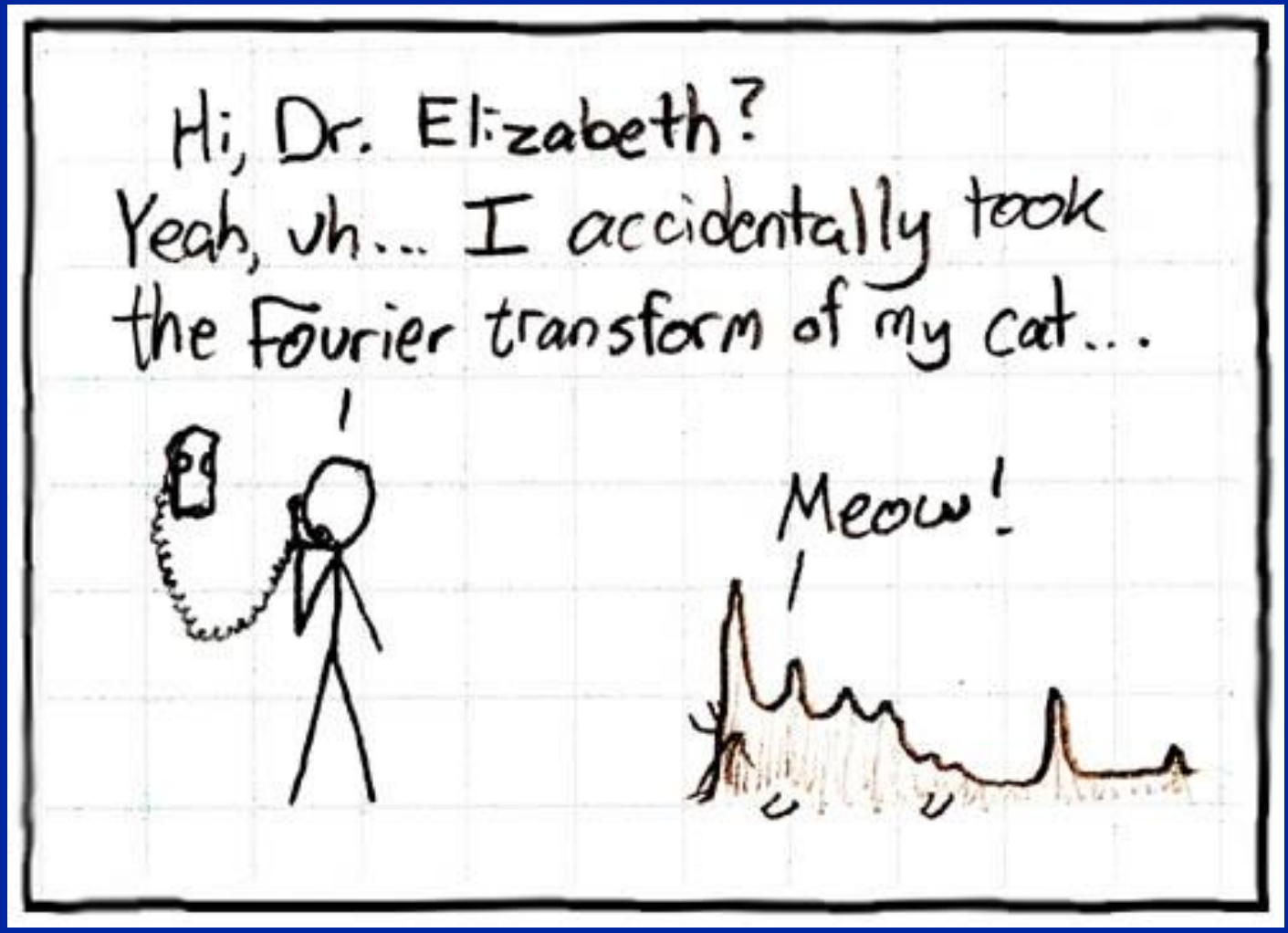
Hi, Dr. Elizabeth?
Yeah, uh... I accidentally took the Fourier transform of my cat...
Meow!

Noll

MRI Physics I & II: Recap

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Magnetic Fields in MRI

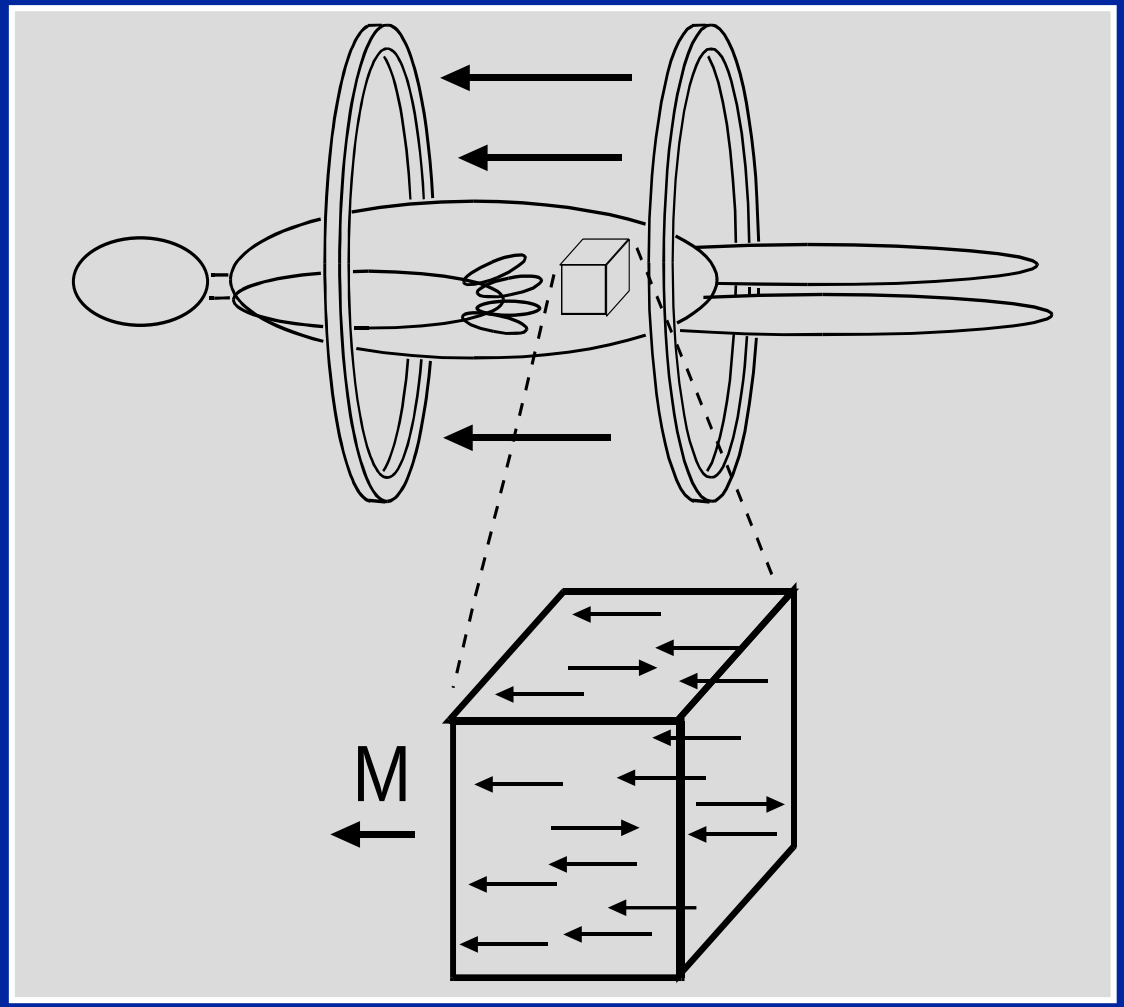
- B_0 – The main magnetic field.
  - Always on (0.5-7 T)
  - Magnetizes the object to be imaged
  - After excitation, the magnetization precesses around B_0 at $\omega_0 = \gamma B_0$

- B_1 – The rotating RF magnetic field.
  - Tips magnetization into transverse plane
  - Performs “excitation”
  - On for brief periods, then off

Protons in a Magnetic Field

Spinning protons become aligned to the magnetic field.

On average - body become magnetized.

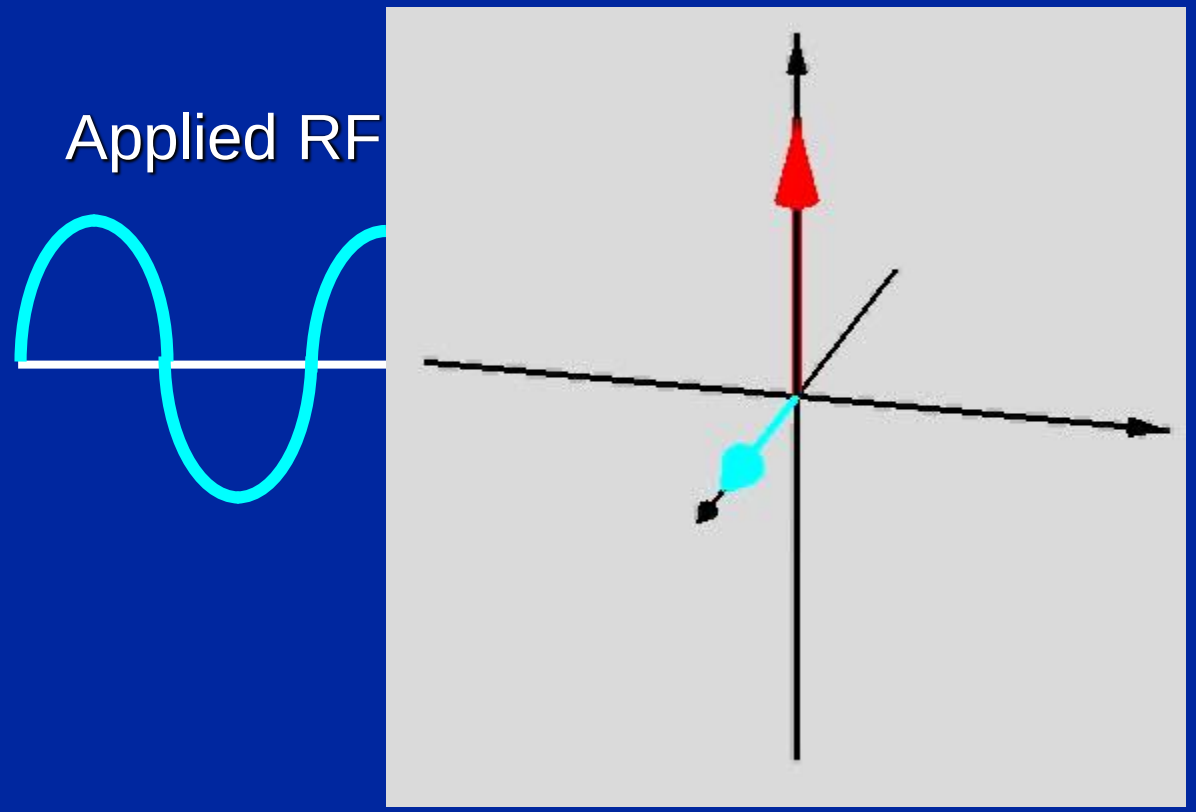


Excitation

Try this: Apply a magnetic field ($\mathbf{B}_1$) rotating at $\omega_0 = \gamma \mathbf{B}_0$ in the plane perpendicular to $\mathbf{B}_0$

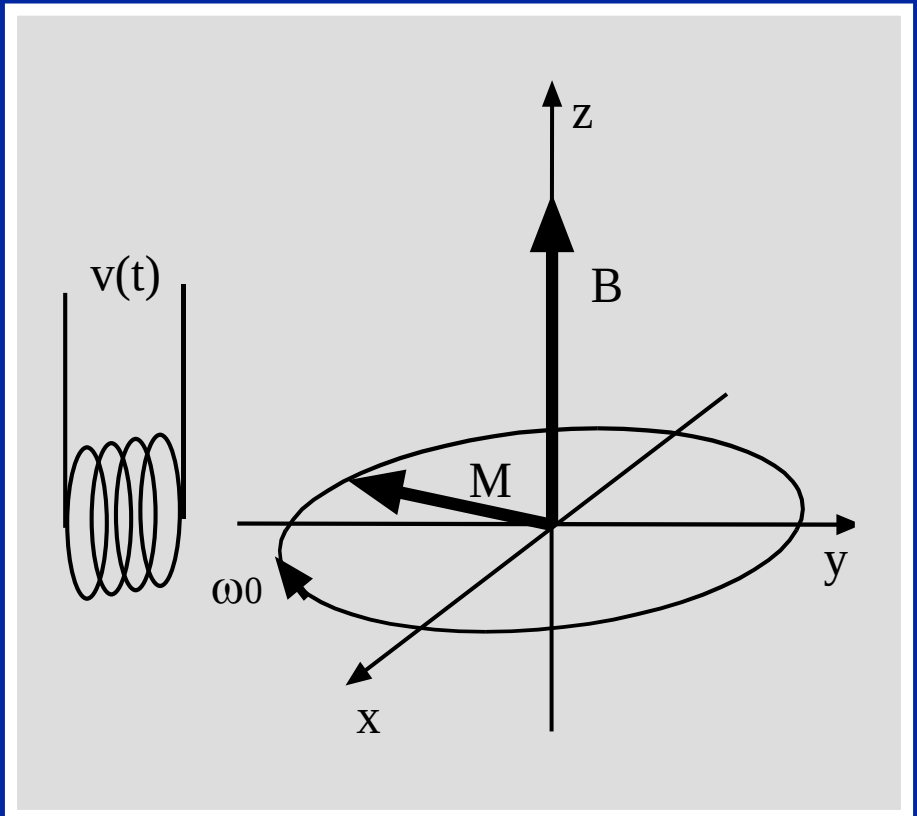
→

Magnetization will tip into transverse plane



90 Degree Flip

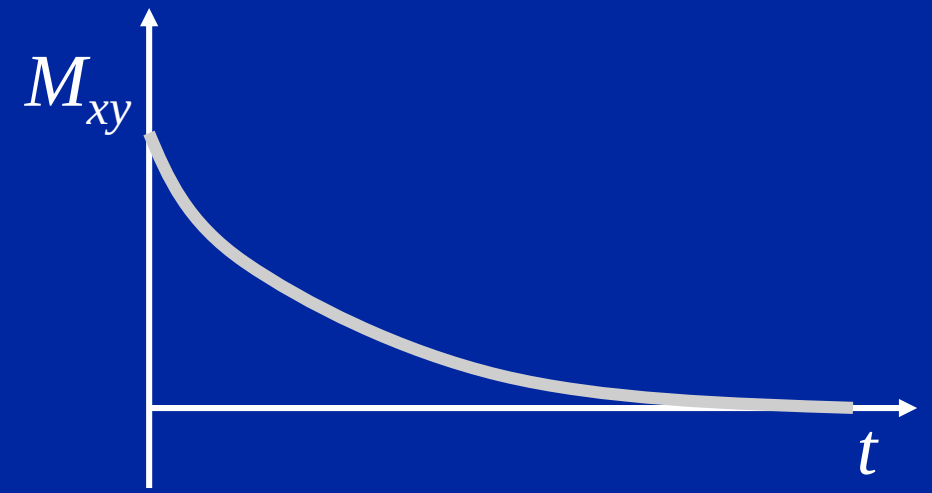
- Excitation routinely stops with the magnetization is fully tipped into the transverse plane
- Signal reception can then begin
- Typical strength is $B_1 = 2 \times 10^{-5}$ T
- 90 degree tip takes about 300 μs



T2 Decay

- Tissue property (typically 10's of ms)
- Spins dephase relative to other spins
- Differential Equation:

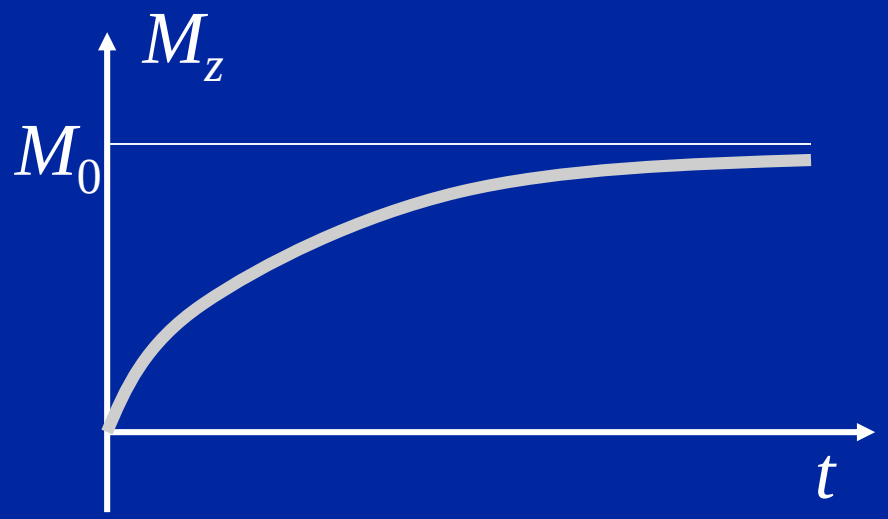
$$\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T2}$$



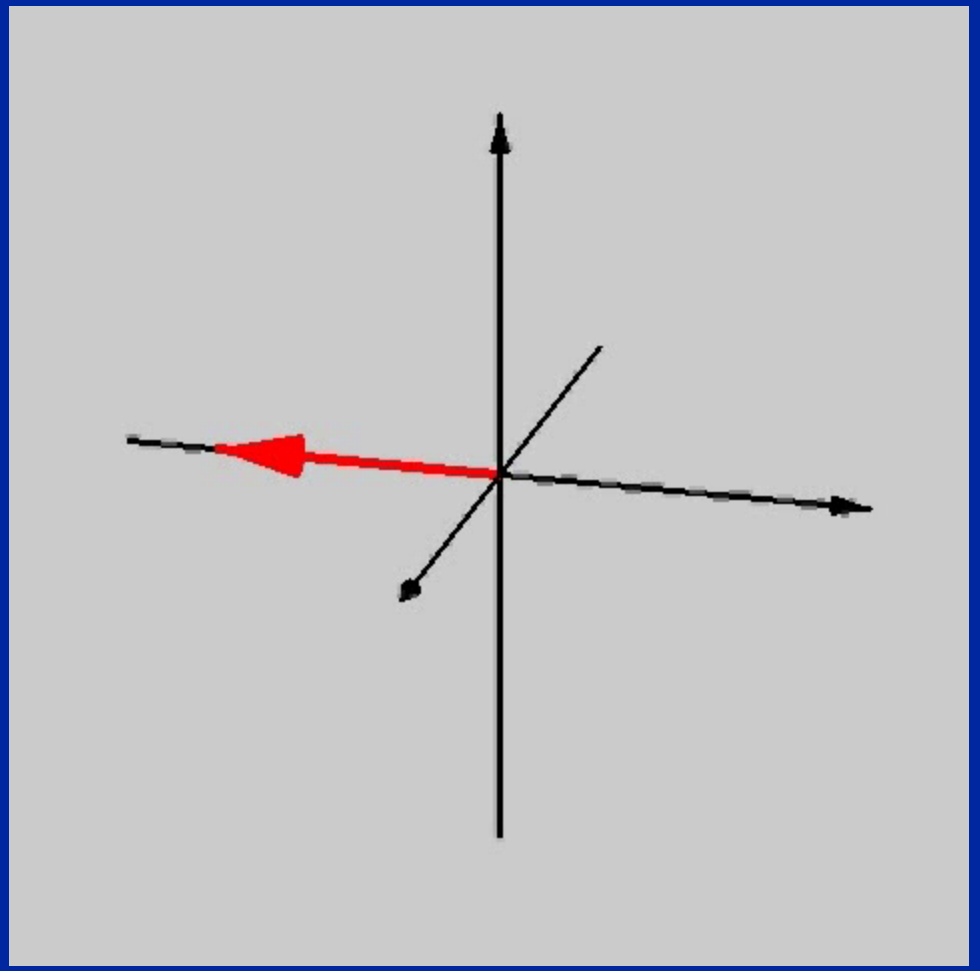
T1 Recovery

- Tissue property (typically 1-3 seconds)
- Spins give up energy into molecular matrix
- Differential Equation:

$$\frac{dM_z}{dt} = -\frac{(M_z - M_0)}{T1}$$



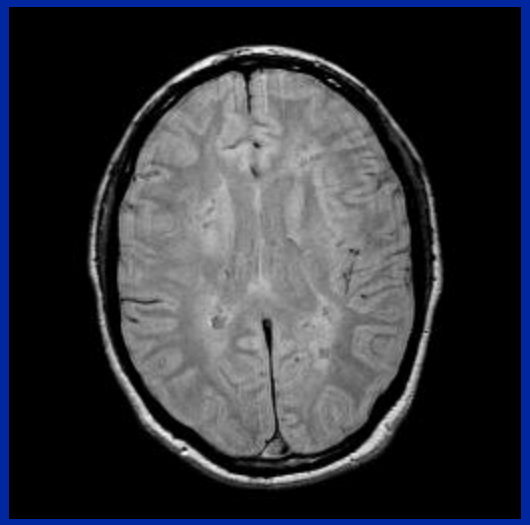
Relaxation



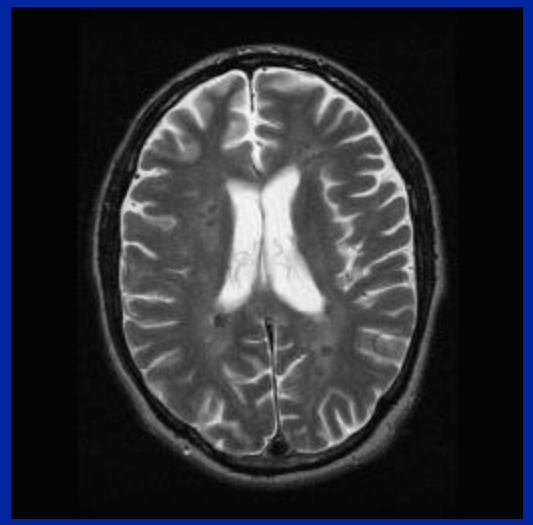
T2 Contrast

- For long TE imaging, tissues with short T2's (rapidly recovering) are darkest
  - Fat < brain tissue
  - White Matter < Grey Matter
  - Gray Matter < CSF

Spin Density



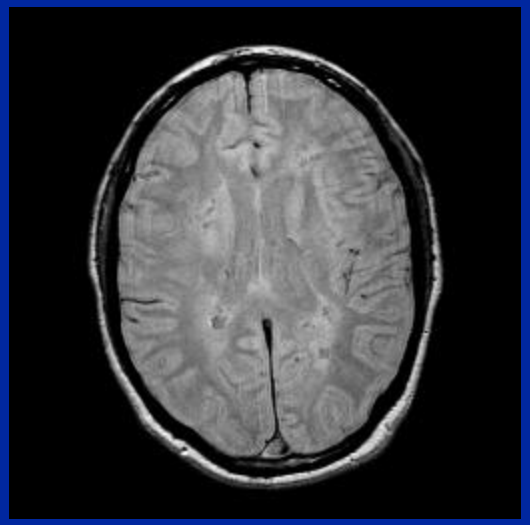
T2 Weighting



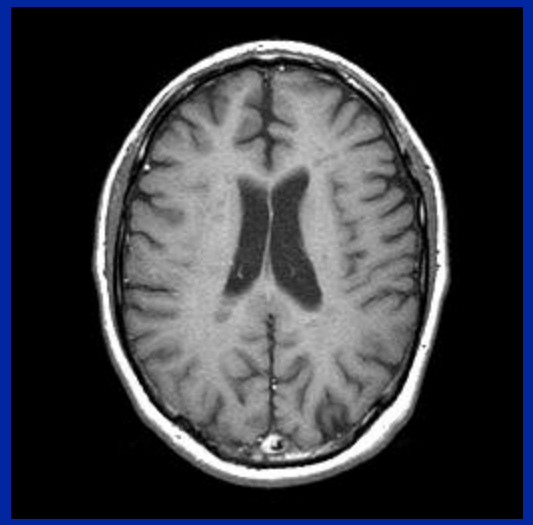
T1 Contrast

- For short TR imaging, tissues with short T1's (rapidly recovering) are brightest
  - Fat > brain tissue
  - White Matter > Grey Matter
  - Gray Matter > CSF

Spin Density



T1 Weighting



Gradient Fields

- The last magnetic field to be used in MRI are the gradient fields
  - 3 of them: G_x, G_y, G_z
  - These are for localization
  - Make the magnetic field different in different parts of the body, e.g. for the x-gradient:

$$B(x) = B_0 + G \cdot x$$

  - Observe the field points in the same direction as B_0 so it adds to B_0.

Frequency Encoding

- A fundamental property of nuclear spins says that the frequency at which they precess (or emit signals) is proportional to the magnetic field strength:

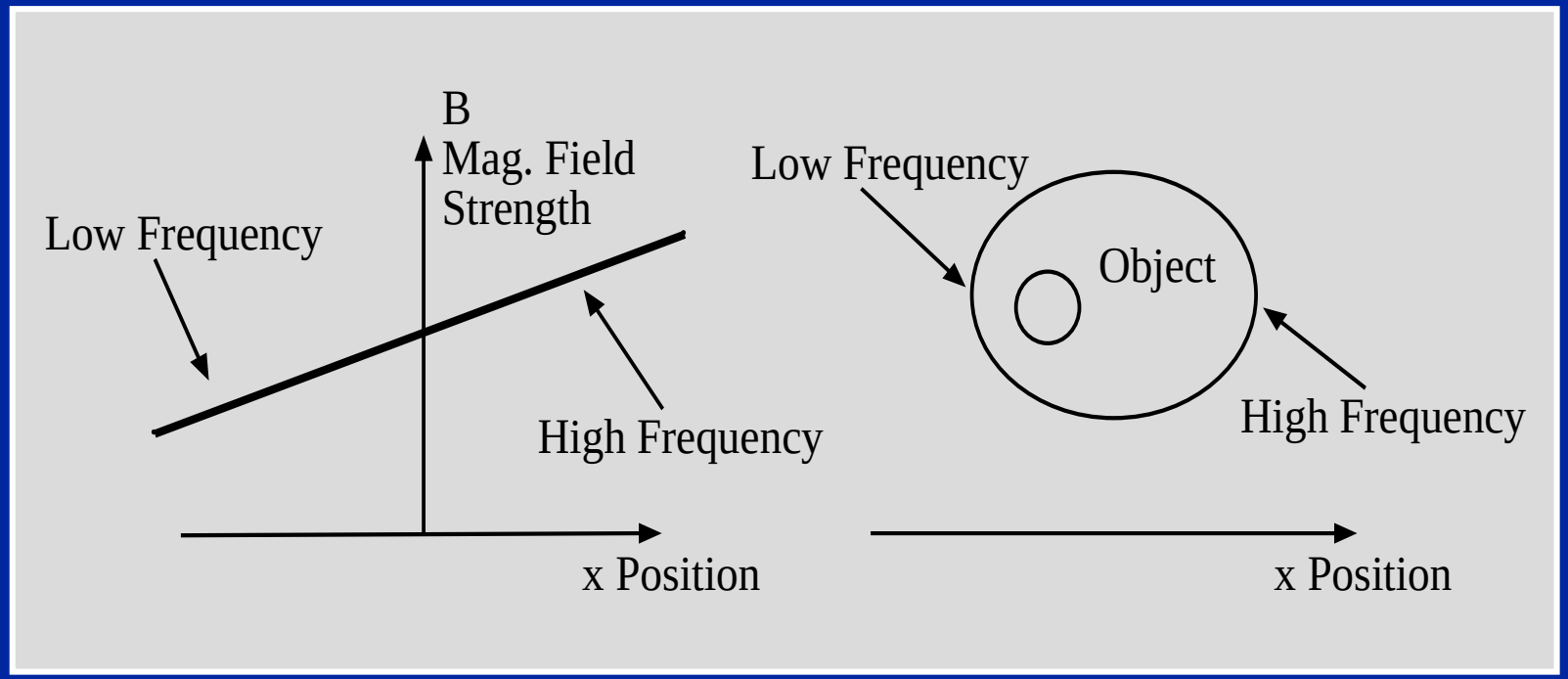
$$\omega = \gamma B$$

- The Larmor Relationship

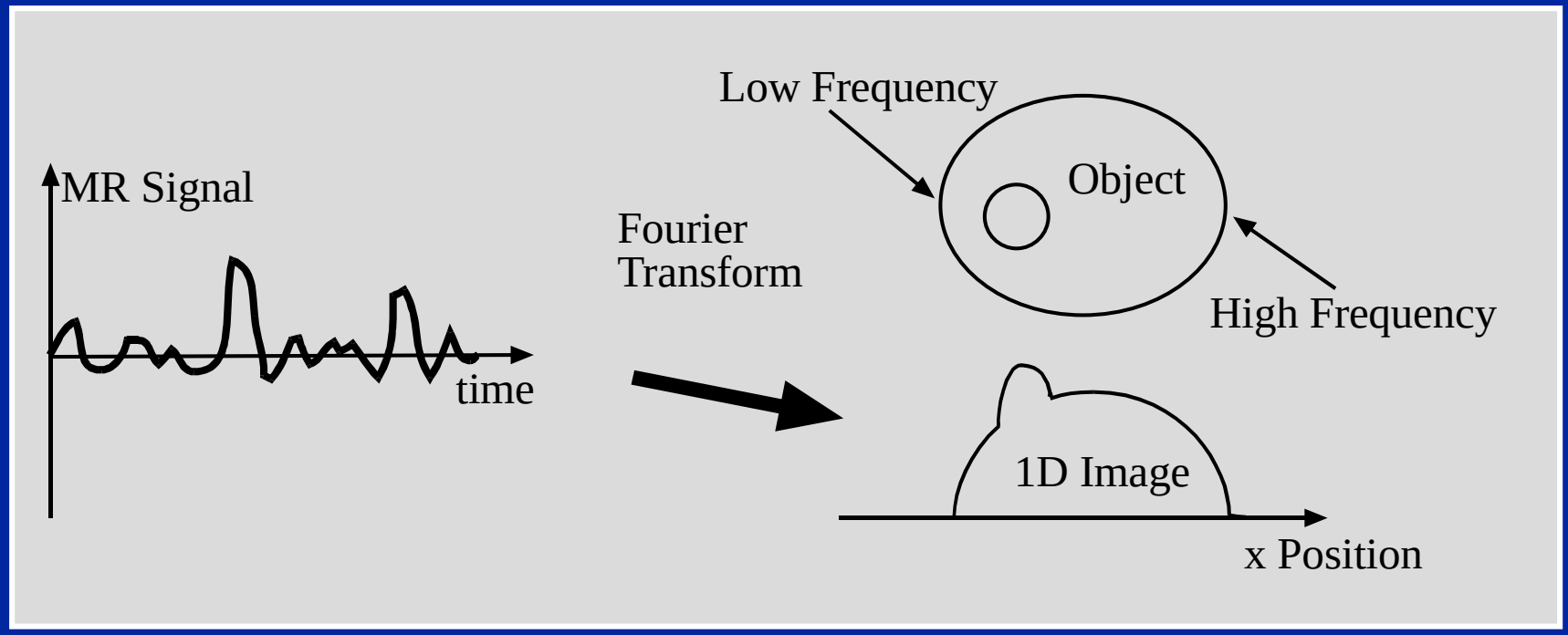
- This says that precession frequency now increases as we move along the x-direction (e.g. as we move rightwards).

$$\omega(x) = \gamma\,(B_0 + G \cdot x).$$

Frequency Encoding

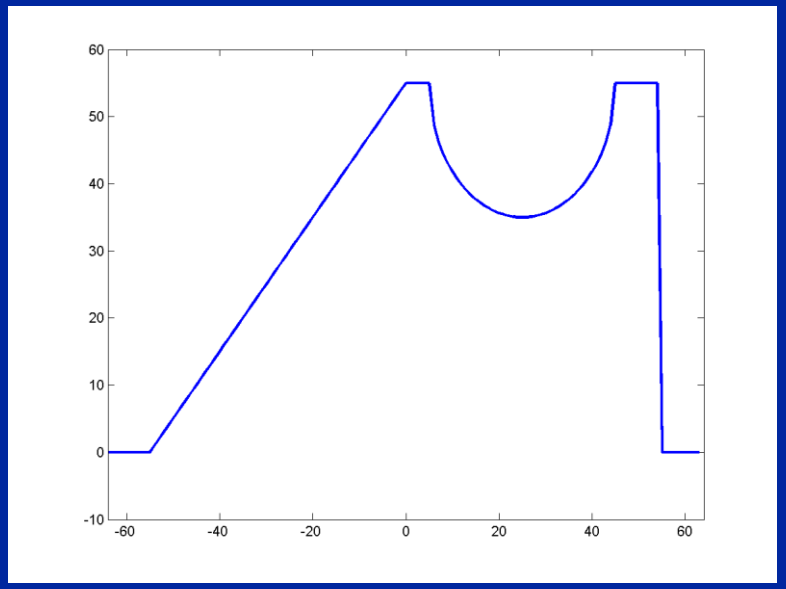


Fourier Transforms

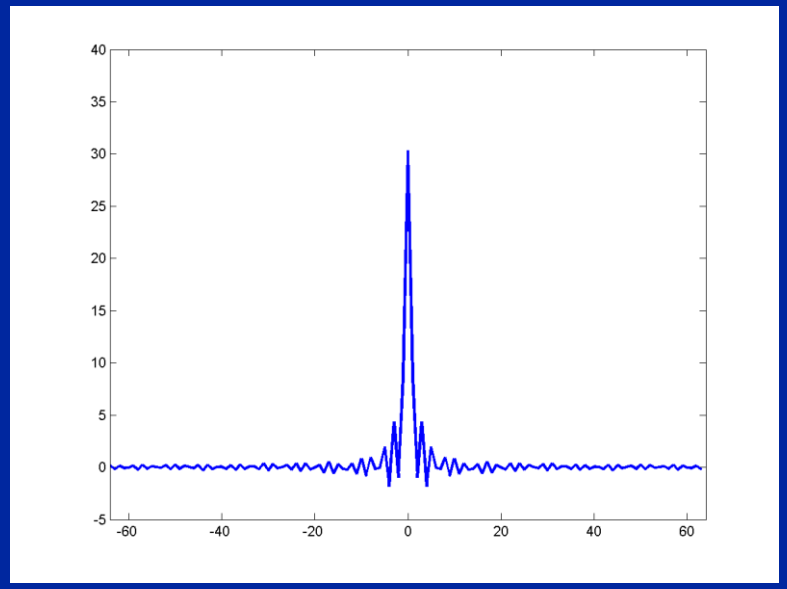


Fourier Representation of Images

- Decomposition of images into frequency components, e.g. into sines and cosines.



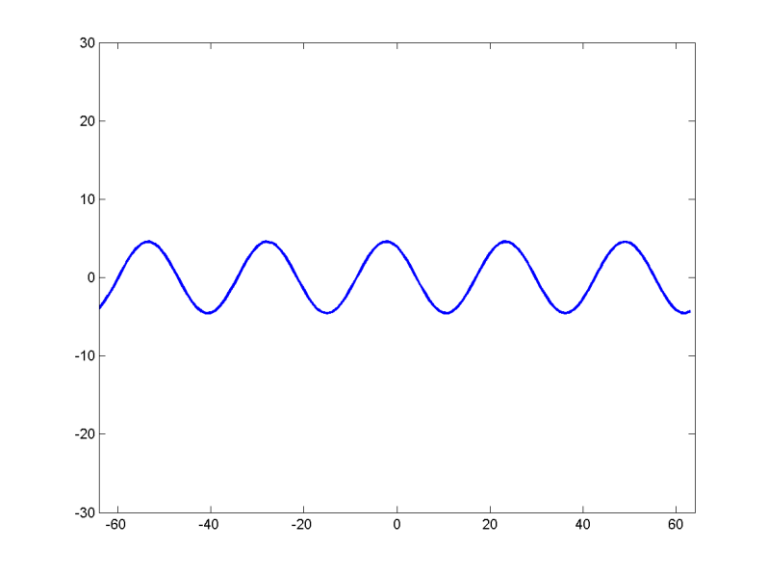
1D Object



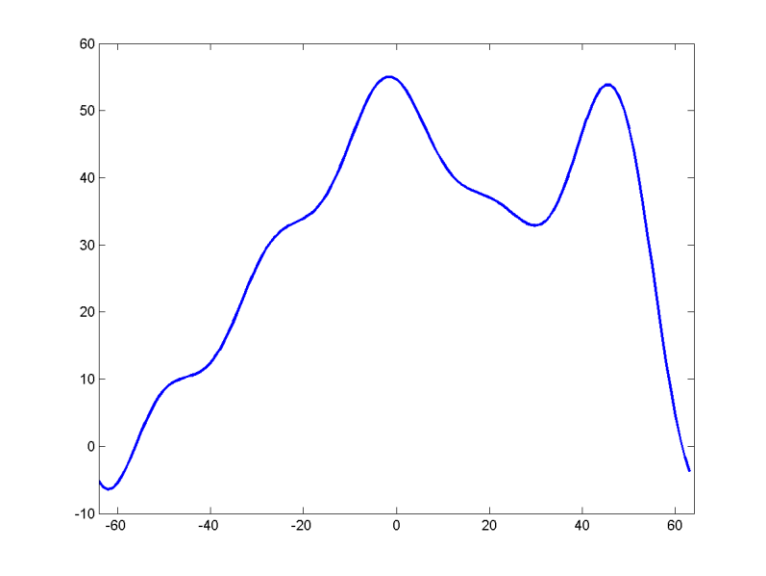
Fourier Data

1D Fourier Transform

5th Frequency Component



New Components

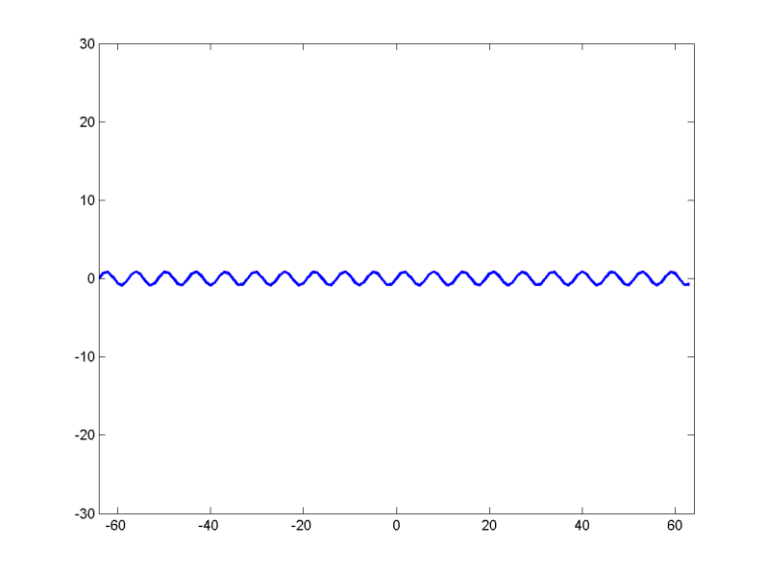


Cumulative Sum of Components

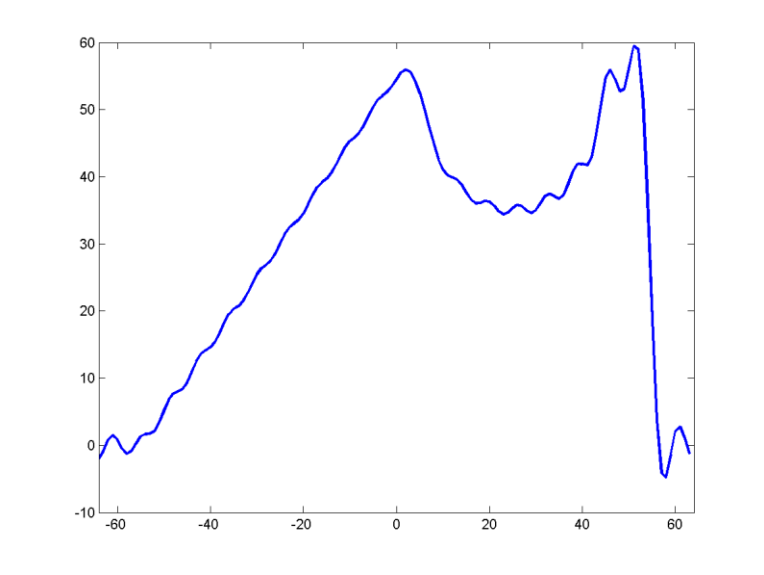
Noll

1D Fourier Transform

20th Frequency Component



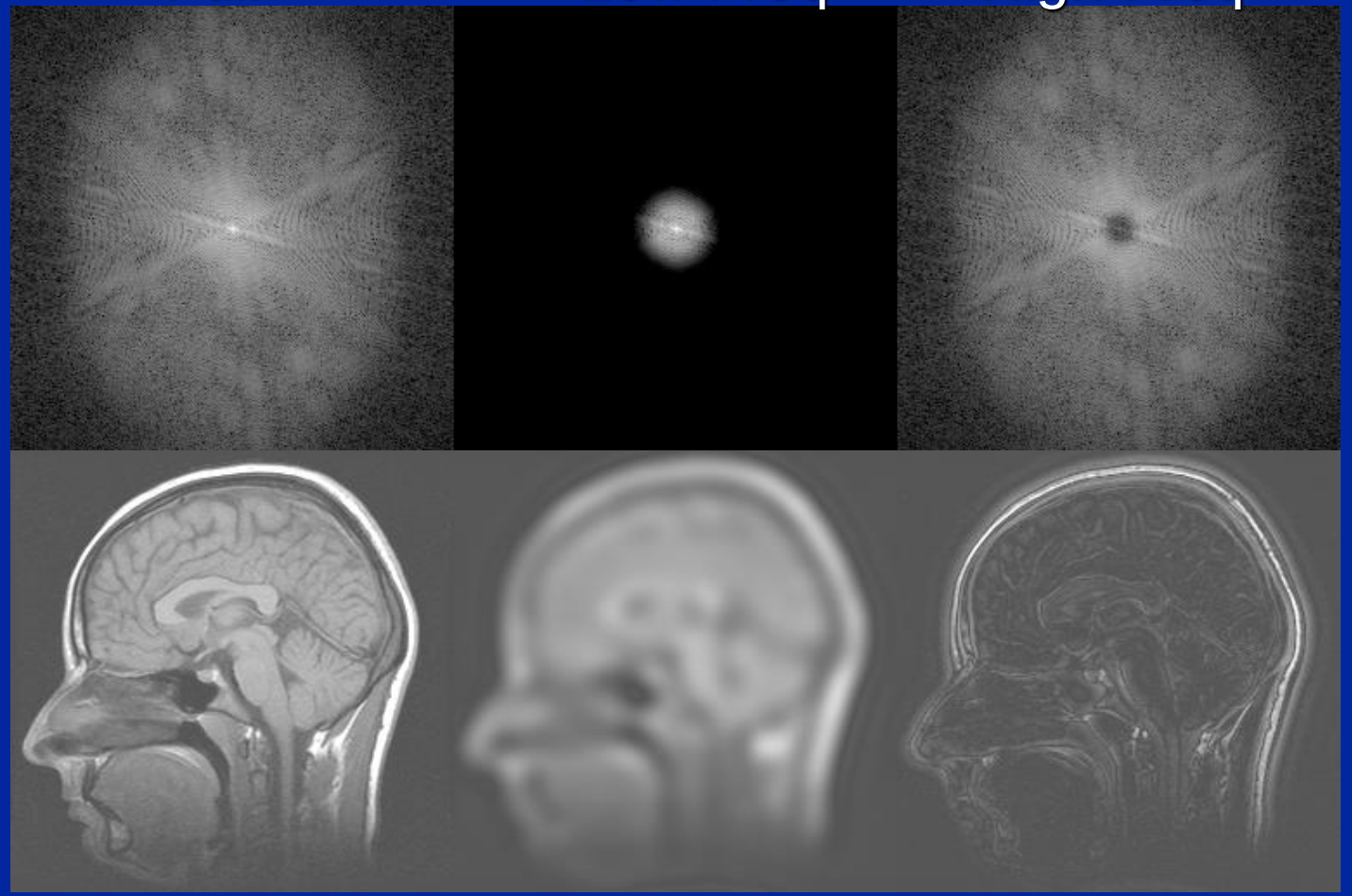
New Components



Cumulative Sum of Components

Noll

Spatial Frequencies in 2D



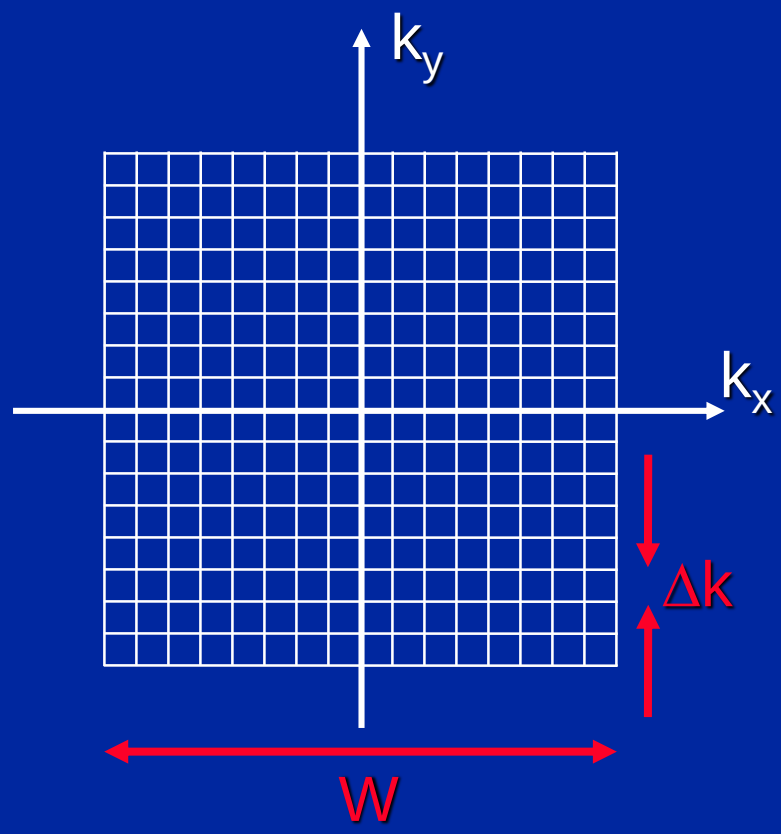
Resolution and Field of View

Resolution is determined by size of the area acquired:

$$\Delta x = 1 / W$$

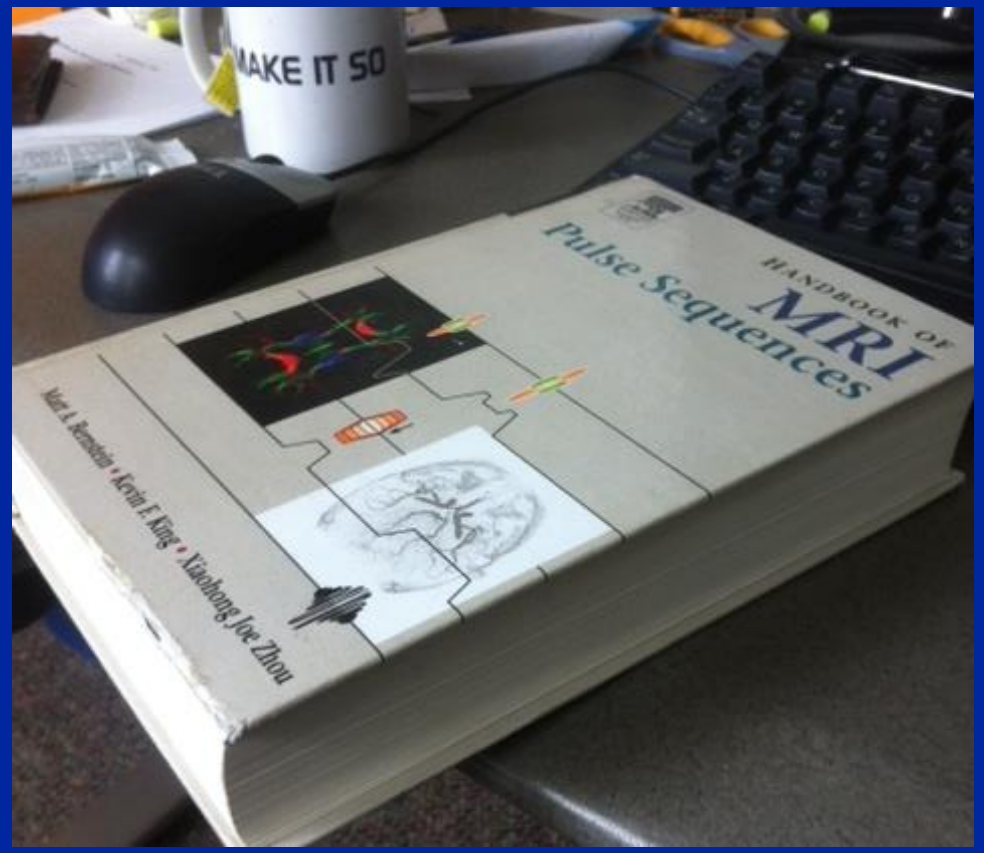
Field of view is determined by spacing of samples:

$$FOV = 1 / \Delta k$$

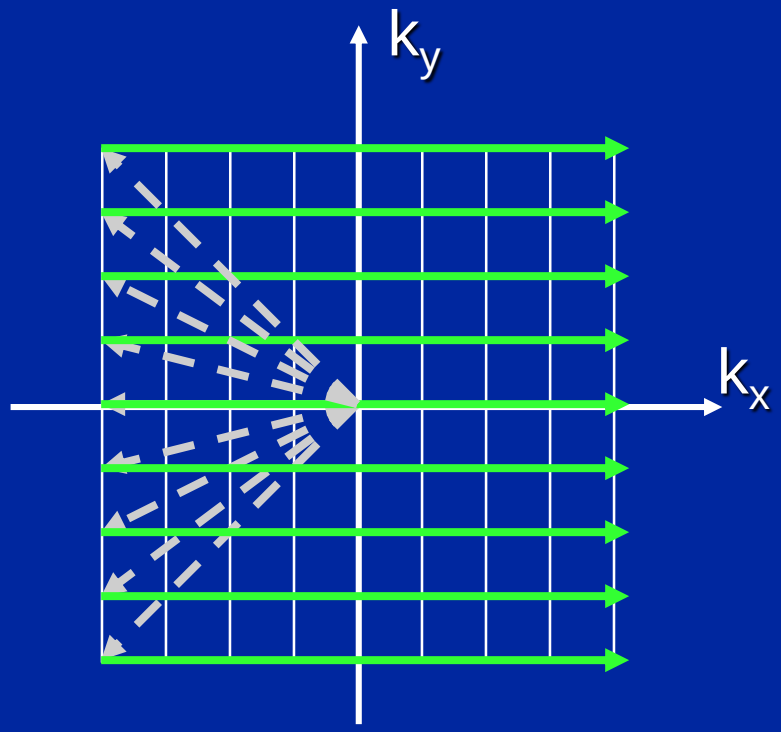


Pulse sequences

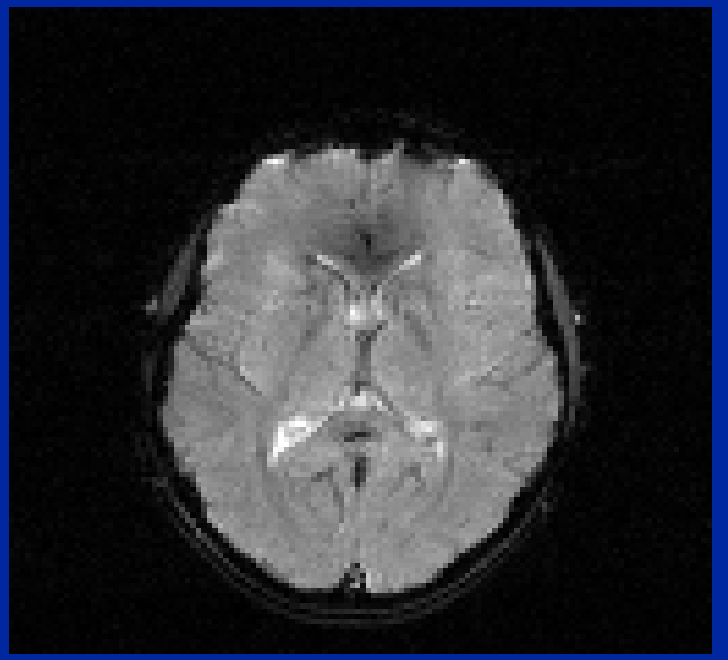
There are many, many ways to excite spins and sample k-space



Conventional (Spin-Warp) Imaging



One Line at a Time

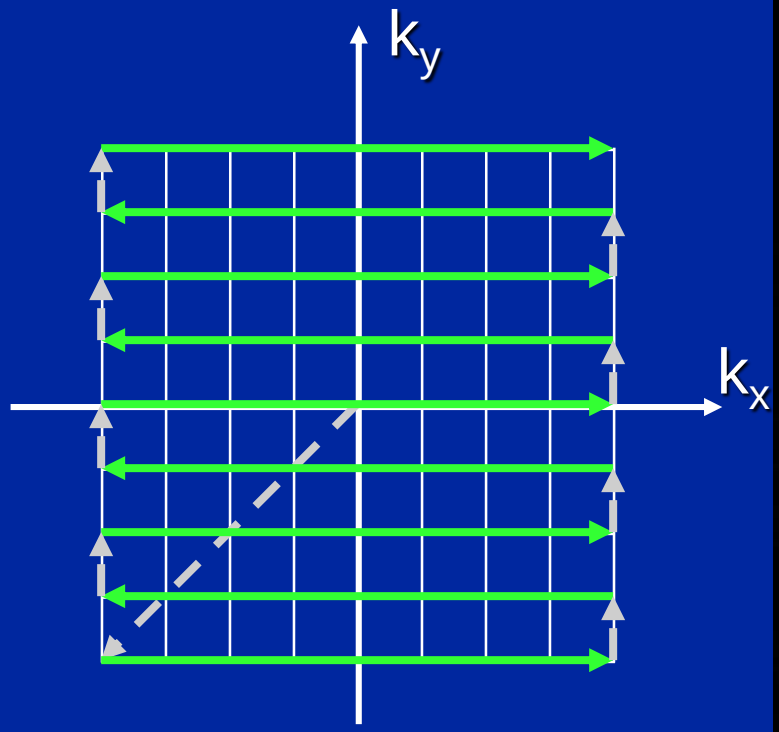


128x128 FLASH/SPGR

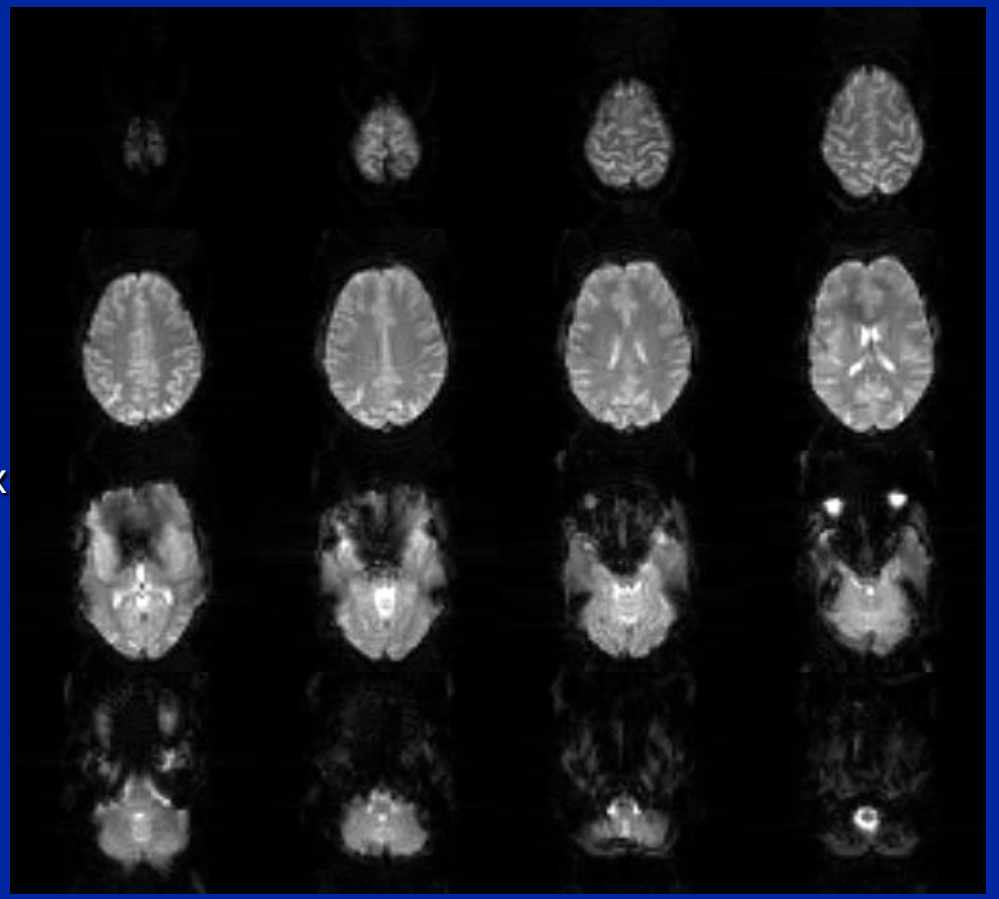
TR/TE/flip = 50ms/30ms/30º

0.2 slices per sec, single slice

Echo Planar Imaging (EPI)



Zig-Zag Pattern



Single-shot EPI, TE = 40 ms,
TR = 2 s, 20 slices

Pulse Sequences

- Two Major Aspects
  - Contrast (Spin Preparation)

What kind of contrast does the image have?
What is the TR, TE, Flip Angle, etc.?
Gradient echo/spin echo/etc.

  - Localization (Image Acquisition)

How is the image acquired?
How is “k-space” sampled?
Spatial Resolution?

What is T2*?

- T2* has two parts:
  - Inter-molecular interactions leading to dephasing, a.k.a. T2 decay
  - Macroscopic or mesoscopic static magnetic field inhomogeneity leading to dephasing, a.k.a. T2'

$$\frac{1}{T2^*} = \frac{1}{T2'} + \frac{1}{T2}$$

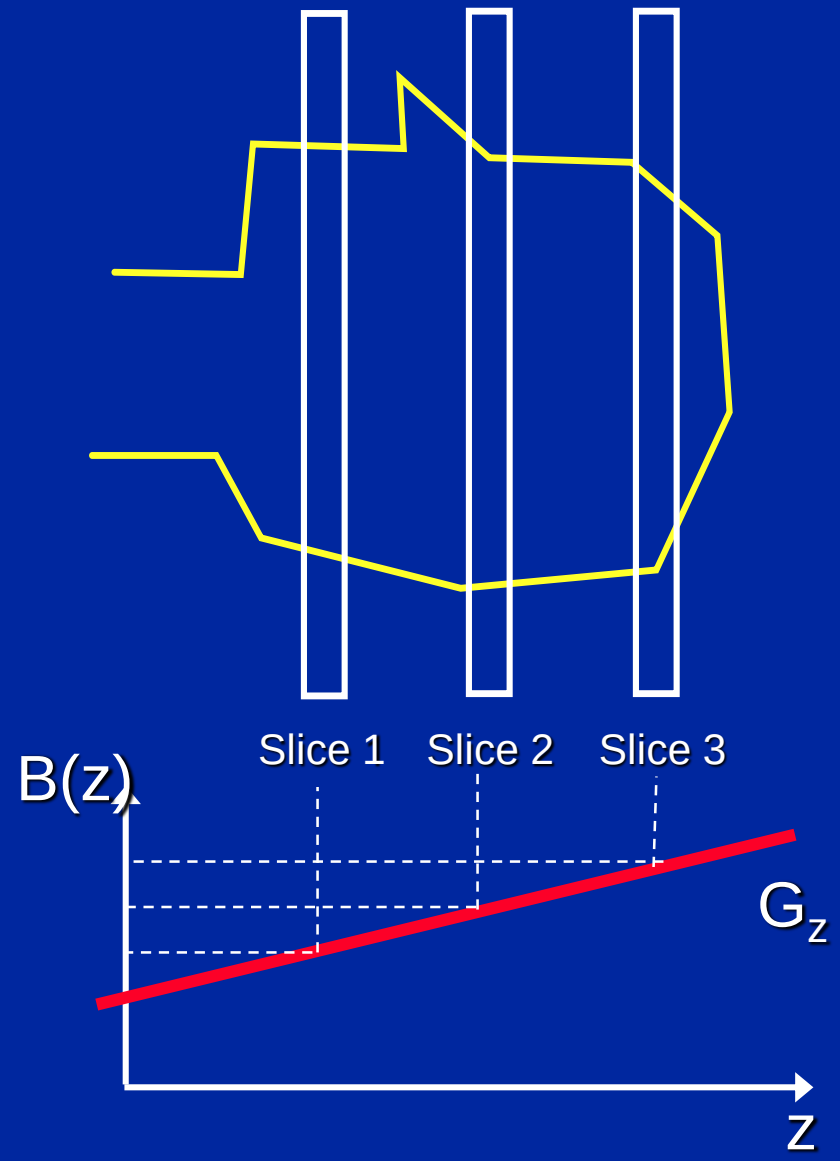
- Pulse sequence issues:
  - Spin echoes are sensitive to T2
  - Gradient echoes are sensitive to T2*

Slice Selection

- The 3rd dimension is localized during excitation
  - "Slice selective excitation"

- Makes use of the resonance phenomenon
  - Only "on-resonant" spins are excited

Slice Selection



With the z-gradient on, slices at different z positions have a different magnetic fields and therefore different frequencies :

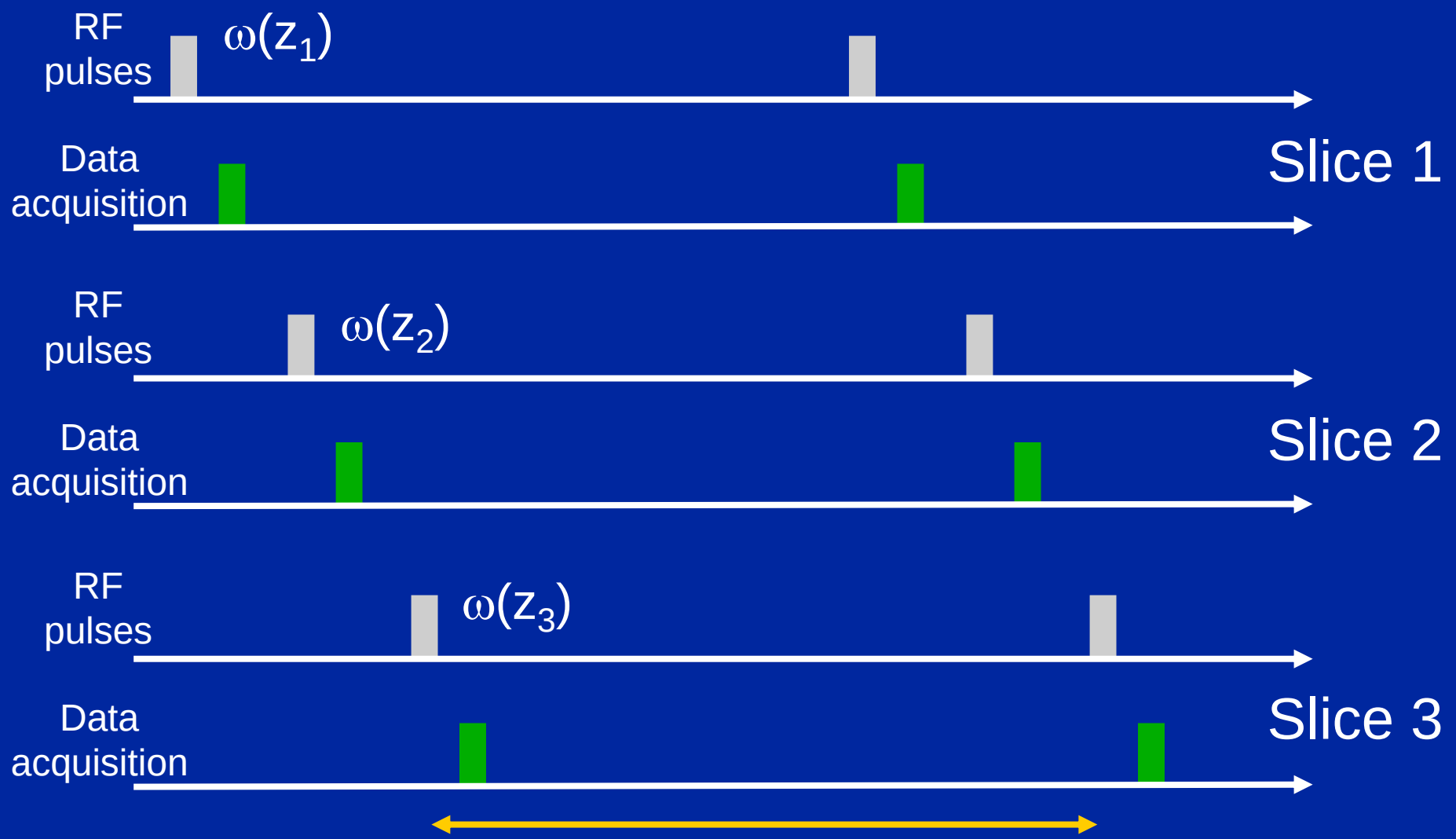
$$\omega(z_1) < \omega(z_2) < \omega(z_3)$$

Multi-Slice Imaging

- Since T1's are long, we often would like to have long TR's (500-4000 ms)

- While one slice is recovering (T1), we can image other slices without perturbing the recovery process

Multi-Slice Imaging



Typical fMRI Protocol

- Calibrations
  - Estimate power deposition, receive coil patterns
- Scout Acquisition
  - Where am I?
- T1-weighted images
  - To align structure to fMRI maps, rule out pathology
- T2-weighted images
  - To rule out pathology (particularly for patient studies)
- fMRI – T2*-weighted, dynamic
  - Task-based, resting state
  - EPI or spiral, multiband EPI
- Diffusion tensor imaging
  - White matter anatomy, micro architecture
- High-resolution 3D T1-weighted images
  - For segmentation of anatomy
- Quantitative parameter mapping

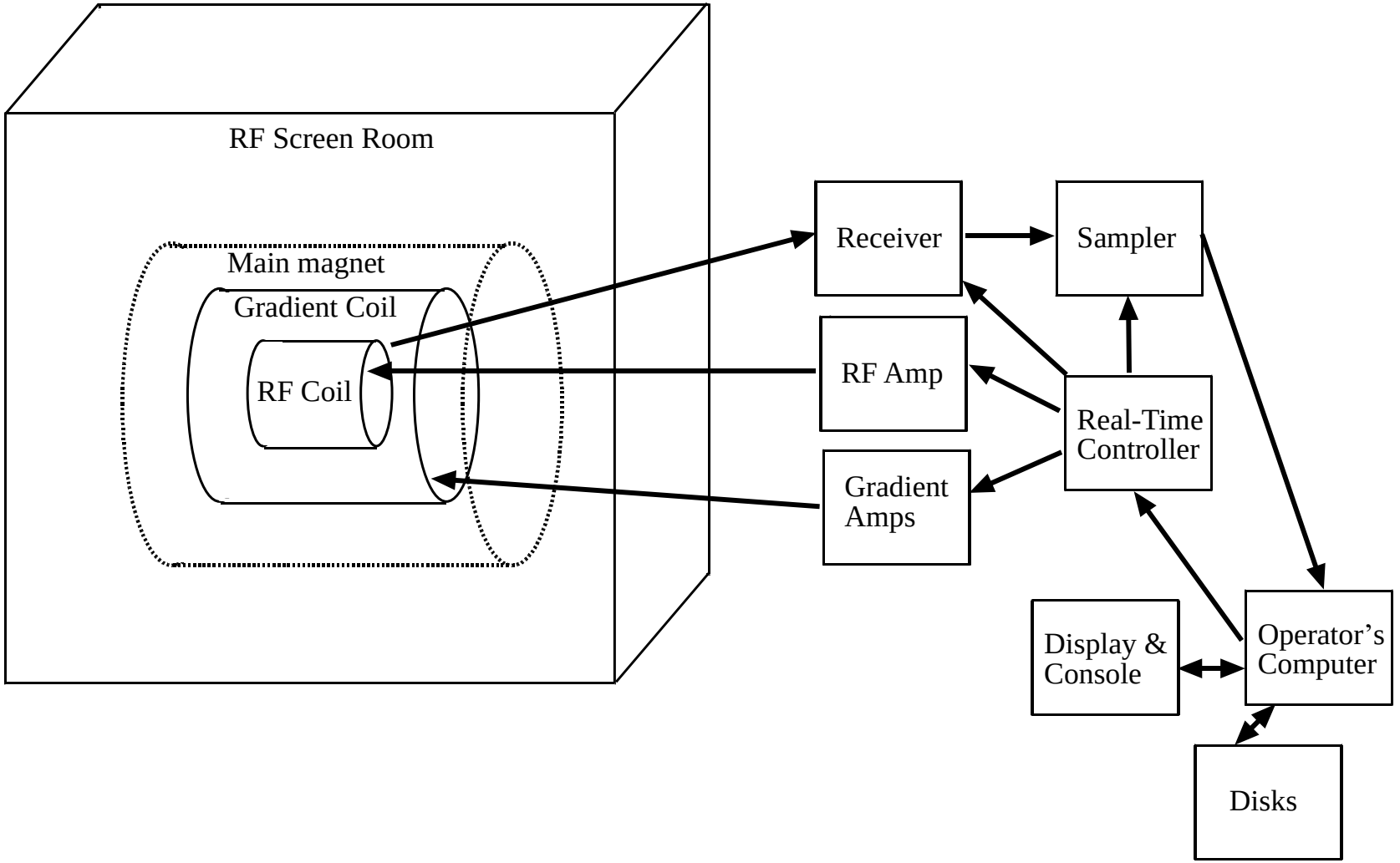
MRI Hardware and Safety

Douglas C. Noll
Biomedical Engineering
University of Michigan

MRI Hardware

- Recall the three magnetic fields
  - B_0
  - B_1
  - G_x, G_y, G_z
- Also, we need pulse control and data acquisition systems

Major MRI Components



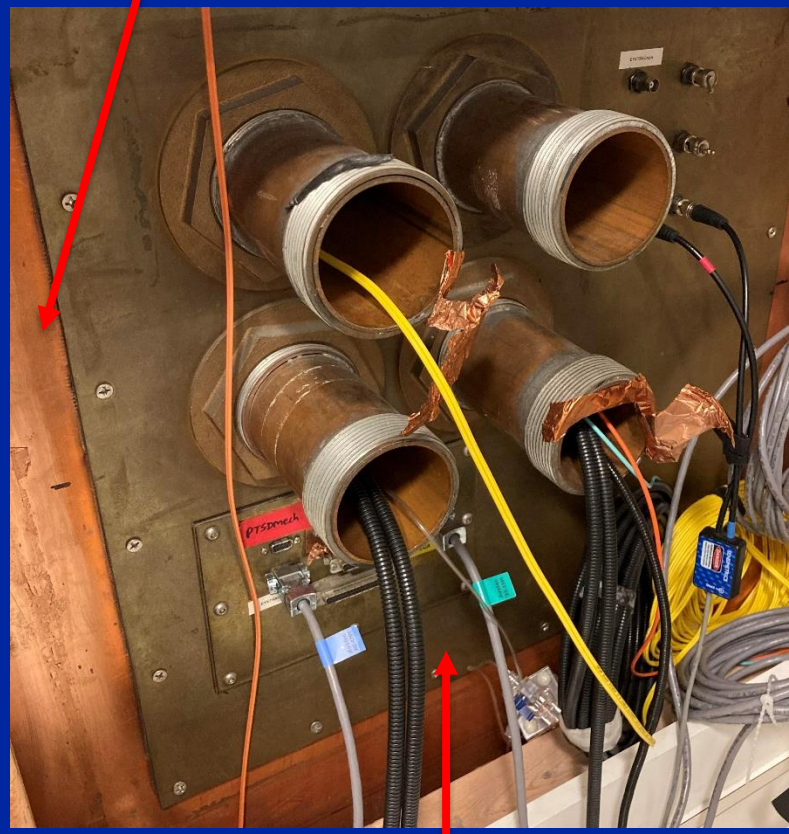
RF Screen Room

- Encloses the MRI device
- Shields MRI scanner from electromagnetic noise from computers, radio stations, etc.
  - MRI signals are weak compared to noise sources
  - Any wires going in/out must be filtered and grounded so they don’t introduce noise
- These rooms can also incorporate magnetic shielding to contain the magnetic field.

RF Screen Room

Metal seals
around doors

Copper walls



Filtered panels for experimental
and MRI equipment

The Main Field

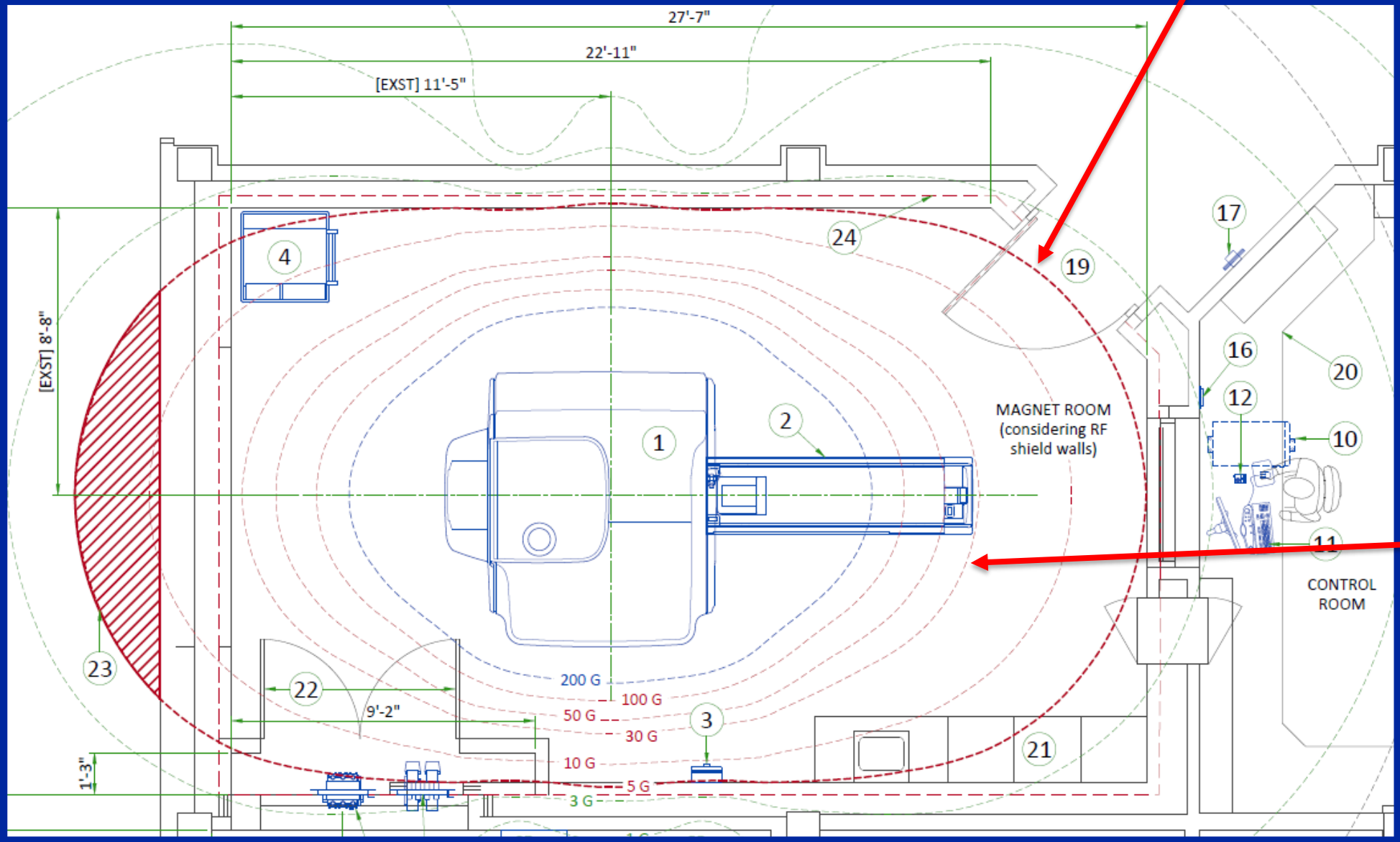
- B_0 range: 0.2 T to 7 T are common
- Higher fields:
  - Higher SNR
  - Slightly longer T1's,
  - Poorer RF homogeneity
  - Higher power deposition
  - Higher cost
- Typically superconducting
  - Filled with liquid helium

Main Field Safety

- MAIN MAGNET IS ALWAYS ON!

- B_0 is the biggest safety concern in MRI
- Mainly attraction of ferrous objects
- Some reports of dizziness, light flashes, unusual tastes, etc. at very high magnetic fields
- Quenching of magnet can result in venting of cryogenic gases
- The FDA has classified 8 T and under as a “non-significant risk”

Main Magnetic Field



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The Main Field

- Safety issues:
  - Attraction of metallic implants (e.g. cochlear implants, neurostimulators, pacemakers, and poorly designed/manufactured stents, screws, pins, aneurysm clips, etc.)
  - Attraction of foreign metal objects (metal in eyes, shapnel, ingested ferrous objects).
  - Affects magnetic switches in pacemakers
  - Ferrous objects brought into the MRI scan room

MRI Screening

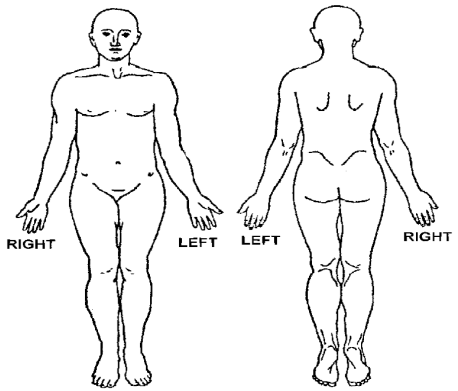
http://fmri.research.umich.edu/documents/safety_screening.pdf

WARNING: Certain implants, devices, or objects may be hazardous to you and/or may interfere with the MR procedure (i.e., MRI, MR angiography, functional MRI, MR spectroscopy). Do not enter the MR system room or MR environment if you have any question or concern regarding an implant, device, or object. Consult the MRI Technologist or Director BEFORE entering the MR system room. The MR system magnet is ALWAYS on.

Please indicate if you have any of the following:

Yes	No	Aneurysm clip(s)
Yes	No	Cardiac pacemaker
Yes	No	Implanted cardioverter defibrillator (ICD)
Yes	No	Electronic implant or device
Yes	No	Magnetically-activated implant or device
Yes	No	Neurostimulation system
Yes	No	Spinal cord stimulator
Yes	No	Internal electrodes or wires
Yes	No	Bone growth/bone fusion stimulator
Yes	No	Cochlear, otologic, or other ear implant
Yes	No	Insulin or other infusion pump
Yes	No	Implanted drug infusion device
Yes	No	Any type of prosthesis (eye, penile, etc.)
Yes	No	Heart valve prosthesis
Yes	No	Eyelid spring or wire
Yes	No	Artificial or prosthetic limb
Yes	No	Metallic stent, filter, or coil
Yes	No	Shunt (spinal or intraventricular)
Yes	No	Vascular access port and/or catheter
Yes	No	Small bowel endoscopy capsule
Yes	No	Swan-Ganz or thermodilution catheter
Yes	No	Medication patch
Yes	No	Any metallic fragment or foreign body
Yes	No	Wire mesh implant
Yes	No	Tissue expander (e.g., breast)
Yes	No	Surgical staples, clips, or metallic sutures
Yes	No	Joint replacement (hip, knee, etc.)
Yes	No	Bone/joint pin, screw, nail, wire, plate, etc.
Yes	No	IUD, diaphragm, or pessary (circle which)
Yes	No	Dental braces
Yes	No	Tattoo or permanent makeup
Yes	No	Body piercing jewelry
Yes	No	Hearing aid (Remove before entering MR system room)
Yes	No	Other implant _____
Yes	No	Breathing problem or motion disorder
Yes	No	Claustrophobia

Please mark on the figure(s) below the location of any implant or metal inside of or on your body.



IMPORTANT INSTRUCTIONS

Before entering the MR environment or MR system room, you must remove all metallic objects including hearing aids, dentures, partial plates, keys, beeper, cell phone, eyeglasses, hair pins, barrettes, jewelry, body piercing jewelry, watch, safety pins, paperclips, money clip, credit cards, bank cards, magnetic strip cards, coins, pens, pocket knife, nail clipper, tools, clothing with metal fasteners, & clothing with metallic threads.

Please consult the MRI Technologist or Director if you have any question or concern BEFORE you enter the MR system room.

NOTE: You will be required to wear earplugs or other hearing protection during the MR procedure to prevent possible problems or hazards related to acoustic noise.

Aneurysm clip(s)
Cardiac pacemaker
Implanted cardioverter defibrillator (ICD)
Electronic implant or device
Magnetically-activated implant or device
Neurostimulation system
Spinal cord stimulator
Internal electrodes or wires
Bone growth/bone fusion stimulator
Cochlear, otologic, or other ear implant
Insulin or other infusion pump
Implanted drug infusion device
Any type of prosthesis (eye, penile, etc.)
Heart valve prosthesis
Eyelid spring or wire
Artificial or prosthetic limb
Metallic stent, filter, or coil
Shunt (spinal or intraventricular)
Vascular access port and/or catheter
Small bowel endoscopy capsule
Swan-Ganz or thermodilution catheter
Medication patch
Any metallic fragment or foreign body

MRI Screening

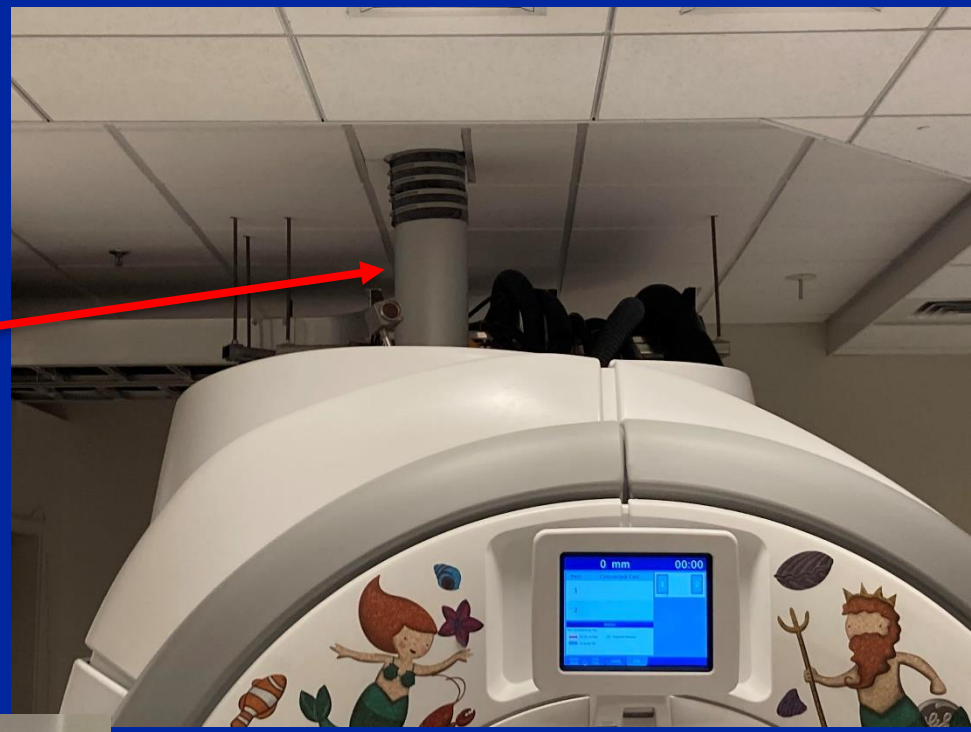
What about stuff you might, but shouldn't bring into the scan room:

- Pens, paper clips, clipboards, scissors
- Stuff in pockets, keys
- Clothing belts, buttons, etc.
- Phones, computers
- Wallets (not a safety issue, but magnetic strips get wiped)

- NOTHING goes into the MRI room without first being cleared by the technologists
- We often use a metal detector to make sure there is no metal on the subjects

Main Field Safety

Quench vent



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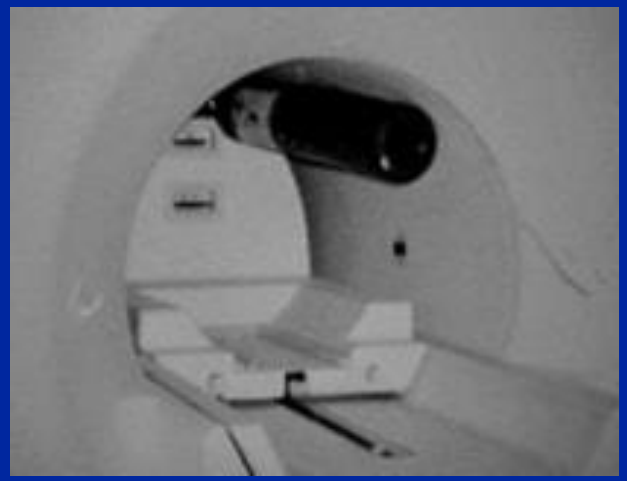
MRI Oops!



Noll

RF Coils

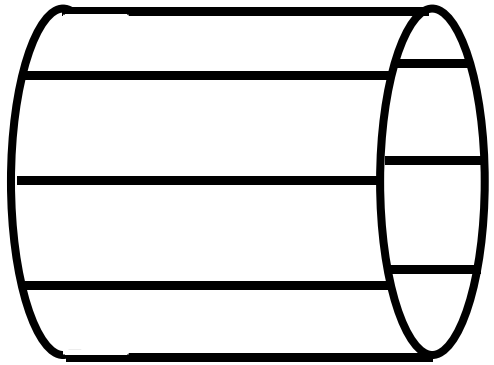
Two purposes:

- Excitation/transmission – tipping magnetization into transverse plane. Requirements:
  - Uniformity of tip angle, covers volume of interest
- Reception – converting precessing spins into voltages. Requirements:
  - Good SNR, sensitive to volume of interest, uniformity not so important

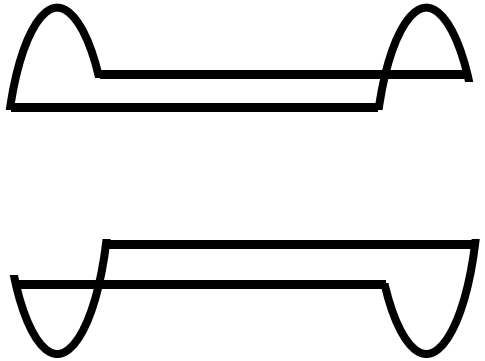
RF Coils

Volume Coils -- Transmit and Receive

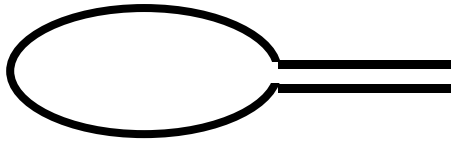
Surface and Array Coils -- Receive Only



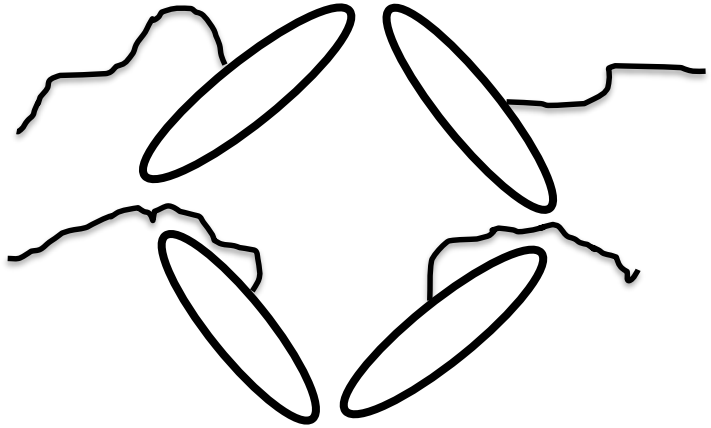
Birdcage Coil



Saddle Coils



Surface Coil



Array Coil

RF Coils

Typical coils:

- Head Coil (volume birdcage coil)
- Body Coil (volume)
  - Built into system (always there)
  - Can be used for receive (but rarely)
  - Used transmit only for most receive arrays
- Surface Coils (typically receive only)
  - Improved SNR vs. volume coils

RF Coils

- Receive arrays (array of surface coils, receive only)
  - The idea here is that one can receive the SNR benefits of surface coils, but over a larger volume.
  - Also allows use of parallel MRI technology because each coil captures a slightly different part of the image volume

Head Arrays

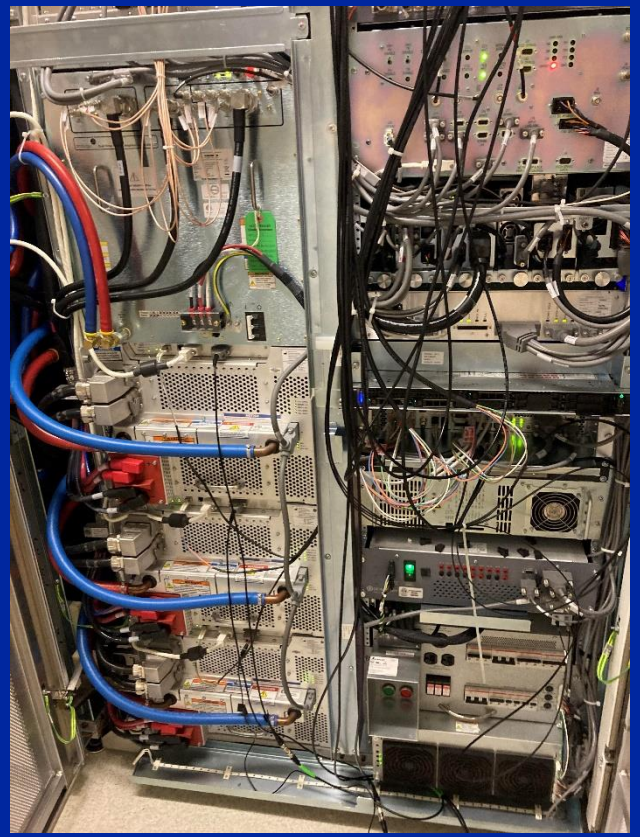
Flex Arrays

RF Safety

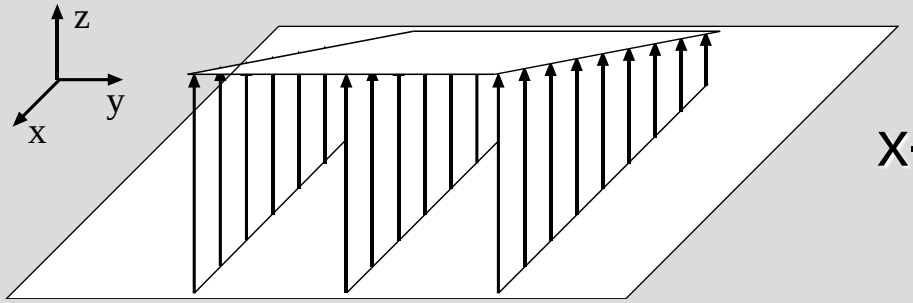
- Diffuse RF heating of the body
  - FDA limits our power deposition (W/kg)
  - Hardware measures this and will shut it down if it gets too high
  - This is why we need to enter patient weight into the scanner
- Focal RF heating around metals and devices
  - Glasses, jewelry & piercings, some tattoos → can lead to burns
  - Implants: cochlear implants, neurostimulators, pacemakers.
  - Usually not a problem (for RF): dental work, stents, screws, pins, aneurysm clips, etc. though could be an issue for B_0

Gradient Fields

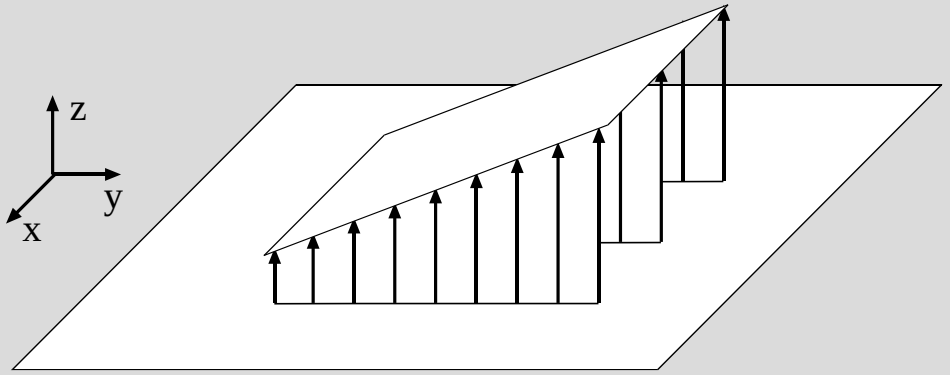
- High power amplifiers generate magnetic fields in the same direction as B_0, but with variations along x, y and z.
- Provide localization of spins in MRI



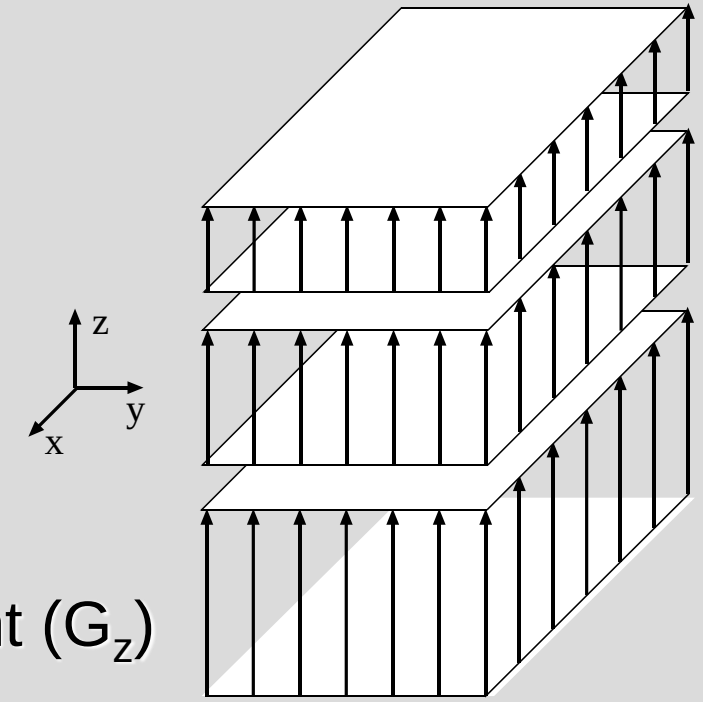
http://mriquestions.com



x-gradient (G_x)



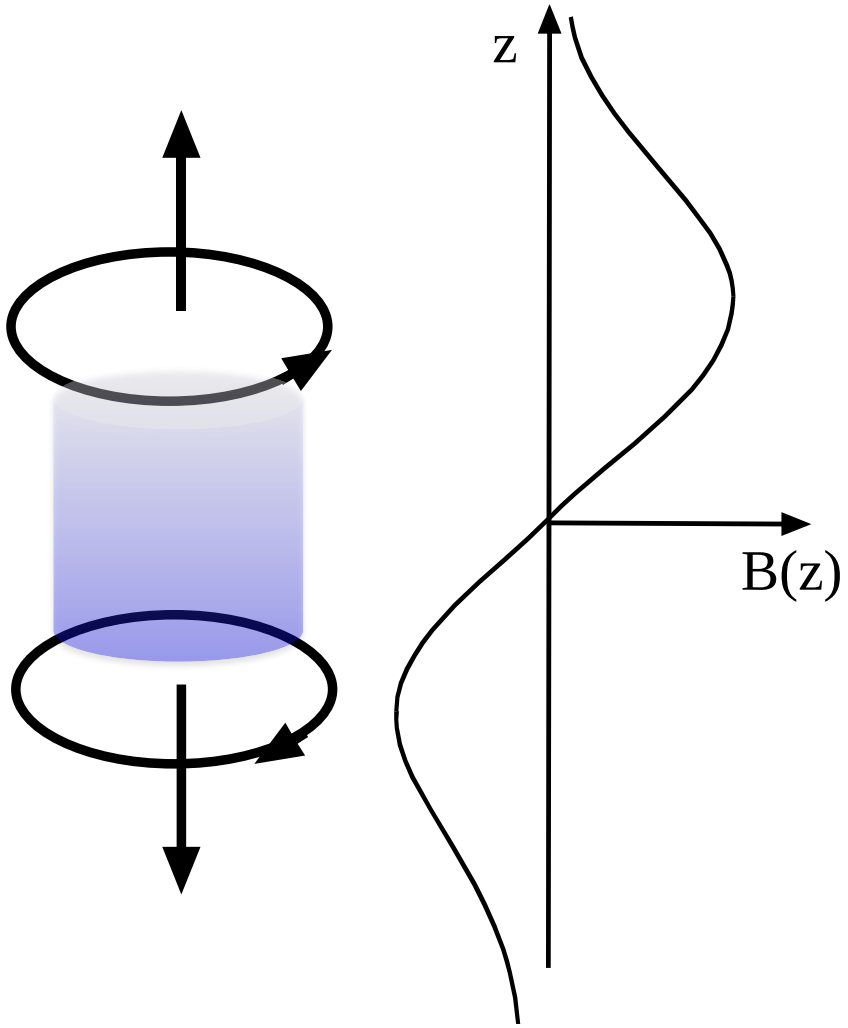
y-gradient (G_y)



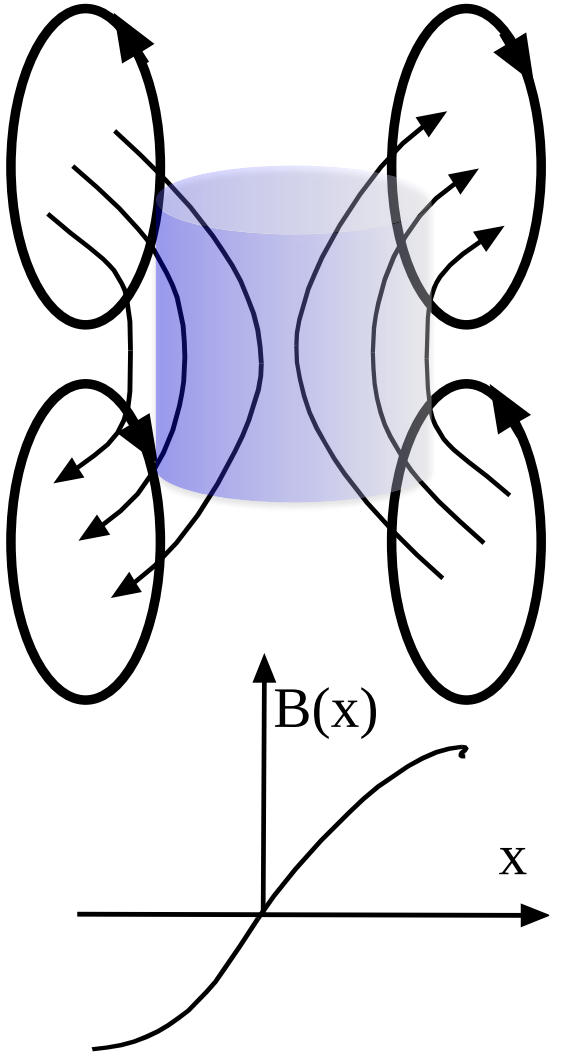
z-gradient (G_z)

B_0

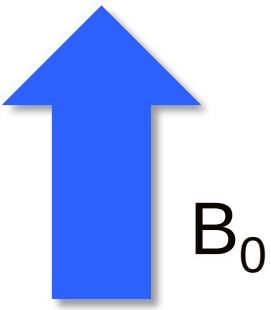
Gradient Coil Designs



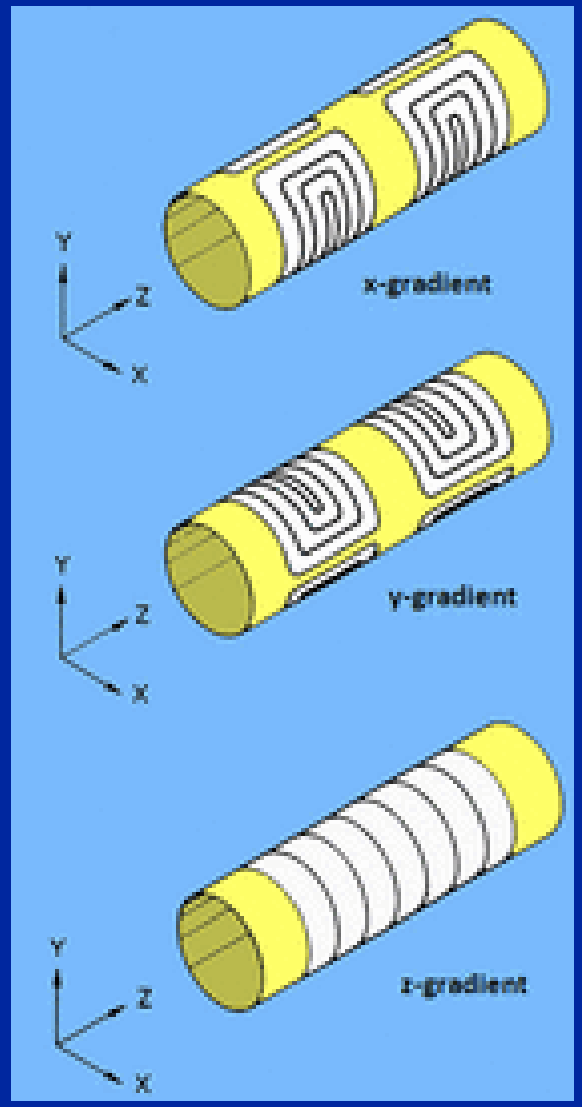
Z Gradient



X,Y Gradients



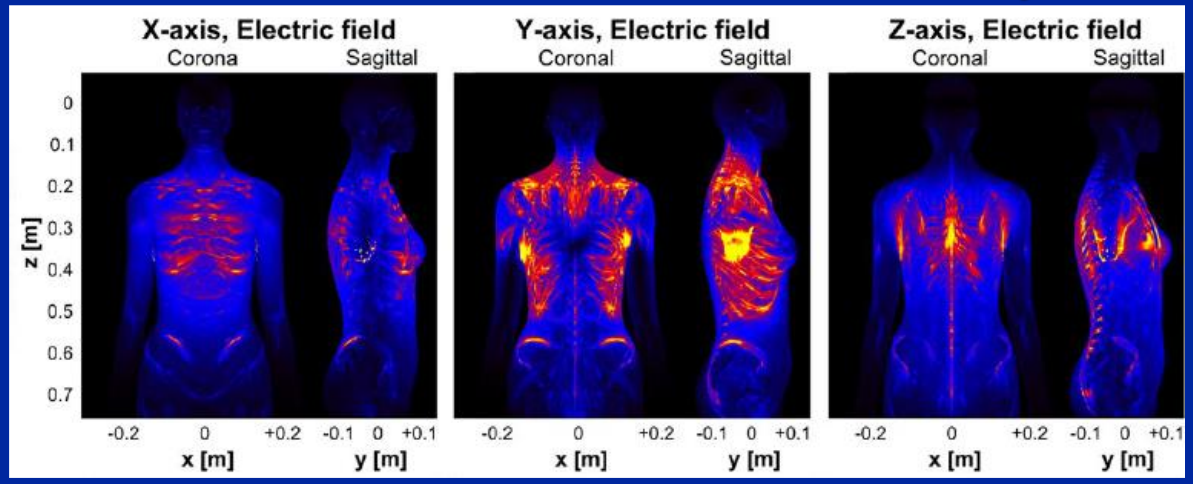
Gradient Coils



http://mriquestions.com

Safety of Gradient Fields

- Main source of power consumption in MRI systems
- Rapid changes of fields can lead to peripheral nerve stimulation (PNS) which can feel like twitching in the back or shoulders
  - FDA guidelines state that stimulation cannot be “painful”
  - Lots of individual variability in sensitivity to PNS



Davids et al,
MRM, 2018

- The gradients are also responsible for the acoustic noise.
  - FDA says it can’t exceed 99 dBA with hearing protection in place.

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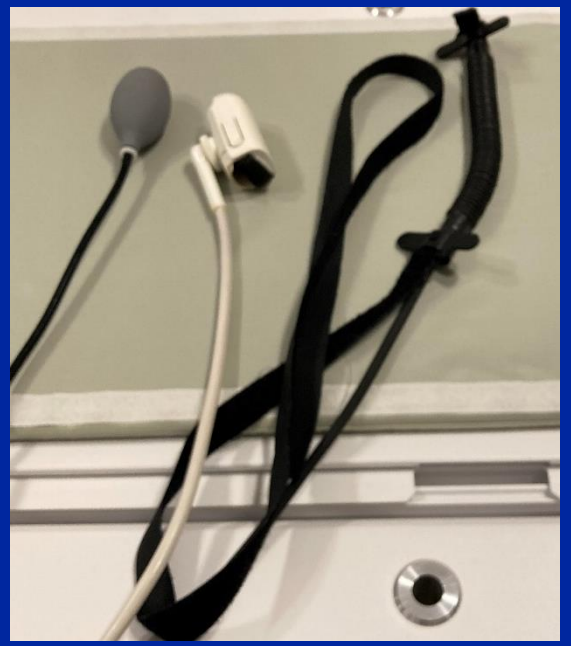
MR Compatible Devices

- Whole industry on MRI compatible devices
- Physiological signals, response collection, stimulus presentation, auditory stimulation, vision corr.



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Other Risks/Safety Matters

- Attraction of ferrous objects
- Focal RF heating
- Loud
- Peripheral nerve stimulation (PNS)
- Dizziness

But also…

- Claustrophobia, anxiety
- Incidental findings (unexpected findings of tumors, etc.)
- Pregnancy is a contraindication for most research studies

MRI Safety Labeling

https://www.fda.gov/media/101221/download

MR Unsafe items should not enter the MRI scanner room. Patients with MR Unsafe devices should not be scanned.

MR Conditional items may safely enter the MRI scanner room only under the very specific conditions provided in the labeling. Patients should not be scanned unless the device can be positively identified as MR Conditional AND the conditions for safe use are met.

The conditions for safe use will be different based on the intended use of the device.

For **items intended to enter the bore of the MRI system**, the MRI Safety labeling should be matched with the MRI system for:

- Static field strength
- Maximum spatial field gradient
- dB/dt limitations (usually only applicable to active implants)
- SAR limits
- Any other conditions needed for safe use of the device, for example restrictions on the types of coils that may be used

When present, information about expected temperature rise and artifact extent may inform the risk/benefit decision of whether or not a patient should undergo an MRI examination. Expected temperature rise and artifact extent information are not conditions that must be met.

Items NOT intended to enter the bore of the MRI system usually have gauss line positioning restrictions or requirements to tether or affix the device to an unmovable part of the room.

MR Safe items pose no safety hazards in the MR environment. They may be placed anywhere in the MR environment. Patients with MR Safe devices have no scanning restrictions.

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FDA Non-Signifiance Risk Guidance

See https://www.fda.gov/media/74201/download

- Main field (B_0) ≤ 8 Tesla for subjects > 1 month age
- Power deposition (SAR) ≤ 3.2 W/kg for heads, averaged over 10 min
- Peripheral nerve stimulation (dB/dt) not cause severe discomfort or pain
- Sound:
  - Peak unweighted sound pressure level ≤ 140 dB.
  - A-weighted RMS SPL ≤ 99 dBA with hearing protection