BCS 513: Introduction to fMRI: Imaging, computational analysis and neural representations

Very simplified MRI physics with no math

Feb 11, 2014

Outline of the lecture

- Introduction of basic nuclear spin physics
- Interaction of nuclei with magnetic field (static, RF, and gradient fields)
- Nuts and bolts of MRI
  - Hardware
  - Pulse sequences
  - Image contrast

MRI in a nutshell

NMR = nuclear magnetic resonance

- nuclear: properties of nuclei in atoms
- magnetic: magnetic field required
- resonance: specific energy transition at radio frequency (RF)

NMR → MRI (1970's and 80's)

- field gradients: spatial encoding

→

Atoms that can be imaged with MRI

$$ {}^{1}_{1}\mathrm{H} \quad {}^{13}_{6}\mathrm{C} \quad {}^{17}_{8}\mathrm{O} \quad {}^{19}_{9}\mathrm{F} \quad {}^{23}_{11}\mathrm{Na} \quad {}^{31}_{15}\mathrm{P} \quad \ldots $$

where: $ {}^{A}_{Z}\mathrm{N} $

N is the abbreviation for the name of the atom
A is the total number of protons+neutrons
Z is the number of protons
A-Z = the number of neutrons

Nuclear: Protons mostly

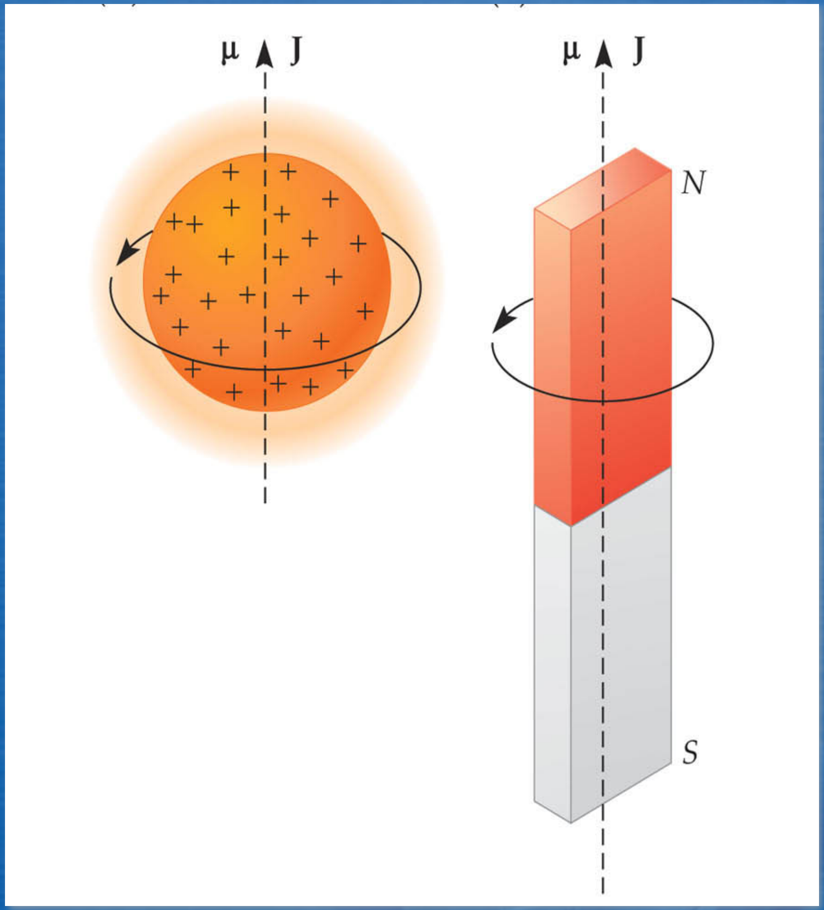
- In order to be imaged, nuclei must:
  - have an odd number of neutrons+protons
  - be abundant in the body

- 1H (proton) is star of MRI!
  - abundant: high concentration in human body
  - high sensitivity, yields largest detectable signals
  - 99% of human MRI and exclusive in this course

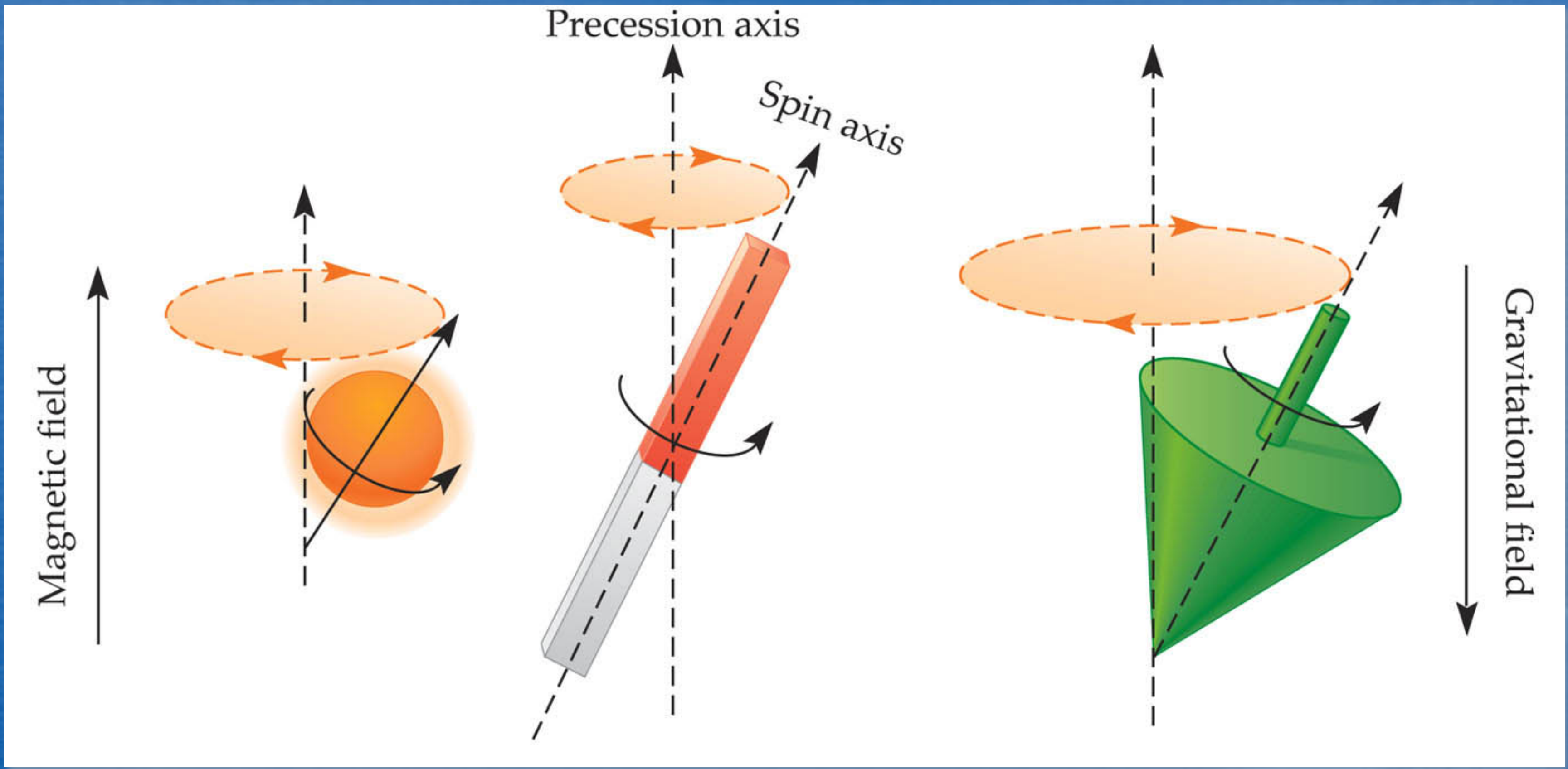
- Can image nuclei other than 1H, but extra hardware needed (different resonance frequency)

Spins, Angular Momentum, and Magnetic moment

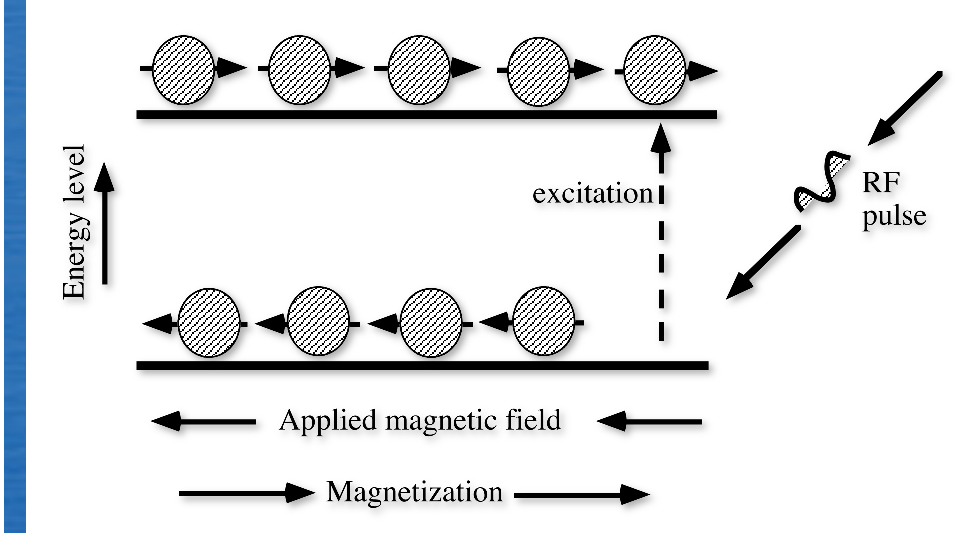
- Spin is an intrinsic QM property of nuclei (and electrons)
- It acts as a current loop with internal angular momentum and magnetic moment: "spinning" and therefore the name spin

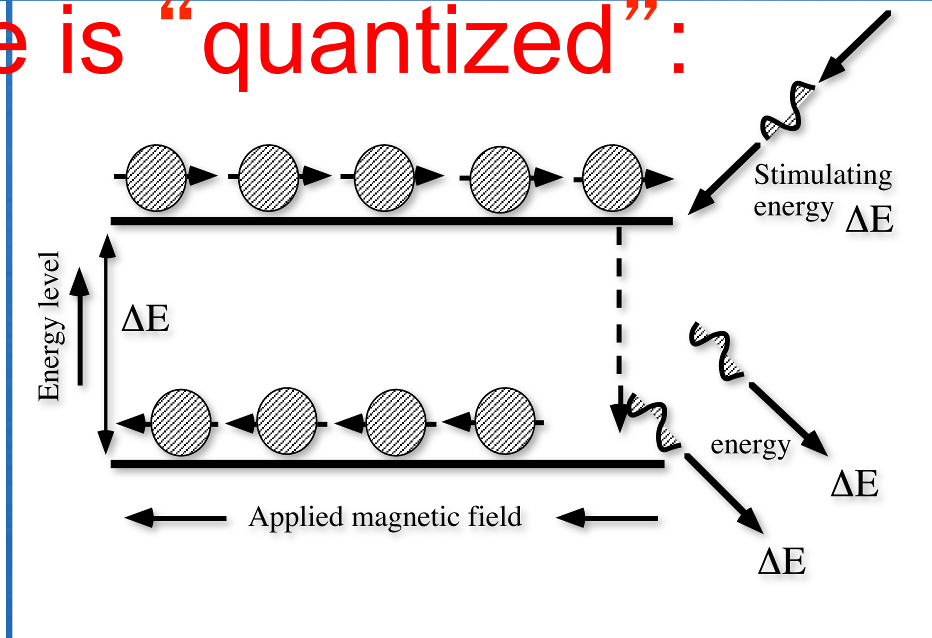


When spins are put into magnetic field (classical view):



In QM, spin state is "quantized":





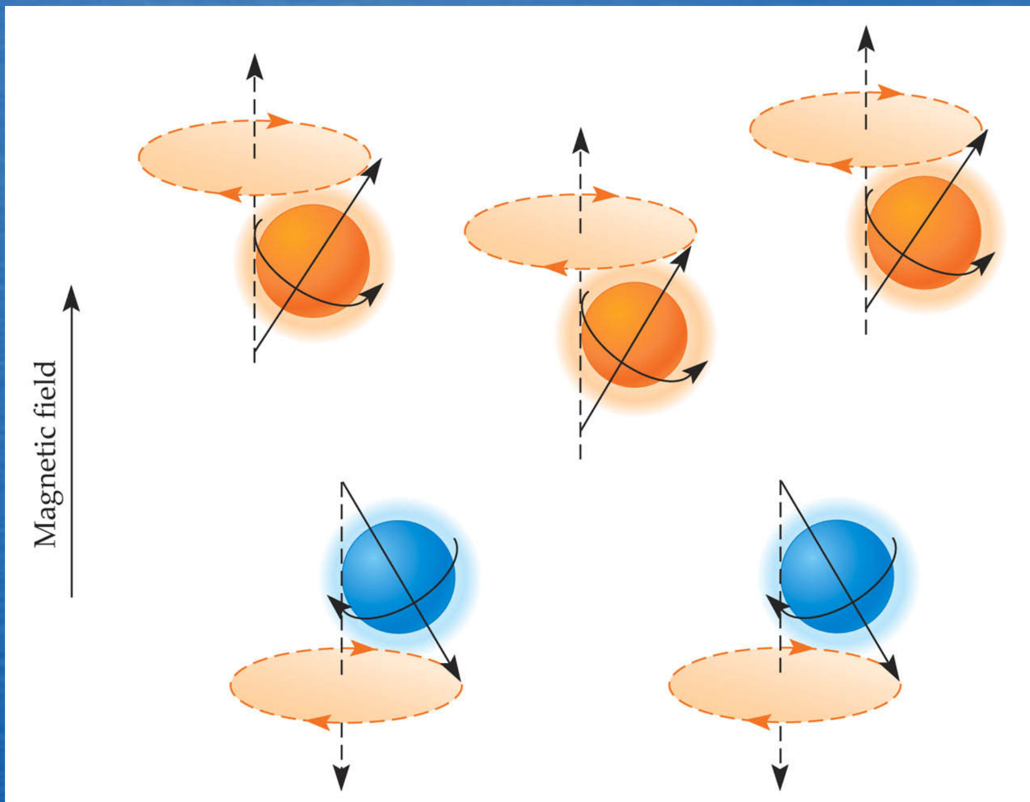
RF excites spins:

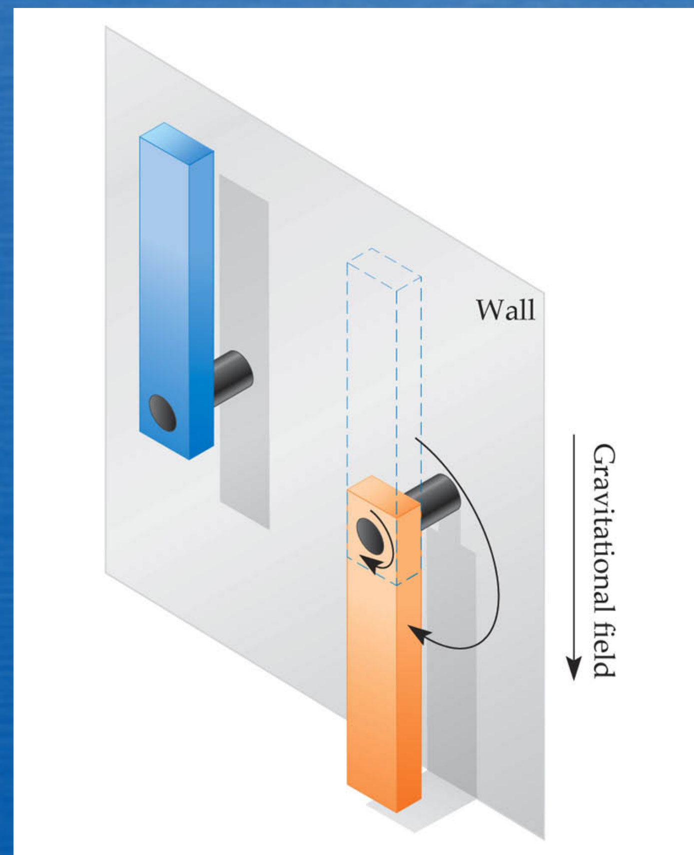
$$\Delta E = \frac{h}{2\pi}\cdot\gamma B_0 = \frac{h}{2\pi}\cdot\omega_0$$

Absorbed energy emitted, inducing voltage in detecting coil

Larmor Frequency $\omega_0 = \gamma B_0$

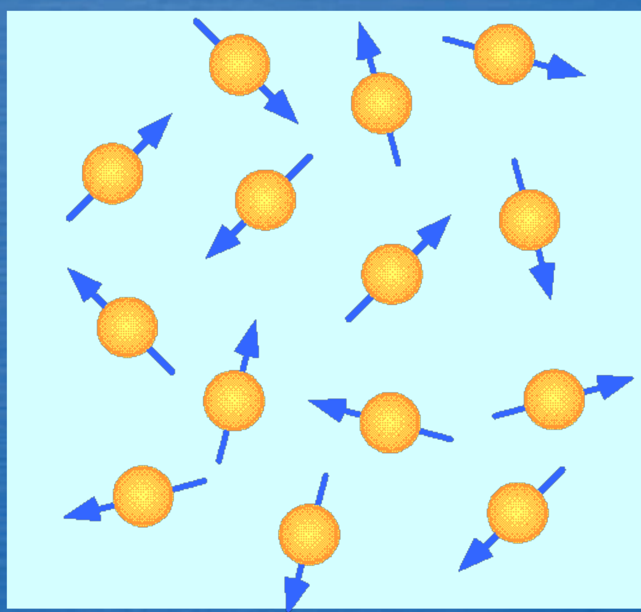
When spins are put into magnetic field (QM view): High and low-energy states





Nuclear Moments from Entire Sample

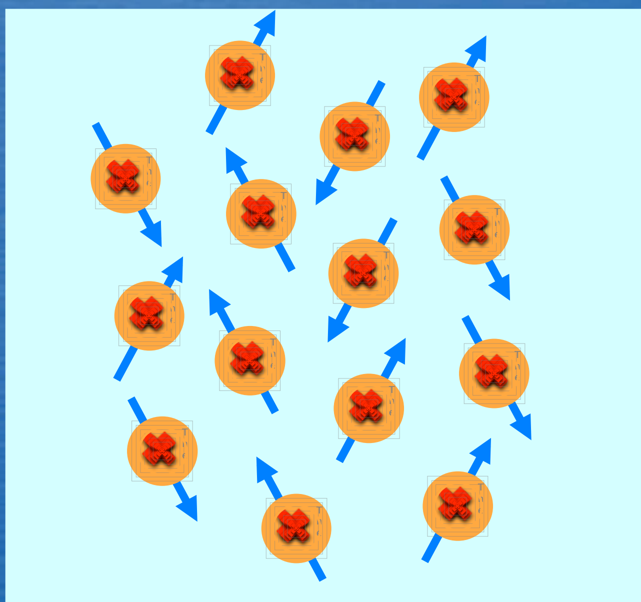
No Magnetic Field



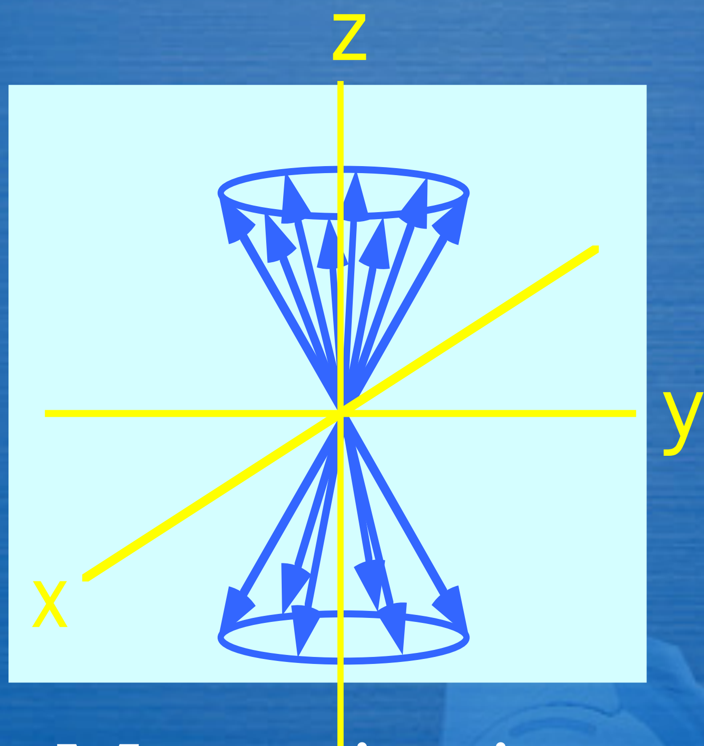
Random Orientation

= No Net Magnetization

Nuclear Moments from Entire Sample



Non-Random Orientation



Net Magnetization

Resonance: Larmor Equation

$$\omega = \gamma B$$

Precession Frequency

Magnetic Field Strength

Resonance: Larmor Equation

$$\omega = \gamma B, \quad \nu = \omega/2\pi$$

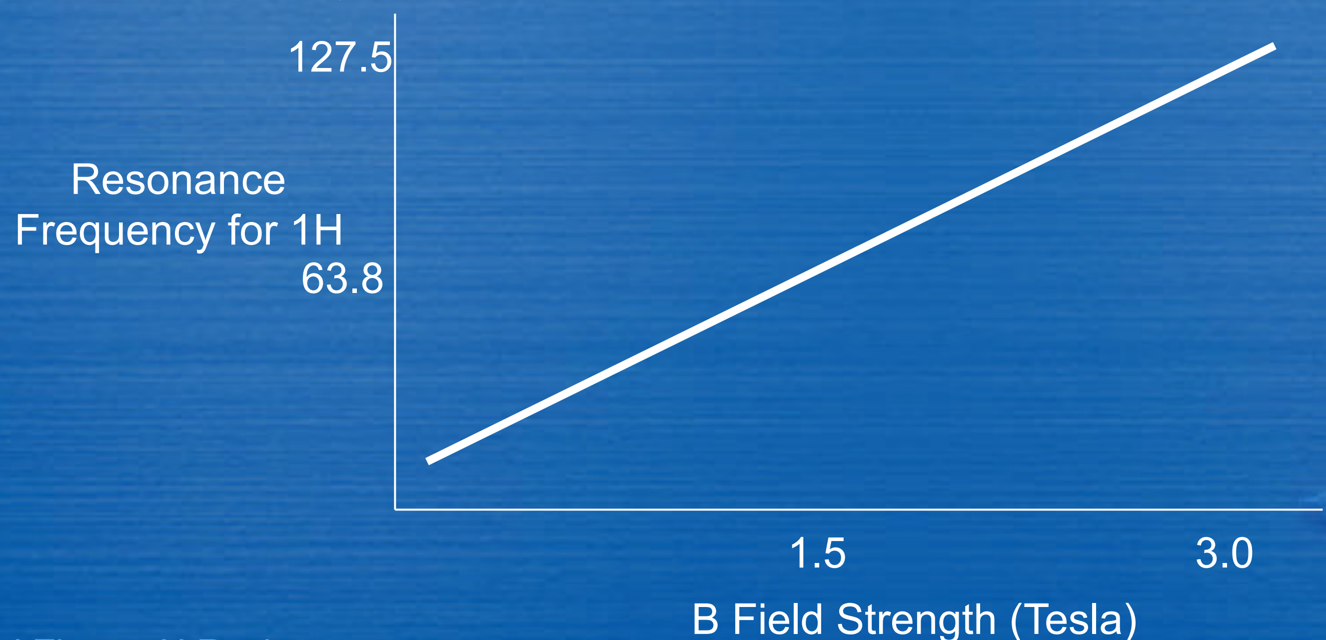
γ = 42.58 MHz/T (for 1H)

At 1.5T, ν ~ 64 MHz

At 3T, ν ~ 128 MHz

Signal ~ B_0 :

High field advantage!



J.Zhong, U Rochester

Very brief history of MRI

- Pauli hypothesis (1924) and Stern/Gerlach expt: discovery of nuclear spins
- Rabbi determination (1938): Resonance
- Bloch and Purcell (1945): Basic components (static and RF magnetic field) of NMR
- Lauterbur and Mansfield (70-80s): field gradients for imaging and EPI (basis for fMRI techniques)
- Ogawa (1990): physiological basis (BOLD) of brain fMRI

From NMR to MRI

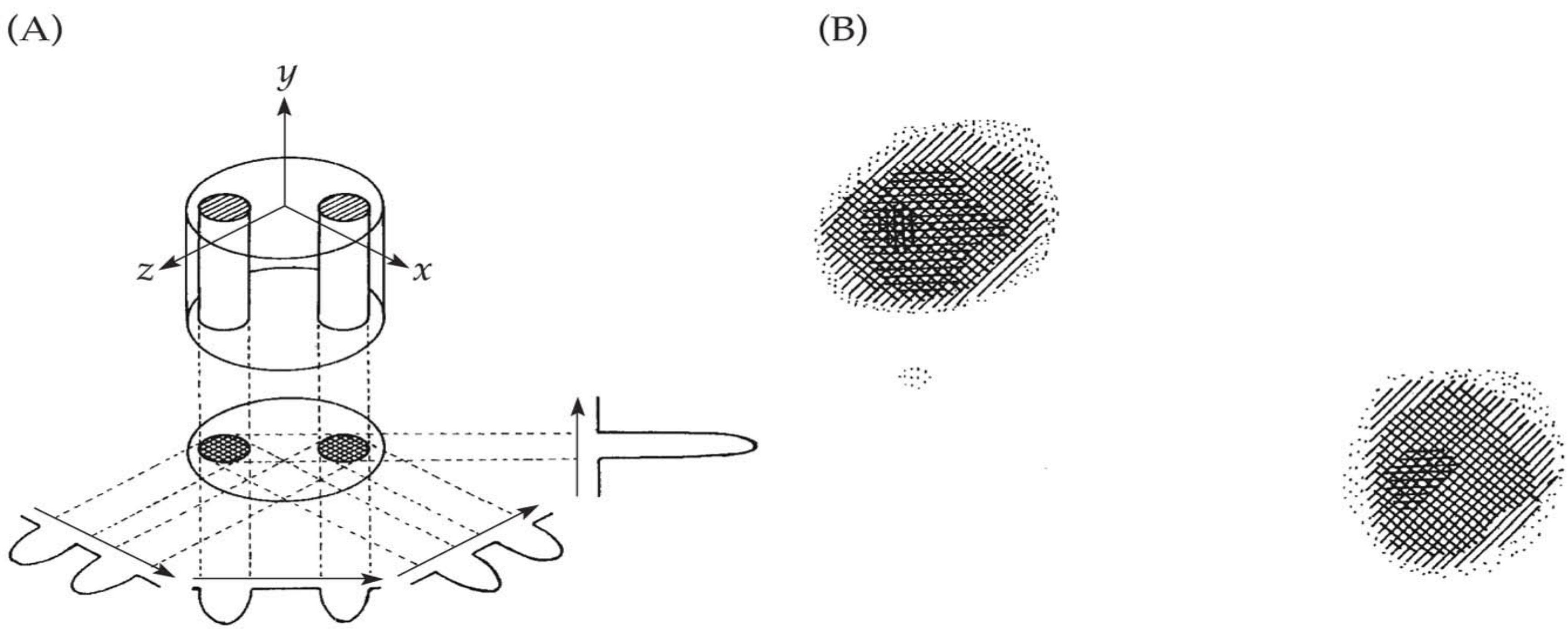
Paul C. Lauterbur   Sir Peter Mansfield

-1973: Lauterbur suggests field gradients can be used to form images

-1977: Mansfield proposes echo-planar imaging (EPI) to acquire images faster

→ Nobel prize 2003 for physiology/medicine

The first MR image from Lauterbur

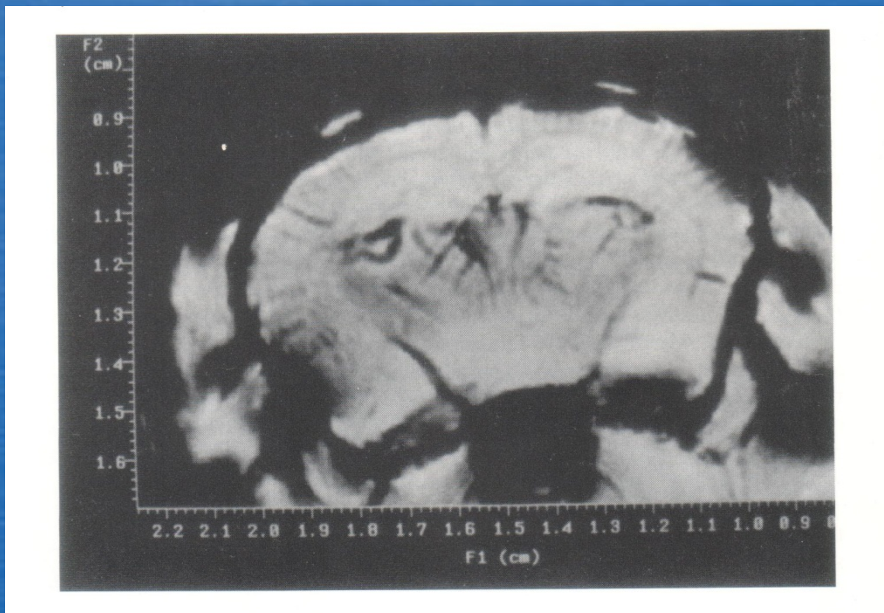


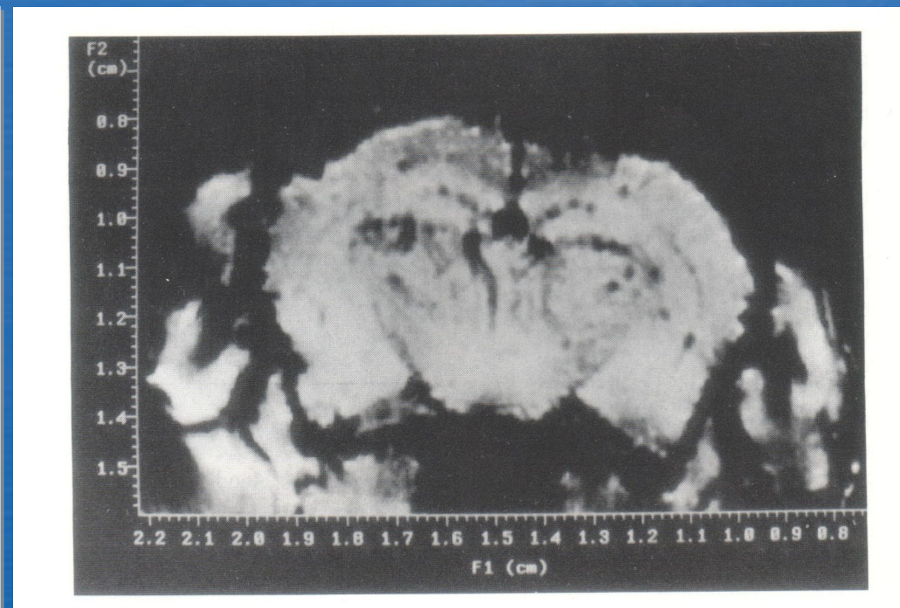
FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 1.12

functional MRI (fMRI)

- 1990: Ogawa observes BOLD effect with T2* in rats blood vessels became more visible as blood oxygen decreased
- 1991: Belliveau observes first functional images using a contrast agent
- 1992: Ogawa & Kwong publish first human brain functional images using BOLD signal

Ogawa first BOLD expt

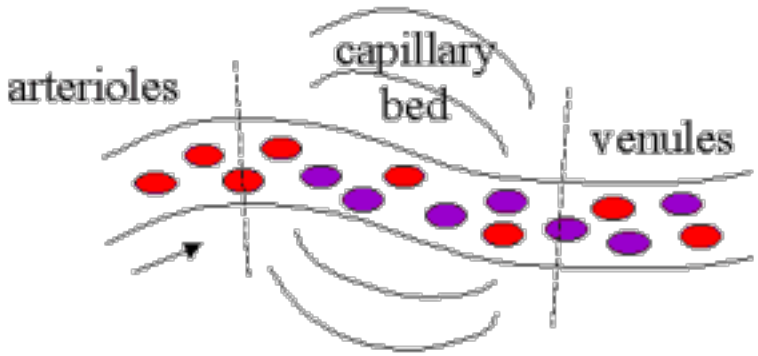




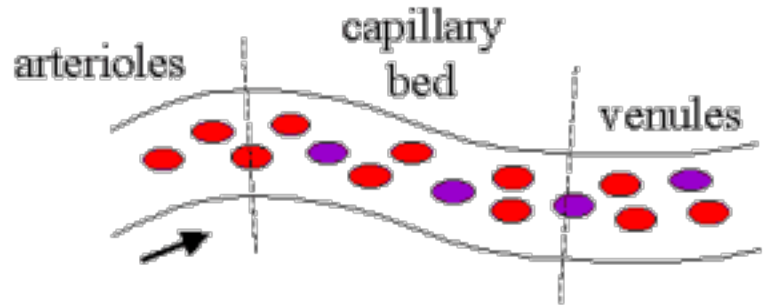
"…the contrast should have high sensitivity towards physiological changes which influence the level of blood oxygenation and could serve as a qualitative detection tool for mapping regional blood oxygen-nation levels in the brain…" Ogawa and Lee, MRM, 1990

fMRI BOLD: Rapid Overview

<u>Basal state</u>

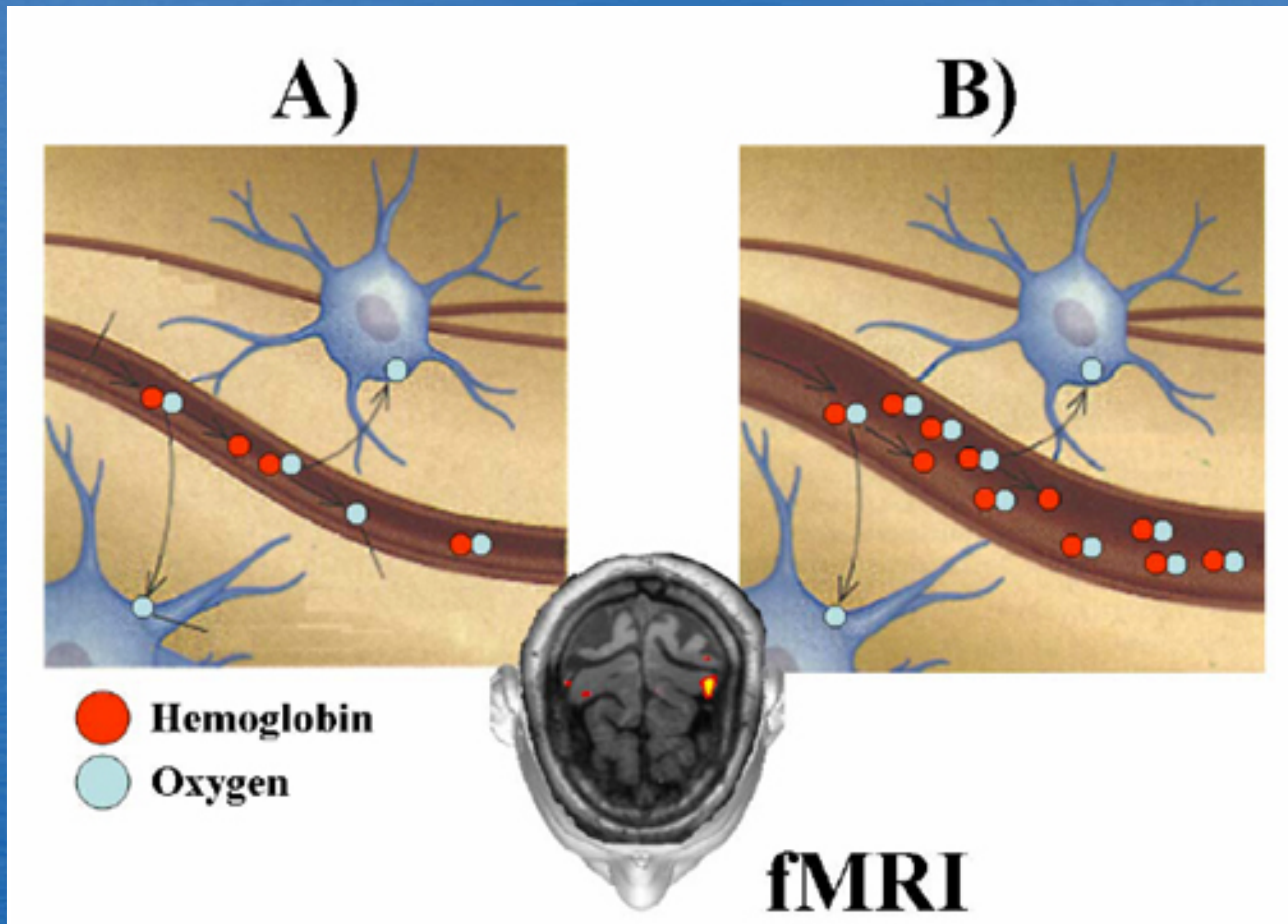


<u>Activated state</u>



- normal flow
- basal level [Hbr]
- basal CBV
- normal MRI signal

- increased flow
- decreased [Hbr] (*lower field gradients around vessels*)
- increased CBV
- increased MRI signal (*from lower field gradients*)


A)
B)
Hemoglobin
Oxygen
fMRI

Magnetic field B: Uniform or linear, static or varying

- B_0:
  - Static, uniform: for spin polarization
- B_1:
  - RF-frequency, usually pulse (short time burst): for signal excitation
- $B_g = x.G(x) + y.G(y) + z.G(z)$
  - Short pulse, change linearly with spatial location: for relating the signal to spatial location

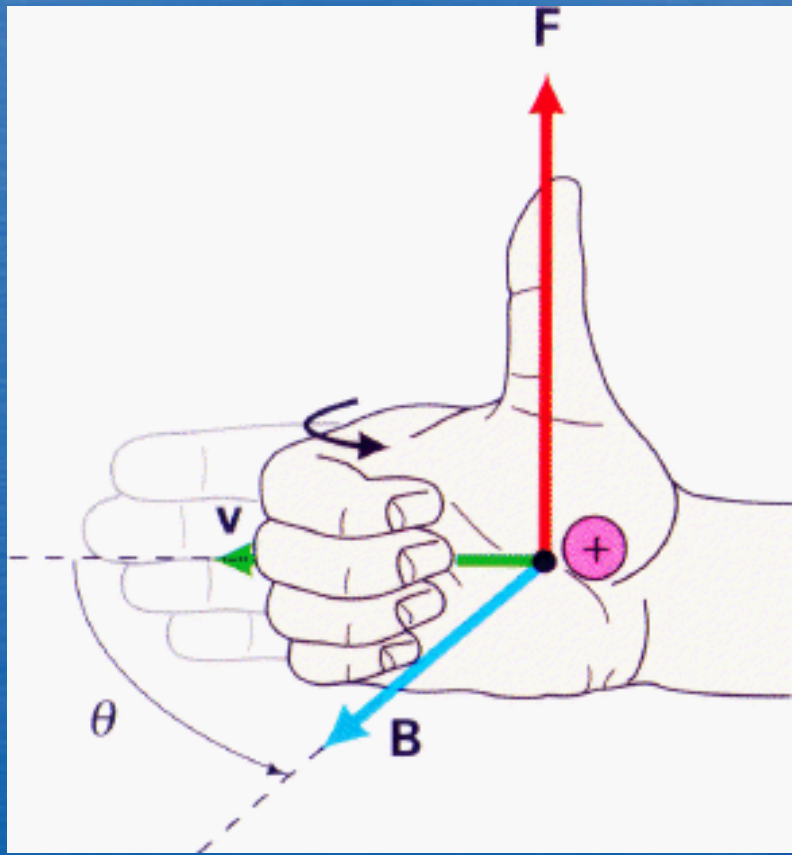
$$B = B_0 + B_1 + B_g$$

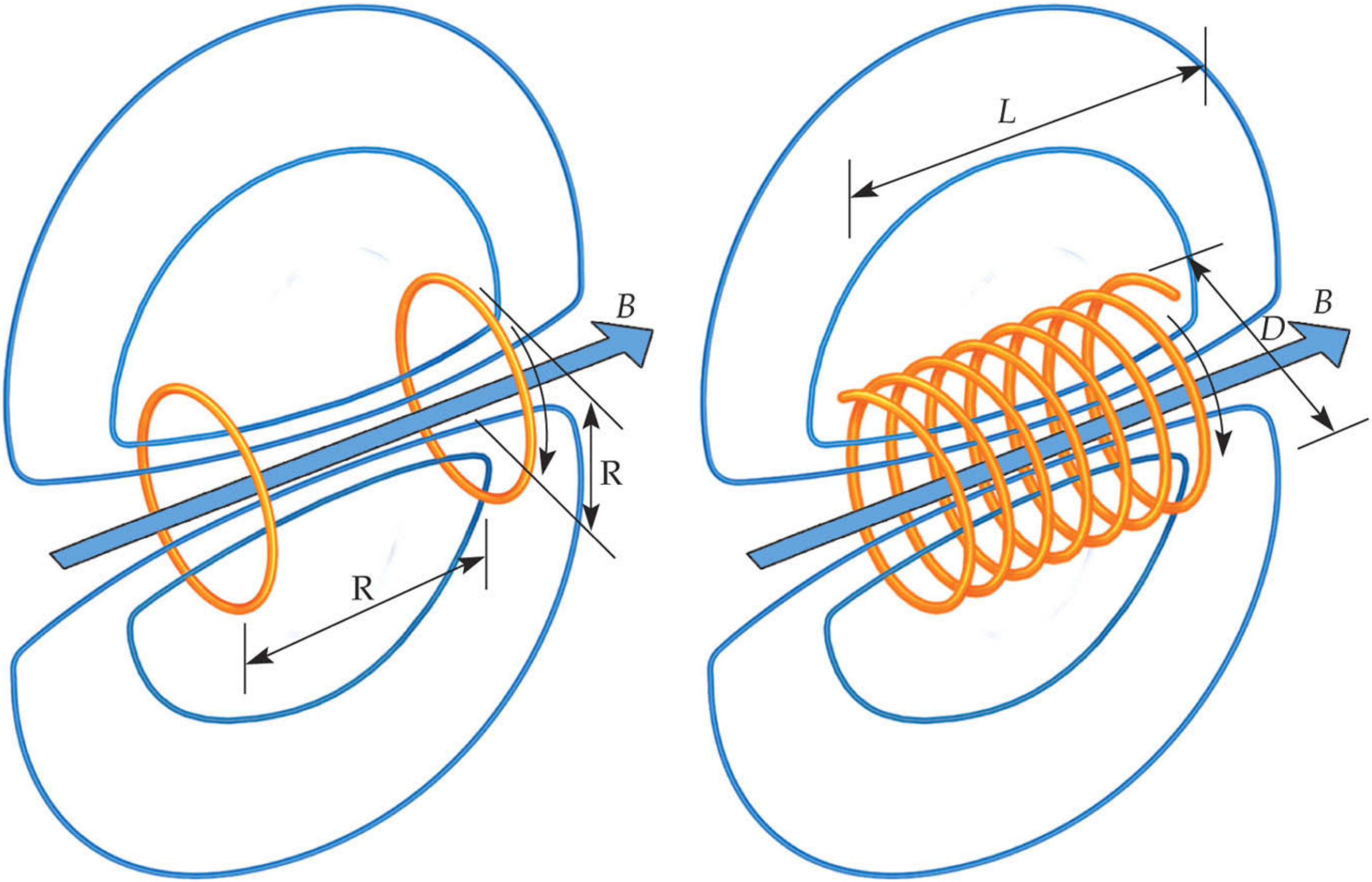
Main hardware of MRI

- Coils to generate three fields:
  - B_0
  - B_1
  - B_g (field gradients)

- Others are supportive
  - shimming for better B_0 homogeneity,
  - physiology monitoring
  - data storage and processing
  - Convenience and safety

Current moving in a loop induces a magnetic field (right-hand rule)





Generation of a static magnetic field

The big magnet: magnetic field

Very strong (and costly)

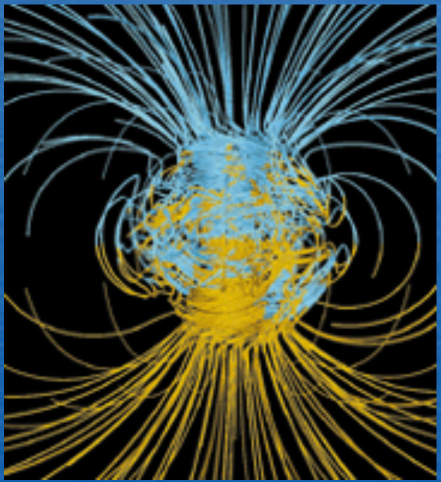
1 Tesla (T) = 10,000 Gauss

Earth's magnetic field = 0.5 Gauss

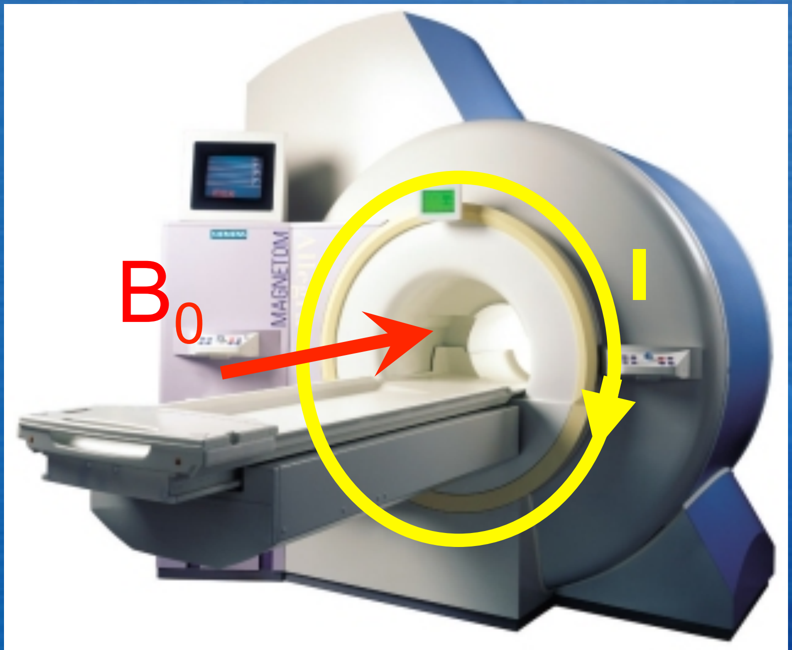
3 Tesla = 3 x 10,000 ÷ 0.5 = 60,000X Earth's magnetic field

Continuously on (can be a safety issue!)

Main field = B_0



x 60,000 =



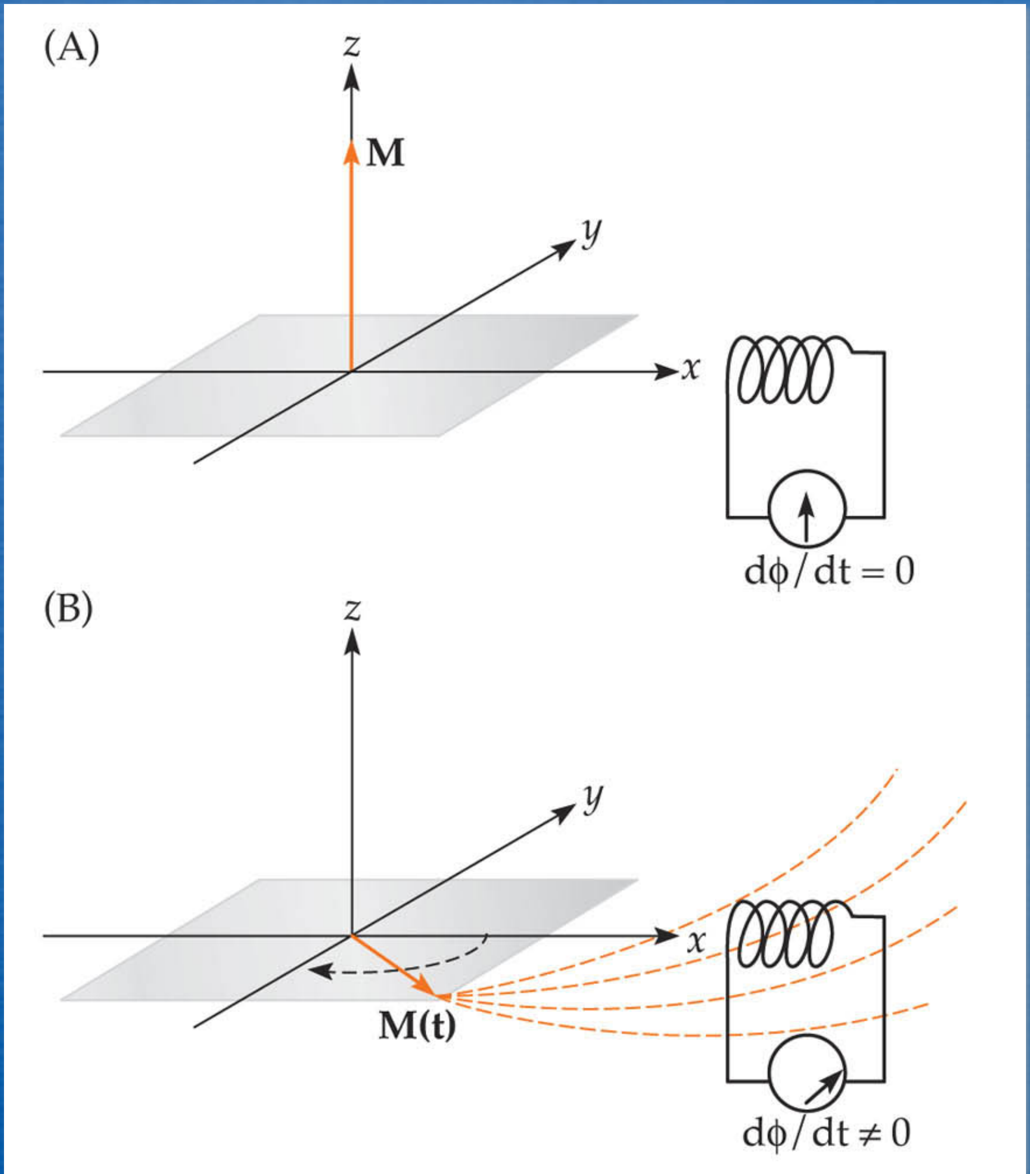
Source: www.spacedaily.com

Digression: small portable MRI

- Larry Wald et al, Harvard-MGH, 2013

- To answer simple questions:
  - acute stroke management: bleed or not, anti-thrombotic treatment or not
  - traumatic brain injury: yes or no
  - tumor follow-ups: grow or not
- Portable: magnet in one hand, electronics in the other (<45kg)
- Low field and low cost: <$3000 for material

MRI signal detection

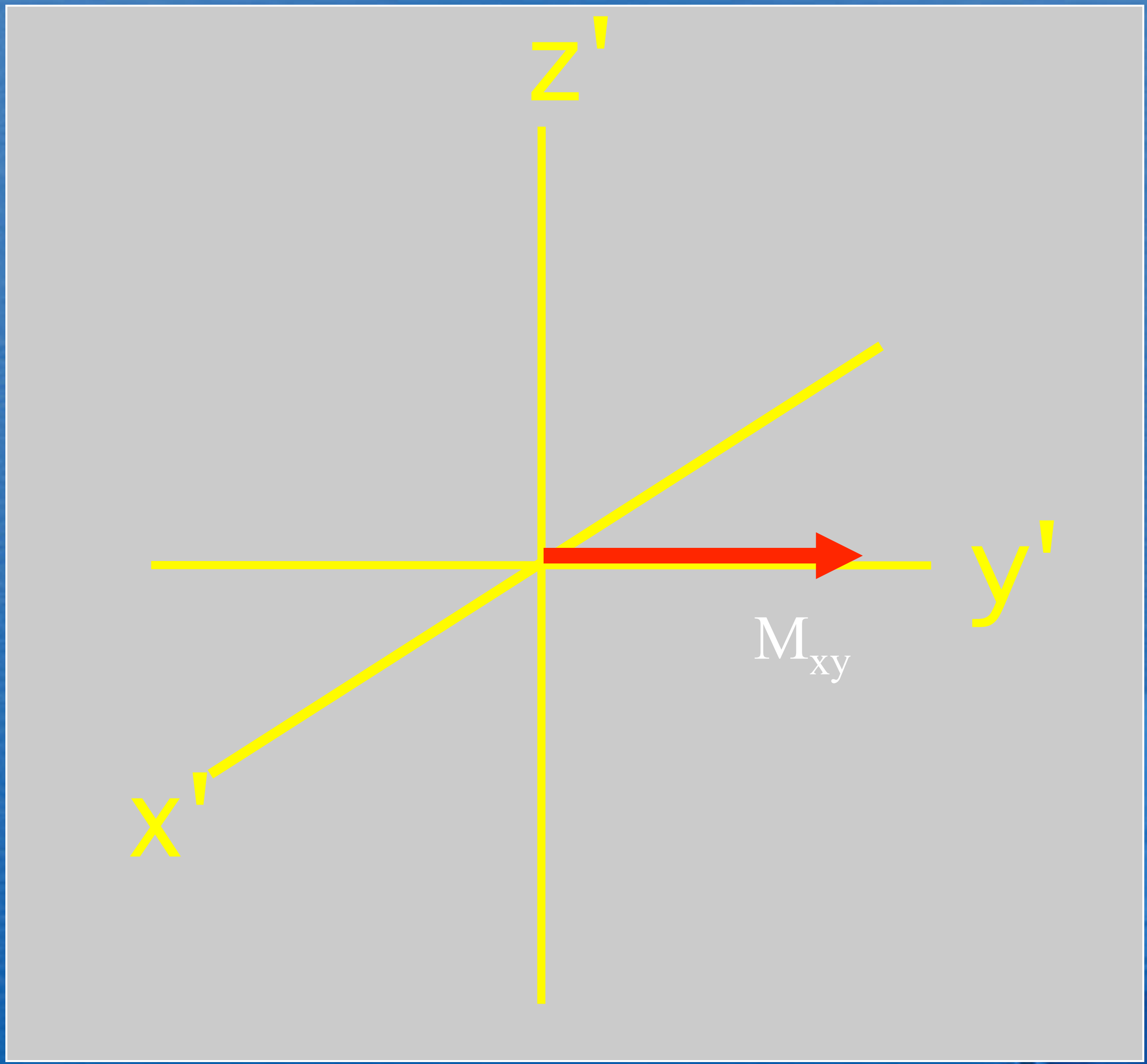


Faraday's law of induction:

Signal will be detected when the magnetization through the cross-section of the coil ("magnetic flux") changes with time

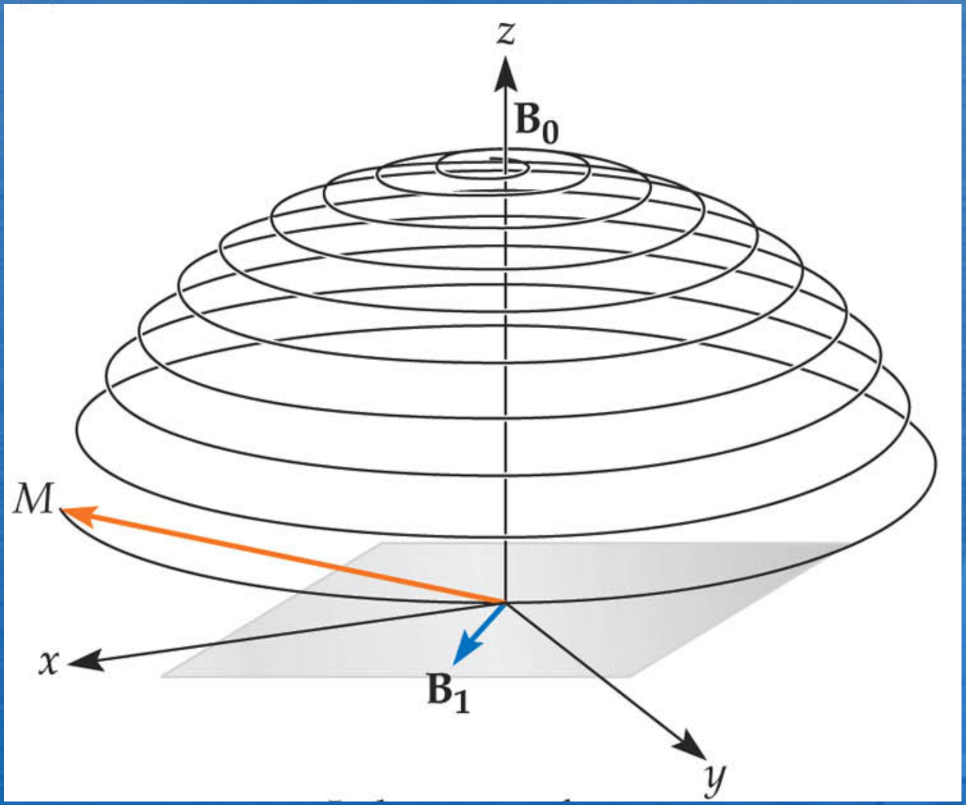
Since the coil is laying in the transverse plane, only M_{xy} can be detected.

Transverse Magnetization: source of MRI signal

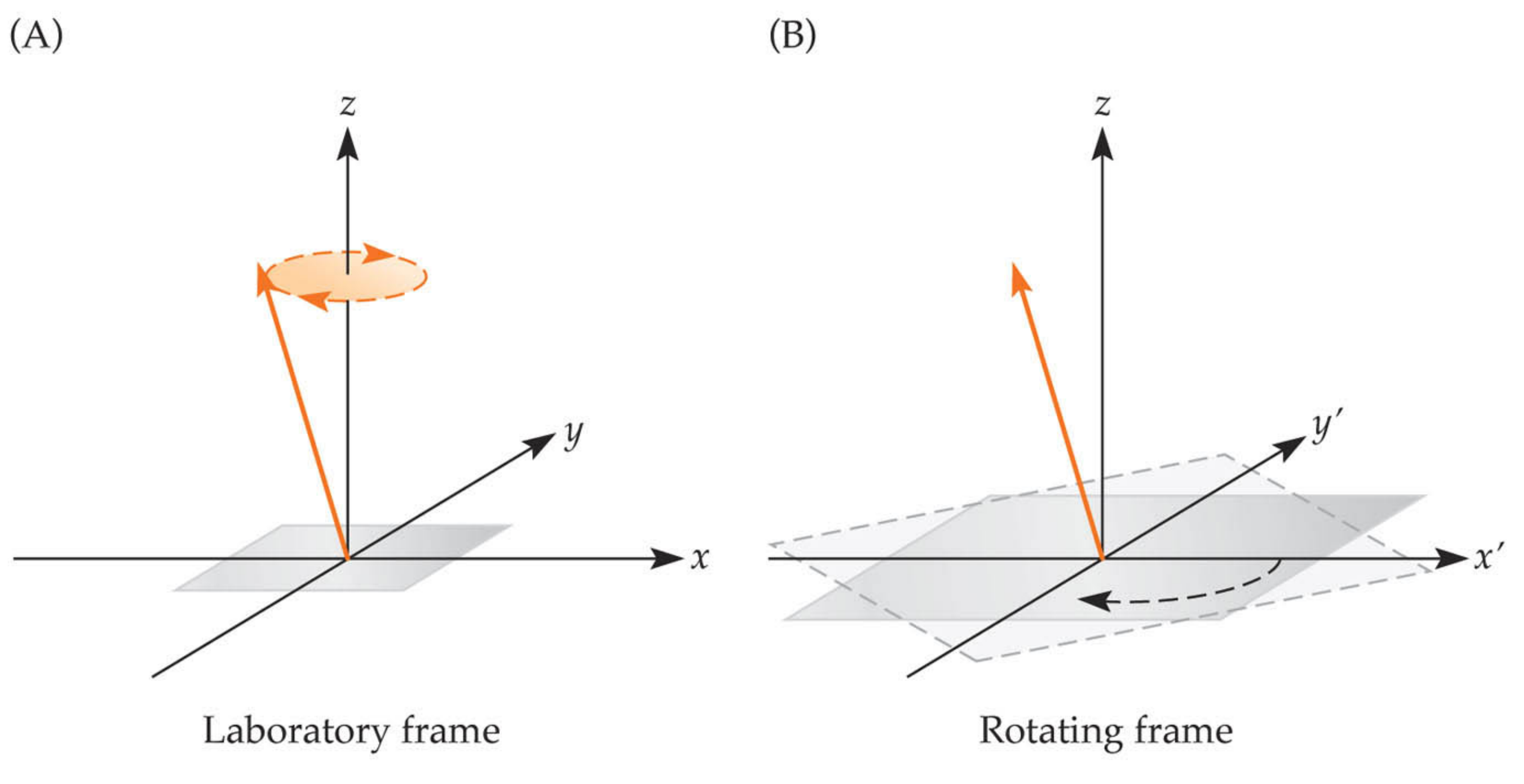


After spins are put into magnetic field: RF pulse makes signal detectable

B_0 and B_1

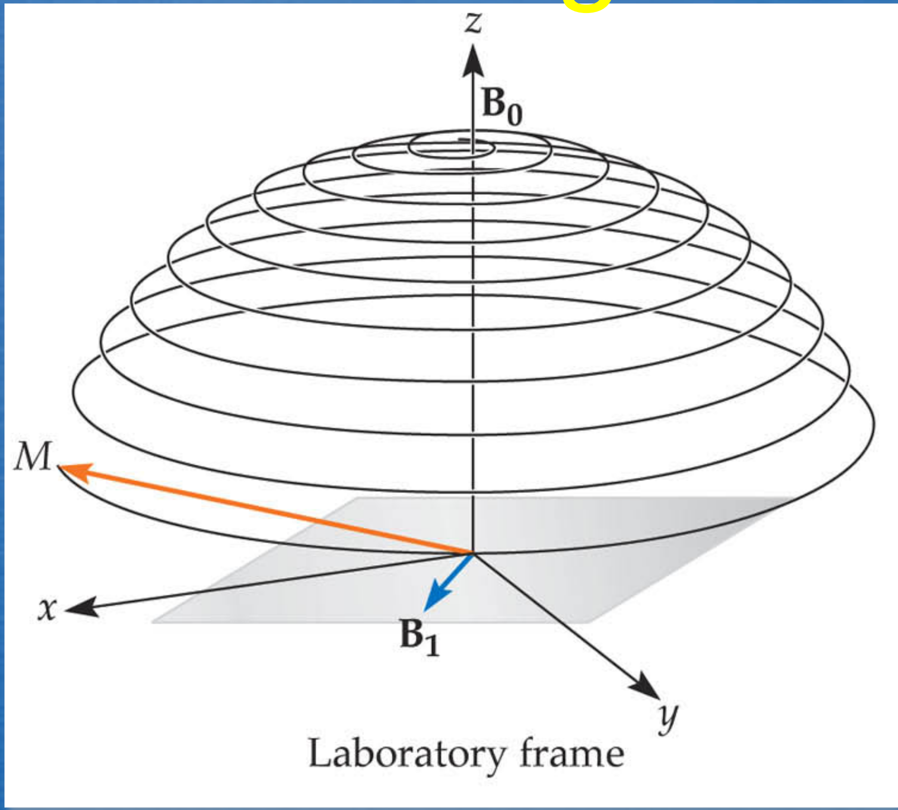


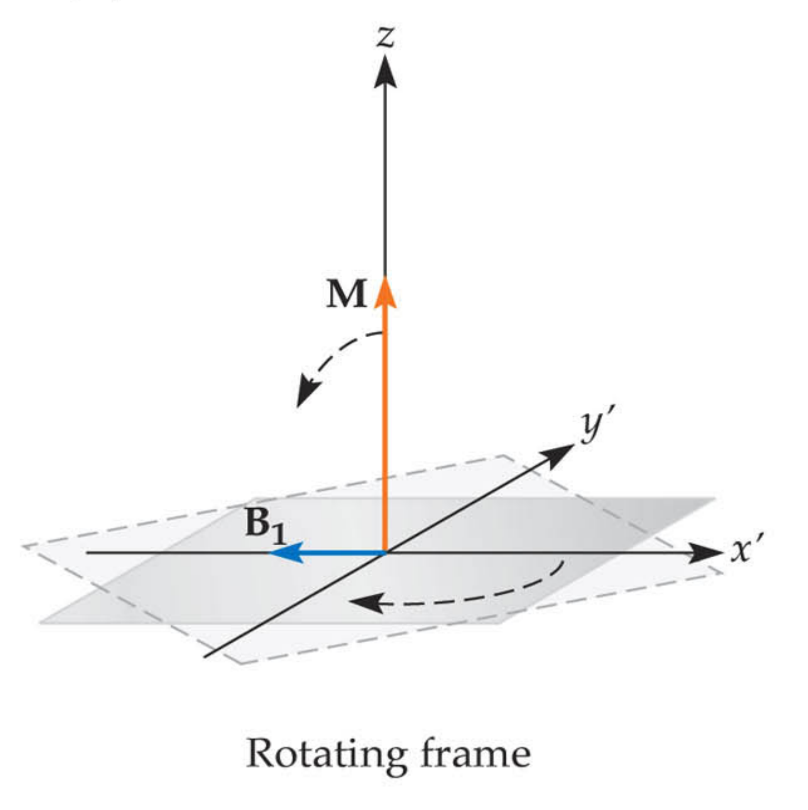
Rotating Frame of Reference



Marry-go-round analogue…

Rotating Frame of Reference





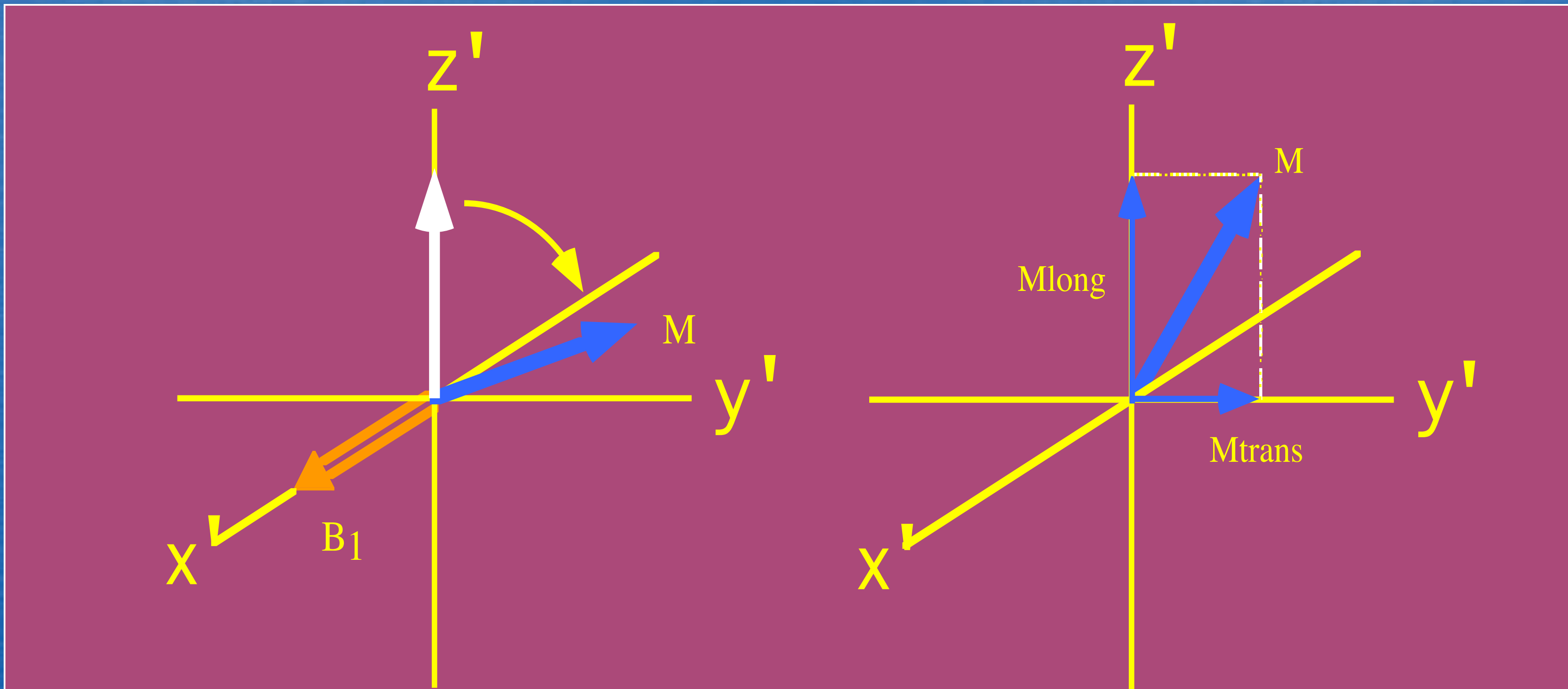
$$\omega = \omega_0$$ "standing on the carousel"

Spiral motion in lab frame → rotation along B1 axis

J.Zhong, U Rochester

Magnetization is tipped using an RF Pulse

Components of Tipped Magnetization



A component of the magnetization can be tipped into the transverse plane to give rise to a signal.

J.Zhong, U Rochester

Resonance: RF freq. = Larmor freq.

$$\omega = \gamma B_0$$

Tip Angle

$$\theta = \omega \Delta t = \gamma B_1 \Delta t$$

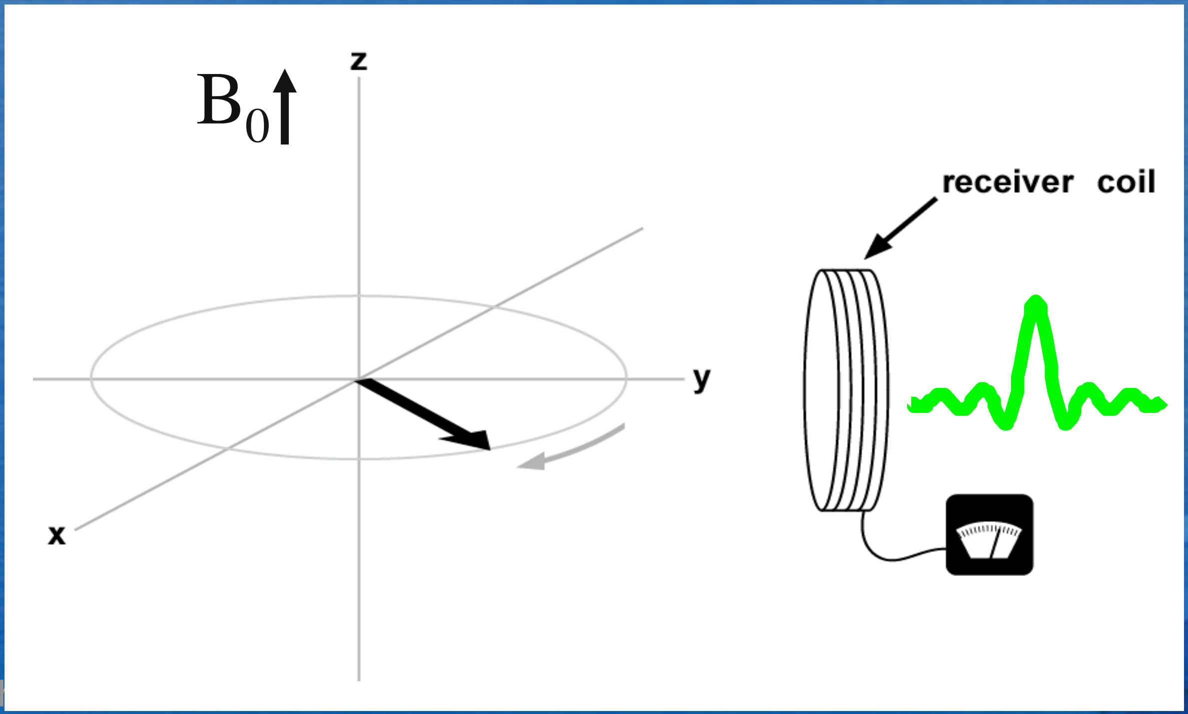
Tip Angle | Amplitude of RF Pulse | Time of Application of RF Pulse a “90°” or $\pi/2$ pulse corresponding to flipping M from z to x-y plane for detection: excitation pulse

A “180°” or π pulse flips M to opposite side. Important for forming spin-echo (later): refocusing or inversion pulse

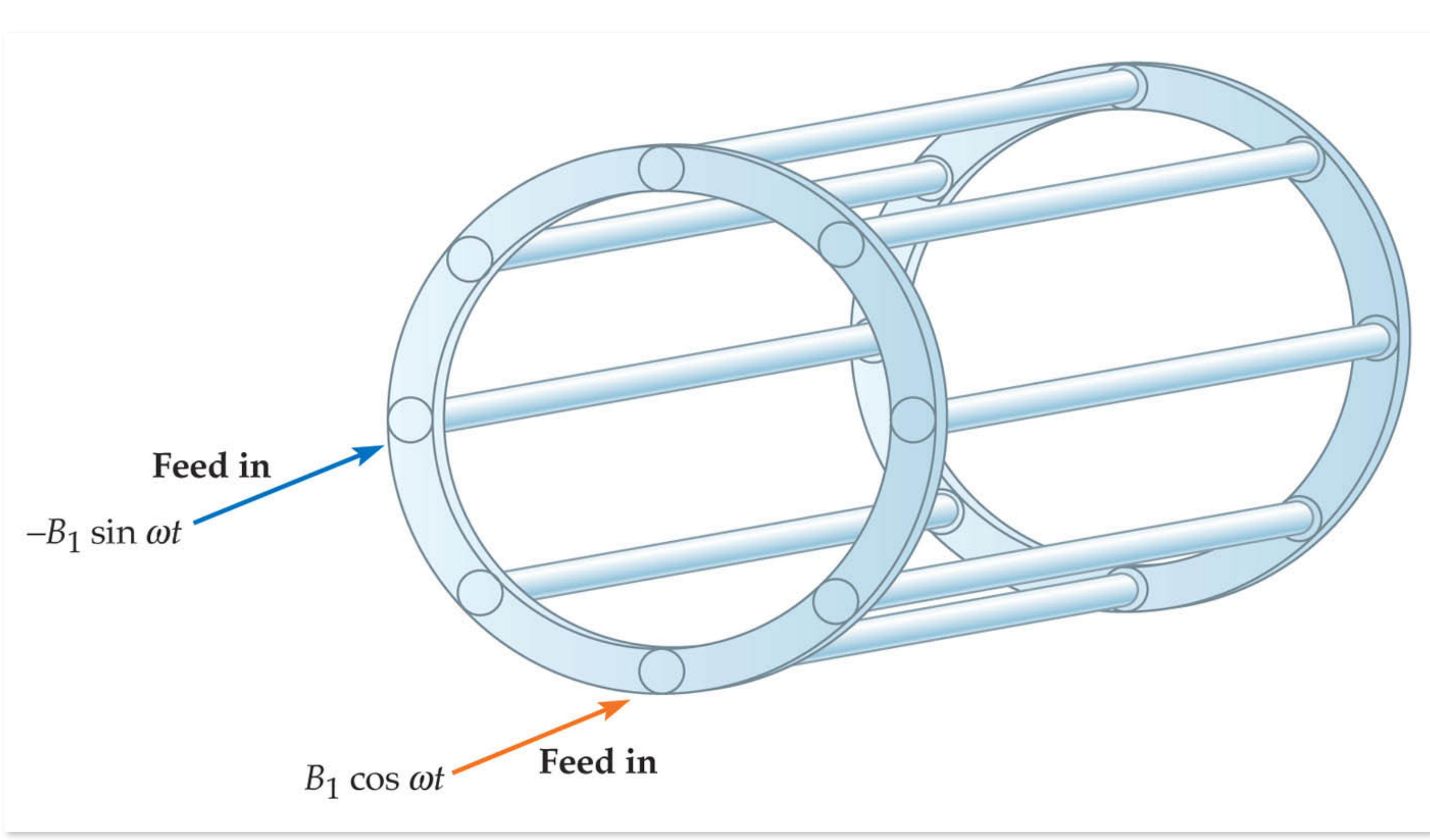
RF excitation and detection

RF coil: apply magnetic field along B1 ($\perp B_0$)

- oscillating field at Larmor frequency, in range of radio transmissions
- same or different coils for receiving and transmission
- fit to the object size for best detection sensitivity (filling factor)

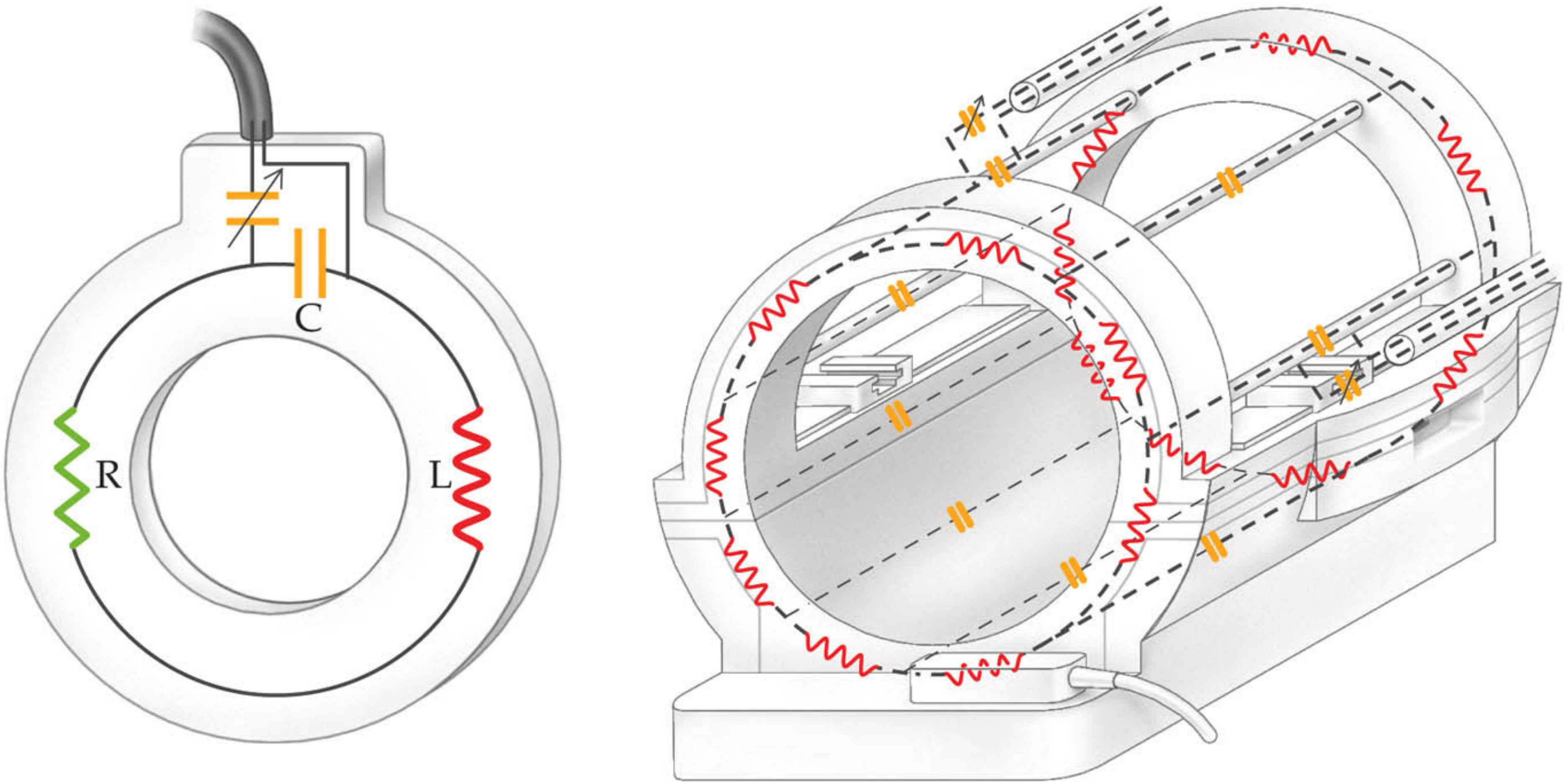


Excitation of MRI signal



(A)

(B)

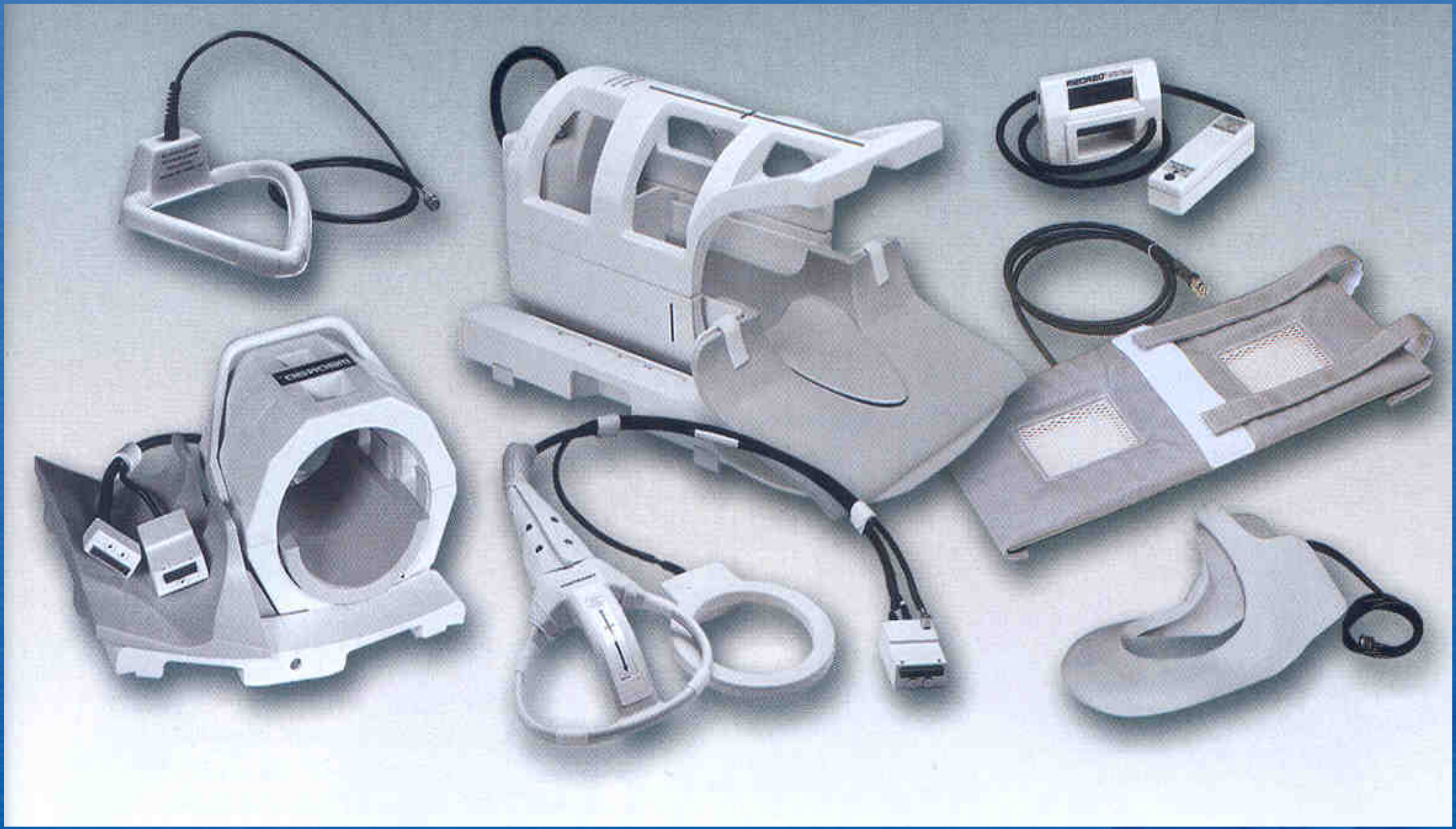


R = Resistor
C = Capacitor
L = Inductor
≠ = Adjustable capacitor

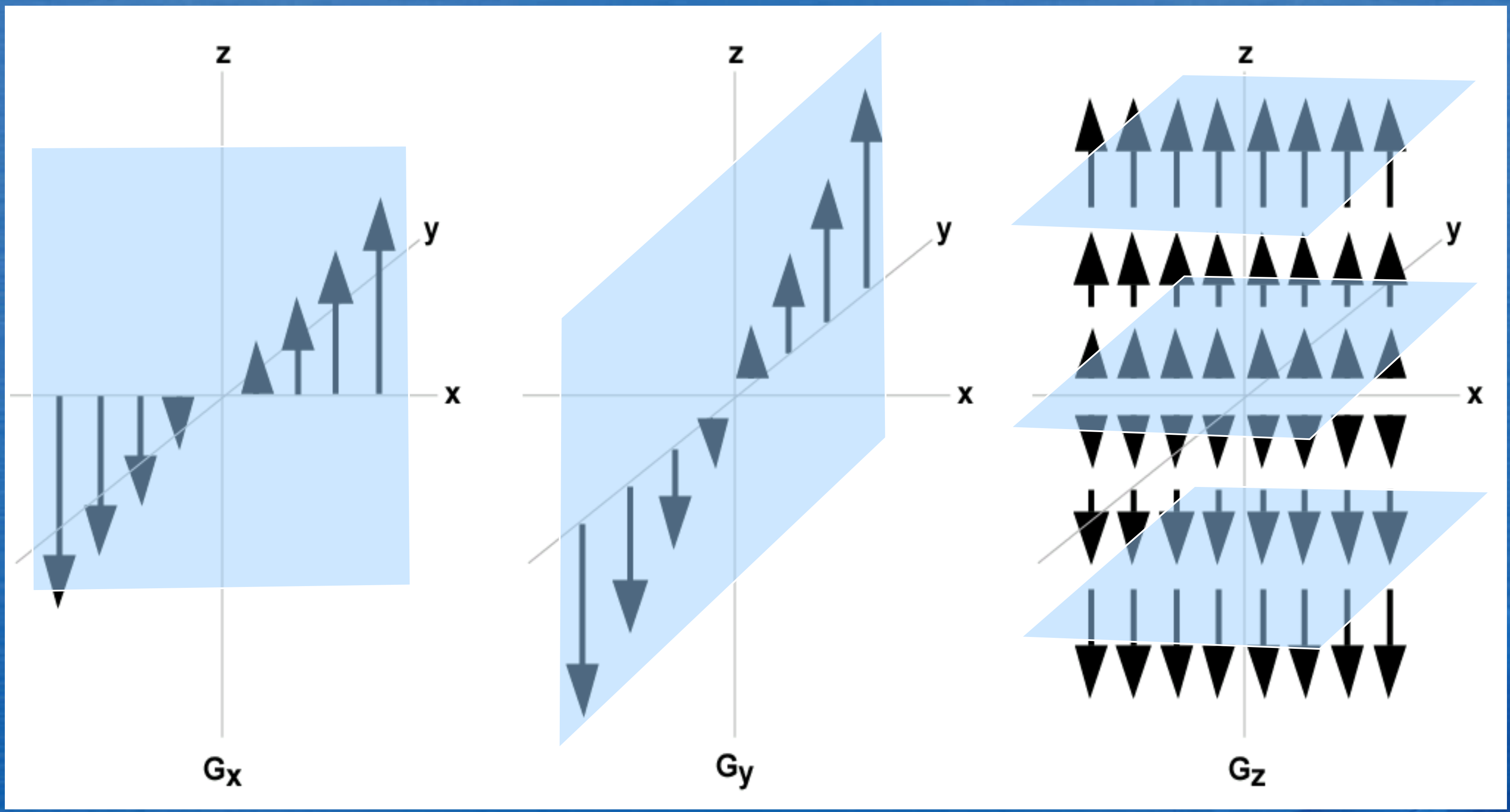
Surface and volume coils

FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 2.4 (Part 1)

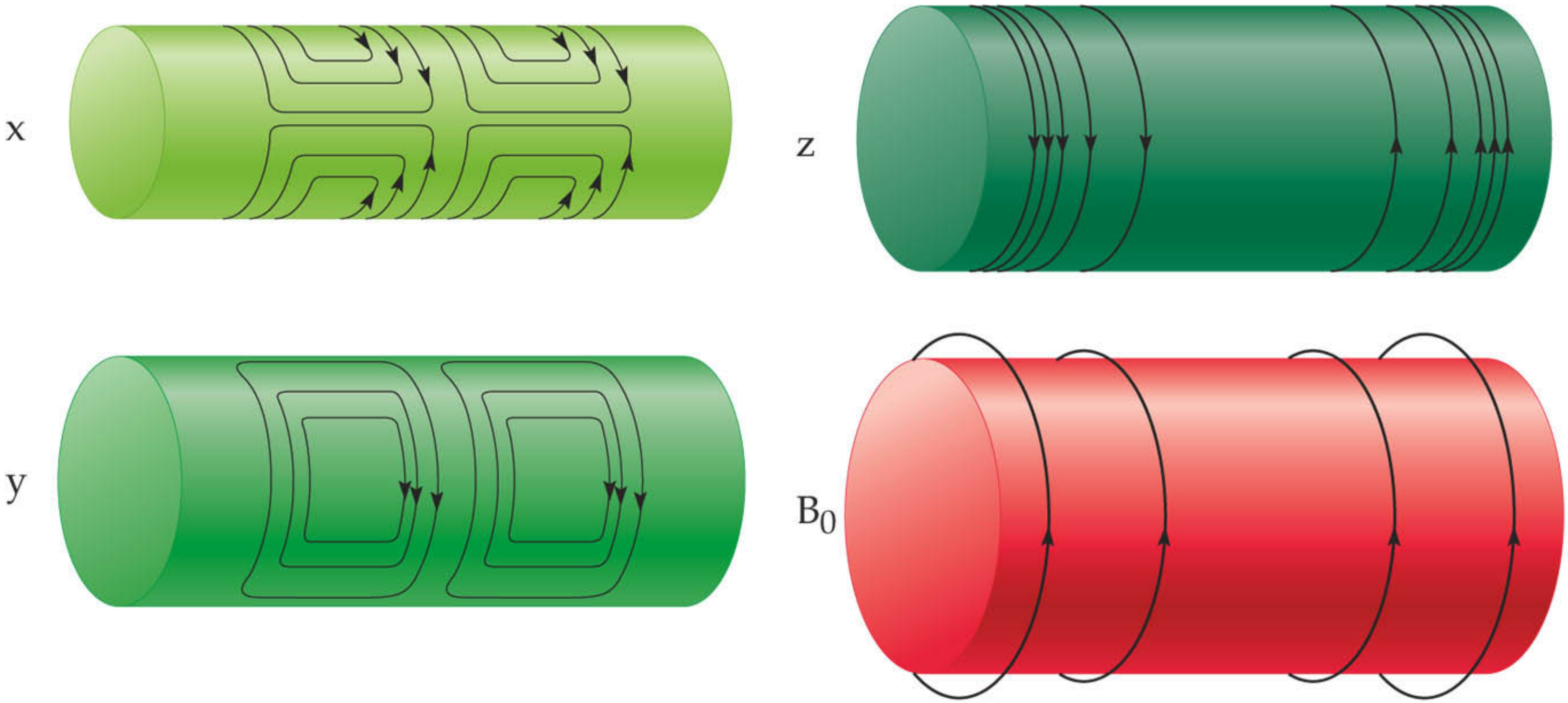
Radiofrequency Coils



Magnetic Field Gradients for spatial encoding

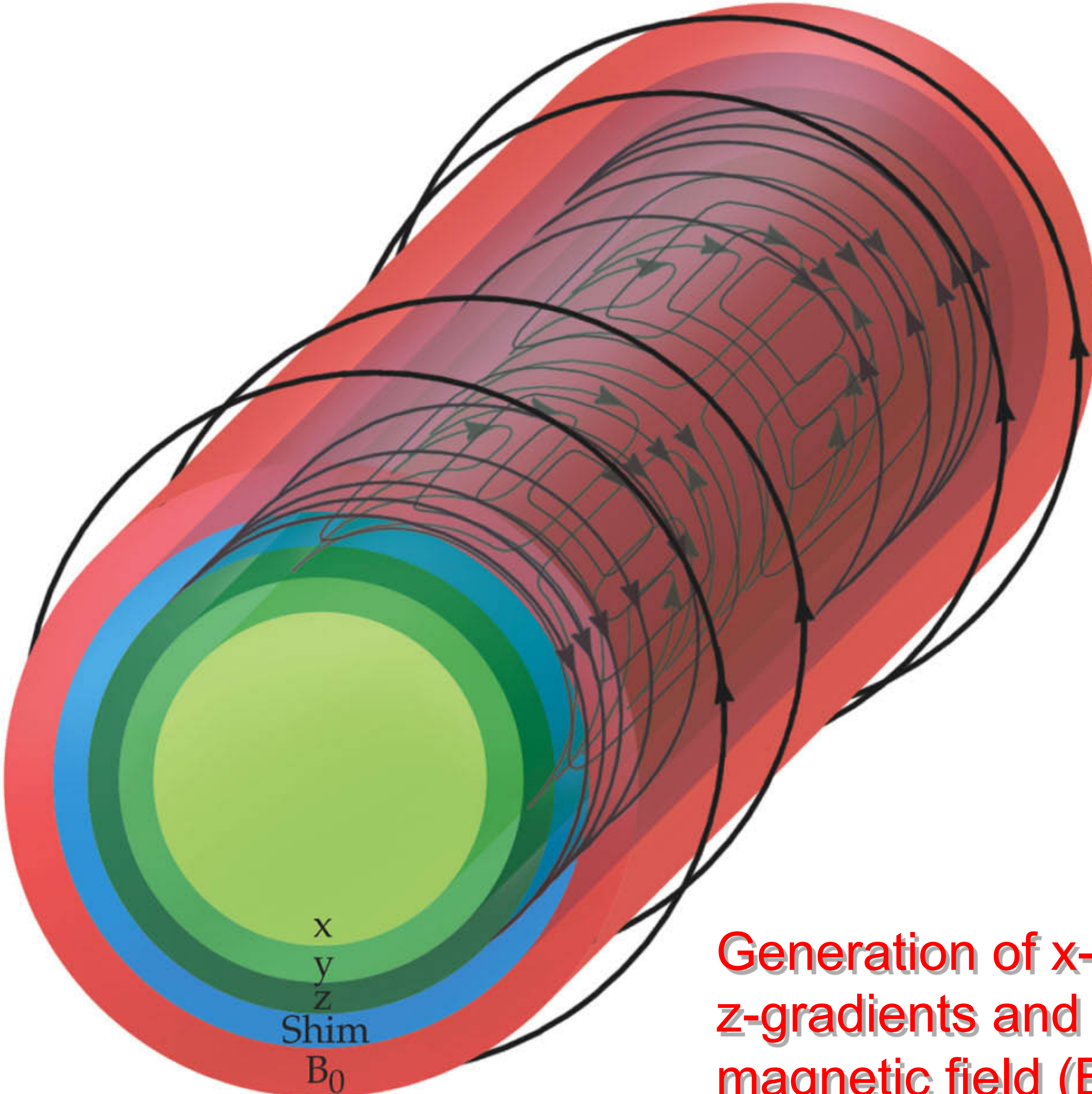


J.Zhong, U Rochester



Generation of x-, y-, and z-gradients and the static magnetic field (B_0)

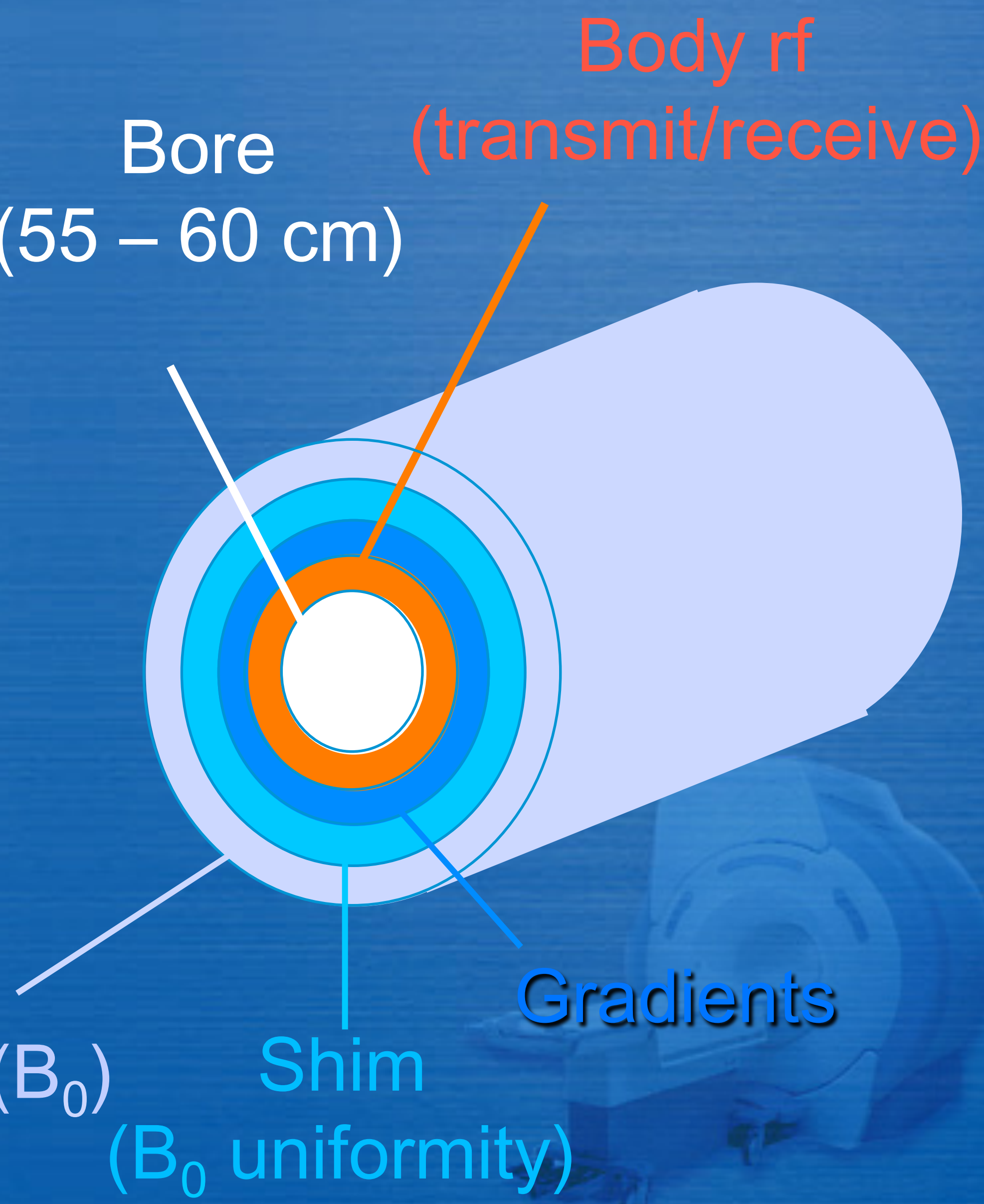
FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 2.7 (Part 2)



Generation of x-, y-, and z-gradients and the static magnetic field (B_0)

FUNCTIONAL MAGNETIC RESONANCE IMAGING, **Figure 2.7 (Part 1)**

B0, Gradient, T/R, and Shim Coils



J.Zhong, U Rochester

From signal to image

- From imaging prospect, how to relate the signal to the spatial distribution of the spins, which is the source of the signal?
- Field gradients are the key for spatial encoding.

Resonance: RF freq. = Larmor freq.

$$\omega = \gamma B$$

Gradient field:

$$B = B(x,y,z)$$
$$= xG(x)+yG(y)+zG(z)$$

Fast Fourier Transform (FFT) - the key step in image formation

Pulse sequences

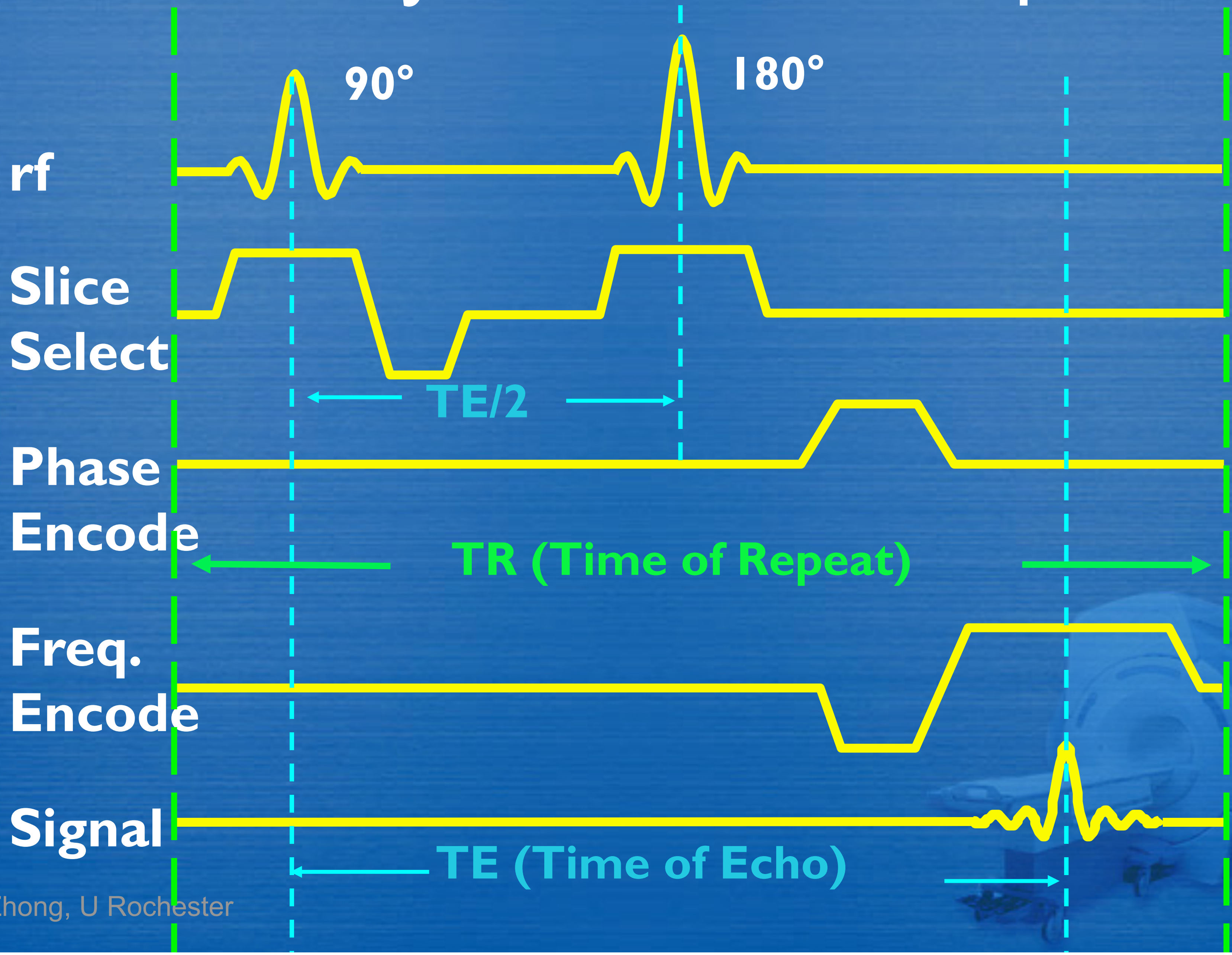
- Well controlled events during signal excitation, evolution, and acquisition
- RF pulses, gradient pulses, signal detection (analog-to-digital, amplify)
- Time intervals and time delays (TE, TR, TI,…)
- Repeated applications for completion of image or signal averaging

Recipe for MRI

1) Put subject in big magnetic field (leave him there)
2) Transmit radio waves into subject [about 3 ms]
3) Turn off radio wave transmitter and turn on gradients
4) Receive radio waves re-transmitted by subject
   – Manipulate re-transmission with magnetic fields during this *readout* interval [10-100 ms: MRI is not a snapshot]
5) Store measured radio wave data vs. time
   – Now go back to 2) to get some more data
6) Process raw data to reconstruct images

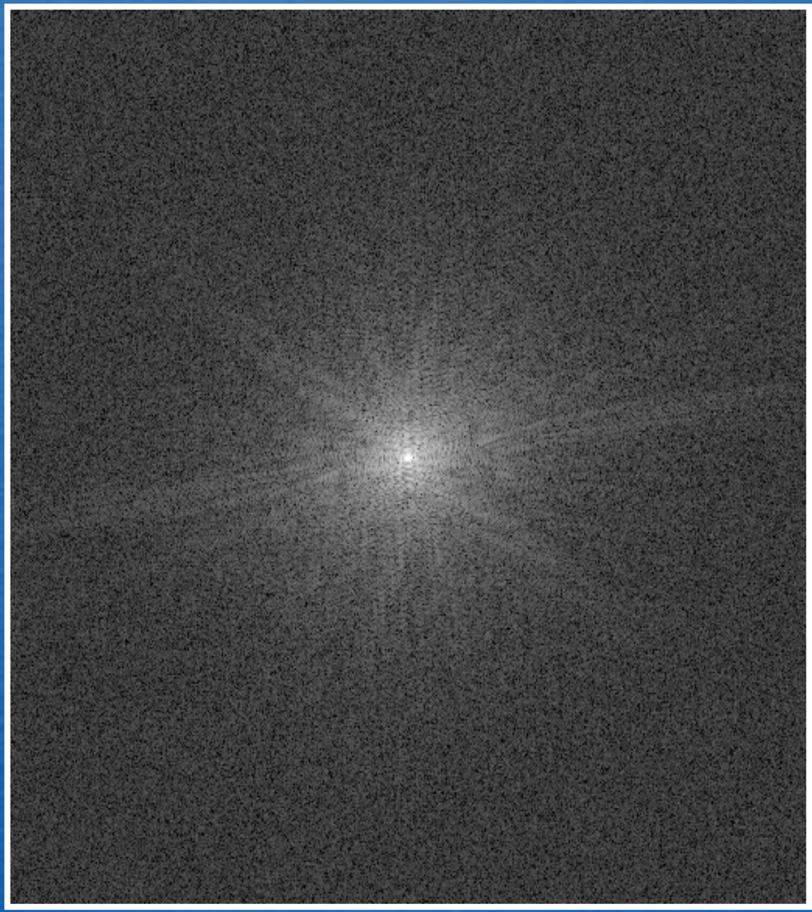
Source: Robert Cox's web slides

Anatomy of a Pulse Sequence

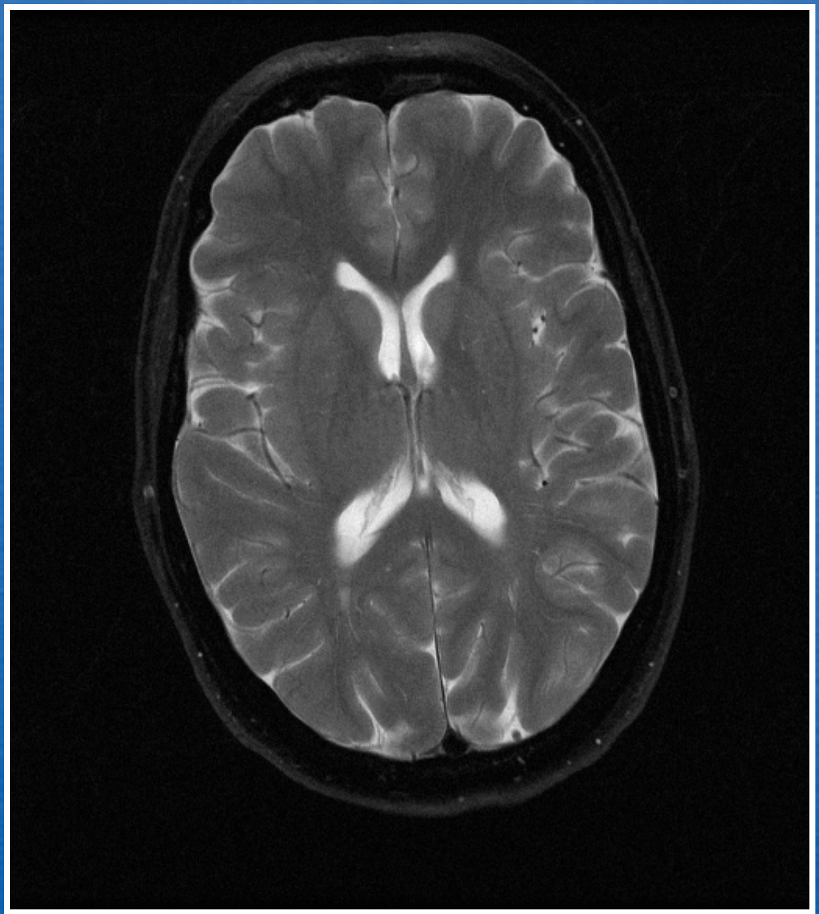


J.Zhong, U Rochester

From data to image: Fast Fourier Transform



⇒
FFT



Key concepts in MRI physics?

- Image formation: Larmor Equation and FFT
- Image contrast and contrast mechanisms
  - T1, T2 and proton density imaging
  - T2* and BOLD
  - Dynamics: static and moving spins
  - Microscopic motion: diffusion

→ Books and previous BCS513 lecture ppt

Advantages of MR

- 3D and arbitrary imaging orientations
- Rich and good soft tissue contrast
- Functional and physiological information
- No radiation
- Very safe

And many brain functional applications!

- BOLD
- Diffusion (DTI, DSI, DKI, HARDI, …)
- ASL
- MRS

Thanks

Questions?