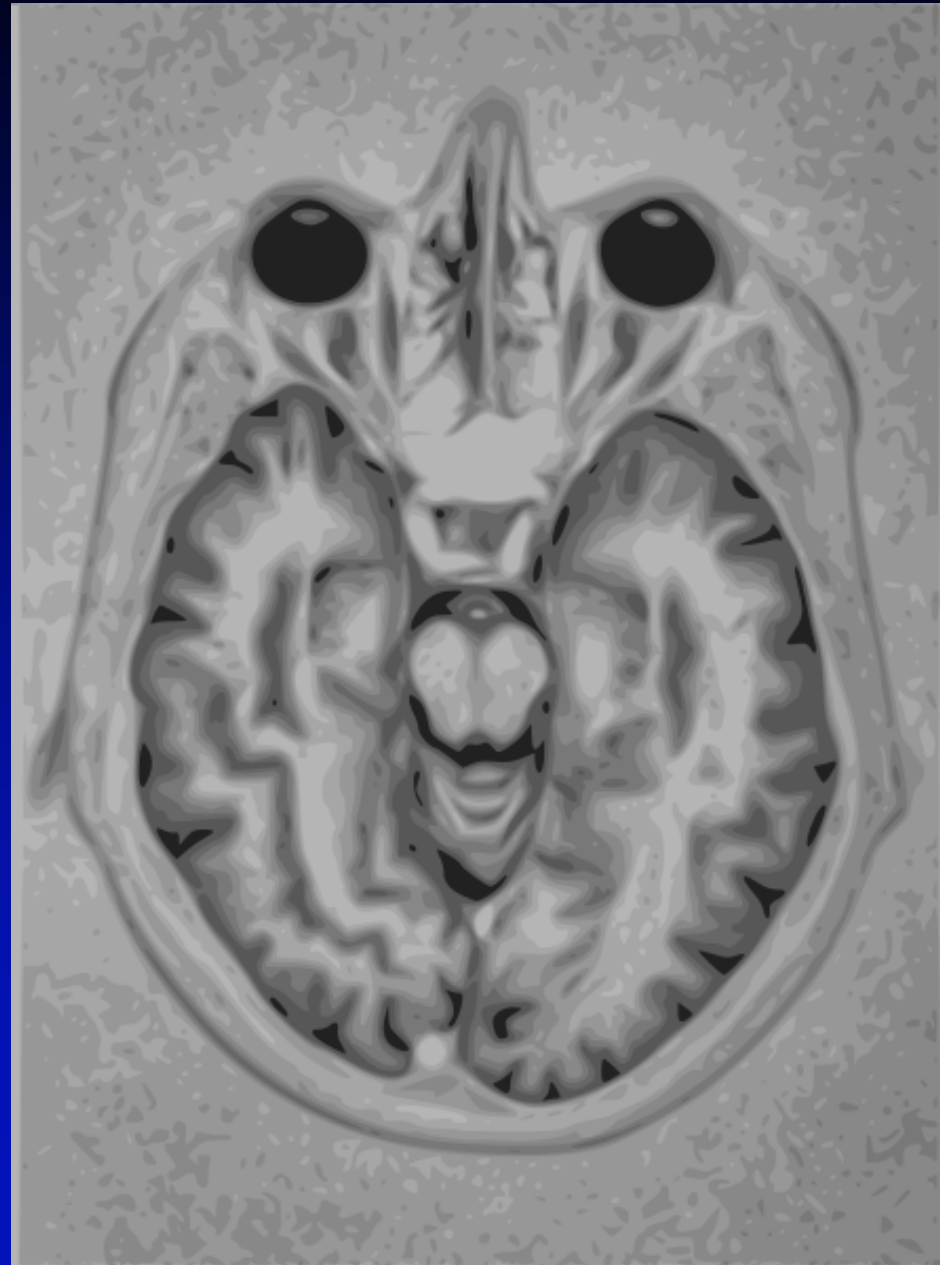
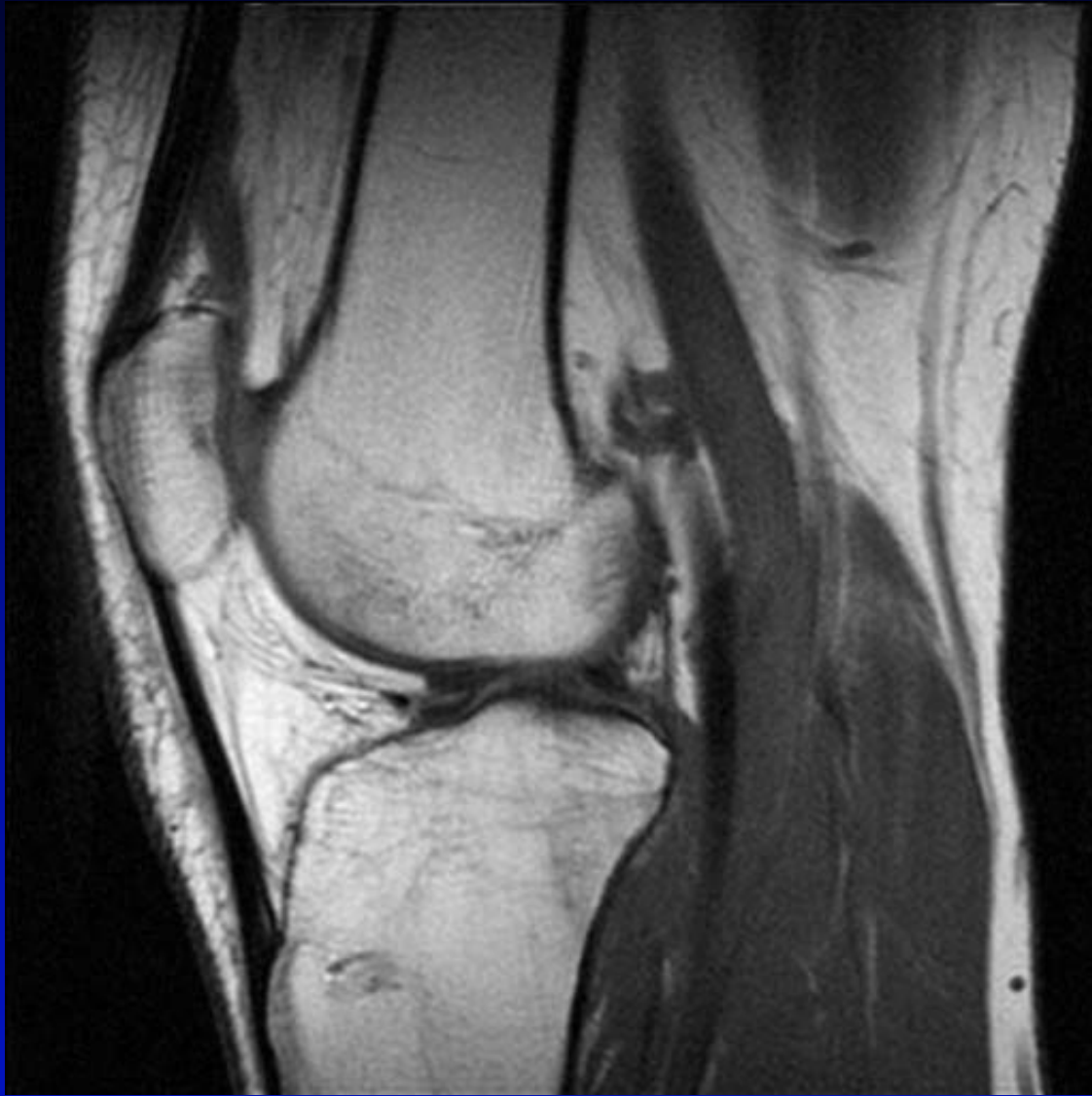
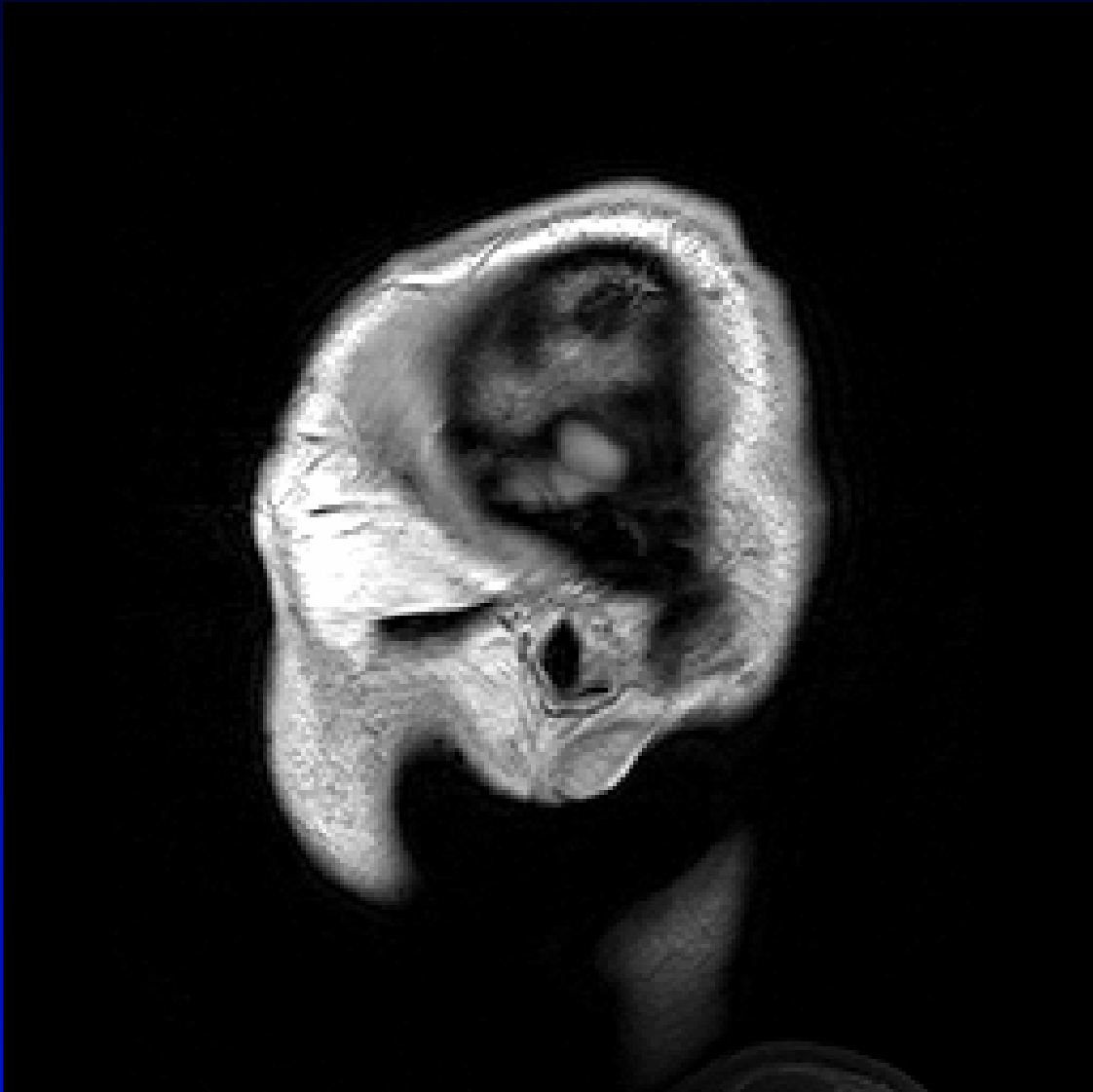


**Nuclear Magnetic Resonance
(NMR)**

**Magnetic Resonance Imaging
(MRI)**



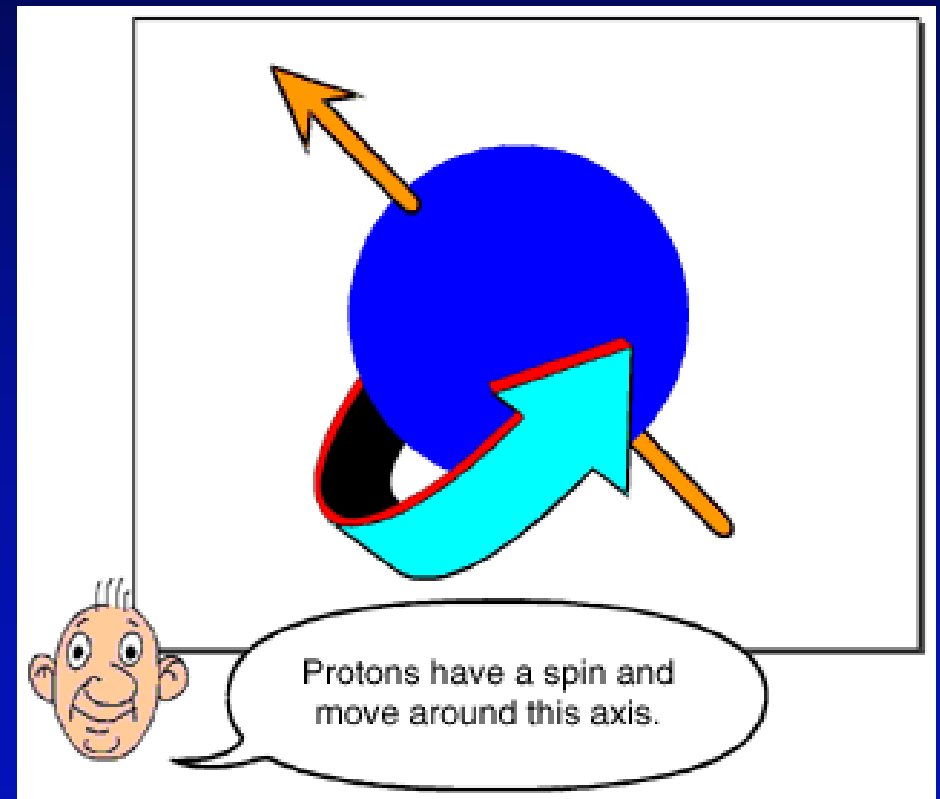


1. What is the source and how is it working?
2. How is contrast created?
3. How is direction created?
4. How is the image constructed?

The source

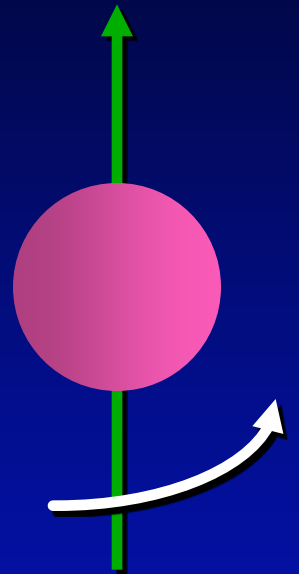
Nuclear Magnetism

Nucleons (protons, neutrons) have a quantum property known as spin ($\frac{1}{2}$ Bohr magneton, $\text{spin}=\frac{1}{2}$)



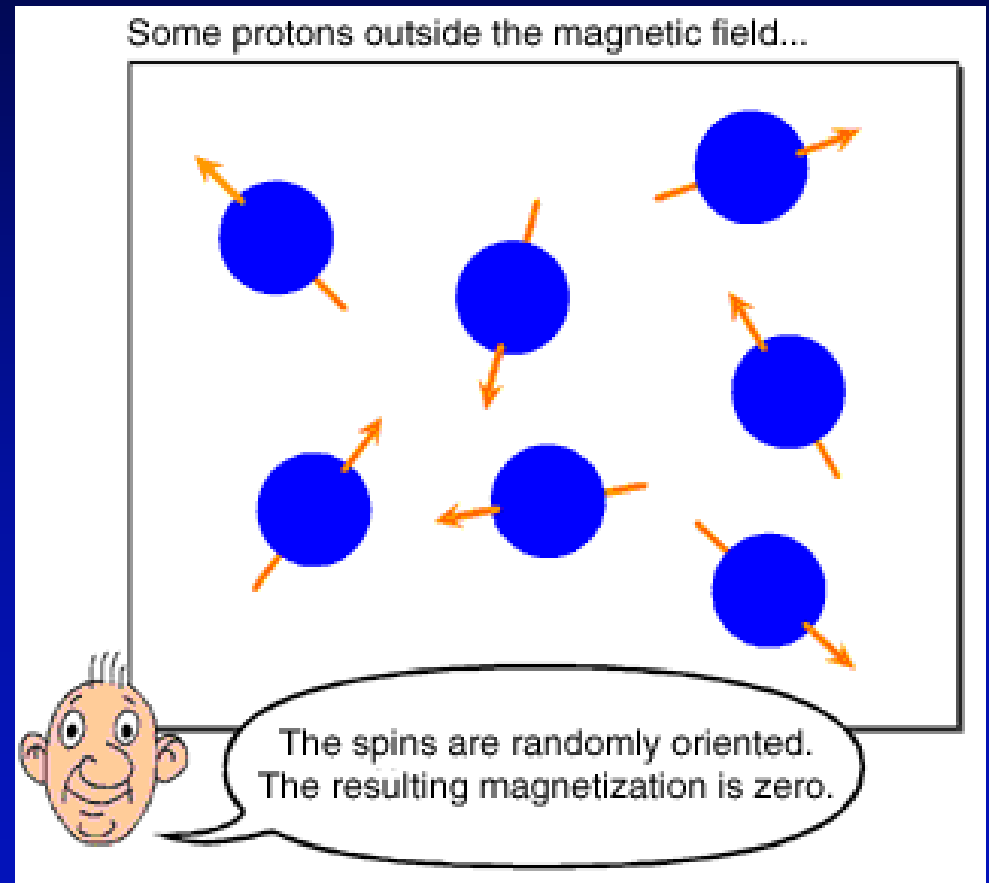
Why are protons important?

- They are plenty in the body
- Positively charged
- They spin about a central axis
- A spinning charge creates a magnetic field
- The arrow indicates the direction of the magnetic field



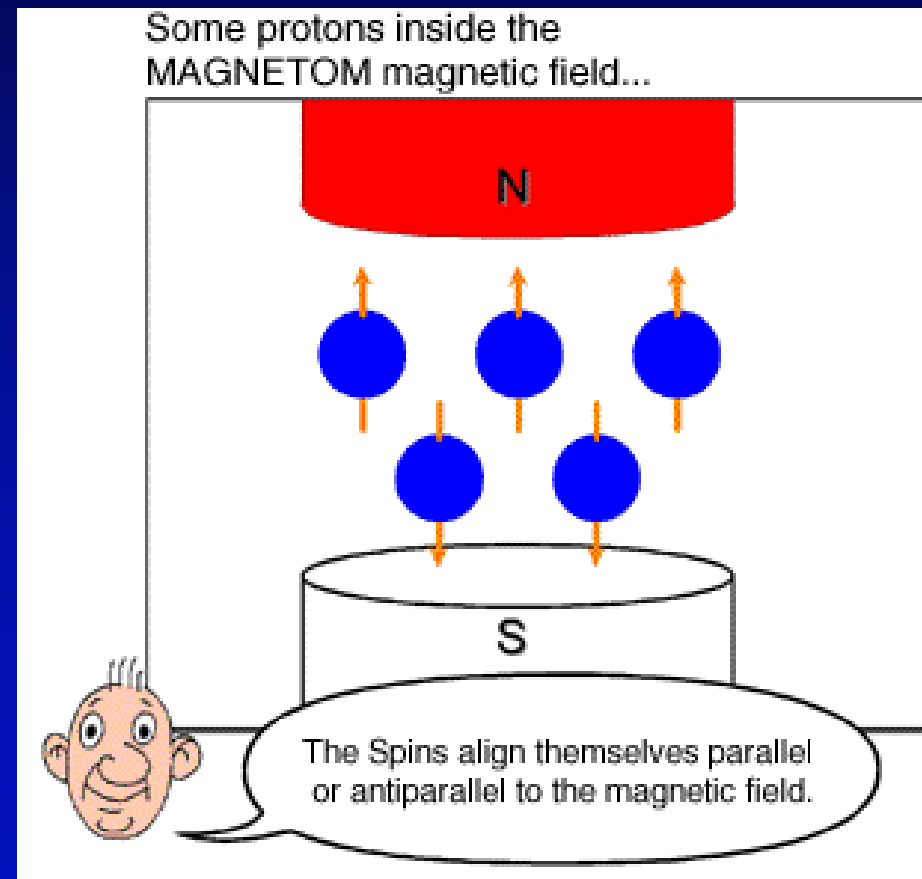
Nuclear Magnetism

Normally the nuclear spins of the protons cancel out and there is no net magnetic field to observe.



Nuclear Magnetism

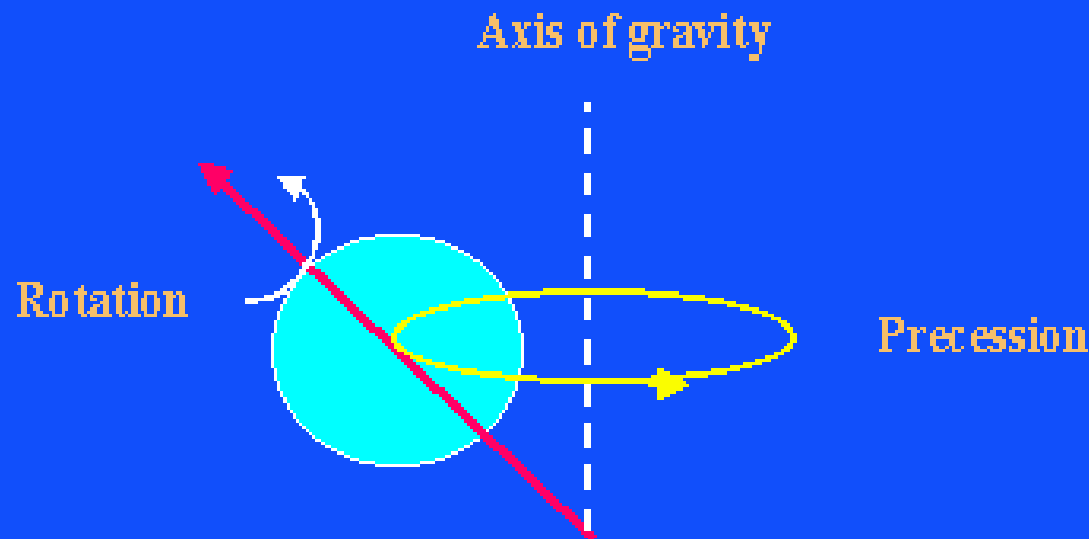
In a homogeneous magnetic field, the proton spin will orient themselves. Most spin will be oriented along the external field giving a net magnetic field.





Rotation and Precession

- When force is applied to a spinning object, the resulting force is perpendicular to that force



Larmor Frequency

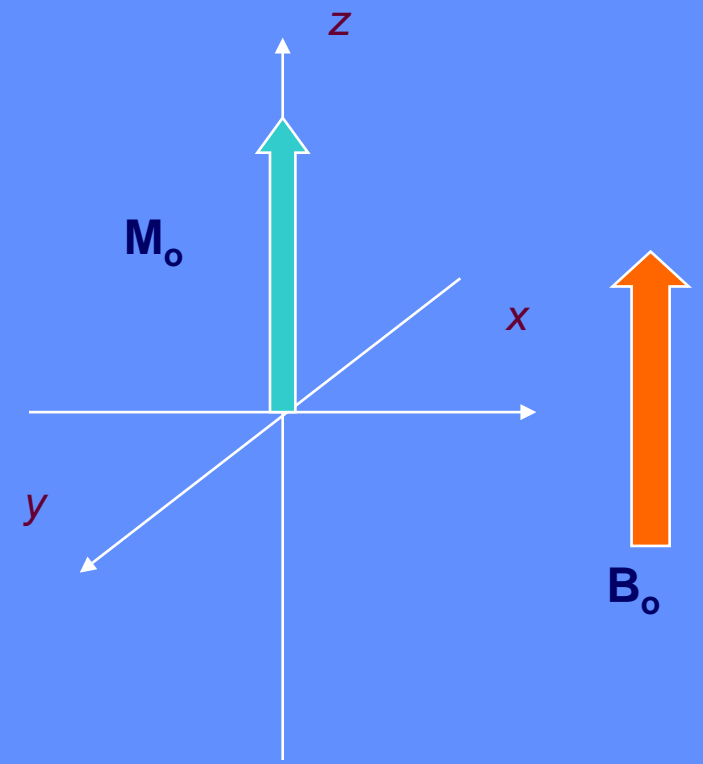
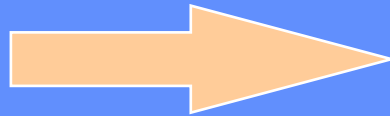
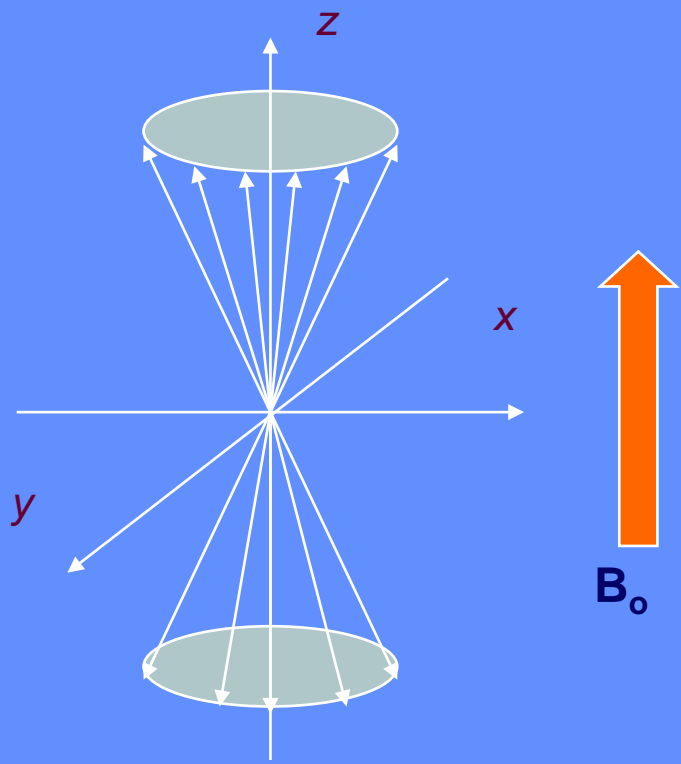
Characteristic angular frequency

$$\omega = \gamma B_0$$

ω = Precession frequency

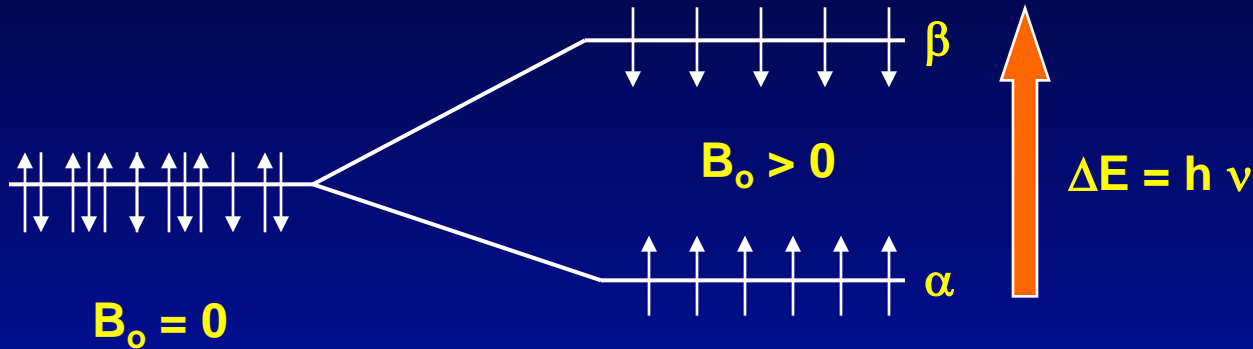
γ = Gyromagnetic constant

B_0 = Static magnetic field strength



Energy and populations

- An external magnetic field create an energy difference between nuclei aligned and against B_0 :



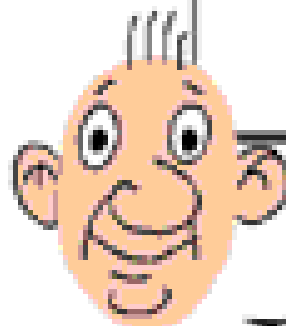
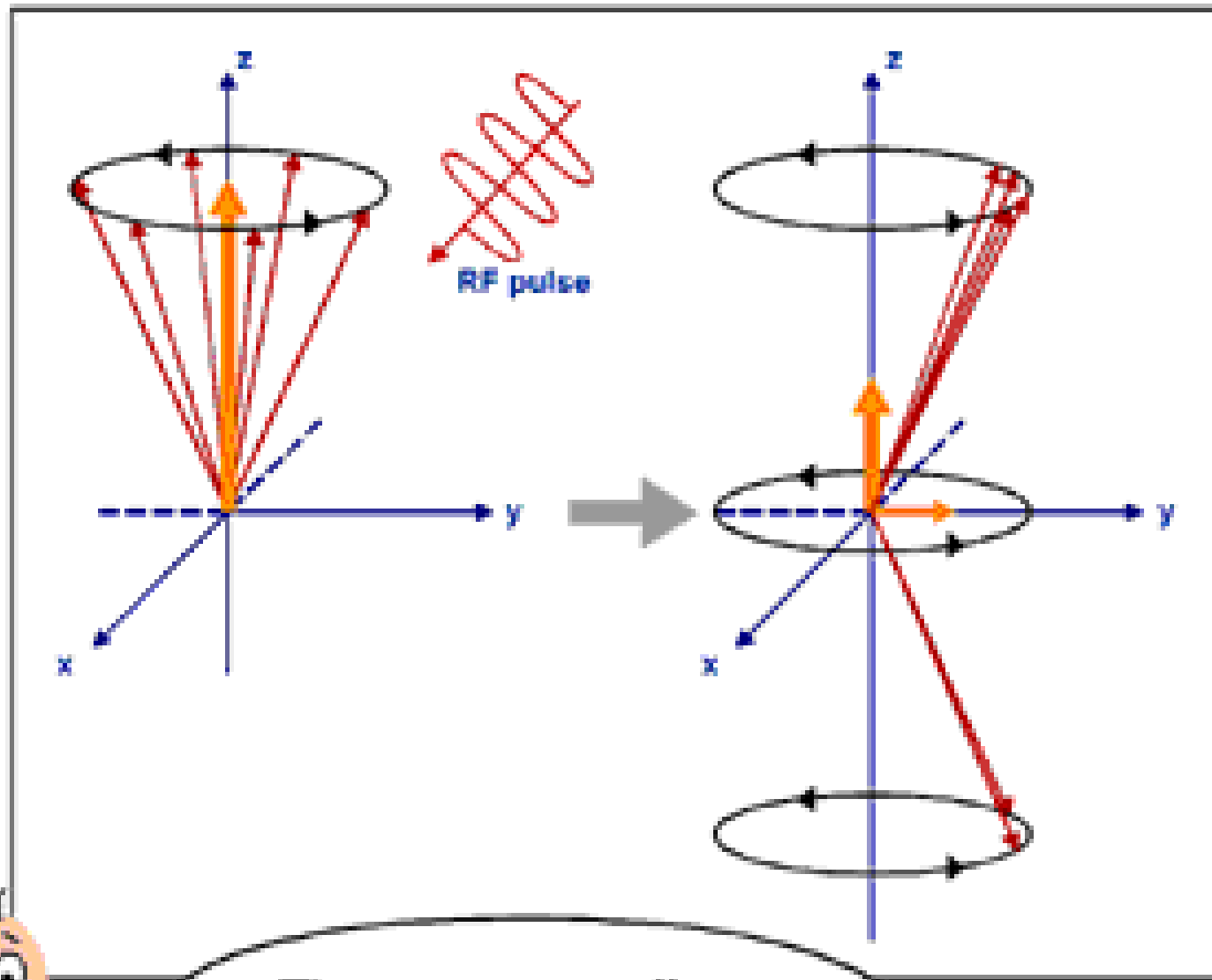
- Each level has a different *population* (N), and the difference between the two is related to the energy difference by the Boltzman distribution:

$$N_{\alpha} / N_{\beta} = e^{\Delta E / kT}$$

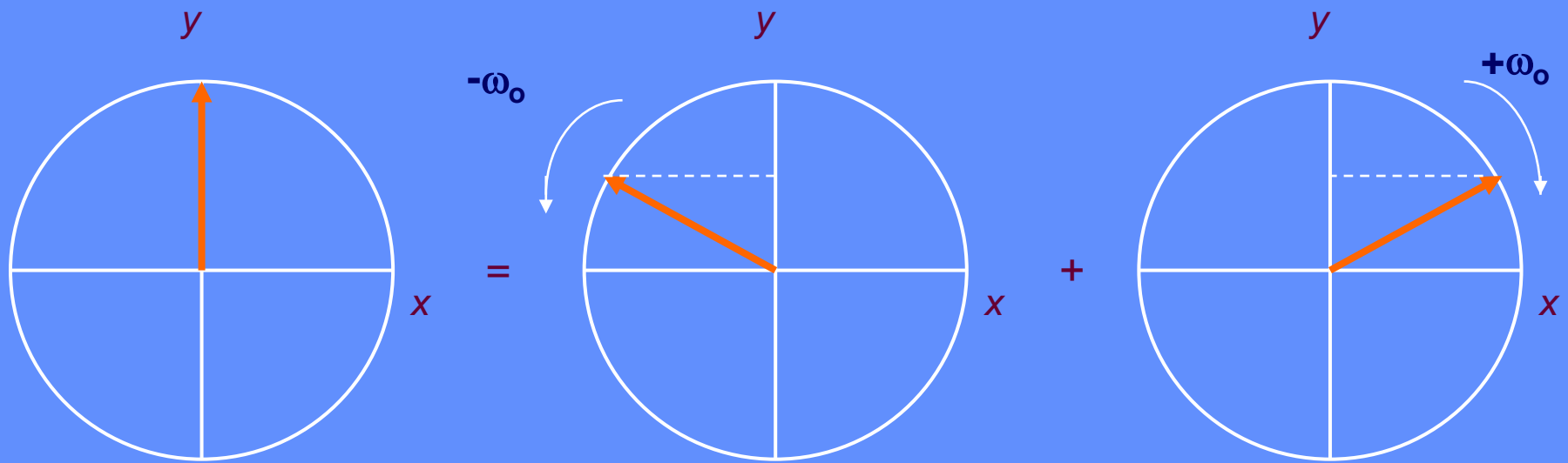
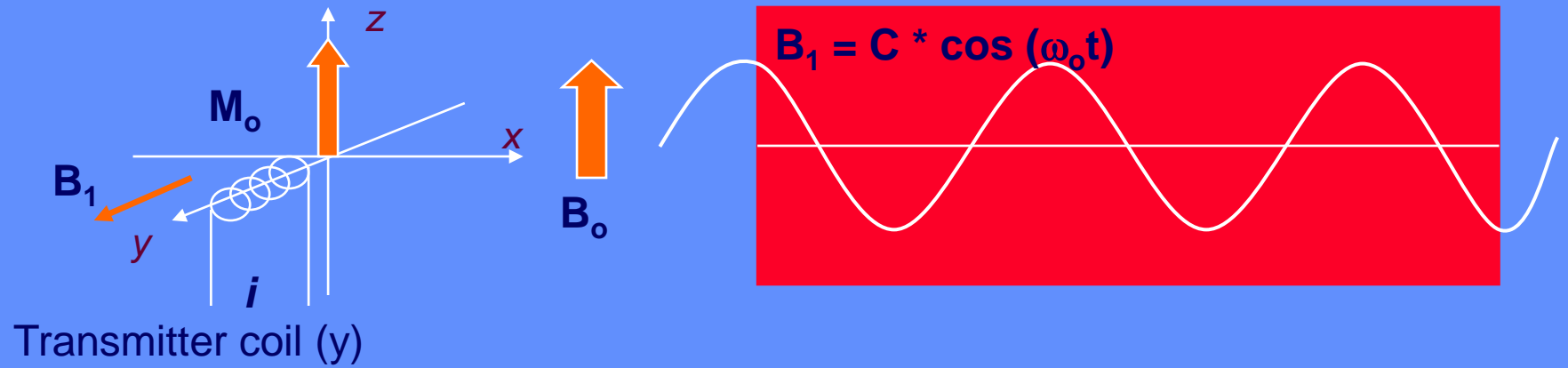
$$N_{\alpha} / N_{\beta} = 1.000064$$

- The ΔE for ^1H at 400 MHz ($B_0 = 9.5 \text{ T}$) is $3.8 \times 10^{-5} \text{ Kcal / mol}$

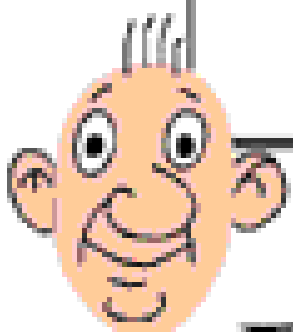
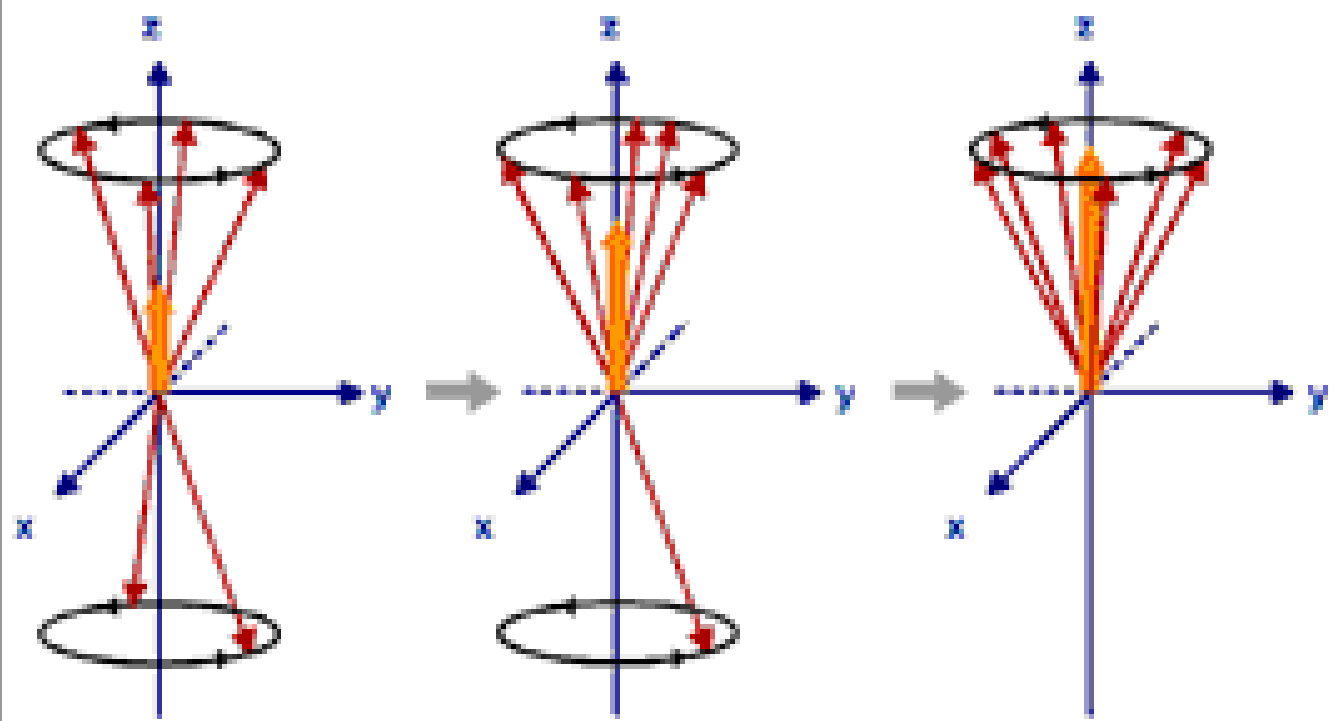
A short RF pulse is emitted...



There are two effects:
The longitudinal and transverse magnetization.



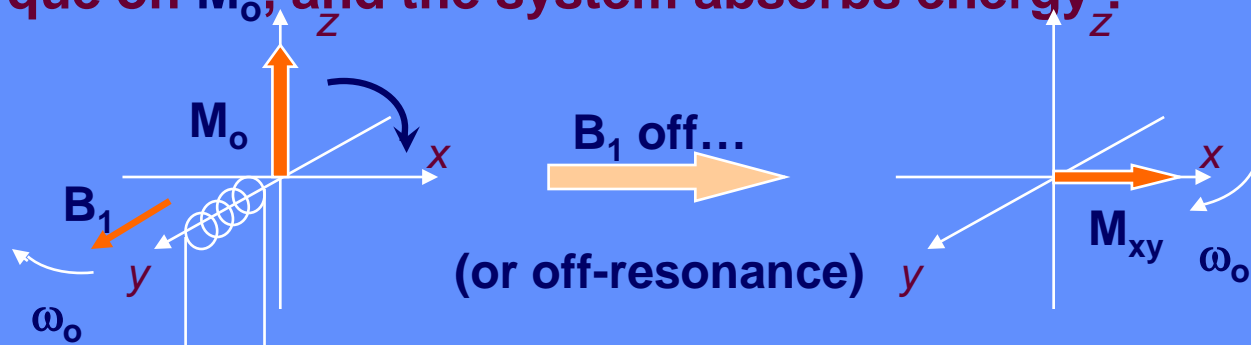
...and the RF pulse is switched off.



This phenomena is called relaxation

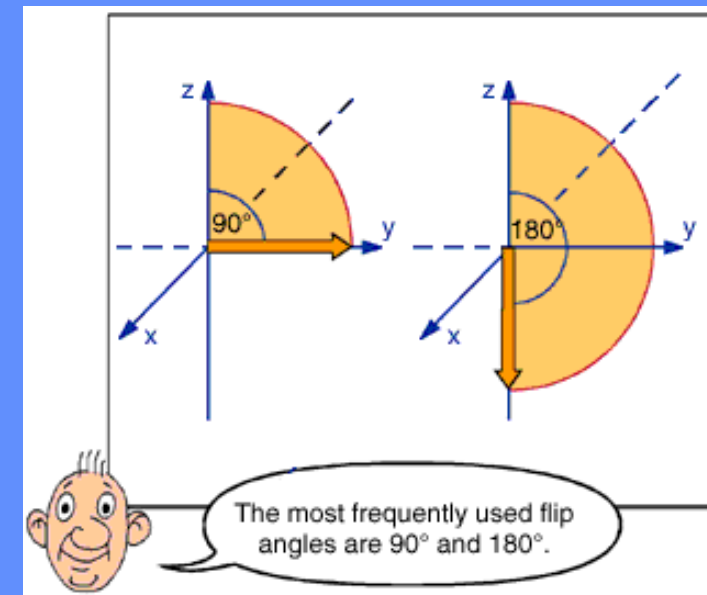
Once again

M_0 is composed by individual atomic spin with the Larmour frequency ω_0 . If a RF field of the same frequency ω_0 is applied a magnetic vector B_1 with the same frequency ω_0 is created that interact with M_0 under a *resonant condition*. The alternating magnetic field generates a torque on M_0 , and the system absorbs energy :



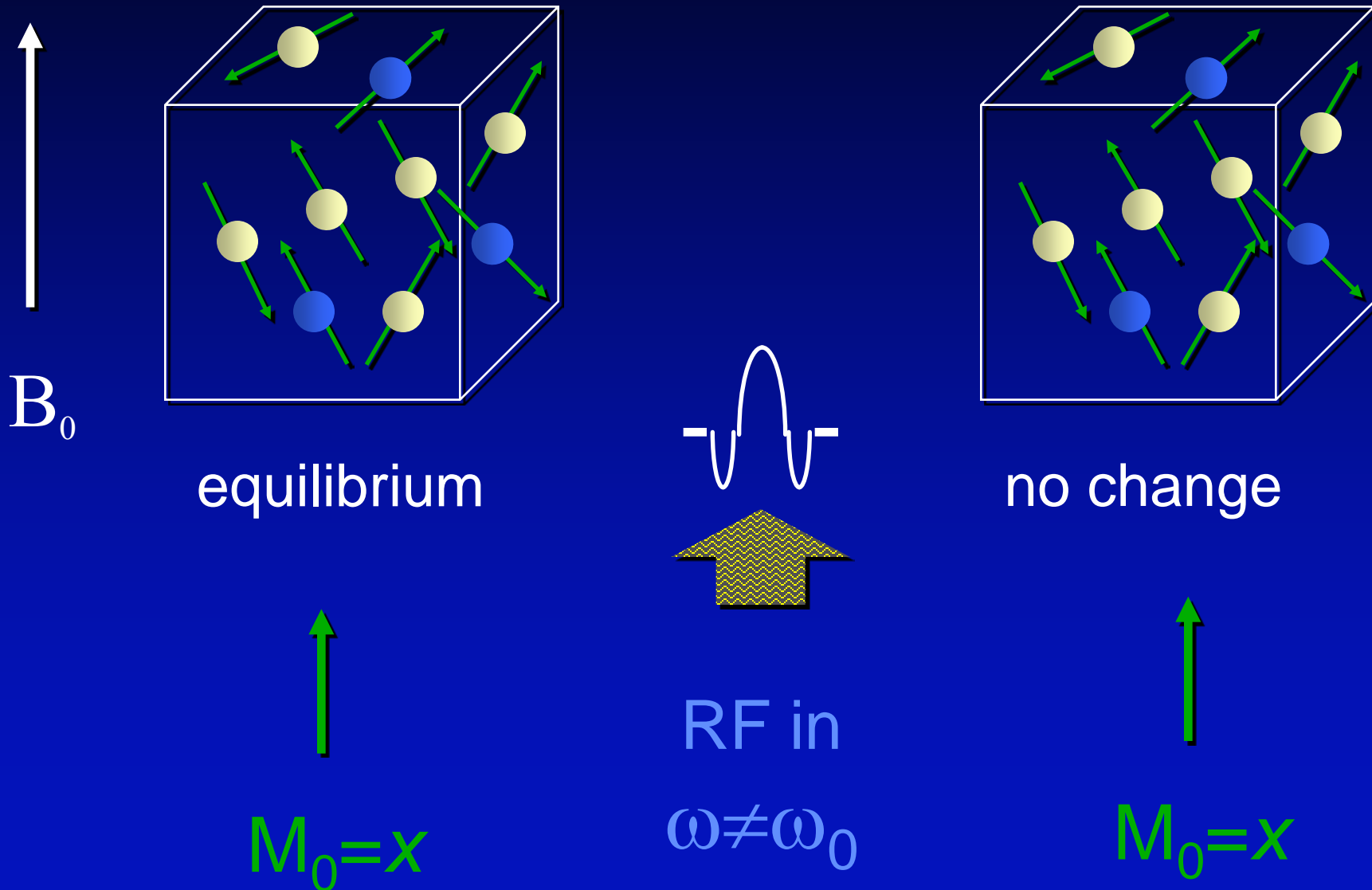
Since the system absorbed energy, the equilibrium of the system is altered. We modified the populations of the N_α and N_β energy levels.

Again, keep in mind that individual spins flipped up or down (a single *quanta*), but M_0 can have a continuous variation.

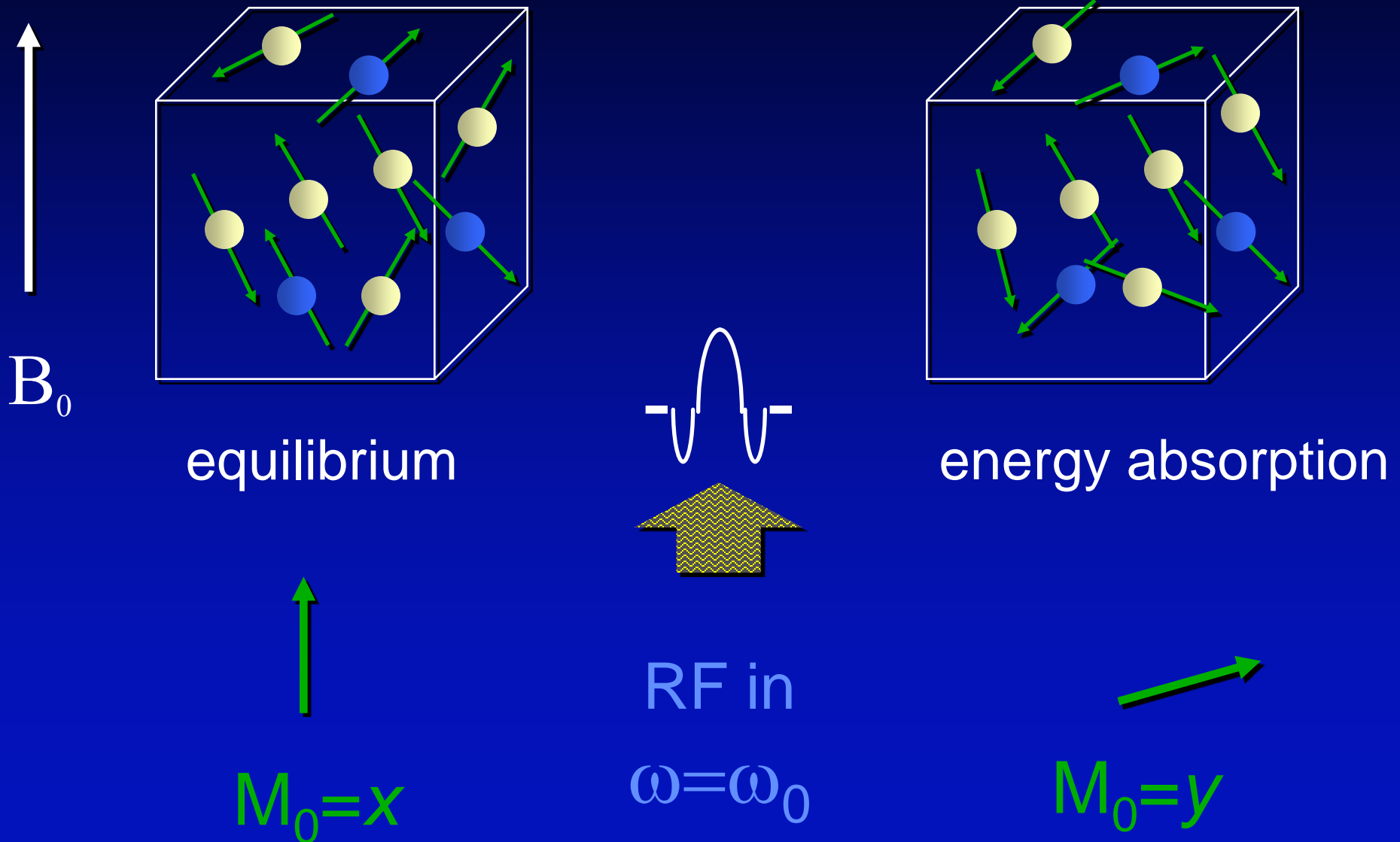


**ENERGY ABSORPTION
MRASUREMENT OF SIGNAL
RELAXATION**

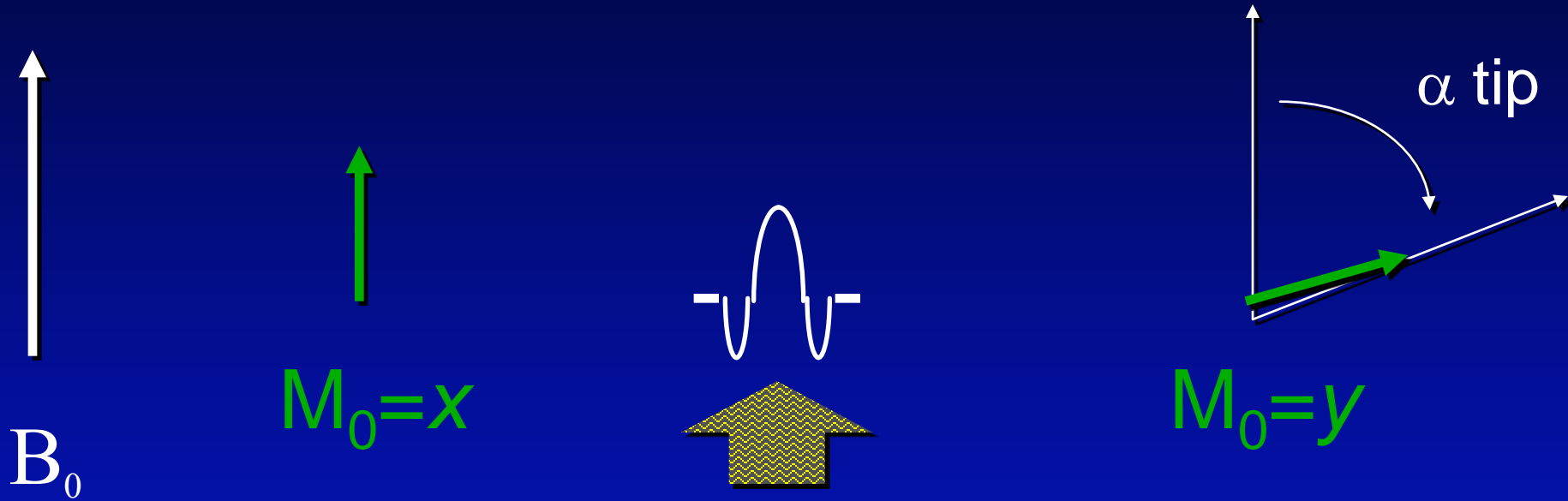
Energy Absorption



Energy Absorption



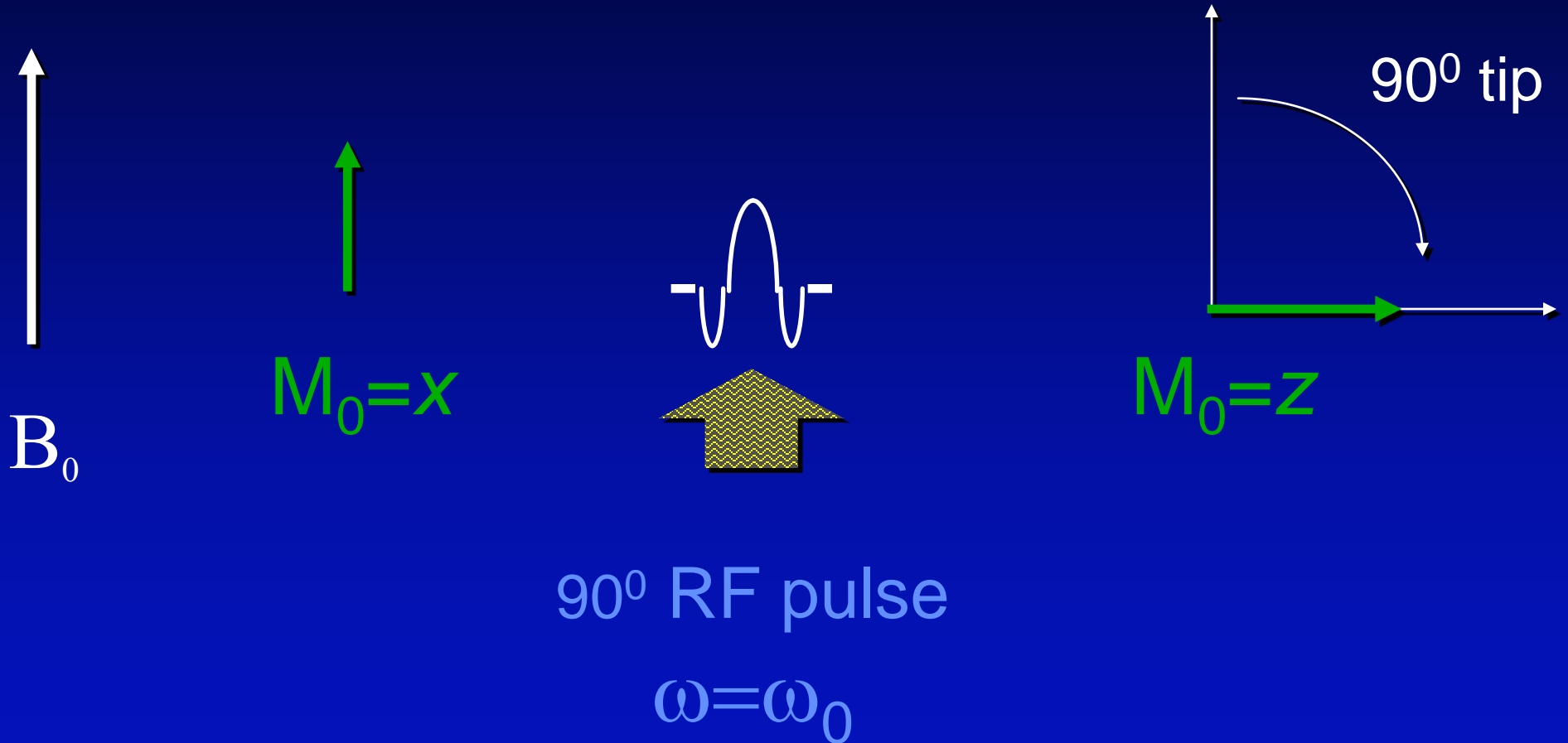
Energy Absorption



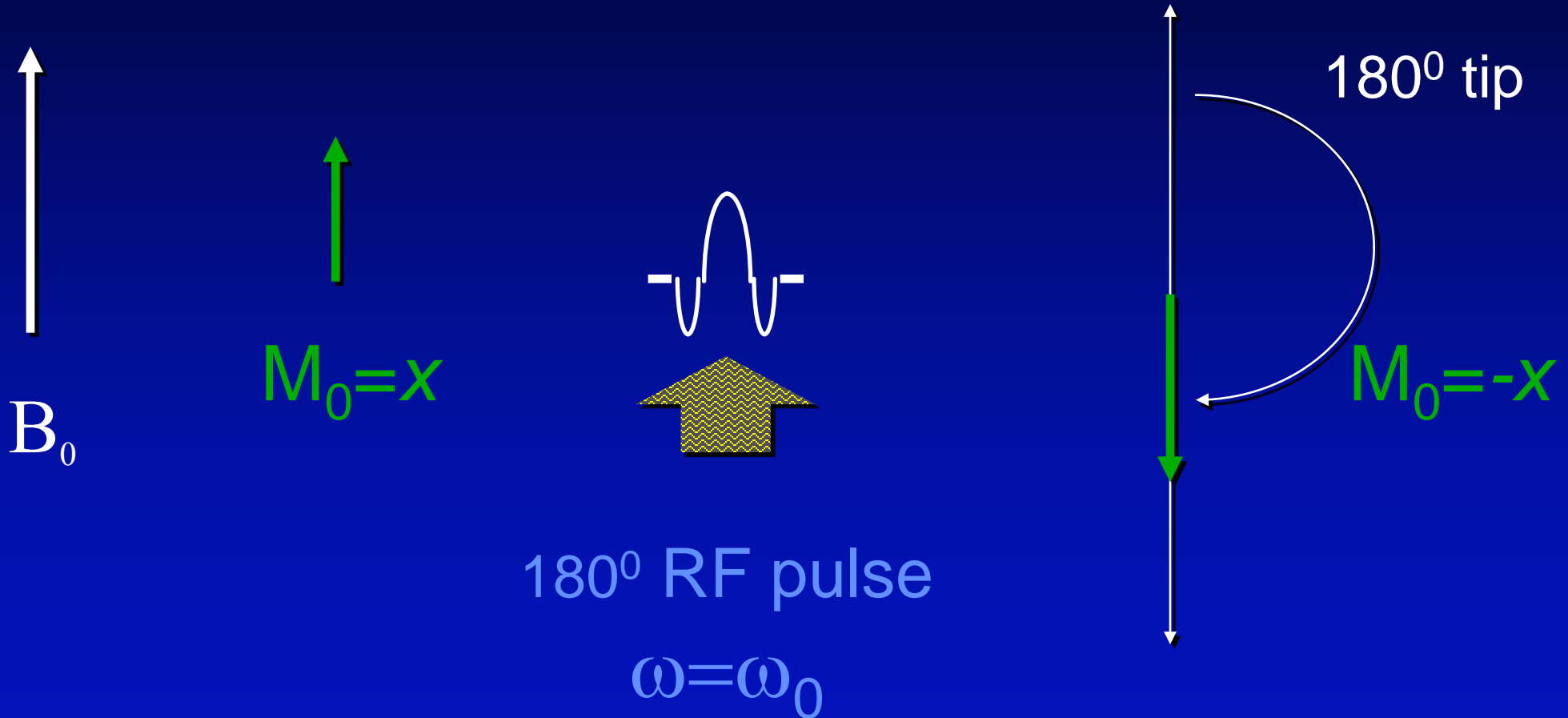
" α " RF pulse

$$\omega = \omega_0$$

Energy Absorption



Energy Absorption

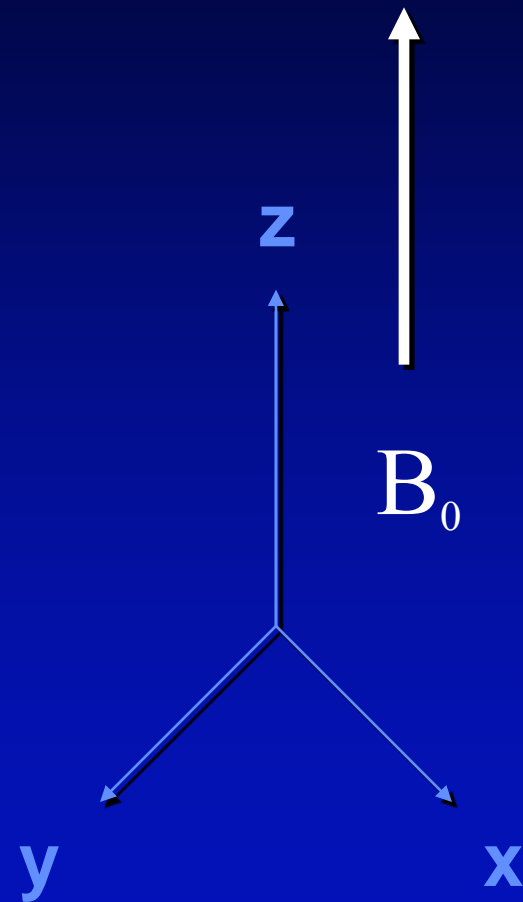


What happens to the released energy?

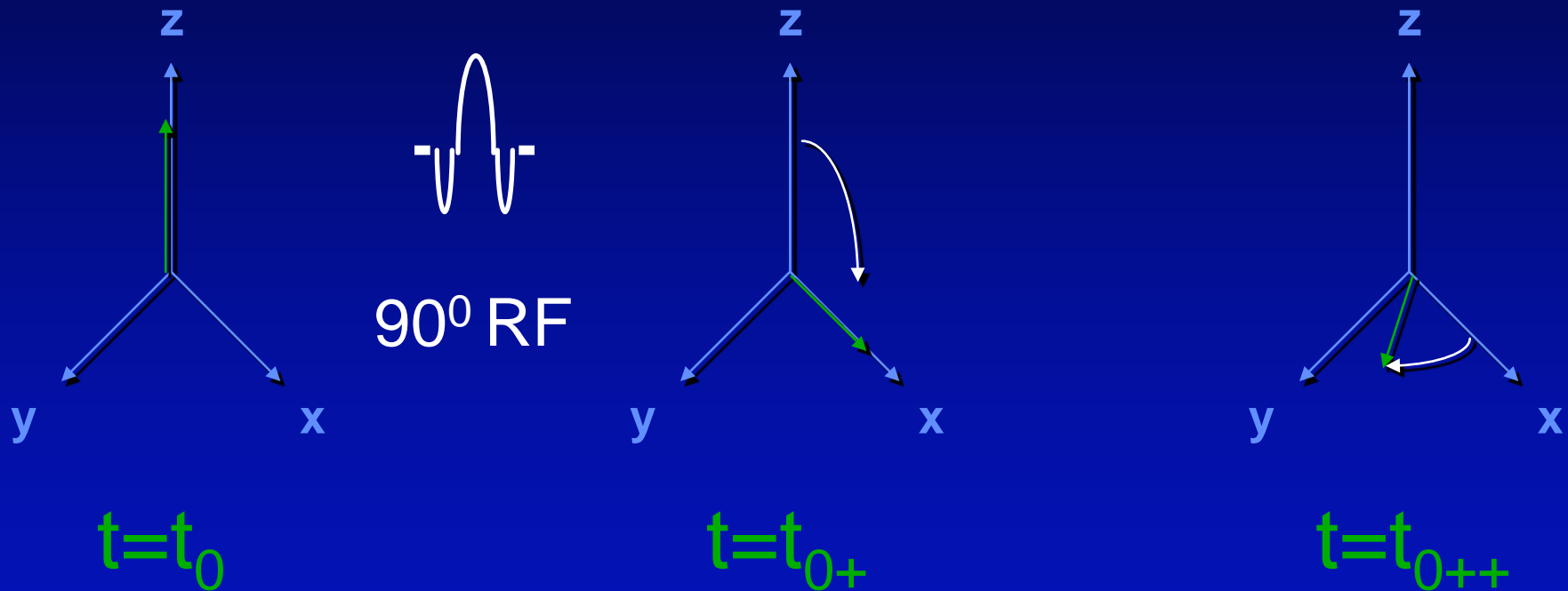
- released as heat
- exchanged and absorbed by other protons
- *released as radio waves*

Measuring the MR Signal

- cannot easily record M_L
- the signal is measured in the transverse (x, y) plane



Rotation in the xy-plane

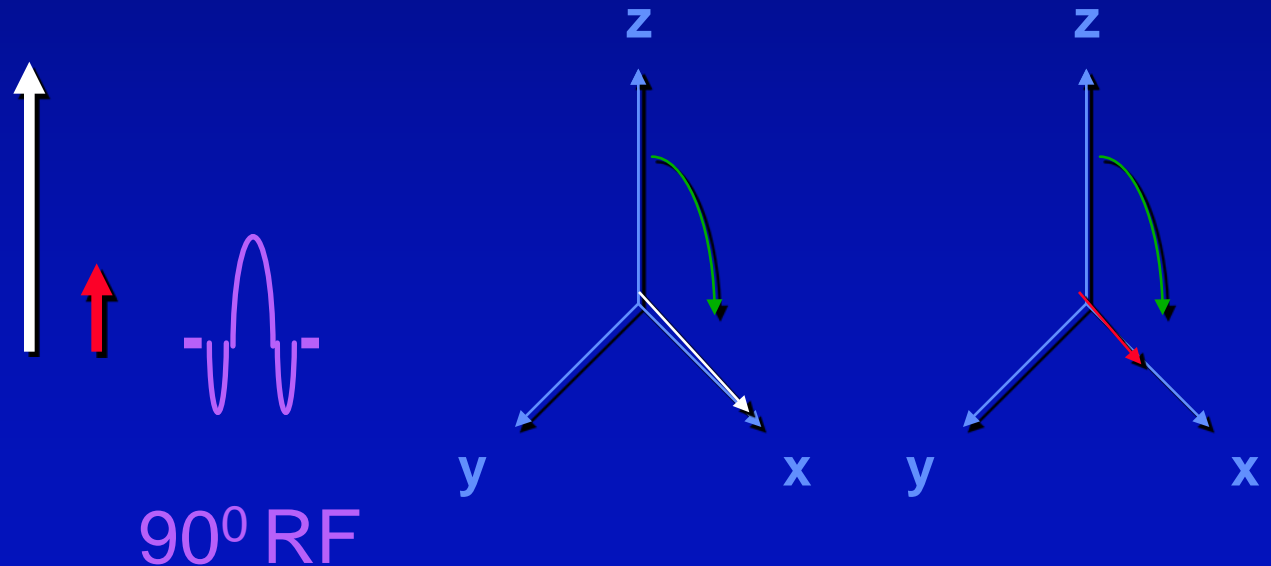


motion in the xy-plane = ω_0
 $\omega_0 \gg T1$ relaxation, MHz vs seconds

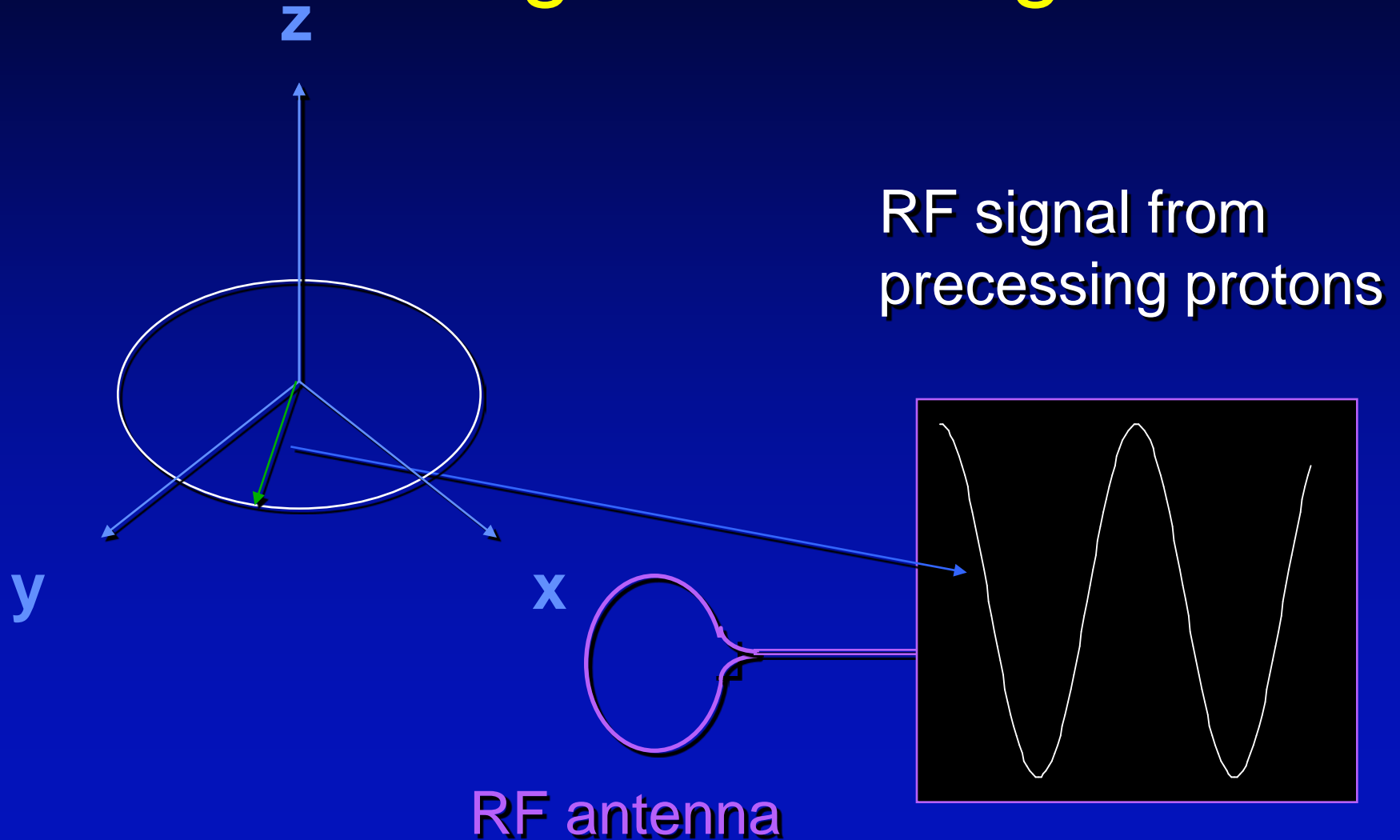
M_{xy} and M_L

- the magnitude of M_{xy} depends on the size of M_L *immediately prior* to the 90° RF pulse

fat protons - short T1
water protons - long T1



Measuring the MR Signal



Relaxation

- **relaxation is the release of energy from an excited state to a lower energy state**
- **protons absorb and release energy in MRI**

CONTRAST

Basic Principle

- The signal in MR images vary due to
 - proton density
 - T1 relaxation
 - T2 relaxation
 - flow
 - contrast

T1 Relaxation

- **synonyms**
 - **longitudinal relaxation**
 - **thermal relaxation**
 - **spin-lattice relaxation**

Equilibrium



90° pulse



Delay time



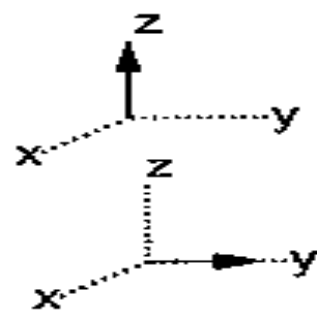
Longitudinal recovery



90° pulse



Resulting FID



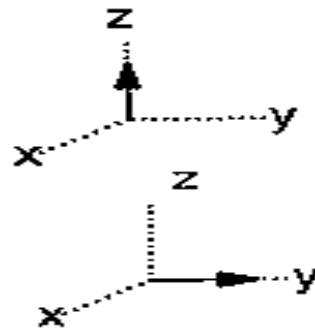
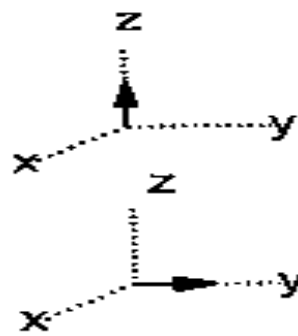
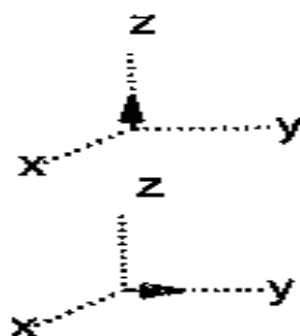
100% Longitudinal Magnetization

0% Longitudinal Magnetization

short

medium

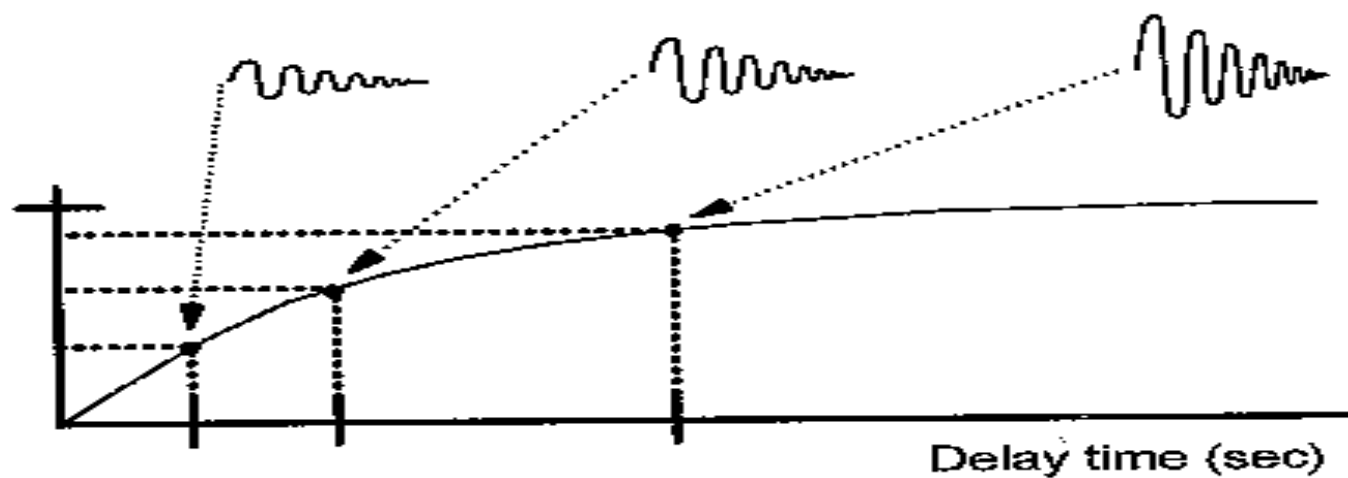
long



100%

Mz recovery

0%



short

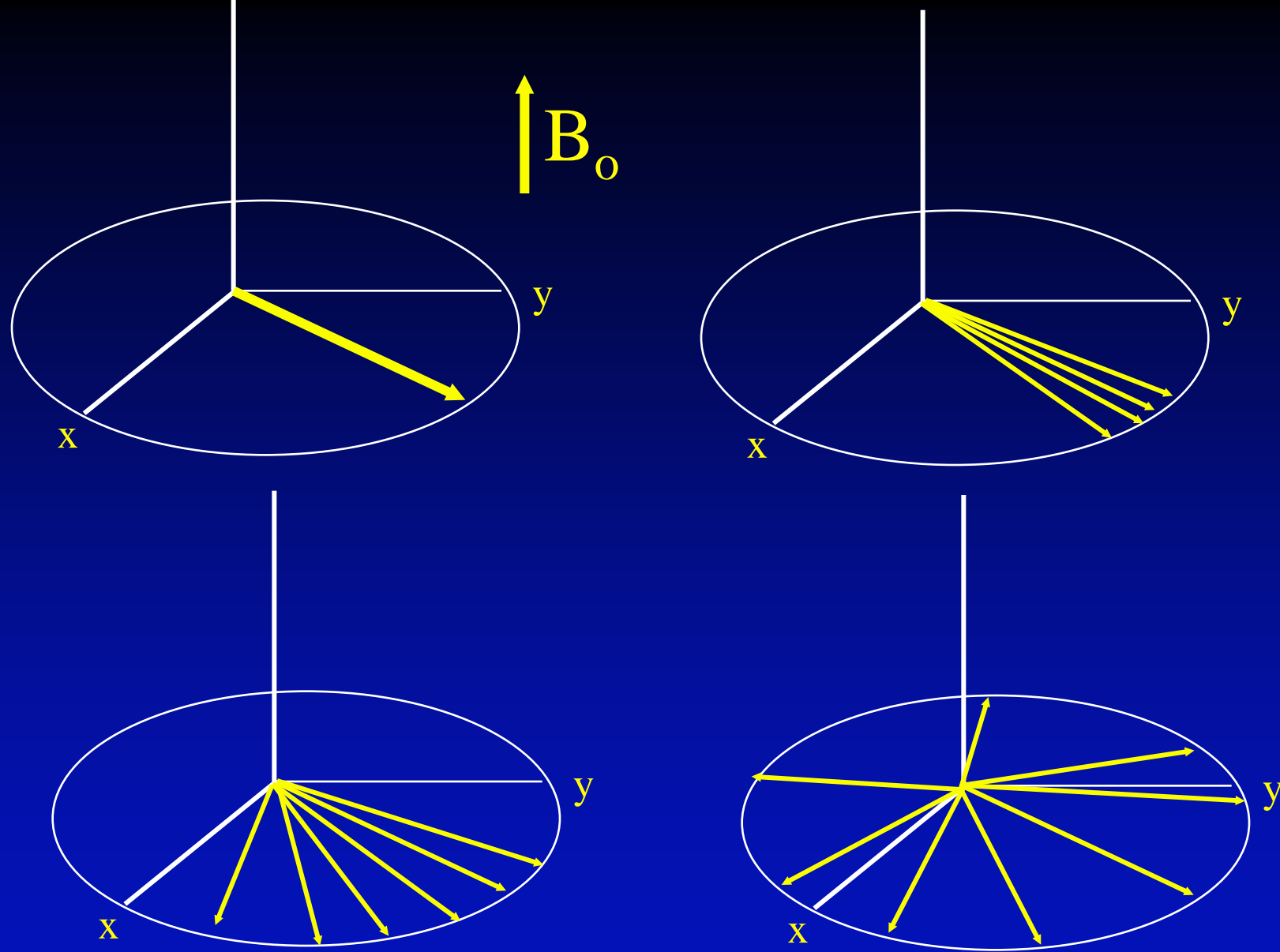
medium

long

Delay time (sec)

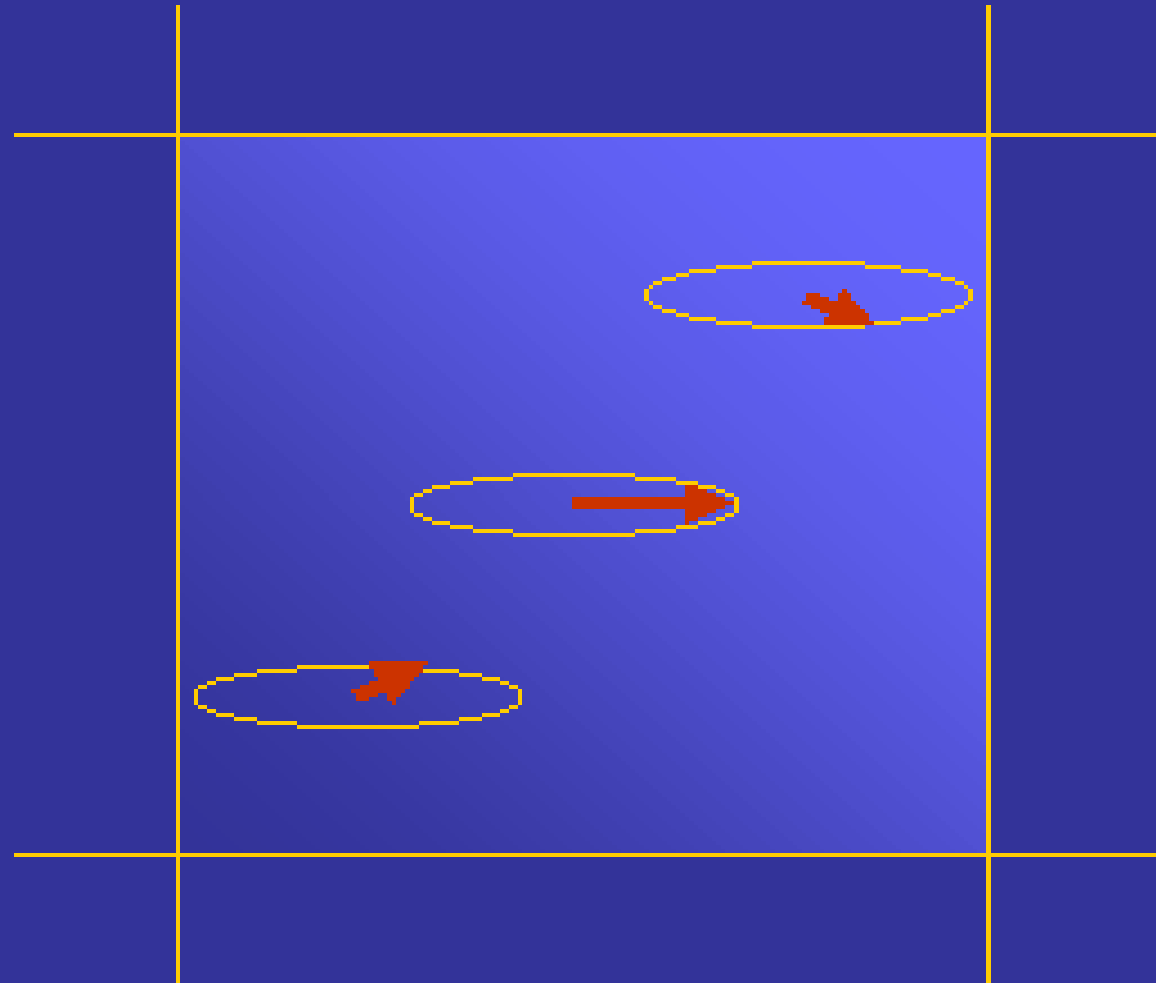
T2 Relaxation

- immediately after the absorption of the RF energy and the initiation of precession, the process of T2 relaxation begins
- results from loss of phase coherence among groups of protons rotating in the transverse plane



Spin Dephasing after excitation

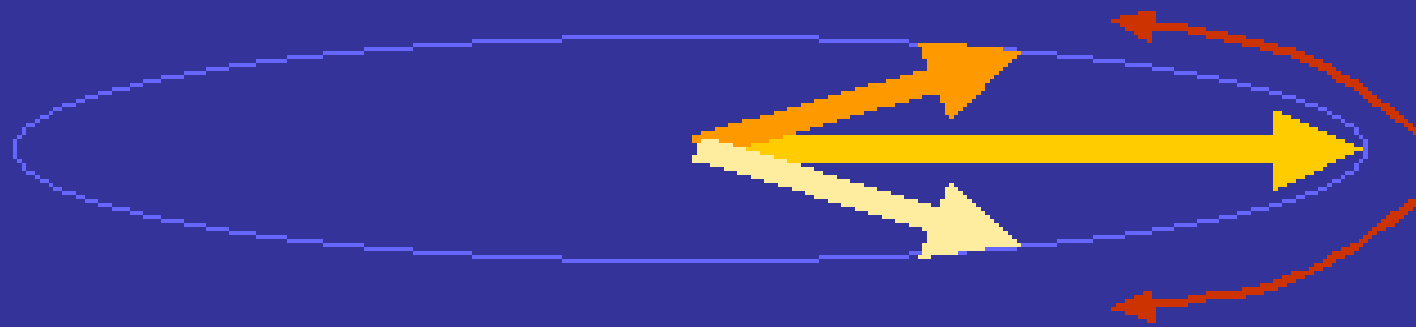
What is T_2^* ?



The Spin Echo



The Spin Echo



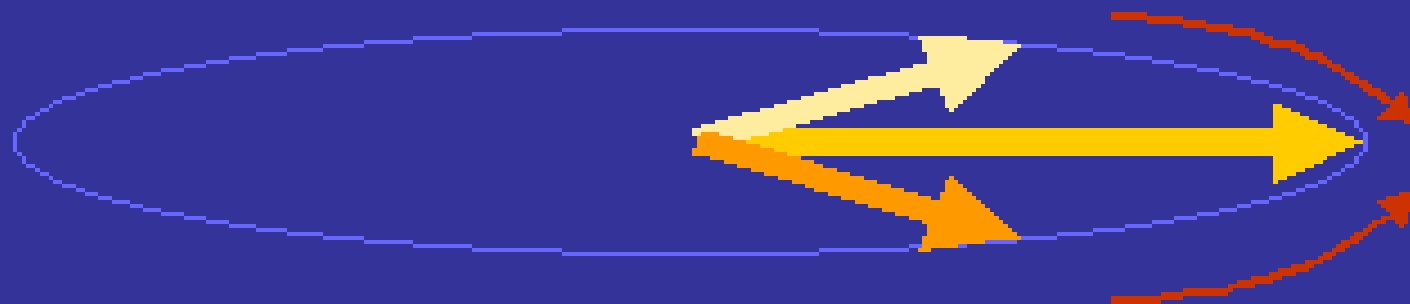
The Spin Echo



The Spin Echo

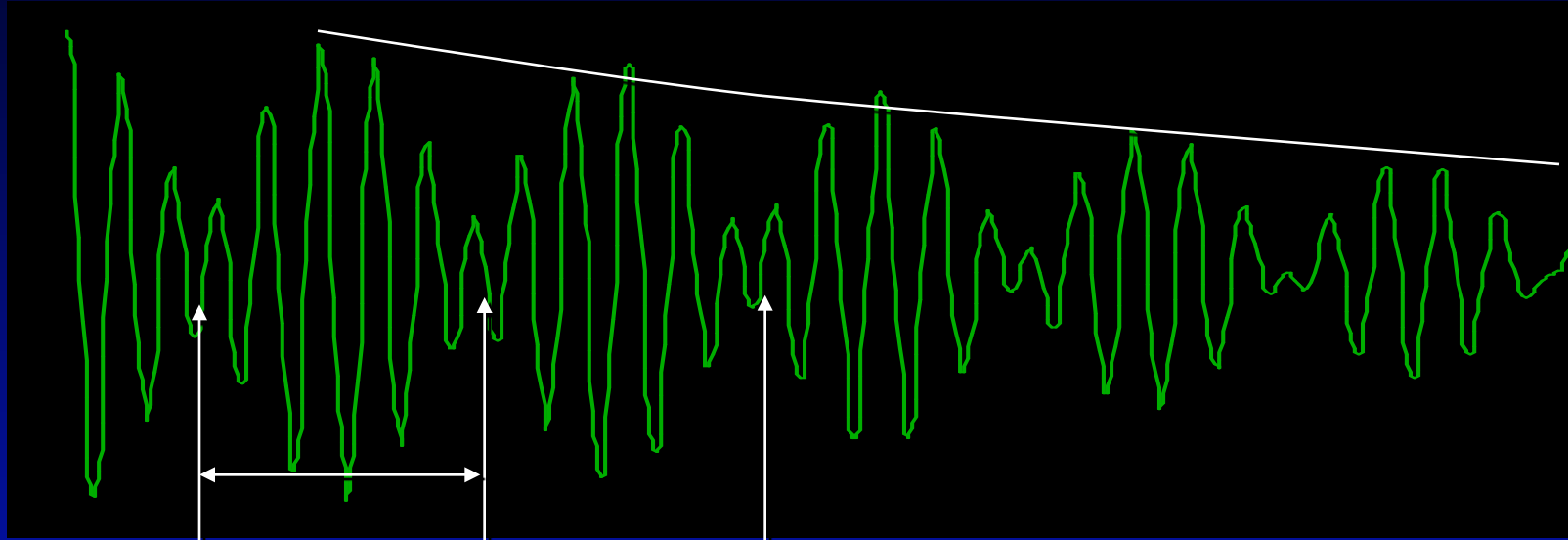


The Spin Echo



The Spin Echo



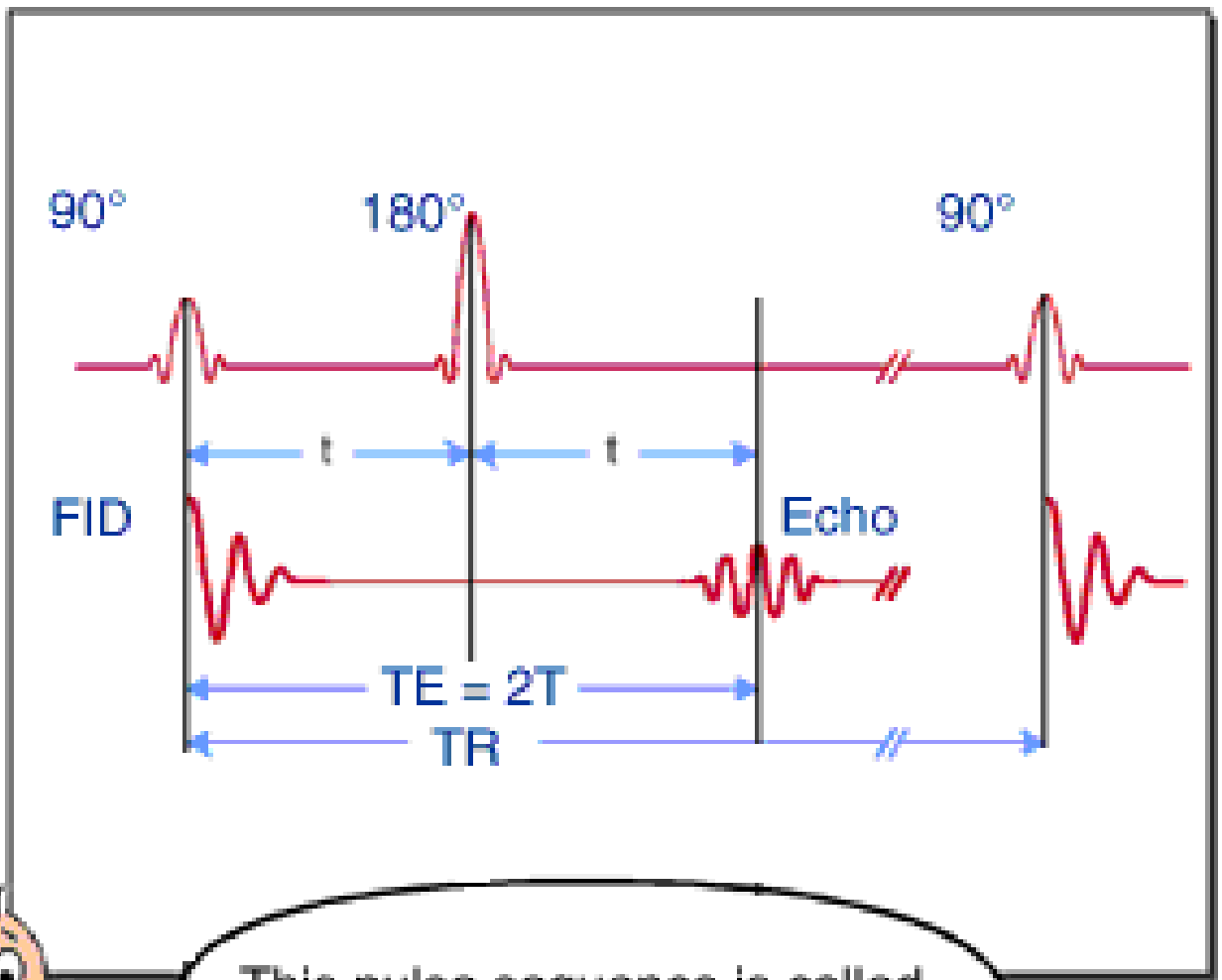


180° TE 180° 180°
Time Echo

returned RF Signal

T2 and T2* Relaxation

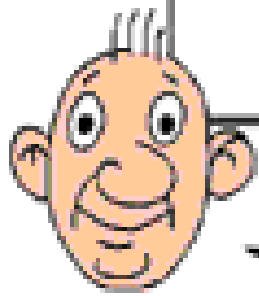
- T2* is the observed T2 relaxation time
- T2 is the natural relaxation time
- $T2^* < T2$



FID=Free Induction Decay

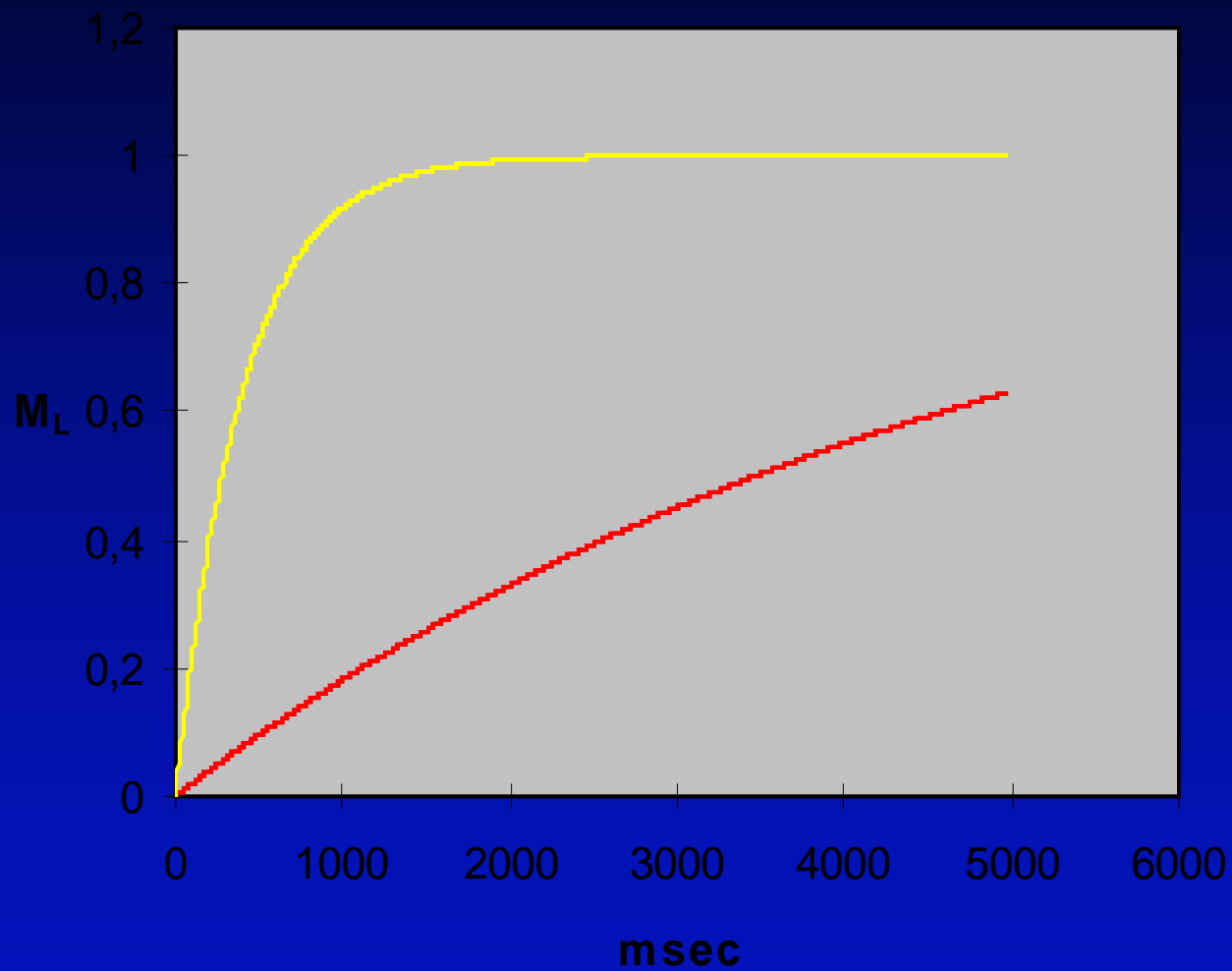
TE=Time Echo

TR=Time Repetition

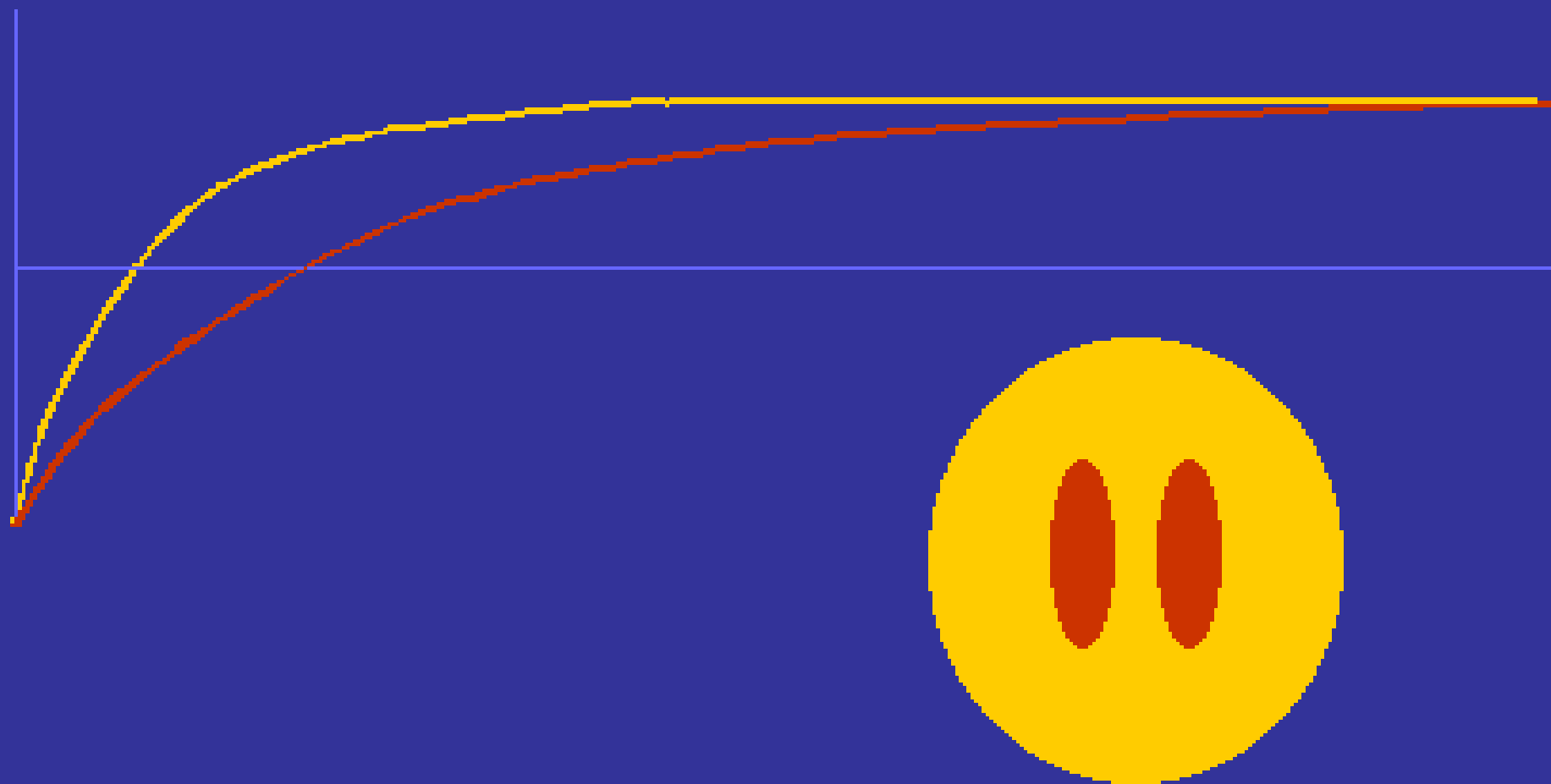


This pulse sequence is called a Spin Echo Sequence.

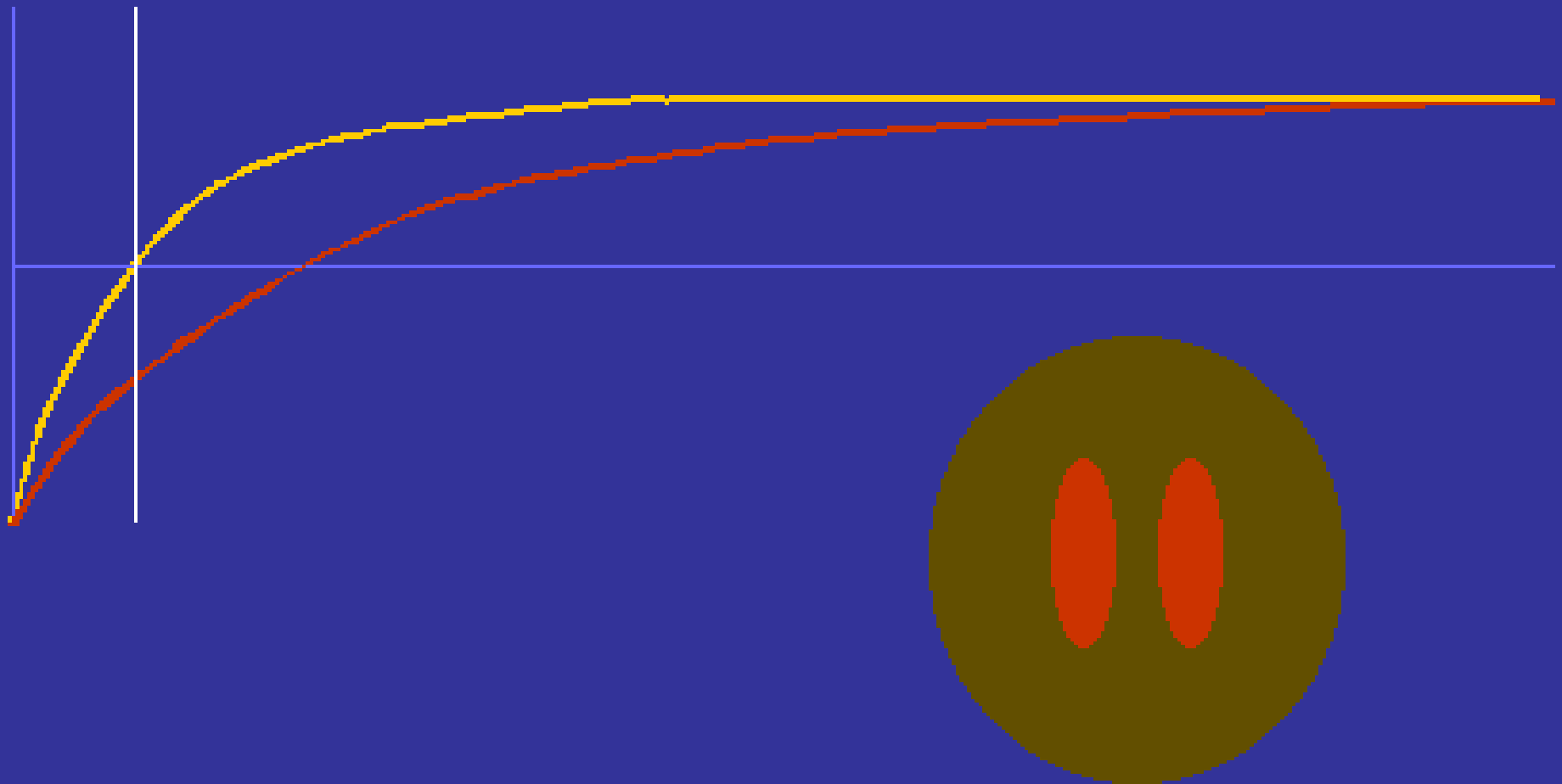
T1 Relaxation



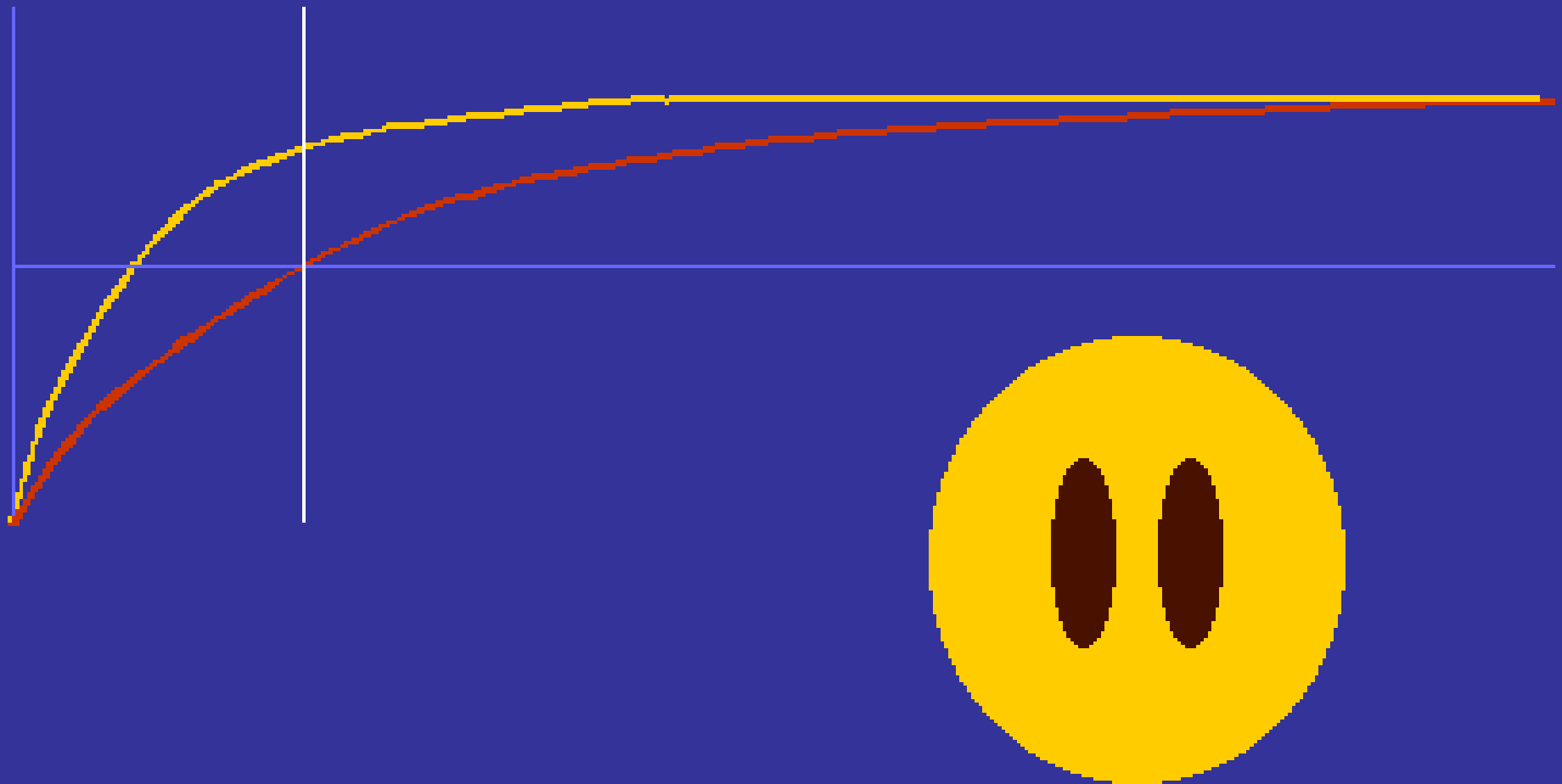
T_1 -Weighted Images



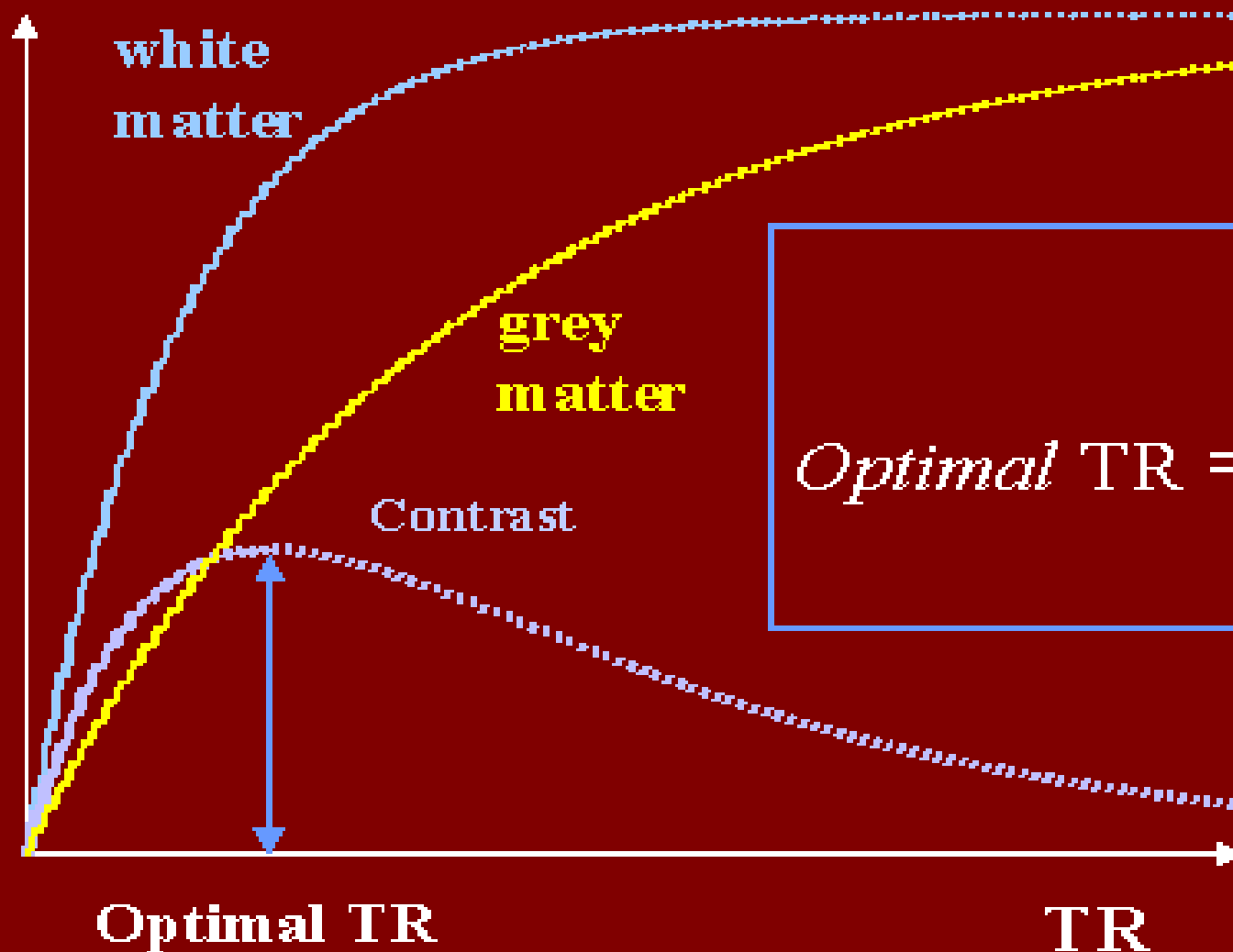
T_1 -Weighted Images



T₁-Weighted Images

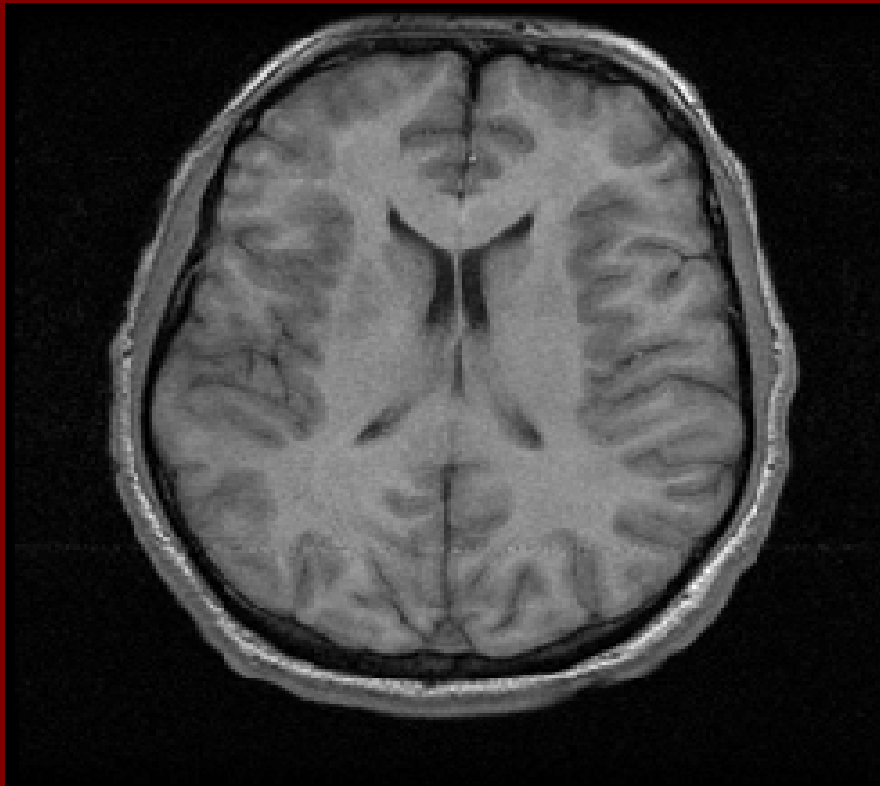


T1 Weighted Imaging



$$\text{Optimal TR} = \frac{\ln\left(\frac{T_{1b}}{T_{1a}}\right) T_{1a} T_{1b}}{T_{1a} - T_{1b}}$$

T1 Weighted Image



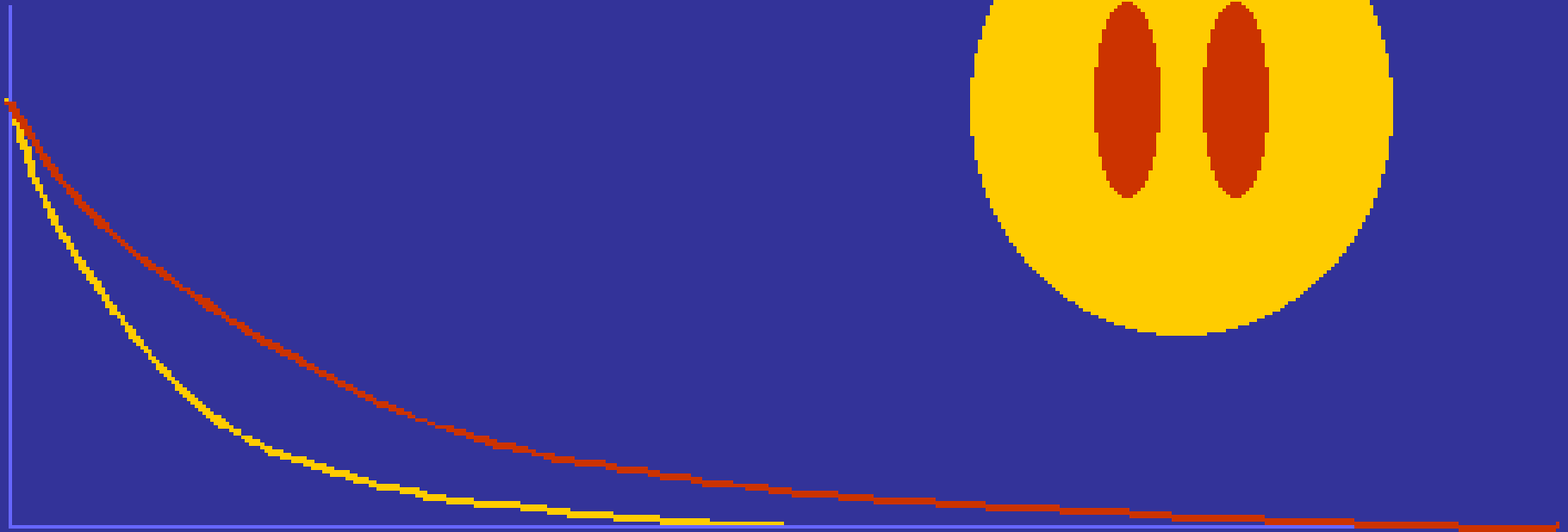
	T_1/s	R_1/s^{-1}
white matter	0.7	1.43
grey matter	1	1
CSF	4	0.25

1.5T

SPGR, TR=14ms, TE=5ms, flip=20°

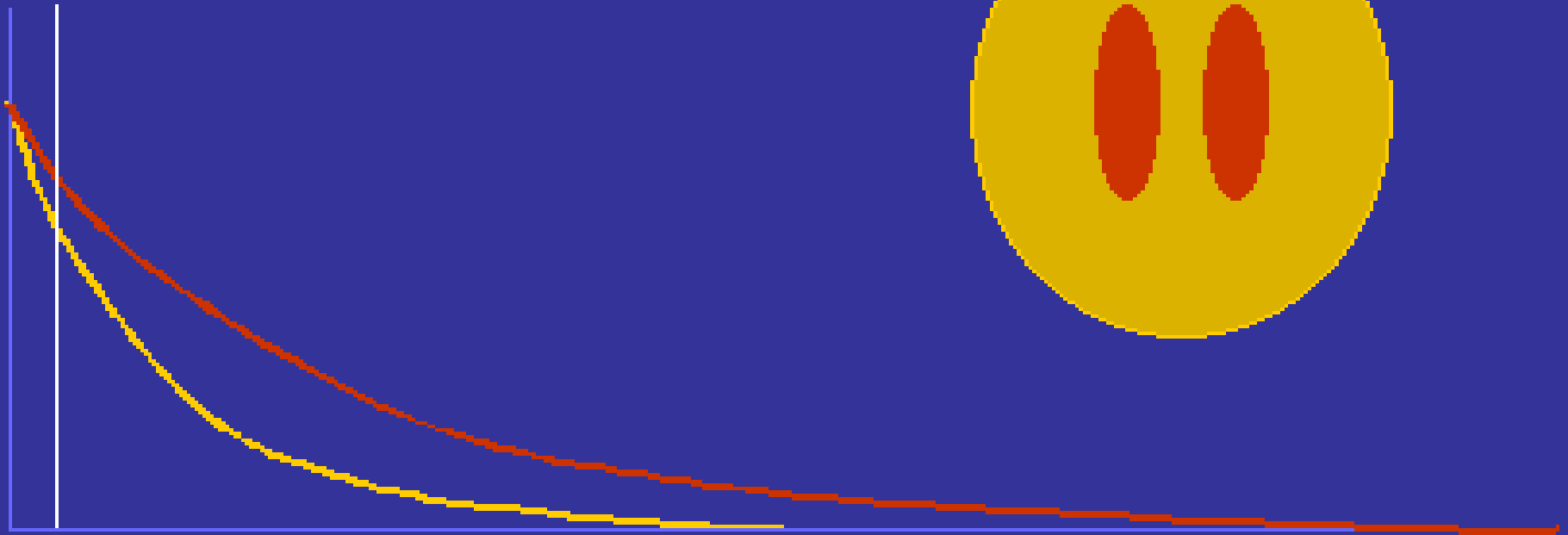
What effect does T_2^* have on Images?

- Effect of echo time



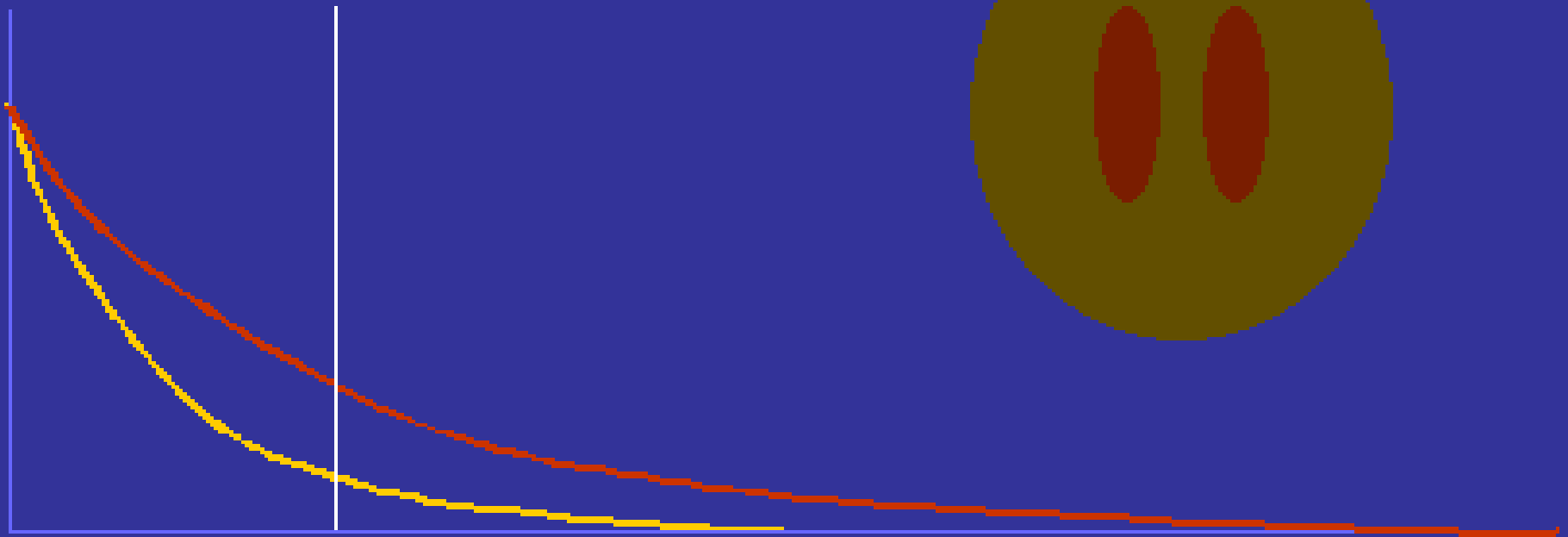
What effect does T_2^* have on Images?

- Effect of echo time



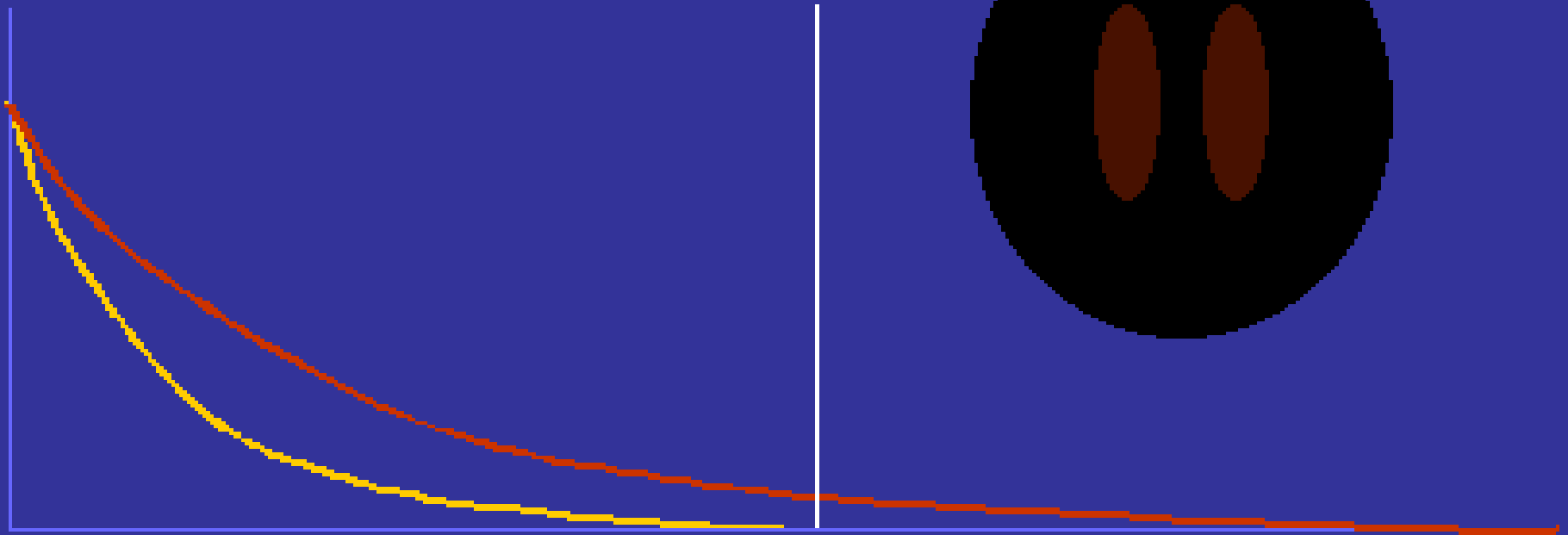
What effect does T_2^* have on Images?

- Effect of echo time

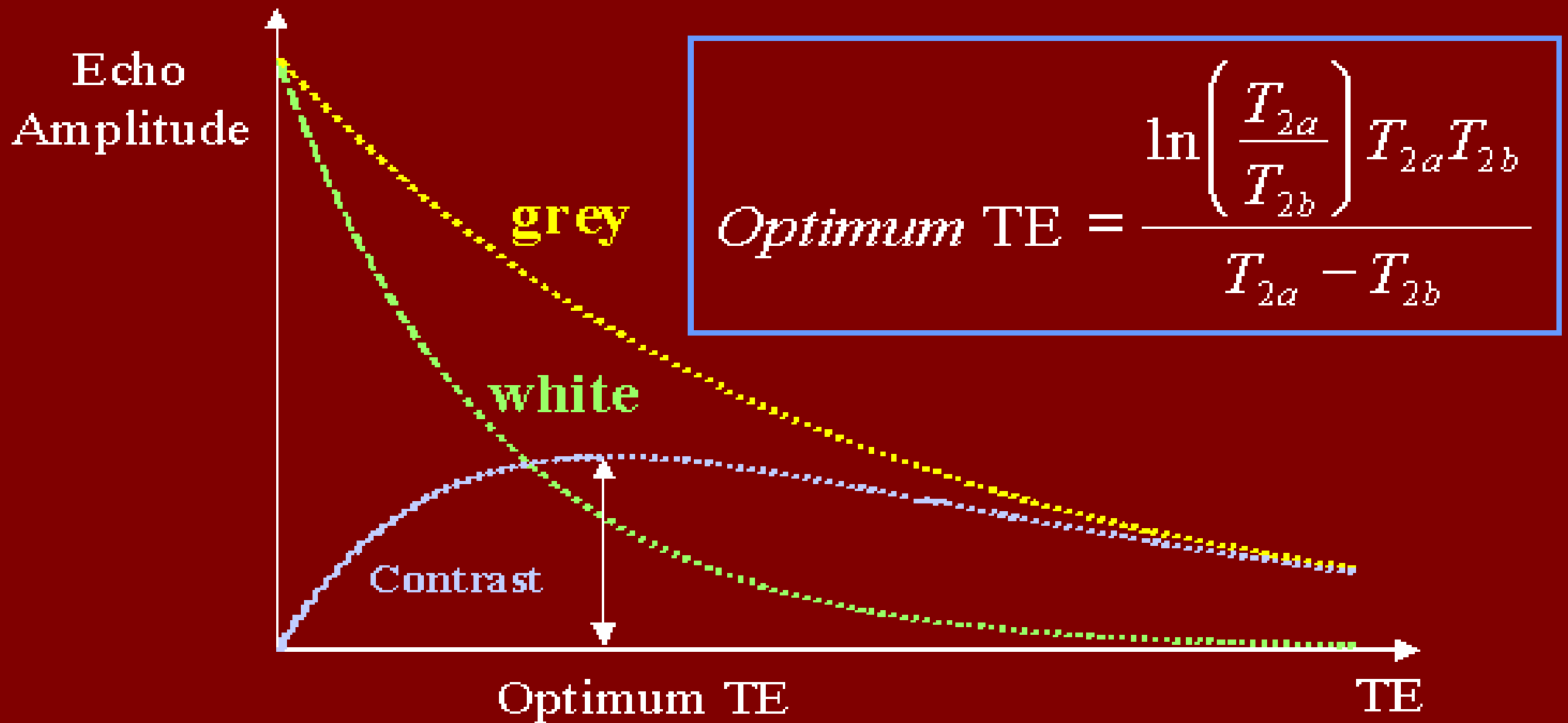


What effect does T_2^* have on Images?

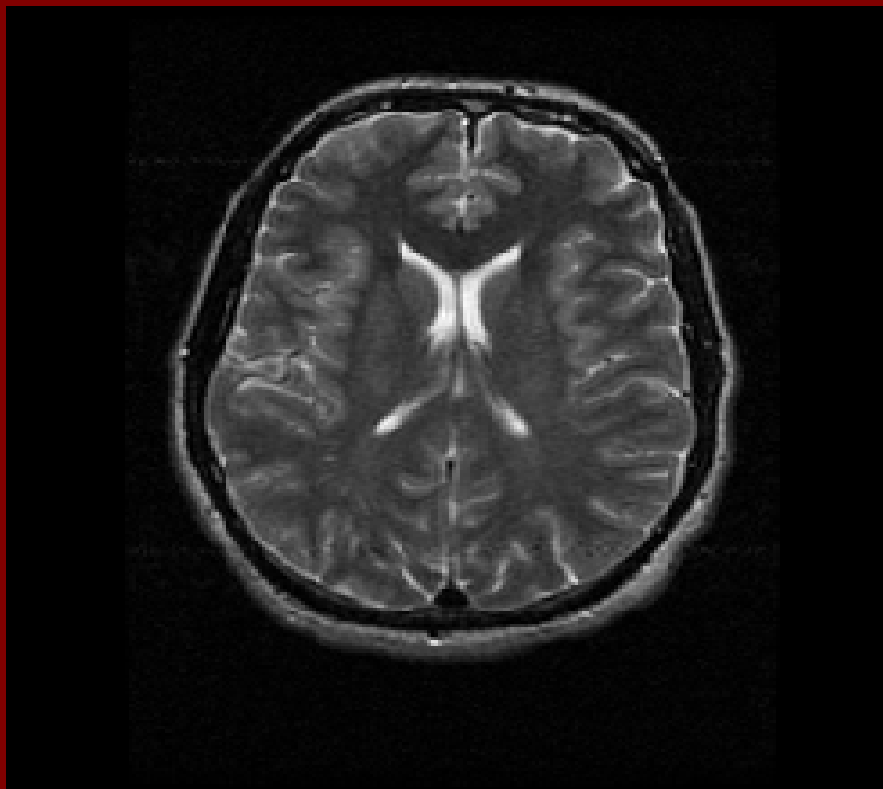
- Effect of echo time



T2 Weighted Imaging



T2 Weighted Image



	T ₂ /ms
CSF	500
grey matter	80–90
white matter	70–80

1.5T

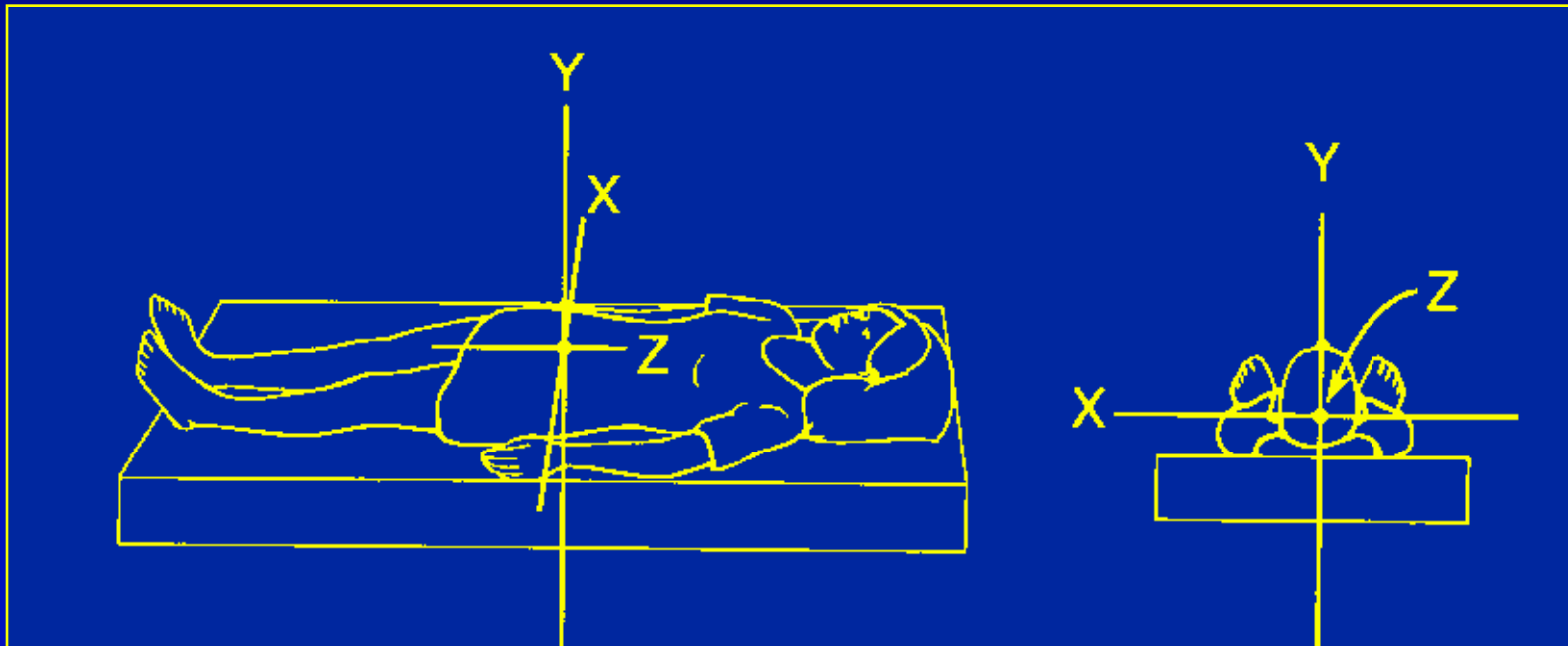
SE, TR=4000ms, TE=100ms

SPATIAL ENCODING

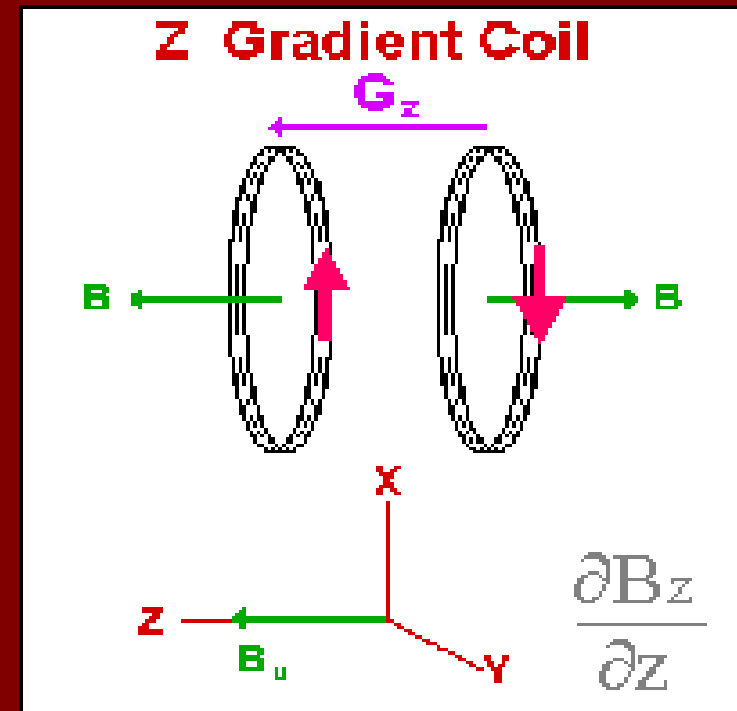
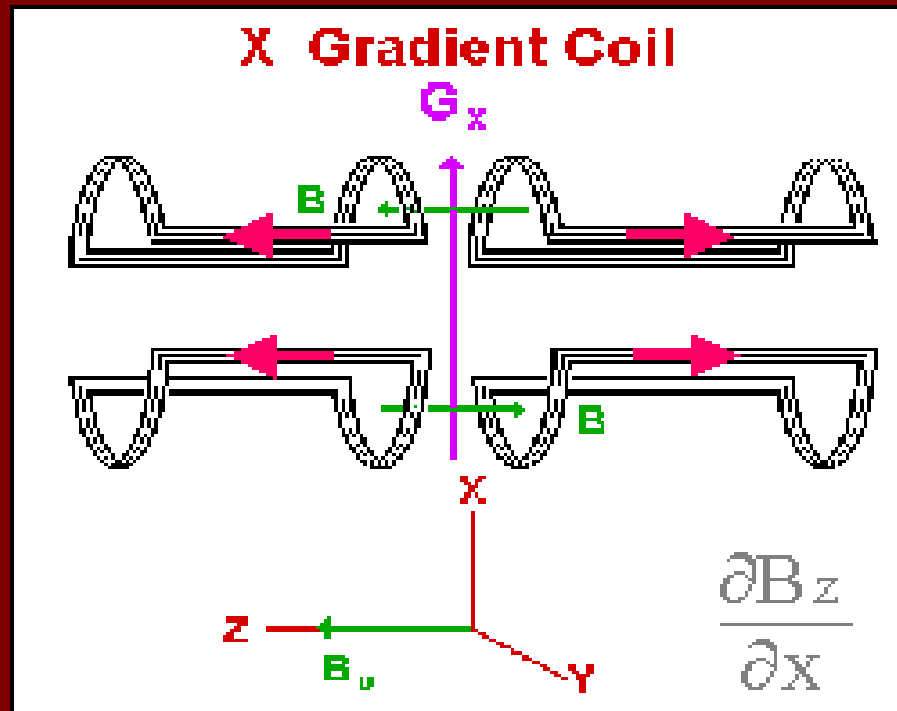
- **Spatial encoding is accomplished by superimposing *gradient* fields.**
- **There are three gradient fields in the **x, y, and z** directions.**
- ***Gradients* alter the magnetic field resulting in a change in resonance frequency or a change in phase.**

MRI

- The main magnetic field is oriented in the z direction.
- Gradient fields are located in the x , y , and z directions.



Principle of Gradient Coil



MRI

- **The three magnetic gradients work together to encode the NMR signal with spatial information.**
- **Remember:** *the resonance frequency depends on the magnetic field strength. Small alterations in the magnetic field by the gradient coils will change the resonance frequency.*

Gradients

- The gradients have different names

Z gradient: slice select

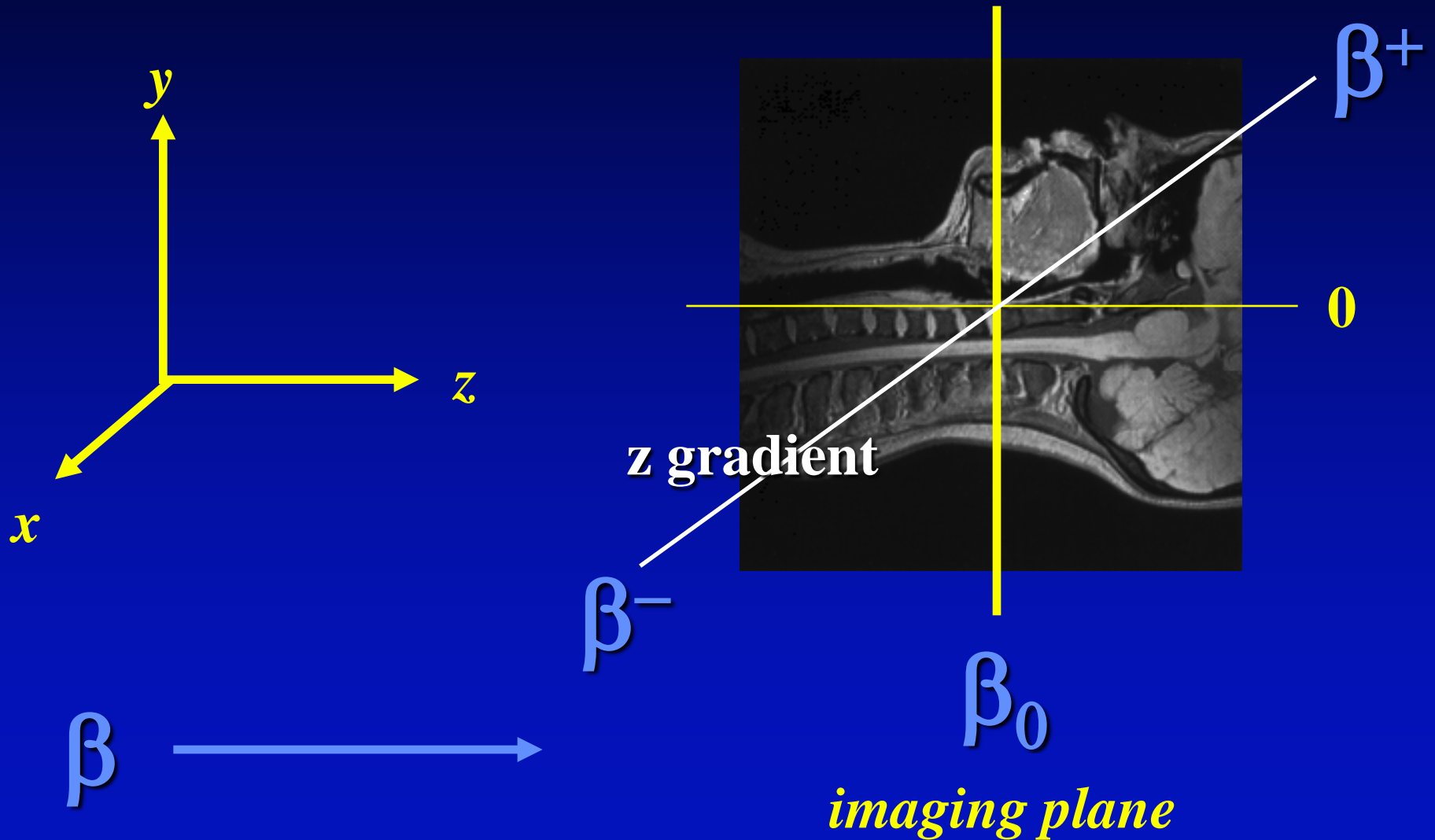
X gradient: frequency encode (readout)

Y gradient: phase encode

Slice Selection

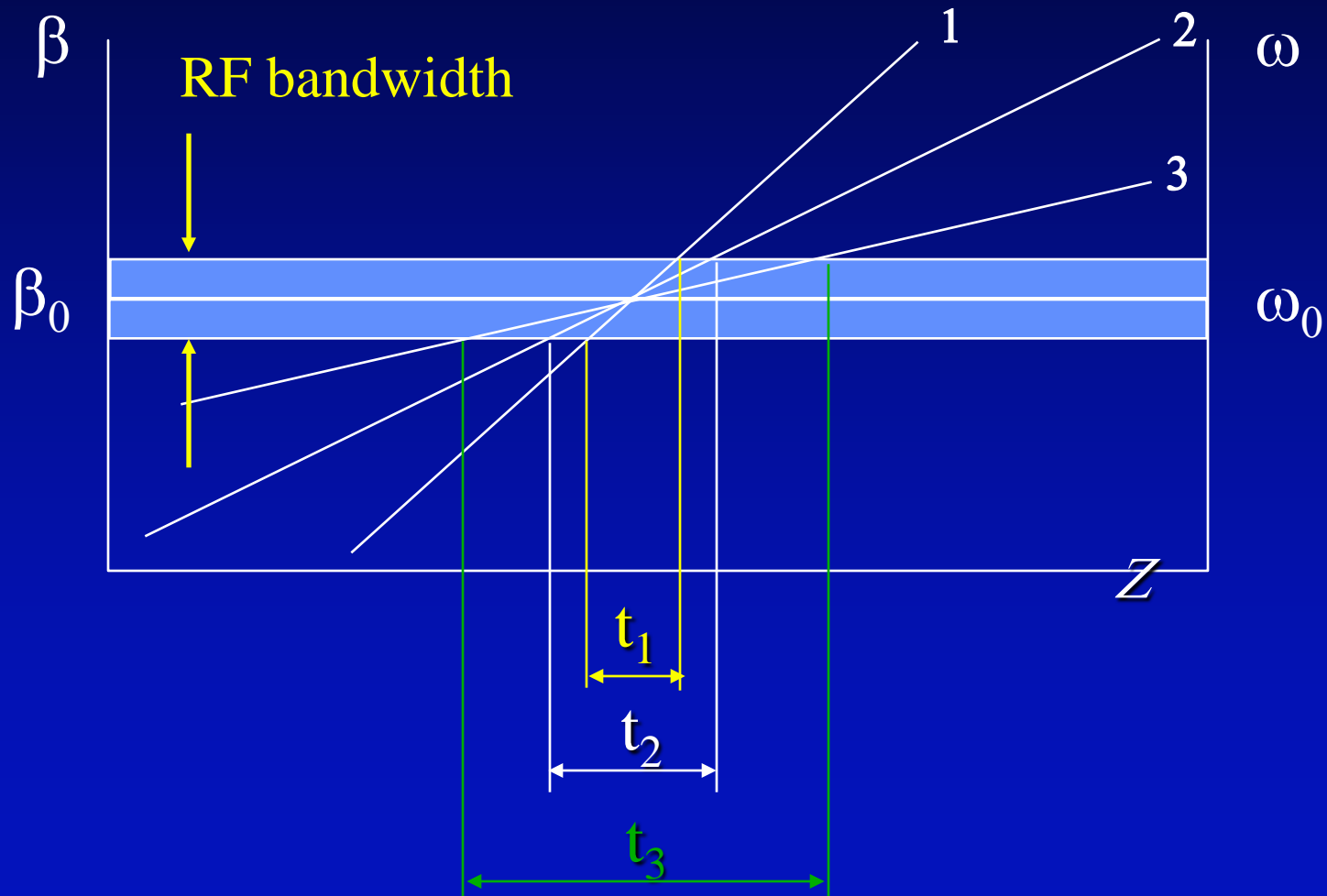
- **For axial imaging, slice selection occurs along the long axis of the magnet.**
- **Superposition of the slice selection gradient causes non-resonance of tissues that are located above and below the plane of interest.**

Slice Selection



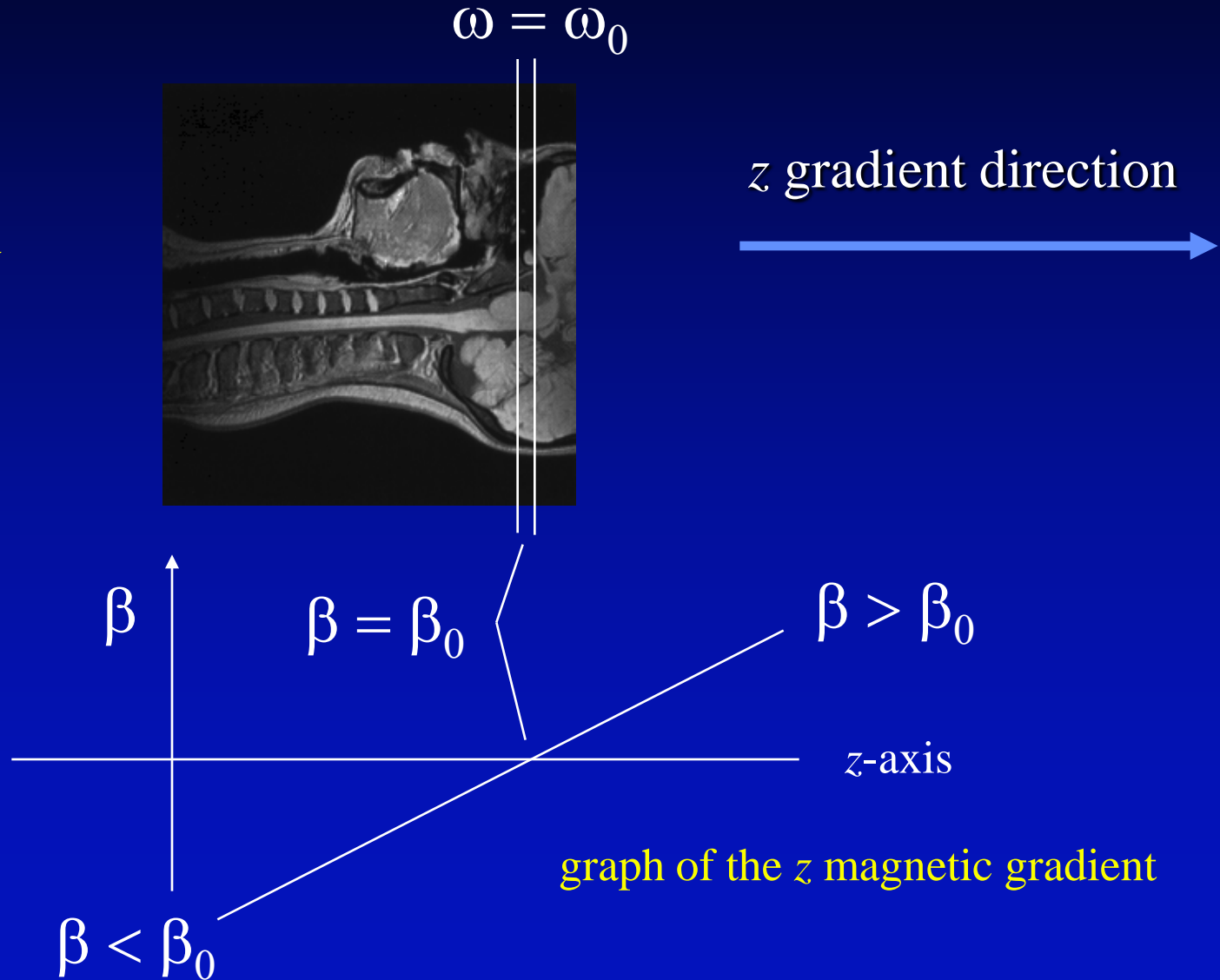
Slice Selection

slice thickness is determined by gradient strength



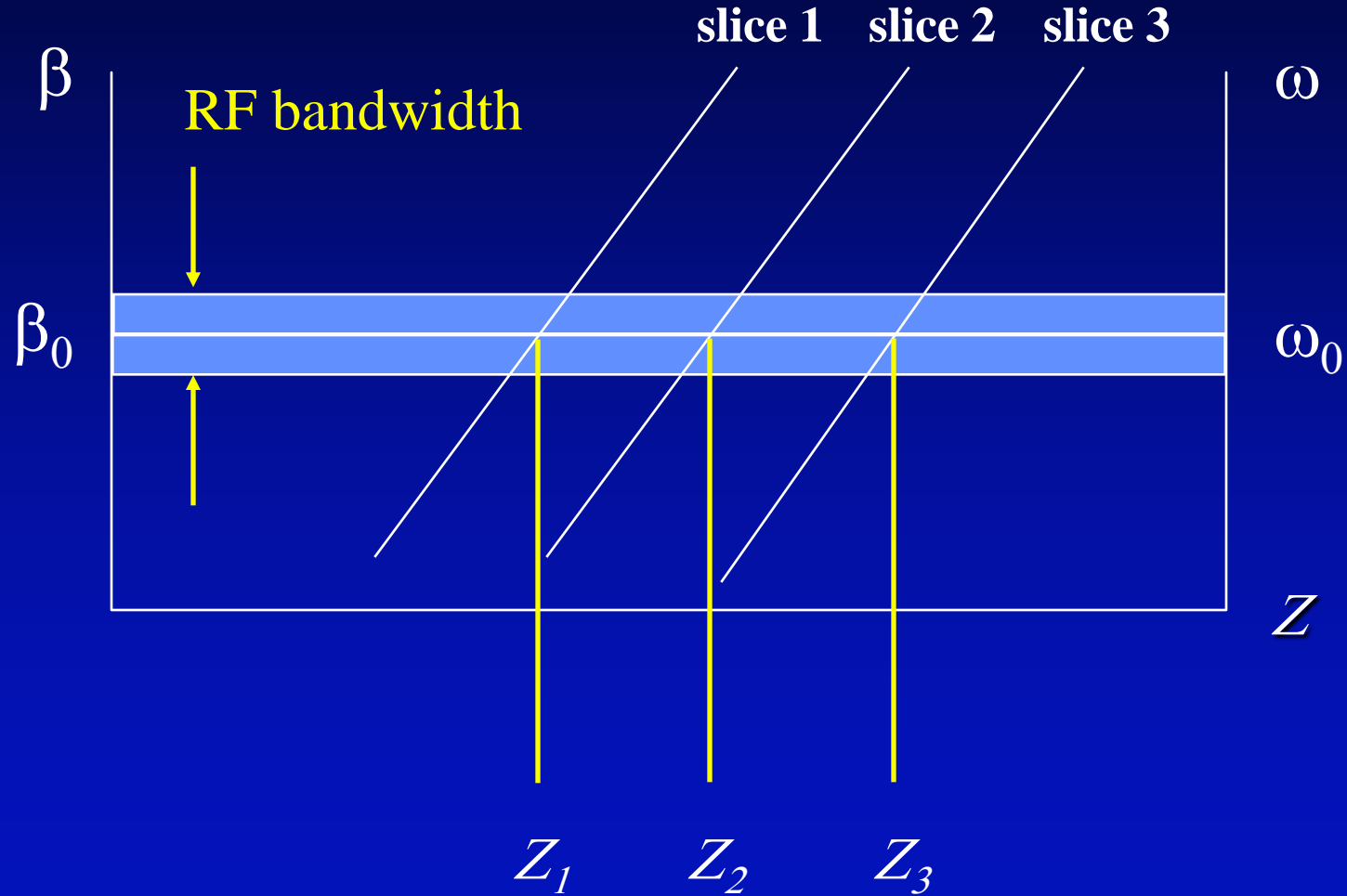
Slice Selection

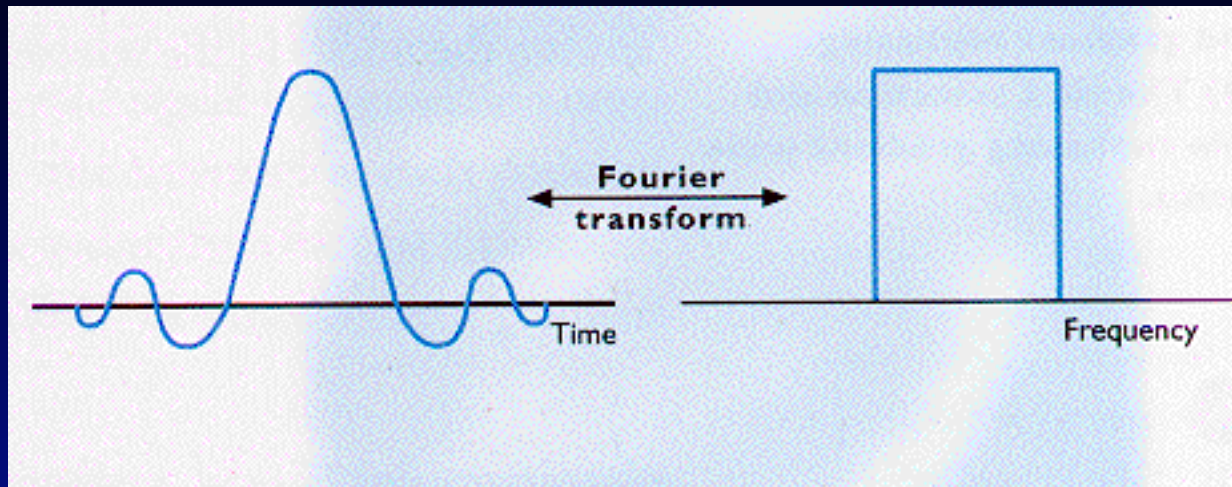
Selection of an axial slice is accomplished by the z gradient.



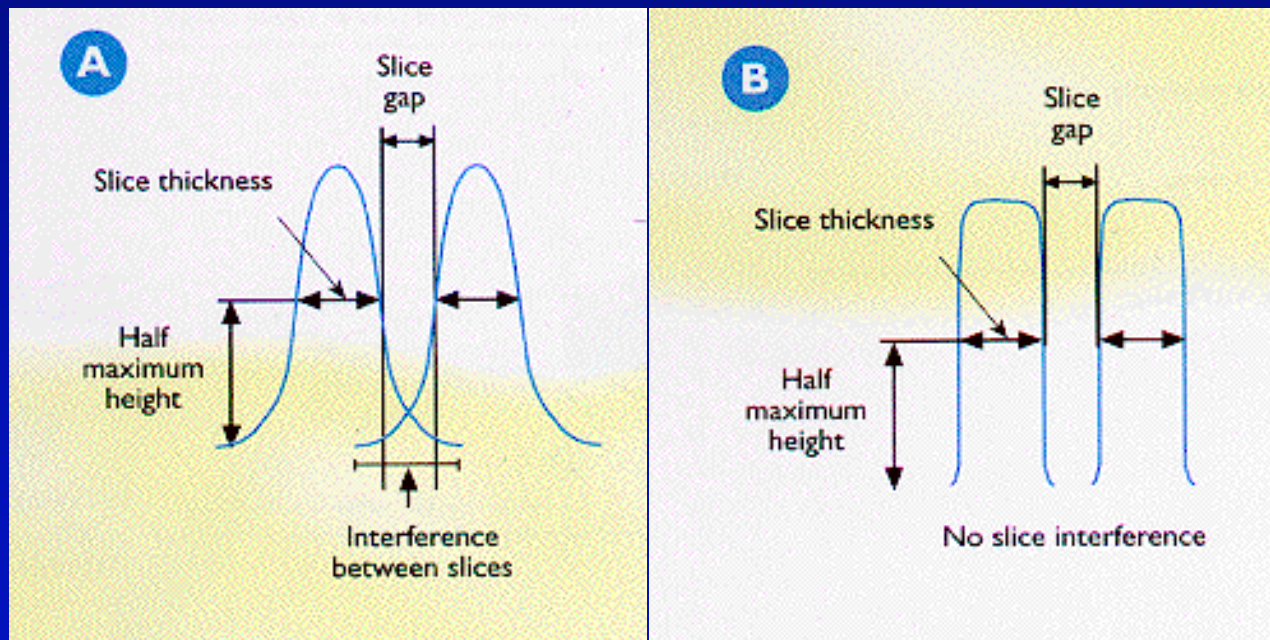
Slice Selection

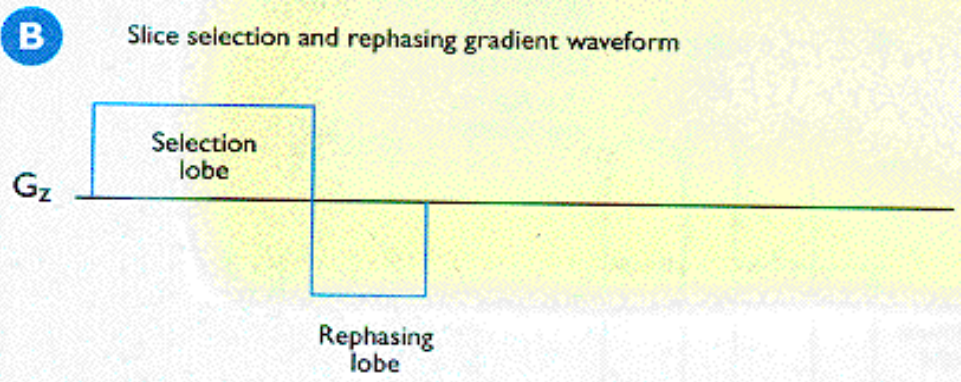
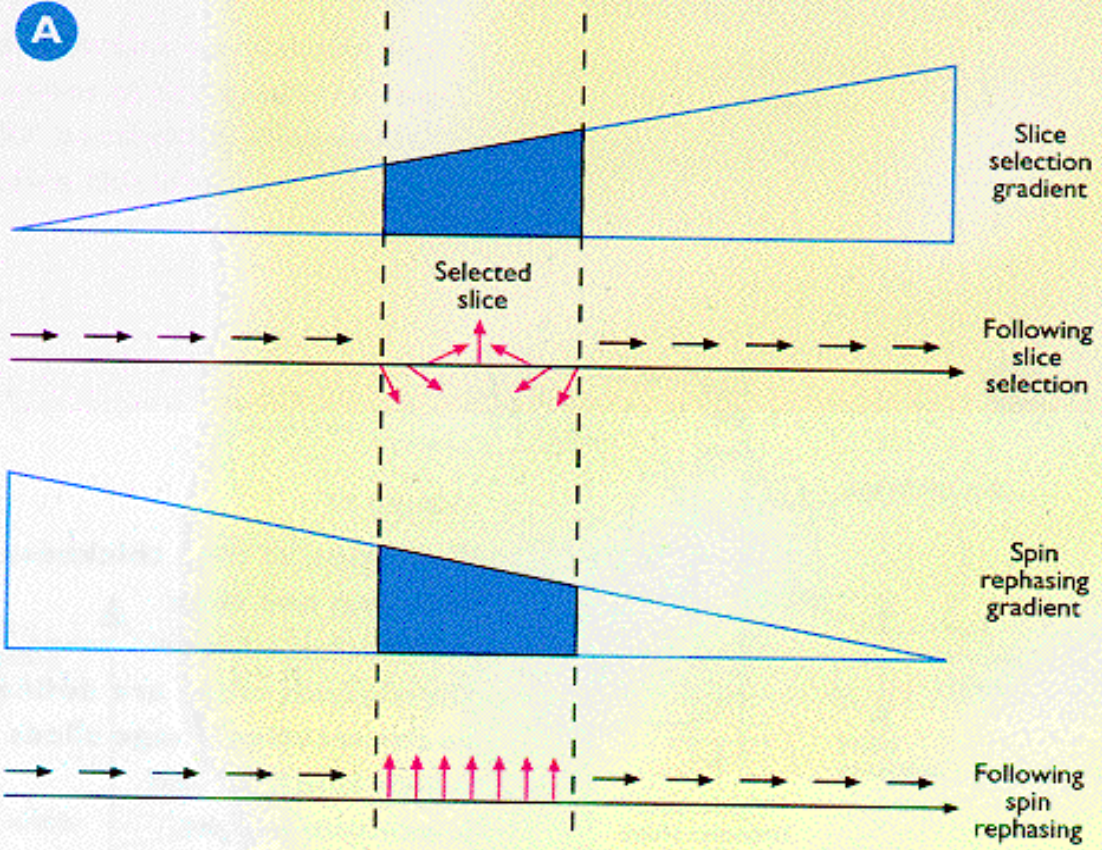
slice location is determined by the null point of the z gradient





The shape of the RF-pulse relates to the thickness and shape of the slice.



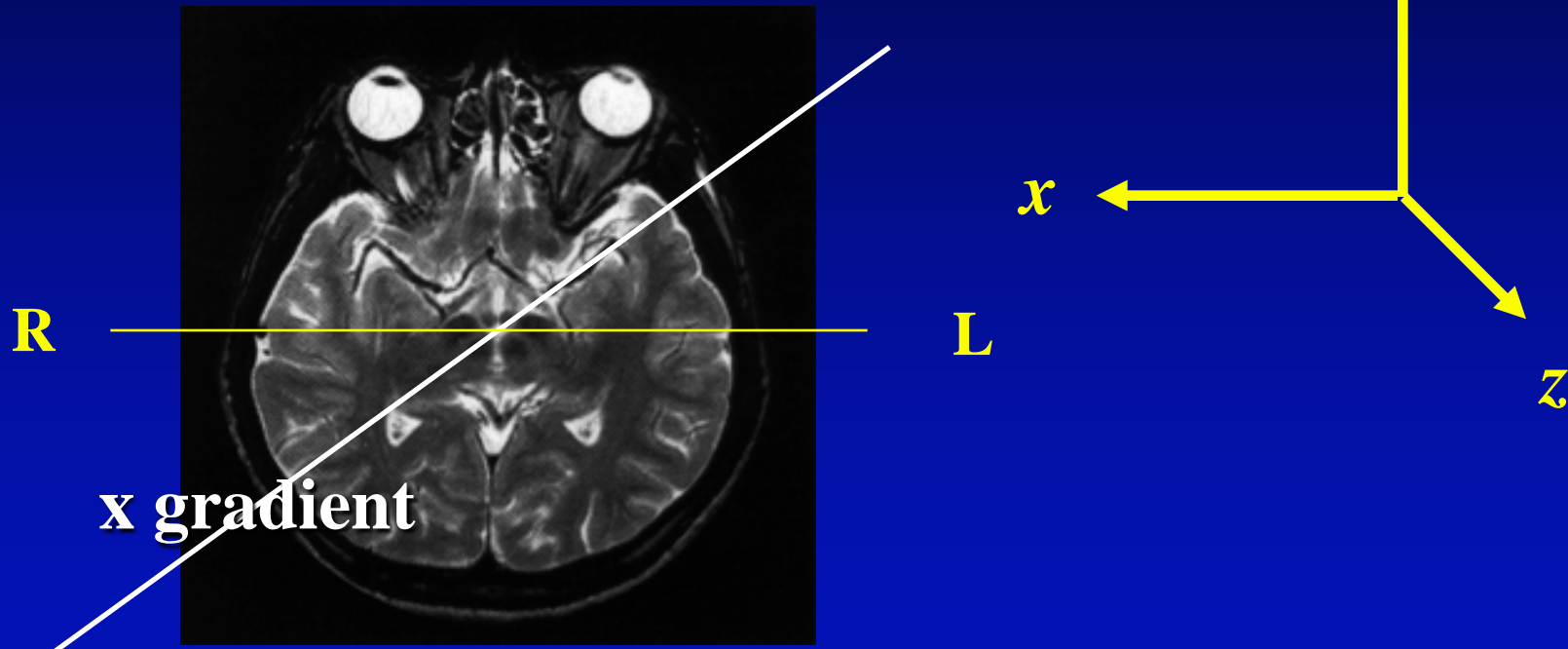


In the gradient field protons will precess with slightly different frequency. They will rapidly be out of phase and the signal strength will decrease.

An opposite gradient will compensate for this. The protons will spin with the same phase which increases the strength of the signal.

Frequency Encoding

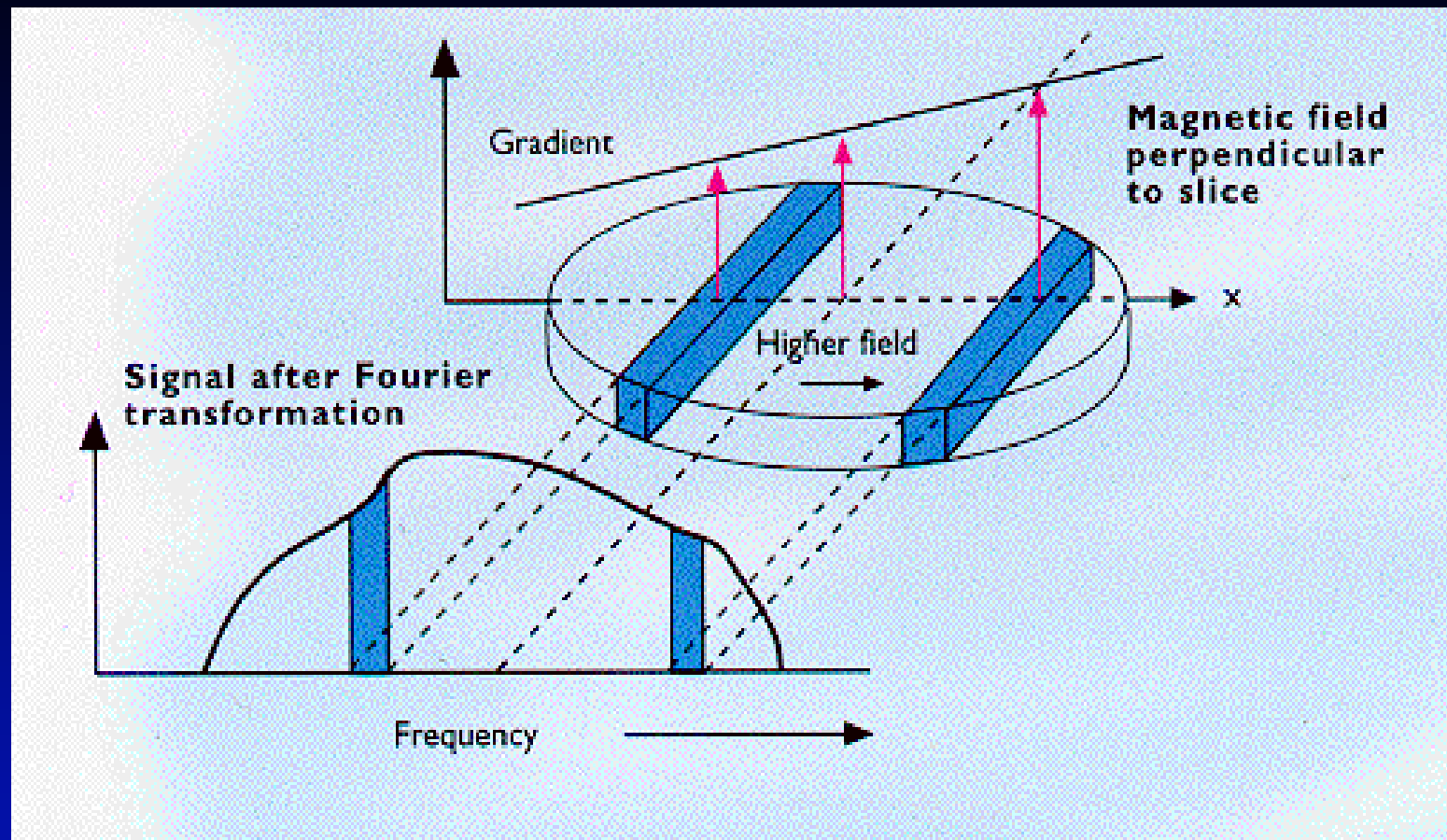
higher frequency



lower frequency

Frequency Encoding

- Within the imaging plane, a small gradient is applied left to right to allow for spatial encoding in the x direction.
- Tissues on the left will have a slightly higher resonance frequency than tissues on the right.
- The superposition of an x gradient on the patient is called *frequency encoding*.
- Frequency encoding enables spatial localization in the L-R direction only.



In the chosen slice the protons will spin with different frequency in the x -gradient. The antenna will pick up a wider frequency spectrum. A Fourier analysis gives the number of spinning protons as a function of frequency which is x -coordinate dependant.

Fourier analysis of the signal give frequency and amplitude

Frequency and x-coordinate is coupled

You get a projection of spin-amplitude as a function of x

Collect projections from all directions

Apply FBP

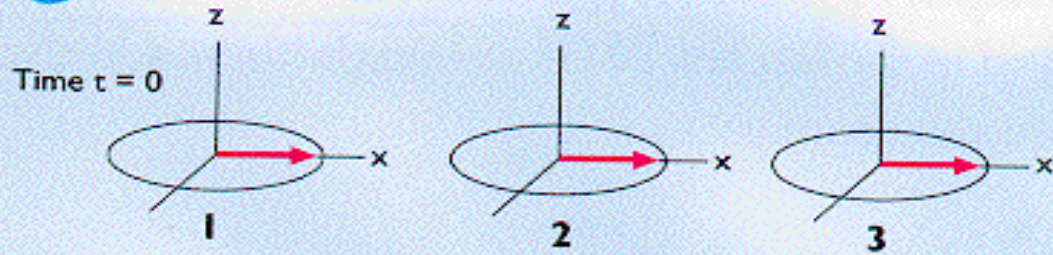
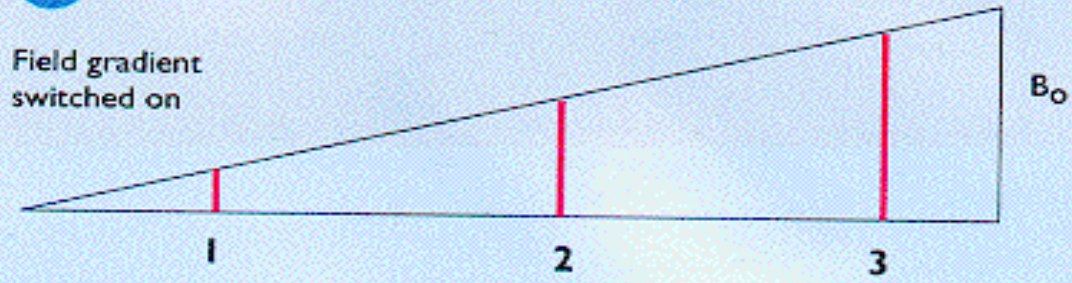
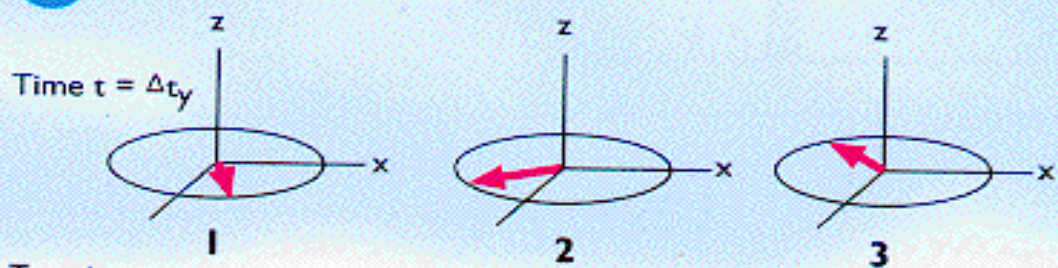
Phase Encoding

- An additional gradient is applied in the y direction to encode the image in the remaining direction.
- Because the x gradient alters the *frequencies* in the received signal according to spatial location, the y gradient must alter the *phase* of the signal.

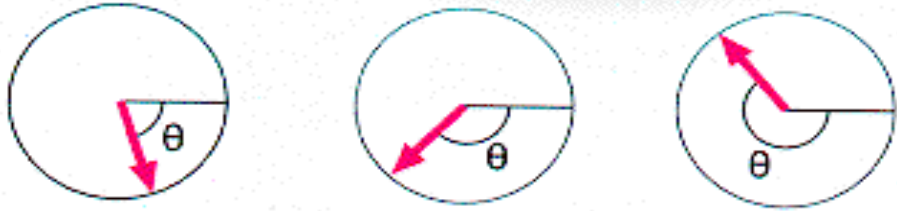
Waves and Frequencies

- **simplest wave is a cosine wave**
- **properties**
 - **frequency (f)**
 - **phase (ϕ)**
 - **amplitude (A)**

$$f(x) = A \cos(2\pi f x + \phi)$$

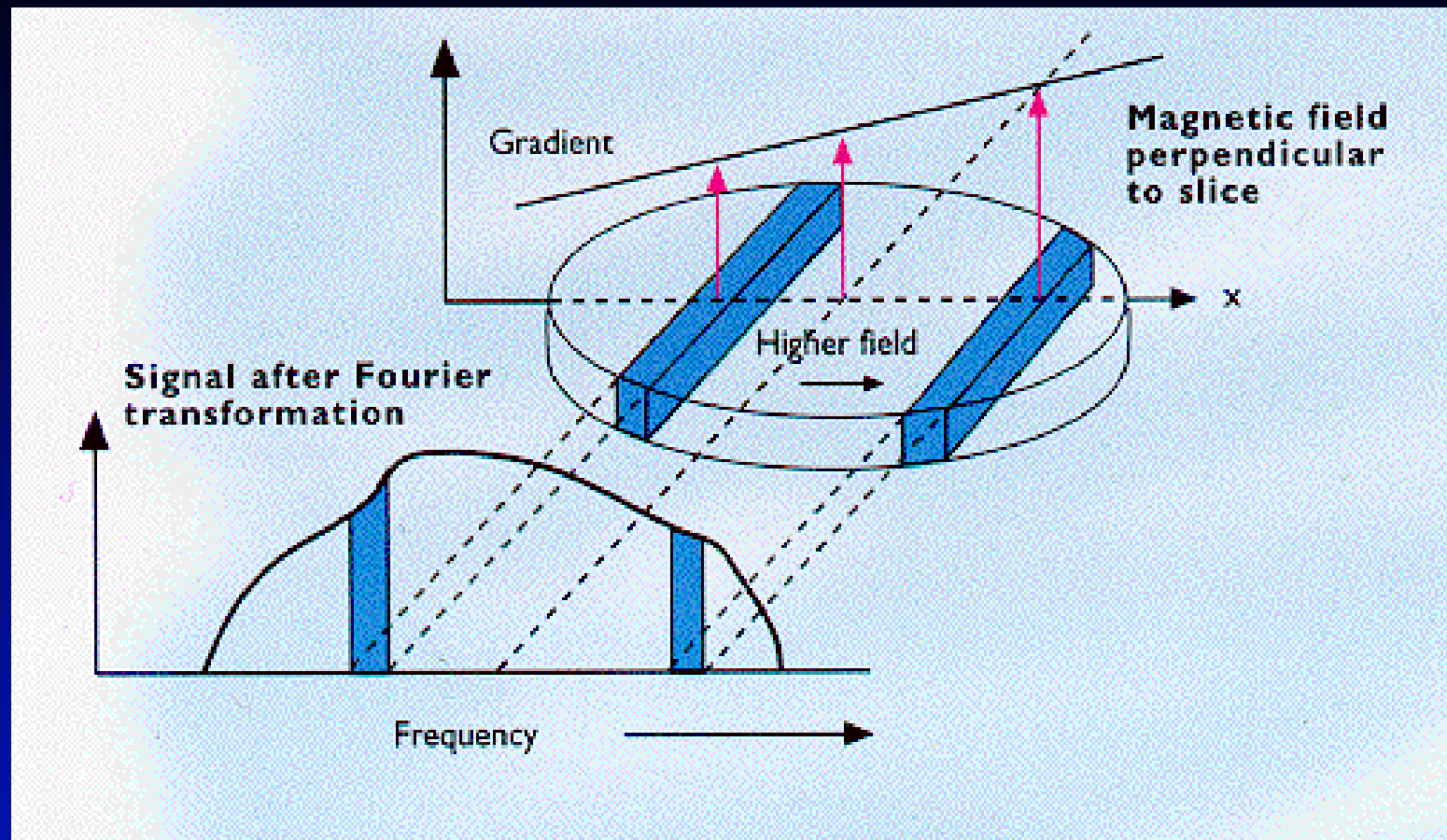
A**B****C**

Top view



After picking out the slice the protons are having the same frequency and the same phase.

For a short moment a gradient is applied (y-gradient). It gives a phase shift which is related to the y-coordinate.



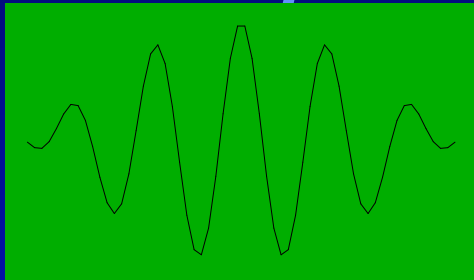
Then we apply the read-out gradient while listening. Each x -position have a variation in phase that contains information about the y -coordinate

Phase Encoding

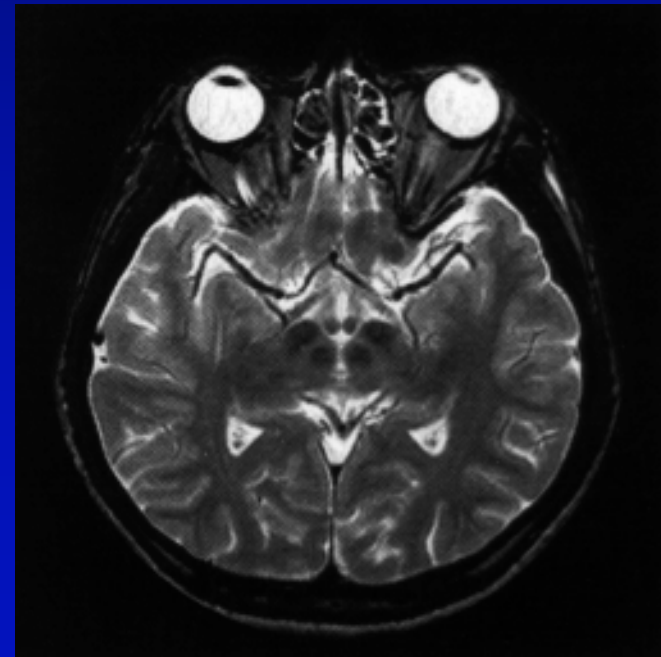
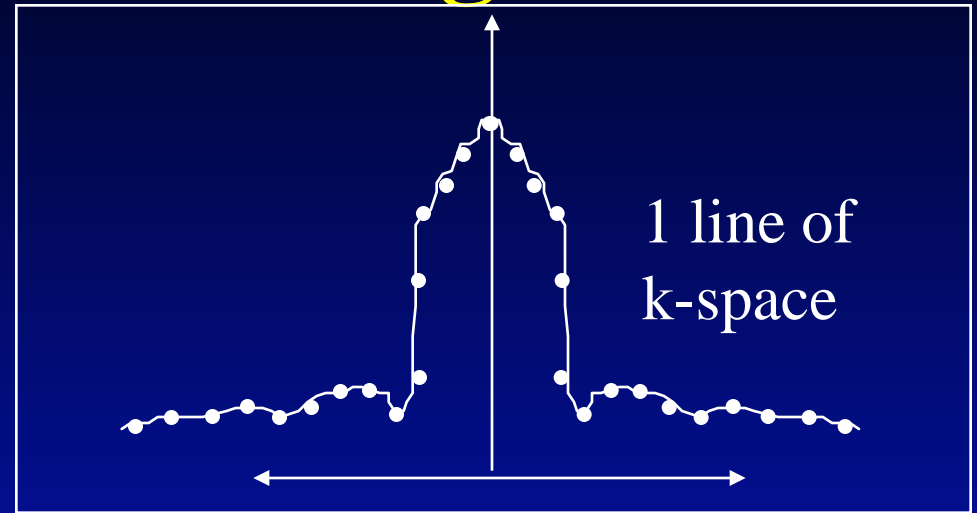
- The technique of phase encoding the second dimension in the imaging plane is sometimes referred to as *spin warping*.
- The phase encoding gradient is “stepped” during the acquisition of image data for a single slice. Each step provides a unique phase encoding.
- For a 256 x 256 square image matrix, 256 unique phase encodings must be performed for each image slice. The second 256 points in the x direction are obtained by A to D conversion of the received signal.

Frequency Encoding

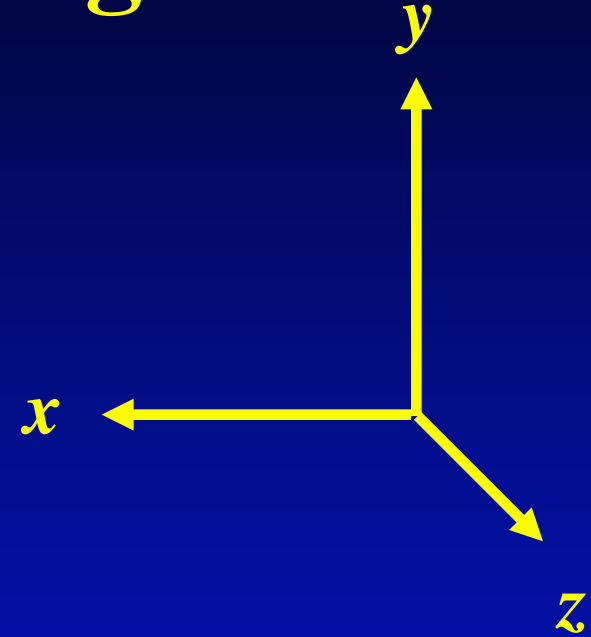
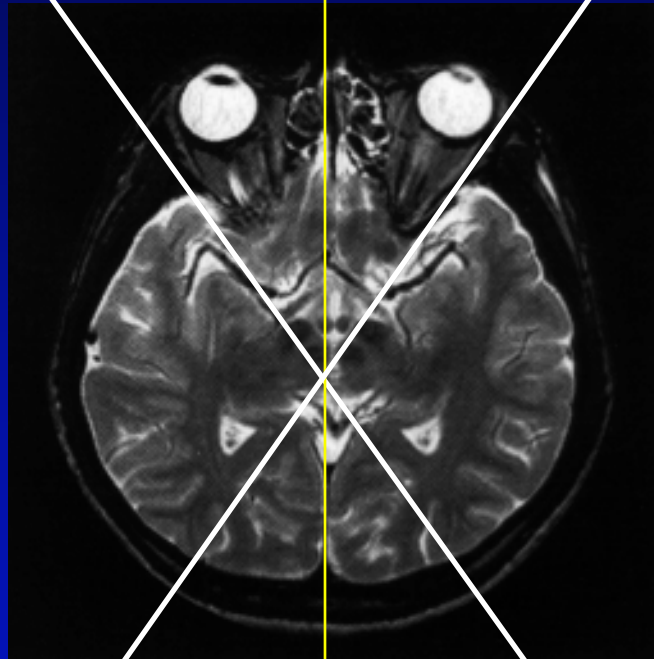
A/D conversion, 256 points



RF signal
from entire slice

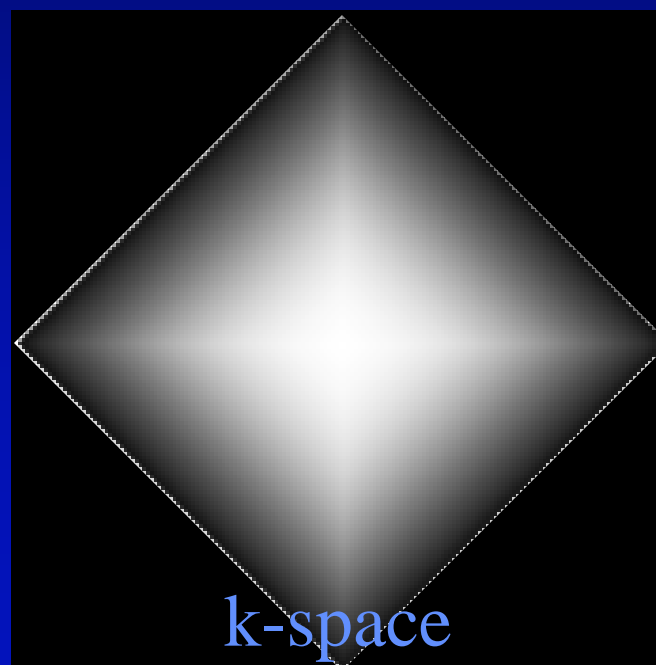
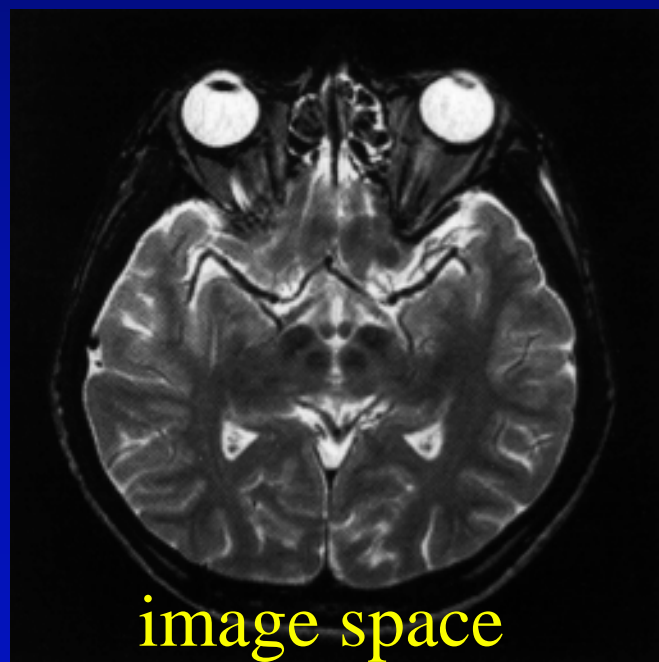
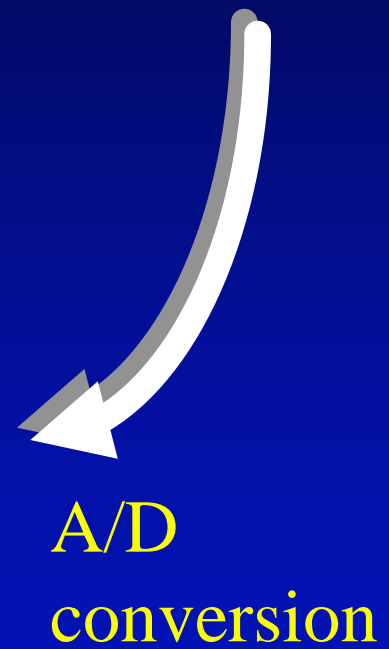
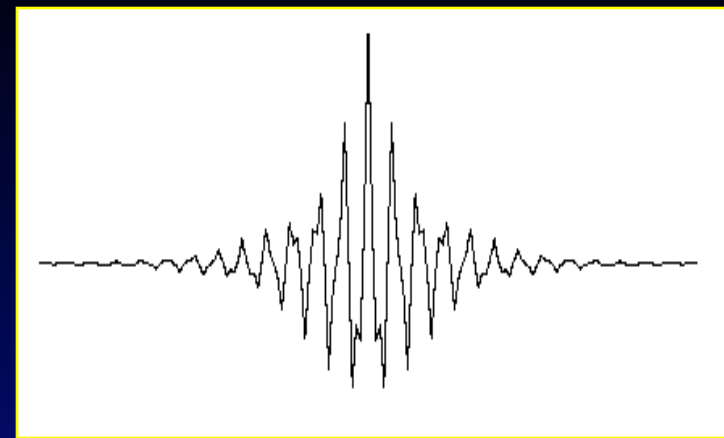
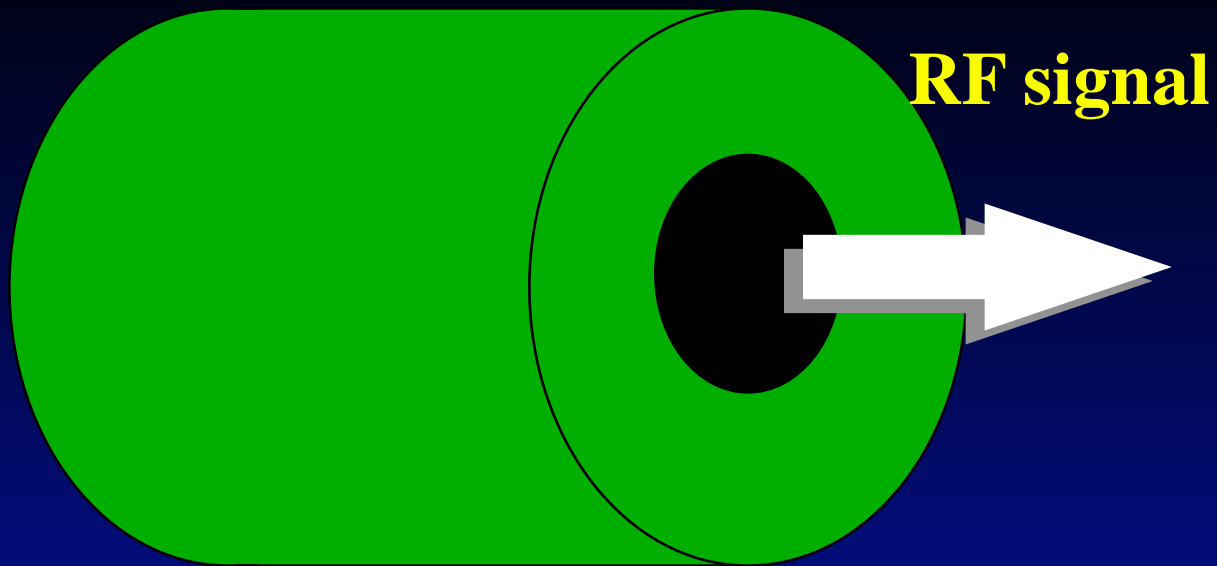


Phase Encoding



y gradient,
phase step #64

y gradient,
phase step #192



What is k-space?

- a mathematical concept
- not a real “space” in the patient nor in the MR scanner
- key to understanding spatial encoding of MR images

k-space is the *temporary image space* in which data from digitized MR signals are stored during data acquisition. When *k*-space is full (at the end of the scan), the data are mathematically processed to produce a final image. Thus *k*-space holds *raw* data before *reconstruction*.

k -space is in spatial frequency domain. We define k_{FE} and k_{PE} such that

and
$$k_{\text{FE}} = \bar{\gamma} G_{\text{FE}} m \Delta t$$

$$k_{\text{PE}} = \bar{\gamma} n \Delta G_{\text{PE}} \tau$$

where

FE refers to *frequency encoding*,

PE to *phase encoding*,

Δt is the sampling time (the reciprocal of sampling frequency),

τ is the duration of G_{PE} ,

(*gamma bar*) is the gyromagnetic ratio,

m is the sample number in the FE direction and

n is the sample number in the PE direction (also known as *partition number*),

The 2D-Fourier Transform of this encoded signal results in a representation of the spin density distribution in two dimensions. k -space has the same number of rows and columns as the final image. During the scan, k -space is filled with raw data one line per TR (Repetition Time).

k-space and the MR Image

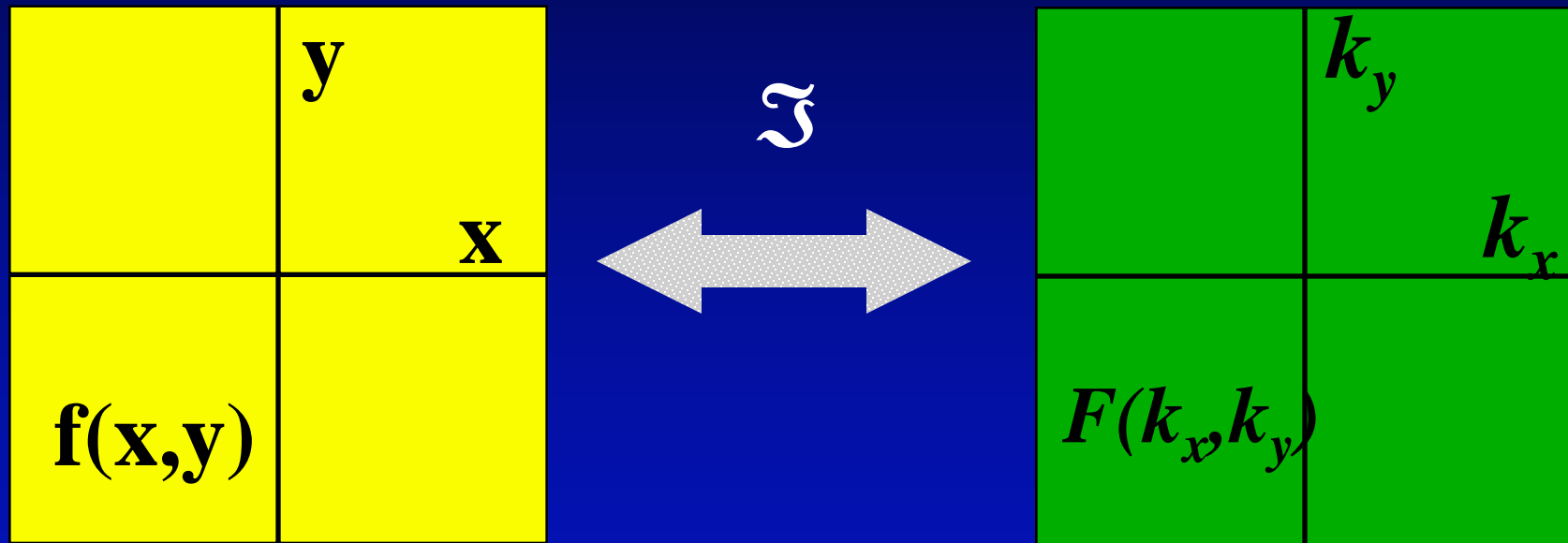


Image-space

K-space

k-space and the MR Image

- **each individual point in the MR image is reconstructed from every point in the k-space representation of the image**
 - **like a card shuffling trick: you must have all of the cards (k-space) to pick the single correct card from the deck**
- **all points of k-space must be collected for a faithful reconstruction of the image**

Discrete Fourier Transform

$F(k_x, k_y)$ is the 2D discrete Fourier transform of the image $f(x, y)$

$$f(x, y) = \frac{1}{N^2} \sum_{k_x=0}^{N-1} \sum_{k_y=0}^{N-1} F(k_x, k_y) e^{j\frac{2\pi}{N} x k_x + j\frac{2\pi}{N} y k_y}$$

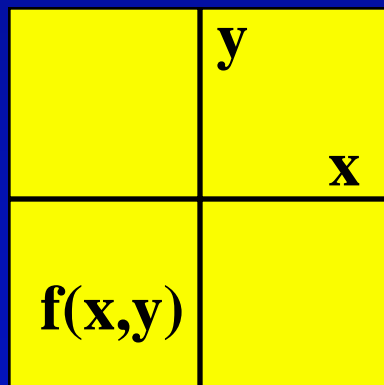
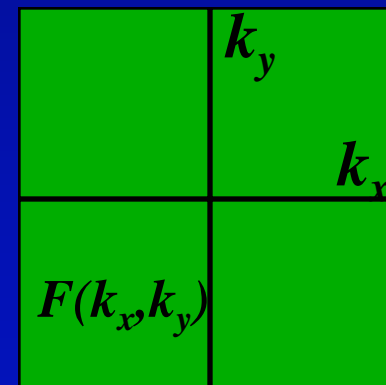


image-space



K-space

k-space and the MR Image

- If the image is a 256 x 256 matrix size, then k-space is also 256 x 256 points.
- The individual points in k-space represent *spatial frequencies* in the image.
- *Image contrast is represented by low spatial frequencies; detail is represented by high spatial frequencies.*



low spatial
frequencies



high spatial
frequencies



all
frequencies

Spatial Frequencies

- **low frequency = contrast**
- **high frequency = detail**
- **The most abrupt change occurs at an edge. Images of edges contain the highest spatial frequencies.**

Properties of k-space



- **k-space is symmetrical**
- **all of the points in k-space must be known to reconstruct the signal faithfully**
- **truncation of k-space results in loss of detail, particularly at edges**
- **most important information centered around the middle of k-space**
- **k-space is the Fourier representation of the waveform**