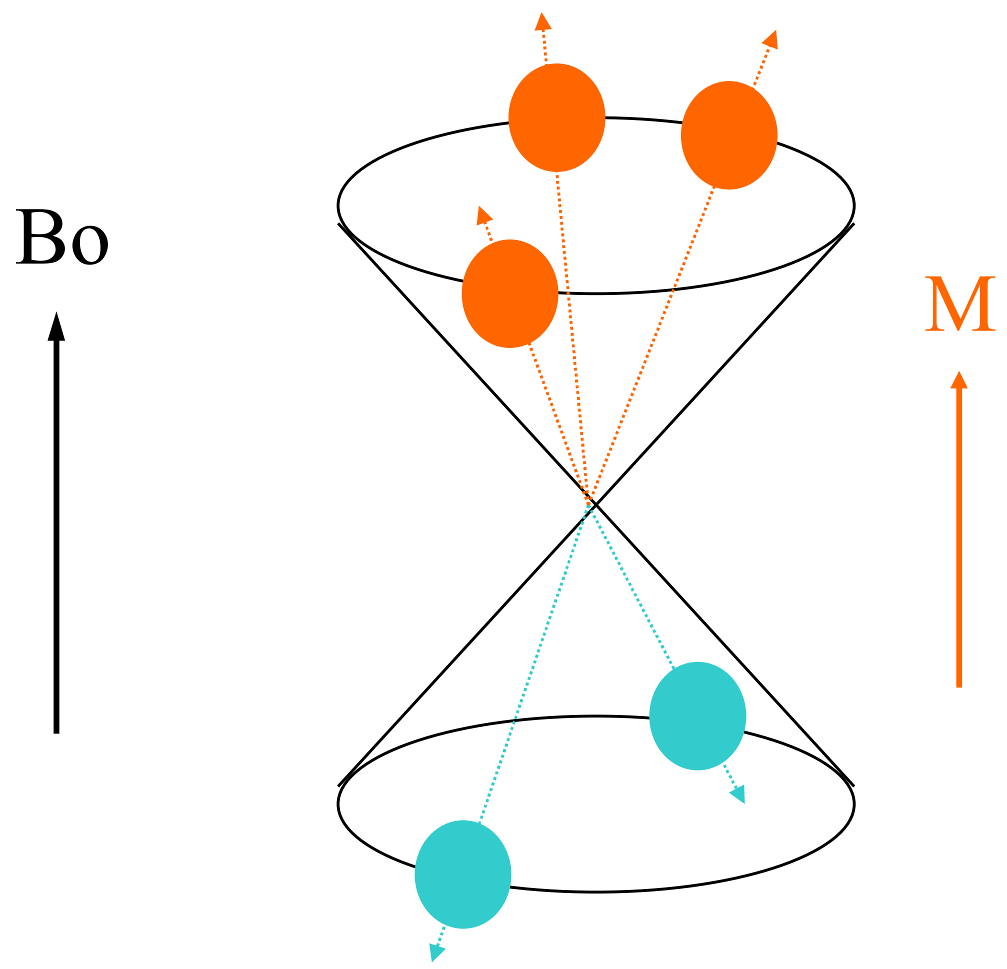
net magnetic moment is *zero*

net magnetic moment is *positive*

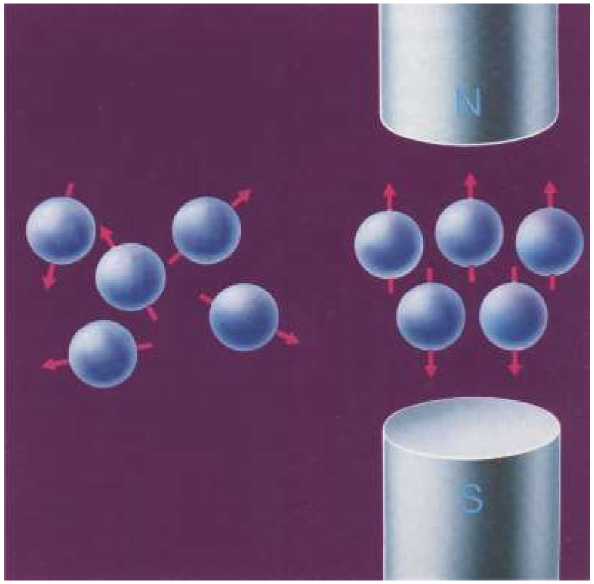
Protons in a Magnetic Field



Net Magnetization



Proton alignment

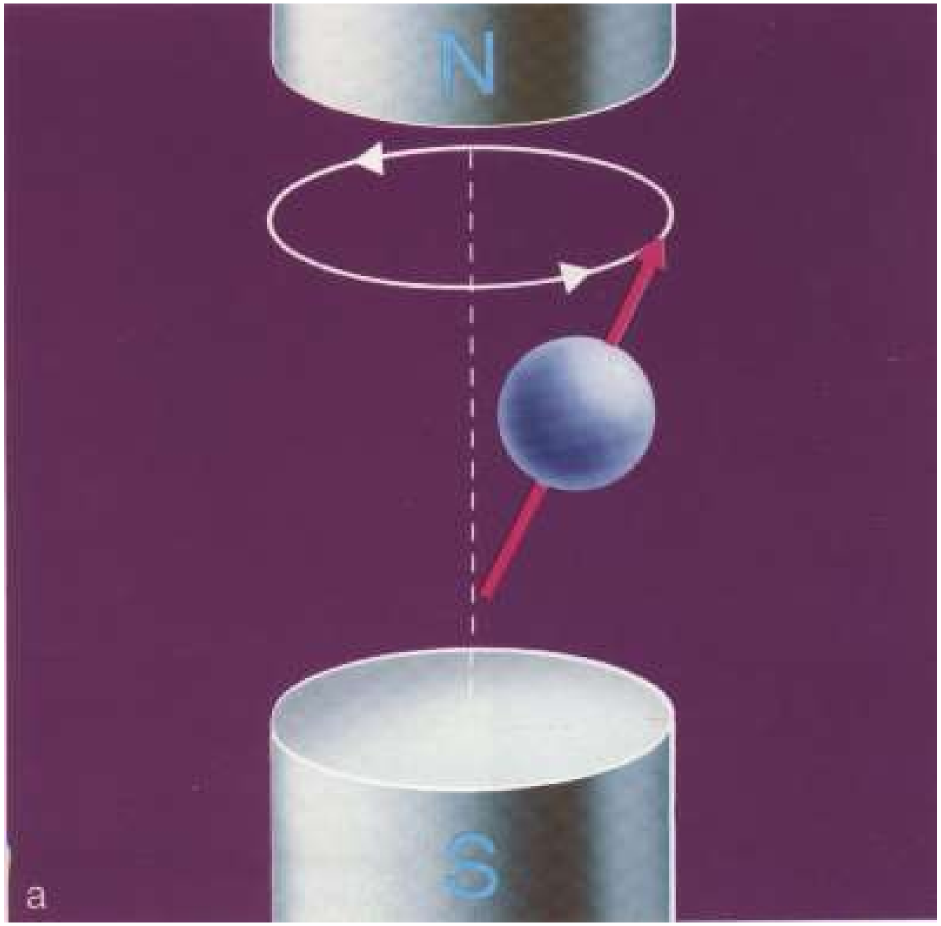


- *Analogy:* Like walking on feet require less energy than on hand, parallel state is preferred to anti-parallel
- The excess amount of protons aligned parallel within a 0.5T field is only 3 per million (3 parts per million); thus 9 ppm for a 1.5T.

Small ppm yet makes difference!!

- Assume a voxel is 2 x 2 x 5 mm = 0.02 ml
- Avogadro's Number says that there are 6.02×10^{23} molecules per mole.
- 1 mole of water weighs 18 grams ($O^{16} + 2H^{1}$), has 2 moles of Hydrogen and fills 18 ml, so............
- 1 voxel of water has $2 \times 6.02 \times 10^{23} \times 0.02 / 18 = 1.338 \times 10^{21}$ total protons
- The total number of excess protons = $1.338 \times 10^{21} \times 9/(2 \times 10^{6})$= **$6.02 \times 10^{15}$ or 6 million billion protons!!!**

Precession



Proton moves in like spinning top in two axis wobbling motion called **precession**.

Precession frequency

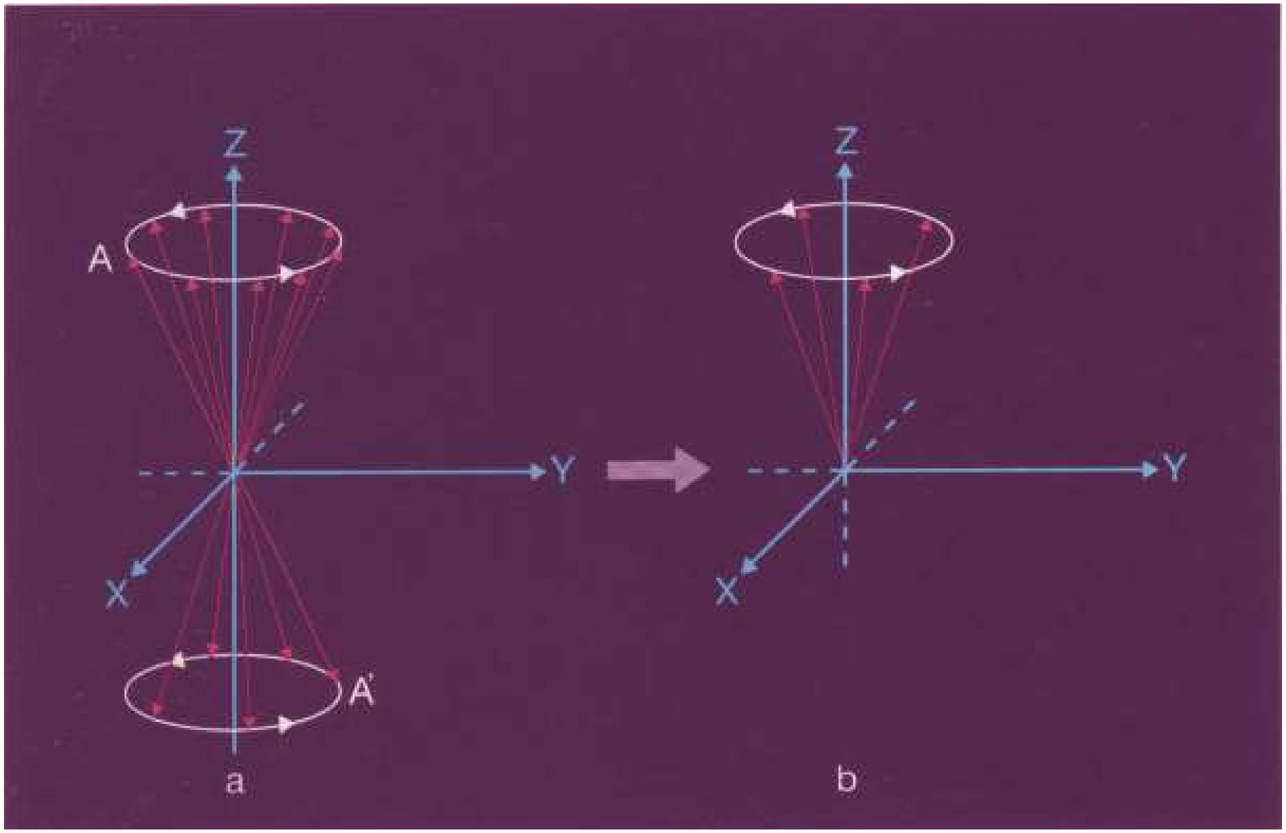
- Precession frequency is dependent on strength of external magnet field.
- It is determined by Larmor Equation: $\omega = \gamma B_0$
  - **ω (omega)** is precession frequency in Hertz (Hz)
  - **γ (gamma)** is gyro-magnetic ratio, for proton is 42.5 MHz/Tesla
  - **Bo** is magnetic field strength in Tesla
- Larmor frequency is needed to calculate the operating frequency of the MRI system. A 1.5 Tesla for example has a Larmor or precessional frequency of: 42.57 x 1.5 = 63.855 MHz.
- The stronger the external magnetic field, the higher the precession frequency.

Enough with PROTONS, let’s talk IMAGING!!

How to obtain an MRI image?

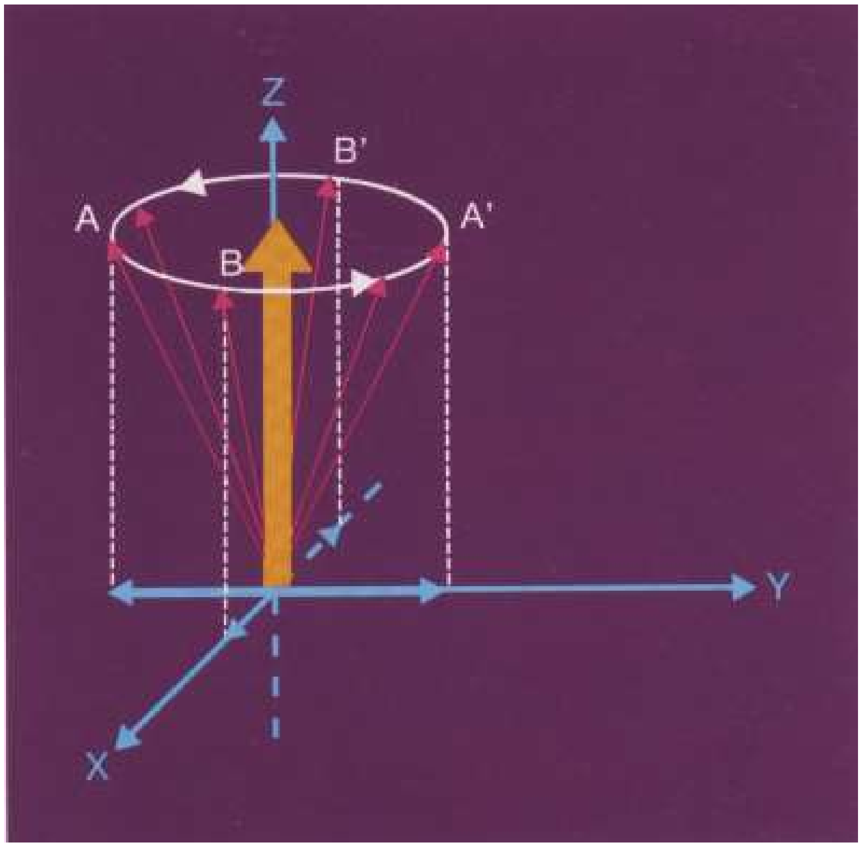
- Patient is put in a magnet (**ALIGNMENT**)
- RF signal is sent (**EXCITATION**)
- RF signal is switched off (**RELAXATION**)
- Patient emits a signal (**ACQUISITION**)
- Reconstruction of image (**COMPUTATION** and **DISPLAY**)

Alignment -- Net magnetic force



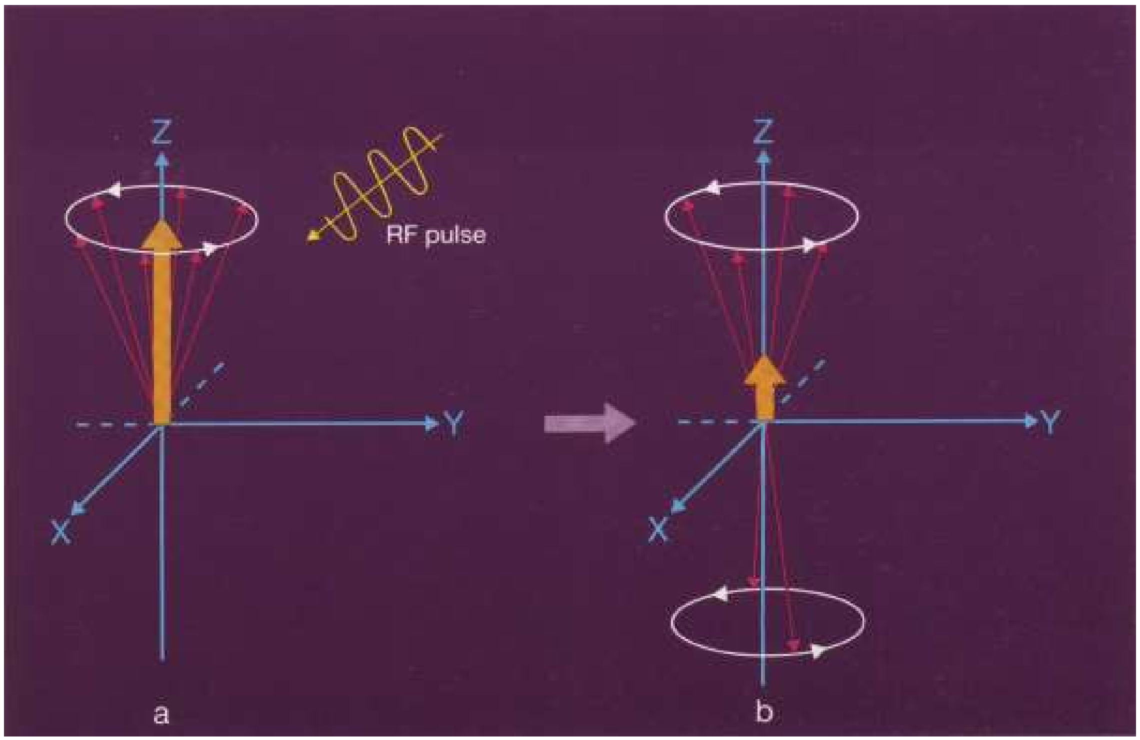
Proton pointing in opposite direction cancels each others magnetic effect in respective direction

Net magnetic force



As there are more protons aligned parallel to the external magnetic filed, there is a net magnetic movement aligned with or **longitudinal** to the external magnetic field.

Excitation: Radio Frequency pulse



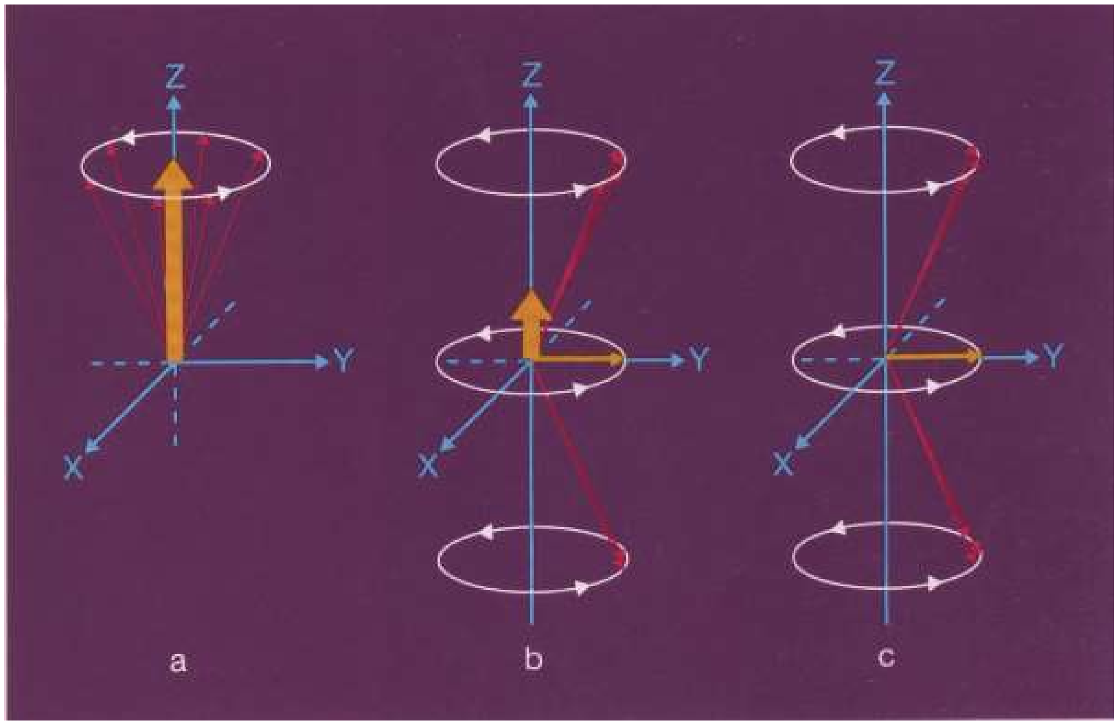
The RF pulse exchange energy with the protons:

- Some of them are lifted to a higher level of energy, pointing down.
- In effect the magnetization along the z-axis decreases, as the protons which point down neutralize the same number of proton pointing up.

Excitation

- Let us assume we work with a 1.5 T system.
- The center or operating frequency for the system is 63.855 MHz.
- In order to manipulate the net magnetization, we will therefore have to send a Radio Frequency (RF) pulse with a frequency that matches the center frequency of the system: 63.855 MHz.
  - This is where the "Resonance" in the name Magnetic Resonance Imaging comes from.
- Only protons that spin with the same frequency as the RF pulse will respond.
- If we would send an RF pulse with a different frequency, let's say 59 MHz, nothing would happen.

RF pulse on proton

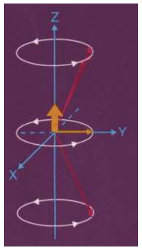


a. In a strong external magnetic field, a new magnetic vector along the external field is established

b. Sending in an RF pulse causes a new **transversal** magnetization while longitudinal magnetization decreases

c. Depending on the RF pulse, longitudinal magnetization may even totally disappear

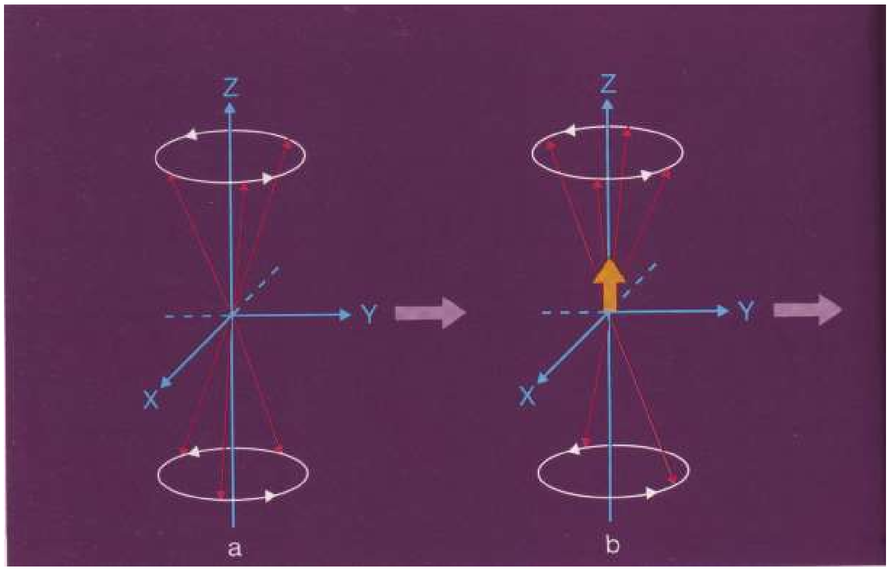
Relaxation

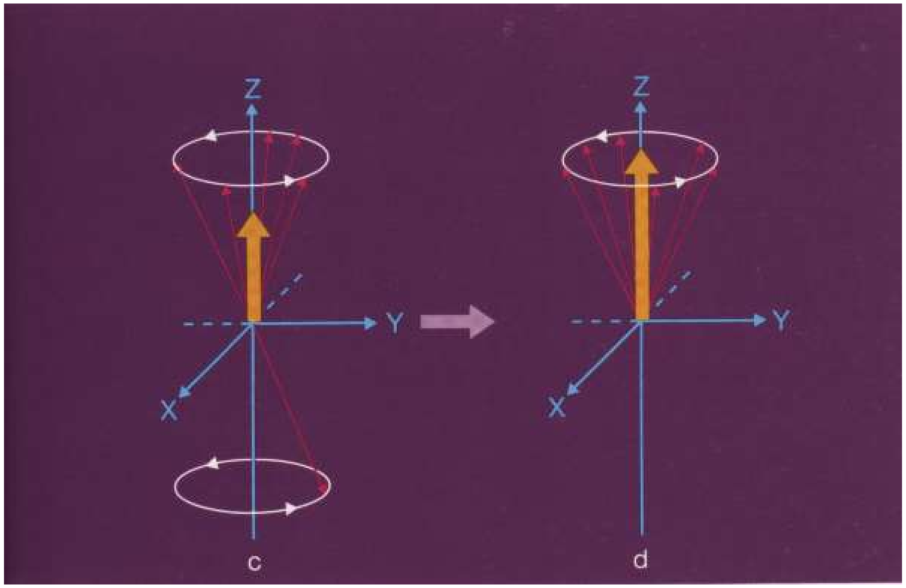


- Now it becomes interesting. We rotated the net magnetization 90º into the X-Y plane. We could also say that we lifted the protons into a higher energy state, same thing.
- This happened because the protons absorbed energy from the RF pulse.
- This is a situation that the protons do not like.
- Remember

- Now something happens that is referred to as Relaxation. The relaxation process can be divided into two parts: T1 and T2 relaxation.

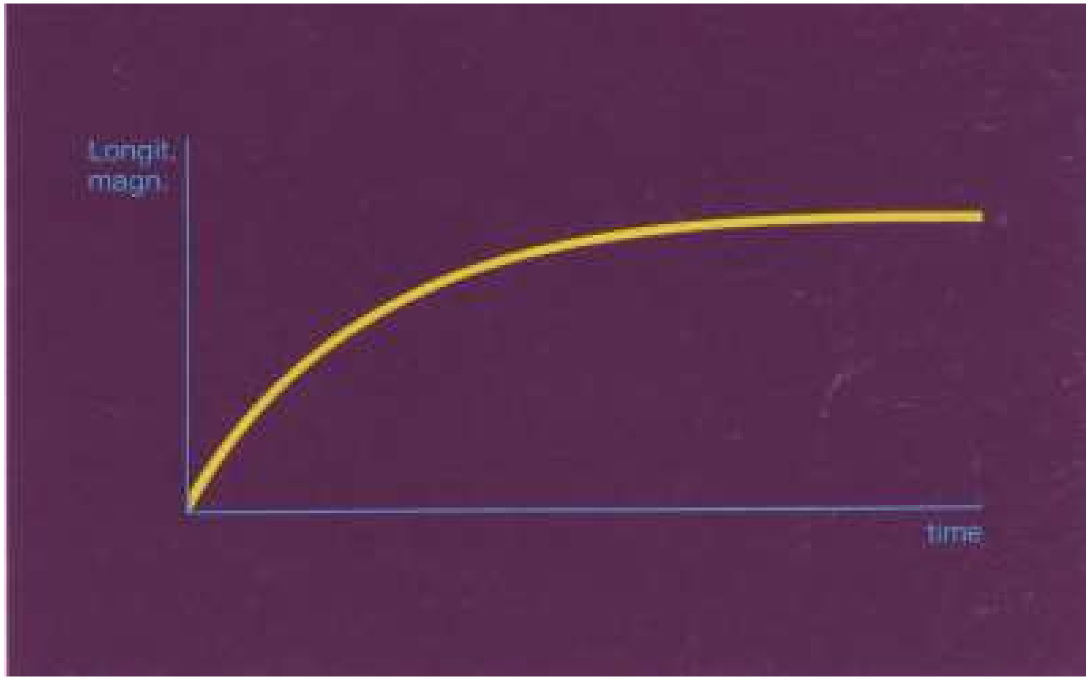
Relaxation: Longitudinal relaxation





- After the RF pulse is switched off, protons go back from their higher to the lower state of energy.
- Longitudinal magnetization increases and grows back to its original value.
- Energy of RF pulse is handed over to the surrounding lattice.
- This process is called longitudinal relaxation (described by a **time constant T1**) or spin-lattice relaxation

T1 Curve

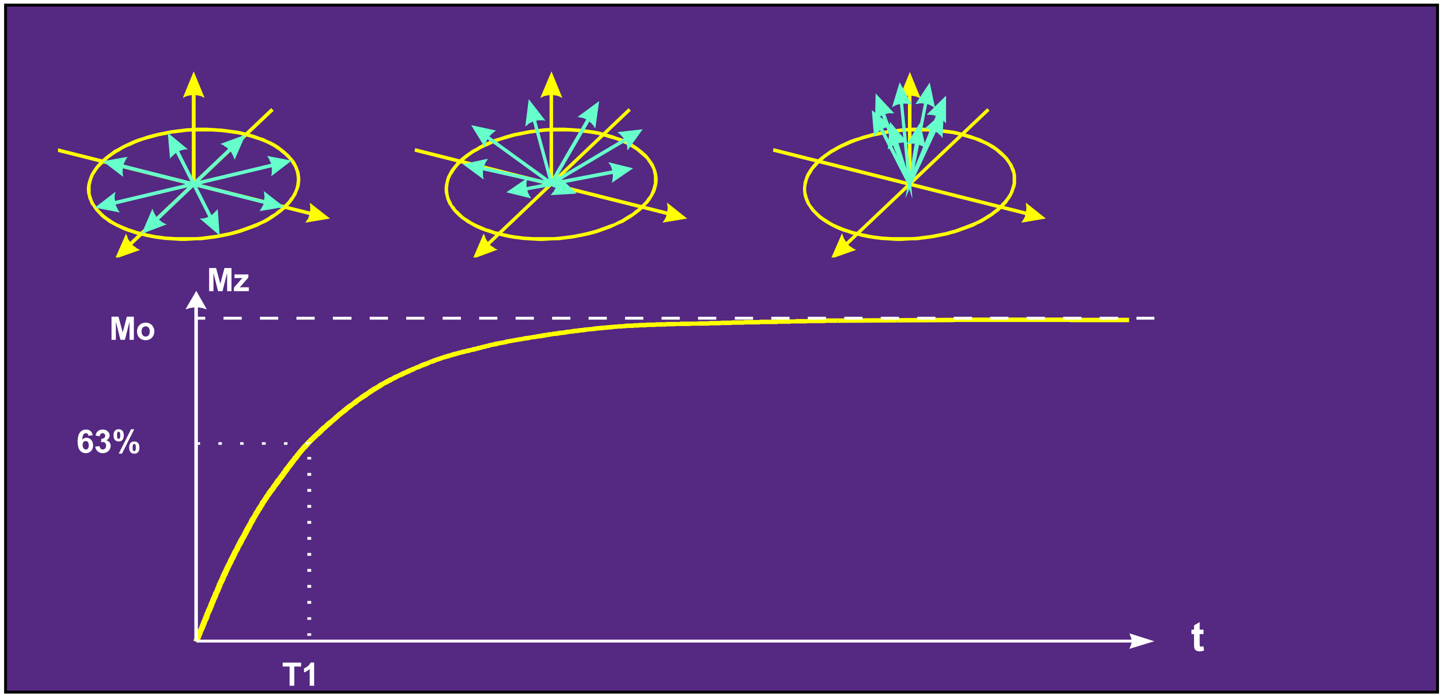


Recovery of longitudinal relaxation vs. time curve

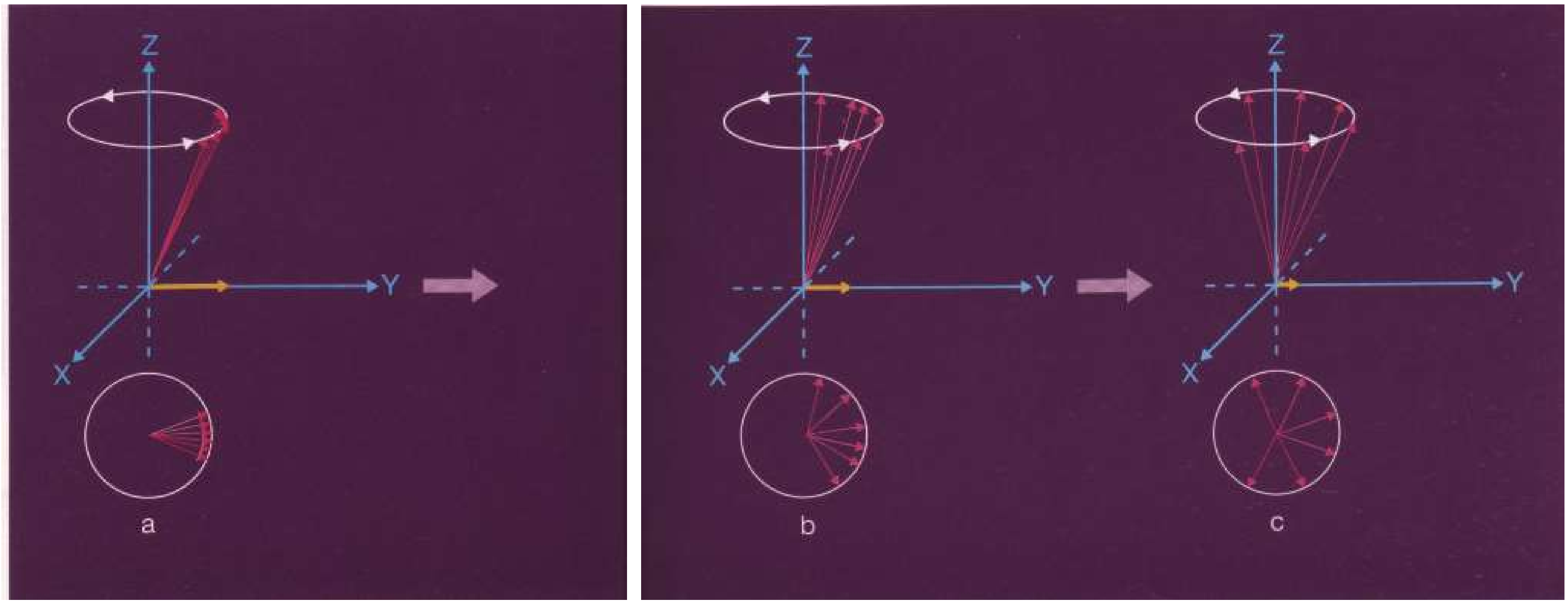
- **T1 is <u>the time it takes for the longitudinal magnetization to recover</u>,** to go back to its original value.
- This actually is not the exact time it takes but a time constant describing how fast this process goes.
- *<u>Analogy:</u>* It is like taking time for one round at a car race. The time gives you an idea of how long the race may take, but not the exact time.

T1 time

- It is difficult to pinpoint the end of the relaxation time exactly. Thus, T1 is not defined as the time when relaxation is completed.
- Instead T1 is defined as the time when about 63% of the original longitudinal magnetization is reached.
- 1/T1 is also called longitudinal relaxation rate (R1)

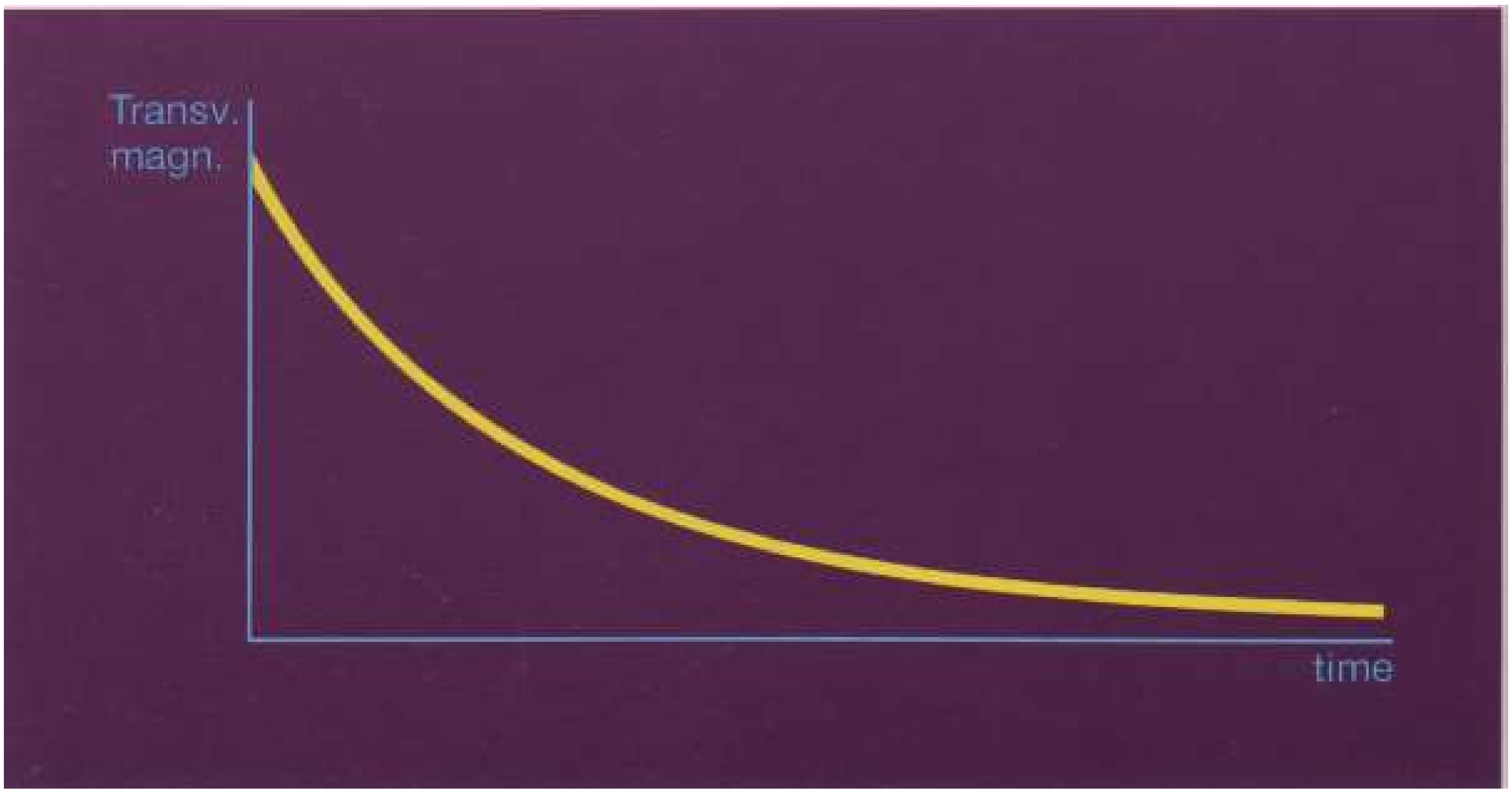


Transverse relaxation



- After the RF pulse is switched off, protons lose phase coherence, they get out of step.
- Transverse magnetization decreases and disappears.
- This transversal relaxation is described by a **time constants T2**.

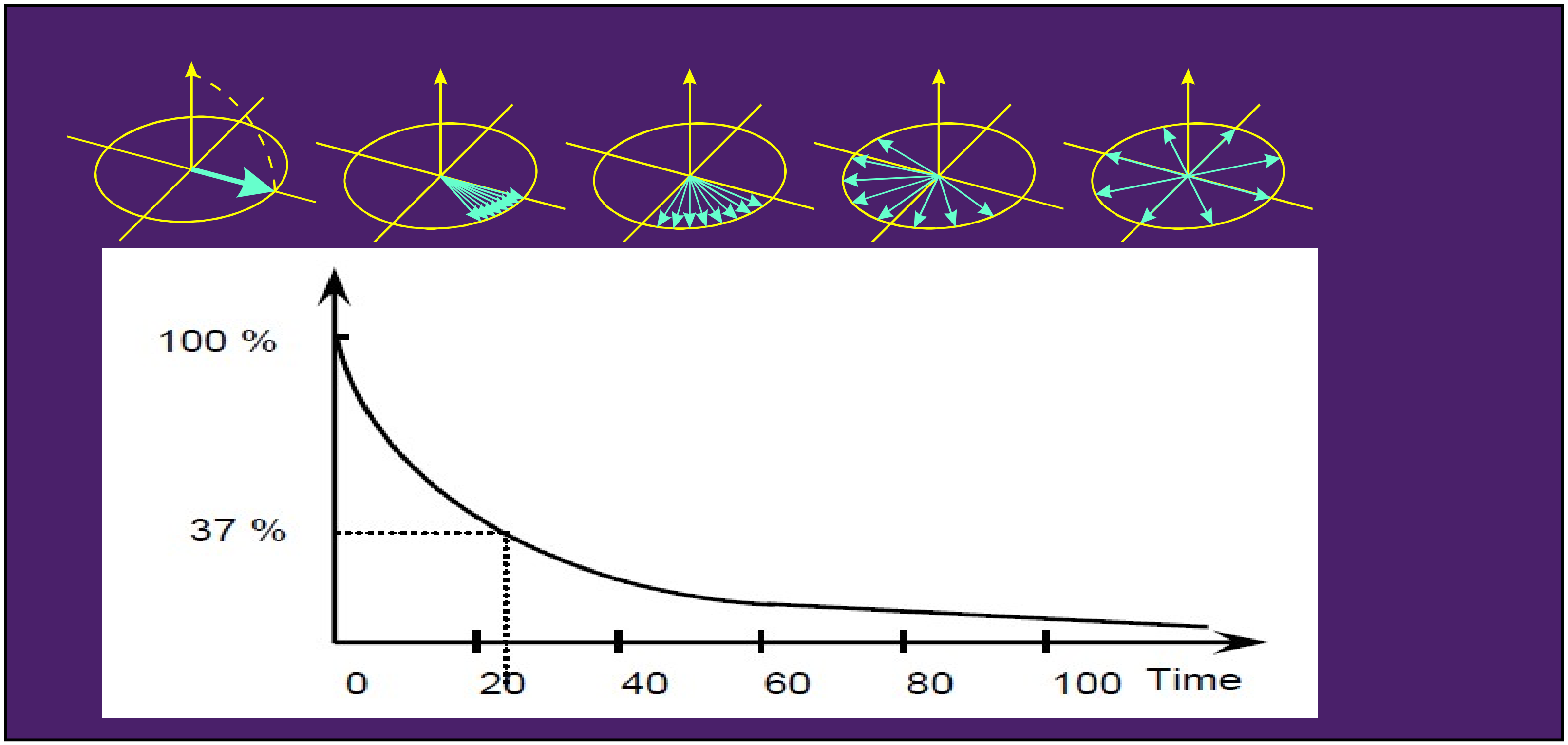
T2 Curve



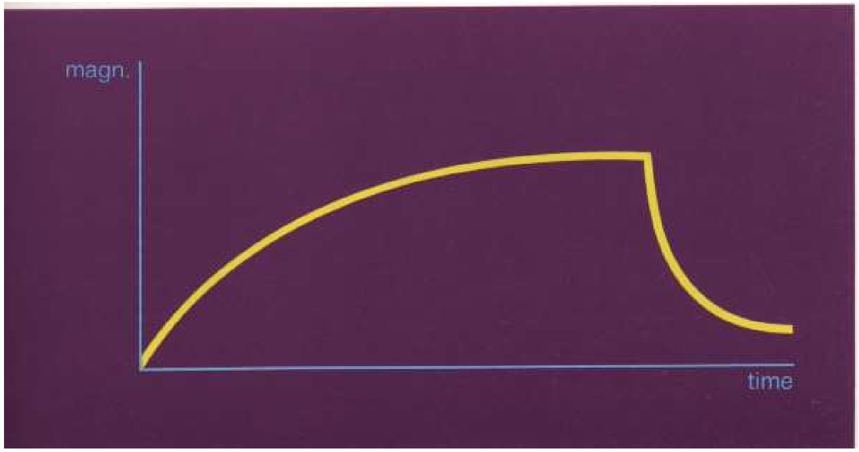
Transverse magnetization vs. time after RF pulse is switched off

Relaxation time

- **<u>T2 is the time when transverse magnetization decreases to 37% of the original value.</u>**
- 1/T2 transverse relaxation rate (R2)



T1 > T2

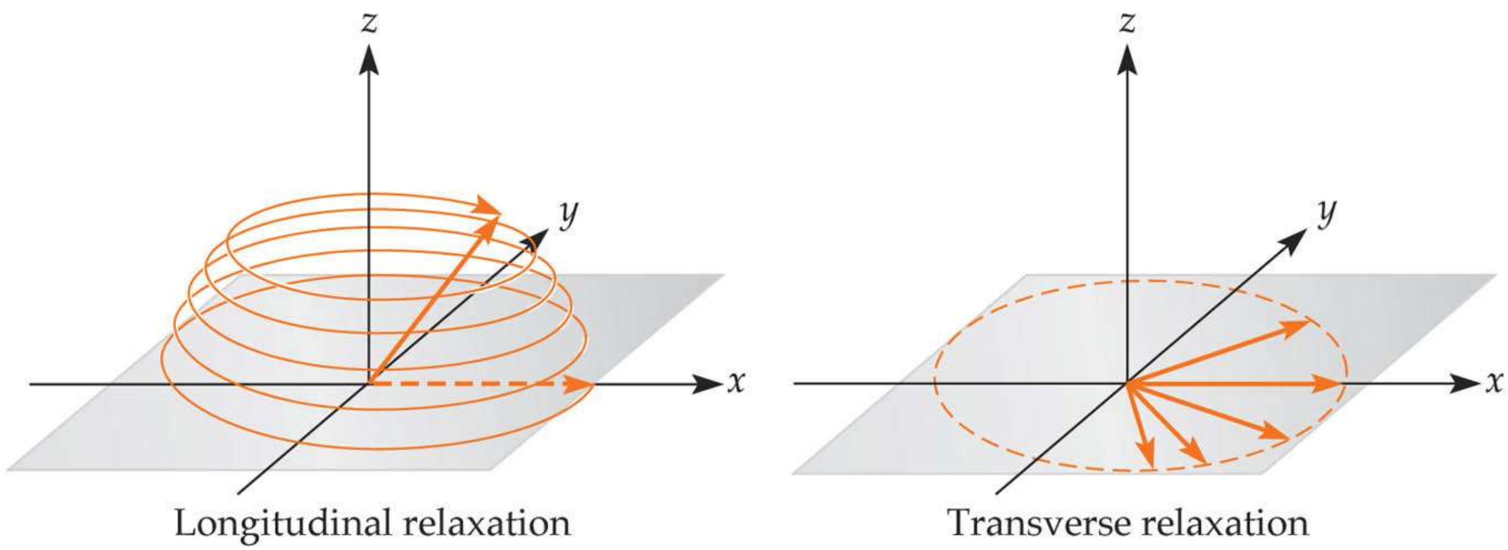


- Coupling of a T1 and T2-curve resembles a mountain with a slope
- **<u>T2 much faster than T1</u>** relaxation
  - T1- 300-2000 msec.
  - T2- 30-150 msec.
- *<u>Analogy</u>:* It takes longer to climb a mountain than to slide or jump down.

Liquids have long T1 & T2

Fat has short T1 & T2

One Last Time



Remember this:

- T_1 and T_2 relaxation are two independent processes, which happen simultaneously.
- T_1 happens along the z-axis; T_2 happens in the x-y plane.
- T_2 is much quicker than T_1

Acquisition

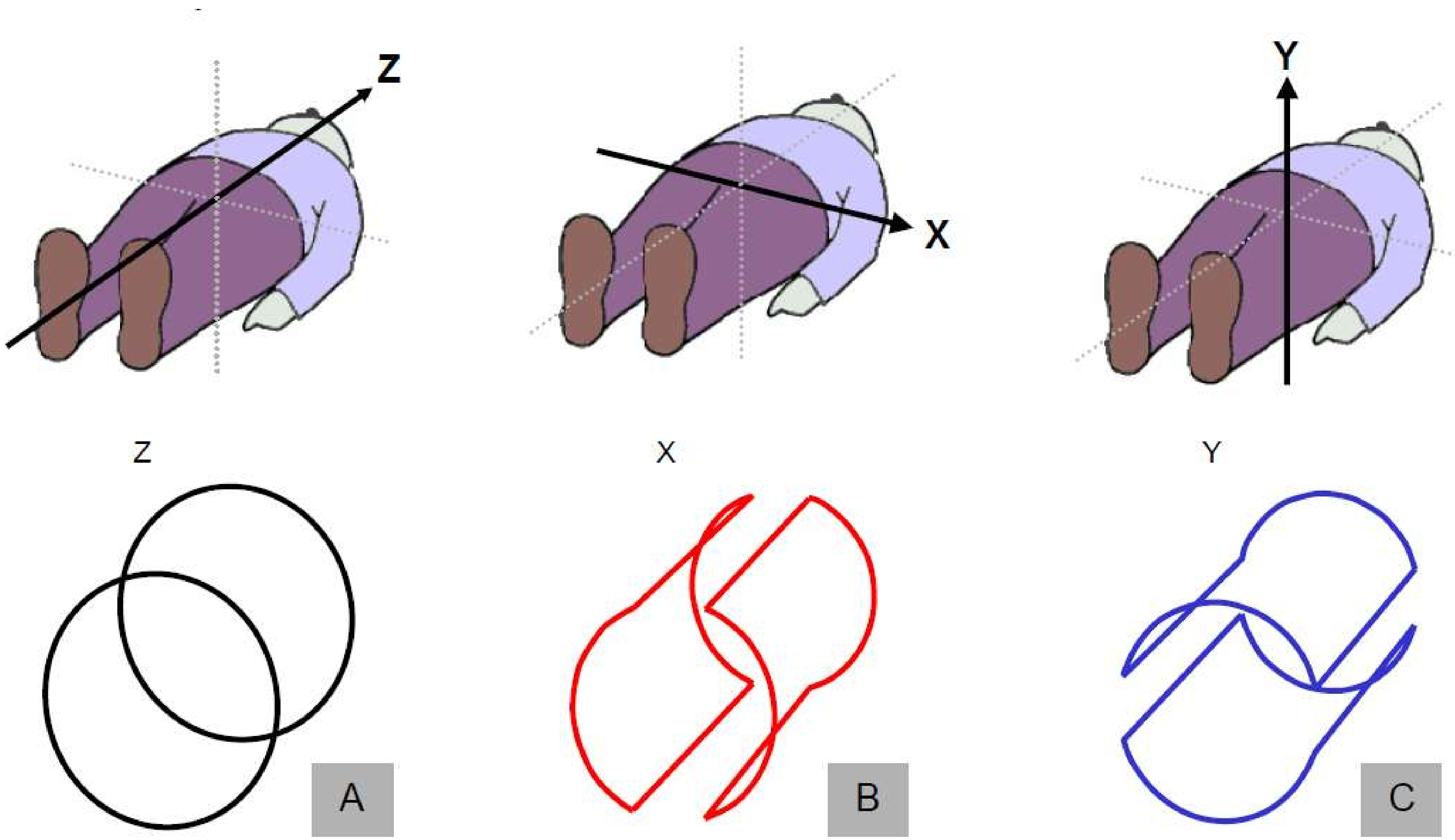
- During the relaxation processes the spins shed their excess energy, which they acquired from the 90º RF pulse, in the shape of radio frequency waves.
- In order to produce an image we need to pick up these waves before they disappear into space.
- This can be done with a **Receive coil.**
- The receive coil can be the same as the **Transmit coil** or a different one.
- The receive coil must be positioned at **right angles** to the main magnetic field (B_o).

Gradients: What and Why?

- Now if we assume we have a 100% homogeneous magnetic field (which it isn't), then all the protons in the body would spin at the Larmor frequency. This also means that all protons would return signal. How do we know whether the signal is coming from the head or from the foot? Well, we don't!!
- **A gradient is simply a deliberate change in the magnetic field**.
- Gradient coils are a set of wires in the magnet, which enable us to create additional magnetic fields, which are, in a way, superimposed on the main magnetic field $B_{o.}$
- Gradients are used in MRI to linearly modify the magnetic field from one point in space to another.

Gradients

Gradients are applied <u>along **an** axis</u> (that is G_x along the x-axis, G_y along the y-axis, G_z along the z-axis).



Effect of Gradient on Rate of Precession

- Each point has slightly different rate of precession & Larmor Frequency.

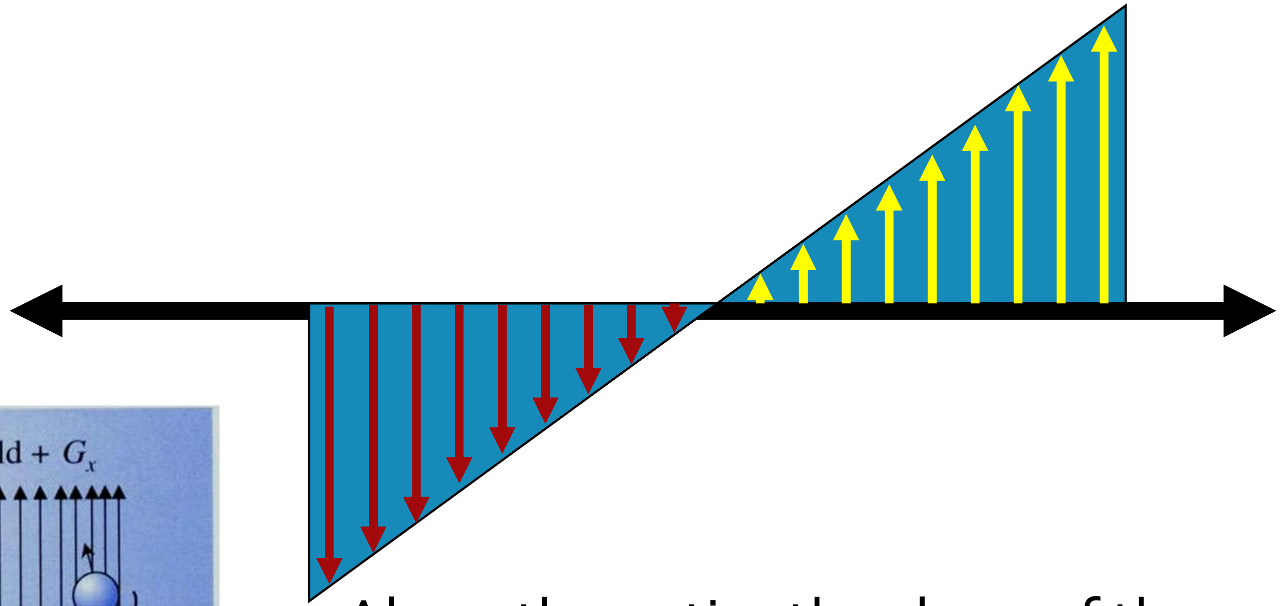
- Variety of signal released by protons returning to z-plane are used to determine the composition of exact location of each point.

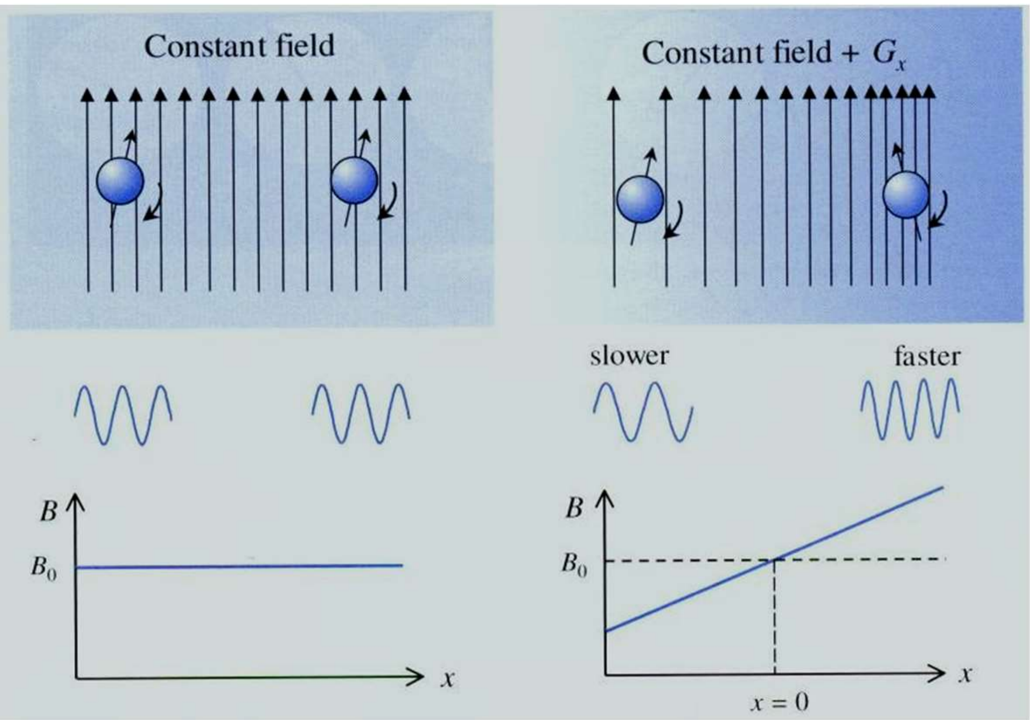
- **Loud Noise:** The magnetic field, which is generated, is very strong. Although the gradient coils are very tightly fixed, the forces exhibited by the gradient coil, are enough to make them vibrate, hence the noise.

Effect of Gradient on Rate of Precession

$$\omega = \gamma B$$

$$B = B_0 + B_1$$





Along the entire the slope of the gradient there is a different B_o field and consequently the protons spin at slightly different frequencies. Therefore, the protons in the head will spin slightly faster than the ones in the iso-centre. The reverse goes for the protons in the feet.

Slice selection

- When we put a patient in the magnet, all the protons, from head to toe, align with B_o. They spin at the Larmor frequency of 63.855 MHz.

- The **G_z -gradient** is switched on. This will generate an additional magnetic field in the z-direction, which is superimposed on B_o.

- There is a slightly stronger B_o field in the head as there is in the iso-centre of the magnet. A stronger B_o field means a higher Larmor frequency.

- Applying the right RF-pulse frequency allows you focus on a thin slice!

Phase encoding

- Encoding the phase
  - **G_y gradient** is switched on very briefly → an additional gradient magnetic field is created in the **Anterior-Posterior direction**.
  - The effect is that **the anterior protons will spin slightly faster than the posterior protons** .
  - Because of this difference, the protons do not spin In-Phase anymore.
  - When the G_y gradient is switched off, each proton within the slice spins with the same frequency BUT each has a different phase

Frequency encoding

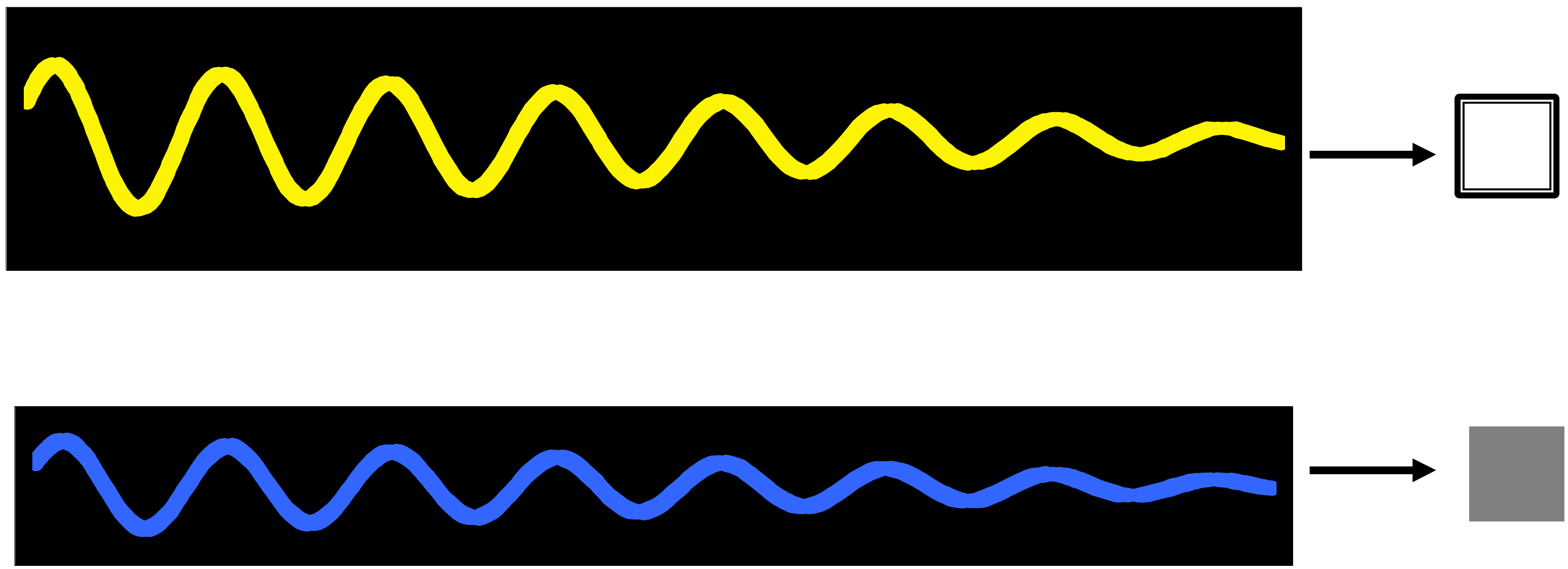
- Encoding the frequency
  - **G_x gradient** is switched on → an additional gradient magnetic field in the left – right direction is applied.
  - The protons **on the right hand side spin with a higher frequency than the ones on the left**.
  - They will accumulate an additional phase shift because of the different frequency, but – and this is very important - the already acquired phase difference, generated by the phase encoding gradient in the previous step, will remain.
  - Now it is possible to determine whether the signal comes from the left, centre or right hand side of the slice.

Gradient Summary

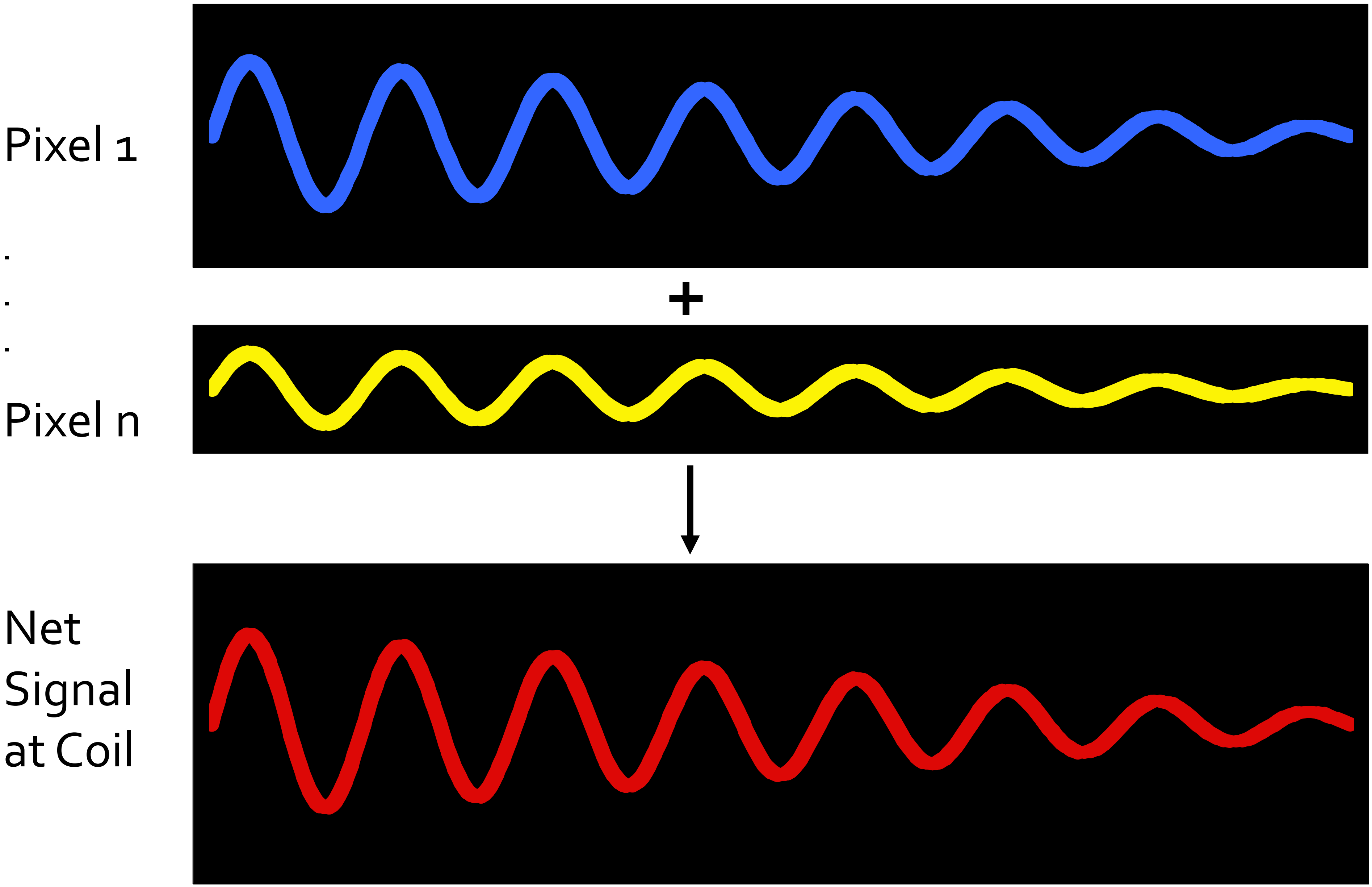
- The **G_z gradient** selected an **axial slice**.
- The **G_y gradient** created rows with **different phases.**
- The **G_x gradient** created columns with **different frequencies.**

Computation: From Proton Signal to Pixel Intensities

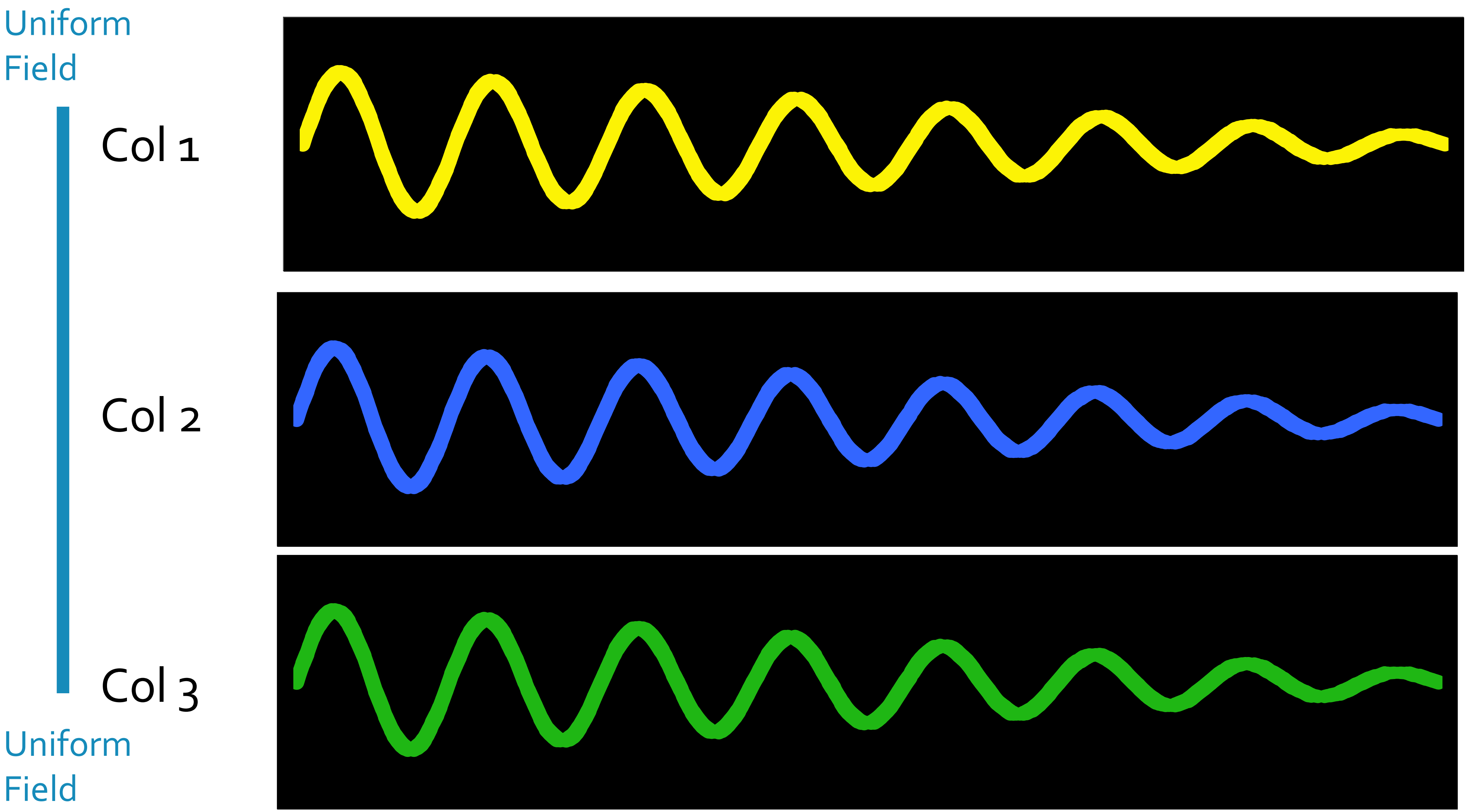
Amplitude of the sinusoidal wave at a pixel used to determine the brightness of the pixel (i.e. color)



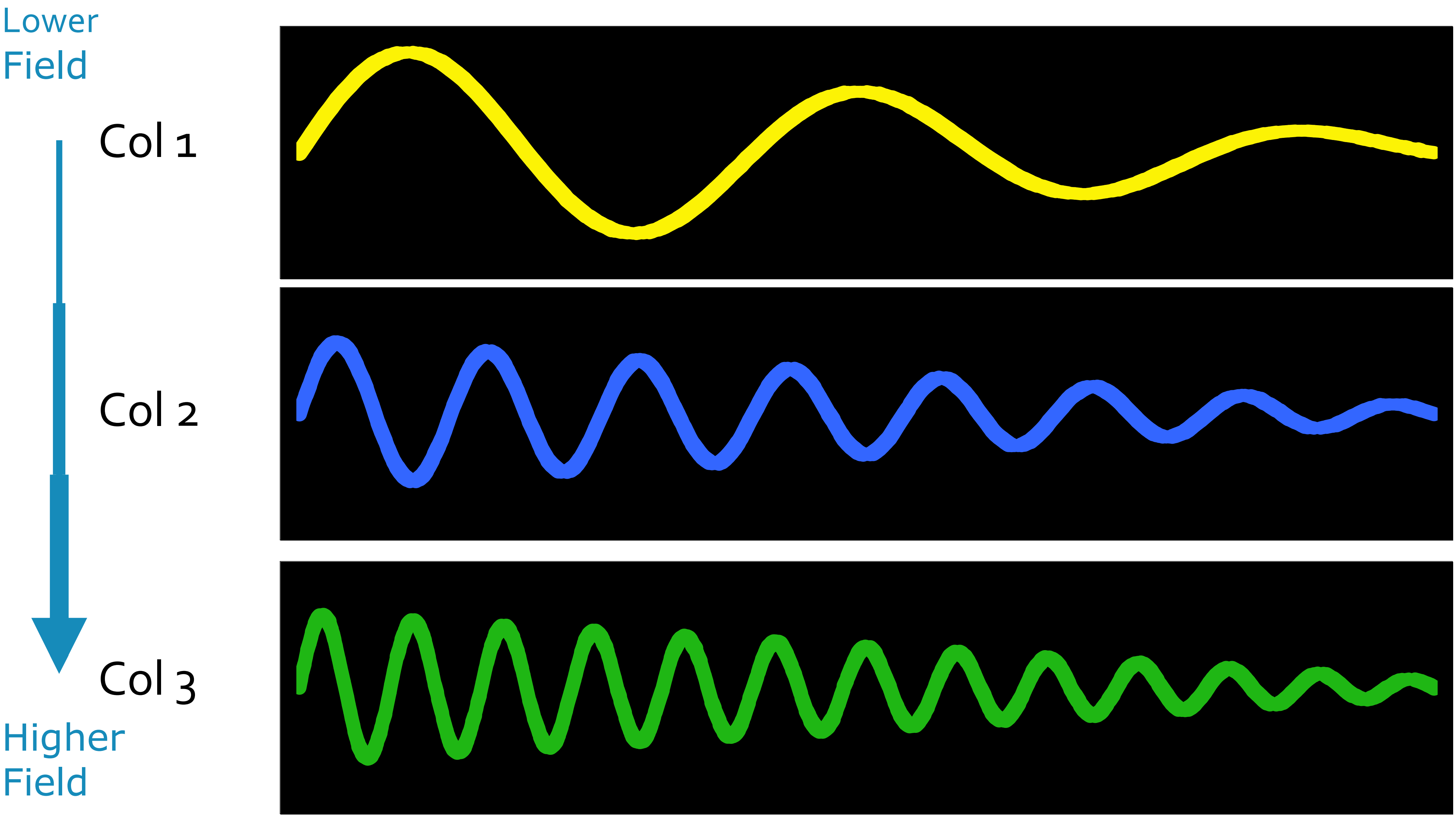
Signal from Multiple Pixels



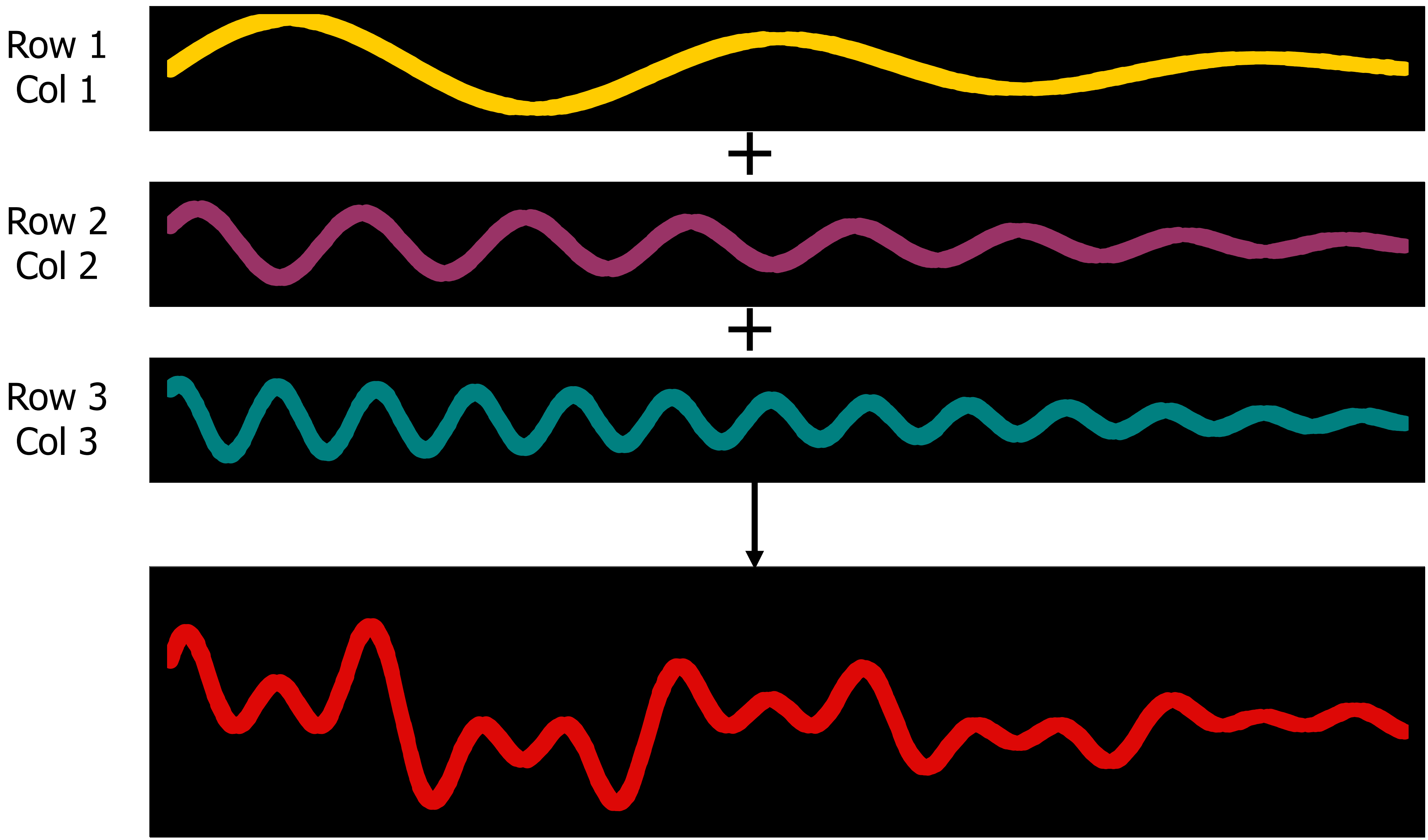
Prior to Gradient



Gradient Applied



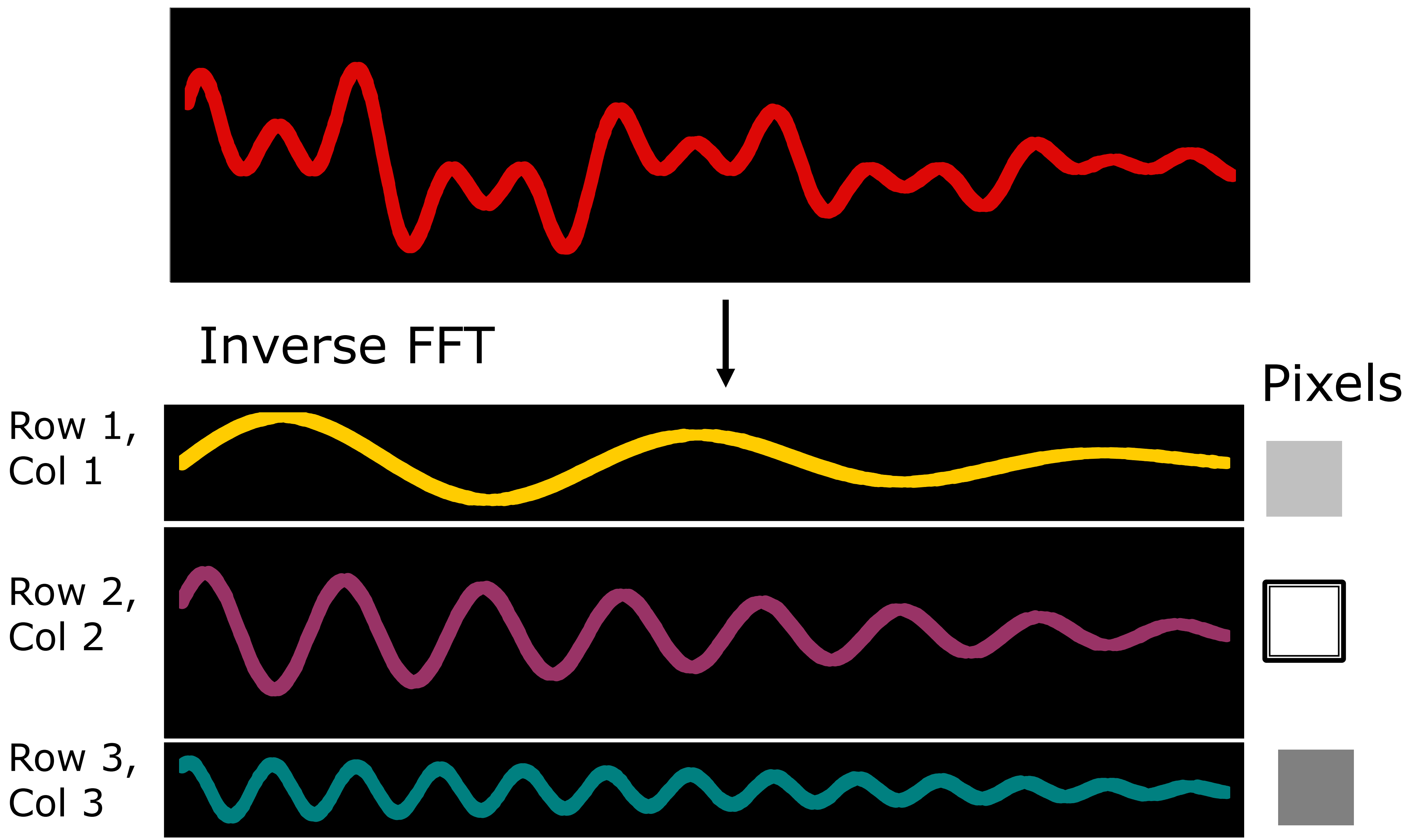
Sum Corresponds to Received Signal



Converting Received Signal into an Image

Signal produced using both frequency and phase encoding can be decomposed using a mathematical technique called the ***Inverse Fourier Transform***

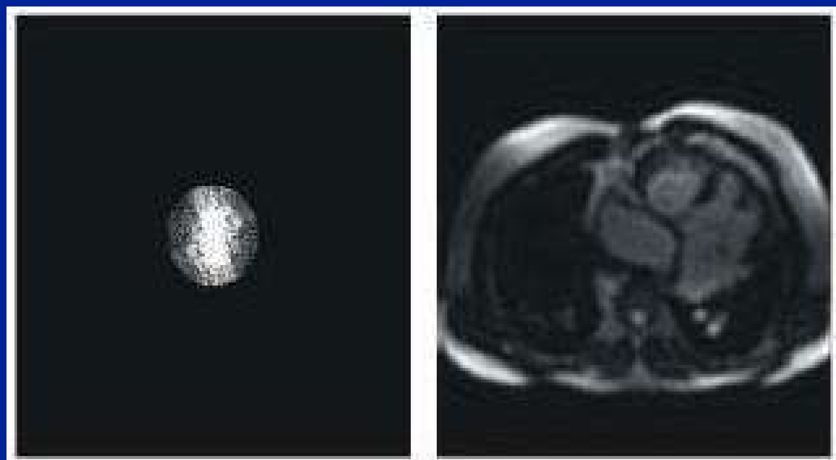
From Signal to Image



Now, we re-transmit the energy for image processing

- The emitted energy is too small to convert them into images (despite 2500 times the magnetic field with resonance RF pulse).
- Hence, repeated "ON-OFF" of RF pulses are required.
- The emitted energy is stored (k-space), analysed and converted into images (inverse Fourier transformation).
- *The raw MRI data prior to becoming an image is what makes up k-space.*

Center of K-space – signal and contrast



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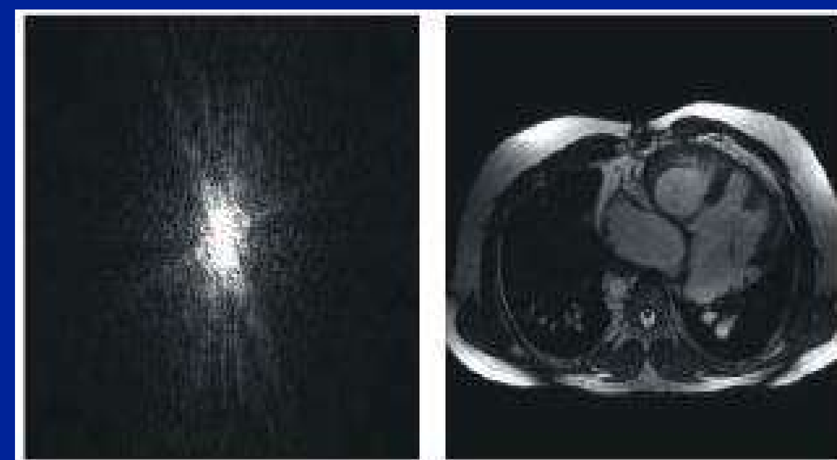
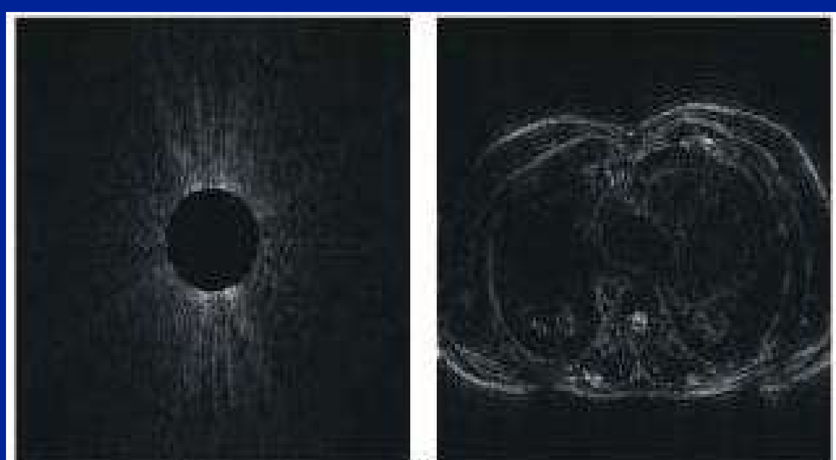


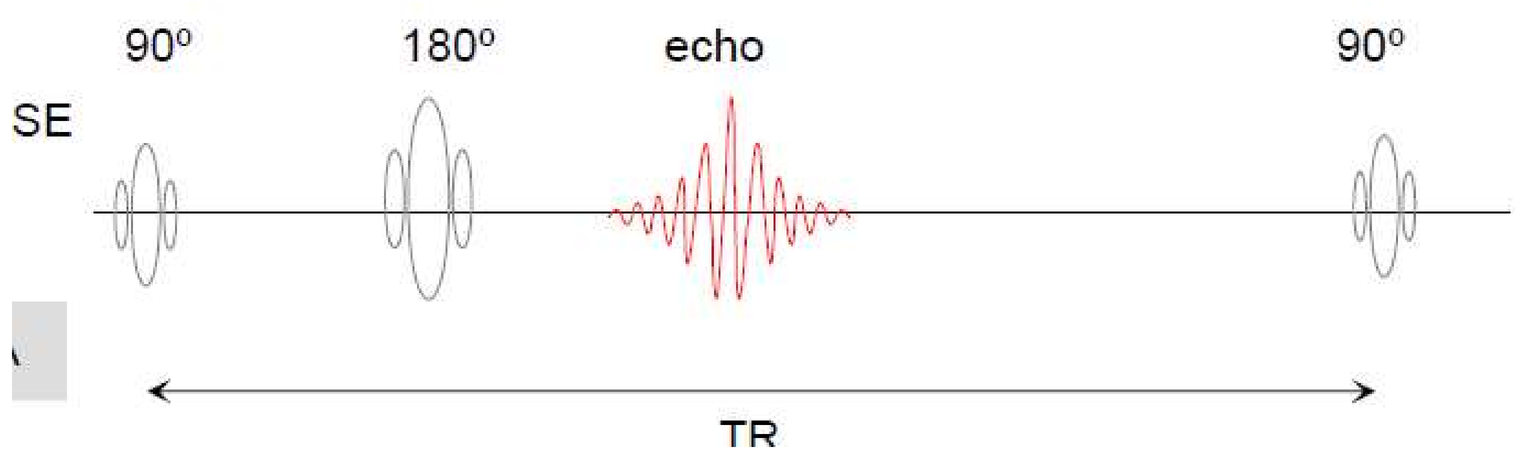


Periphery of k-space – spatial resolution (sharpness)

More parameters you hear about!

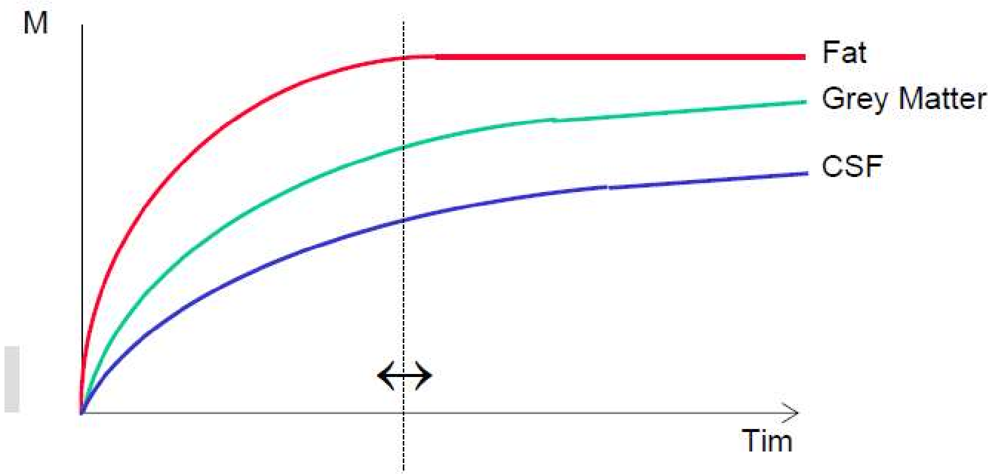
Repetition Time "TR"

- TR is the time between two excitation pulses
- It affects the length of relaxation period after application of one RF excitation pulse to the beginning of the next.



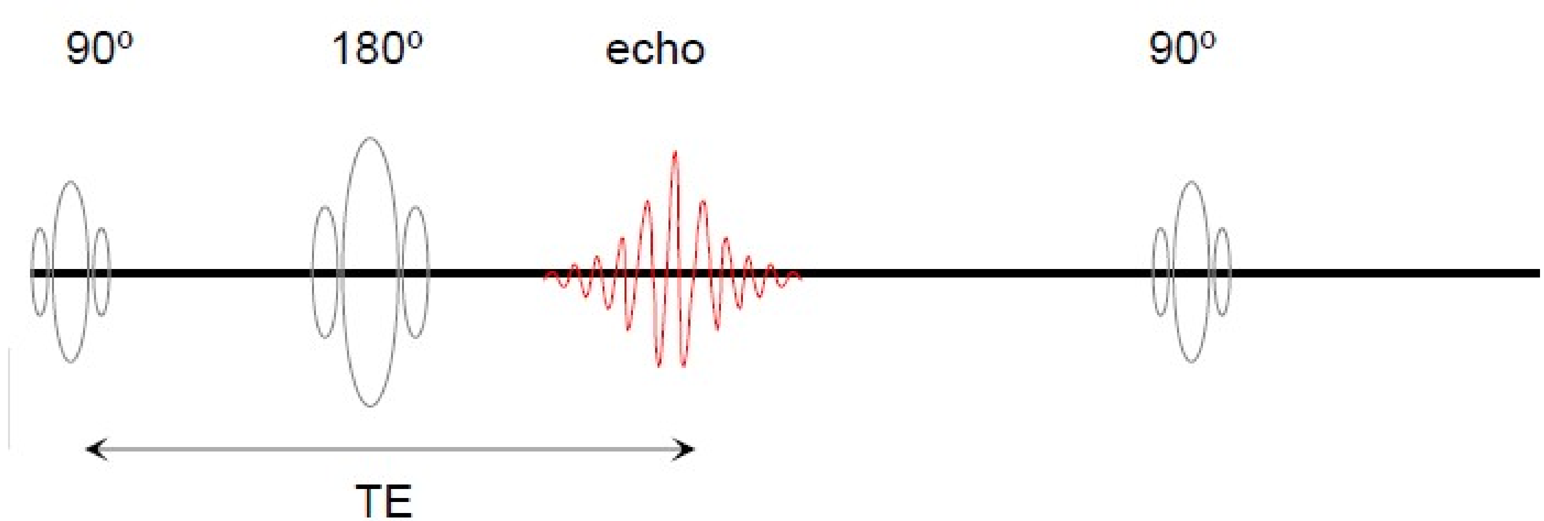
TR

- **Increasing** the TR has the following effects on the image:
  - Less image contrast. More time is allowed for T1 relaxation to take place; the difference in amplitudes of the magnetization vectors is smaller. Therefore…
  - More Proton Density contrast.
  - More signal. There is more magnetization available for the next excitation.
  - Increase of scan time.



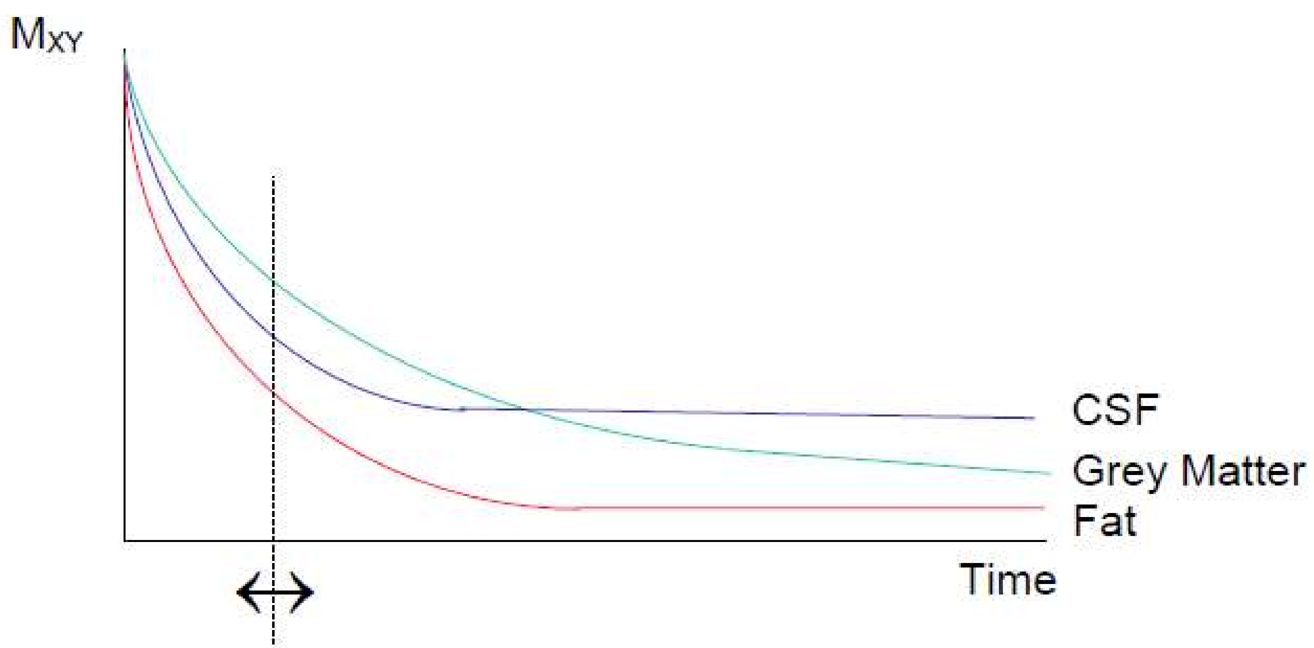
Echo Time "TE"

- TE is the time between the excitation pulse and the echo.
- It is an important parameter because the choice of TE influences **image contrast** dramatically in all types of sequences.
- TE determines how much transverse relaxation will occur before reading one row of the image.



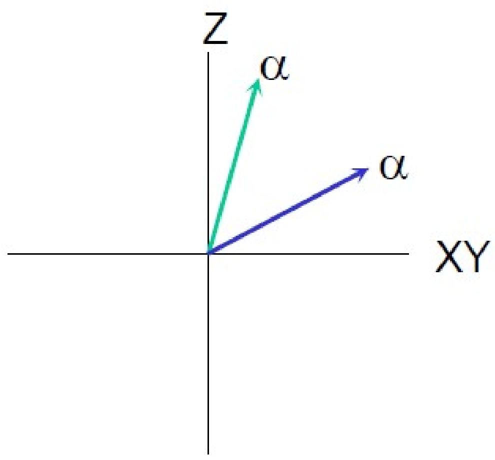
TE

- Increasing the TE has these effects:
  - More T2 contrast. An increase of TE allows for more de-phasing.
  - Less signal.
  - Possible contrast swap.

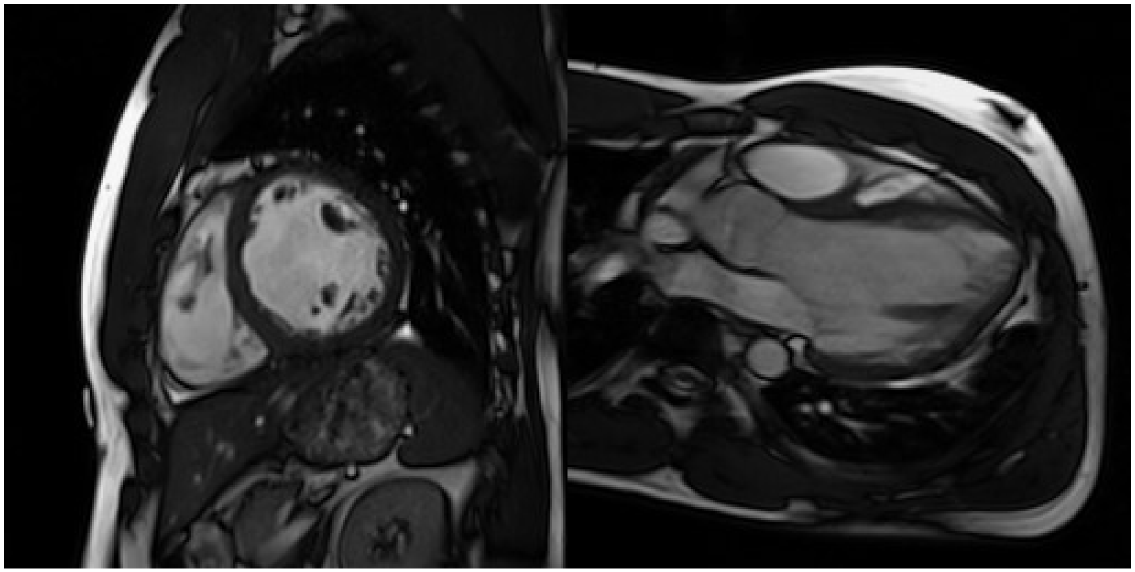


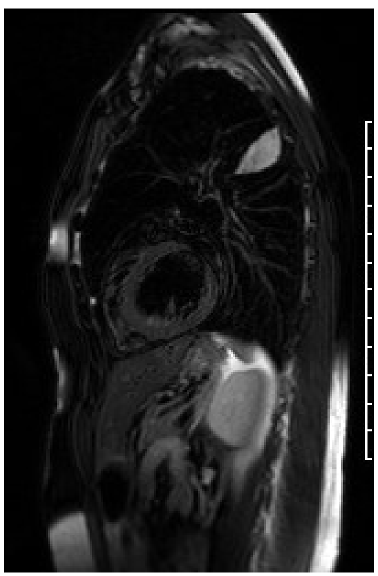
Flip Angle

- The Flip Angle (FA) determines how much the net magnetization vector is tilted towards the X-Y plane
- Increasing the FA (in a Gradient Echo sequence) has these effects:
  - More T1 contrast.
  - More signal.
  - Possible contrast swap.



And that's some of the physics behind MRI images!!





THANK YOU