MRI Systems & Safety

Daniel B. Ennis, Ph.D.
Magnetic Resonance Research Labs

DEnnis@mednet.ucla.edu
310.206.0713 (Office)
http://mrrl.ucla.edu

David Geffen
School of Medicine

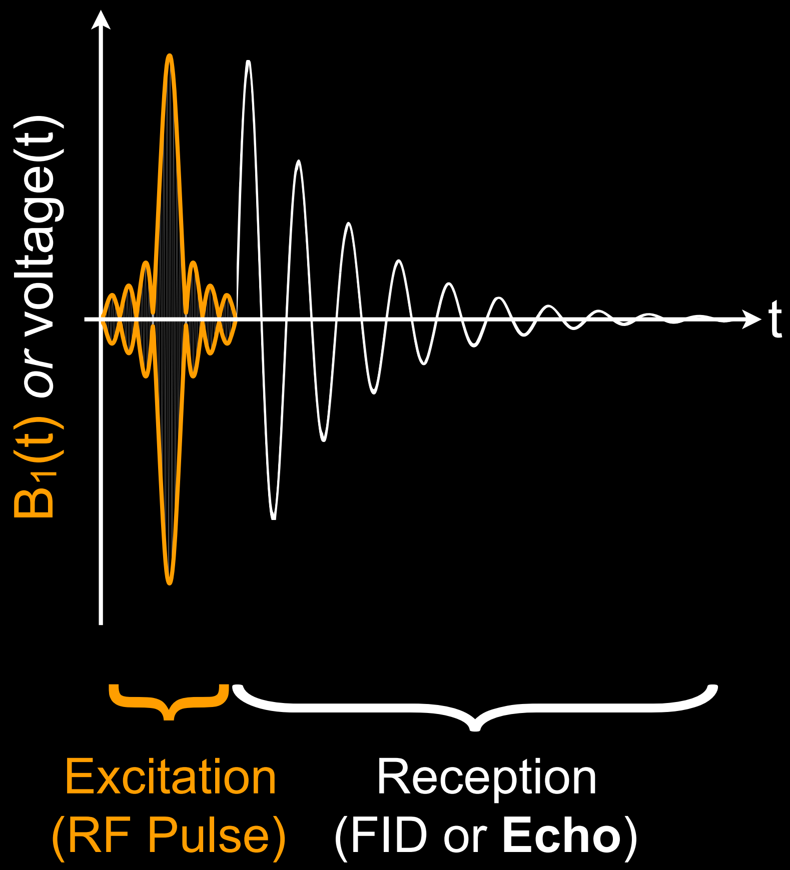
UCLA
Radiology

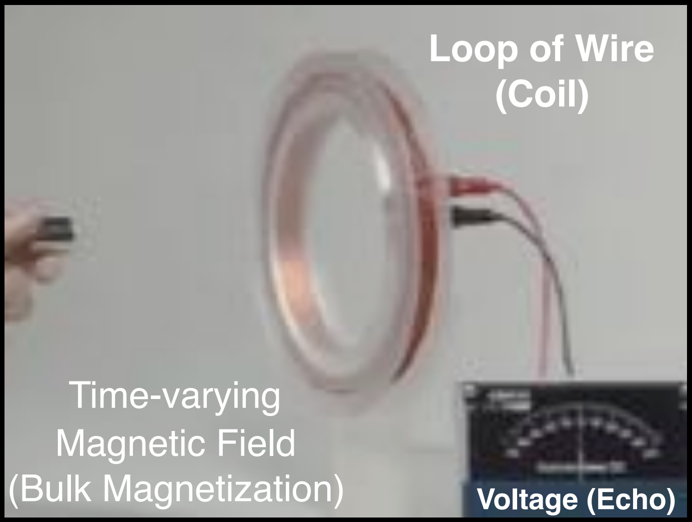
What is MRI?

- **Magnetic**
  - **We need a big magnet**
- **Resonance**
  - **Excitation energy has to be on-resonance**
- **Imaging**
  - **We can make pretty pictures**

What is MRI?

MRI follows a classic excitation-reception paradigm.





Faraday's Law of Induction

MRI encodes spatial information and image contrast in the echo.

Requirements for MRI

- **NMR Active Nuclei**
  - e.g. ^1H in H_20
- **Magnetic Field (B_0)**
  - Polarizer
- **RF System (B_1)**
  - Exciter
- **Coil**
  - Receiver
- **Gradients (G_X, G_Y, G_Z)**
  - Spatial Encoding (imaging!)
- **Computers**
  - Image reconstruction

Cardiac MRI Exam Set-up

MRI Hardware

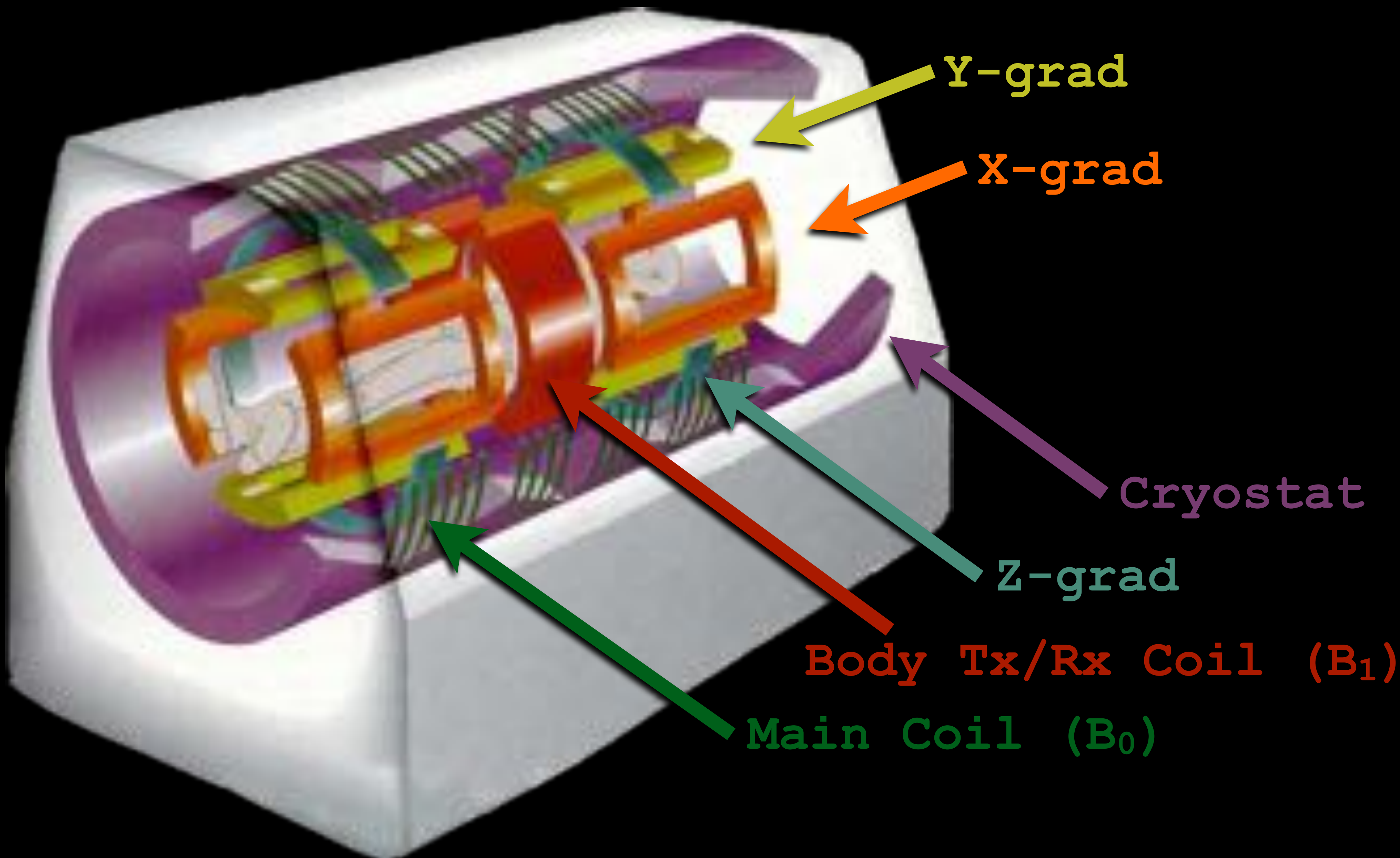


Image Adapted From: http://www.ee.duke.edu/~jshorey

MRI Advantages

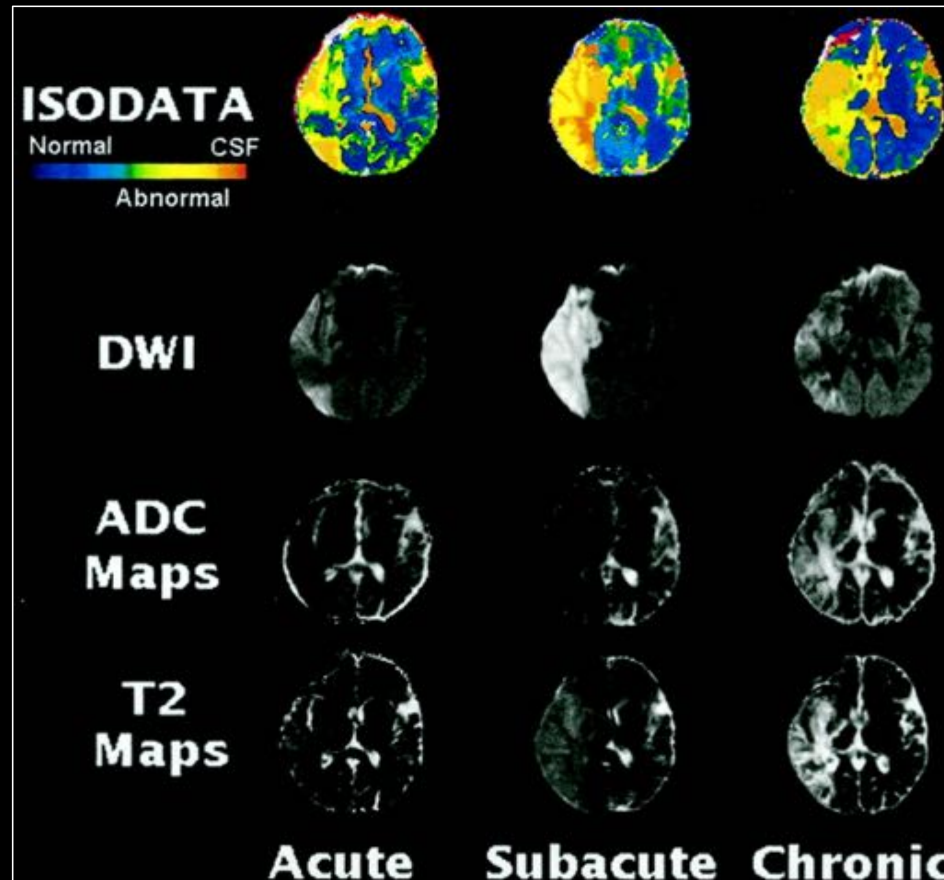
Soft Tissue Contrast





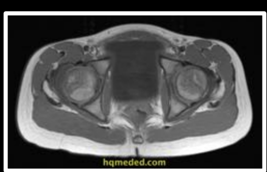
(Quantitative) Tissue Characterization

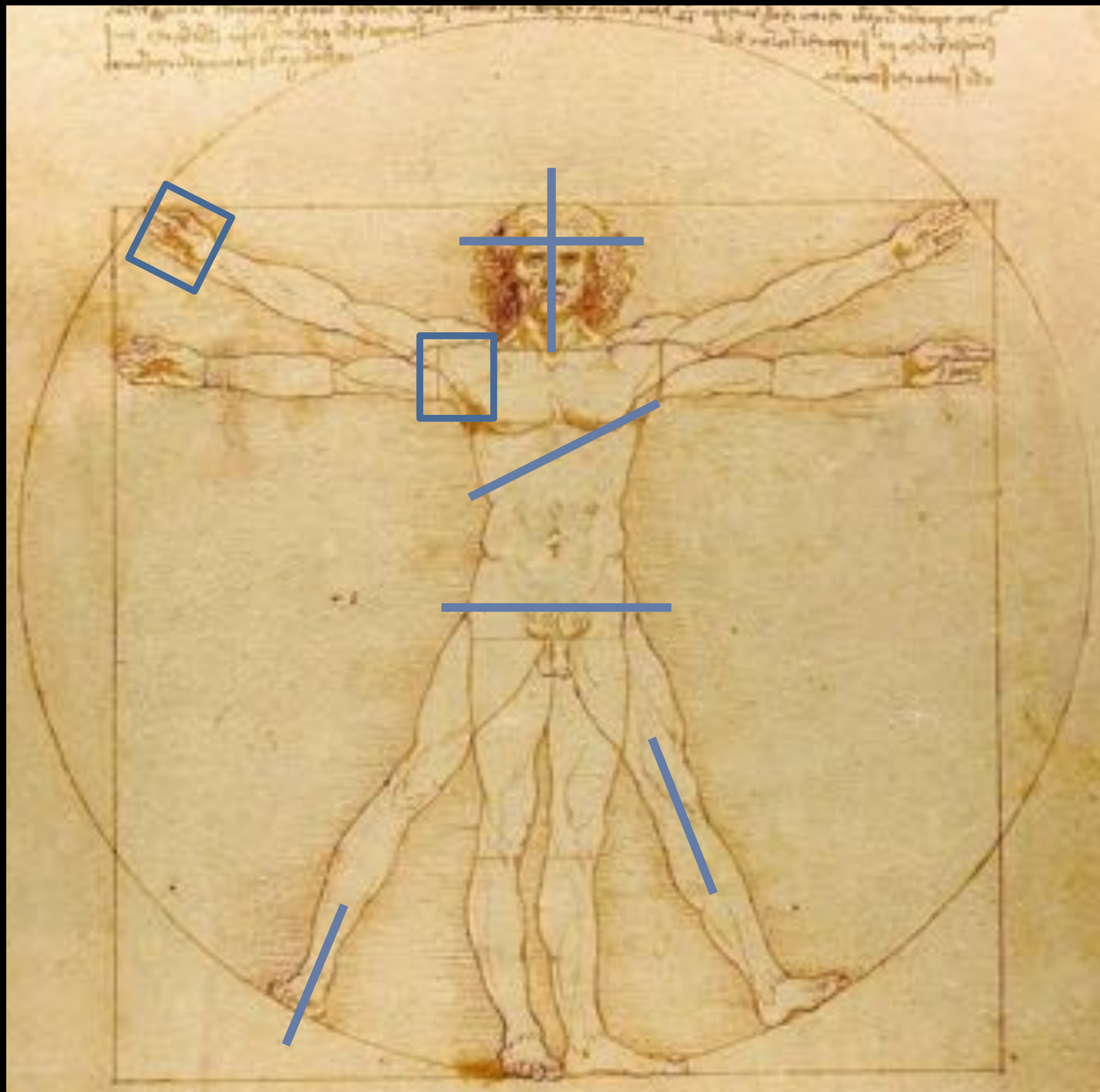
- **Routine**
  - T_1, T_2, T_2^*, proton weighted
  - Perfusion
  - Diffusion
  - Contrast enhancement
    - Tumor evaluation
    - Angiography
- **Advanced**
  - T1- and T2-mapping
  - Fat/Water & Iron quantification
  - Spectroscopy (molecular)
  - Susceptibility weighted imaging (SWI) for blood products and calcium
  - Non-contrast angiography

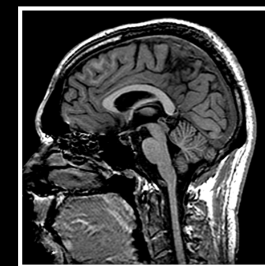


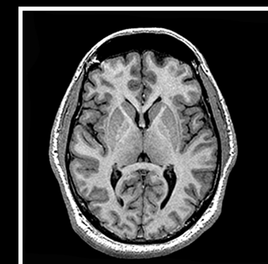
Demonstration of the multiparametric ISODATA segmentation methodology and corresponding DWI (b=1000 s/mm2), ADC map, and T2 map at different times after stroke. *Jacobs M A et al. Stroke. 2001;32:950-957*

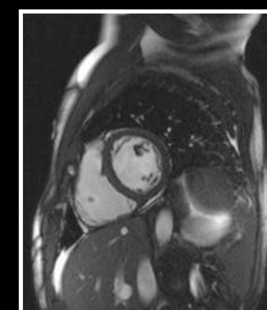
Arbitrary Imaging Planes





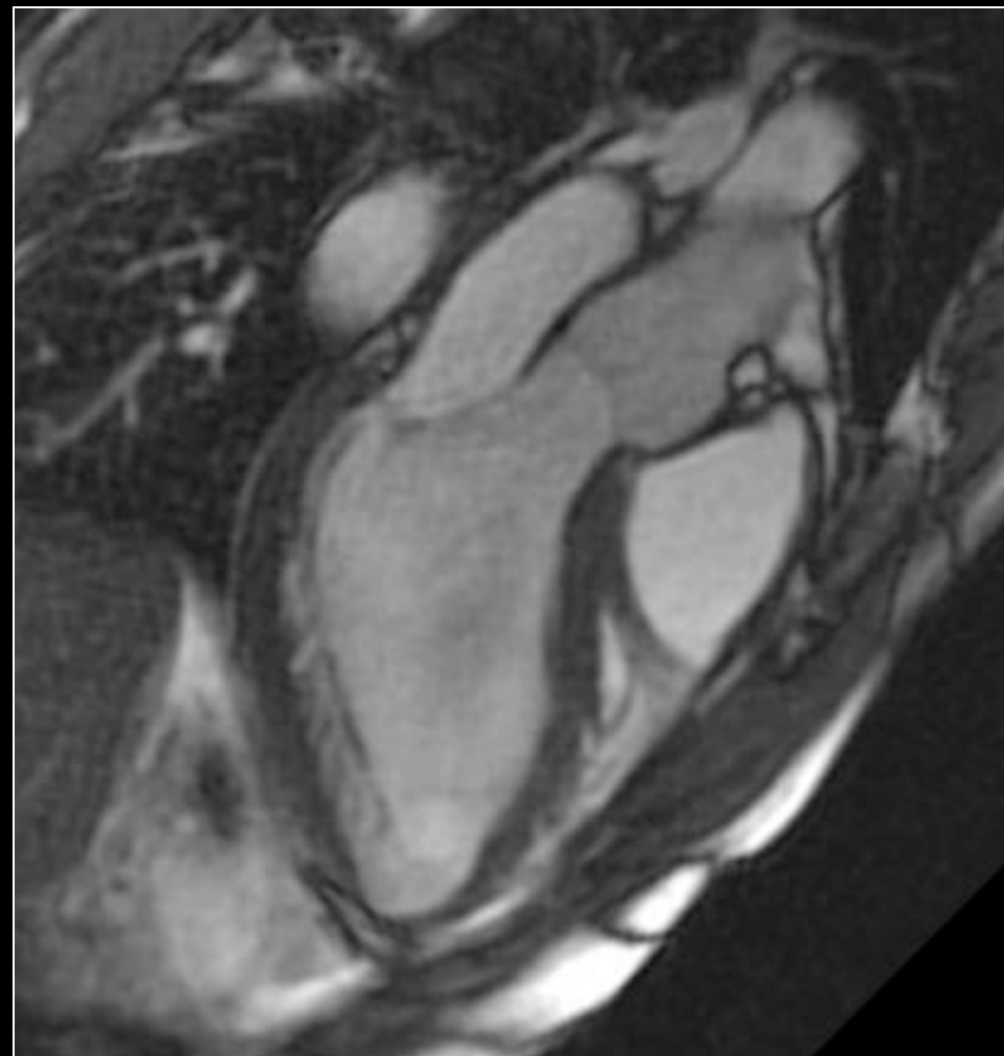






No Ionizing Radiation

Image Physiologic Motion



MRI Disadvantages

MRI - Disadvantages

- **Safety**
  - Main Field (B_0)
  - Radiofrequency Field (B_1)
  - Gradients (G_x, G_y, and G_z)
- **Slow**
- **Expensive**
- **Non-specific**
- **Technically challenging**
- **Not 1° for all indications**

Patient Screening Forms

MAGNETIC RESONANCE (MR) PROCEDURE SCREENING FORM FOR PATIENTS

Date _____/_____/_____ Patient Number ______________________

Name ____ Age ________ Height ________ Weight ________
Last name First name Middle Initial

Date of Birth _____/_____/_____ Male ☐ Female ☐ Body Part to be Examined _________________________
month day year

Address ____ Telephone (home) (_____) _____-_________

City ____ Telephone (work) (_____) _____-_________

State _______________________ Zip Code ___________

Reason for MRI and/or Symptoms ____

Referring Physician __________________________________ Telephone (_____) _____-______________

1. Have you had prior surgery or an operation (e.g., arthroscopy, endoscopy, etc.) of any kind? ☐ No ☐ Yes
   If yes, please indicate the date and type of surgery:
   Date _____/_____/_____ Type of surgery ____
   Date _____/_____/_____ Type of surgery ____
2. Have you had a prior diagnostic imaging study or examination (MRI, CT, Ultrasound, X-ray, etc.)? ☐No ☐ Yes
   If yes, please list:

	Body part	Date	Facility
MRI	______________________	_____/_____/_____	________________________________
CT/CAT Scan	______________________	_____/_____/_____	________________________________
X-Ray	______________________	_____/_____/_____	________________________________
Ultrasound	______________________	_____/_____/_____	________________________________
Nuclear Medicine	______________________	_____/_____/_____	________________________________
Other_________	______________________	_____/_____/_____	________________________________

3. Have you experienced any problem related to a previous MRI examination or MR procedure? ☐ No ☐ Yes
   If yes, please describe: ____
4. Have you had an injury to the eye involving a metallic object or fragment (e.g., metallic slivers, shavings, foreign body, etc.)? ☐ No ☐ Yes
   If yes, please describe: ____
5. Have you ever been injured by a metallic object or foreign body (e.g., BB, bullet, shrapnel, etc.)? ☐ No ☐ Yes
   If yes, please describe: ____
6. Are you currently taking or have you recently taken any medication or drug? ☐ No ☐ Yes
   If yes, please list:____
7. Are you allergic to any medication? ☐ No ☐ Yes
   If yes, please list:____
8. Do you have a history of asthma, allergic reaction, respiratory disease, or reaction to a contrast medium or dye used for an MRI, CT, or X-ray examination? ☐ No ☐ Yes
9. Do you have anemia or any disease(s) that affects your blood, a history of renal (kidney) disease, renal (kidney) failure, renal (kidney) transplant, high blood pressure (hypertension), liver (hepatic) disease or seizures? No ☐ Yes
   If yes, please describe: ____

For female patients:

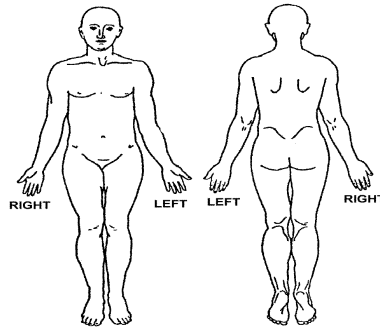
10. Date of last menstrual period:_____/_____/_____ Post menopausal? ☐ No ☐ Yes
11. Are you pregnant or experiencing a late menstrual period? ☐ No ☐ Yes
12. Are you taking oral contraceptives or receiving hormonal treatment? ☐ No ☐ Yes
13. Are you taking any type of fertility medication or having fertility treatments? ☐ No ☐ Yes
    If yes, please describe: ____
14. Are you currently breastfeeding? ☐ No ☐ Yes

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 Radiologist 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 Radiation seeds or implants
- ☐ Yes ☐ No Swan-Ganz or thermodilution catheter
- ☐ Yes ☐ No Medication patch (Nicotine, Nitroglycerine)
- ☐ 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
- ☐ Yes ☐ No Dentures or partial plates
- ☐ 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 Radiologist if you have any question or concern BEFORE you enter the MR system room.

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

I attest that the above information is correct to the best of my knowledge. I read and understand the contents of this form and had the opportunity to ask questions regarding the information on this form and regarding the MR procedure that I am about to undergo.

Signature of Person Completing Form: _____________________________________ Date _____/_____/_____
Signature

Form Completed By: ☐ Patient ☐ Relative ☐ Nurse _________________________________ ___________________________
Print name Relationship to patient

Form Information Reviewed By: ___________________________________ ____
Print name Signature

☐ MRI Technologist ☐ Nurse ☐ Radiologist ☐ Other____

David Geffen School of Medicine

Patient *and* personnel screening before an MRI exam is critical.

UCLA Radiology

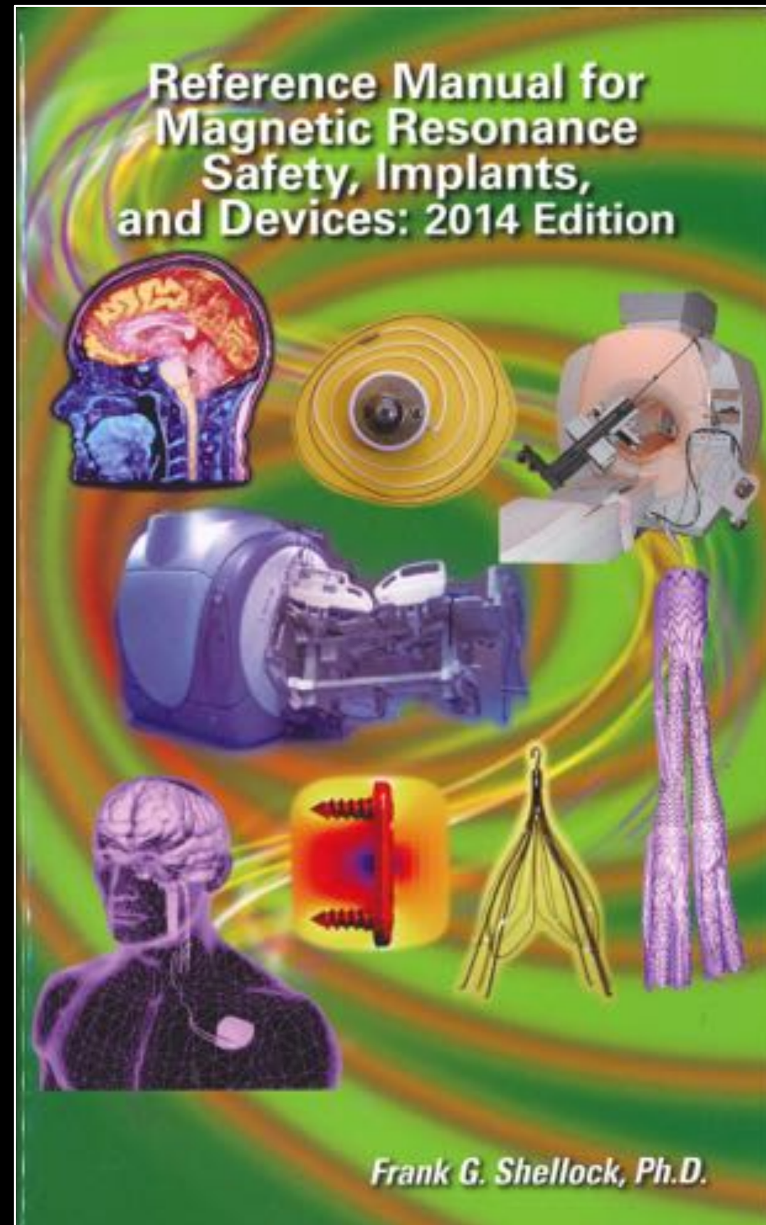
MRI - Contraindication?

Box 2 Example of a check list with potential contraindications to an MRI examination

If any of the following is checked, evaluation of the individual risk has to be performed before the MRI examination

- Aneurysm clip(s)
- Any metallic fragment or foreign body
- Coronary and peripheral artery stents
- Aortic stent graft
- Prosthetic heart valves and annuloplasty rings
- Cardiac occluder devices
- Vena cava filters and embolisation coils
- Haemodynamic monitoring and temporary pacing devices, eg, Swan–Ganz catheter
- Haemodynamic support devices
- Cardiac pacemaker
- Implanted cardioverter-defibrillator (ICD)
- Retained transvenous pacemaker and defibrillator leads
- Electronic implant or device, eg, insulin pump or other infusion pump
- Permanent contraceptive devices, diaphragm, or pessary
- Cochlear, otologic, or other ear implant
- Neurostimulation system
- Shunt (spinal or intraventricular)
- Vascular access port and/or catheter
- Tissue expander (eg, breast)
- Joint replacement (eg, hip, knee, etc)
- Any type of prosthesis (eg, eye, penile, etc)
- Tattoo or permanent makeup
- Known claustrophobia
- Body piercing jewellery
- Hearing aid
- Renal insufficiency
- Known/possible pregnancy or breast feeding

Modified from: Shellock FG, Crues JV. MR procedures: biologic effects, safety, and patient care. *Radiology* 2004;**232**:635–52.



MRI Safety Designations

MR Safe: "An item that poses no known hazards in all MR environments." (e.g. a plastic Petri dish)

MR Conditional: "An item that has been demonstrated to pose no known hazards in a specified MR environment with specified conditions of use. Field conditions that define the specified MR environment include field strength, spatial gradient, dB/dt (time rate of change of the magnetic field), radio frequency fields, and specific absorption rate. Additional conditions, including specific configurations of the item, may be required." (e.g. a Patient Monitor)

MR Unsafe: "An item that is known to pose hazards in all MR environments." (e.g. Floor Buffer)

"MRI Compatible" is not an FDA term.

B_0 Safety – Room Safety

$2.9 Million Settlement Closes Colombini MRI Death Case

5 Replies

This week the settlement documents were released — closing the chapter on the lawsuit that arose from the seminal event in MRI safety, the 2001 oxygen tank fatality of then-six-year-old Michael Colombini.

Not MRI Compatible

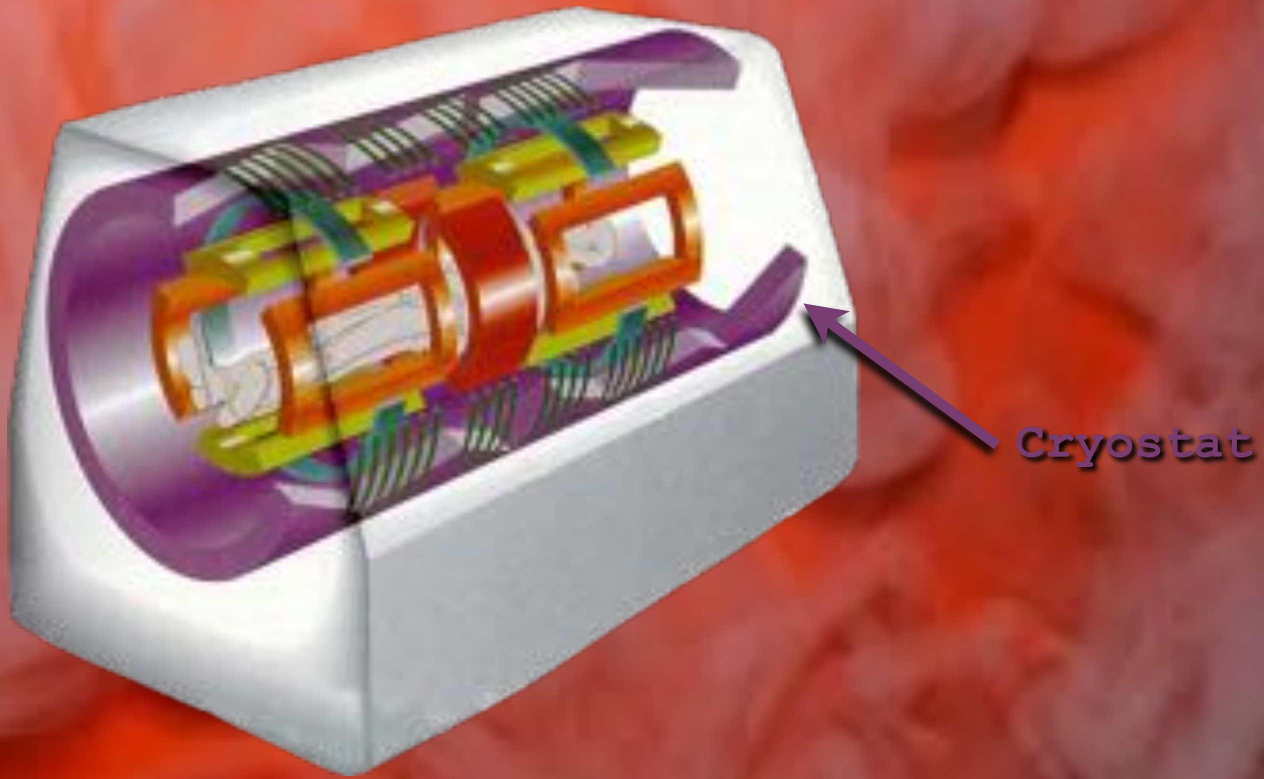
MRI Compatible

B_0 is VERY strong and ALWAYS on.

B_0 Safety – Implanted Devices

B_0 exerts a force or torque on implanted ferromagnetic devices.

B_0 Safety – Cryogen Gases



B_0 is cooled with liquid helium (cryogen).

RF (B_1) Safety - SAR Limits

- **RF pulses deposit energy in the body.**
- **Specific Absorption Rate [W/kg]**
  - Rate of energy absorption during exposure to RF
- High-field (>1.5T) imaging with high flip angles (>45-90°) can be challenging. $\mathrm{SAR} \propto \omega_0^2 B_1^2 \propto B_0^2 \alpha^2$

Limit	Whole-Body Average
Normal (all patients)	**2 W/kg (0.5°C)**
First level (supervised)	**4 W/kg (1°C)**

The scanner (FDA!) limits SAR, which in turn limits the max. flip angle.

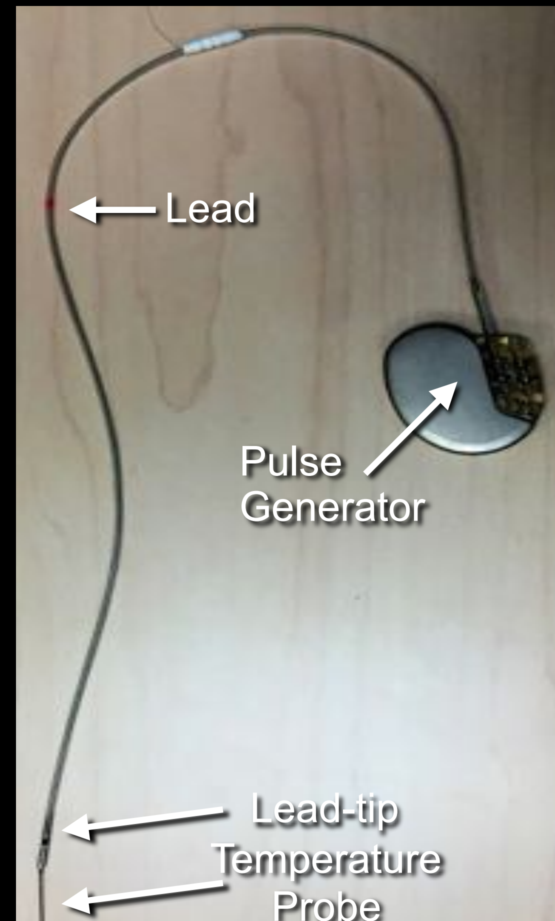
Bottomley PA. Turning up the heat on MRI. J Am Coll Radiol 2008;5(7):853-855.

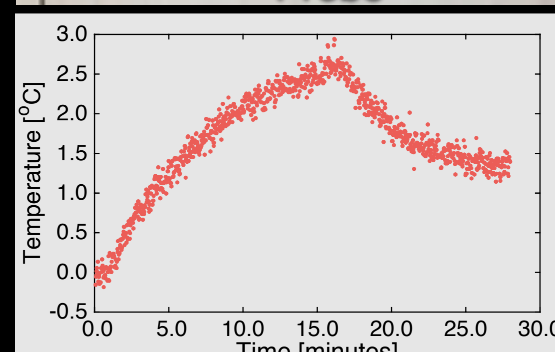
RF (B_1) Safety - Burns & Heating

- **Tissue burns**
- **RF induced heating of implanted devices**

Eising EG et al. J. Clin. Imaging 2010;34(4):293-297.

Solution: Avoid skin-to-skin loops; avoid arms directly touching scanner bore.

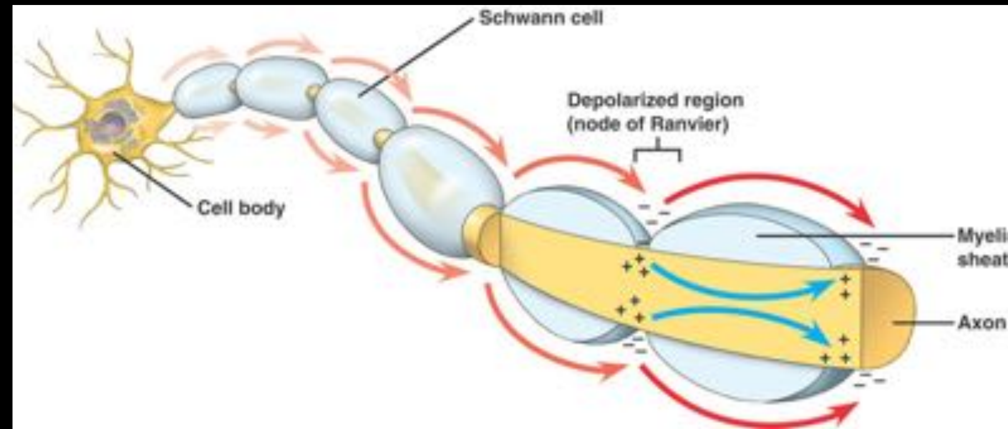


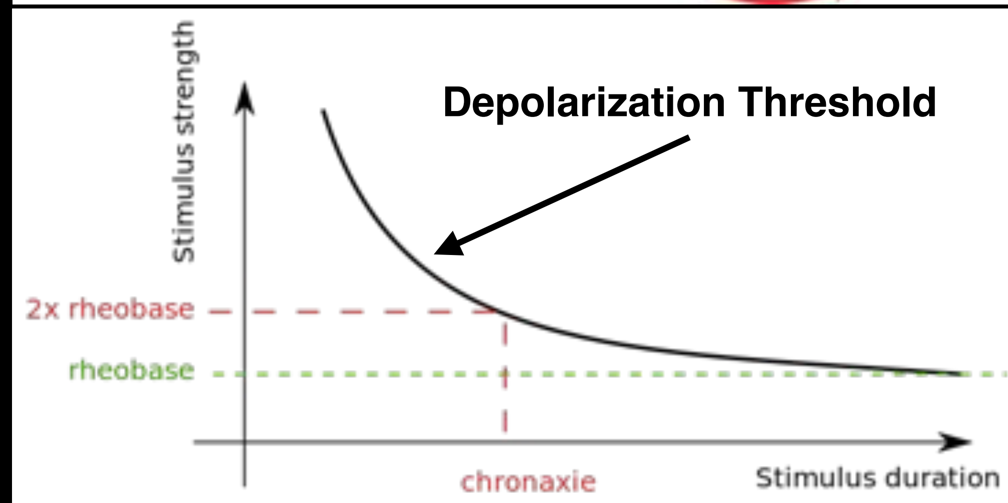


RF energy contributes to patient and device heating (or burns!).

Gradient Safety

- **Noise**
- **Peripheral nerve stimulation (PNS)**





Solution: Ear plugs Head phones

Solution: De-rate gradient slew rates, but this increases scan time.

Time-varying gradients induce mechanical vibrations and PNS.

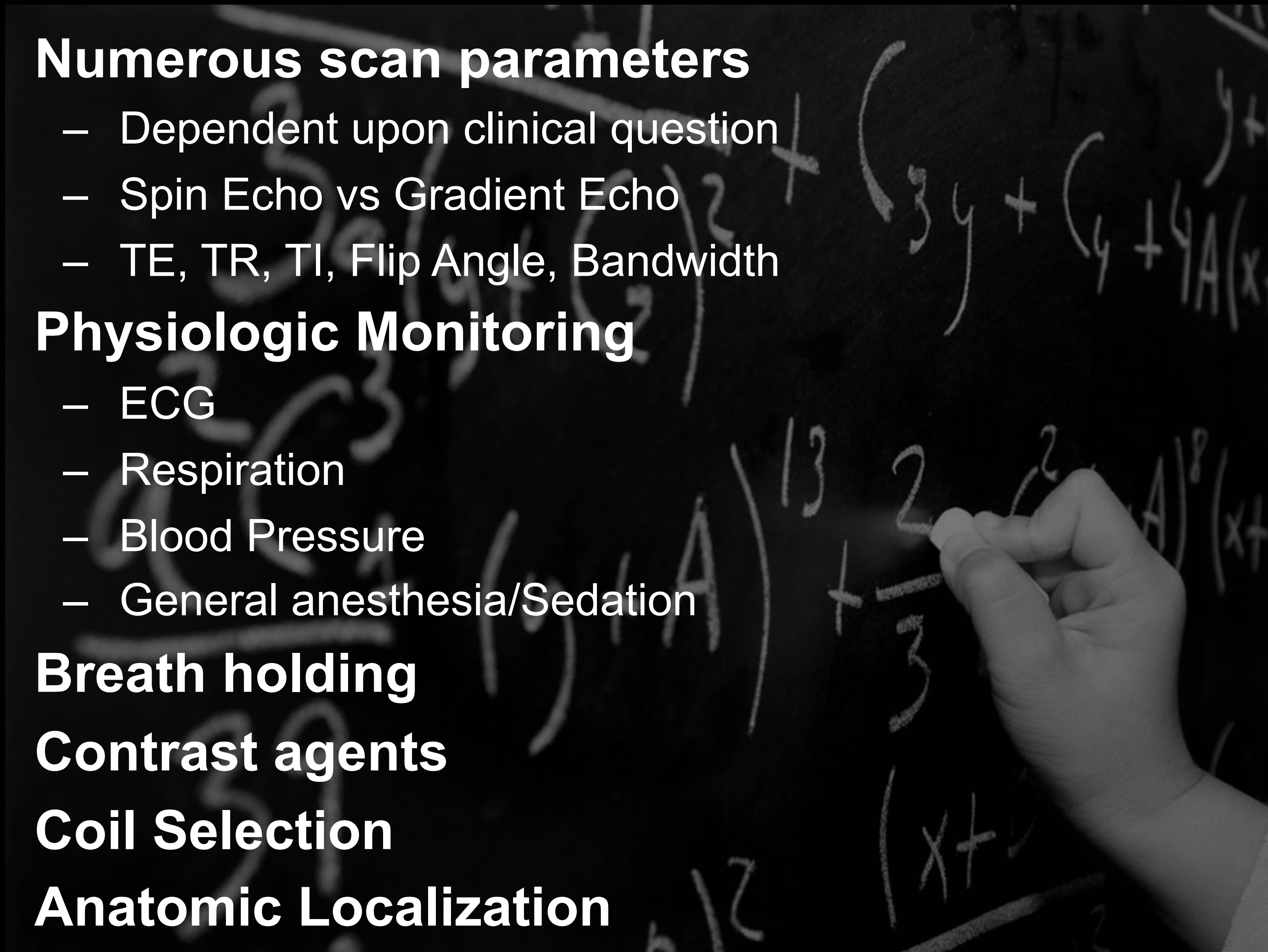
Exogenous Contrast Agents Safety

- **Contrast agents are used to:**
  - **Increase MRI signal intensity in:**
    - Blood, perfused tissues, tumors
  - **Decrease MRI signals intensity in:**
    - Lymph nodes
- **Contrast agents can cause:**
  - **Hypotension**
  - **Allergic reactions**
  - **Gd-based agents (previously…) associated with nephrogenic systemic fibrosis.**

MRI is Expensive

- **Purchase**
  - **$1-3 million**
- **Site**
  - **$0.5-1.0 million**
- **Maintain (Service Contract)**
  - **$100,000 per year**
- **Operate**
  - **$500-1000/hour**

Technically Challenging



- **Numerous scan parameters**
  - Dependent upon clinical question
  - Spin Echo vs Gradient Echo
  - TE, TR, TI, Flip Angle, Bandwidth
- **Physiologic Monitoring**
  - ECG
  - Respiration
  - Blood Pressure
  - General anesthesia/Sedation
- **Breath holding**
- **Contrast agents**
- **Coil Selection**
- **Anatomic Localization**

Quiz: MRI Safety - True or False?

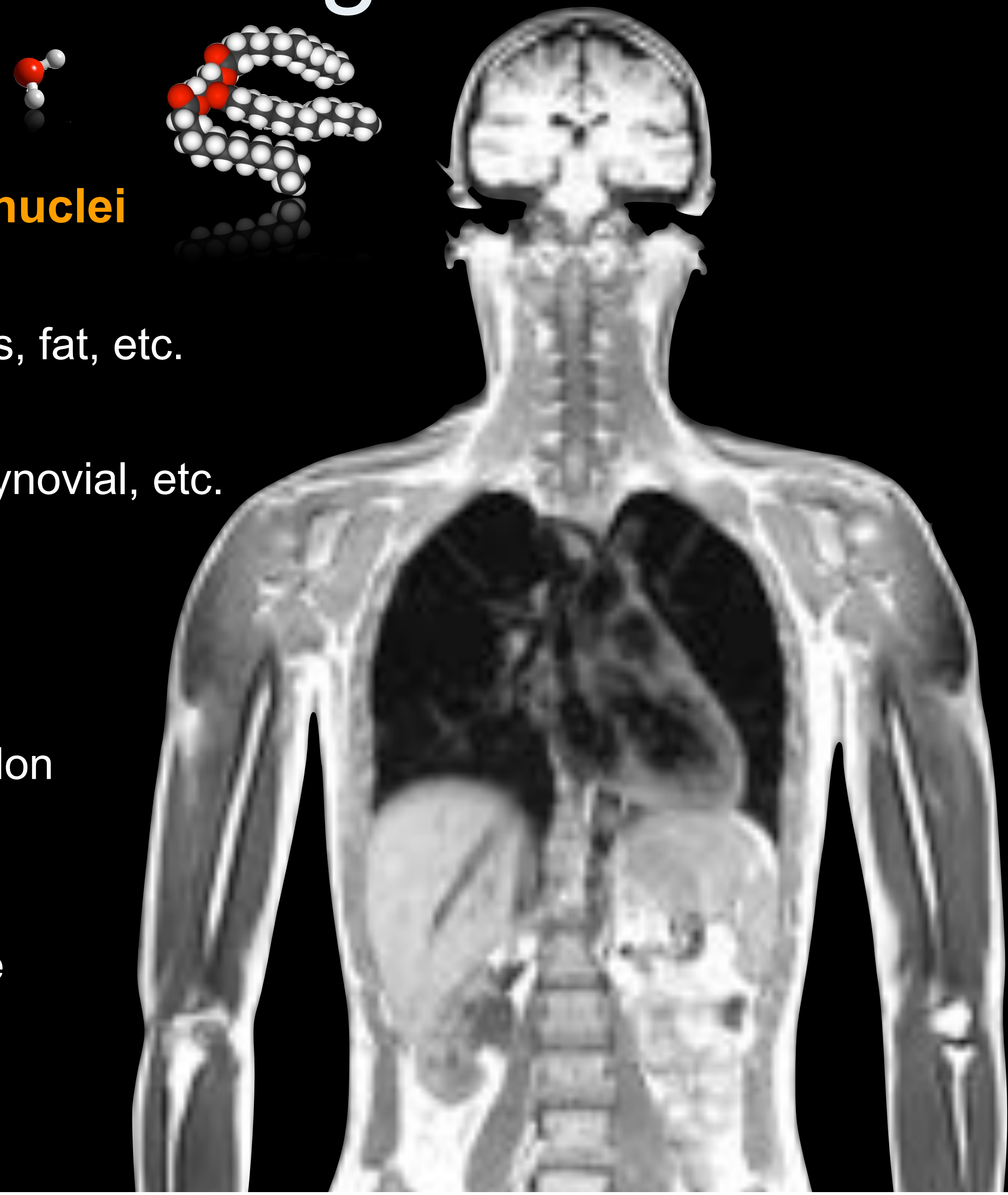
1. Faraday's Law of Induction explains how spins produce a current in a coil.
2. Gradients heat the patient and RF pulses causes peripheral nerve stimulation (PNS).
3. Gradients can dislodge and heat implanted devices.
4. SAR limits constrain scan parameters.
5. Increasing the flip angle or decreasing the TR helps reduce patient heating.
6. Cryogen gases are oxygen rich and MRI contrast agents are 100% safe.

Learning Objectives

- Explain the importance of Faraday to MRI.
- Name the requirements for MRI and the function of each component.
- Appreciate the MRI screening process required for all patients.
- Describe the FDA labeling for MRI "compatibility."
- List five (or more!) advantages of disadvantage of MRI.

Nuclear Magnetic Resonance

MRI Signal

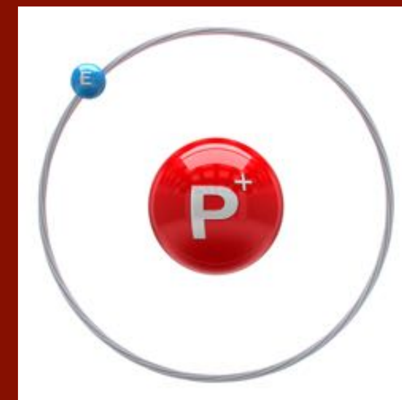


- Signal from:
  - **Water and fat**
    - **NMR active nuclei**
  - Soft tissues
    - Muscle, organs, fat, etc.
  - Fluids
    - CSF, Blood, Synovial, etc.
- Signal *not* from:
  - Hard Tissues
    - Cortical Bone
    - Ligament/Tendon
    - Teeth
  - Gases
    - Lung air space
    - Sinuses
    - Bowel

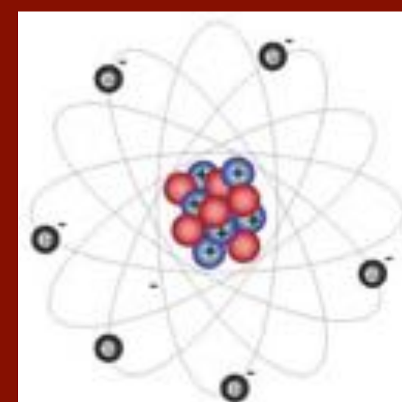
NMR Active Nuclei

- Spin + Charge + Mass $\Longrightarrow$ NMR Active
  - Spin? ***Intrinsic*** form of angular momentum.
- Nuclei have spin angular momentum if:
  - Odd atomic mass (# protons+neutrons)

    And/Or
  - Odd atomic number (# of protons)
- Spin angular momentum
  - Leads to precession
  - Spin ≠ precession (a top spins *and* precesses)
- Frequency of precession (Larmor Frequency)
  - Gyromagnetic Ratio (γ, gamma)
    - Physical constant
    - Unique for each NMR active nuclei



Hydrogen



Carbon-13

What is so special about ^{1}H? Spin, charge, and mass!

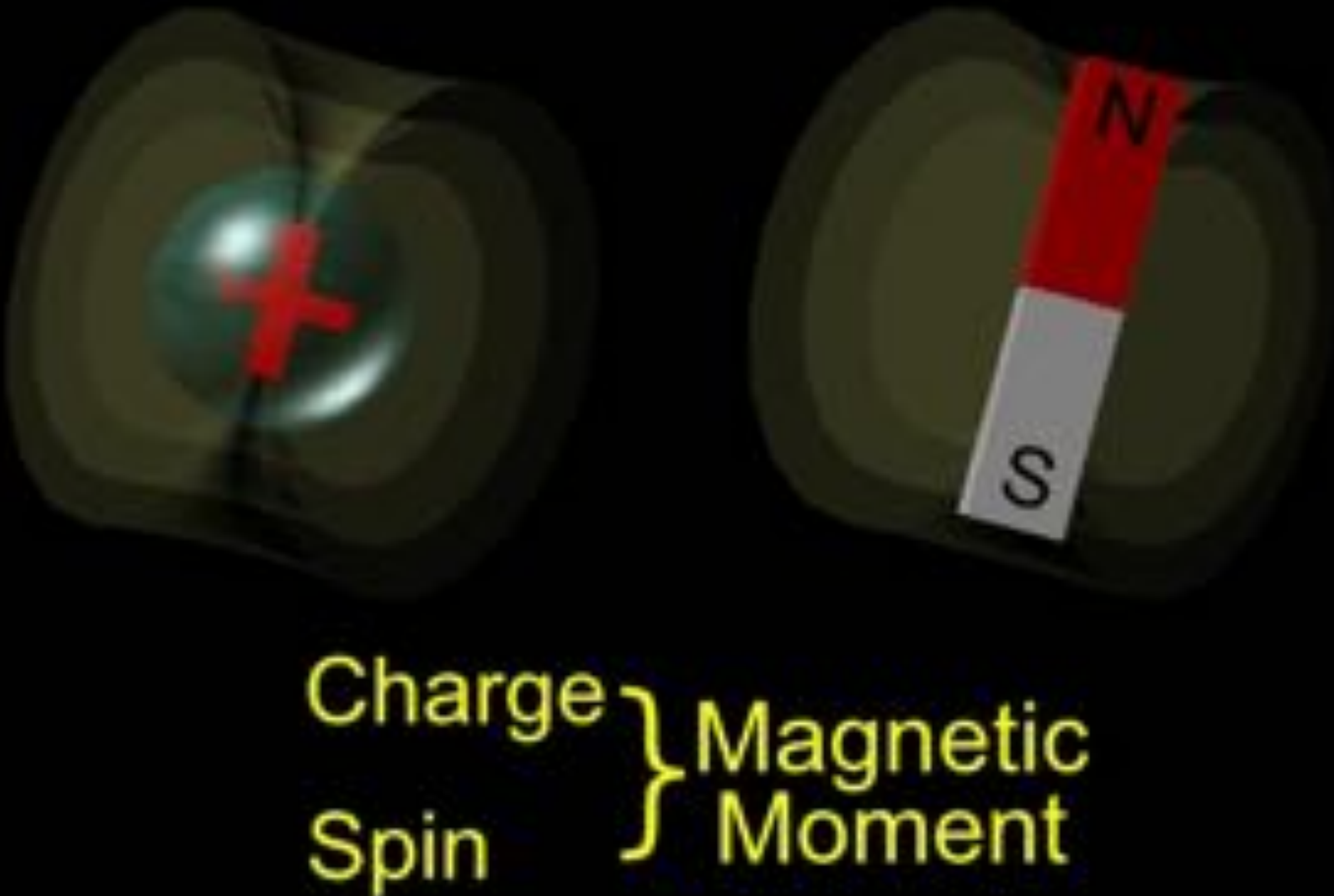
NMR Active Nuclei

Isotope	*Spin [I]*	Gyromagnetic Ratio [MHz/T]	Relative Sensitivity	Natural Abundance	Absolute Sensitivity
^{1}H	**1/2**	**42.57**	**1**	**0.9980**	**9.98E-01**
^{2}H	1	6.54	9.65E-06	0.0002	1.93E-09
^{12}C	0	---	---	0.9890	---
^{13}C	**1/2**	**10.71**	**0.016**	**0.0110**	**1.76E-04**
^{14}N	1	3.08	0.001	0.9960	9.96E-04
^{15}N	**1/2**	**-4.32**	**0.001**	**0.0040**	**4.00E-06**
^{16}O	0	---	---	0.9890	---
^{17}O	5/2	-5.77	0.029	0.0004	1.16E-05
^{19}F	**1/2**	**40.05**	**0.83**	**1.0000**	**8.30E-01**
^{23}Na	**3/2**	**11.26**	**0.093**	**1.0000**	**9.30E-02**
^{31}P	**1/2**	**17.24**	**0.066**	**1.0000**	**6.60E-02**

The ***relative sensitivity*** is at constant magnetic field and equal number of nuclei.
The ***absolute sensitivity*** is the relative sensitivity multiplied by natural abundance.

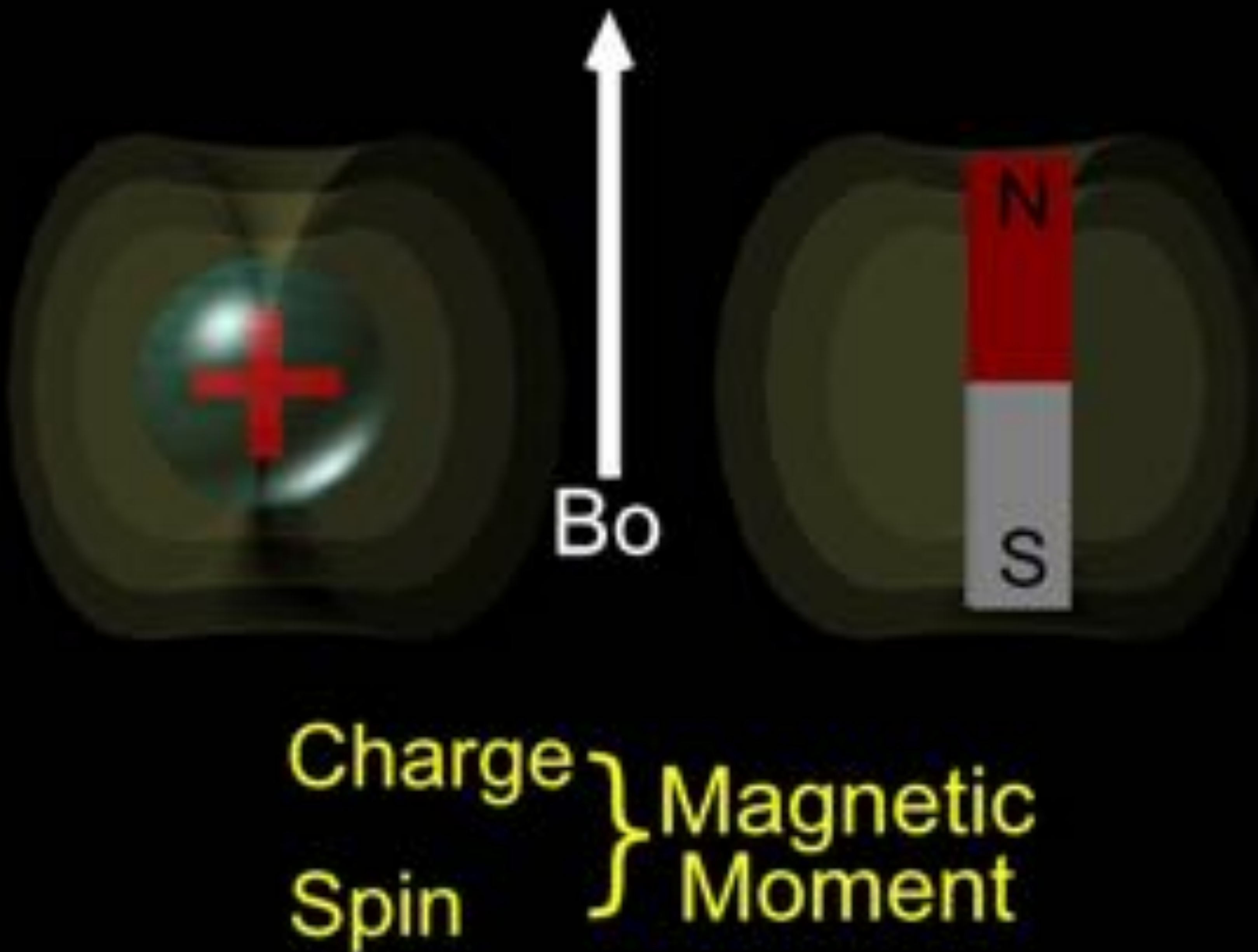
NMR Phenomena

Magnetic Moment



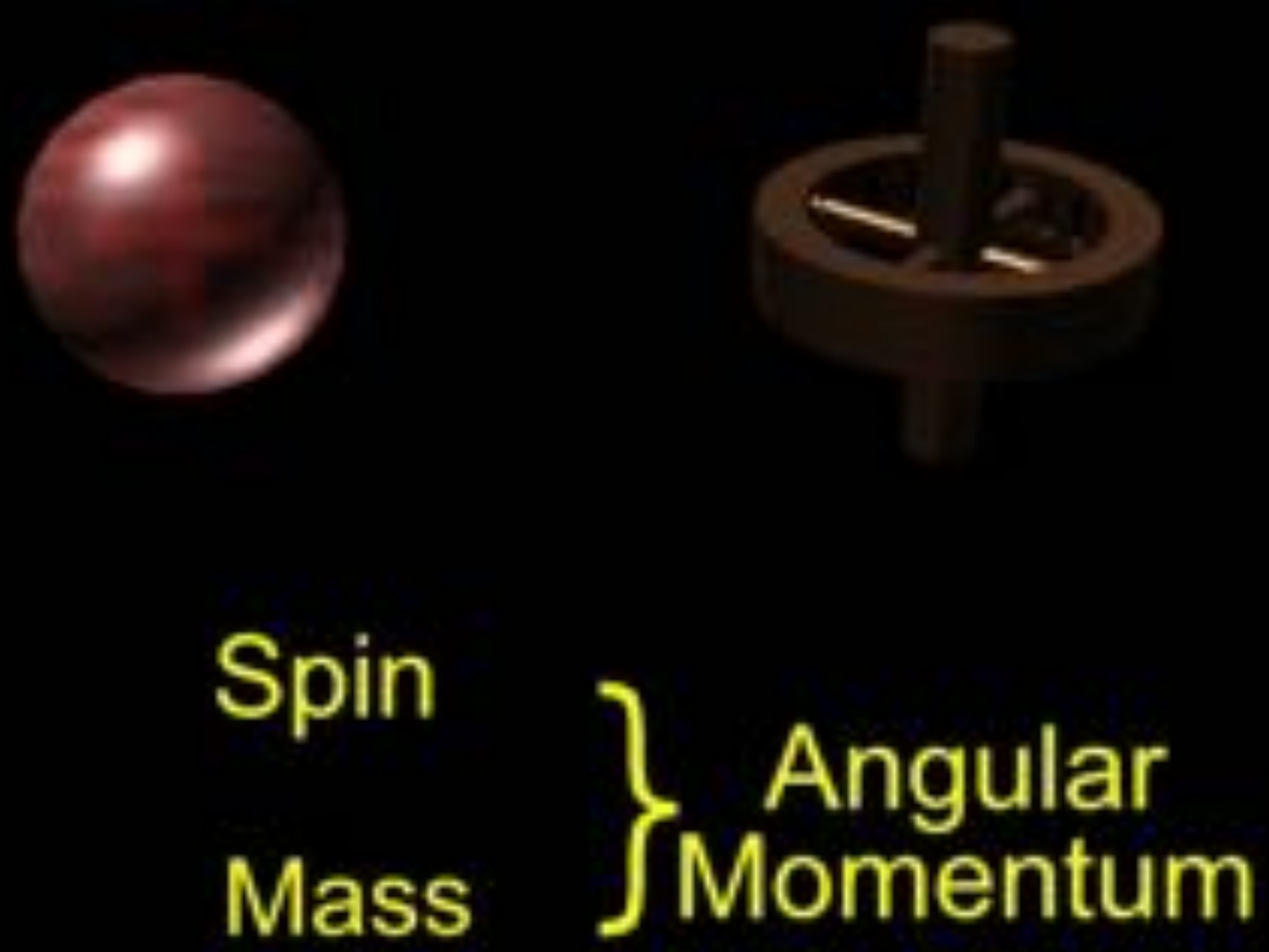
Protons behave like small magnets because of spin and charge.

Magnetic Moment



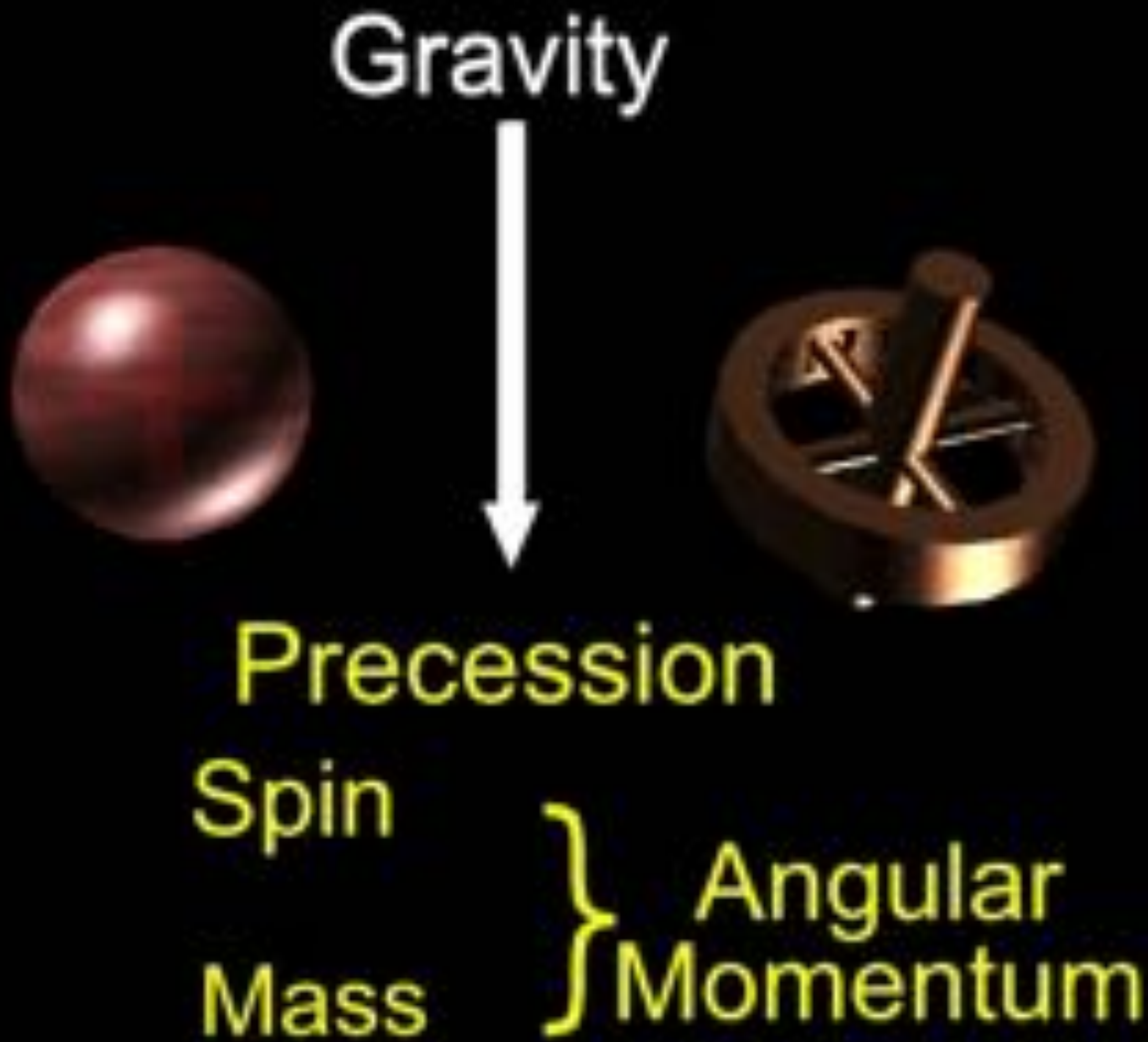
Protons (small magnets) align with an external magnetic field (B_0).

Angular Momentum



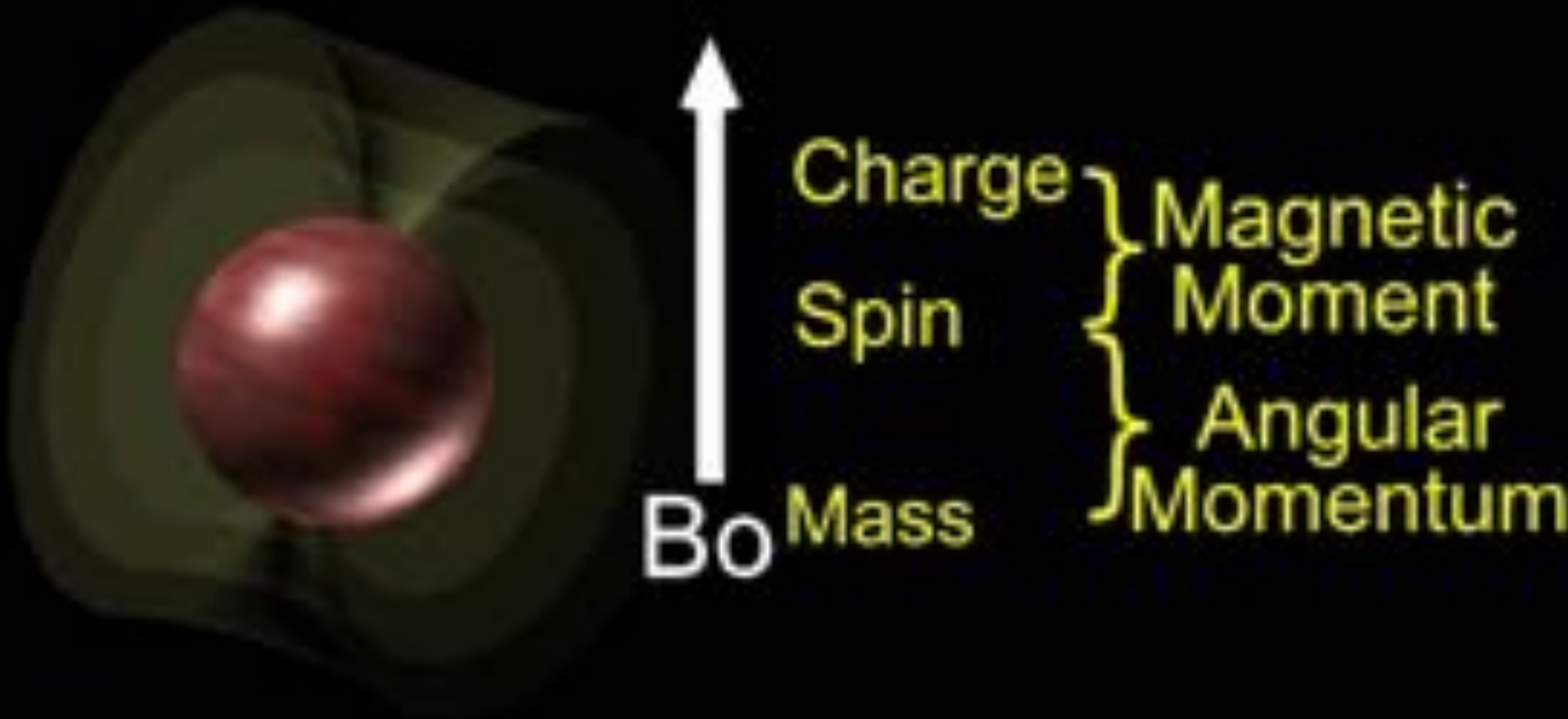
Protons have angular momentum because of spin and mass.

Precession (Top Analogy)



A spinning tops precesses in a gravitational field.
A spinning proton precesses in a magnetic (B_0) field.

Larmor Frequency



Larmor Frequency $= \omega = \gamma B_o$

The frequency of precession is the Larmor frequency.

Larmor Equation

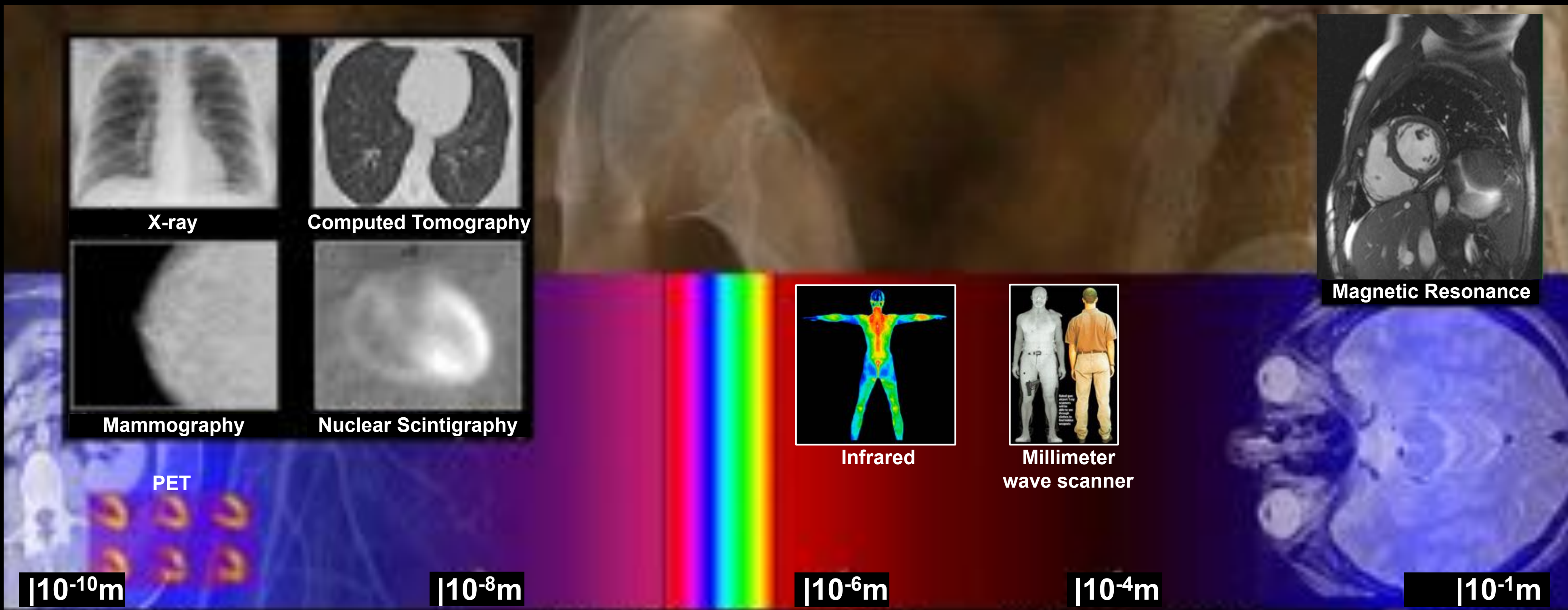
- **Spin≠Precession**
  - **Protons *intrinsically* have spin**
  - **Protons *precess* in the presence of a B-field**
- **Larmor frequency increases with:**
  - **Larger B_0**
  - **Higher gyromagnetic ratio**
  - **Higher frequencies produce stronger signals...**

$$\omega = \gamma B_0$$

Electromagnetic Spectrum

← **Increasing Frequency (f)**

Exahertz — Megahertz



Increasing Wavelength (λ) →

$$c = f\lambda$$

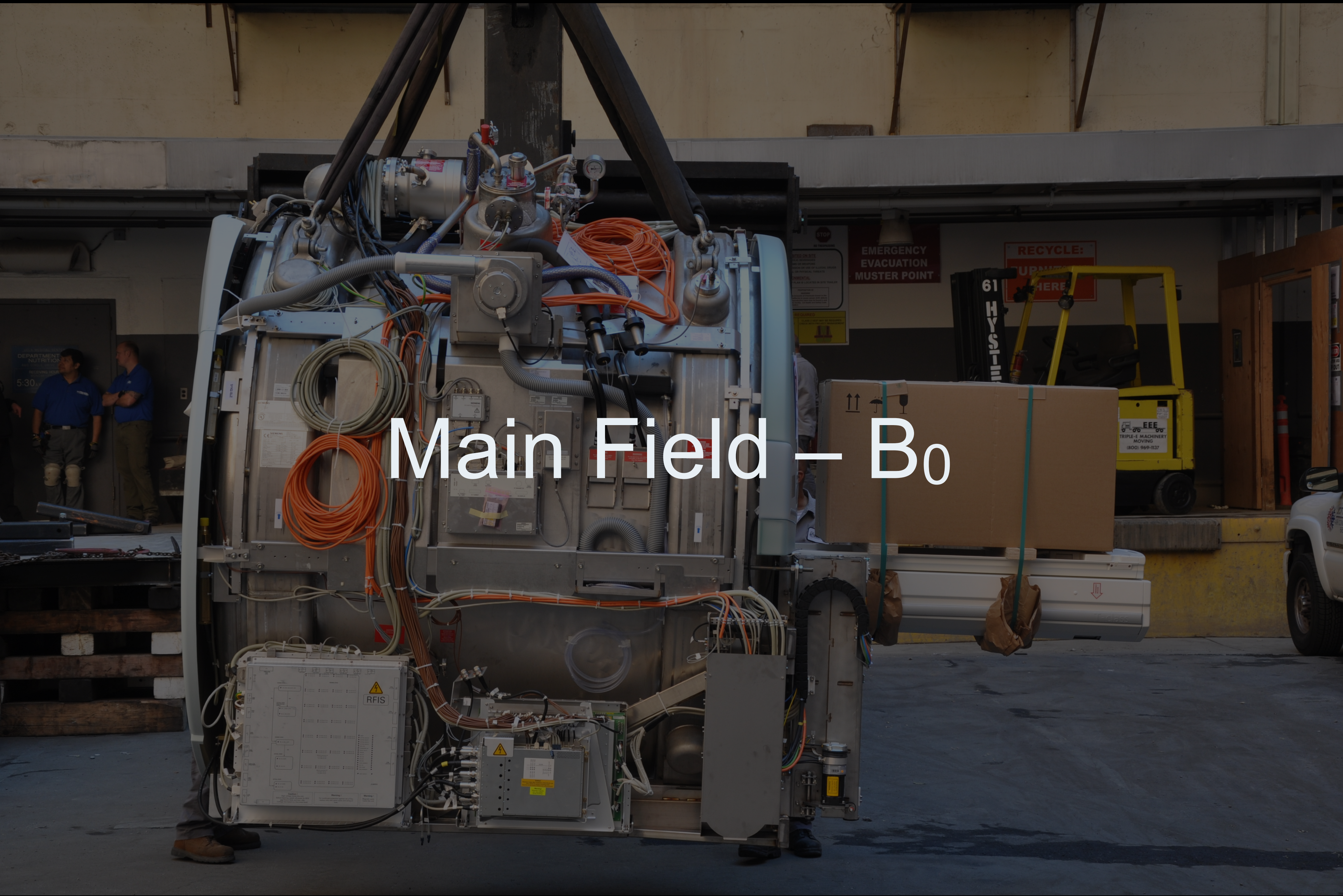
Speed of Light — Frequency — Wavelength

MRI uses “low" frequencies (“long” wavelengths) for imaging compared to PET and CT.

Quiz: NMR - True or False?

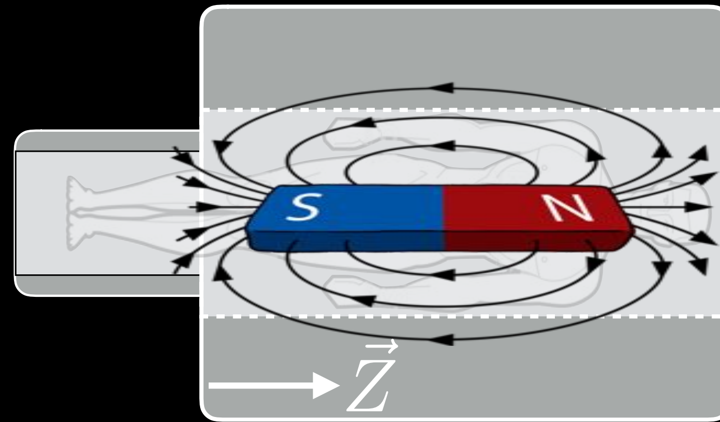
1. Electron spin is the key to NMR.
2. MRI is *nothing* without speed, charge, and mass.
3. All atomic nuclei are NMR active.
4. Spin and precession are the same.
5. Higher fields lead to faster precession.
6. ALL of the spins align with the B_0 field.

Main Field – B_0

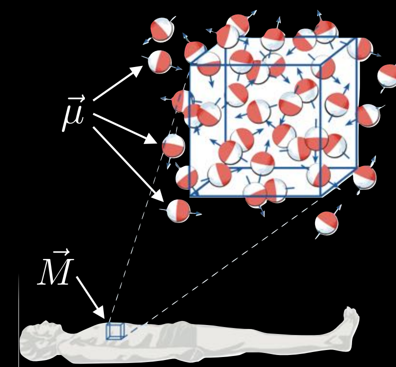


Main Field (B_0) - Principles

- B_0 is a strong magnetic field
  - >1.5T
  - Z-oriented



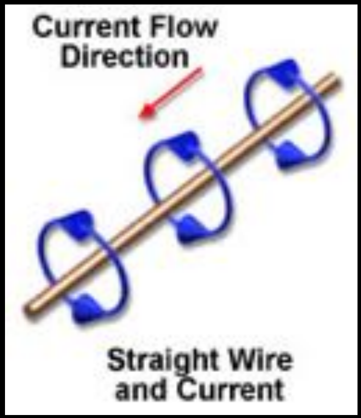
- B_0 generates $\vec{M}$ (bulk magnetization)
  - More B_0, more $\vec{M}$



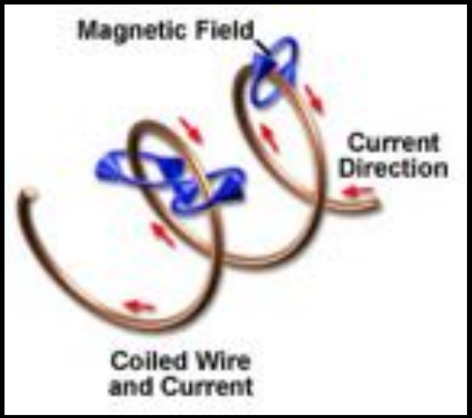
- B_0 forces $\vec{M}$ to precess
  - Larmor Equation

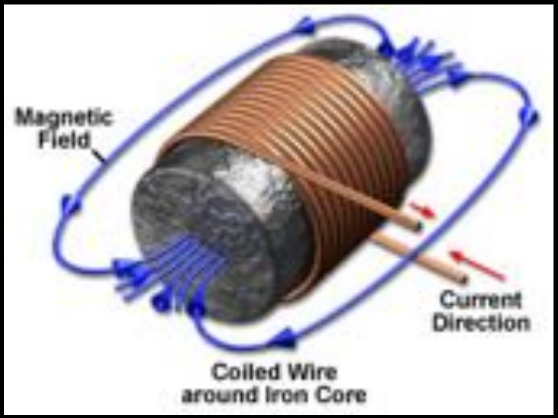
$$\omega = \gamma B$$

Currents & Magnetic Fields



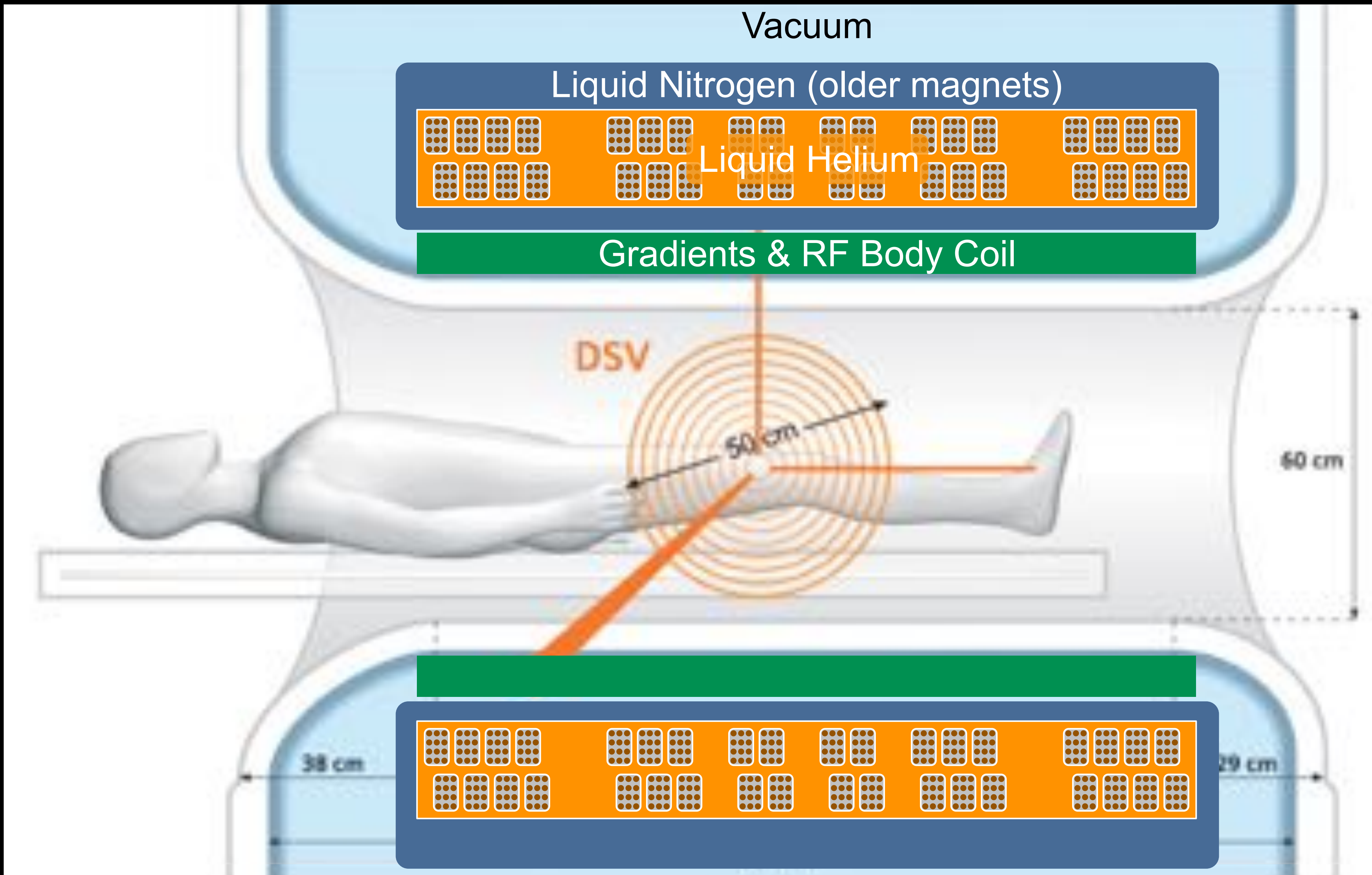
Left-hand Rule





Electromagnet – A current in a wire generates a magnetic field.

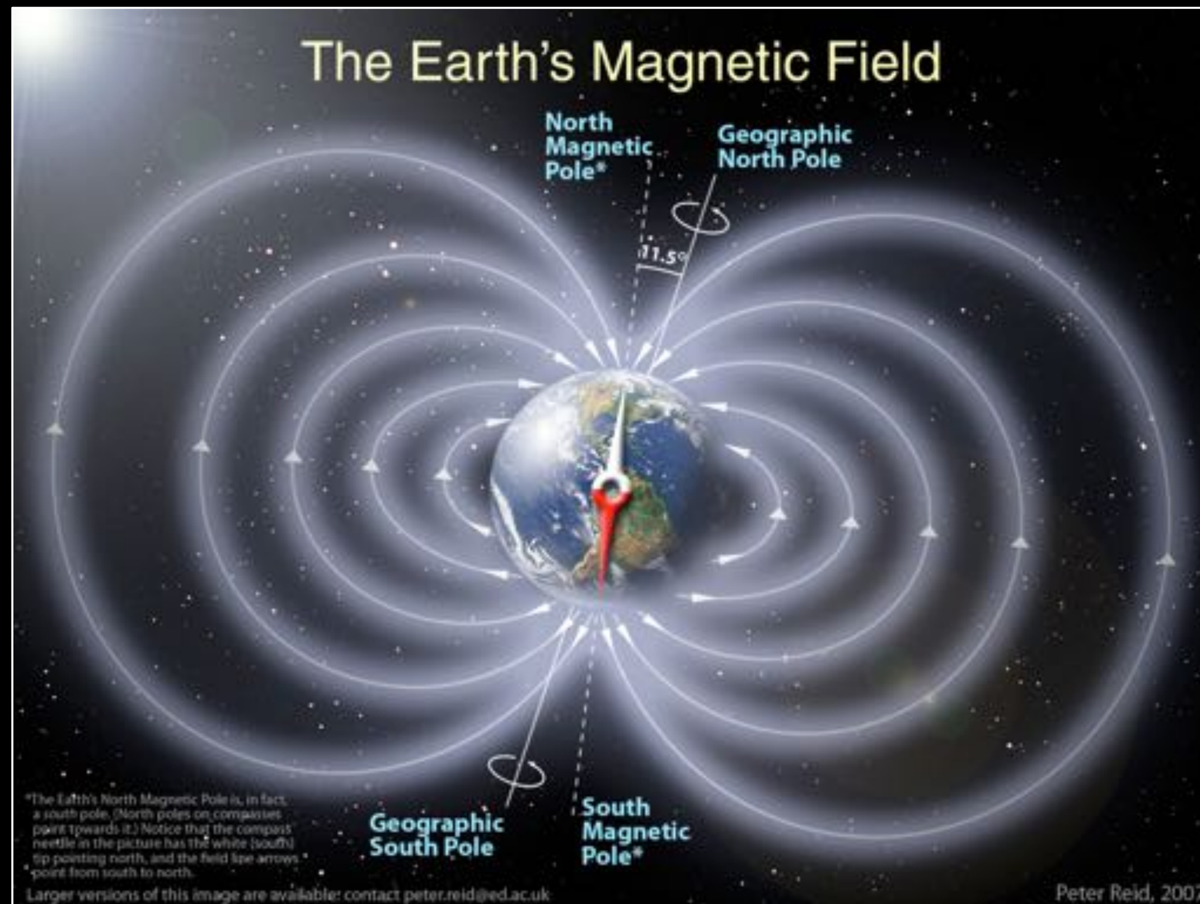
Superconducting Magnet



MRI scanners are superconducting electromagnets.

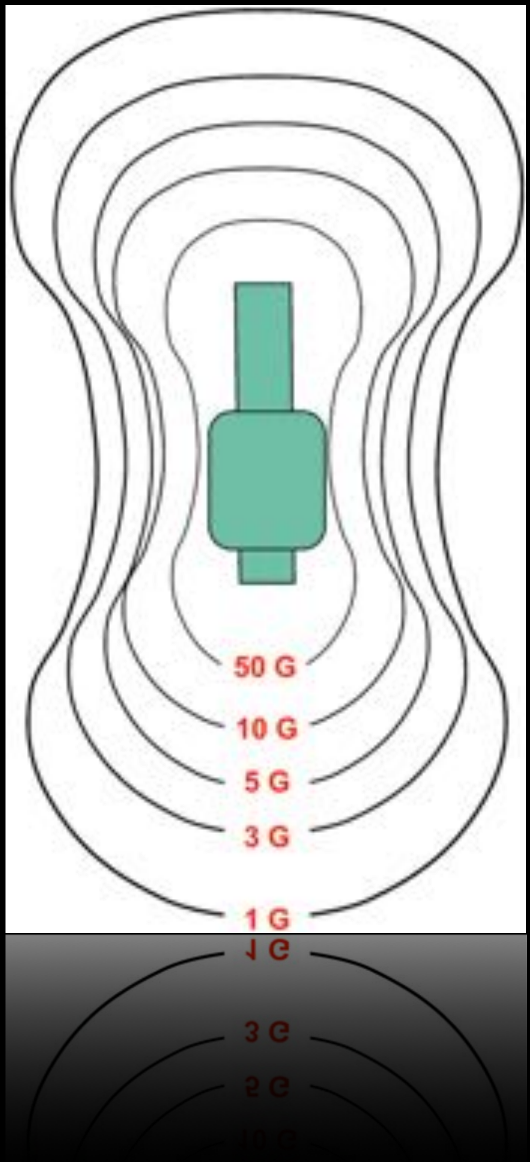
Main Field (B_0) – Strength

- Earth's magnetic field
  - 0.5 Gauss
- Refrigerator magnet
  - 10-100 Gauss
- B_0 Field
  - 0.5T = 5000 Gauss
  - 1.5T = 15000 Gauss
  - 3.0T = 30000 Gauss



Main Field (B_0) – Shielding

- **Shielding** reduces foot print
  - Reduces install cost
  - Reduces interference
- **Passive Shielding**
  - Iron room shielding
  - Heavy, not cheap
- **Active Shielding**
  - Super-conducting coils that oppose (shield) B_0 fringe field
- "**Five Gauss Line**"
  - Threshold beyond which ferromagnetic objects are strictly prohibited
  - 5G=0.5mT



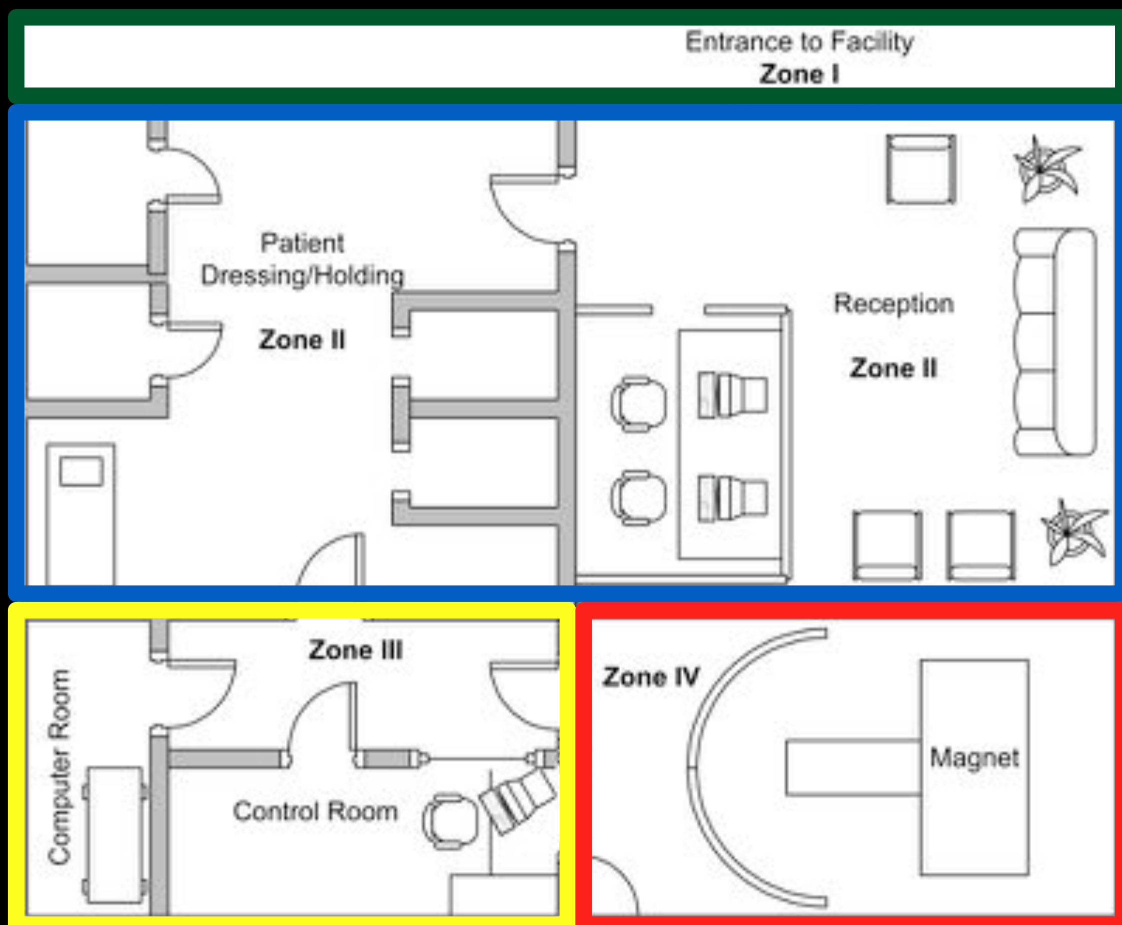
MRI Zones

MRI

MRI ZONE I	MRI Access Area

NOTICE

MRI ZONE II	MRI Patient Screening and Preparation



NOTICE

MRI ZONE II	MRI Patient Screening and Preparation

CAUTION

MRI ZONE III	**Restricted Access** Screened MRI Patients and MRI Personnel Only

DANGER

MRI ZONE IV	**Restricted Access** Screened MRI Patients Under Direct Supervision of Trained MRI Personnel Only

ACR Guidance Document on MR Safe Practices: 2013; *JMRI* 37:501–530 (2013)

B_0 Strength - Advantages

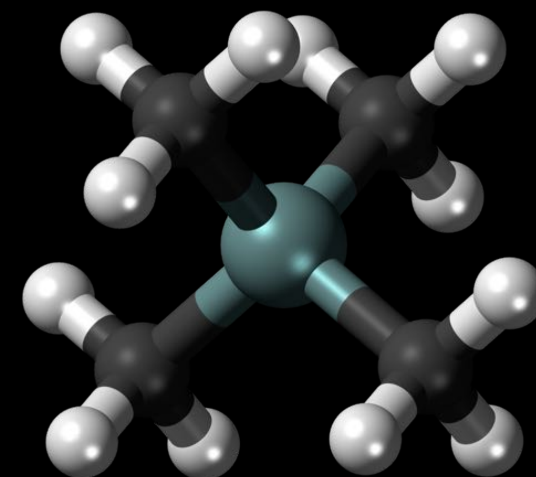
- ⬆ $B_0 \Longrightarrow$ ⬆ Polarization ($|\vec{M}|$) = ⬆ SNR
  - $SNR \propto B_0^{7/4}$ (⬆Polarization + ⬆Larmor Frequency)
    - ⬆ Spatial resolution
    - ⬆ Temporal resolution
    - ⬇Scan time

B_0 Strength - Disadvantages

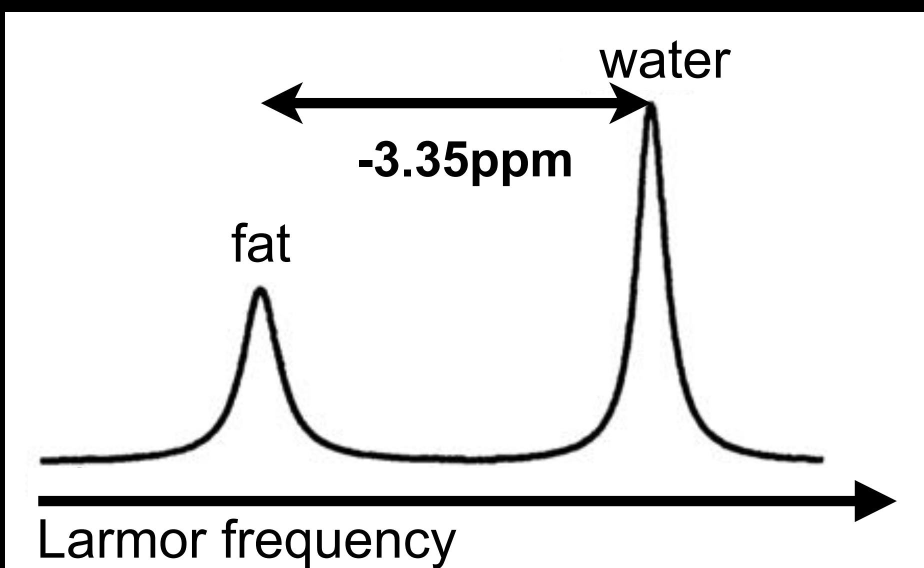
- ⬆ $B_0 \Longrightarrow$ ⬆ Specific Absorption Ratio (SAR)
  - Energy absorbed by body [W/kg]
  - $SAR \propto B_0^2$
- ⬆ $B_0 \Longrightarrow$ ⬆ Chemical shift (Δf)
  - ⬆ Δf between fat and water
    - Fat and water have different Larmor frequencies
      - ~220Hz different at 1.5T
      - ~440Hz different at 3.0T
    - Fat is *more* spatially mis-registered @ 3T
  - Good for spectroscopy…
- ⬆ $B_0 \Longrightarrow$ ⬆ Cost
  - ~$1,000,000 per Tesla
  - More shielding

Chemical Shift

- [1]H precesses at different frequencies
  - H_20 *vs.* $-CH_2$ (fat) *vs.* tetramethylsilane
- Orbiting electrons shield the nucleus
- Referenced against tetramethylsilane
  - Assigned a chemical shift of zero



tetramethylsilane



$$B = B_0 (1 - \delta)$$

$$\delta_{-\mathrm{CH_2}} = 3.35ppm$$

$3.35 \times 10^{-6} \cdot 64\text{MHz} = 214\text{Hz}$

Quiz: Main Field - True or False?

1. B_0 is rare earth permanent magnet.
2. 1 Tesla=1000 Gauss.
3. Higher fields increase polarization, which contributes to better image quality.
4. Exams at higher fields have lower SAR.
5. ^1H always precess at the same Larmor frequency.

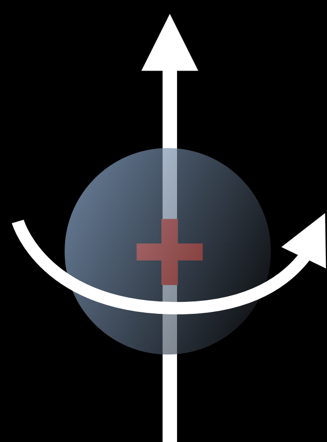
Bulk Magnetization ($\vec{\mathrm{M}}$)

Magnetic Dipole Moments

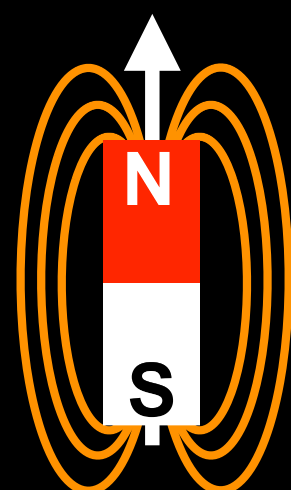
Spin + Charge ➠ Magnetic Moment ➠ $\vec{\mu}$ [J•T^{-1} *or* kg•m^2/s^2]

"a measure of the strength of the system's net magnetic source"
--http://en.wikipedia.org/wiki/Magnetic_moment

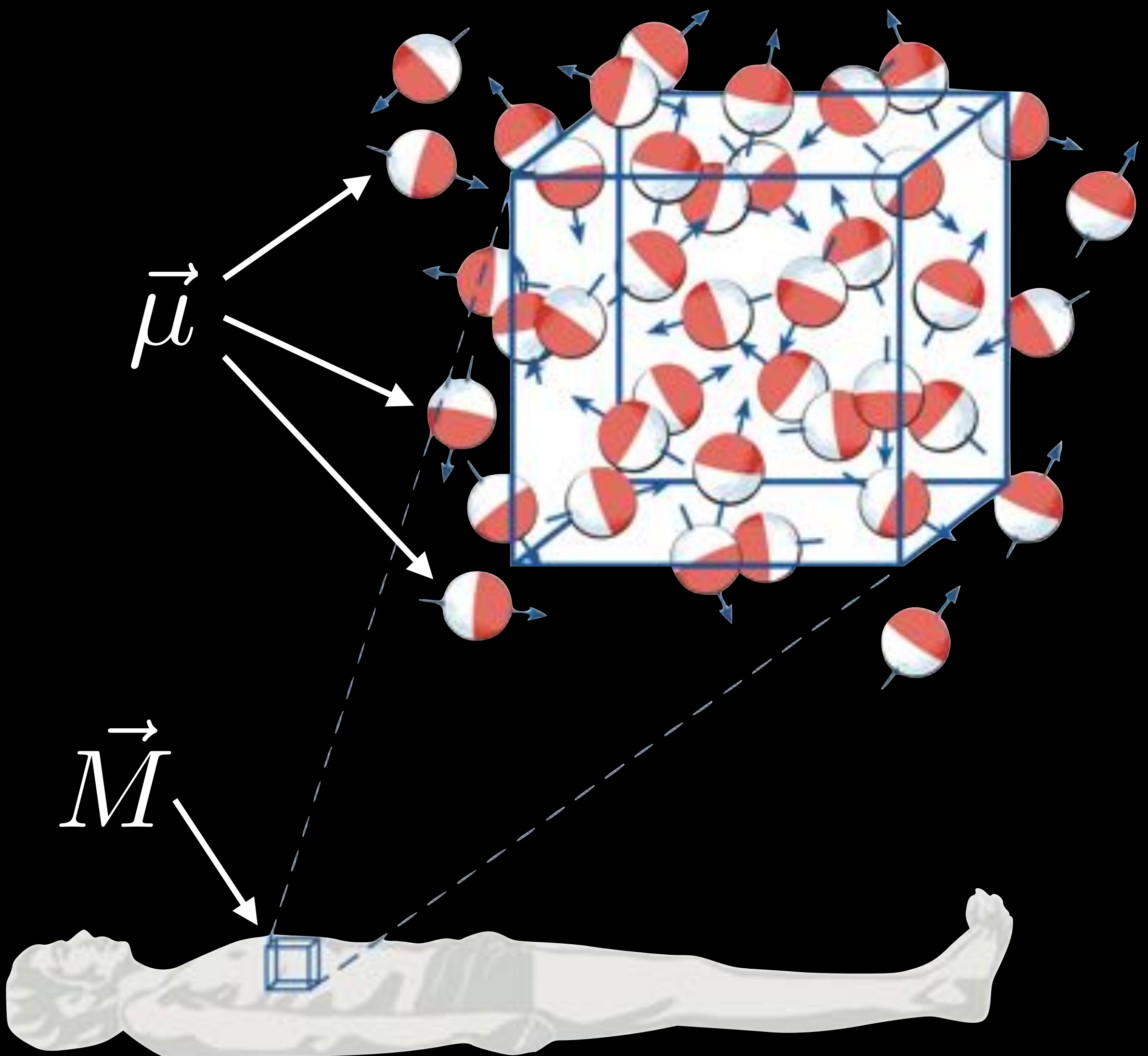
$\vec{\mu}$



$\vec{\mu}$



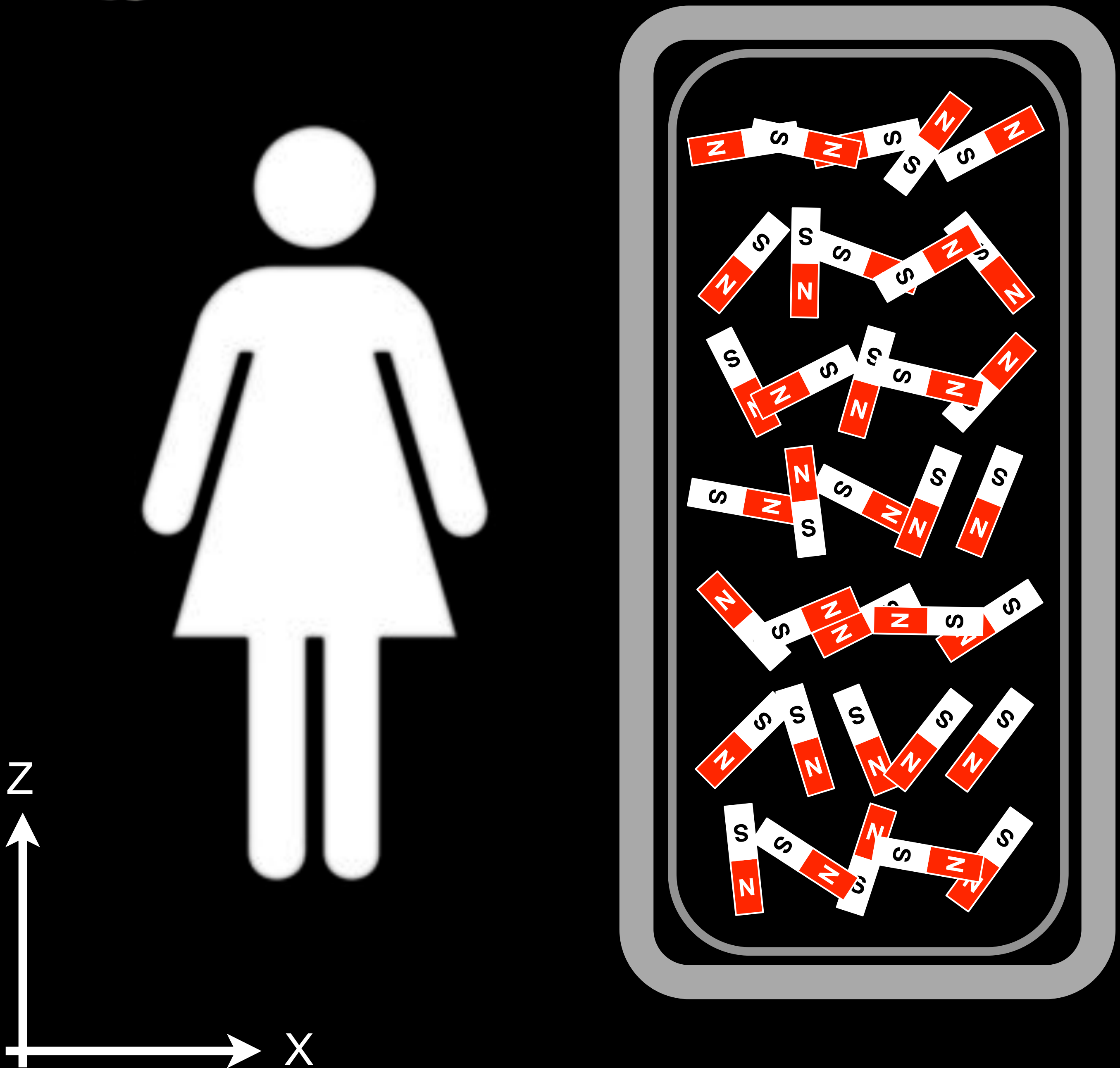
Bulk Magnetization



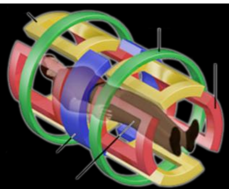
$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$

N_{total}=0.24x10^{23} (Avogadro!) spins in a 2x2x10mm voxel

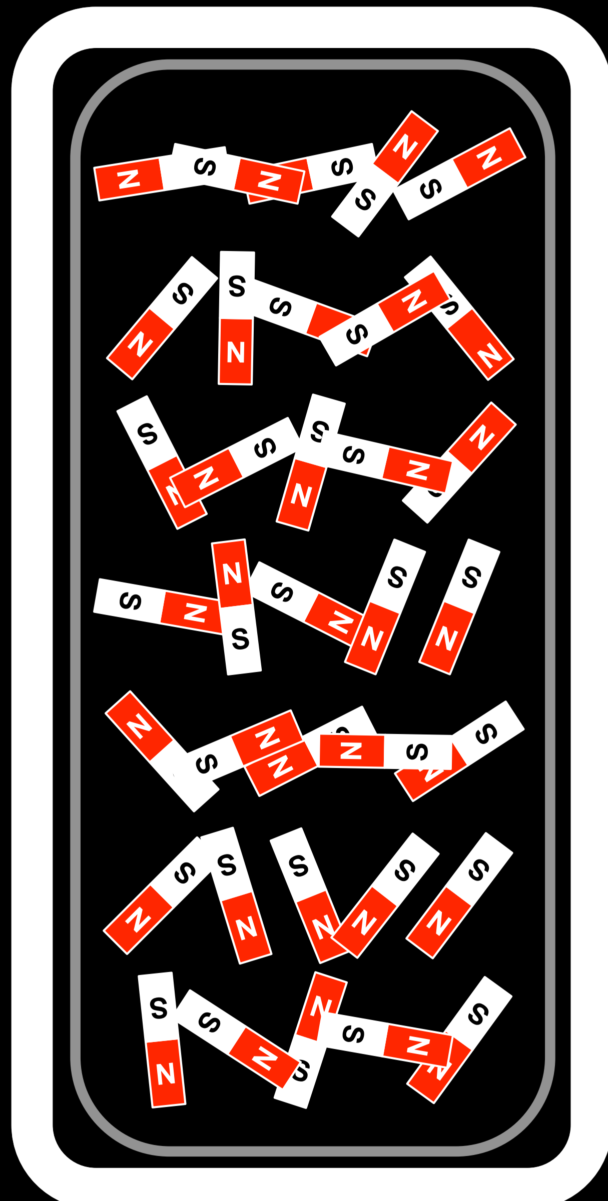
B_0 Field OFF

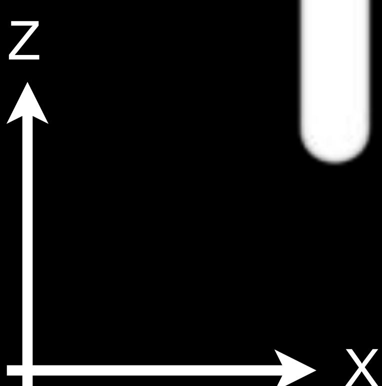


Spins point in all directions.



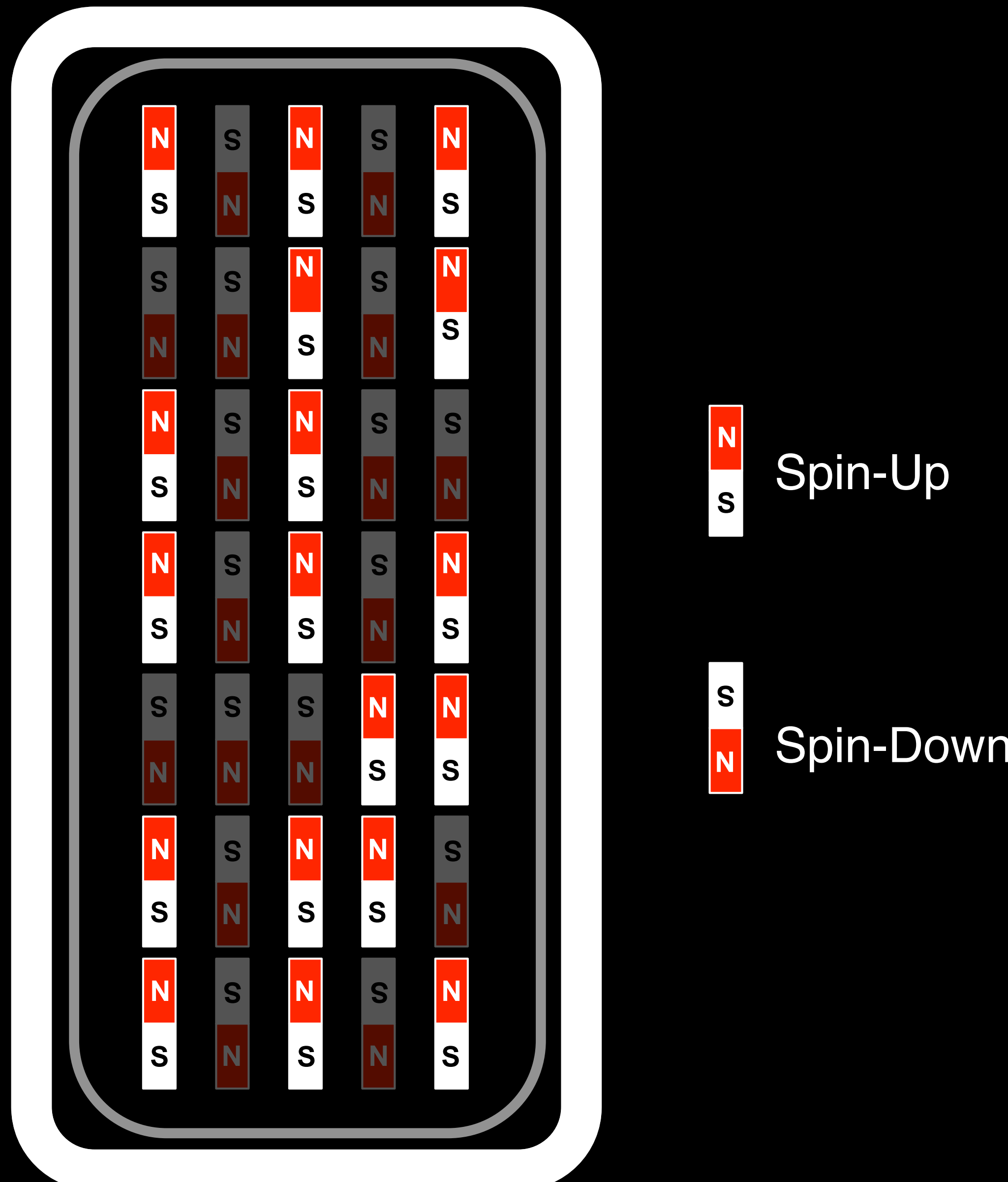
B_0 Field ON





B_0 polarizes the spins and generates bulk magnetization.

B_0 Field ON



Only a very small number are spin-up relative to spin-down.

Zeeman Splitting

$$\frac{N_\uparrow - N_\downarrow}{N_{total}} \approx \frac{\gamma h B_0}{2KT}$$

$$\begin{array}{lcl}
\gamma & = & 42.58 \times 10^6 \text{ Hz/T} \\
h & = & 6.6 \times 10^{-}34 \text{ J} \cdot \text{s [Planck' Constant]} \\
T & = & 300\text{K (room temperature)} \\
K & = & 1.38 \times 10^{-23} \text{ J/K [Boltzmann Constant]} \\
B_0 & = & 1.5\text{T}
\end{array}$$

$$\frac{N_\uparrow - N_\downarrow}{N_{total}} \approx \frac{42.58 \times 10^6 \cdot 6.6 \times 10^{-34} \cdot 1.5}{2 \cdot 1.38 \times 10^{-23} \cdot 300} \approx 4.5 \times 10^{-6}$$

Only a few PPM difference (up vs. down). MRI has relatively low sensitivity.

Learning Objectives

- List tissues that do and do not produce MRI signals.
- Name three NMR active nuclei and the gyromagnetic ratio for the most important one.
- Write out the Larmor Equation and define each term.
- Understand the importance of the "Five Gauss Line."
- Appreciate advantages/disadvantages of higher B_0.
- Explain why MRI has low sensitivity.
- Describe the importance of the superconducting electromagnet in MRI.

Off-Resonance

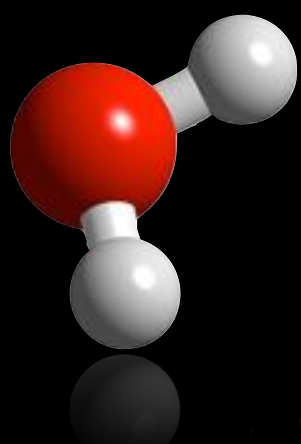
B_0 Field Inhomogeneity

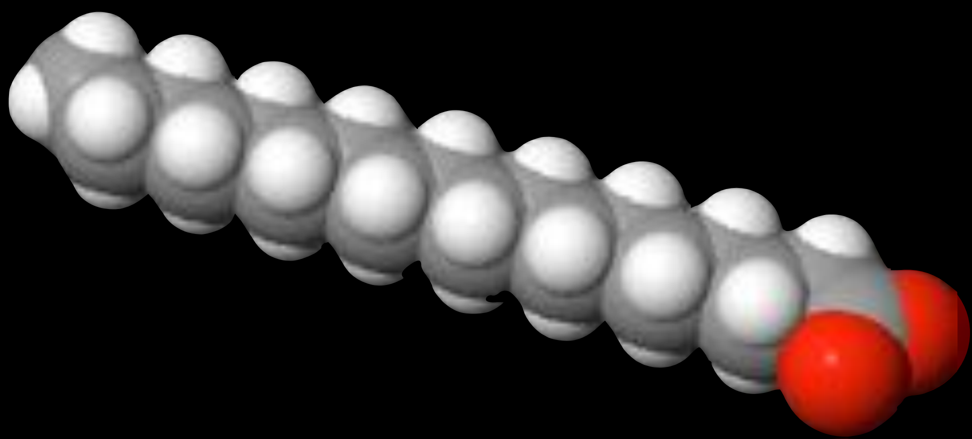
- **<u>Problem</u>**: Magnets (B_0) aren't perfect
- B_0 field inhomogeneity induces image and phase artifacts
  - geometric distortion, image shifts, decreased SNR, and off-resonance errors
- B_0 homogeneity improved by:
  - ***Passive Shimming***
    - Placement of ferromagnetic structures within the bore to improve field uniformity
  - ***Active Shimming***
    - Small "always on" currents in the gradient coils improve the field
    - Fine-tuned during pre-scan

Off Resonance & Isochromats

- ***Isochromat*** - Group of nuclear spins with the same resonant frequency.
- Ideally all spins in a system have the same resonance frequency
- Multiple isochromats arise from:
  - B_0 inhomogeneity (heterogeneity!)
  - Chemical shift effects
  - Magnetic susceptibility differences
  - Gradients (G_x, G_y, and G_z)

Sources of Off-resonance

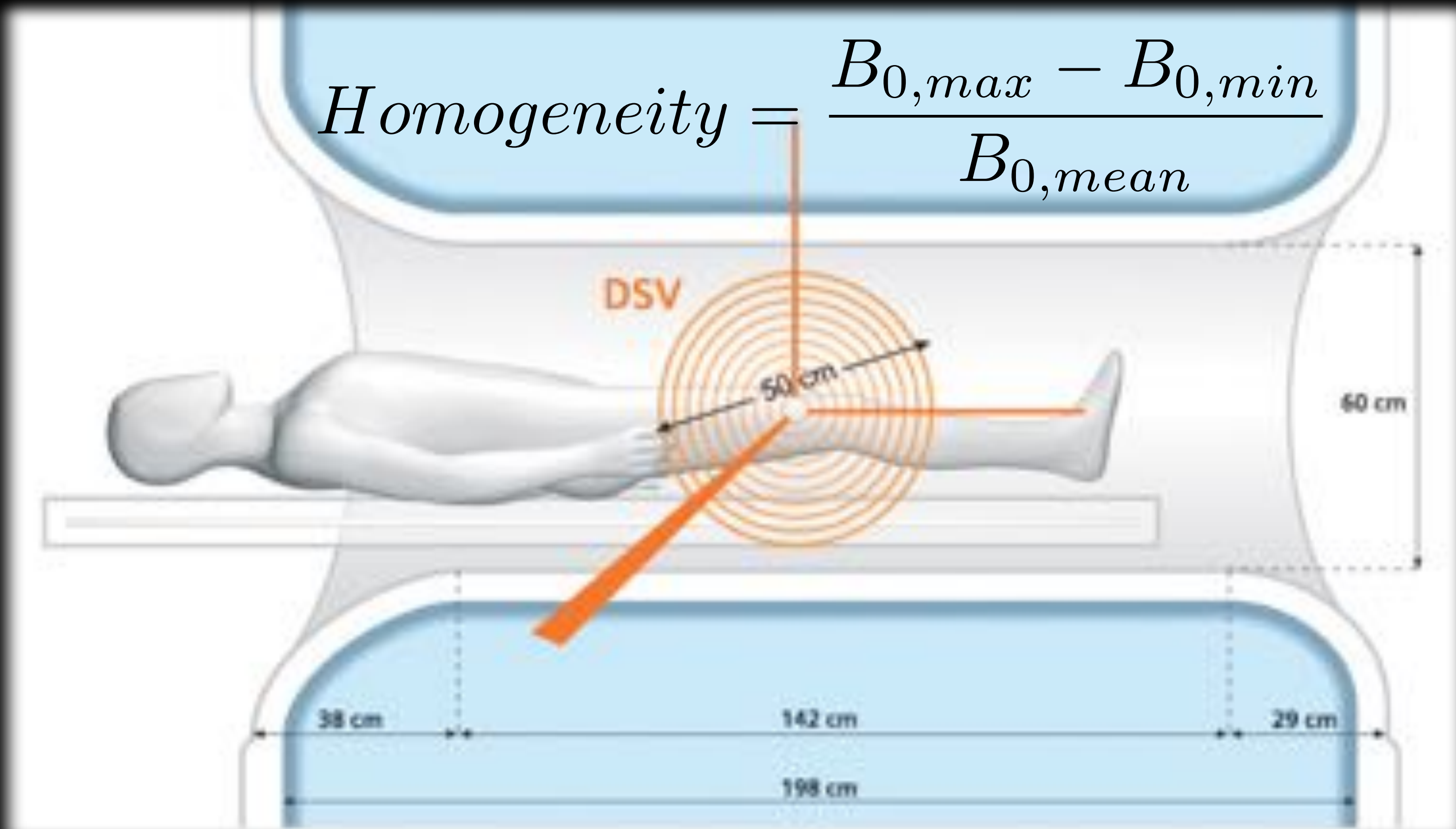




Off resonance refers to spins that resonate at a frequency different than γB_0.

B_0 Field Inhomogeneity

$$Homogeneity = \frac{B_{0,max} - B_{0,min}}{B_{0,mean}}$$



Homogeneity

- 0.25 ppm VRMS* for a 40 cm (16 inch) DSV†
- 1.00 ppm VRMS for a 50 cm (20 inch) DSV
  - <4ppm peak-peak variation

B_0 is "perfect" to within a few PPM.

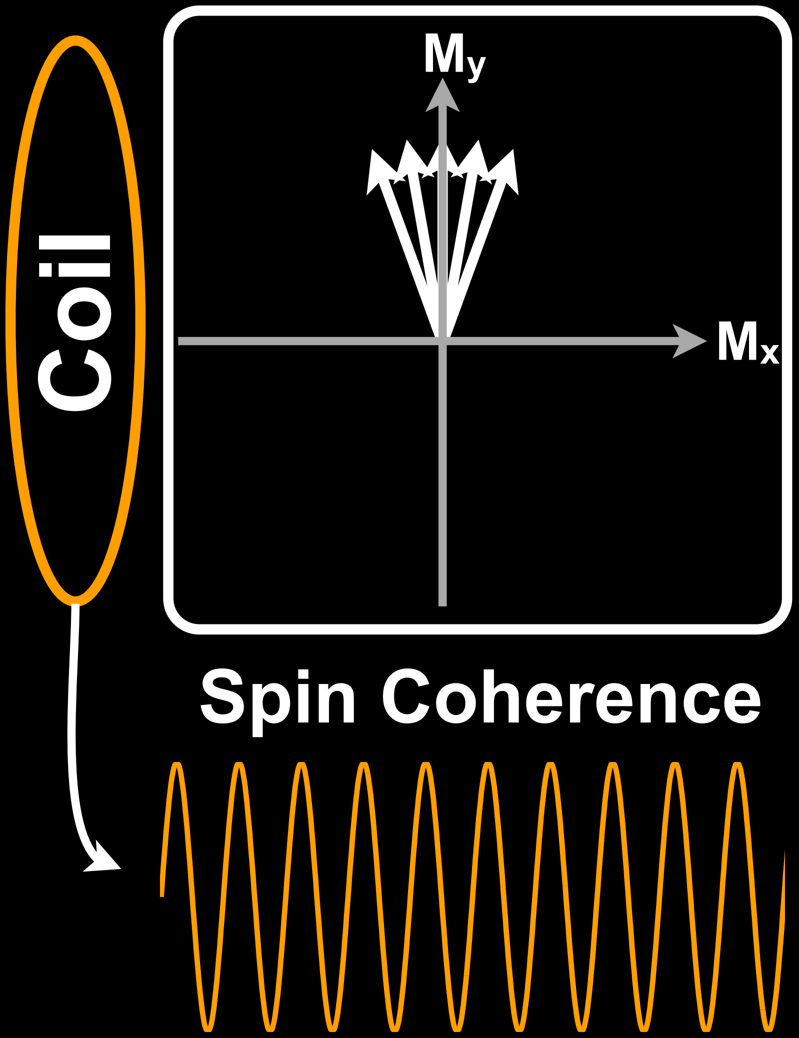
*Diameter Spherical Volume, †Volume Root-mean-square

Off-resonance Spin Dephasing

- Loss of spin phase coherence, usually within a voxel, which leads to a decreased echo (signal) amplitude.

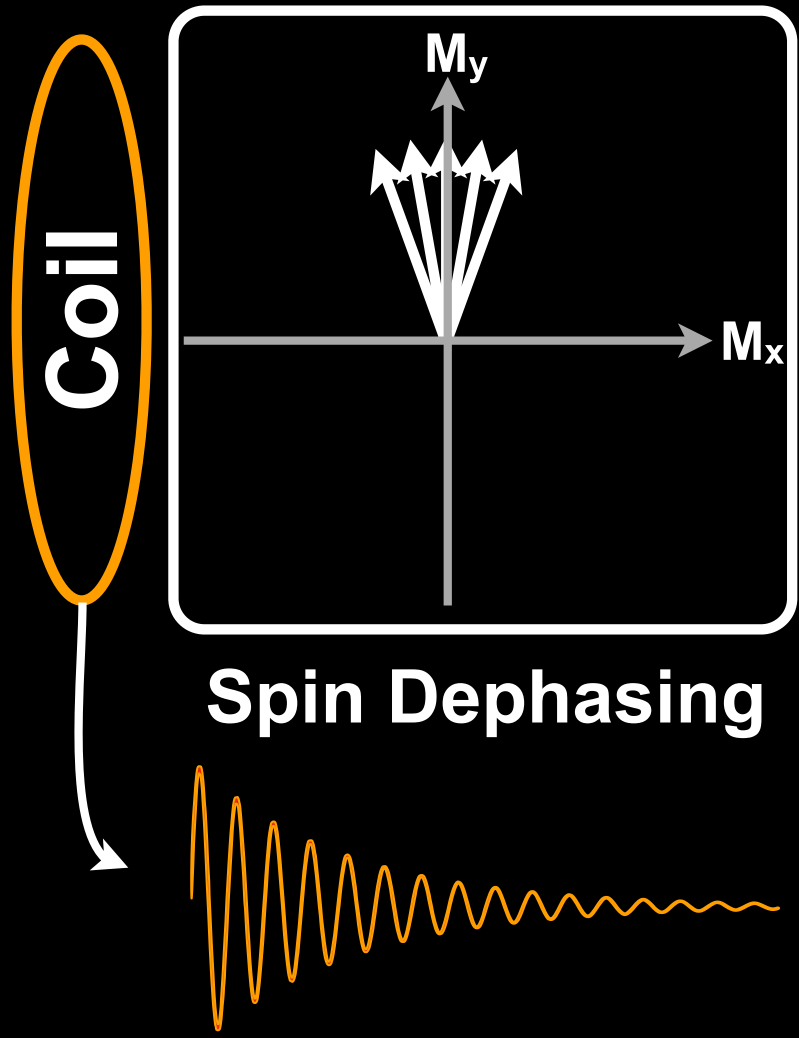
Intravoxel Spin Dephasing

Homogenous **Intravoxel Field**



Spin Coherence

Inhomogenous **Intravoxel Field**



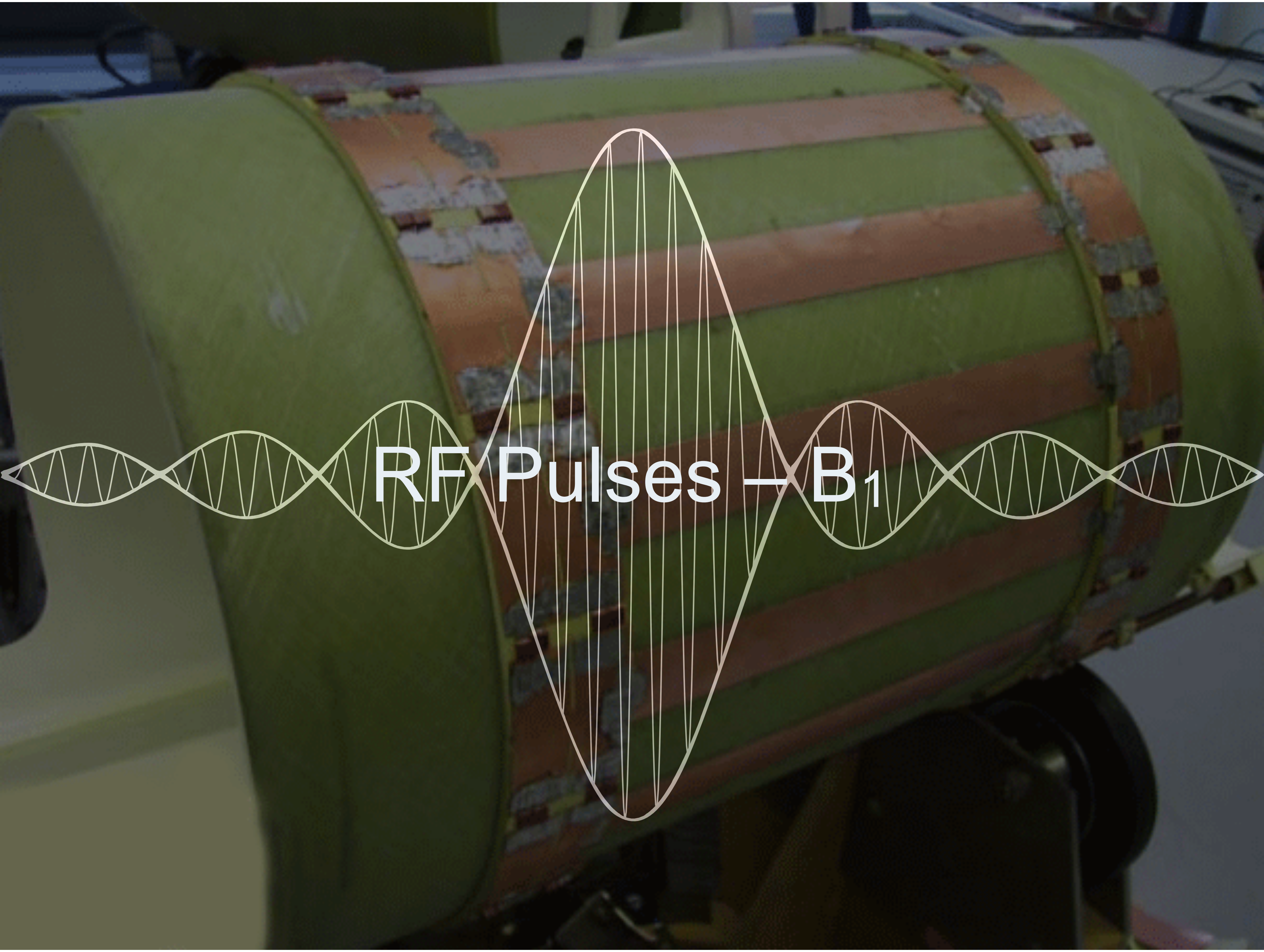
Spin Dephasing

Signal loss from off-resonance spin dephasing.

Quiz: Off-Resonance - True or False?

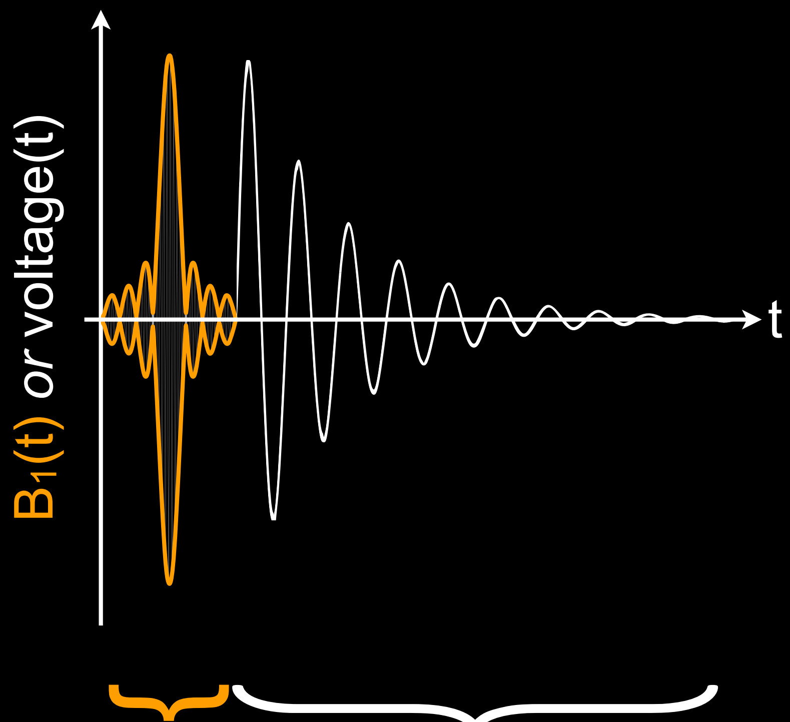
1. Fat is the only source of off-resonance.
2. Intravoxel spin dephasing leads to signal losses.
3. The specific chemical environment of ^1H shifts the local magnetic field and hence the Larmor frequency.
4. Active and passive shields improve B_0 homogeneity.

RF Pulses – B_1



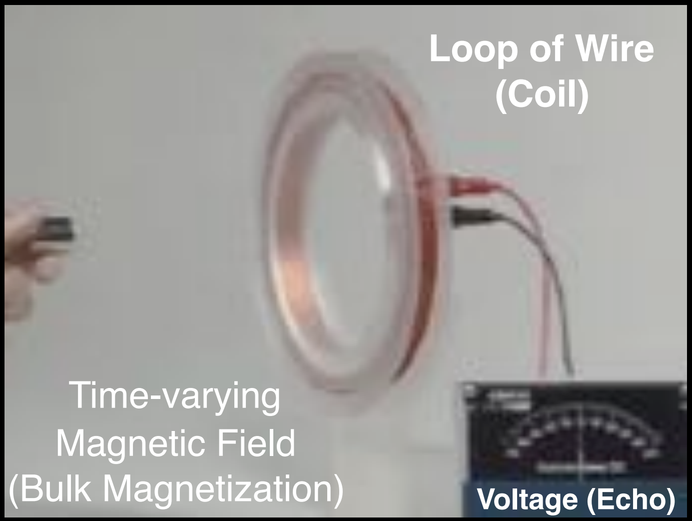
Excitation-Reception

MRI follows a classic excitation-reception paradigm.



Excitation
(RF Pulse)

Reception
(FID or **Echo**)



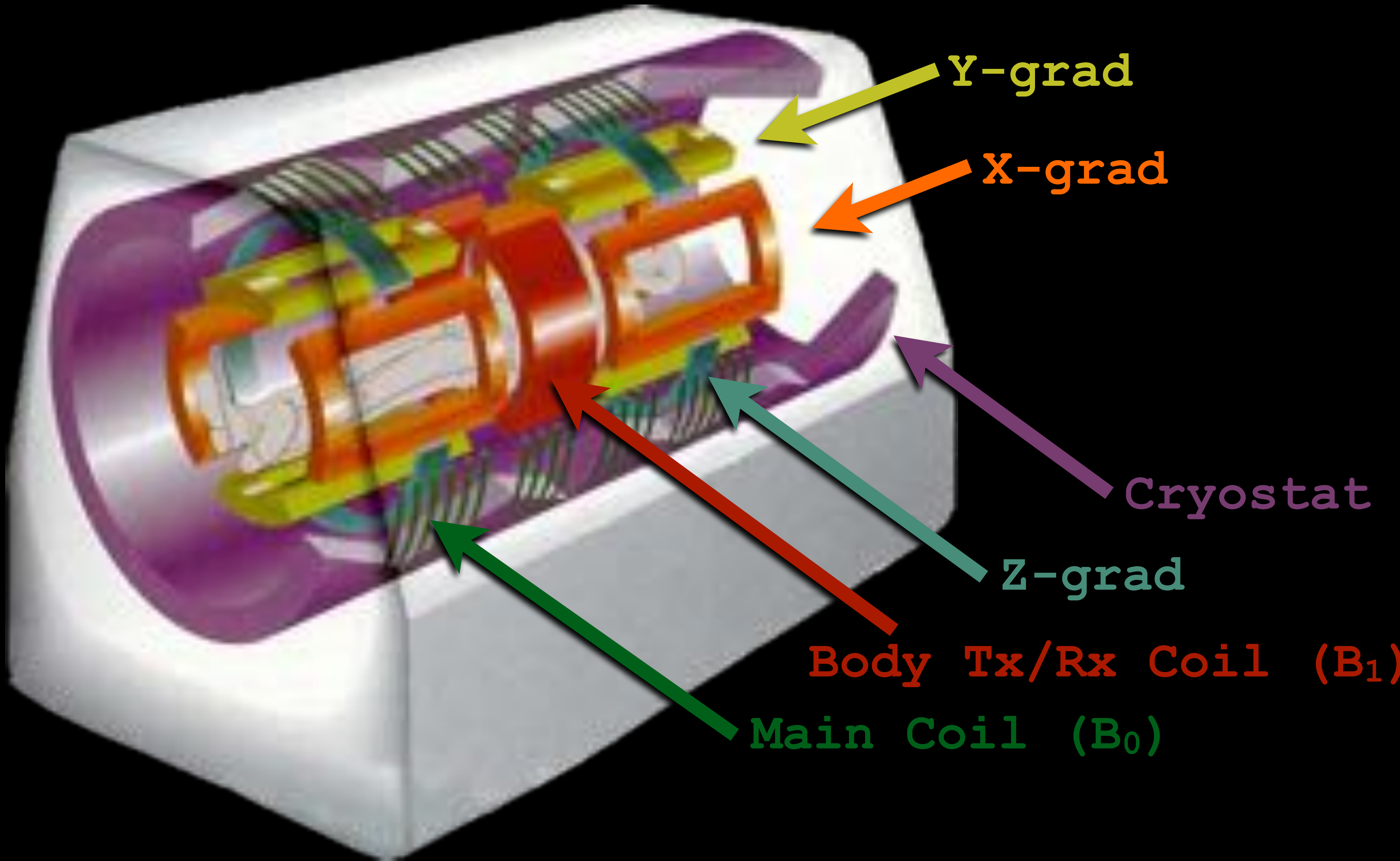
Faraday's Law of Induction

MRI uses RF (B_1) pulses to excite spins.

B_1 Field - RF Pulse

- **B_1 is a**
  - **radiofrequency (RF)**
    - **42.58MHz/T (63MHz at 1.5T)**
  - **short duration pulse (~0.1 to 5ms)**
  - **small amplitude**
    - **$<30\ \mu T$**
  - **circularly polarized**
    - **rotates at Larmor frequency**
  - **magnetic field**
  - **perpendicular to B_0**

MRI Hardware



MRI systems use the “body coil” to excite spins with RF (B_1) pulses.

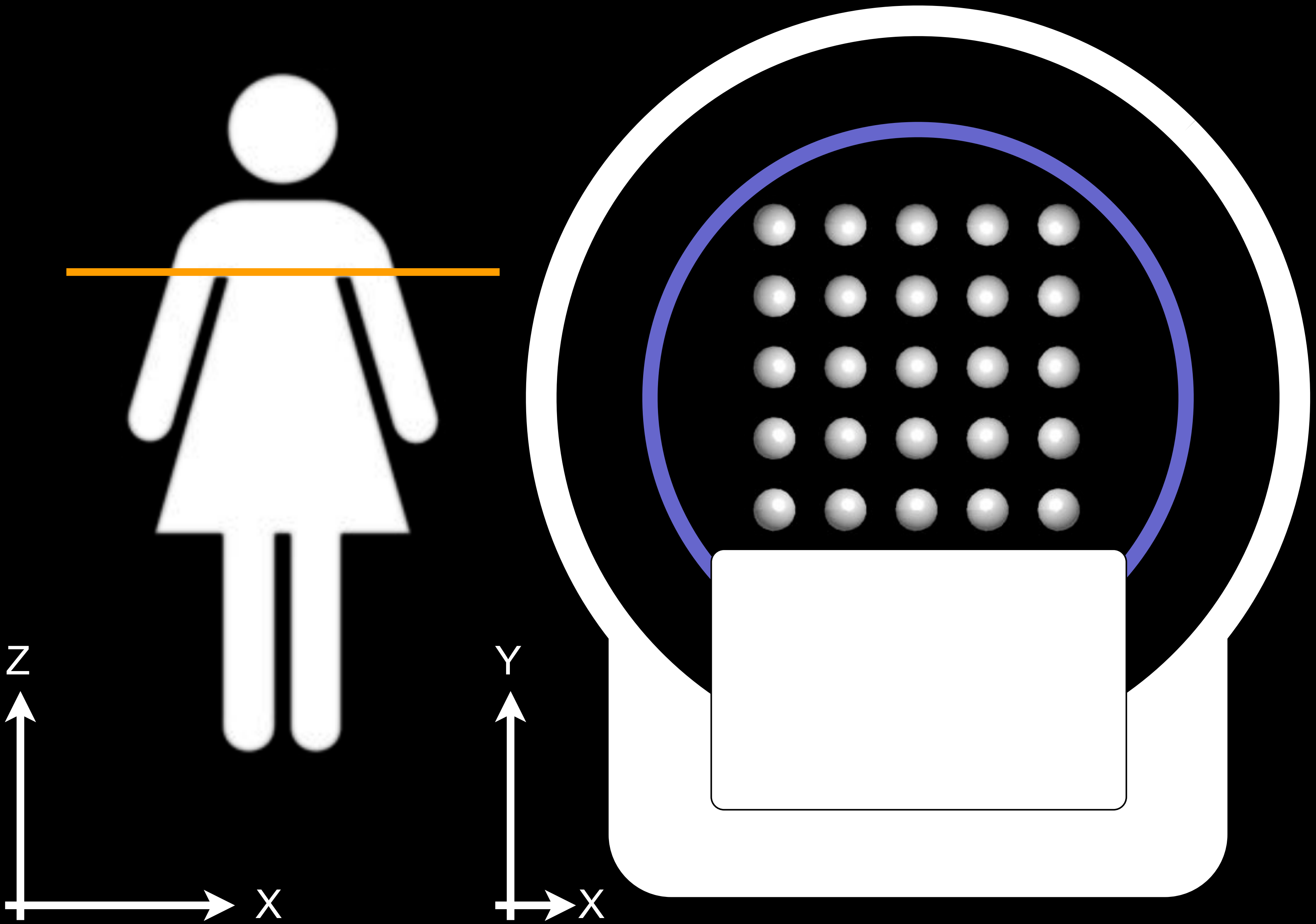
Image Adapted From: http://www.ee.duke.edu/~jshorey

RF Shielding

- **RF fields are close to FM radio**
  - **^{1}H @ 1.5T ⇒ 63.85 MHz**
  - **^{1}H @ 3.0T ⇒ 127.71 MHz**
  - **KROQ ⇒ 106.7 MHz**
- **Need to shield local sources from interfering**
- **Copper room shielding required**

MRI rooms are shielded with a Faraday cage to prevent RF energy from getting into the MRI suite.

RF (B_1) Excitation



RF pulses generate transverse magnetization for a *slice*.

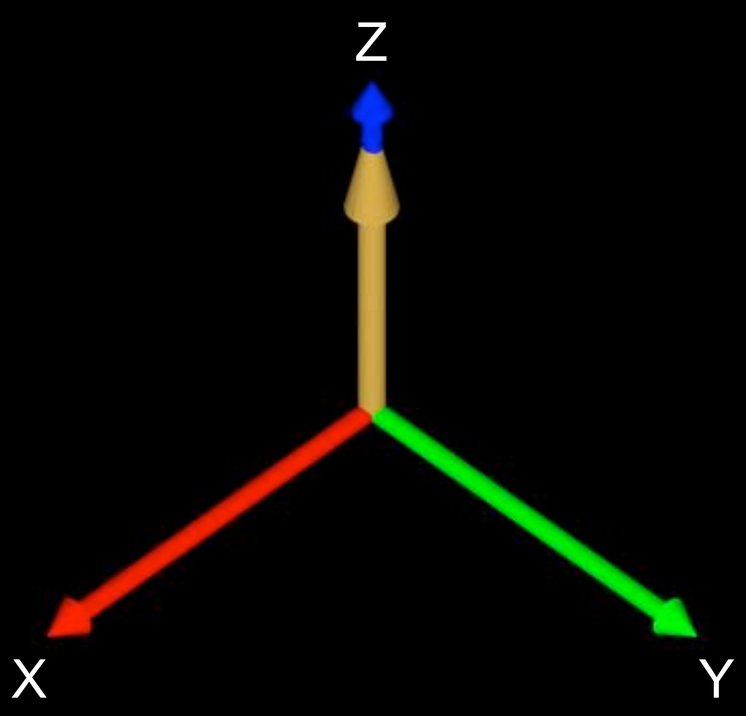
Types of RF Pulses

- **Excitation Pulses**
- **Inversion Pulses**
- **Refocusing Pulses**
- **Saturation Pulses**
- **Spectrally Selective Pulses**
- **Spectral-spatial Pulses**
- **Adiabatic Pulses**

RF Pulses: Lab vs. Rotating Frame

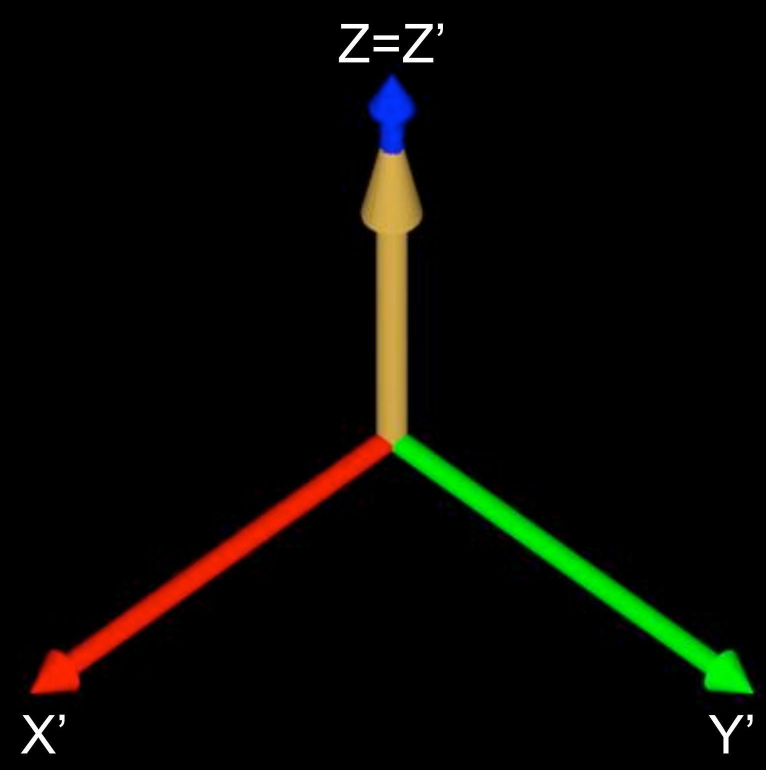
- **The rotating frame simplifies the mathematics and permits more intuitive understanding.**

90° RF (Laboratory Frame)



Spins Precess

90° RF (Rotating Frame)

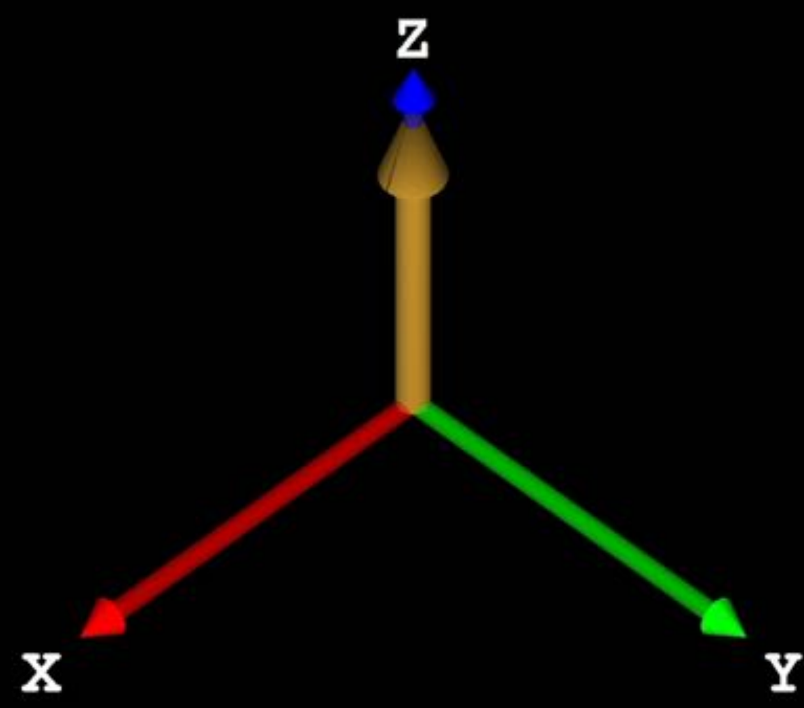


Observer Precesses

Note: Both coordinate frames share the same z-axis.

Excitation Pulses - Applications

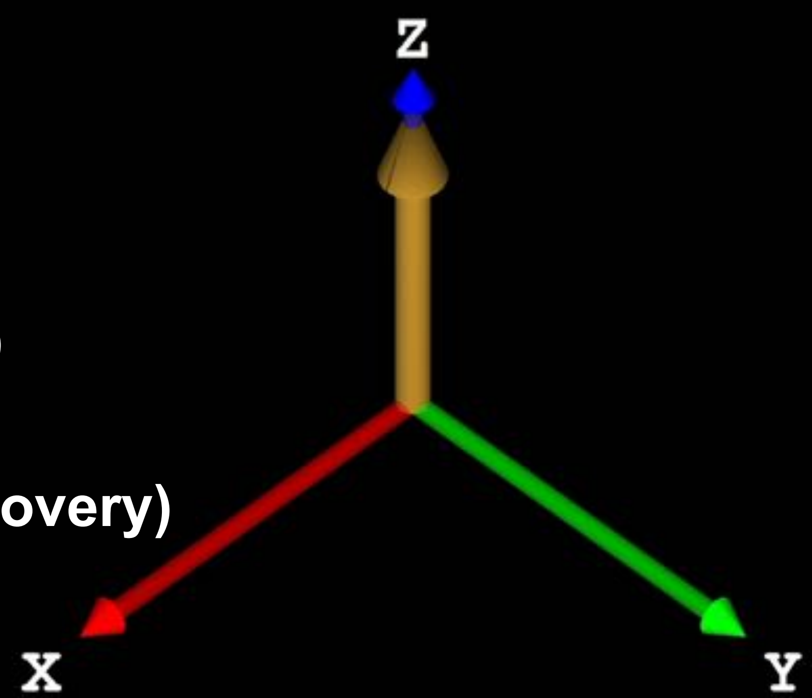
- **90° RF Pulse**
  - **Spin Echo**
  - **Saturation Recovery**
- **Small Flip Angle (<~20°)**
  - **FLASH (Fast Low Angle Shot)**
    - **AKA SPGR**
- **Moderate Flip Angle (30°-90°)**
  - **TrueFISP**
    - **AKA FIESTA, Balanced FFE**



Excitation pulses generate detectable transverse magnetization.

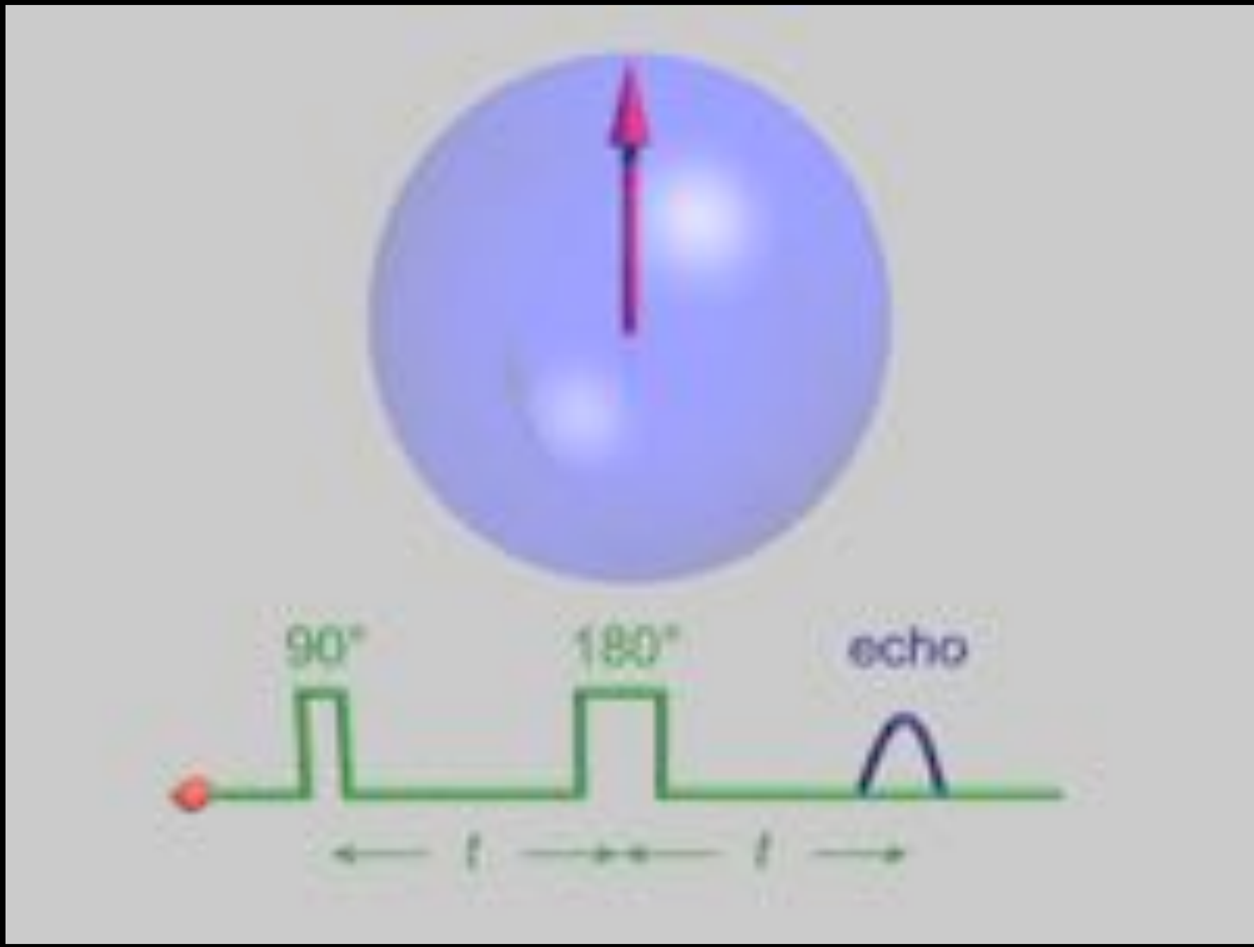
Inversion Pulse - Applications

- **Invert Mz to -Mz**
  - **Ideally produce no Mxy**
- **T1 species nulling/attenuation**
  - **STIR (Short Tau Inversion Recovery)**
    - **Suppress specific tissue-T1**
  - **SPECIAL (Spectral Inversion at Lipids)**
    - **Suppress lipid signals (short T1)**
  - **FLAIR (Fluid Attenuated Inversion Recovery)**
    - **Suppress fluid signal (long T1)**
  - **IR-Prep**
    - **Attenuate T1-species without nulling**
- **Quantitative T1 mapping**



Refocusing Pulses & Spin Echoes

- **180° RF Pulse**
  - **Provides optimally refocused M_{XY}**
  - **Largest spin echo signal**
- **Refocus spin dephasing due to off-resonance:**
  - **imaging gradients**
  - **local magnetic field inhomogeneity**
  - **magnetic susceptibility variation**
  - **chemical shift**



Refocusing RF pulses mitigate off-resonance spin dephasing.

https://en.wikipedia.org/wiki/Spin_echo

Refocusing Pulses - Applications

- **Spin Echo imaging**
- **RARE**
  - **Rapid Acquisition with Relaxation Enhancement**
  - **RF Excitation followed by 180° train**
  - **Reduce acquisition time by N-echoes**
  - **Common for T2-weighted imaging**
  - **AKA Fast Spin Echo**
- **Spin-Echo EPI**
  - **Single-shot common for diffusion weighting**
- **Navigator Echoes**
- **Quantitative T2 Mapping**

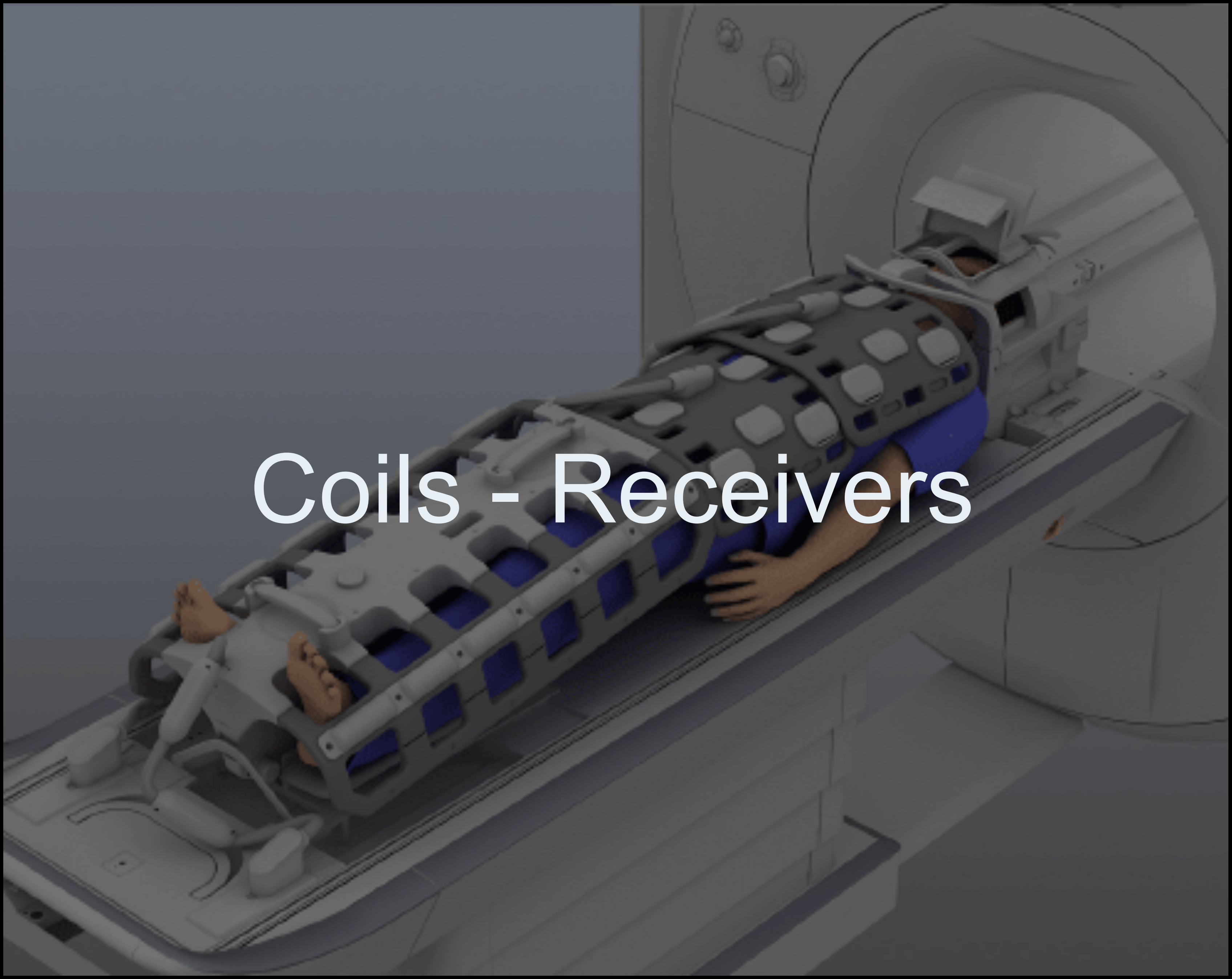
Quiz: RF Pulses - True or False?

1. RF pulses are the main source of patient heating.
2. RF pulses excite spins and create transverse magnetization.
3. RF pulses are typically 100s of ms long.
4. Excitation pulses are not required for imaging.
5. Inversion pulse change image contrast.

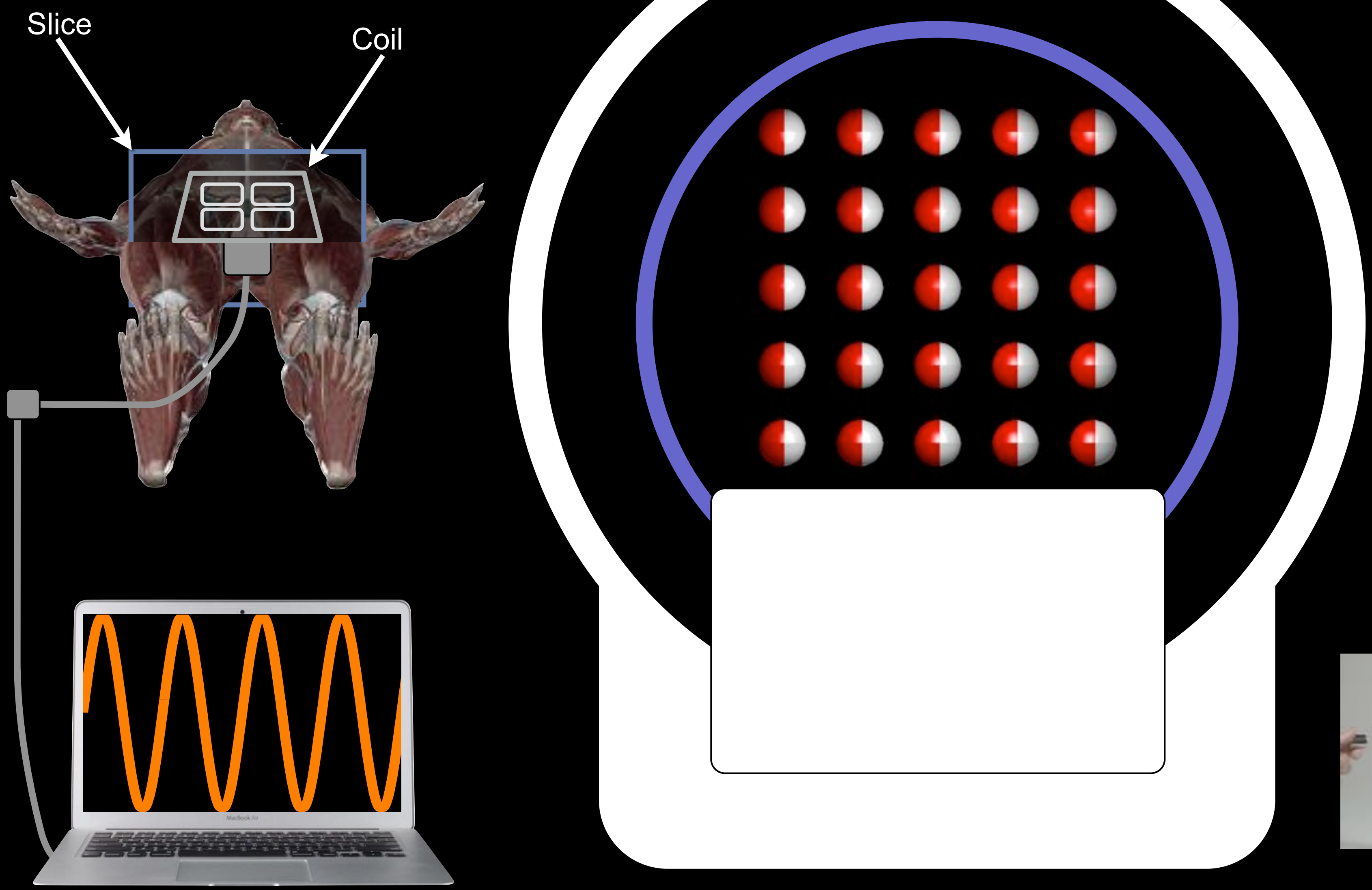
Learning Objectives

- Distinguish between B_0 shielding and shimming.
- List several causes of off-resonance.
- Explain the impact of intravoxel spin dephasing on MRI signals.
- Appreciate the strength and duration of RF pulses.
- Explain the importance of RF shielding.
- Describe three kinds of RF pulse applications.

Coils - Receivers



Faraday's Law of Induction

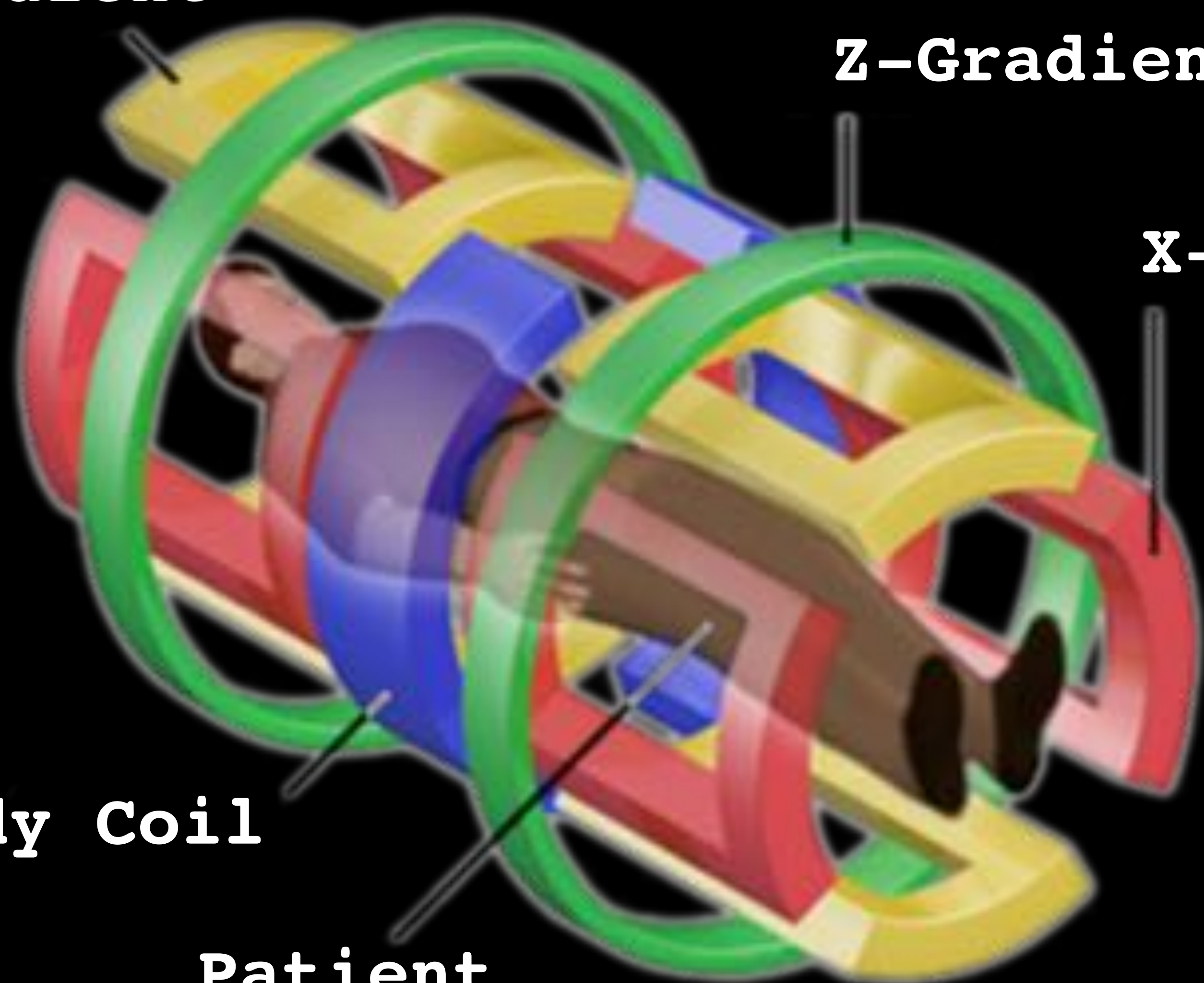


The trick is to encode spatial information and image contrast in the echo.

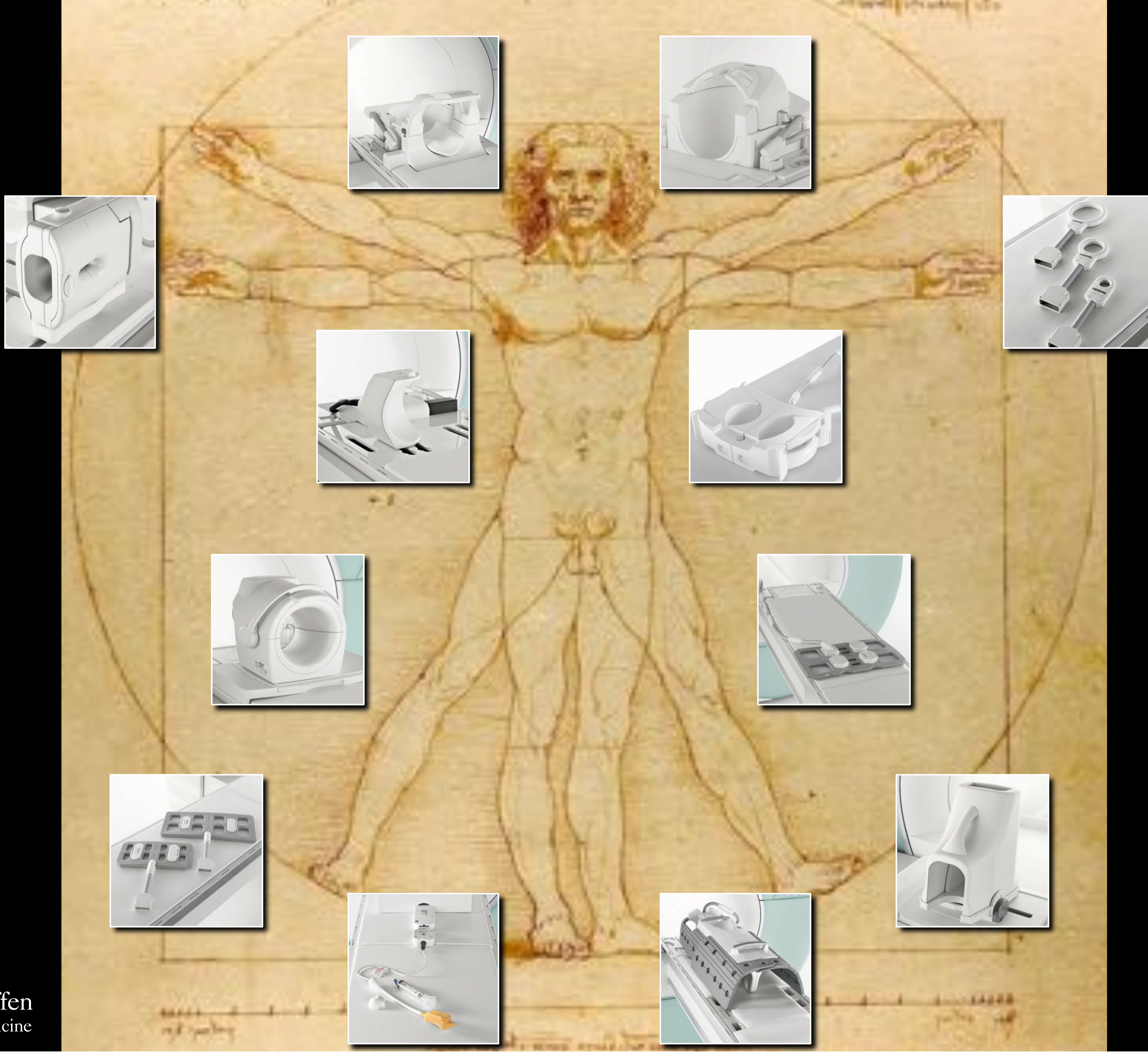
Coils

- Coils <u>transmit</u> the B_1 field
  - Typically Body Coil
  - Sometimes Head or Knee Coil is a Tx/Rx
- Coils <u>receive</u> the NMR signal
  - Typically Head, Knee, Body, Surface, etc.
  - Very infrequently use the body coil

MRI Instrumentation



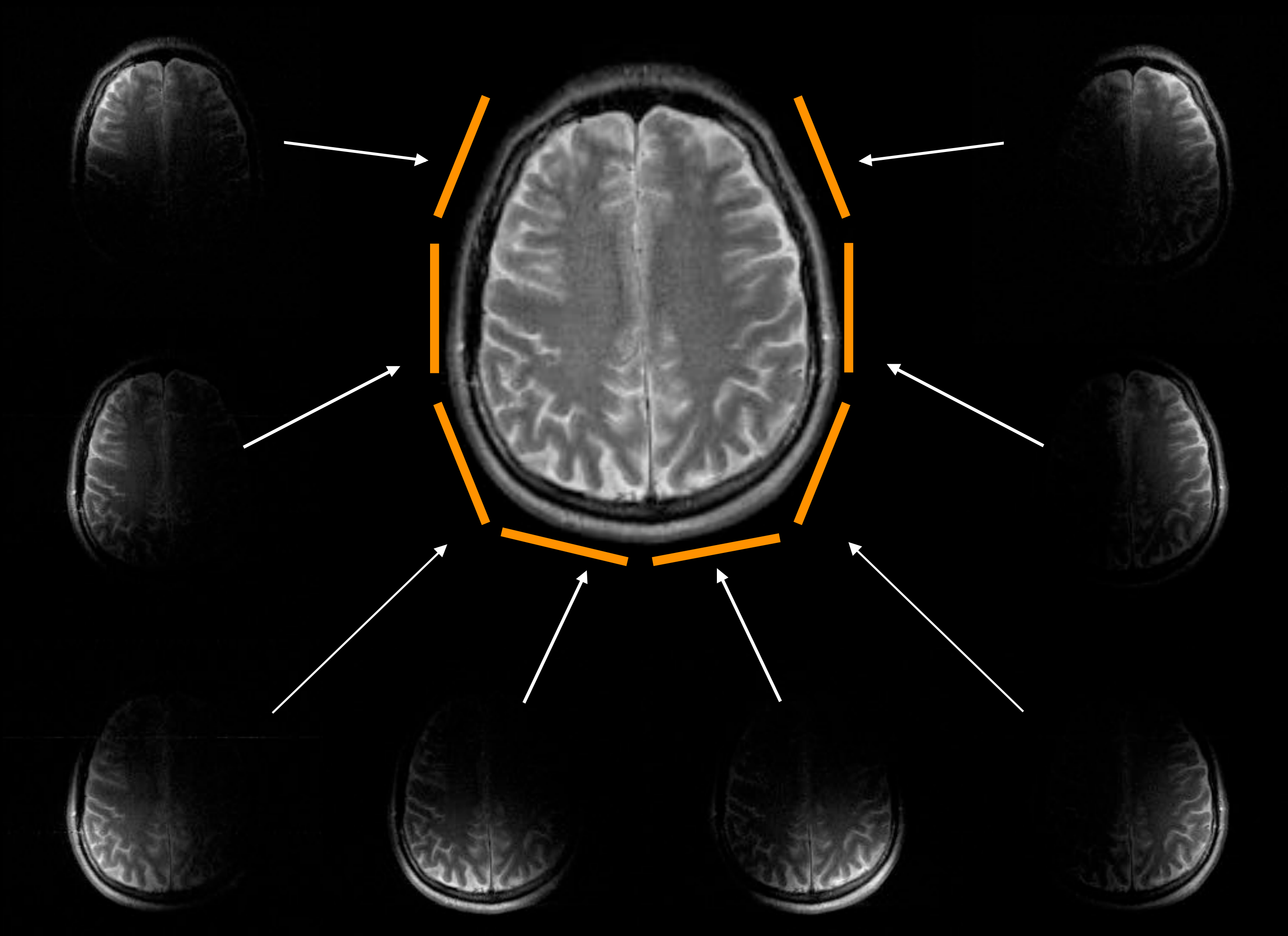
Coils



Coils

- **Volume Coils** (Body, Head, Knee)
  - Typically better SNR than surface coils
  - Typically "birdcage" in design
    - Best RF field homogeneity of all coils
    - Uniform B_1 over extent of volume
- **Surface Coils** (Torso, Spine, Cardiac)
  - Flexible positioning/placement
  - High SNR near coil
    - SNR falls off quickly with distance
  - Quadrature and phased arrays improve SNR
    - Compared to single channel loop coils

8-Channel Head Coil



Each coil element (channel) has a unique sensitivity profile.

Quiz: Coils - True or False?

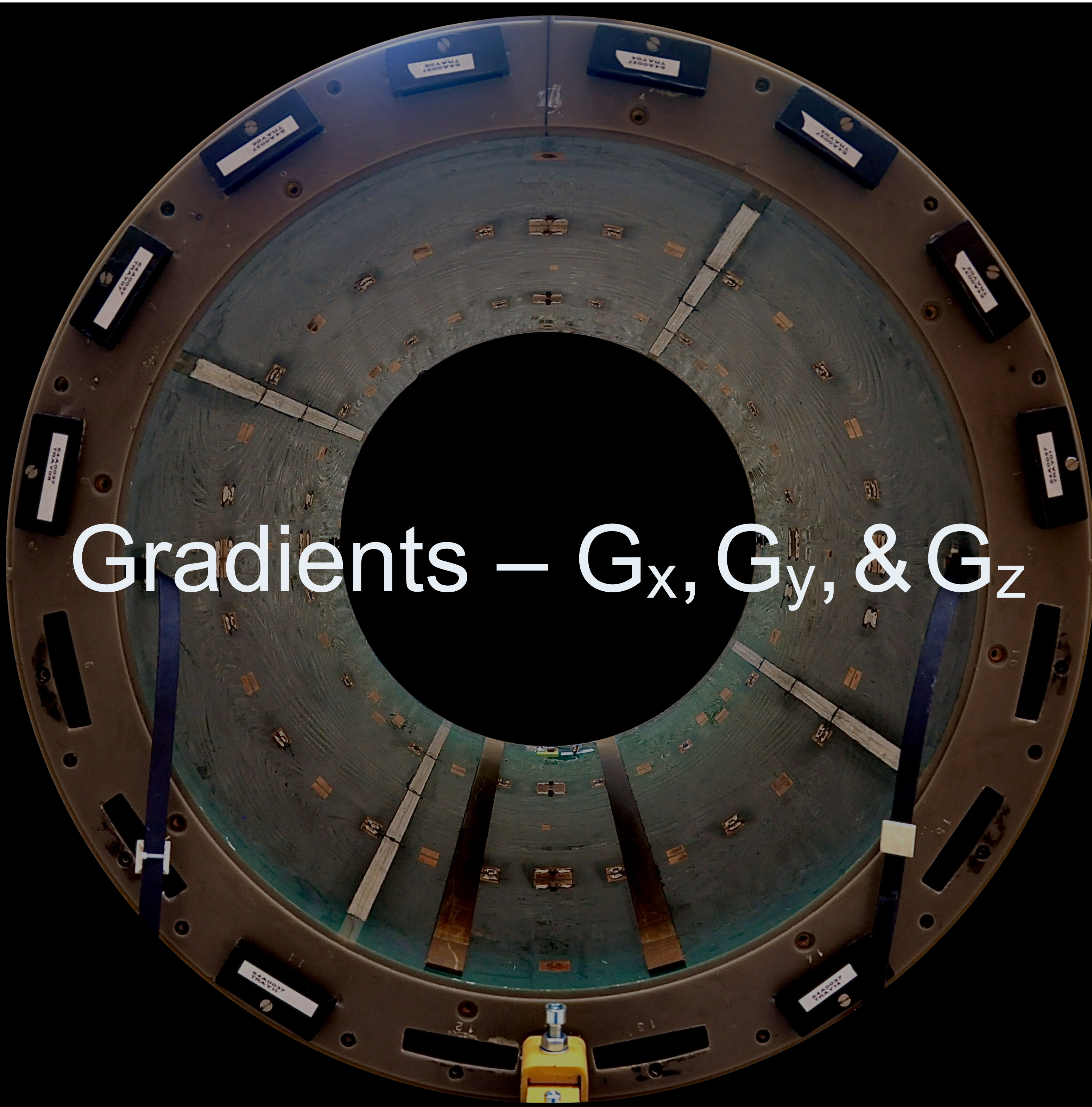
1. Faraday's Law of Induction is the principal underlying signal reception.

2. The body coil is typically used for receiving the MRI signals.

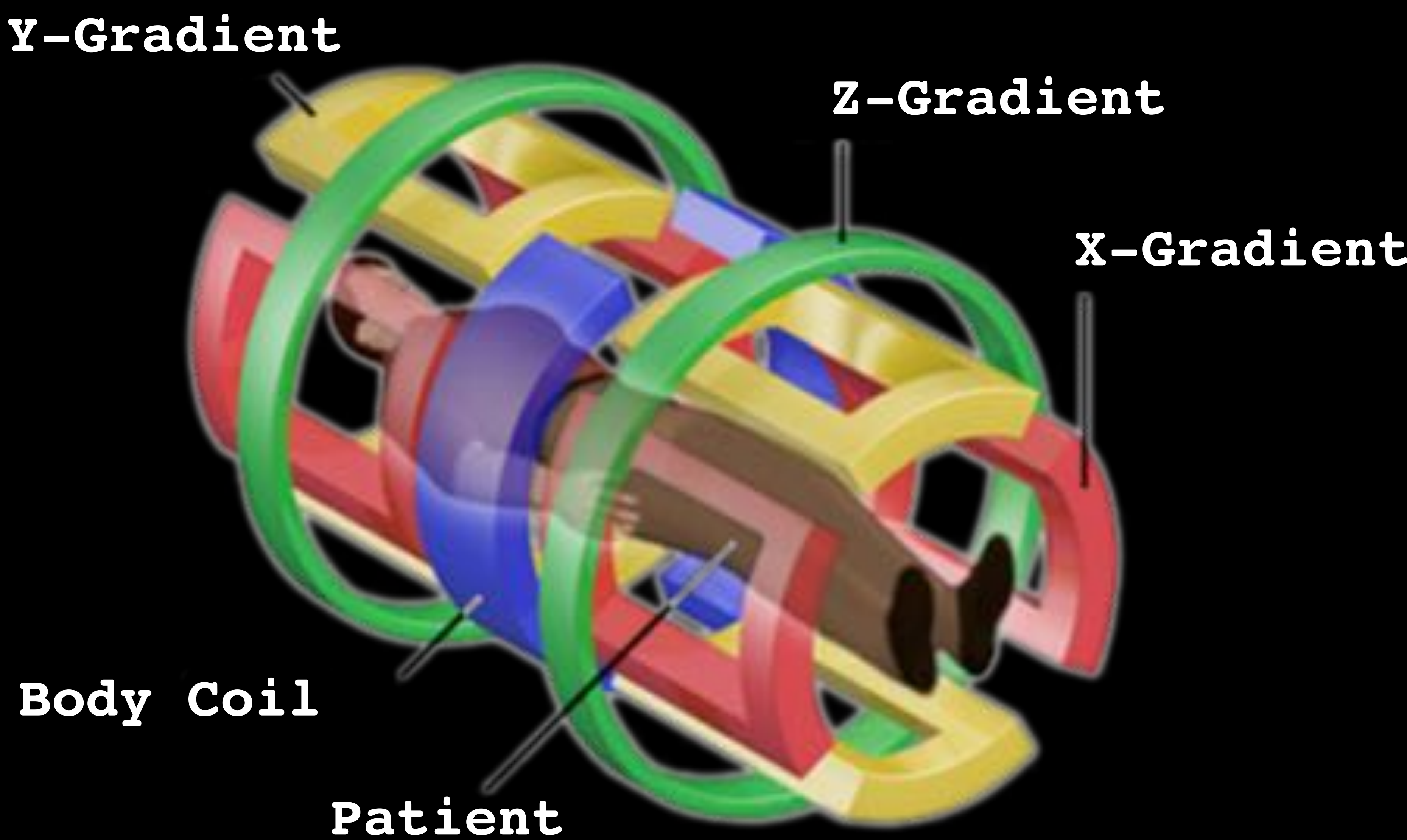
3. Surface coils transmit RF excitation pulses.

4. Most coils work for most body parts.

Gradients – G_x, G_y, & G_z



MRI Instrumentation



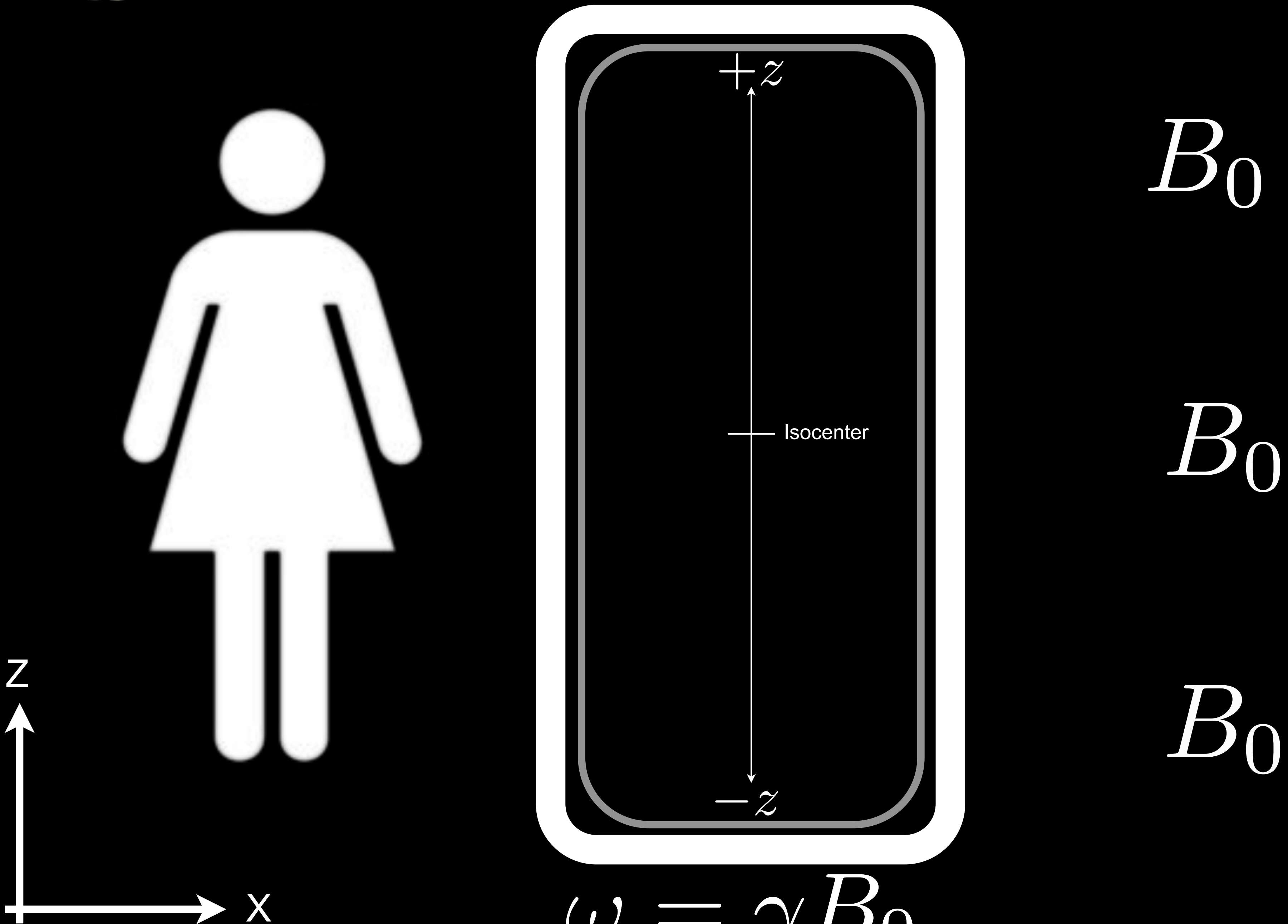
Gradients

- Primary function
  - Encode spatial information
    - Slice selection
    - Phase encoding
    - Frequency encoding
- Secondary functions
  - Sensitize/de-sensitize images to motion
  - Minimize artifacts (crushers & spoilers)
  - Magnetization re-phasing in slice selection
  - Magnetization de-phasing during readout

Gradients

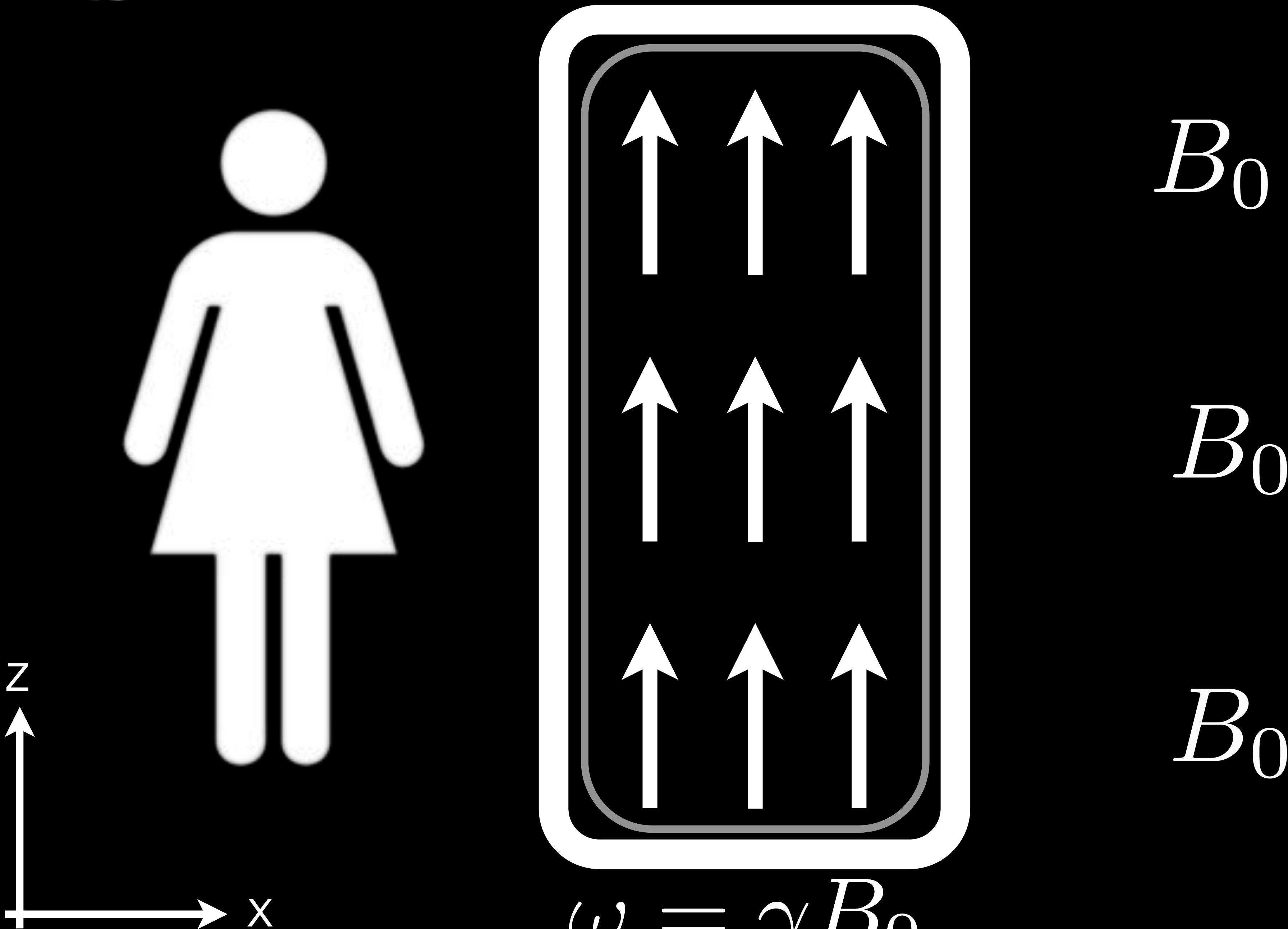
- Gradients are a:
  - Small
    - <5G/cm (±0.0075T @ edge of 30cm FOV)
  - Spatially varying
    - Linear gradients
    - Adds to B_0 only in Z-direction
  - Time varying
    - Slewrate Max. ~150-200mT/m/ms
    - Typically on for a few milliseconds.
  - Magnetic field
    - Adds/Subtracts to the B_0 field
  - Parallel to B_0
- Gradients are NOT:
  - Fields perpendicular to B_0

No Gradients Turned On



$$\omega = \gamma B_0$$

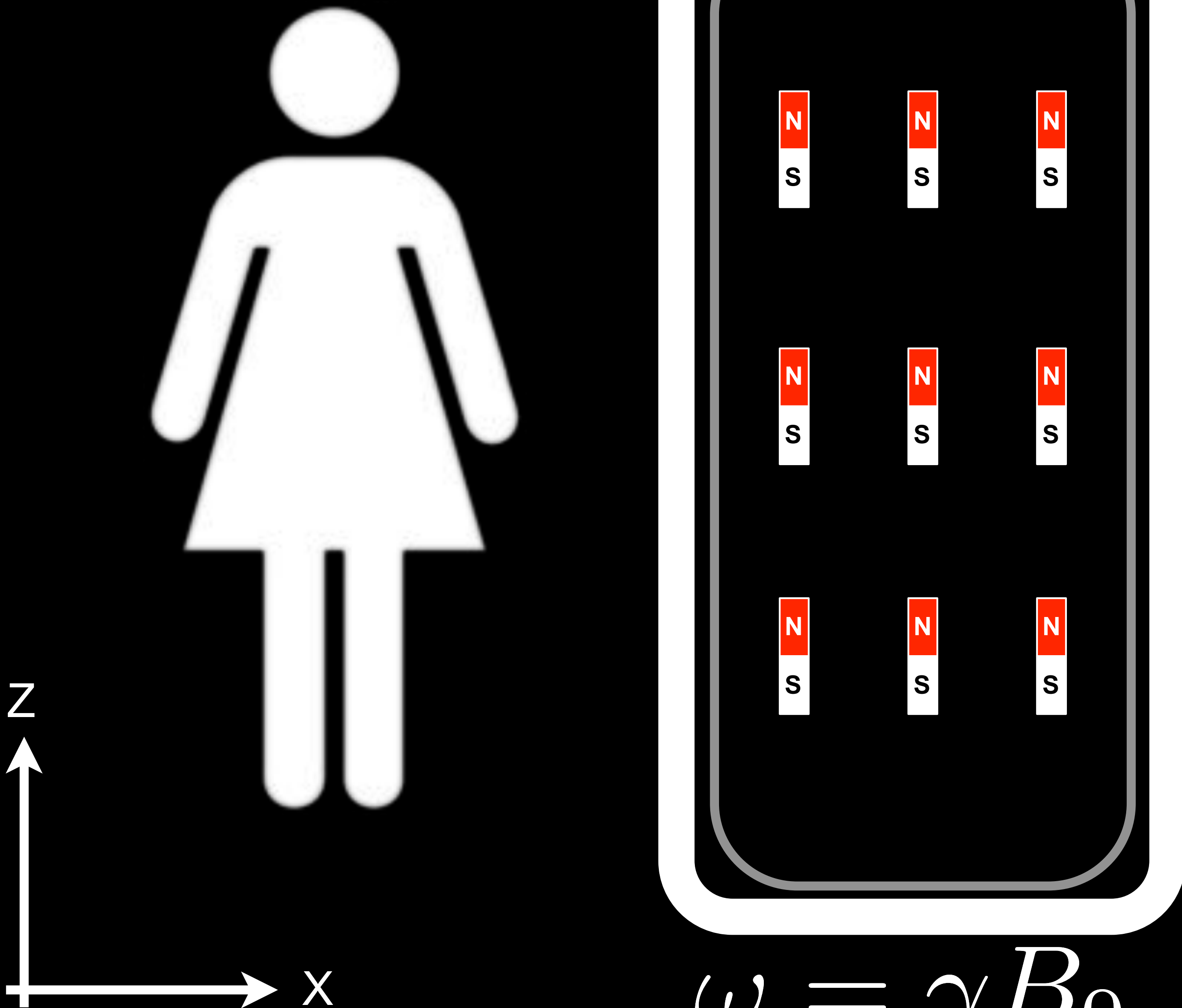
No Gradients Turned On



$$\omega = \gamma B_0$$

Length of arrow indicates strength of local field.

No Gradients Turned On



B_0

B_0

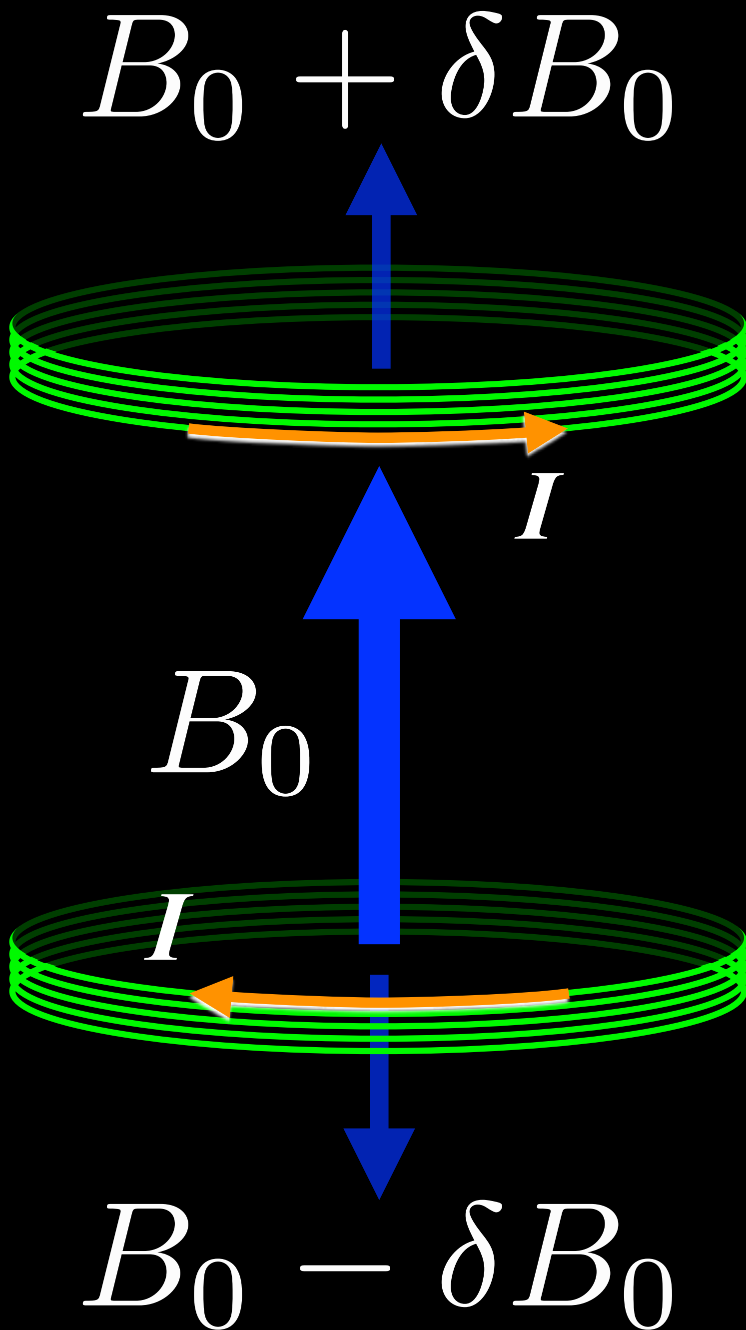
B_0

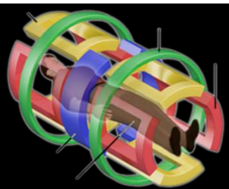
$$\omega = \gamma B_0$$

Everything precesses at the Larmor frequency.

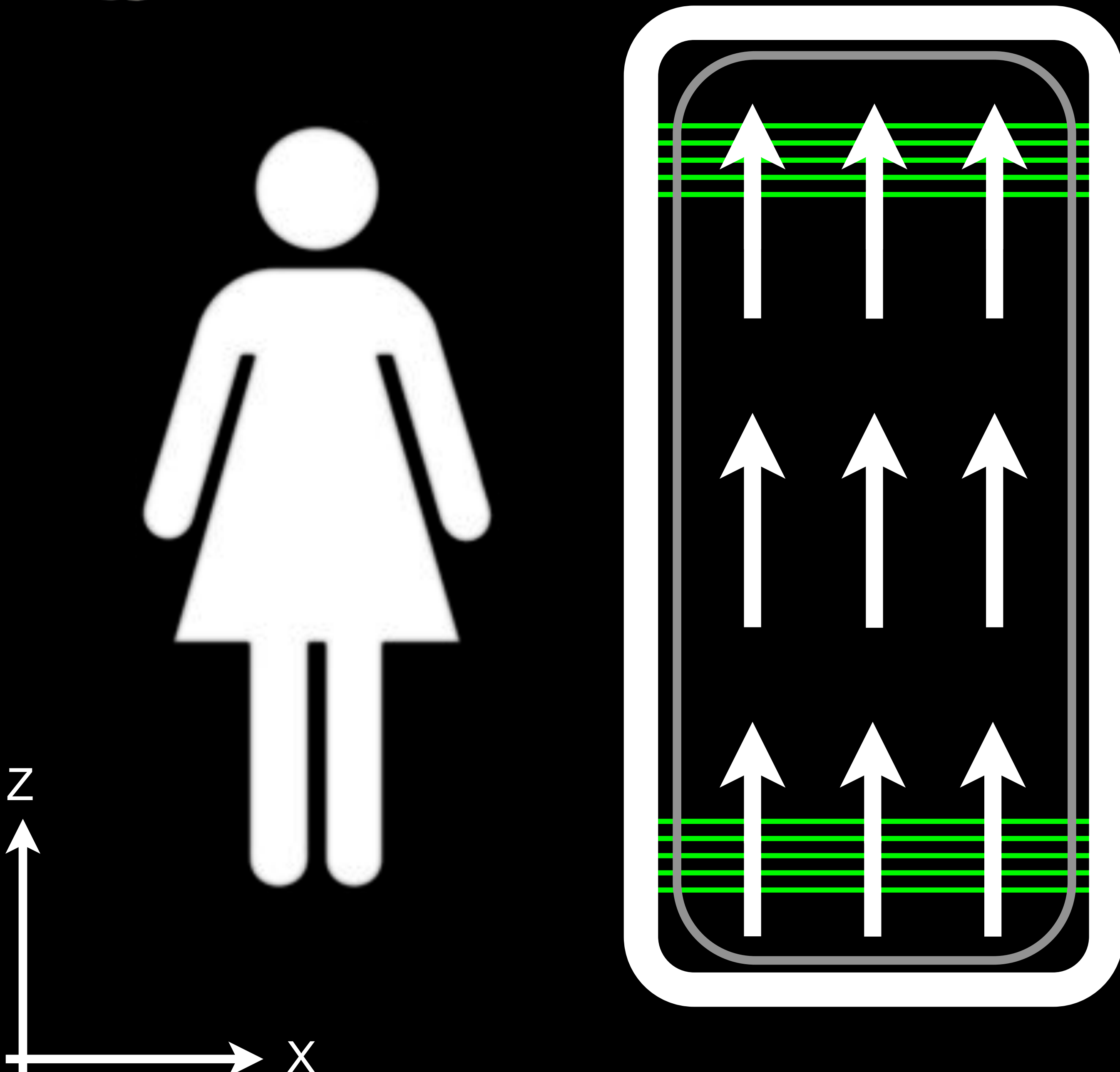
Z Gradients

Maxwell Pair Coil





Z-Gradients



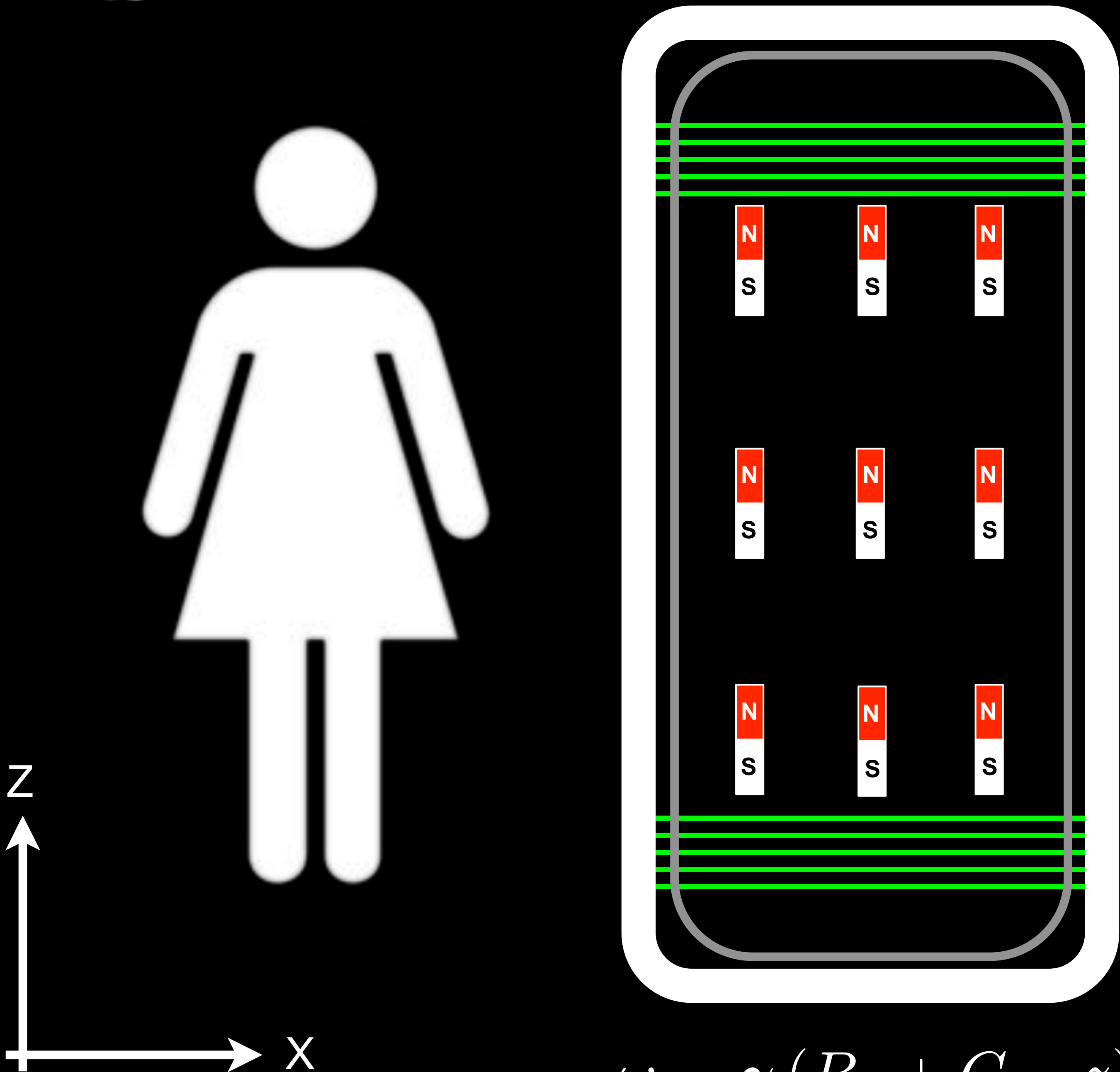
$$B_0 + \delta B_0$$

$$B_0$$

$$B_0 - \delta B_0$$

Length of arrow indicates strength of local field.

Z-Gradients



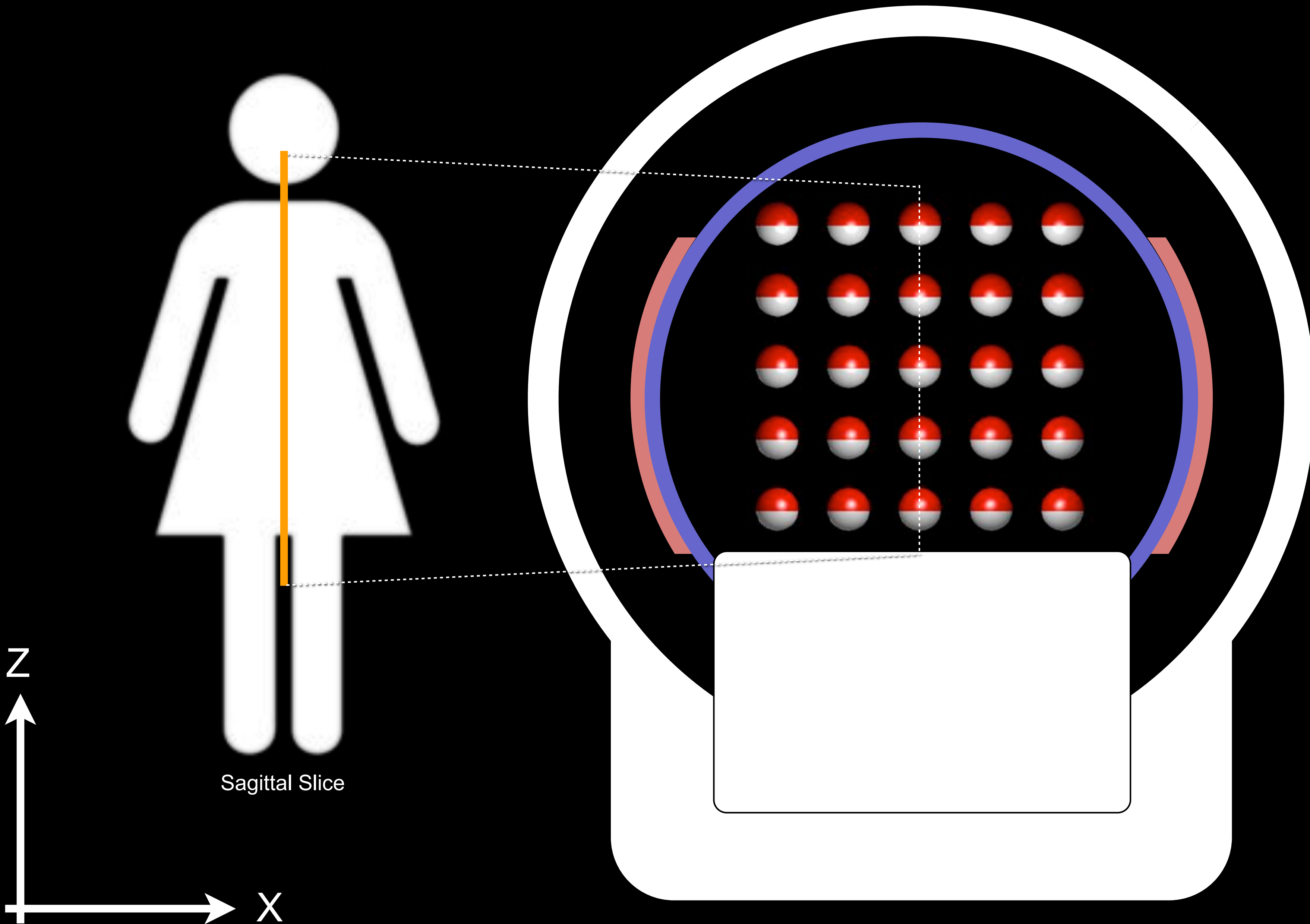
$$B_0 + \delta B_0$$

$$B_0$$

$$B_0 - \delta B_0$$

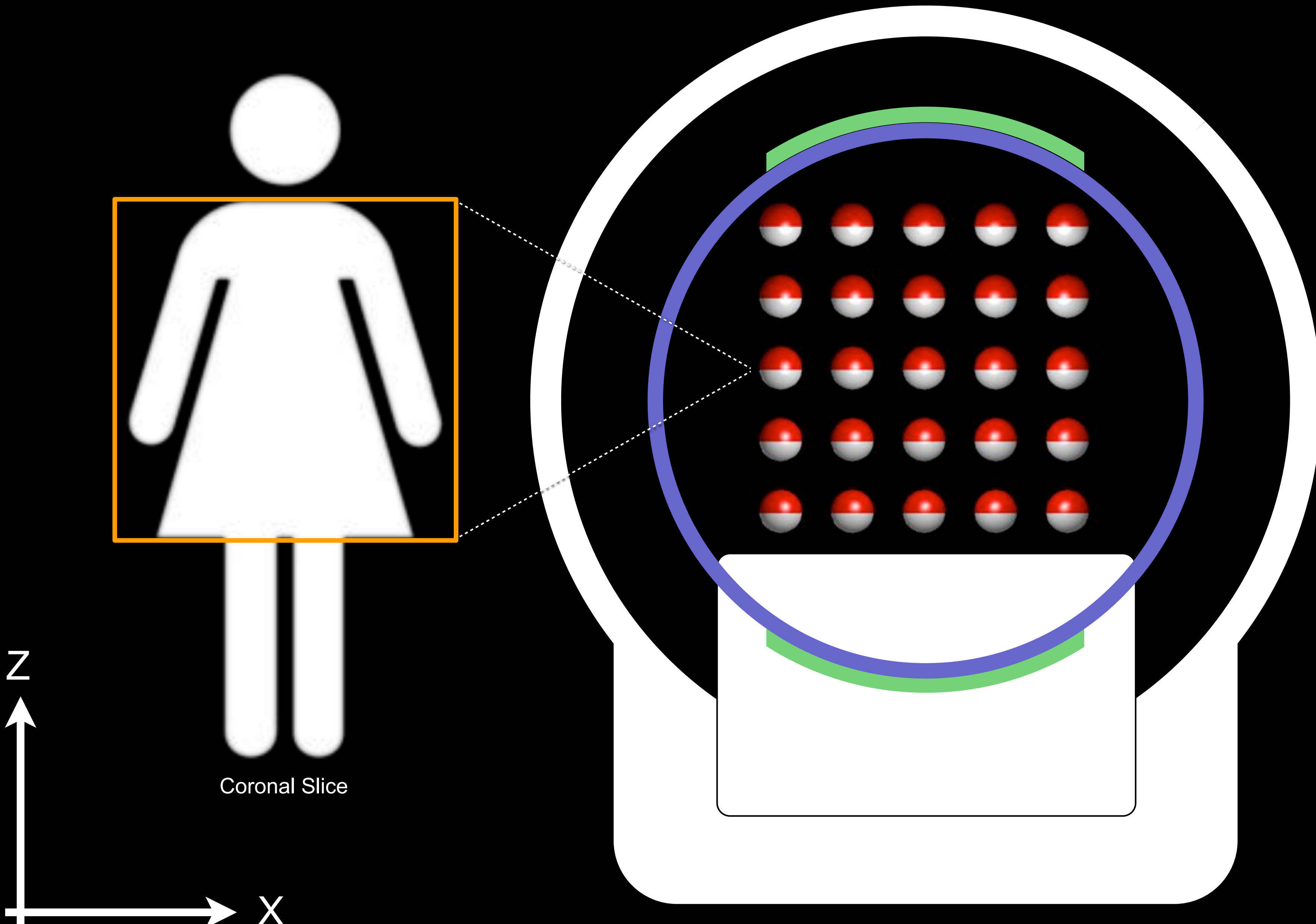
$$\omega = \gamma \left(B_0 + G_z \cdot z \right)$$

Spins and X-Gradients



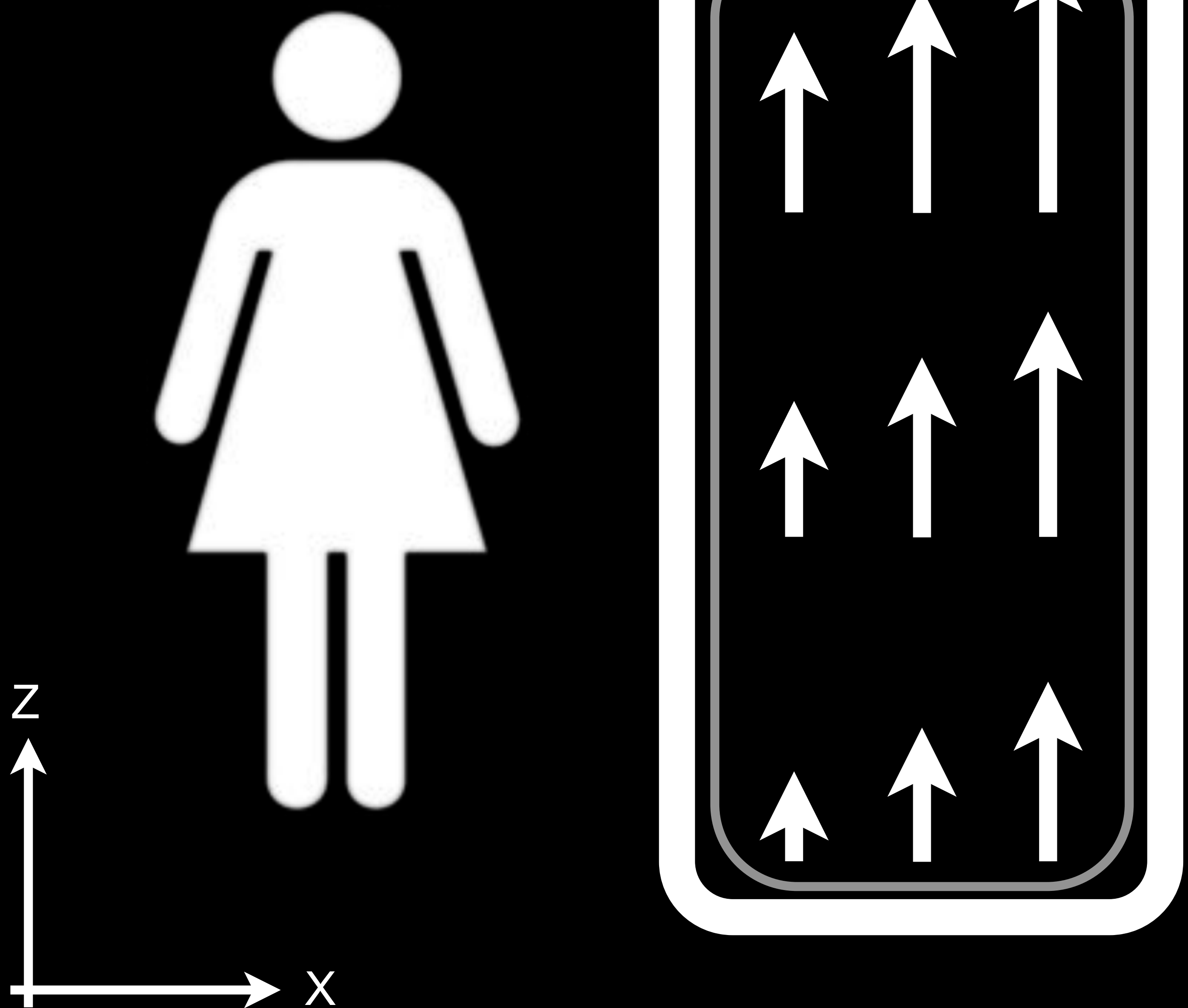
Gradients give rise to isochromats (planes of common frequency).

Spins and Y-Gradients

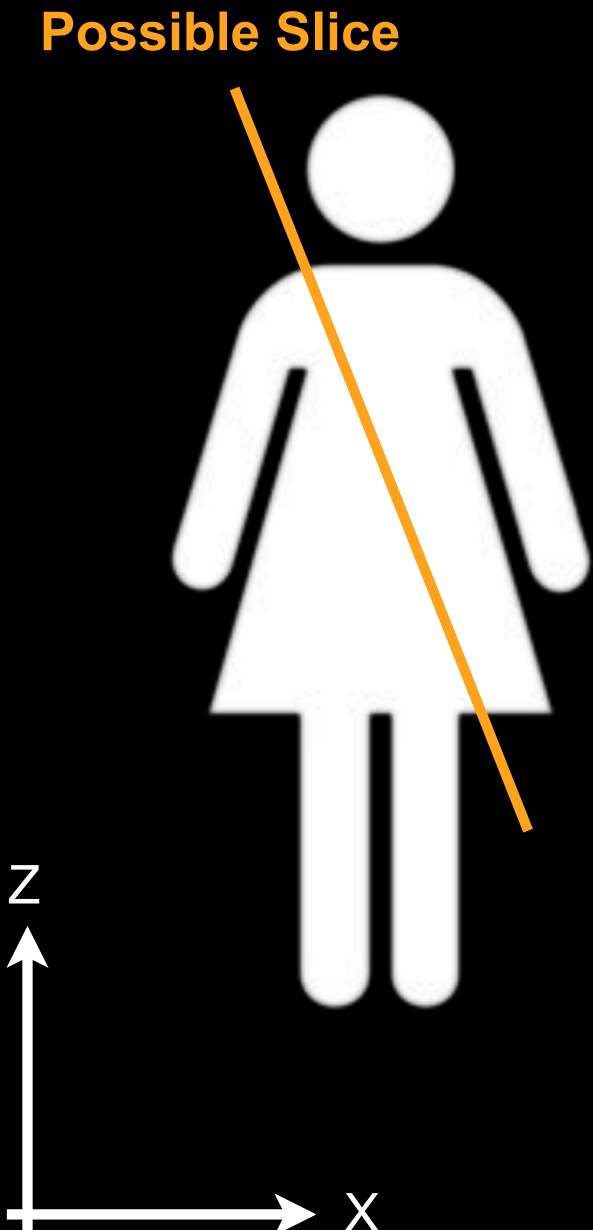


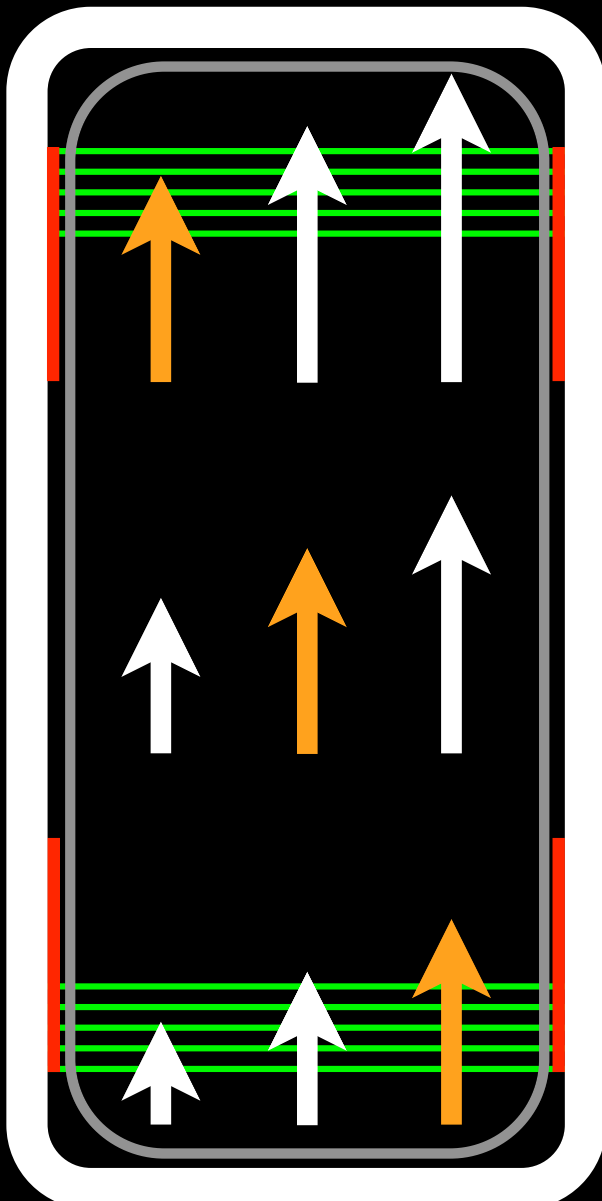
Gradients add/subtract to B_0 along a specific direction.

How do we do this?



X+Z-Gradients

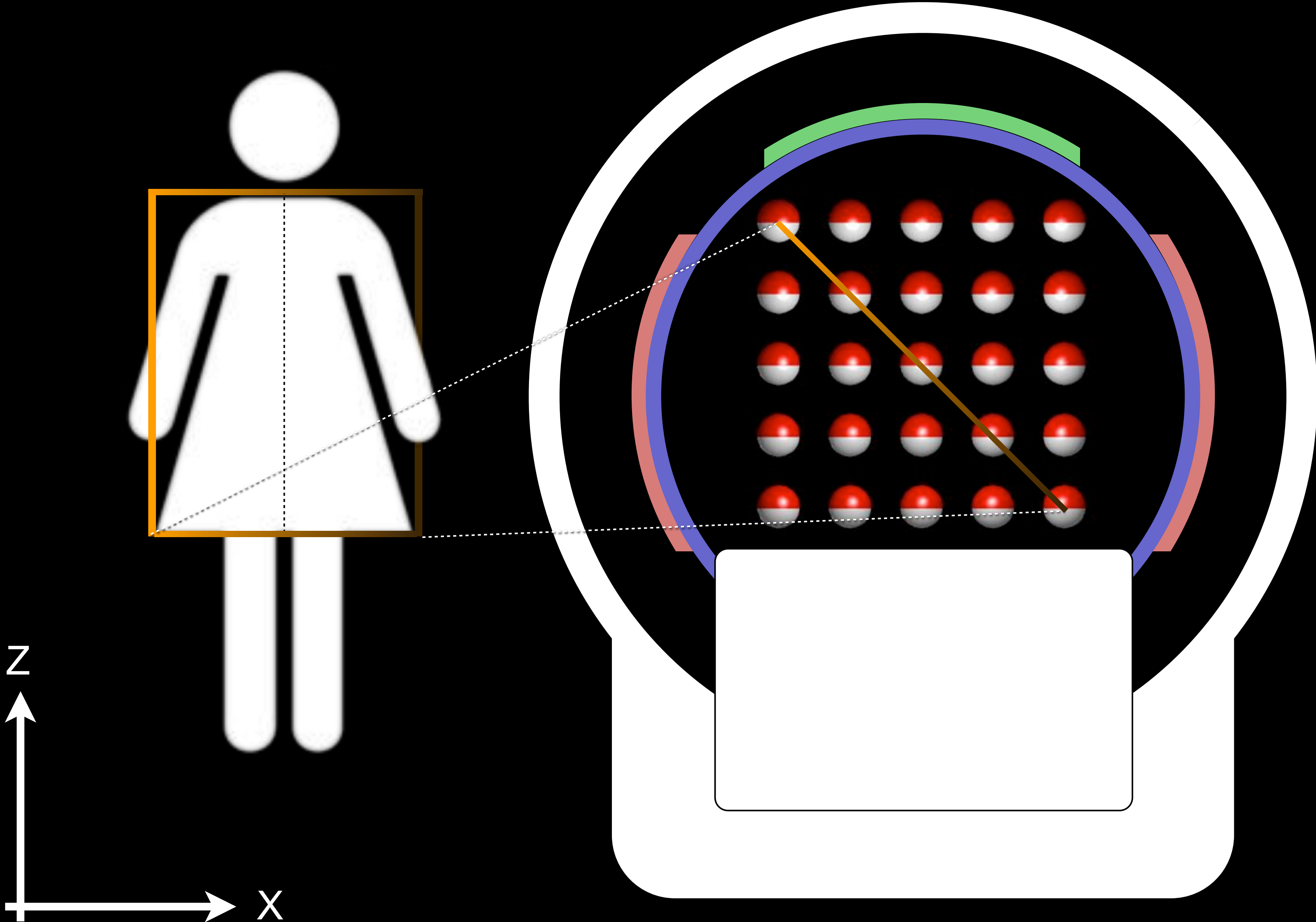




$$\omega = \gamma B_0$$

Spin Isochromat

Spins and X- & Y-Gradients



Simultaneously gradients create an arbitrary isochromat plane.

Quiz: Gradients - True or False?

1. Gradients are primarily used to make the B_0-field more homogeneous.

2. Gradients are essential to spatial encoding.

3. X, Y, and Z gradients can not be applied simultaneously.

Learning Objectives

- Distinguish between the body *transmit* and body *receive* coils.
- Appreciate that each coil is specialized for imaging the anatomy of interest.
- Characterize the strength and duration of gradient induced fields.
- Describe how gradients contribute to spatial localization.

Summary

- **NMR Active Nuclei**
  - e.g. ^{1}H in $H_2 0$
- **Magnetic Field (B_0)**
  - Polarizer
- **RF System (B_1)**
  - Exciter
- **Coil**
  - Receiver
- **Gradients (G_X, G_Y, G_Z)**
  - Spatial Encoding (imaging!)
- **Computers**
  - Image reconstruction

Thanks!

Daniel B. Ennis, Ph.D.
Magnetic Resonance Research Labs

DEnnis@mednet.ucla.edu
310.206.0713 (Office)
http://mrrl.ucla.edu

David Geffen
School of Medicine

UCLA
Radiology

On-Line Resources

- My Course: http://mrrl.ucla.edu/pages/m219_syllabus_2017
- https://www.healthcare.siemens.com/magnetic-resonance-imaging/magnetom-world/publications/mr-basics
    - "Magnets, Spins, and Resonances: An introduction to the basics of Magnetic Resonance" and more…
- http://www.magnet.fsu.edu/education/tutorials/magnetacademy
- http://www.mr-tip.com
- http://www.cis.rit.edu/htbooks/mri/
- Many more...