By Yiming Xiao

A BRIEF INTRODUCTION TO

THE PRINCIPLES OF MRI

WHAT IS IN THIS LECTURE?

- Some bits of history of MRI
- How are MR images generated?

  basic physics, image contrast & k-space
- What can you do with MRI?

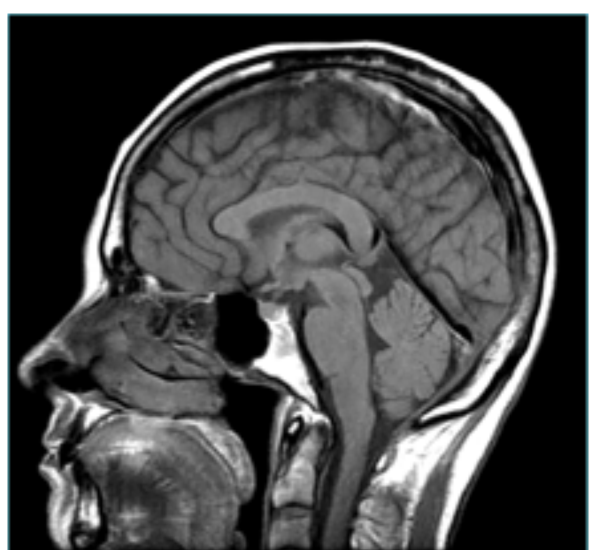
WHAT IS NOT IN THIS LECTURE?

- Complicated Quantum Physics
- Long derivation of equations

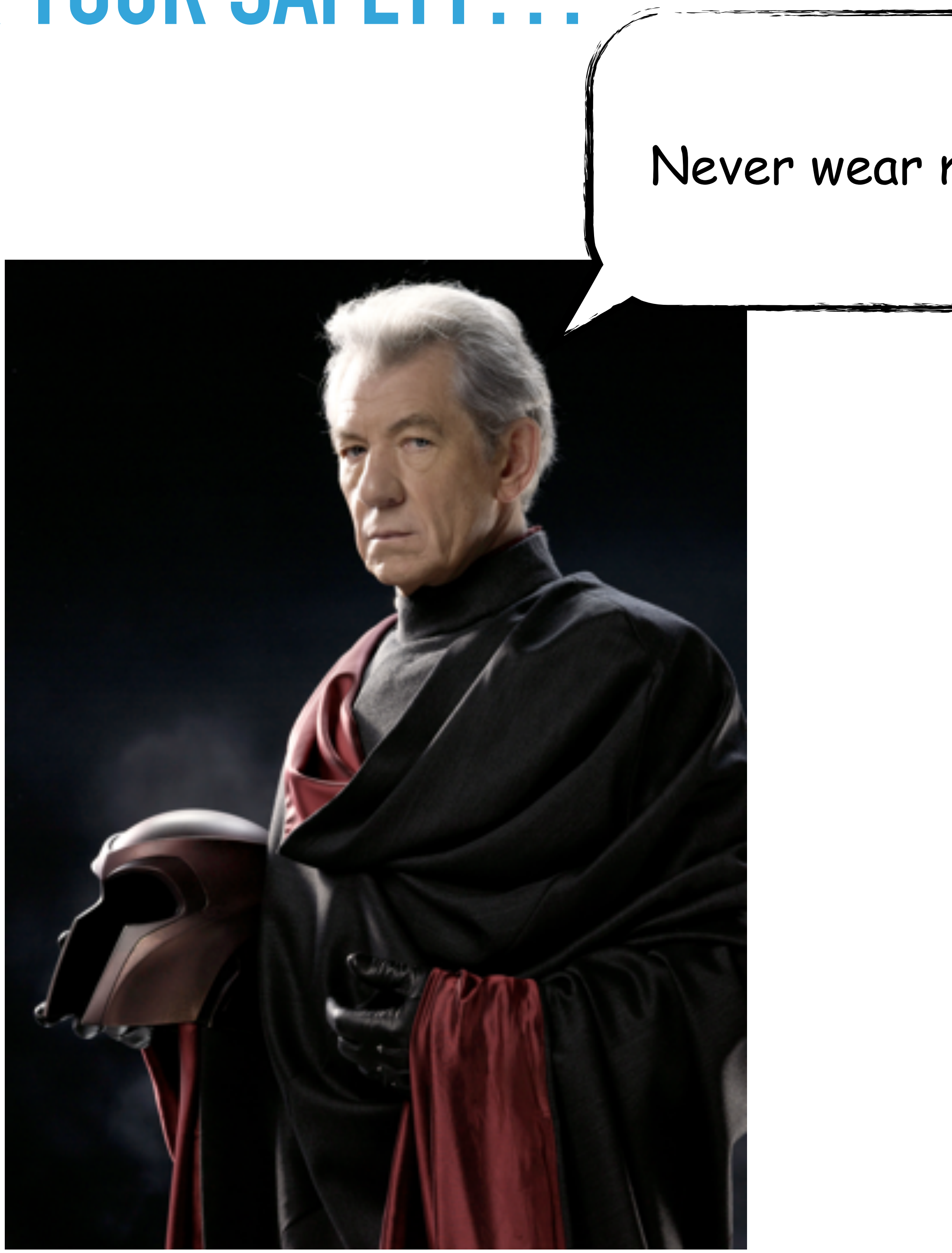
WHAT IS MRI?
– A FIRST LOOK

MRI = MAGNETIC RESONANCE IMAGING






FOR YOUR SAFETY…



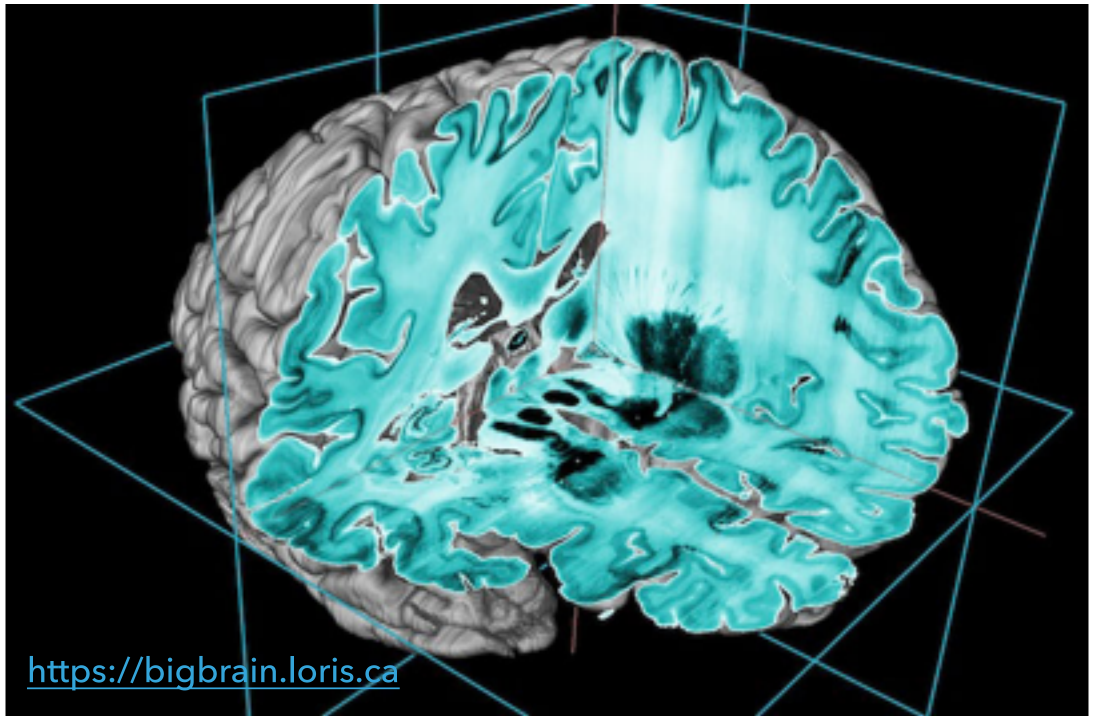
WHY USE MRI?

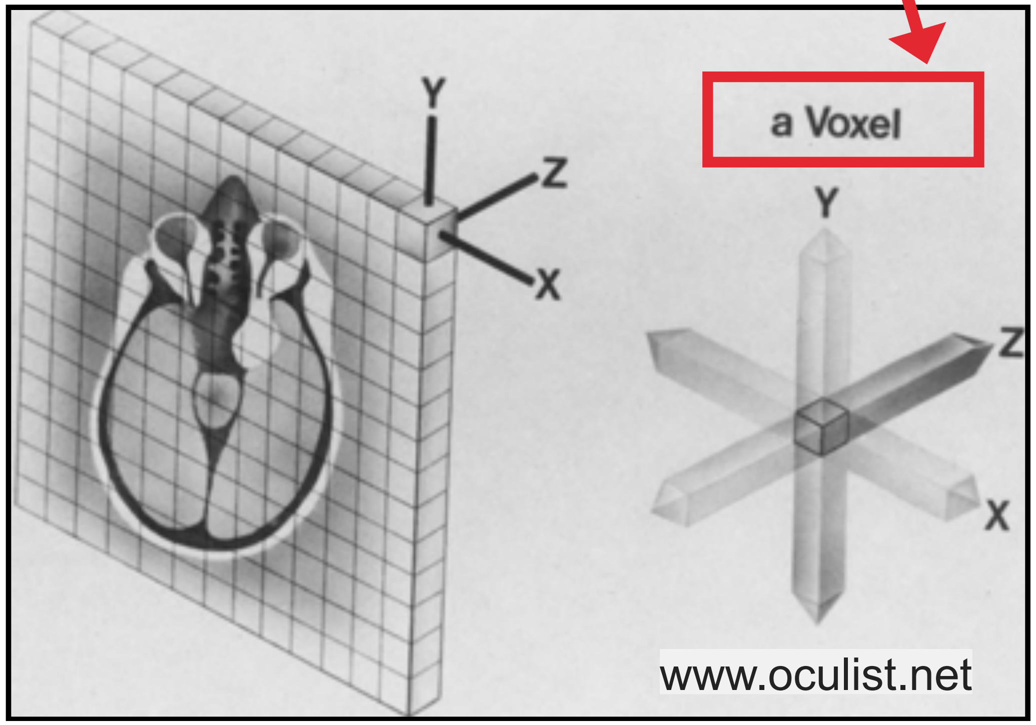
- Non-invasive investigation of the anatomy

WHY USE MRI?

- Non-invasive investigation of the anatomy
- 3D volumetric imaging

Pixel in 3D

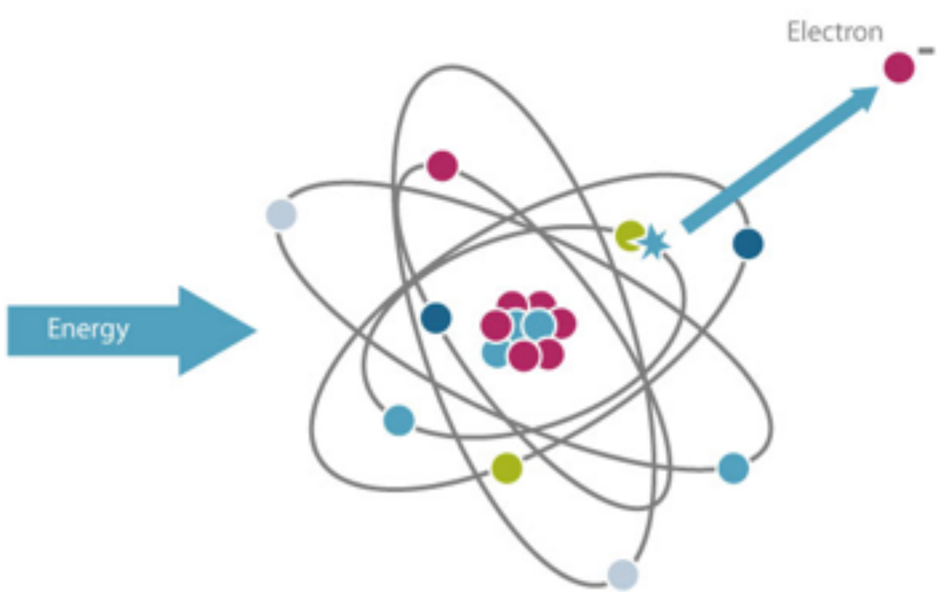




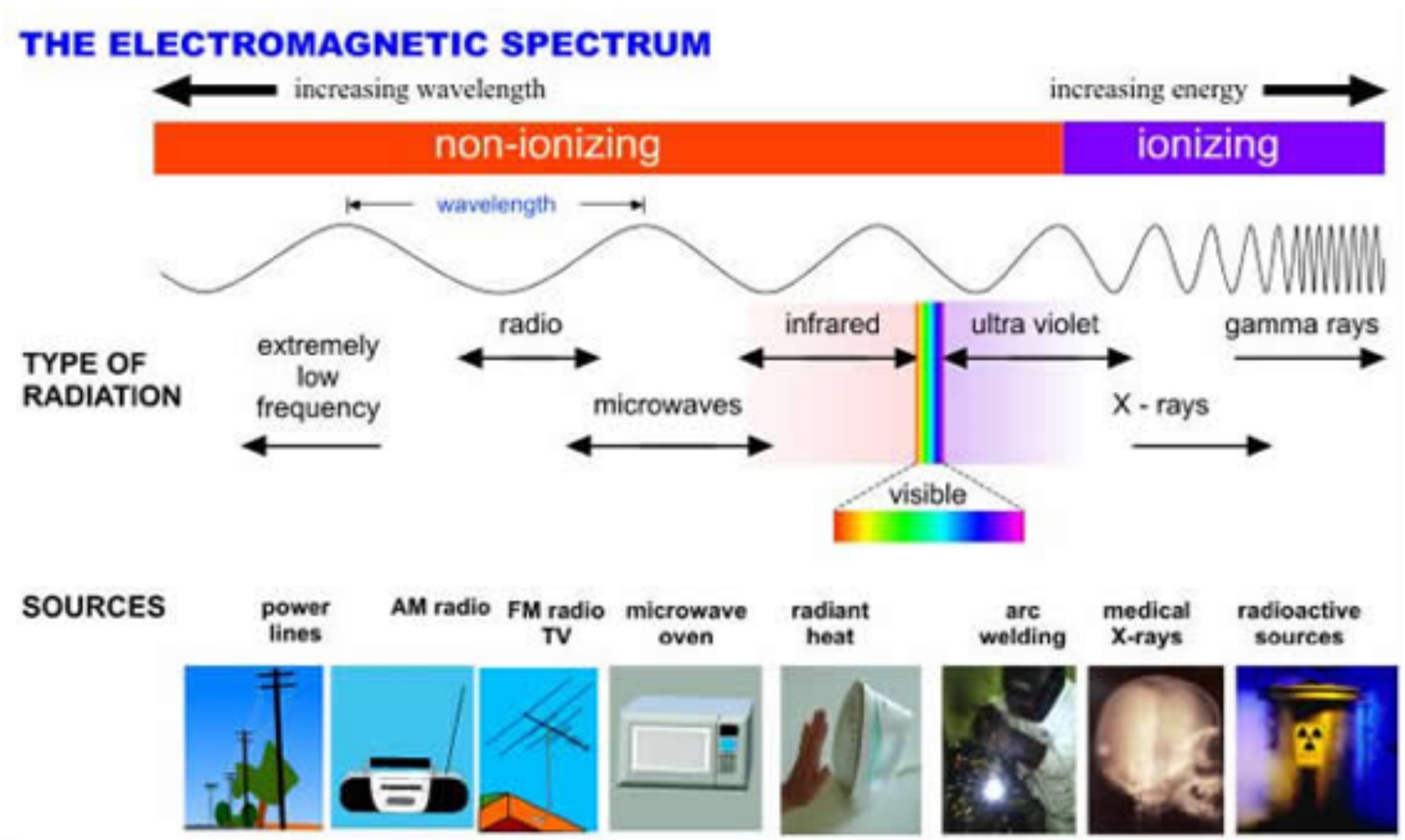
More intuitive & capability to quantify volumes

WHY USE MRI?

- Non-invasive investigation of the anatomy
- 3D volumetric imaging
- Non-ionizing radiation



ionizing radiation



www.arpansa.gov.au

WHY USE MRI?

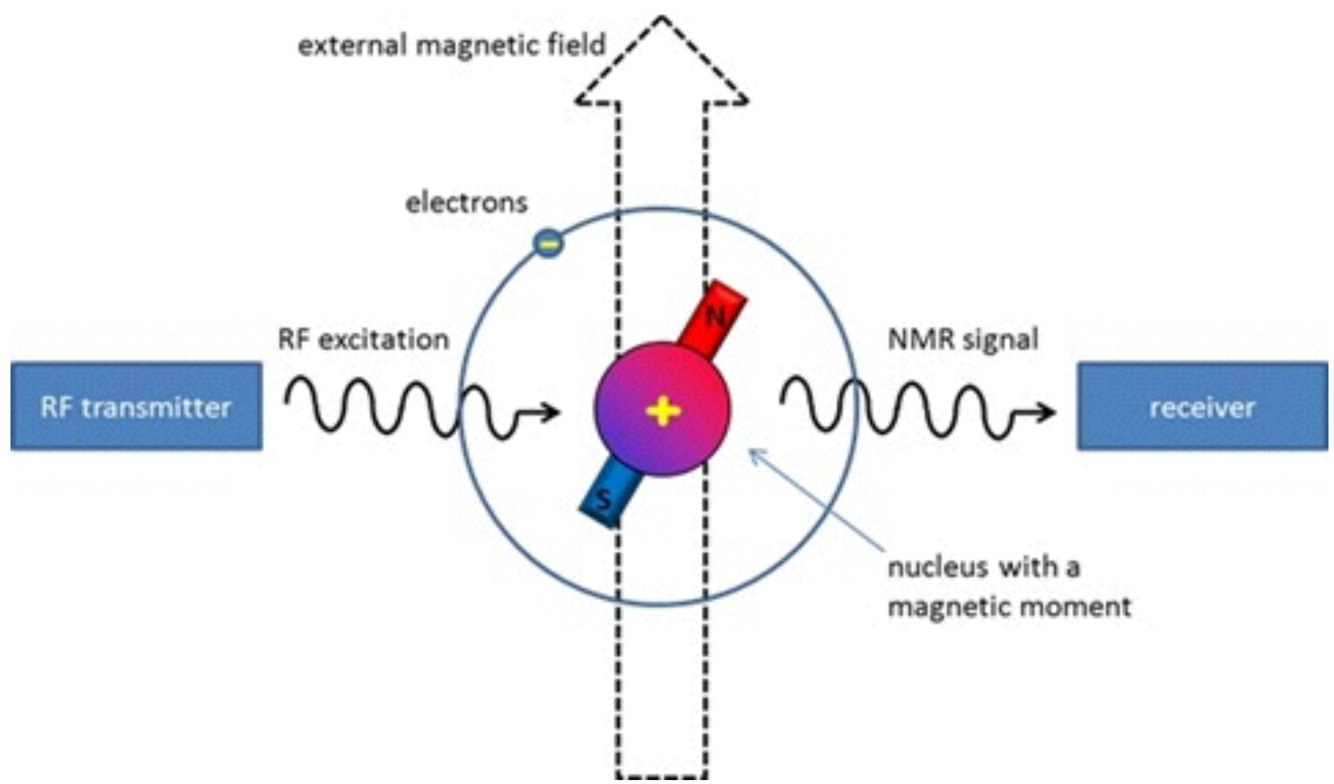
- Non-invasive investigation of the anatomy
- 3D volumetric imaging
- No ionizing radiation
- Great for soft body tissues

For bone or metal materials, CT or X-ray is still recommended..

WHY USE MRI?

- Non-invasive investigation of the anatomy
- 3D volumetric imaging
- No ionizing radiation
- Great for soft body tissues
- Capability of measuring various chemical/physical/functional properties of organs, and we are still exploring

WHERE IS SOURCE OF THE SIGNAL ?

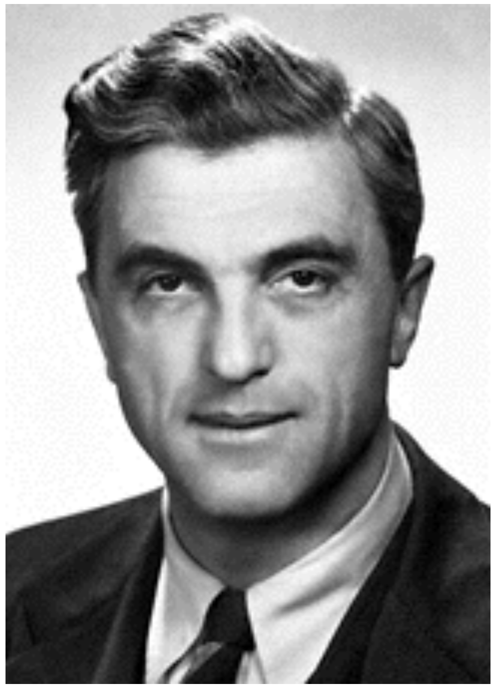


Nuclear magnetic resonance (NMR) phenomenon

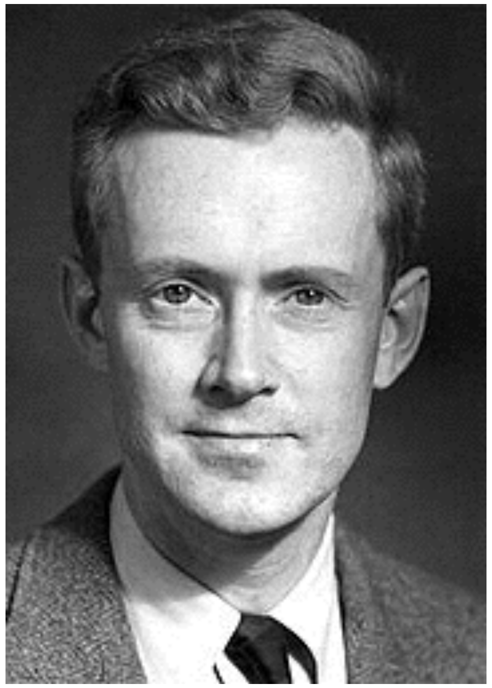
When placed in a magnetic field, a nucleus can absorb and later emit energy

WHERE IS SOURCE OF THE SIGNAL ?

- NMR was first experimentally observed in 1945, nearly simultaneously by the research groups of Felix Bloch at Stanford University, and Edward Purcell at Harvard University.
- Bloch and Purcell were jointly awarded the Nobel Prize in Physics in 1952 for their discovery of Nuclear Magnetic Resonance Spectroscopy.



Felix Bloch



Edward Purcell

GOING FOR AN NMRI?

Nuclear Magnetic resonance imaging (NMRI)

OR

Magnetic Resonance Imaging (MRI)

GOING FOR AN NMRI?

Nuclear Magnetic resonance imaging (NMRI)

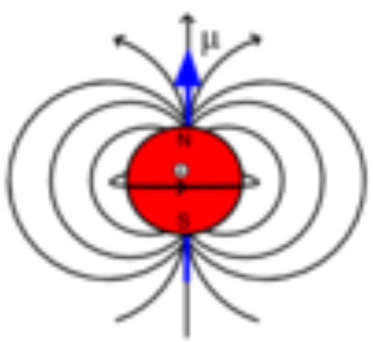
OR

Magnetic Resonance Imaging (MRI)

Name change in the 1980s

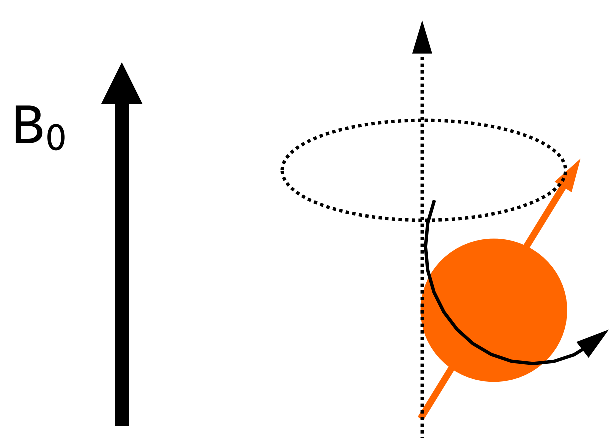
HOW TO GET AN MR IMAGE?

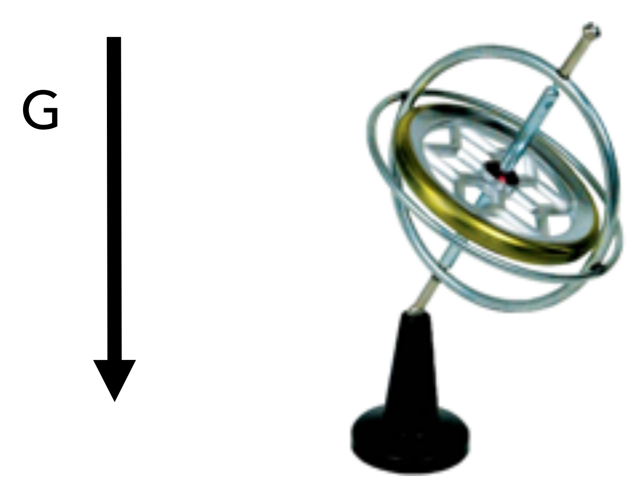
WHAT IS A SPIN?



If a nucleus of an atom has an odd number of protons or neutrons, the atom possesses a nonzero <u>spin angular momentum **S**, which is called a nuclear spin</u> and is associated with a magnetic dipole moment **μ**.

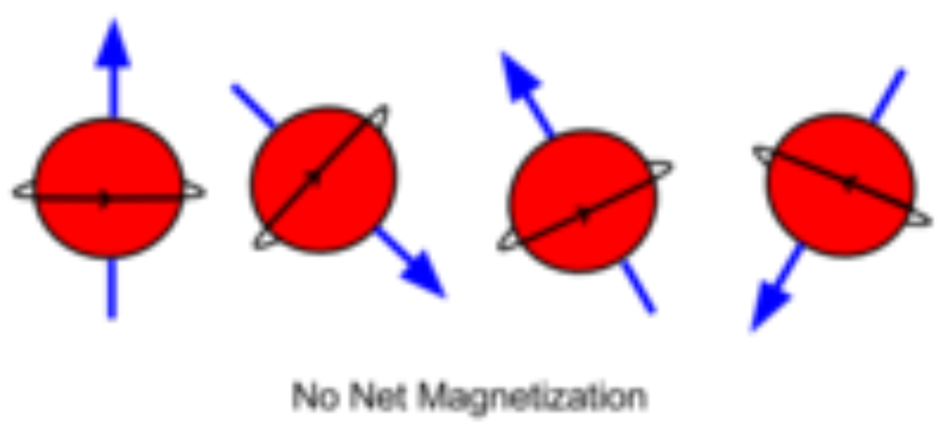
- For MRIs, we often deal with ^{1}H atoms, as 70% of us is H_2O.
- The particle is not actually spinning or rotating.
- *Spin* interacts with electromagnetic fields whereas *classic angular momentum (L)* interacts with gravitational fields.





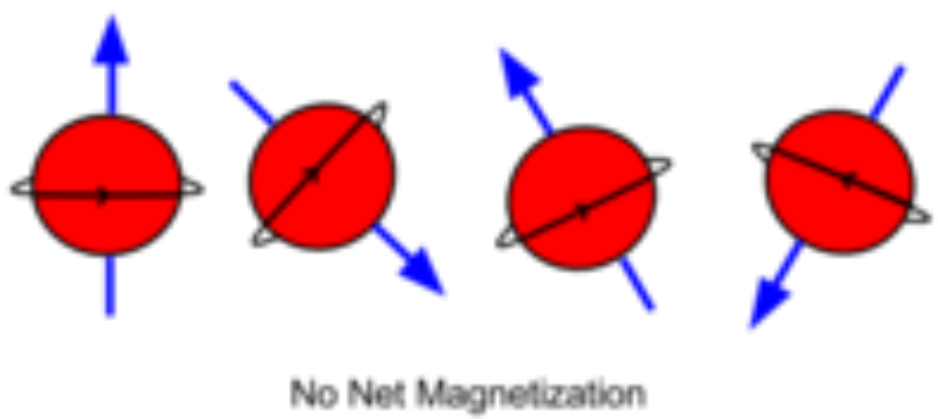
Precession

MAGNETIZATION $\mathbf{M} = \Sigma\mu$

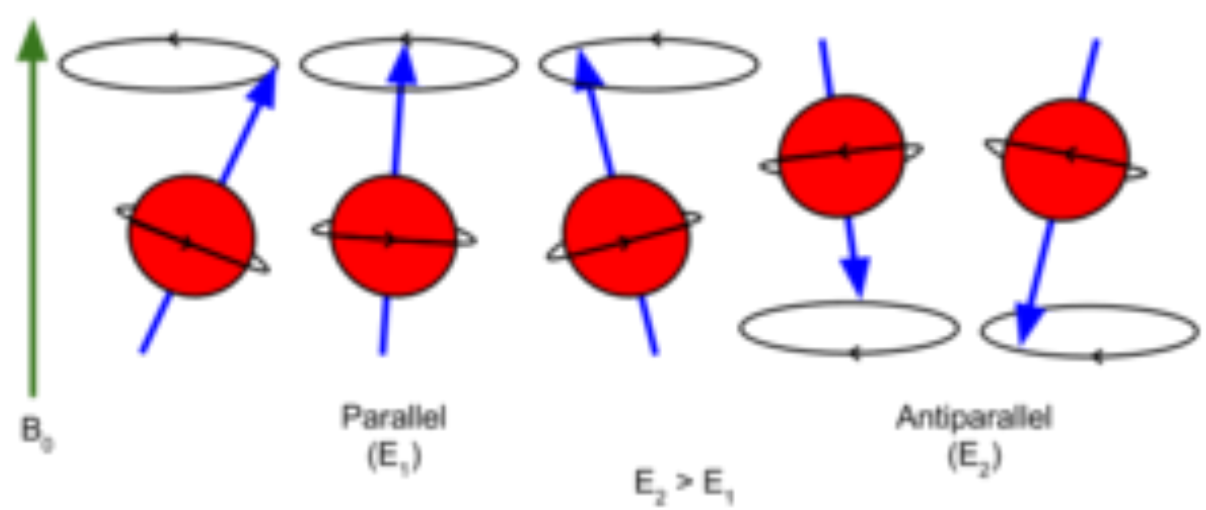


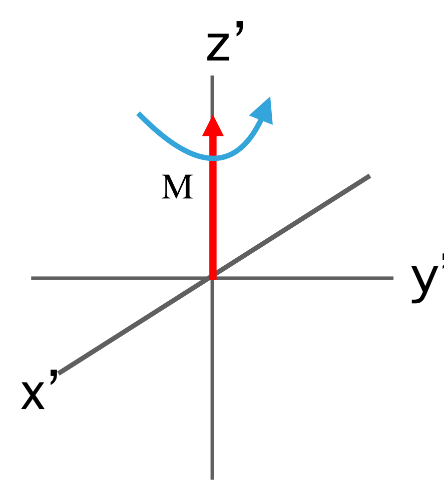
Random alignment

MAGNETIZATION $\mathbf{M} = \Sigma\mu$



Random alignment



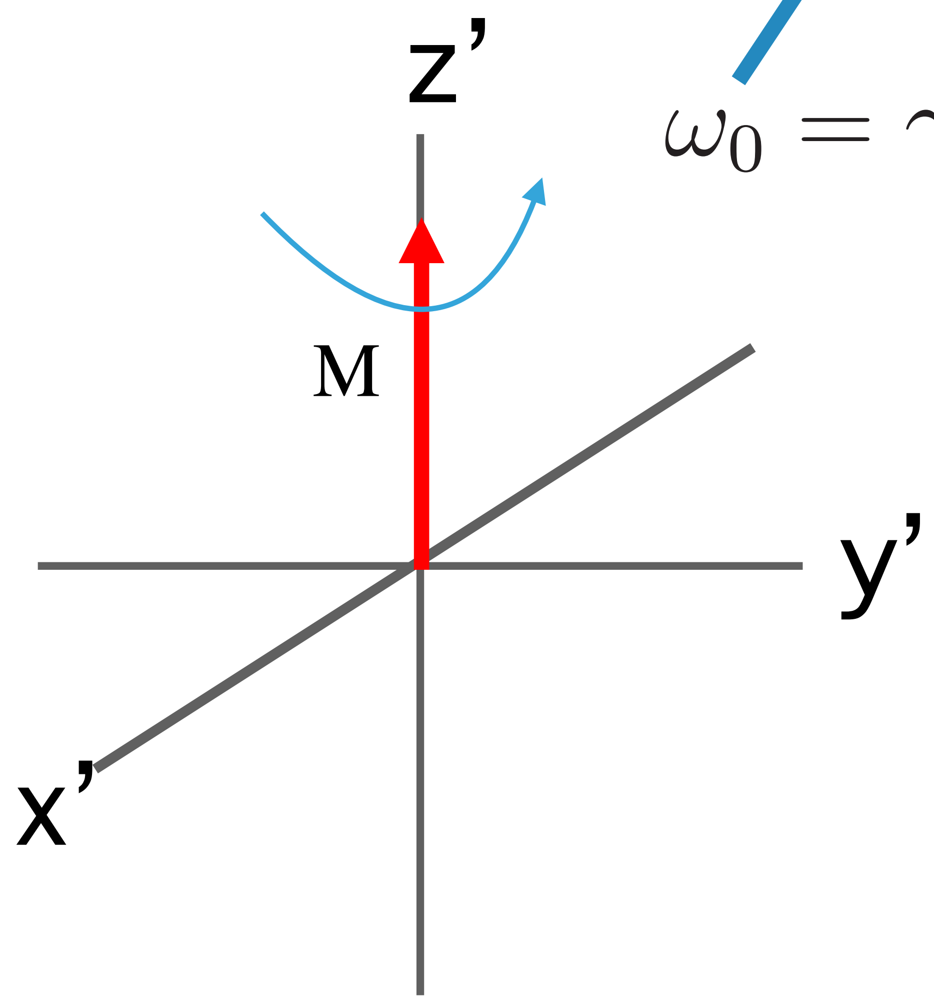


Alignment

The population ratio of two states obeys the Boltzmann distribution

MAGNETIZATION $\mathbf{M} = \Sigma\mu$

Larmor frequency

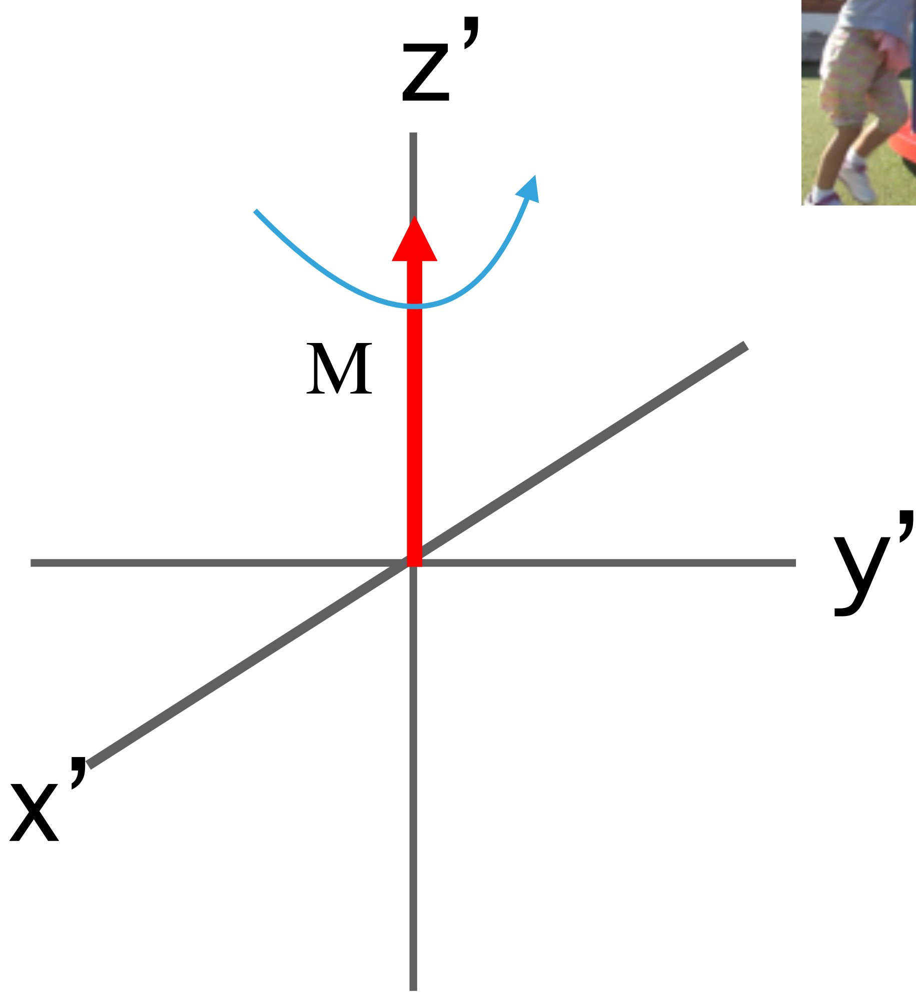


$$\omega_0 = \gamma B_0$$

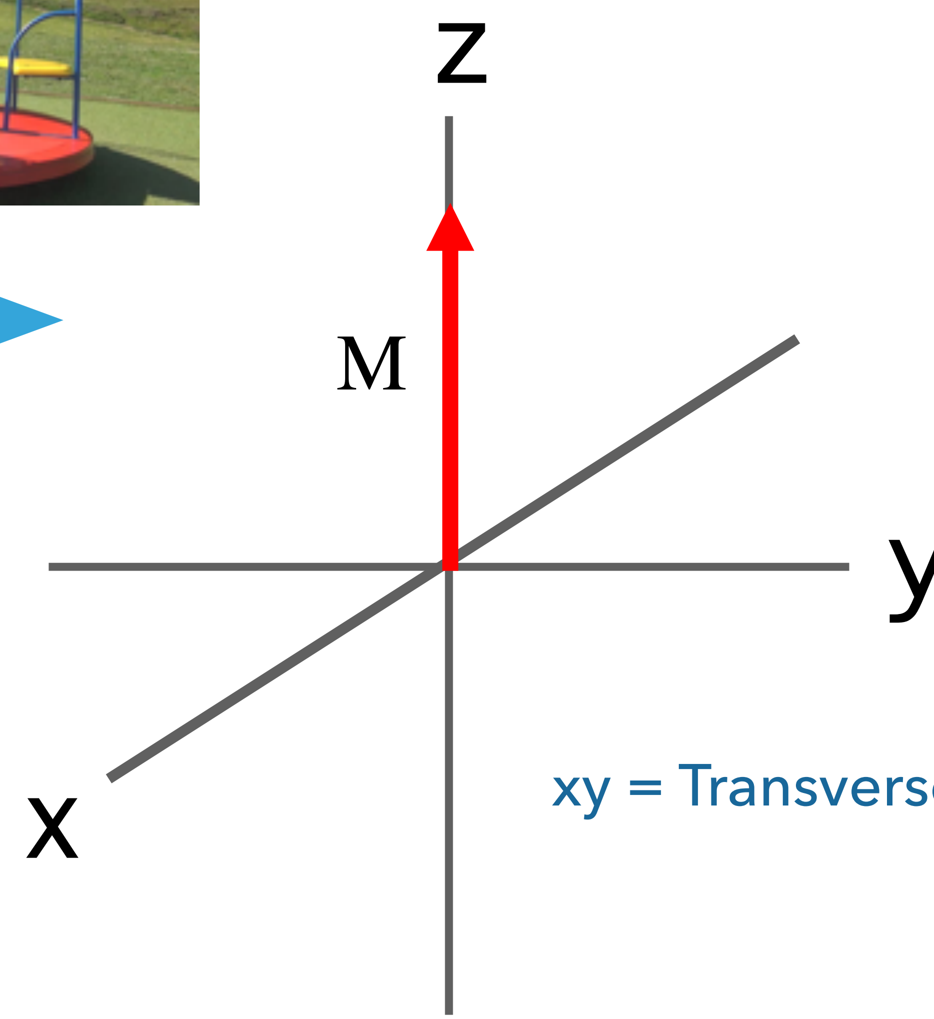
gyromagnetic ratio,
unique to different atoms

MAGNETIZATION $\mathrm{M} = \Sigma\mu$

z = Longitudinal direction



Absolute Frame

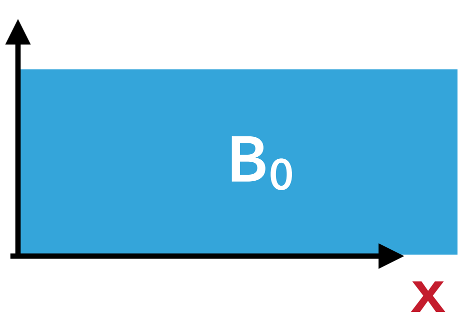


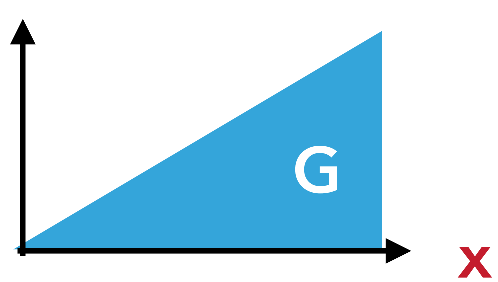
xy = Transverse plane

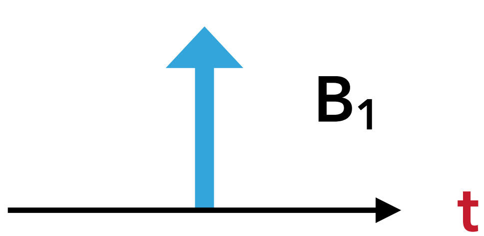
Rotating Frame

THE 3 MAGNETIC FIELDS IN MRI

- **B_0** field: the main field in an MRI scanner (0.5T,1.5T, 3T, 7T & 9.4T)
- **B_1** field: small (~1/10,000T) radio frequency pulse to tip the spin out of equilibrium to produce the signals that determine the image intensity
- **G** field: the spatially varying gradient field that helps encode spatial information to MRI signals







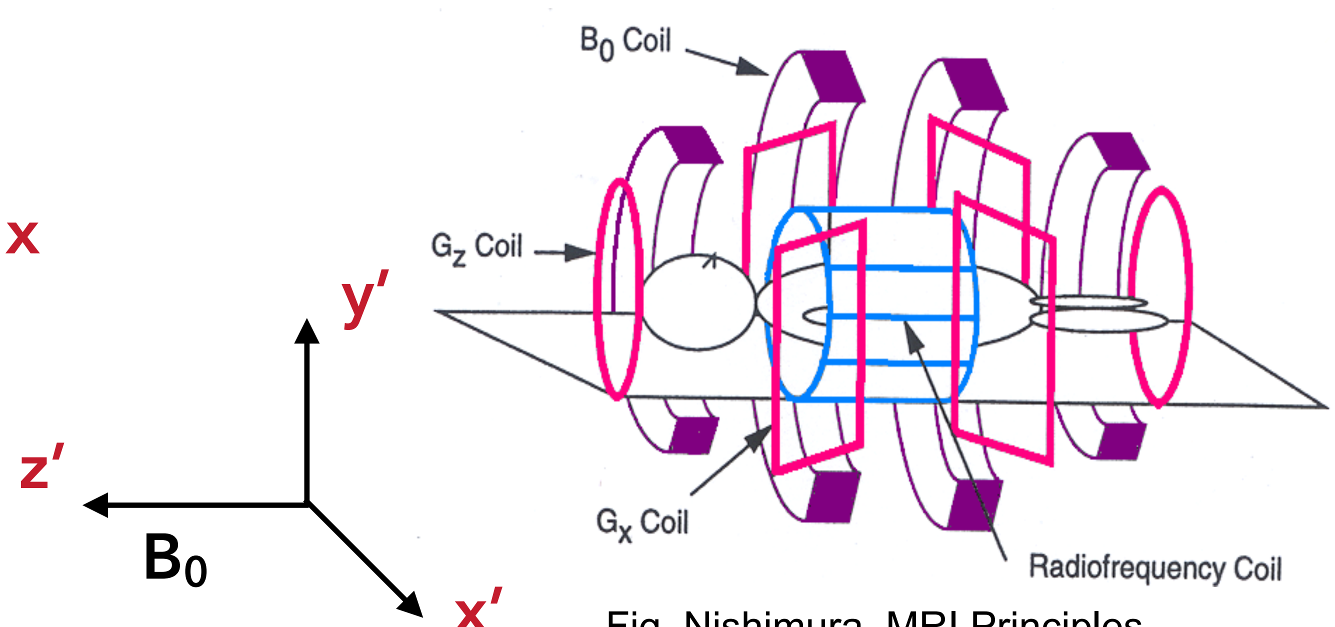
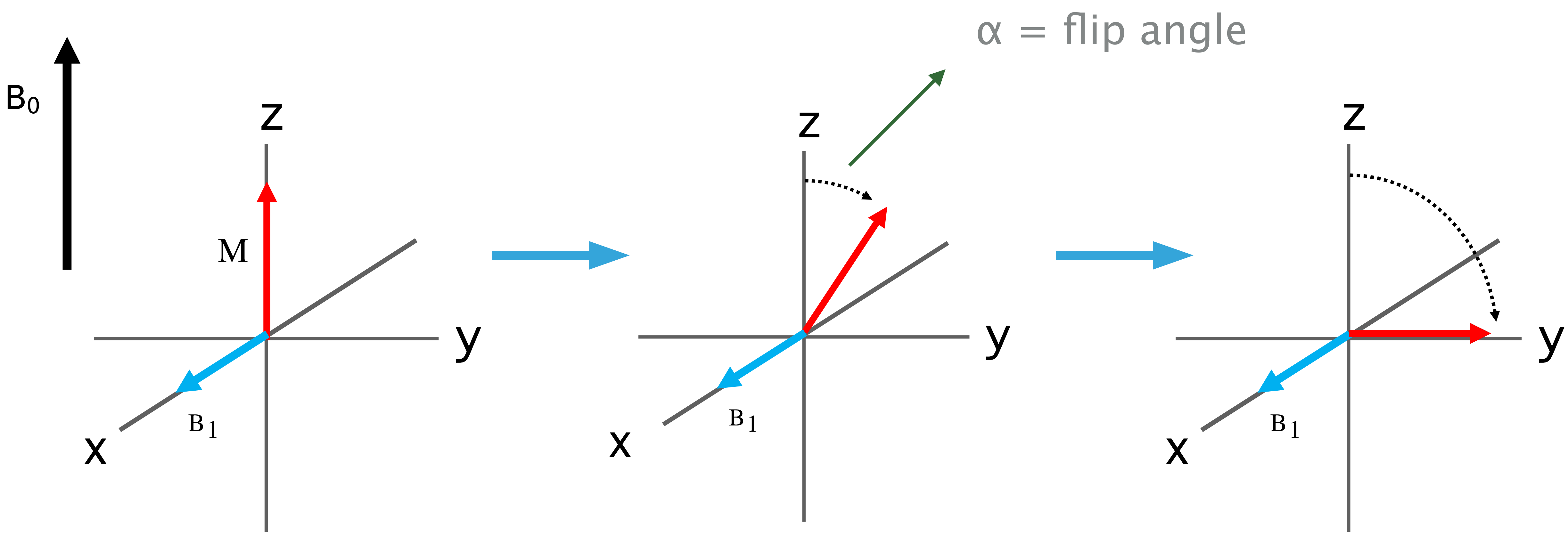


Fig. Nishimura, MRI Principles

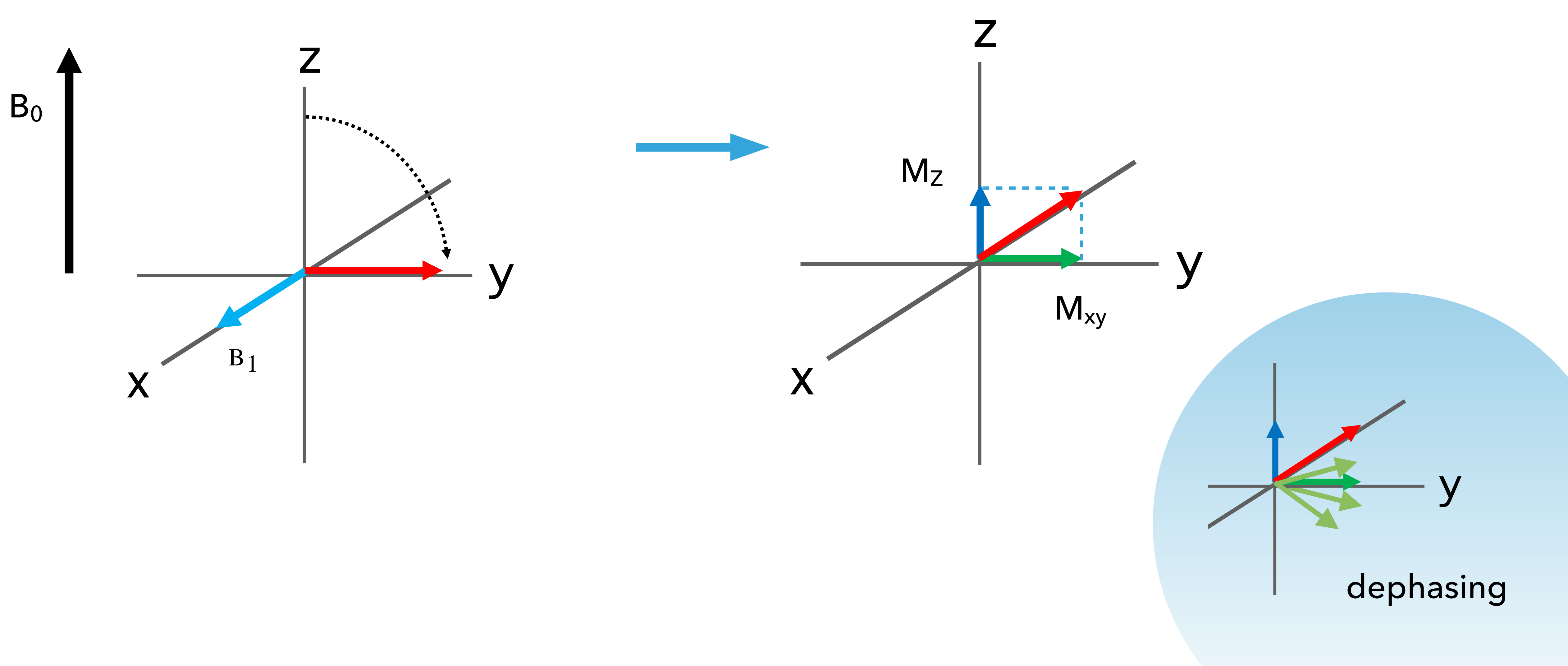
EXCITATION & RELAXATION

- **Excite** nuclei = tip the magnetization away from the z-direction by $\mathbf{B_1}$.
- The angle depends on the duration and magnitude of $\mathbf{B_1}$.
- $\mathbf{B_1}$ is tuned to the Larmor frequency to induce magnetic resonance.
- Energy is absorbed.



EXCITATION & RELAXATION

- **Relaxation** : the process of returning to the magnetization's equilibrium state
- T_1 relaxation: the longitudinal component $\mathbf{M_z}$ grows back
- T_2 relaxation: the transverse component $\mathbf{M_{xy}}$ diminishes



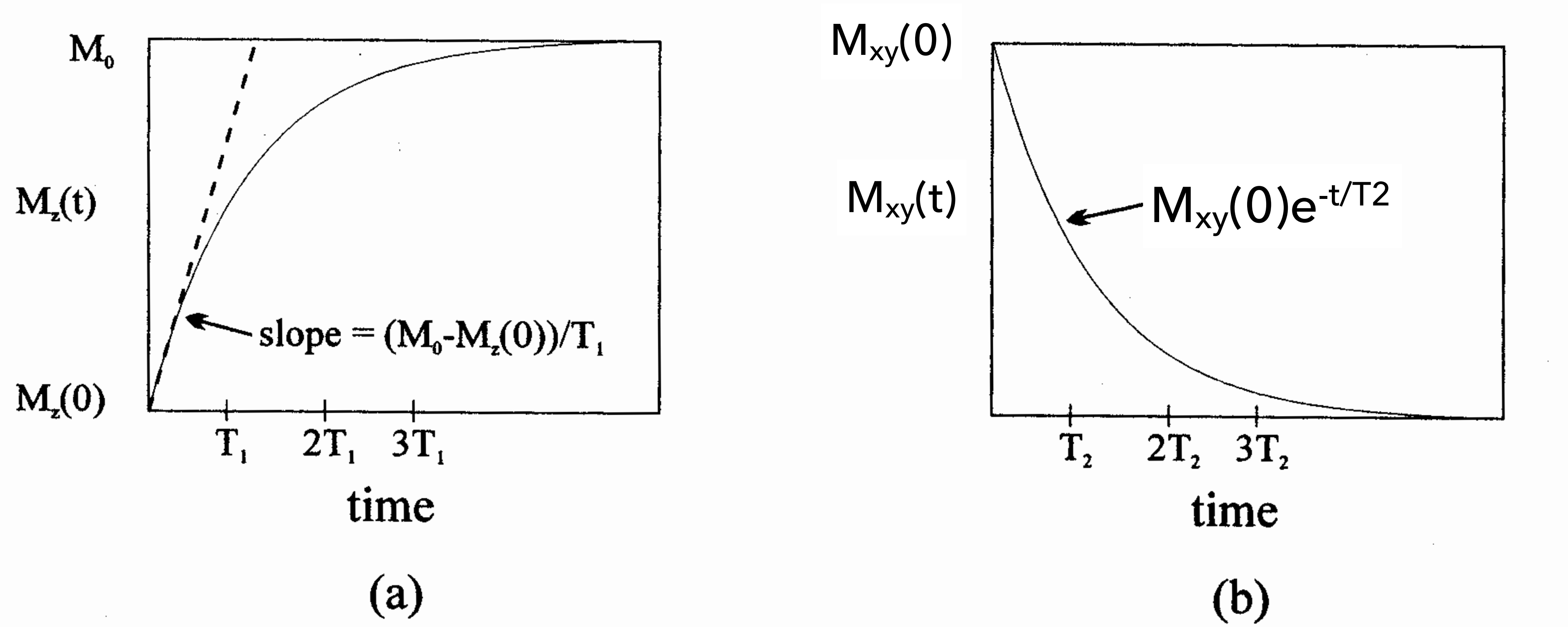


Fig. 4.1: (a) The regrowth of the longitudinal component of magnetization from the initial value $M_z(0)$ to the equilibrium value M_0. (b) The decay of the magnitude of the transverse magnetization from an initial value.

Tissue	T_1 (ms)	T_2 (ms)
gray matter (GM)	950	100
white matter (WM)	600	80
muscle	900	50
cerebrospinal fluid (CSF)	4500	2200
fat	250	60
blood	1200	100-200[3]

Fig. Nishimura, MRI Principles

BLOCH EQUATION

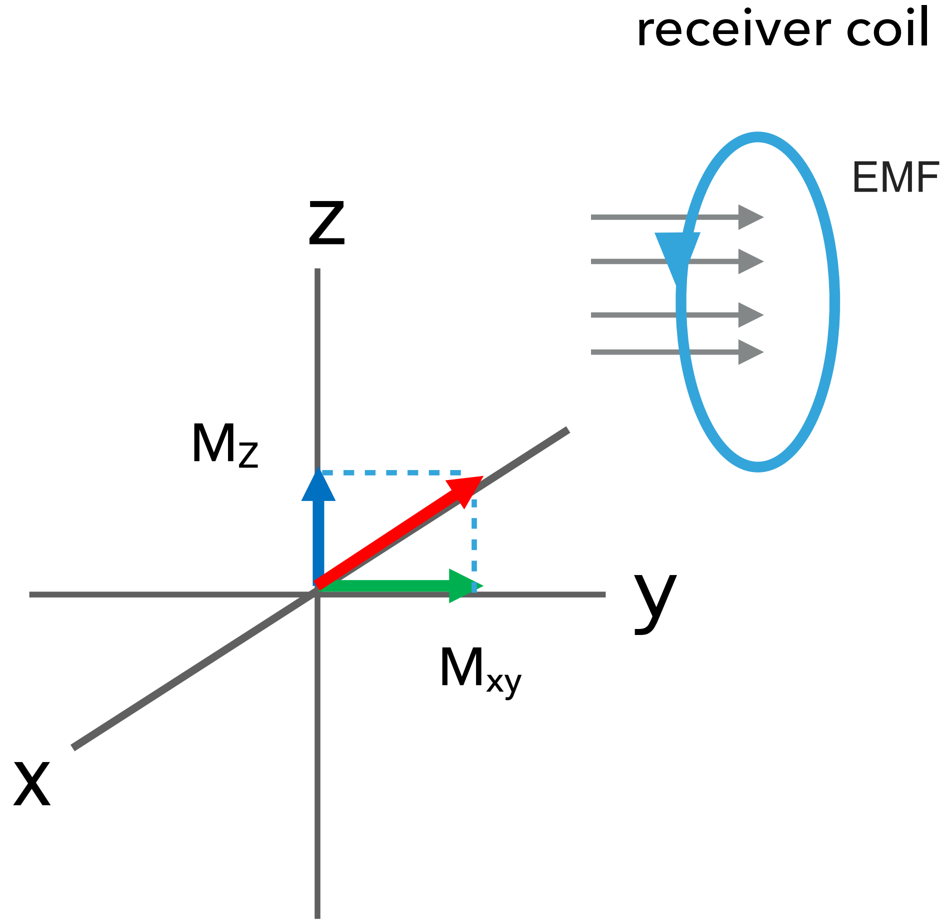
$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma \mathbf{B} - \frac{M_x \mathbf{i} + M_y \mathbf{j}}{T_2} - \frac{(M_z - M_0)\mathbf{k}}{T_1}$$

Precession due to
the Main field, the torque

Evolution of M
in transverse plane

Evolution of M
in longitudinal direction

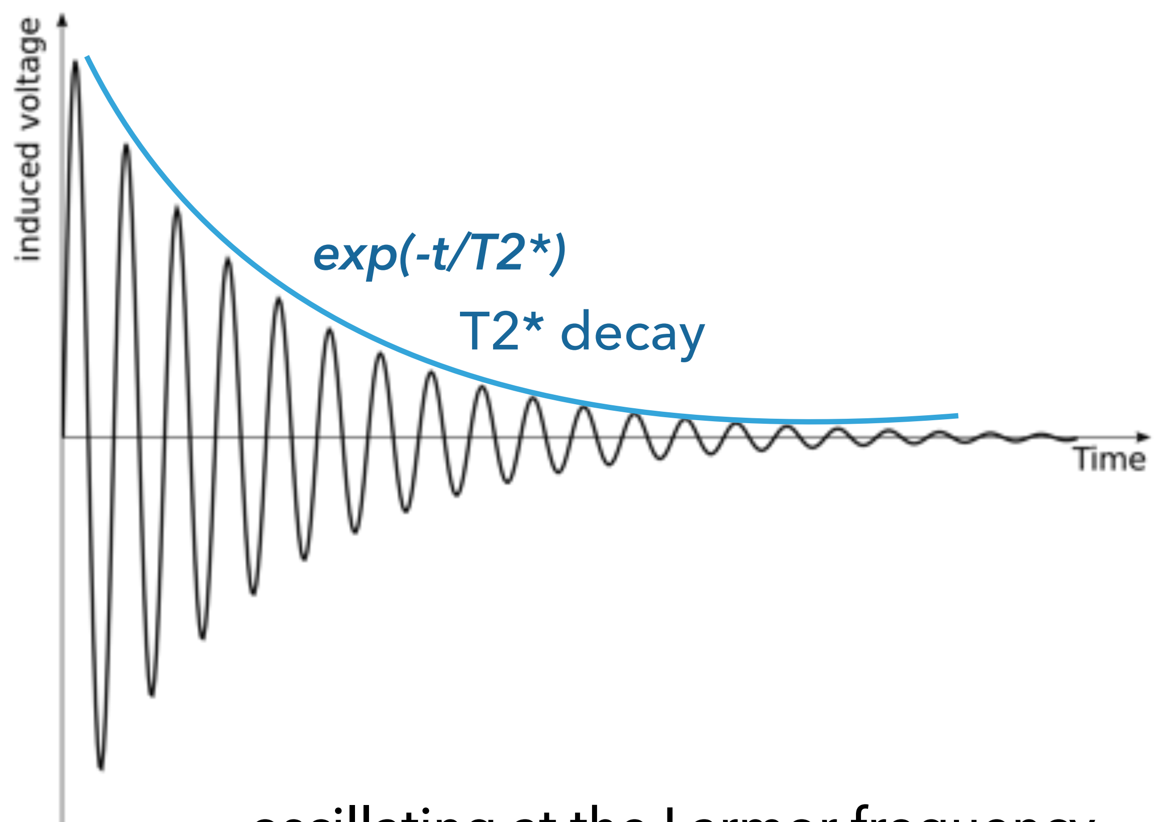
FREE INDUCTION DECAY (FID)



Faraday's law of induction

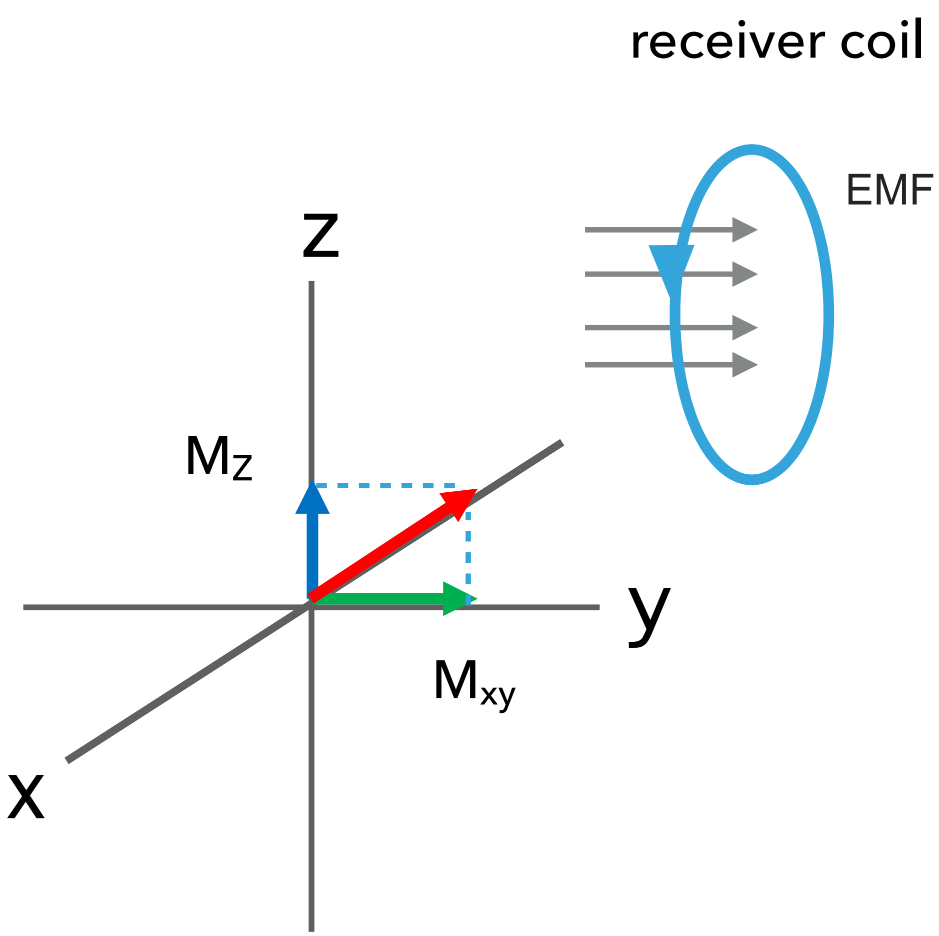
T2* = 1/(1/T2+1/T2′)

magnetic field inhomogeneity

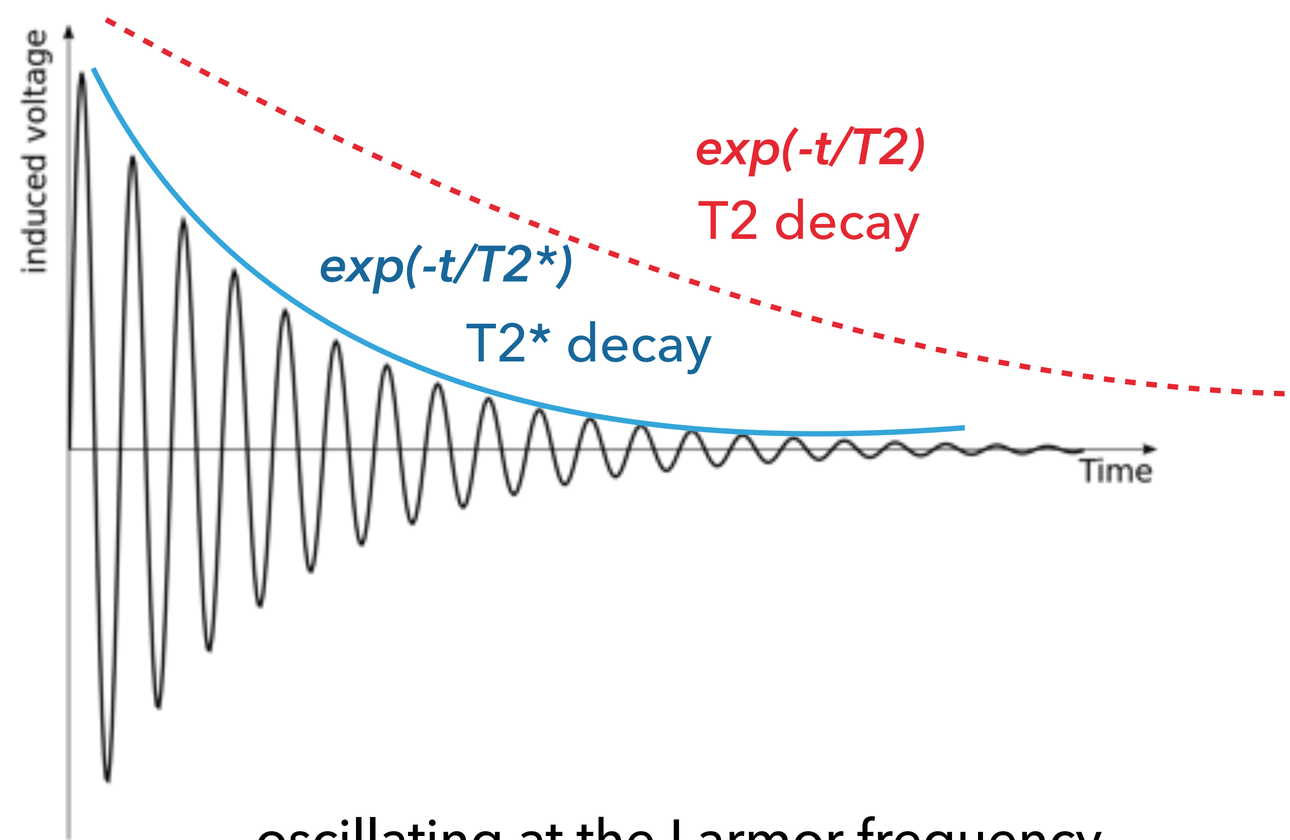


oscillating at the Larmor frequency

FREE INDUCTION DECAY (FID)



Faraday's law of induction



oscillating at the Larmor frequency

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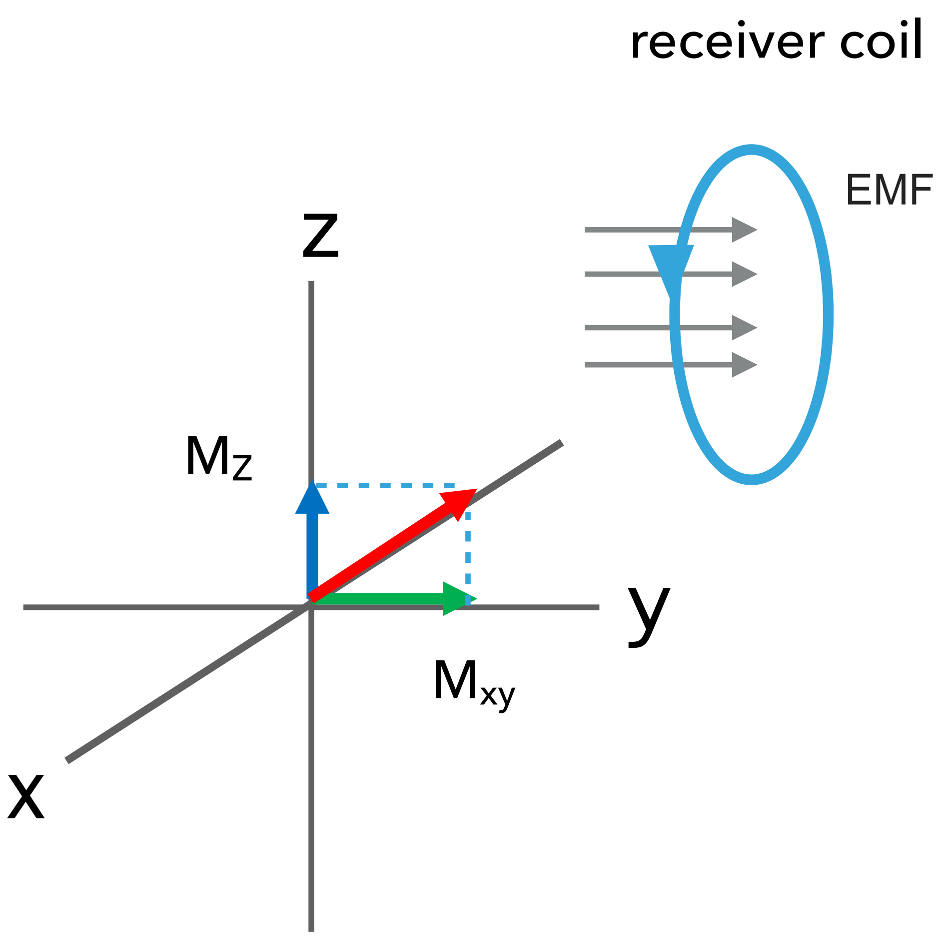
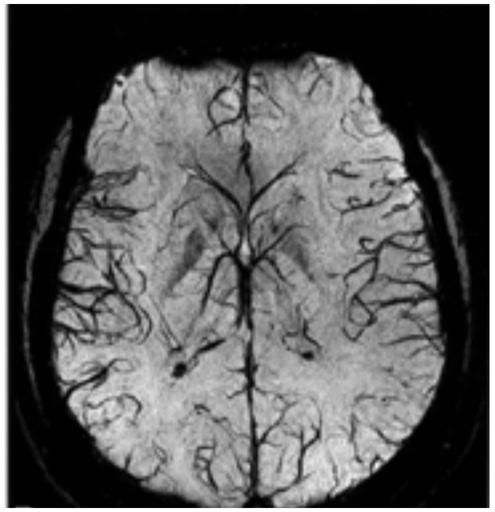
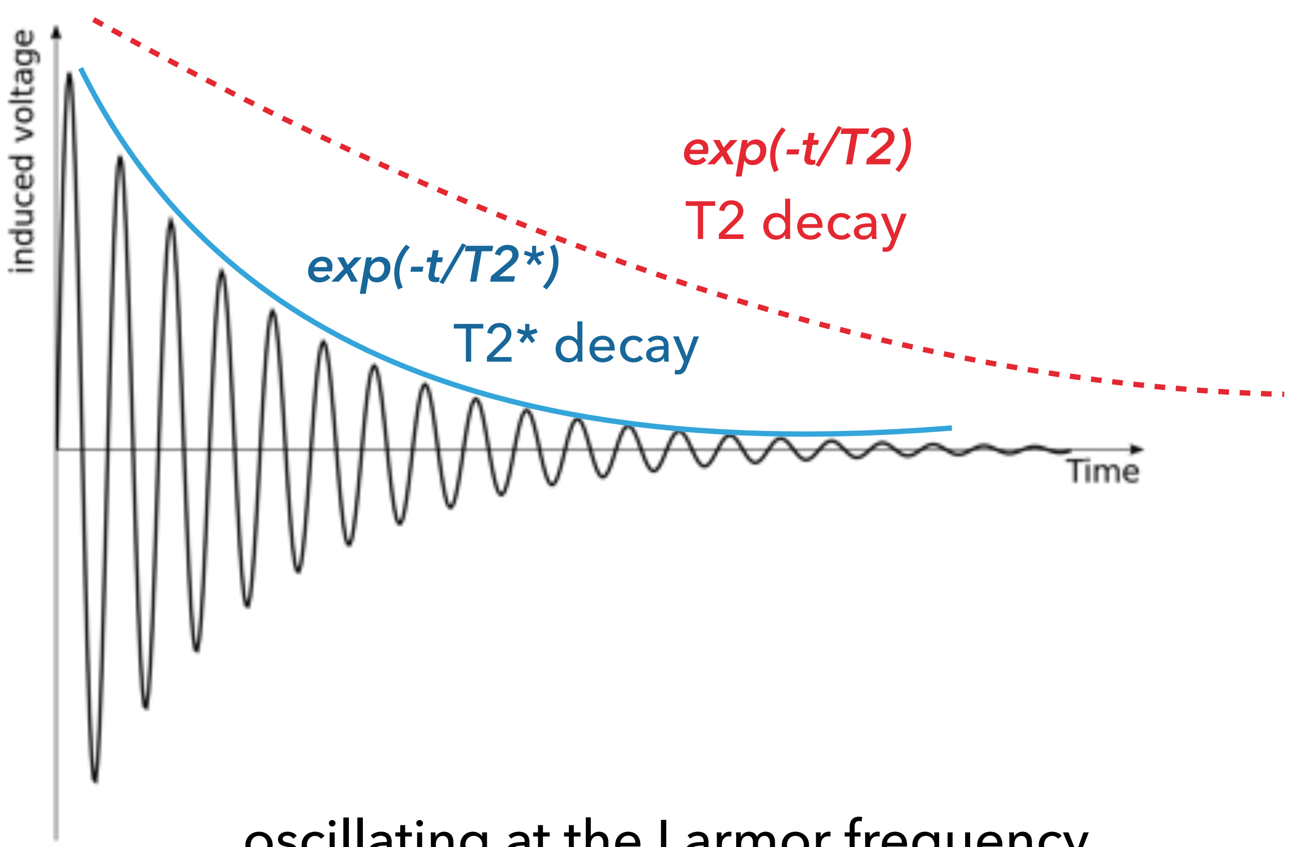


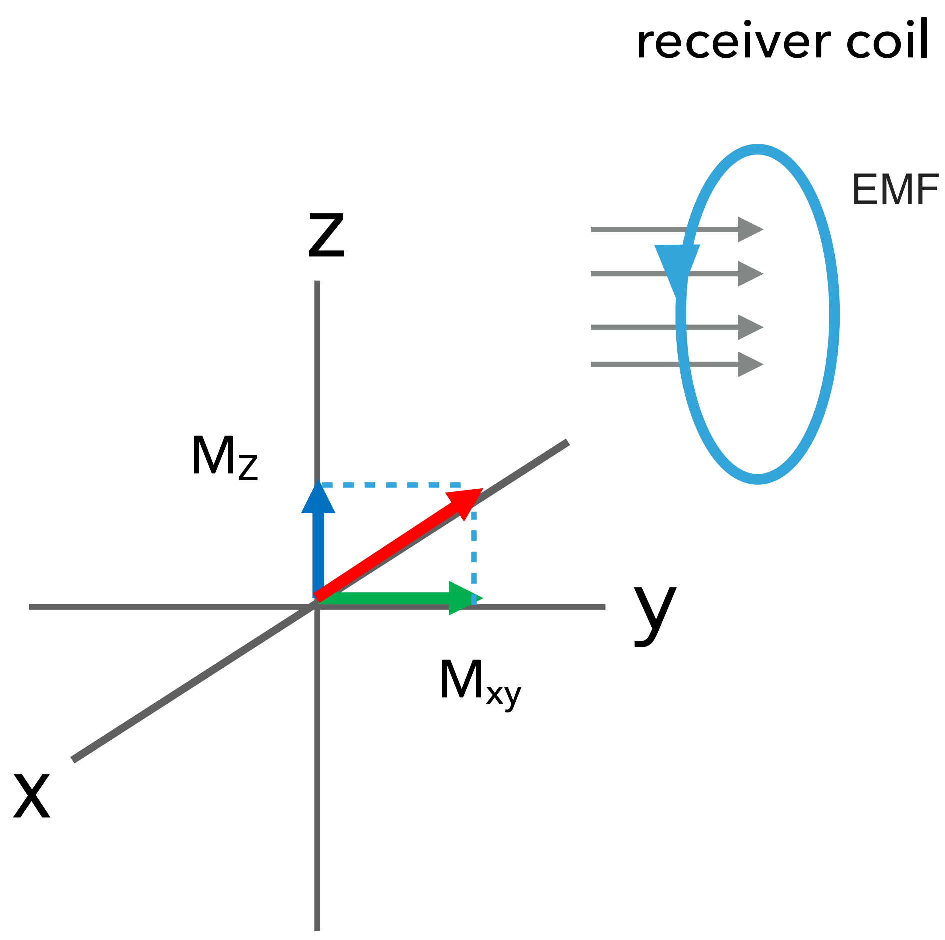
Faraday's law of induction





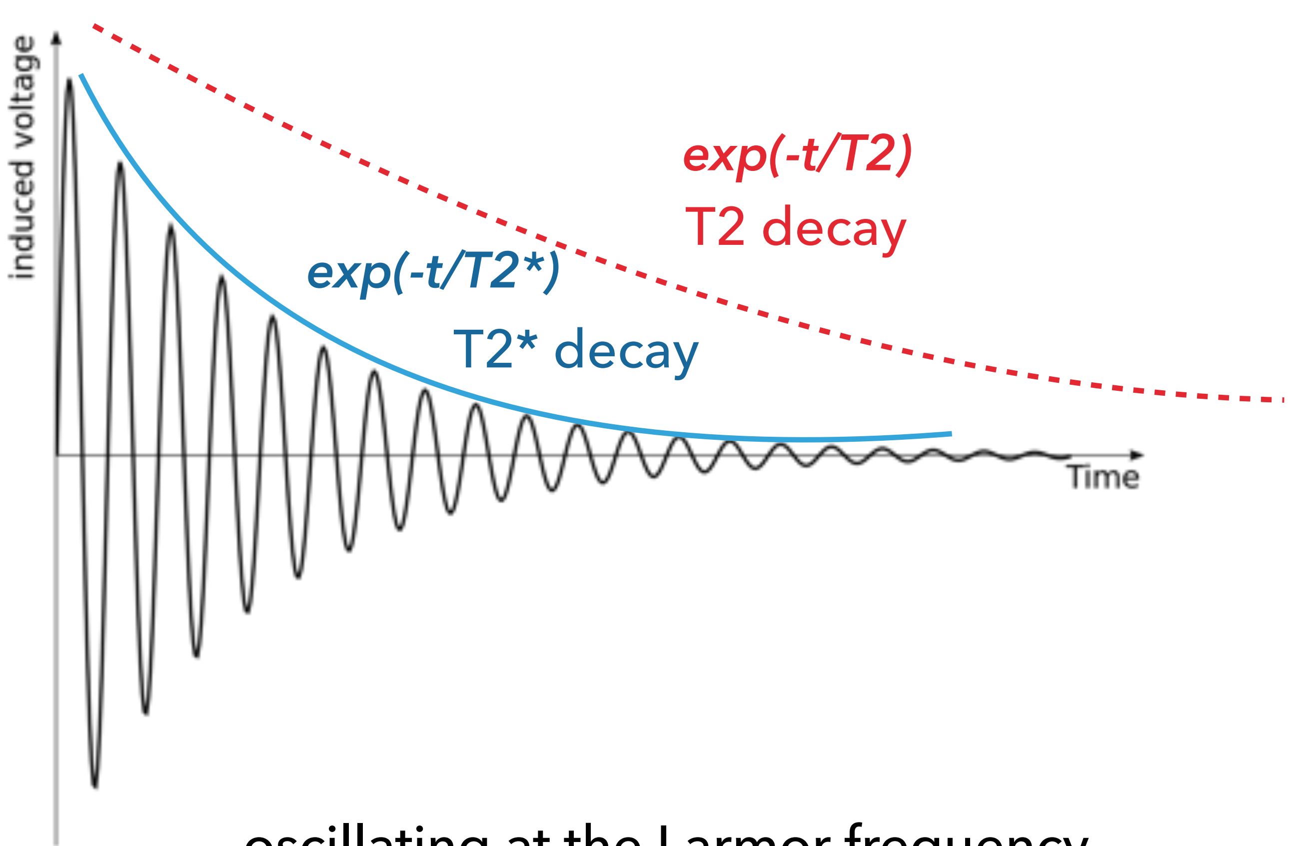
oscillating at the Larmor frequency

FREE INDUCTION DECAY (FID)



Faraday's law of induction

THIS IS SIGNAL TO CONSTRUCT THE MR IMAGES

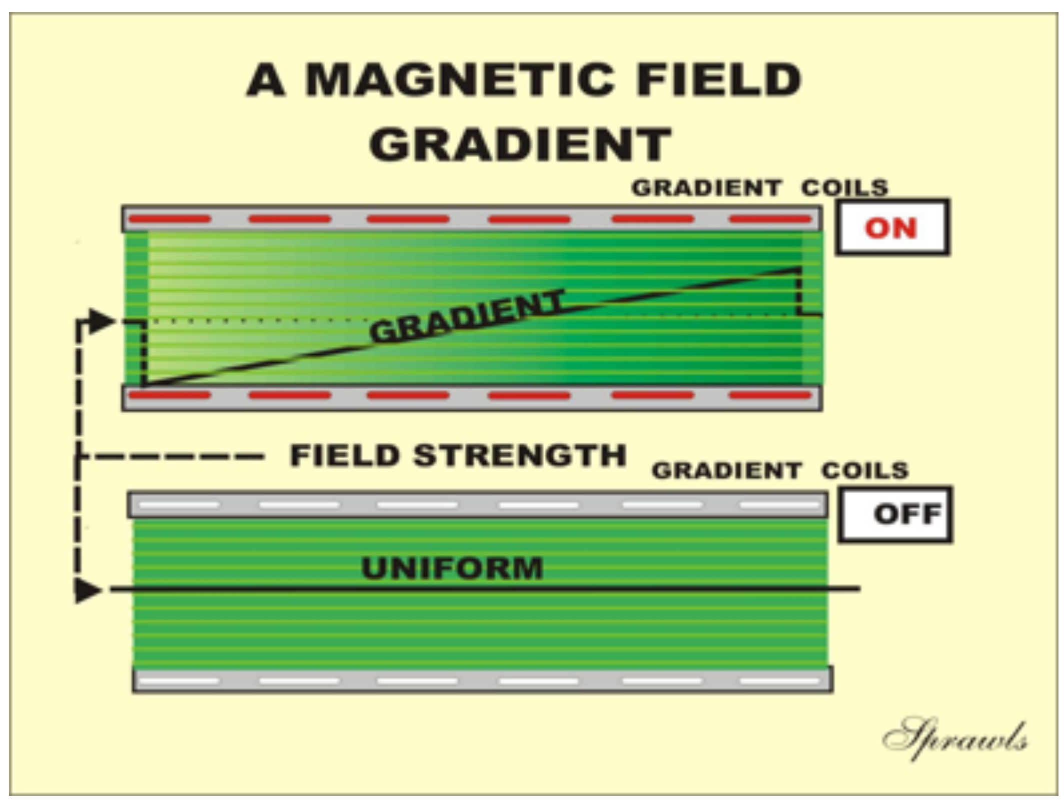


oscillating at the Larmor frequency

So what happens to the gradient field ?

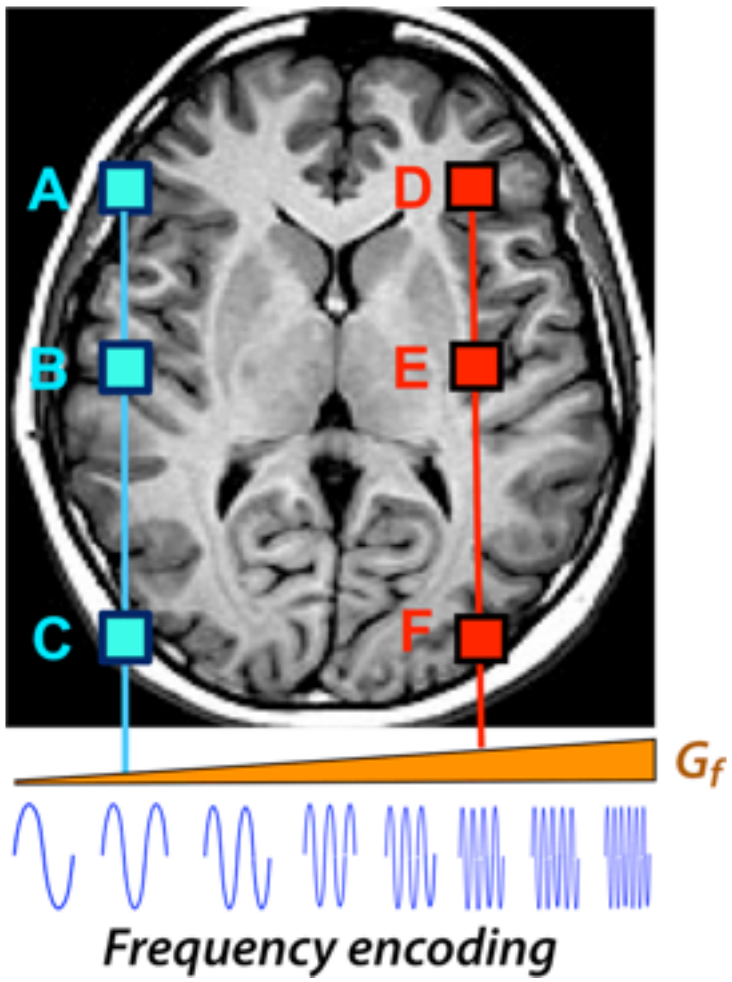
$$\mathbf{G} = (\mathbf{G}_x, \mathbf{G}_y, \mathbf{G}_z)$$

TWO EFFECTS



FREQUENCY ENCODING

mriquestions.com



COMPUTING THE SIGNAL

solution to the bloch equation

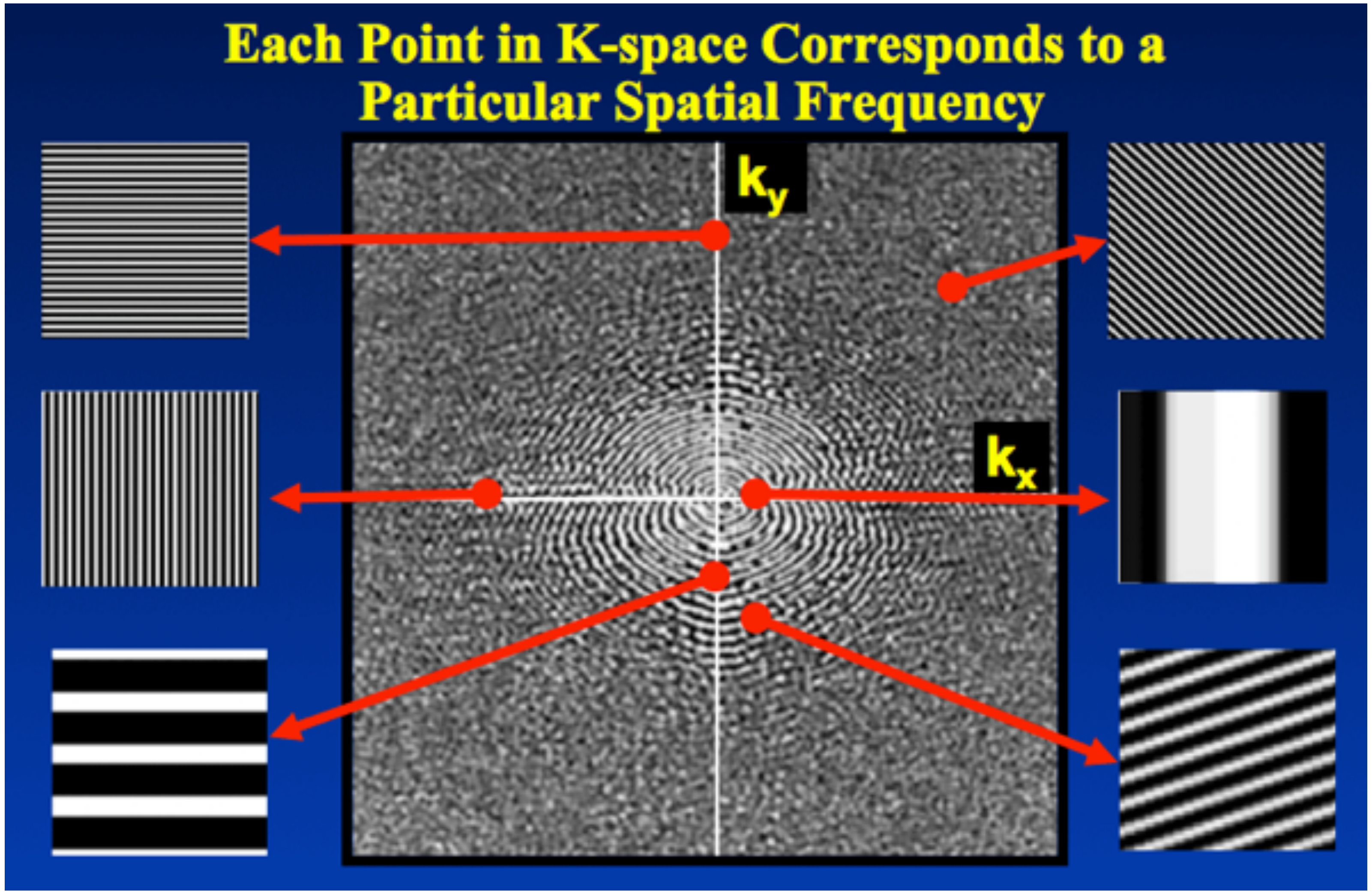
$$s_r(t) = \int M(\mathbf{r}, t) dV = \iiint M(x, y, z, t) dx dy dz$$

A lot of math later….

$$s(t) = \iiint m(x, y, z) e^{-i2\pi[k_x(t)x + k_y(t)y + k_z(t)z]} dx dy dz$$

where $k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(\tau) d\tau$, $k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(\tau) d\tau$, and $k_z(t) = \frac{\gamma}{2\pi} \int_0^t G_z(\tau) d\tau$.

K-SPACE



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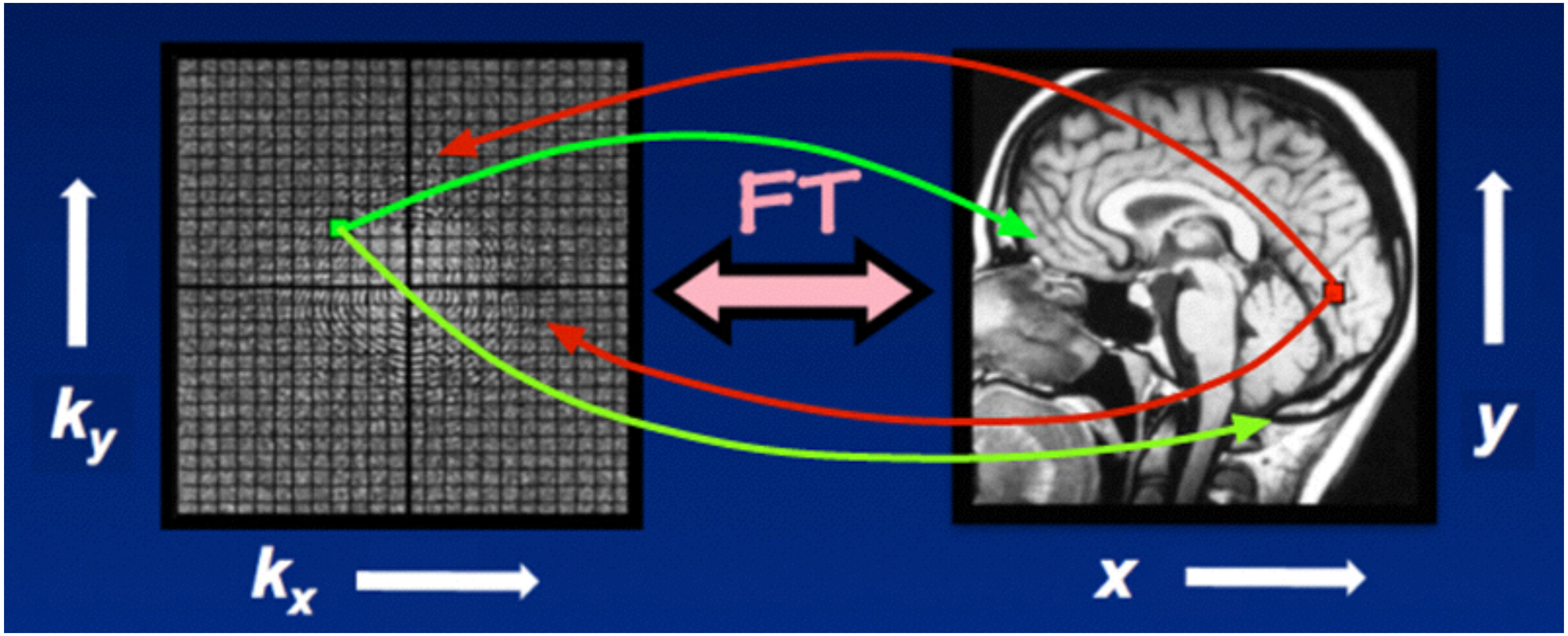
FROM K-SPACE TO AN IMAGE



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FROM K-SPACE TO AN IMAGE

- The connection between k-space and the Fourier transformation was discovered by Peter Mansfield and Paul C. Lauterbur in the 1970s.

- They shared the Nobel Prize in Physics in 2003 for their works that made volumetric imaging possible with MRI

Peter Mansfield

Paul C. Lauterbur

SEQUENCE PROGRAMMING & IMAGE CONTRAST

PULSE SEQUENCE DESIGN

An MRI pulse sequence is a pre-set program on how and when to apply changing gradient fields, RF pulses, and data acquisition events to the scan subject.

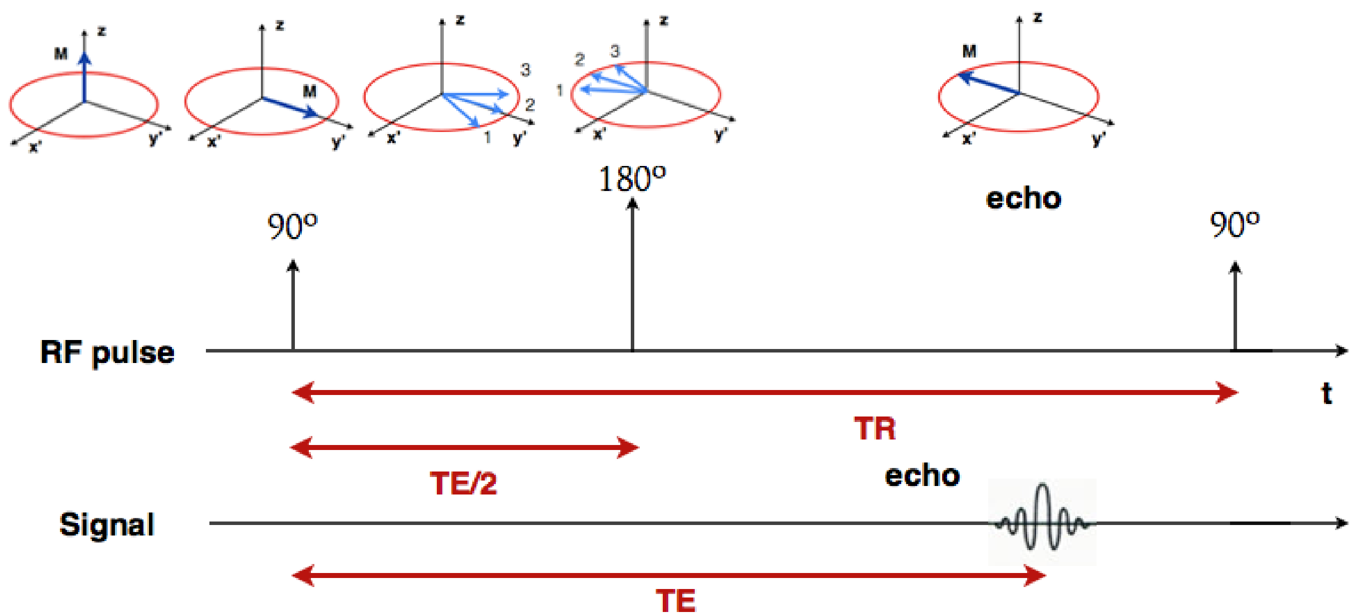
THREE VARIABLES

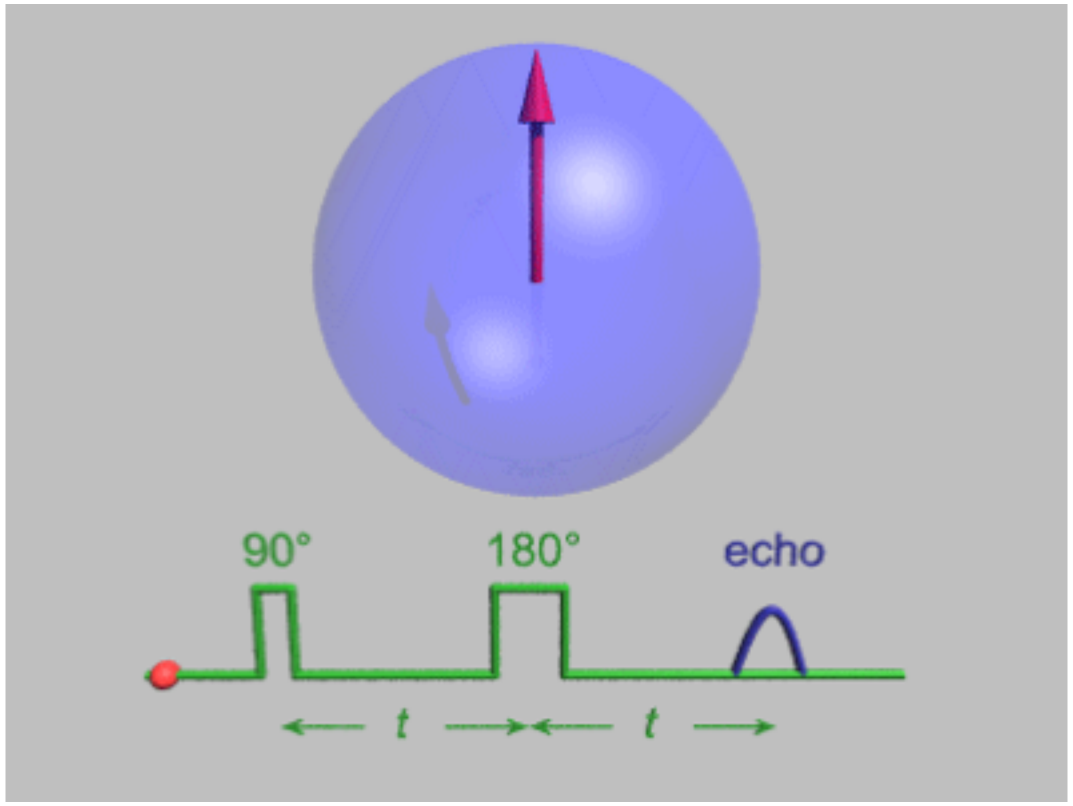
1. Repetition Time (TR) is the time from the application of an excitation RF pulse to the next.

2. Echo Time (TE) presents the time between the application of the excitation RF pulse and the peak of the echo signal or signal readout.

3. Flip angle (FA) is the angle that the net magnetization is tipped relative to the main field direction by the RF pulse.

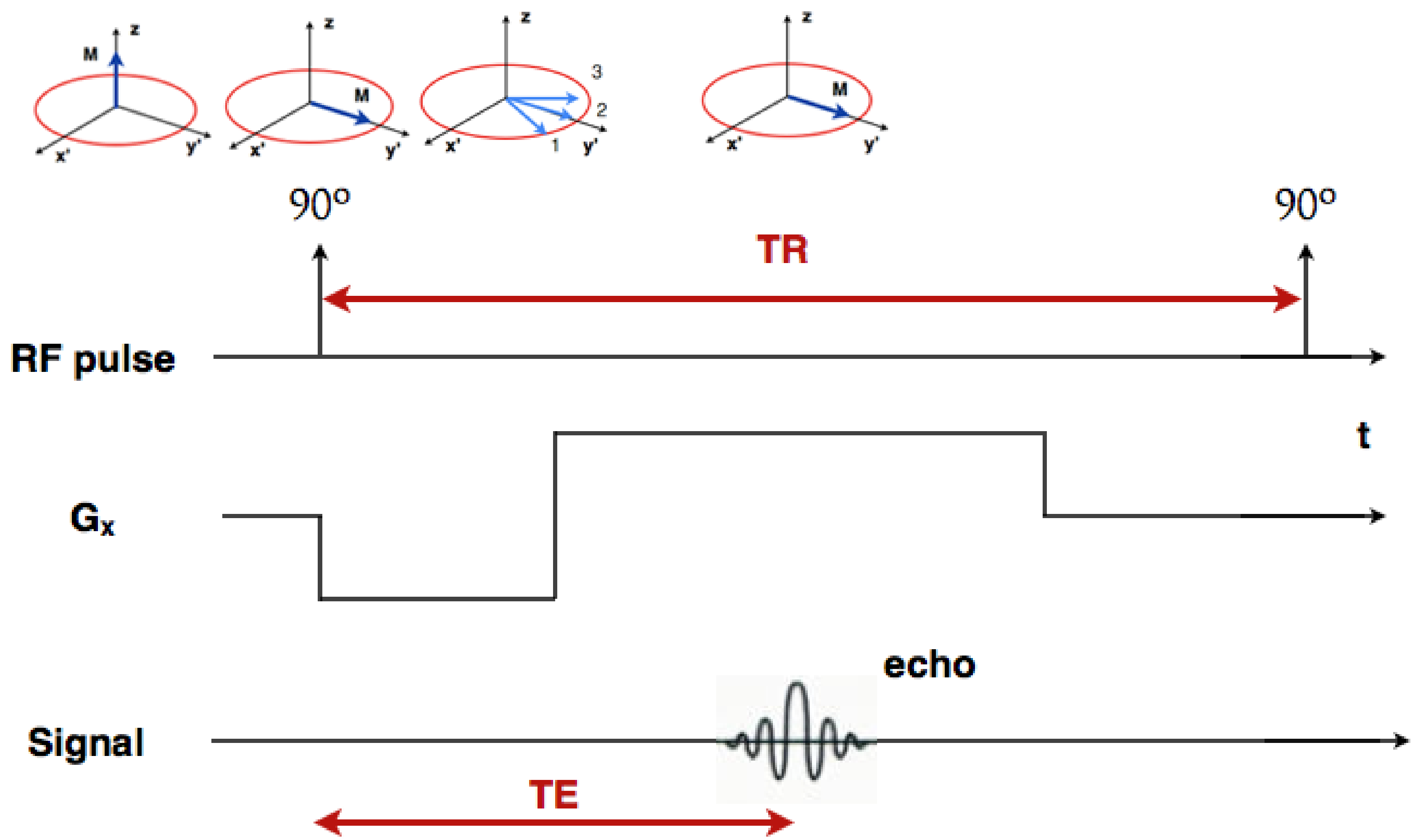
SPIN-ECHO (SE) SEQUENCE





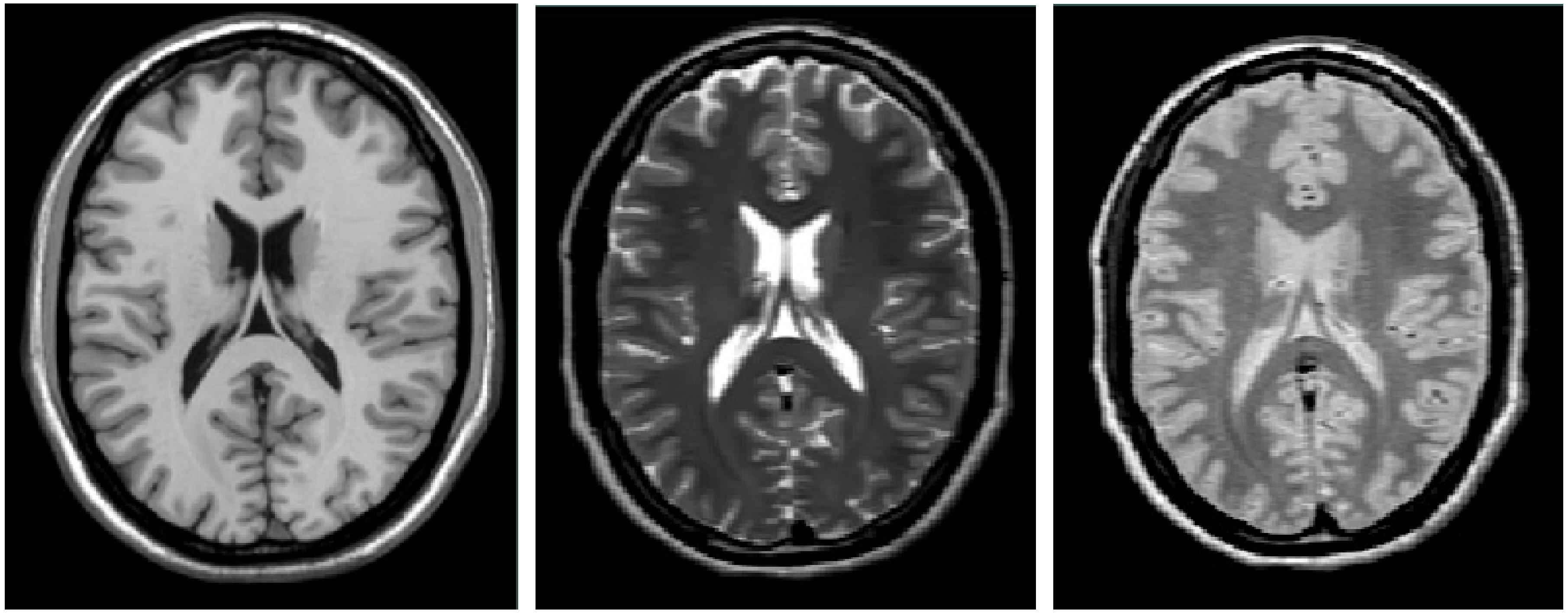
This ensures T2 relaxation

GRADIENT-ECHO (GRE) SEQUENCE



This can be used to take advantage of T2* relaxation

IMAGE CONTRASTS



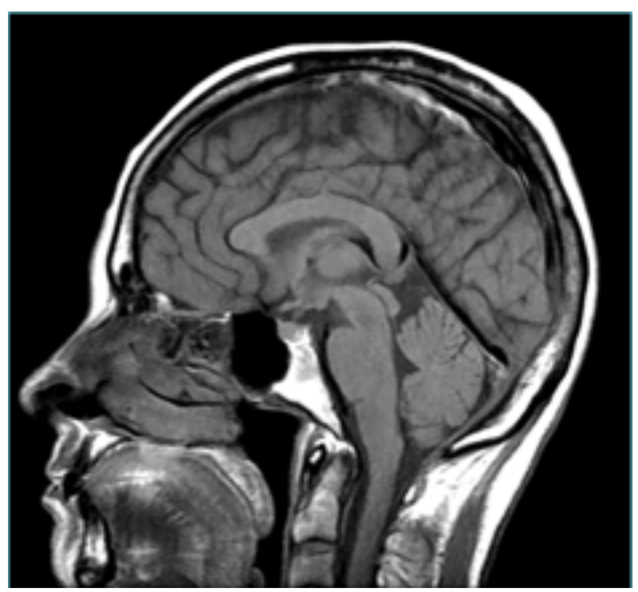
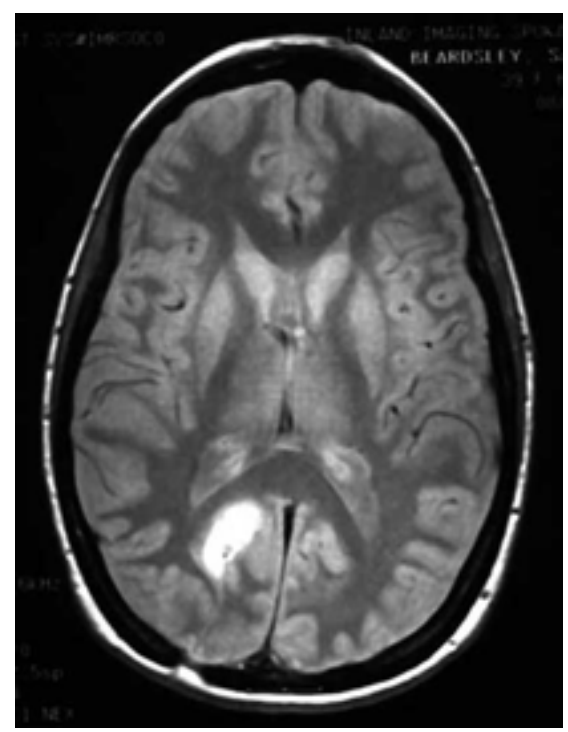
(a) T1w MRI (b) T2w MR (c) PDw MRI

$$\rho_m = \rho_0 e^{-TE/T2*} \frac{sin\alpha(1 - e^{-TR/T1})}{1 - cos\alpha \cdot e^{-TR/T1}}$$

WHAT CAN WE USE MRI FOR?

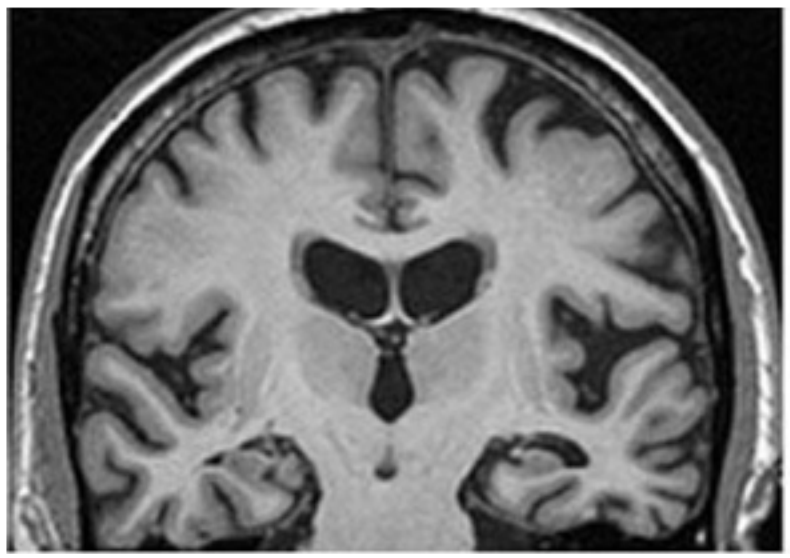
REVEALING THE ANATOMY

- Qualitatively and quantitatively imaging the structures
- Tendons, muscles, fat, tumours, lesion & blood vessels
- Surgical planning and structural analysis

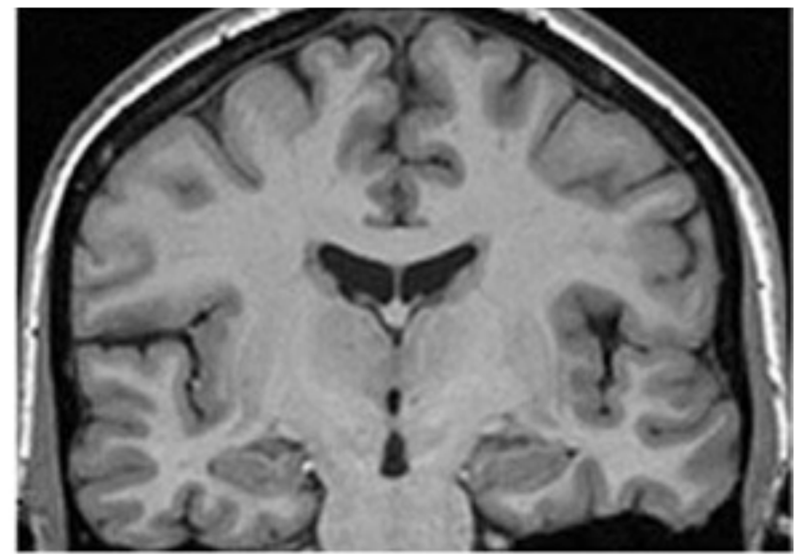





REVEALING THE ANATOMY

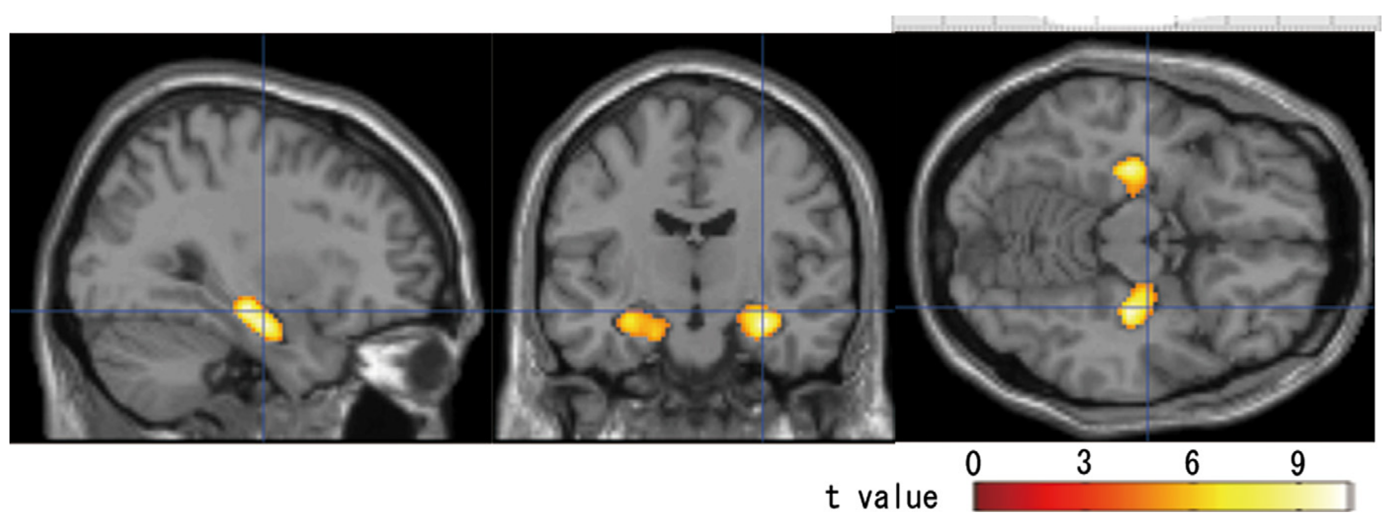
- Morphometric Analysis



Alzheimer’s Disease

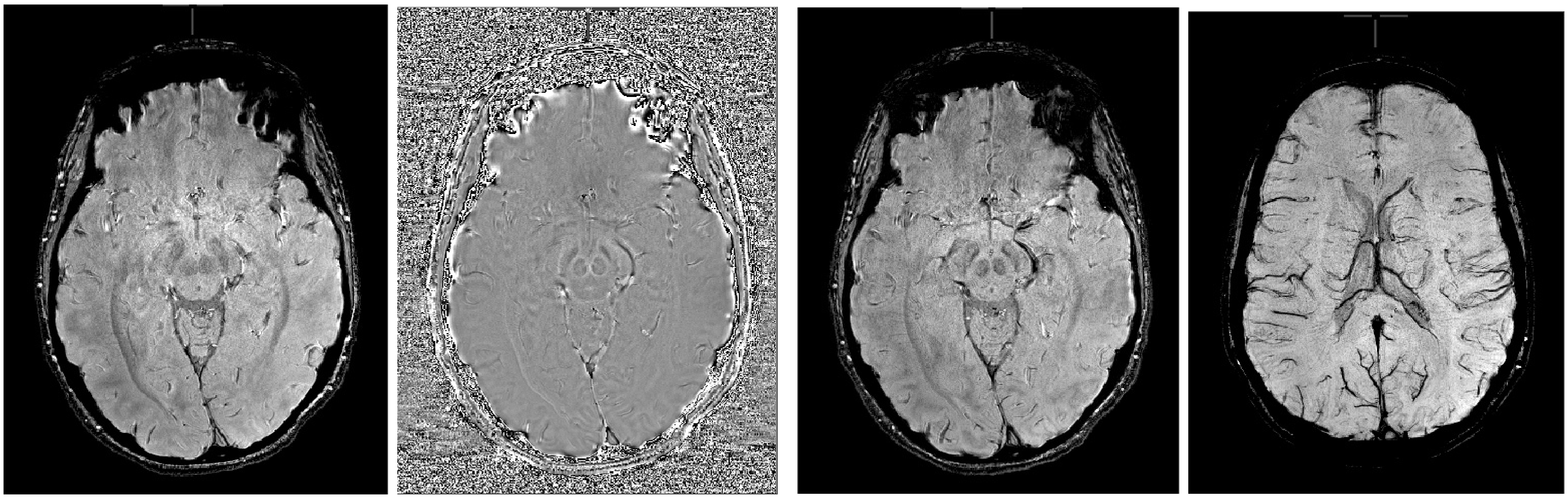


Healthy



Imabayashi et al., 2013

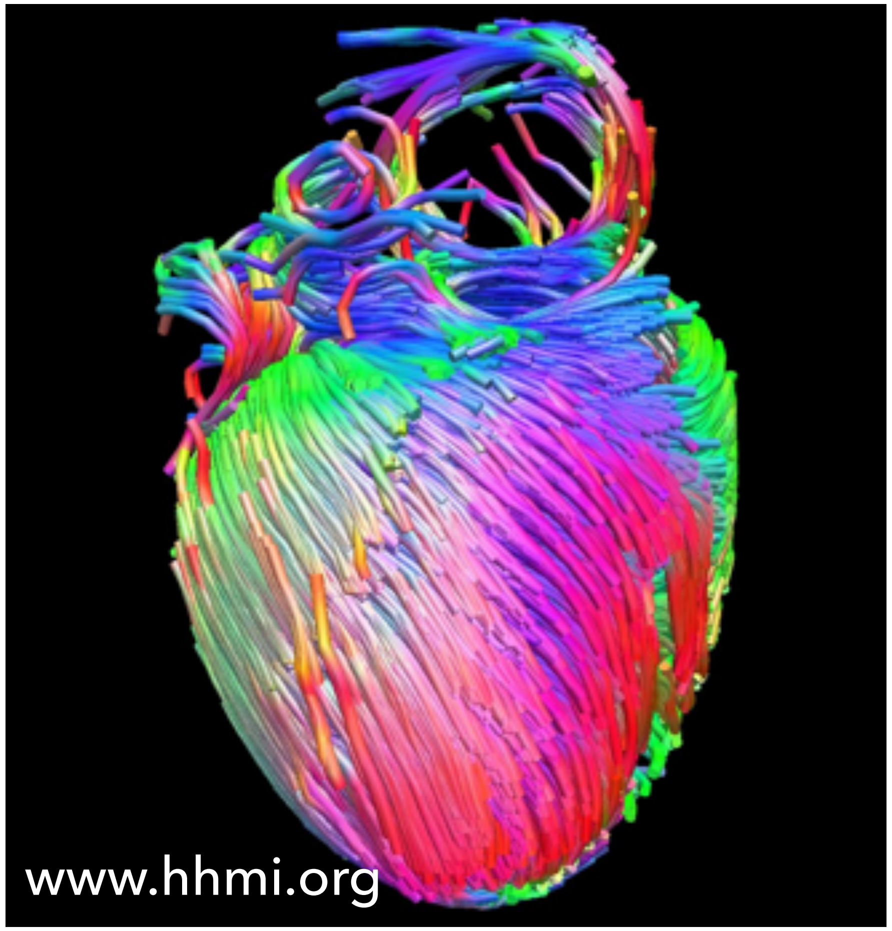
SUSCEPTIBILITY-WEIGHTED IMAGING (SWI)

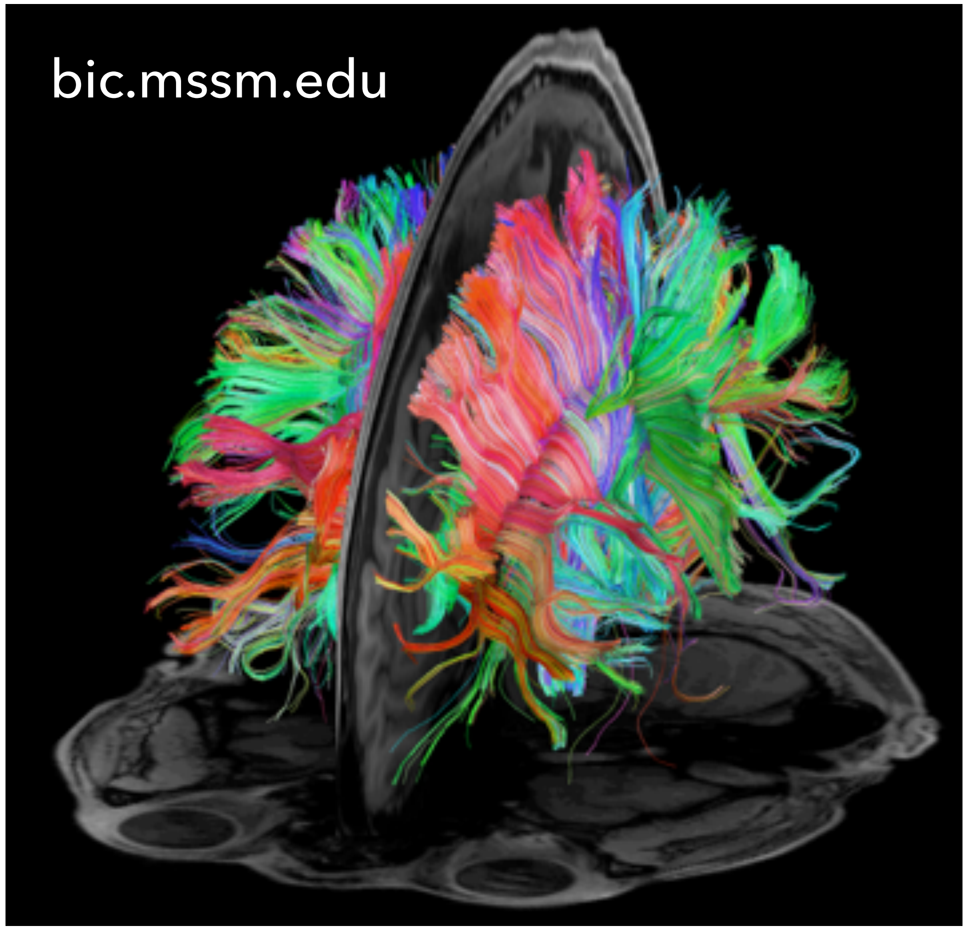


- Use iron in the tissue as natural contrast enhancement
- Reveals veins in the brain
- Lesions, micro-bleeding, and measure iron cumulation

IMAGING FIBRES IN AN ORGAN

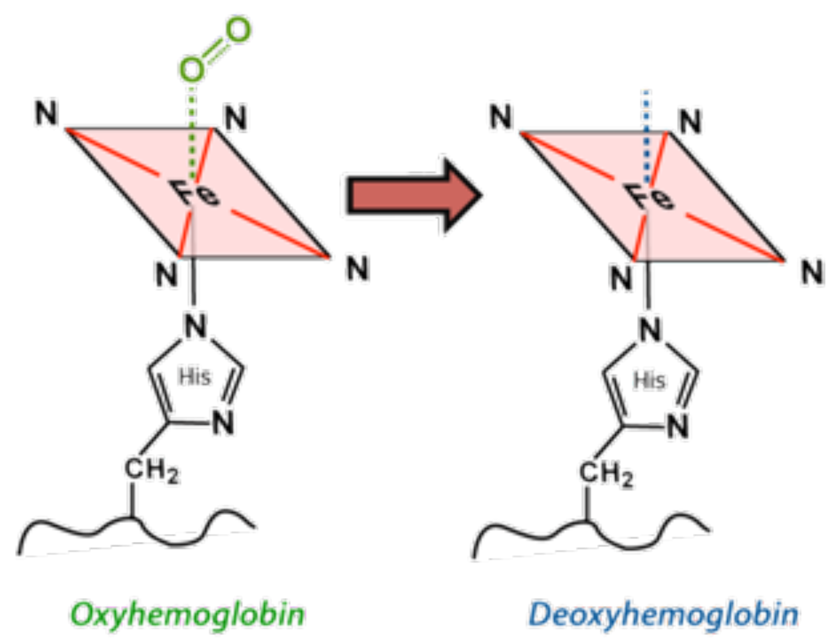
Diffusion-tensor image (DTI): image water diffusion directions



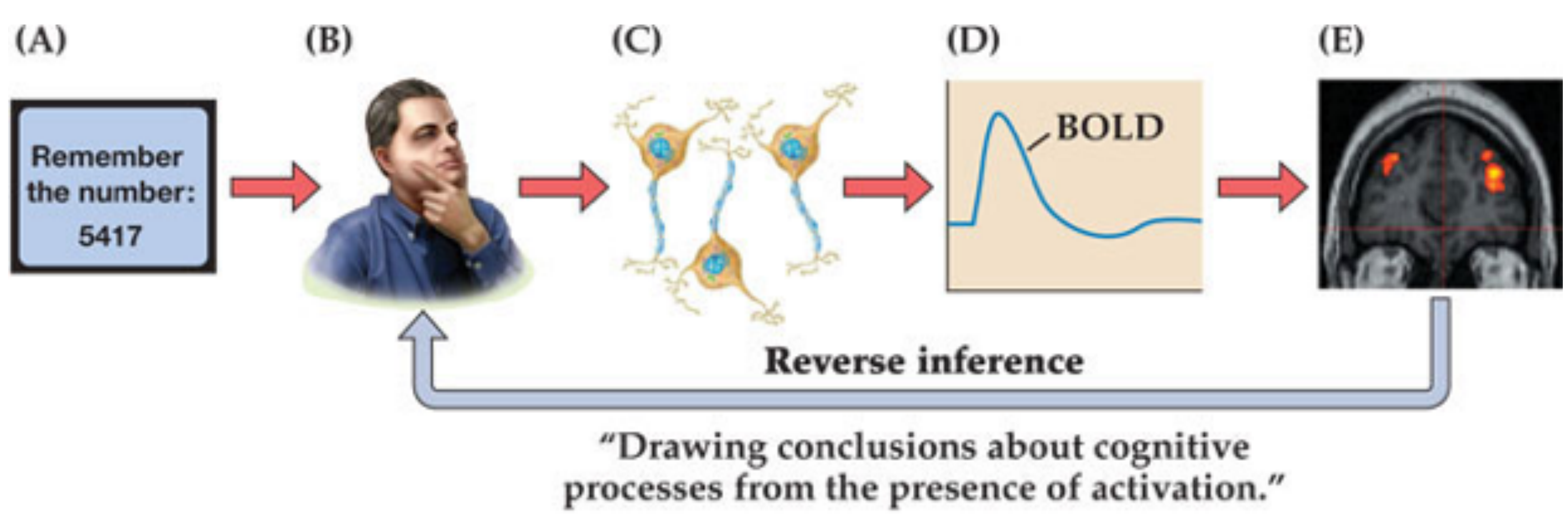


BRAIN ACTIVITY

- Functional MRI (fMRI) measures the blood-oxygen-dependent (BOLD) signal



Diamagnetic Paramagnetic



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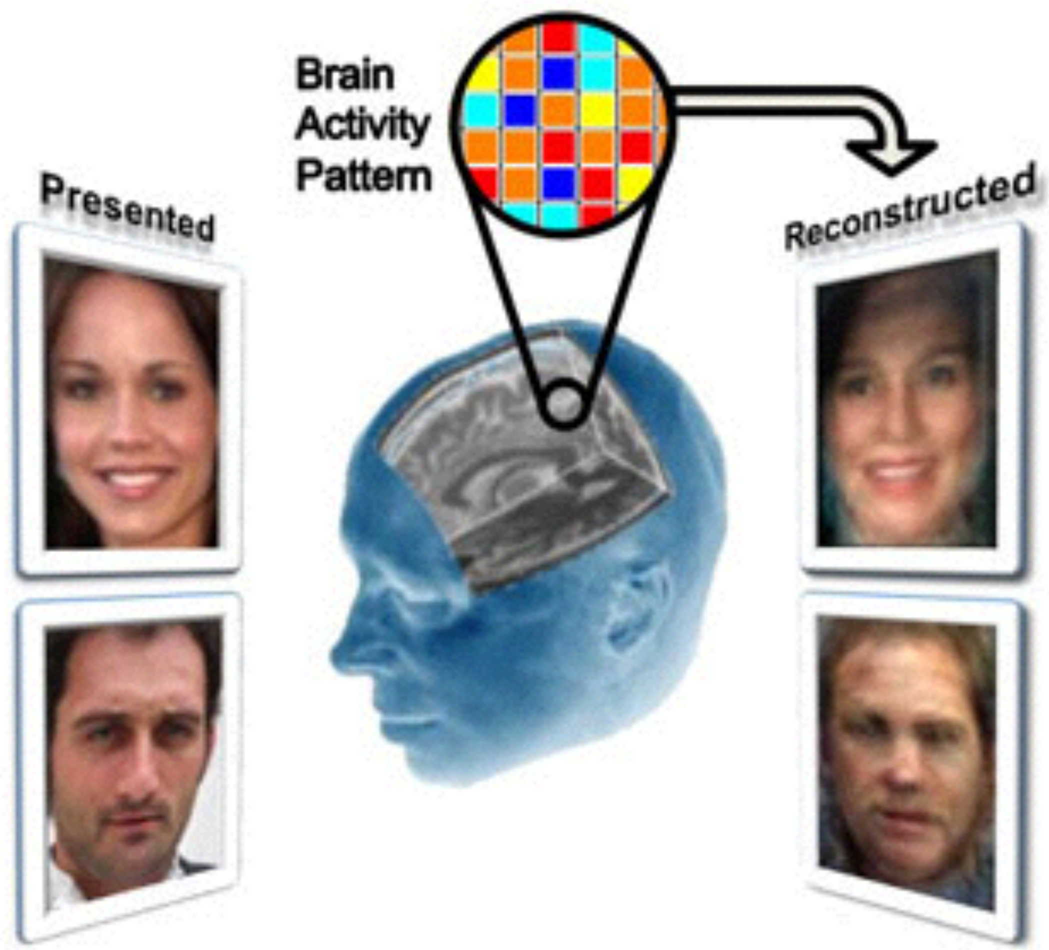
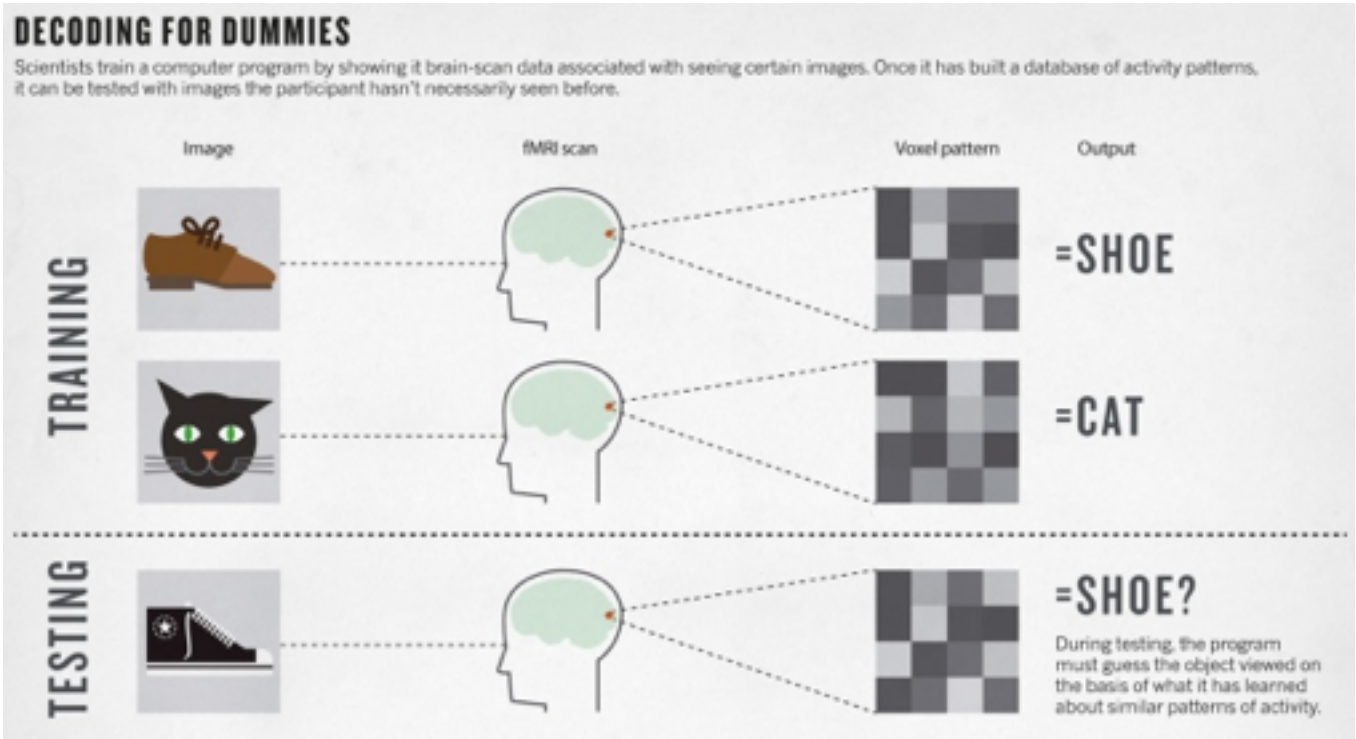
BRAIN ACTIVITY



www.nydailynews.com



www.nature.com

IN SUMMARY

- MRI is based on the nuclear magnetic resonance (NMR) phenomenon
- Three main magnetic fields interact with spins to generate FID
- Different image contrasts can be generated by playing with the timing and duration that the magnetic fields are applied.
- K-space vs image space
- Many applications, but need the help of image processing and data science

TAKE HOME MESSAGE

Not all MRIs are equal

Get to know your images before processing them!

WHAT WE DID NOT TALK ABOUT

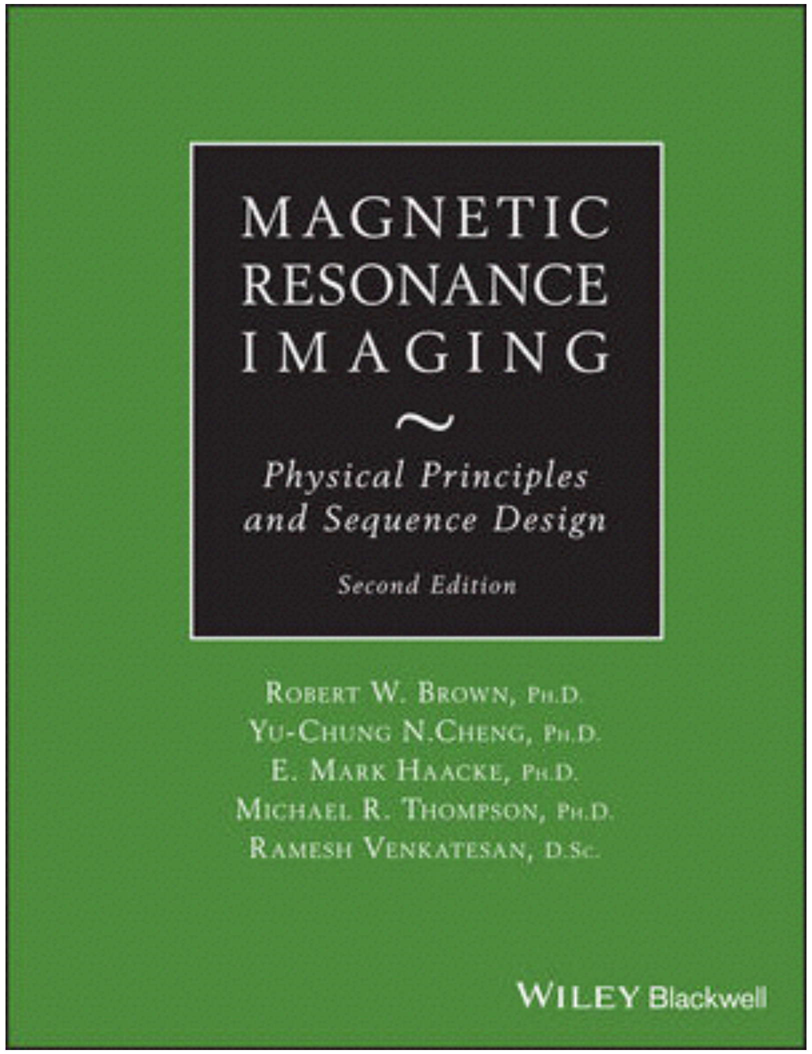
- How to control the image resolution
- Signa-to-noise ratio (SNR)
- Imaging artifacts
- Mechanism of fast imaging & more…

WANT TO KNOW THE COMPLETE STORY?

Xray Physics - Interactive Radiology Physics
Check out the MRI physics section
    http://www.xrayphysics.com/sequences.html

Joseph Hornak's Web Tutorial, *The Basics of MRI*
    http://www.cis.rit.edu/htbooks/mri

E. Mark Haacke, et al 2014 Magnetic Resonance Imaging: Physical Principles and Sequence Design, 2nd Ed.



QUESTIONS?