MRI Systems I: B0 and Bulk Magnetization

M219 - Principles and Applications of MRI

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1/11/2022

Course Overview

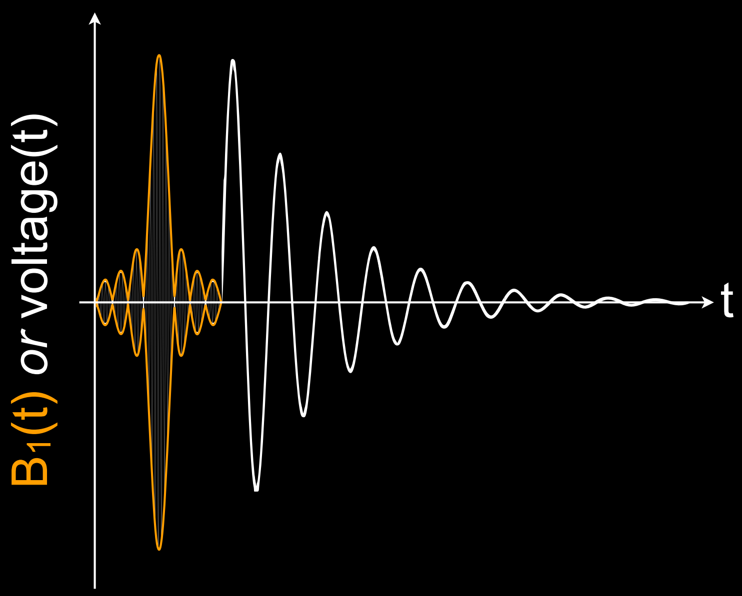
- Course website
  - https://mrrl.ucla.edu/pages/m219
- 2023 course schedule
  - https://mrrl.ucla.edu/pages/m219_2023
- Assignments
  - Homework #1 will be out on 1/16 (due on 1/30)
- Office hours, Fridays 10-12pm
  - In-person (Ueberroth, 1417B)
  - Zoom is also available

What is MRI?

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

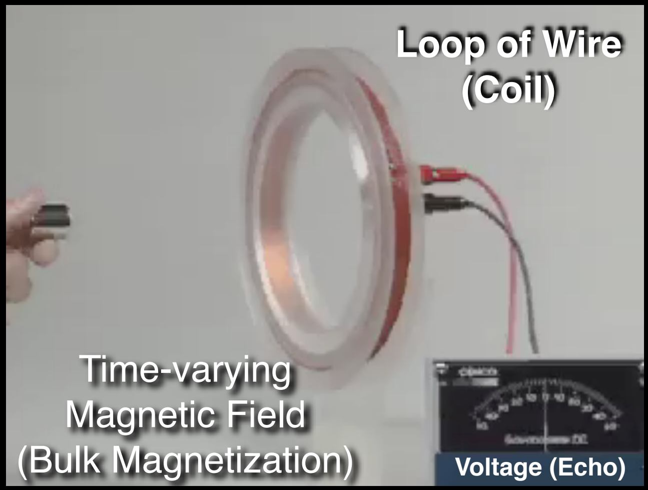
What is MRI?

MRI follows a classic excitation-reception paradigm.



Excitation
(RF Pulse)

Reception
(FID or **Echo**)



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

MRI Hardware

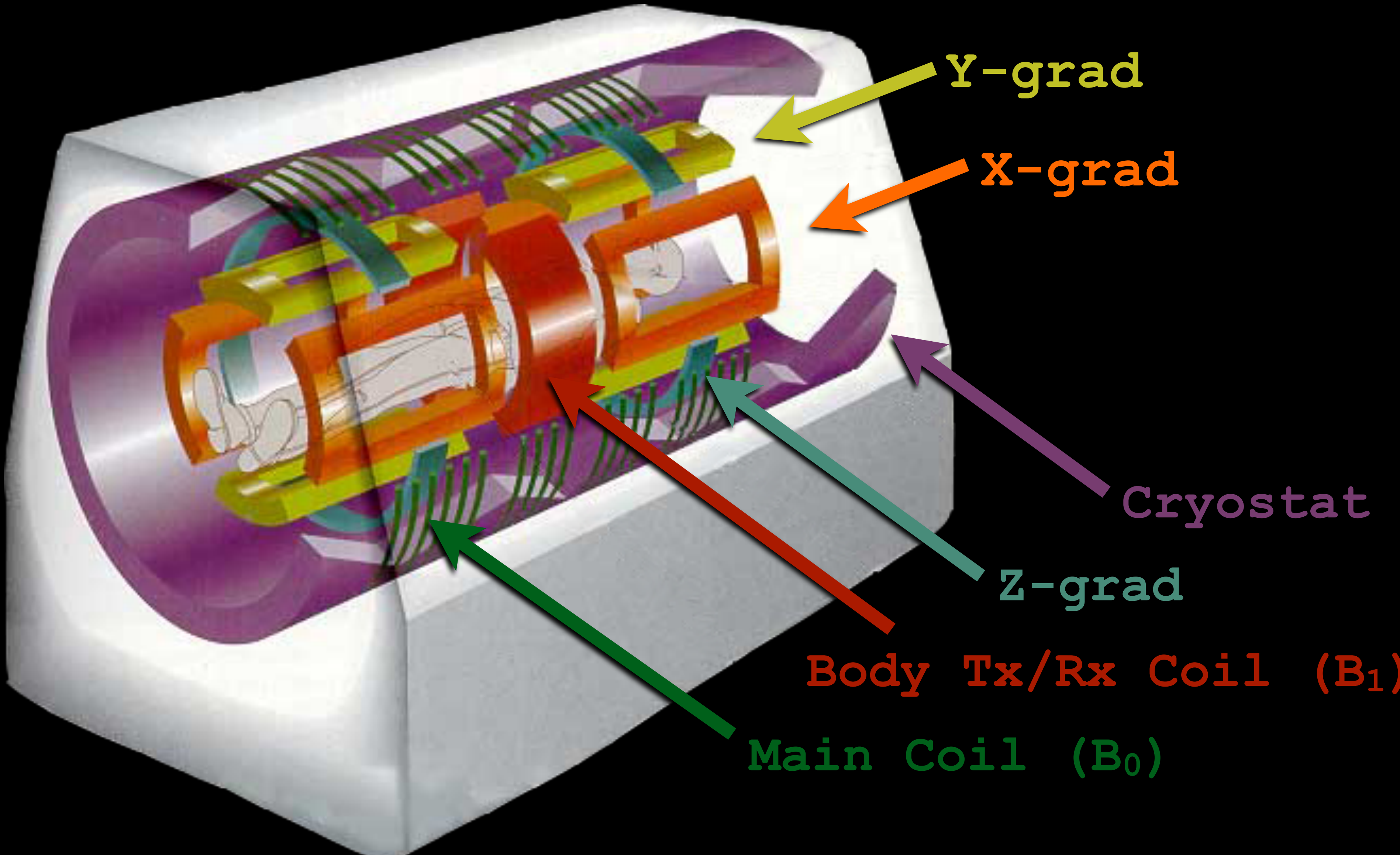


Image Adapted From: http://www.ee.duke.edu/~jshorey

Nuclear Spin

Classical View

Atoms having odd # of protons and/or neutrons → **Spin angular momentum**

$$\vec{S} = \hbar \vec{I}$$

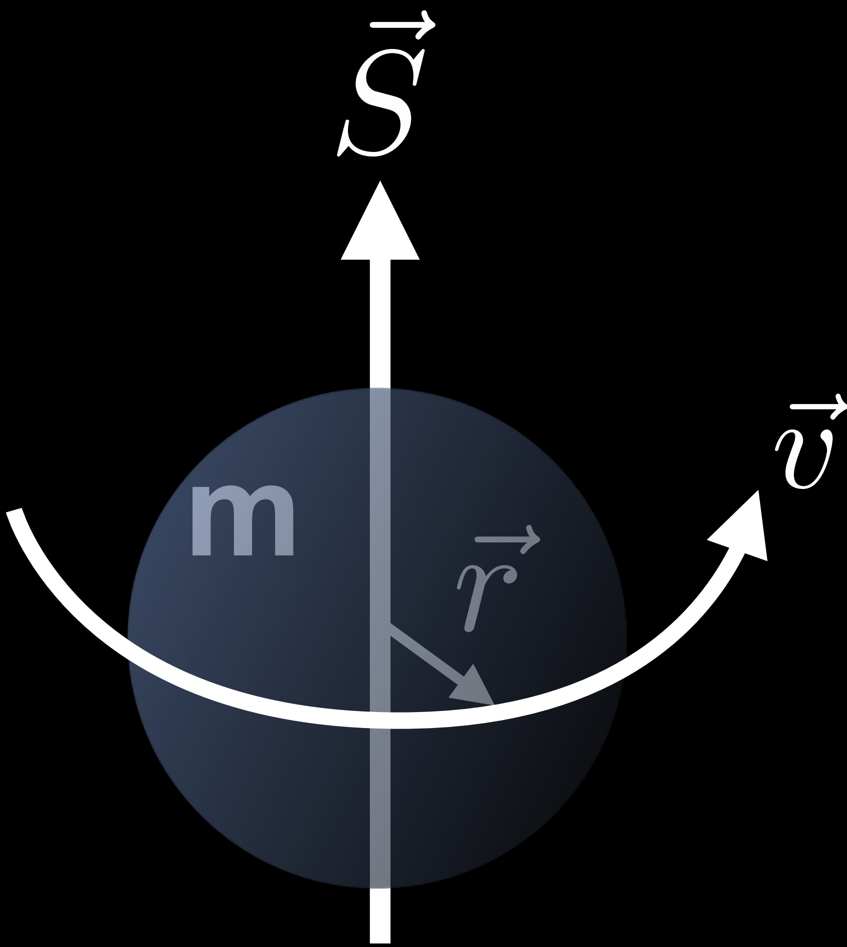
Planck's constant

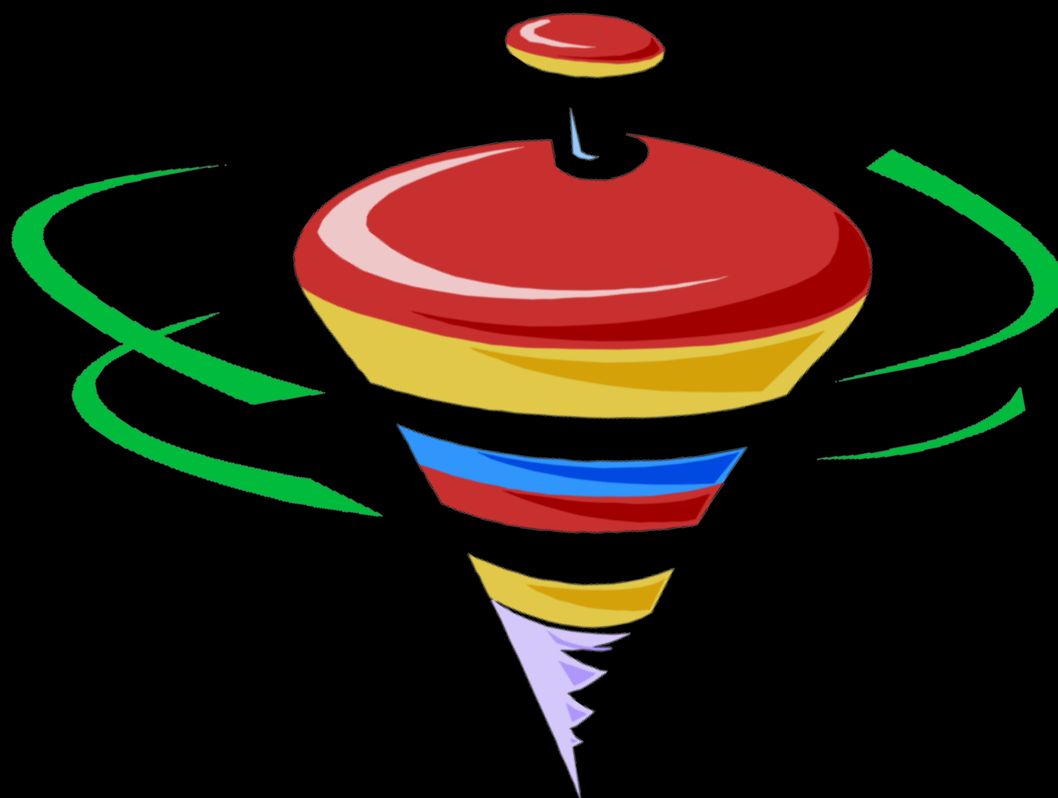
Spin quantum #

- Nuclei with an odd mass number have ***half-integral spin***
  - Spin-1/2 – ^{1}H, ^{13}C, ^{15}N, ^{19}F, ^{31}P
  - Spin-3/2 – ^{23}Na
- Nuclei with an even mass number and an even charge number have ***zero spin***
  - ^{12}C and ^{16}O

Spin Angular Momentum

Spin + Mass ➠ Spin Angular Momentum ➠ $\vec{S}$ [kg·m²s⁻¹]

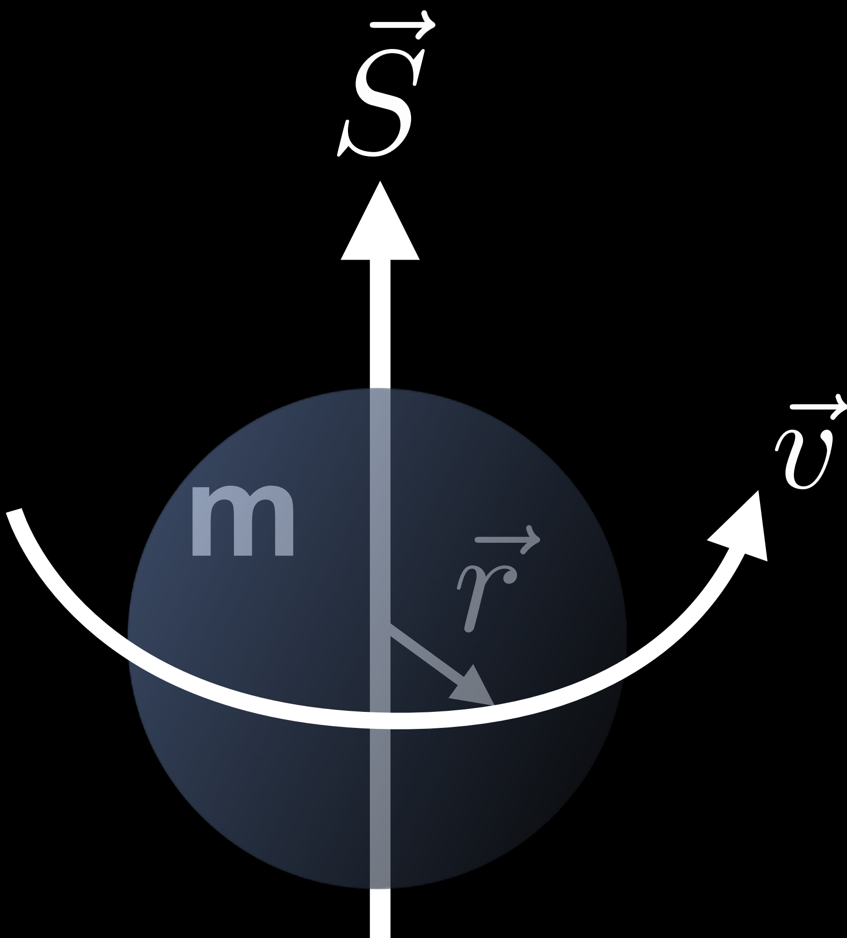




Hydrogen nuclei have spin angular momentum.

Spin Angular Momentum

Spin + Mass ➠ Spin Angular Momentum ➠ $\vec{S}$ [kg·m^{2}s^{-1}]



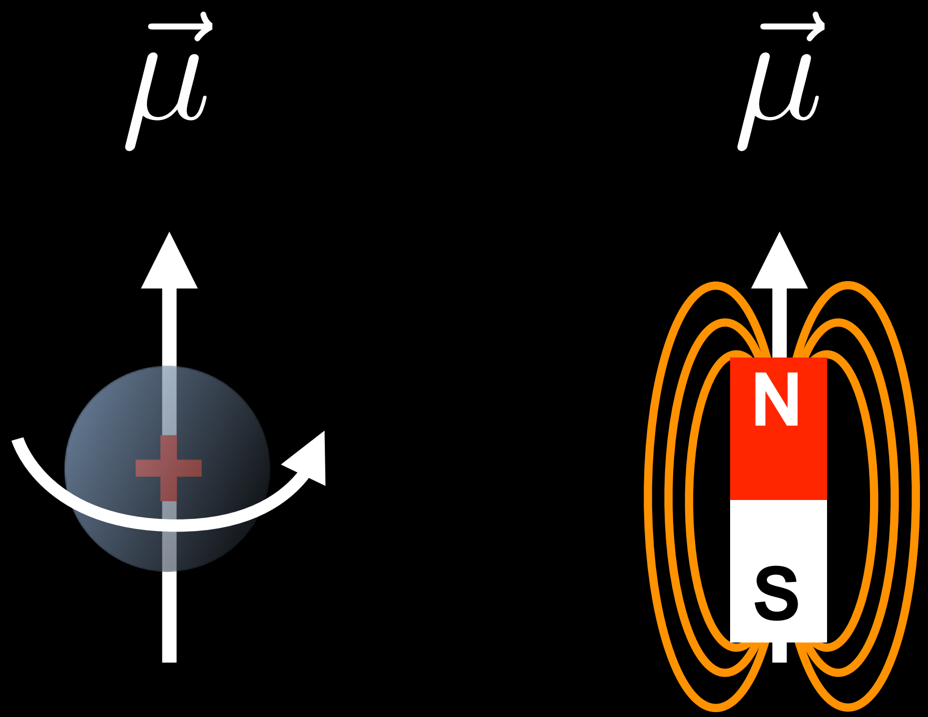
$$\vec{S} = \vec{r} \times \vec{p}$$
$$= \vec{r} \times m\vec{v}$$

Hydrogen nuclei have spin angular momentum.

Magnetic Dipole Moments

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

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



Hydrogen nuclei have magnetic dipole moments.

Gyromagnetic Ratio

- Gyromagnetic Ratio
  - Physical constant
  - Unique for each NMR active nuclei
  - Ratio of the magnetic moment to the angular momentum

$$\overrightarrow{\mu} = \gamma \overrightarrow{S} = \gamma \hbar \overrightarrow{I}$$

  - Governs the frequency of ***precession***
  - Gamma vs. Gamma-bar

$$\bar{\gamma} = \gamma / 2\pi$$

NMR Active Nuclei

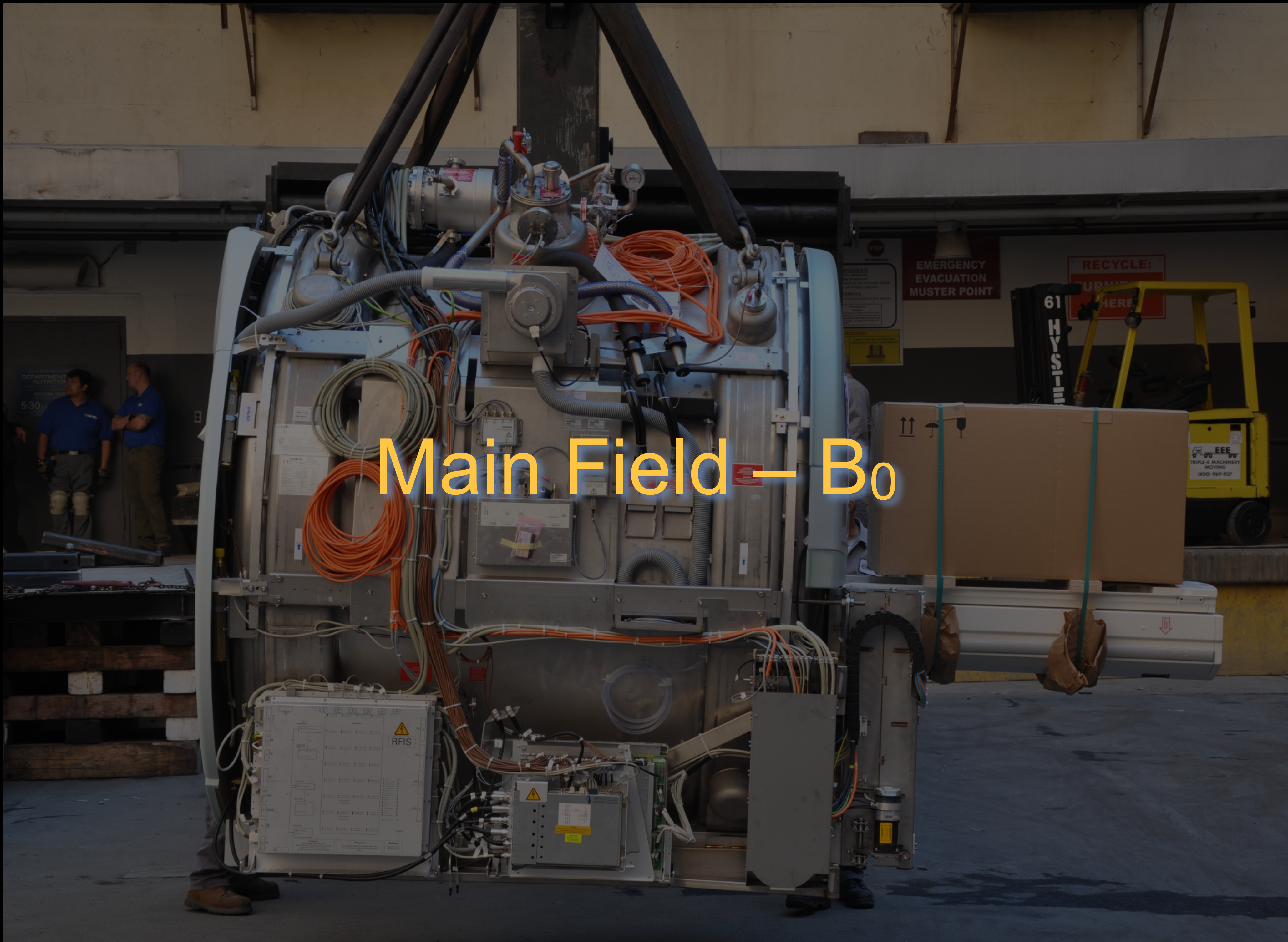
Isotope	*Spin [I]*	Natural Abundance	Gyromagnetic Ratio [MHz/T]	Relative Sensitivity	Absolute Sensitivity
^{1}H	**1/2**	**0.9980**	**42.57**	**1**	**9.98E-01**
^{2}H	1	0.0160	6.54	0.015	2.40E-04
^{12}C	0	0.9890	---	---	---
^{13}C	**1/2**	**0.0110**	**10.71**	**0.016**	**1.76E-04**
^{14}N	1	0.9960	3.08	0.001	9.96E-04
^{15}N	**1/2**	**0.0040**	**-4.32**	**0.001**	**4.00E-06**
^{16}O	0	0.9890	---	---	---
^{17}O	5/2	0.0004	-5.77	0.029	1.16E-05
^{19}F	**1/2**	**1.0000**	**40.05**	**0.83**	**8.30E-01**
^{23}Na	**3/2**	**1.0000**	**11.26**	**0.093**	**9.30E-02**
^{31}P	**1/2**	**1.0000**	**17.24**	**0.066**	**6.60E-02**

The ***relative*** sensitivity is at constant magnetic field and equal number of nuclei.

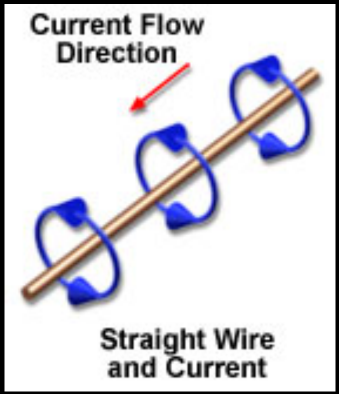
– Using a factor of $\gamma^{\frac{11}{4}} I\left(I+1\right)$; ^{1}H is the reference standard.

The ***absolute*** sensitivity is the relative sensitivity multiplied by natural abundance.

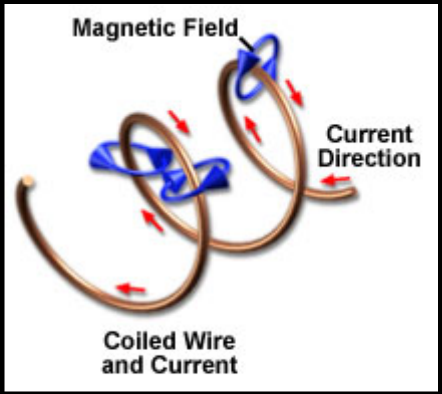
Main Field – B_0

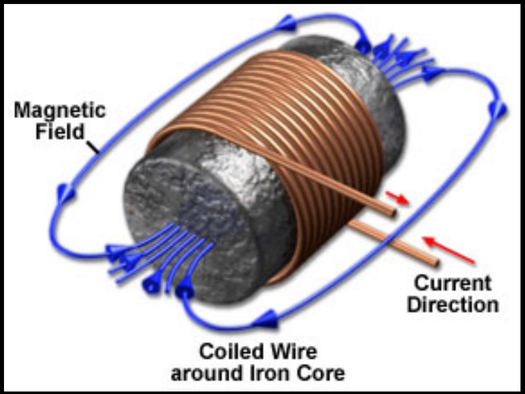


Currents & Magnetic Fields



Left-hand Rule

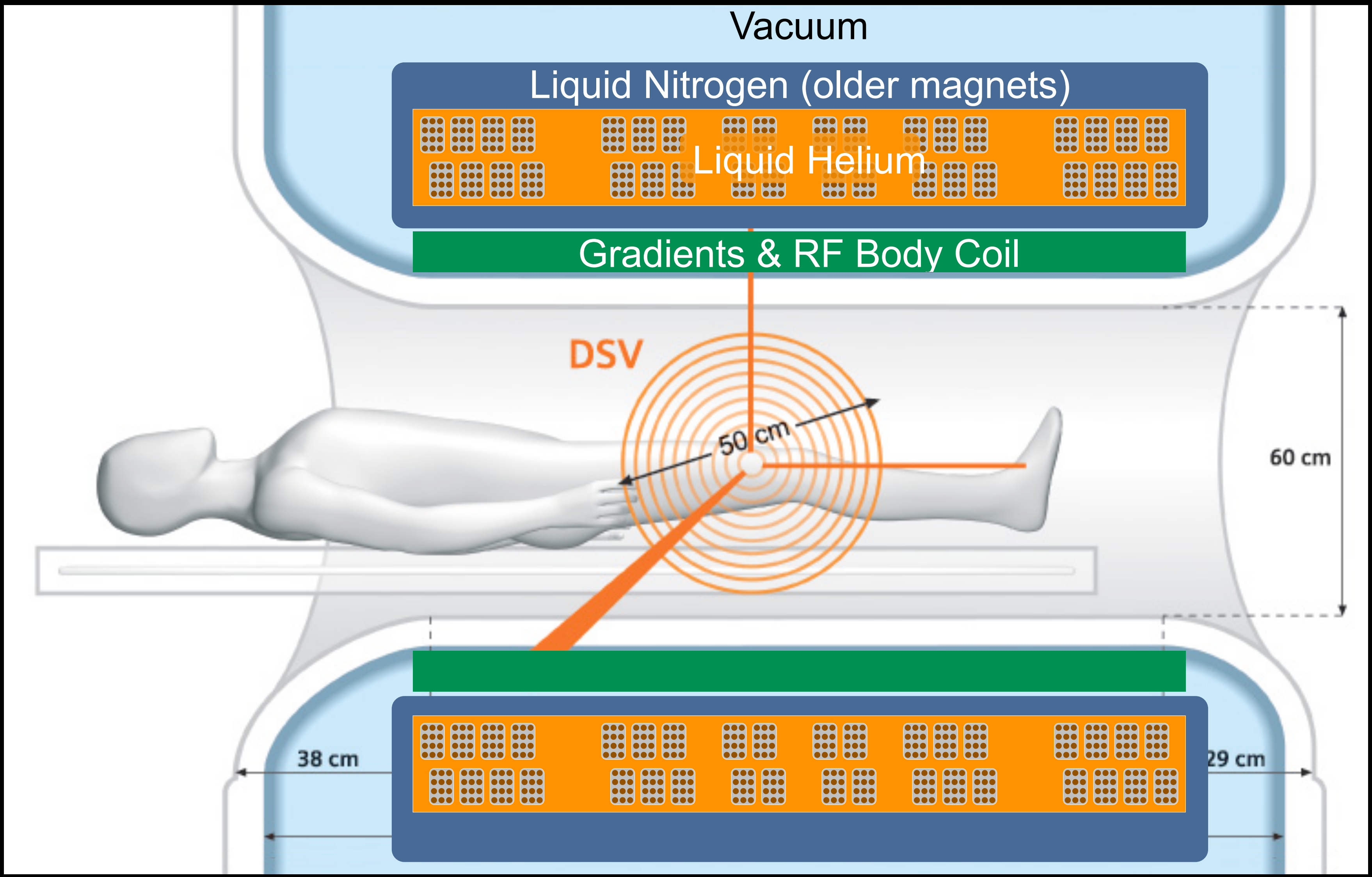




Electromagnet – A current in a wire generates a magnetic field.

http://www.magnet.fsu.edu/education/tutorials/magnetacademy/

Superconducting Electromagnet



MRI scanners are superconducting electromagnets.

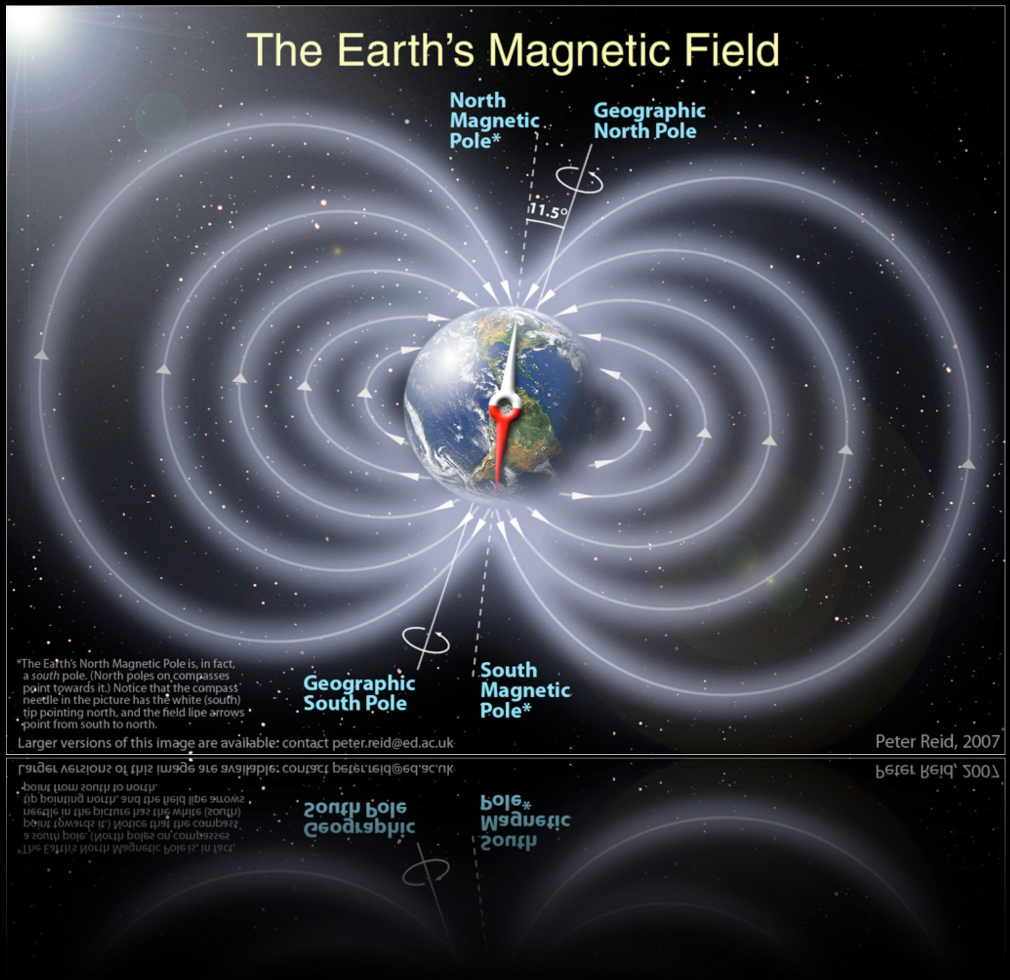
B_0 Field

- B_0 field is:
  - Spatially uniform (over a volume of interest)
    - ~50cm @ isocenter
  - Temporally stable
    - $B_0(t)=B_0(t=0)e^{-(R/L)/t}$
    - Decays <1ppm/hour
  - Oriented along the z-axis ($\vec{k}$)
    - Long axis of the scanner.

$$\vec{B}_0 = B_0\vec{k}$$

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



B_0 Strength - Advantages

- ⬆ $B_0 \implies$ ⬆ Polarization ($|\vec{M}|$) = ⬆ SNR
  - ⬆Polarization, therefore more $\vec{M}$ for imaging.
  - SNR $\propto B_0^{7/4}$ (⬆Polarization + ⬆Larmor Frequency)
    - ⬆ Spatial resolution
    - ⬆ Temporal resolution
    - ⬇ Scan time

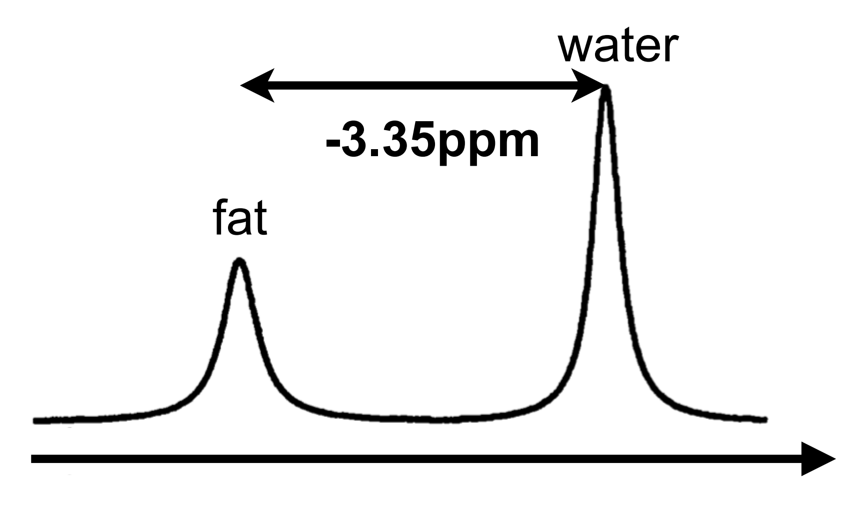
B_0 Strength - Disadvantages

- ⬆ $B_0 \Longrightarrow$ ⬆ Specific Absorption Ratio (SAR)
  - Energy absorbed by body [W/kg]
  - $SAR \propto B_0^2$
- ⬆ $B_0 \Longrightarrow$ ⬆ Cost
  - ~$1,000,000 per Tesla
  - More shielding

Higher B_0 leads to higher SAR for patients and higher costs.

B_0 Strength - Disadvantages

- ⬆ $B_0 \Longrightarrow$ ⬆ 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 <u>*more*</u> spatially mis-registered @ 3T
  - Good for spectroscopy…



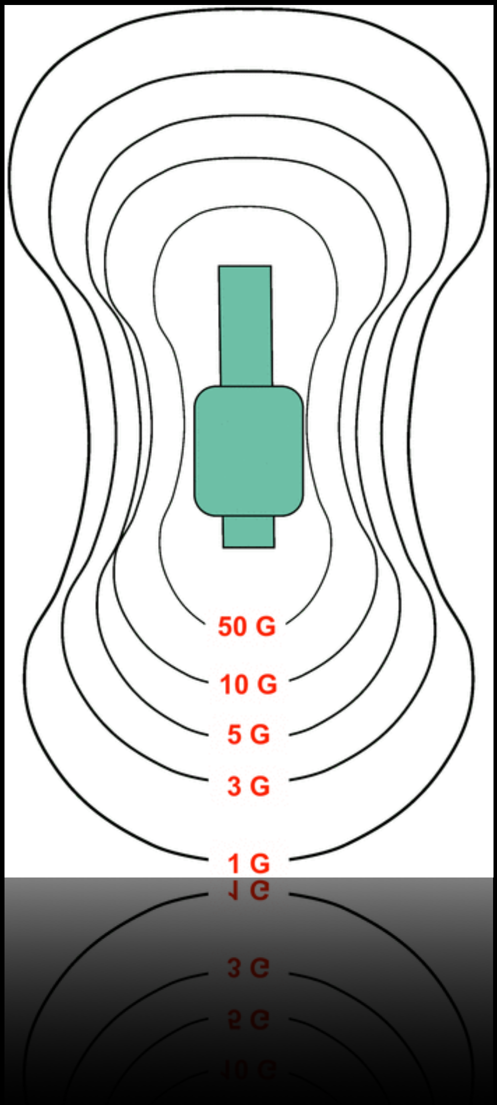
$$B = B_0\left(1-\delta\right)$$

$$\delta_{-\mathrm{CH}_2} = 3.35ppm$$

Chemical Shift – Fat ($-CH_2$) is ~220Hz *lower* at 1.5T

Main Field (B_0) – Shielding

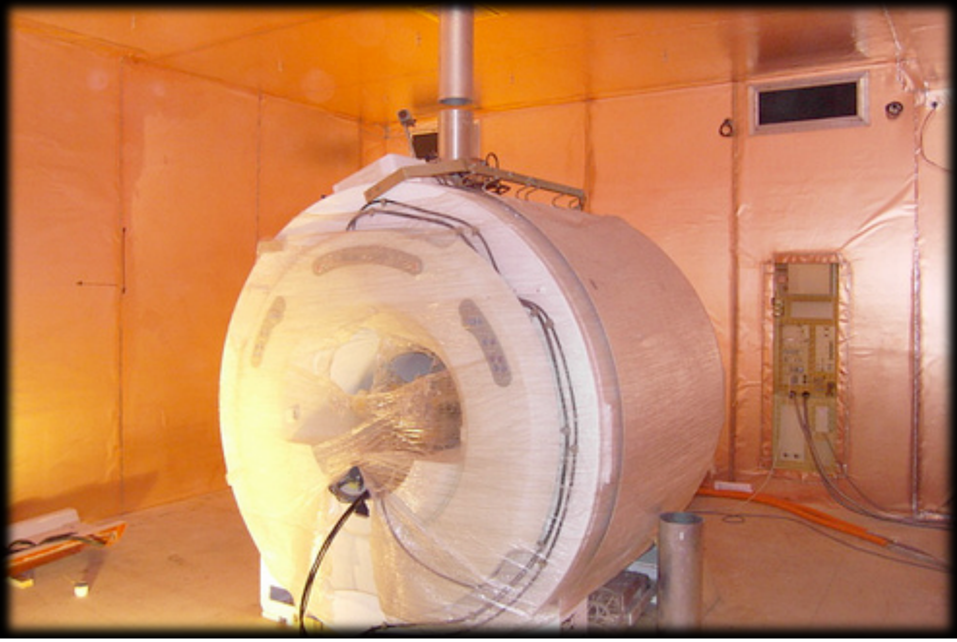
- **Problem**: The B_0 field extends well beyond the scanner.
- **Shielding** reduces B_0 foot print
  - Reduces install cost
  - Reduces interference
- **Passive Shielding**
  - Iron room shielding
  - Heavy, not cheap
- **Active Shielding**
  - Super-conducting coils that oppose (shield) B_0 fringe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



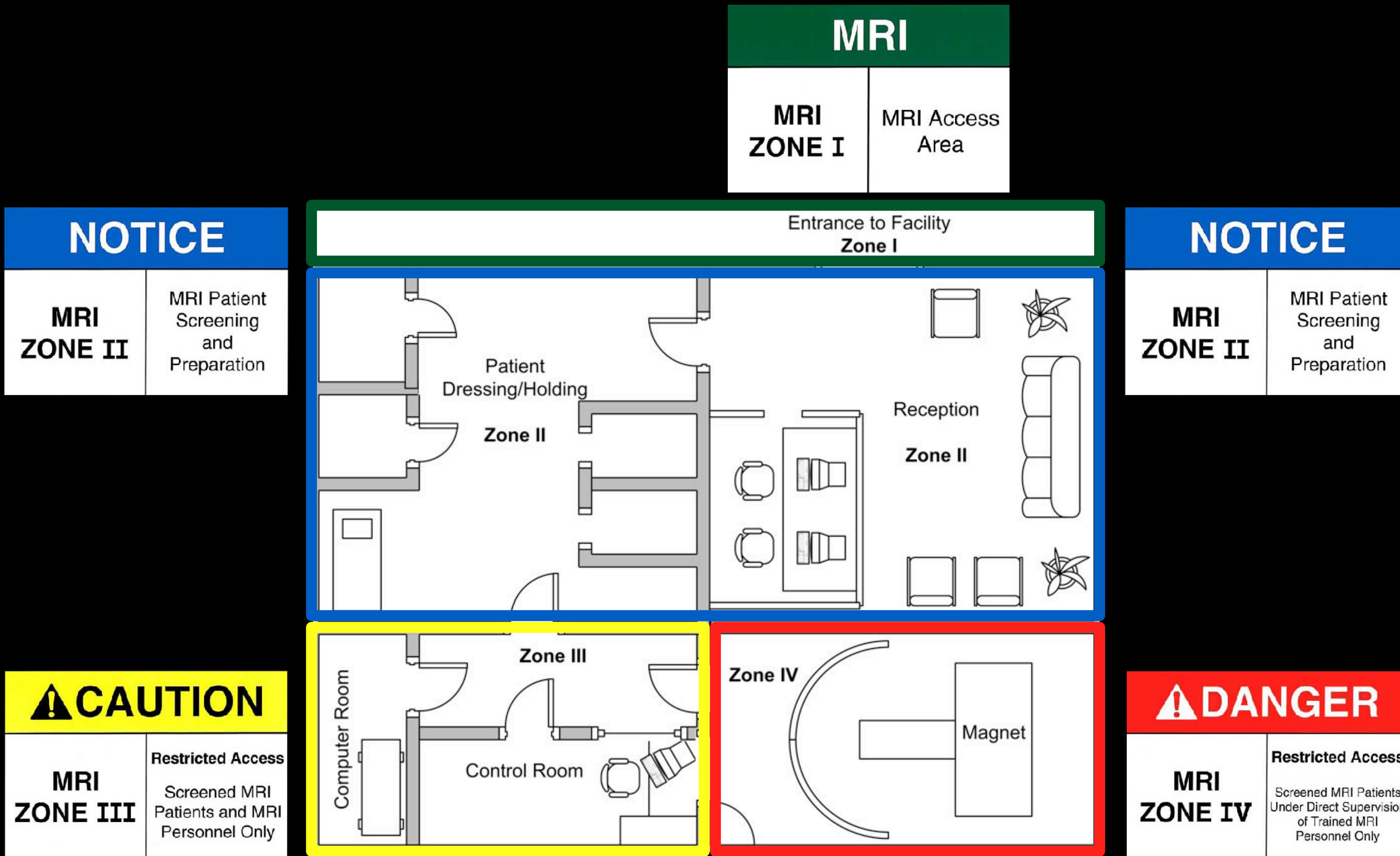
ACR Guidance Document on MR Safe Practices: 2013; *JMRI* 37:501–530 (2013)

RF Shielding

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



MRI Zones



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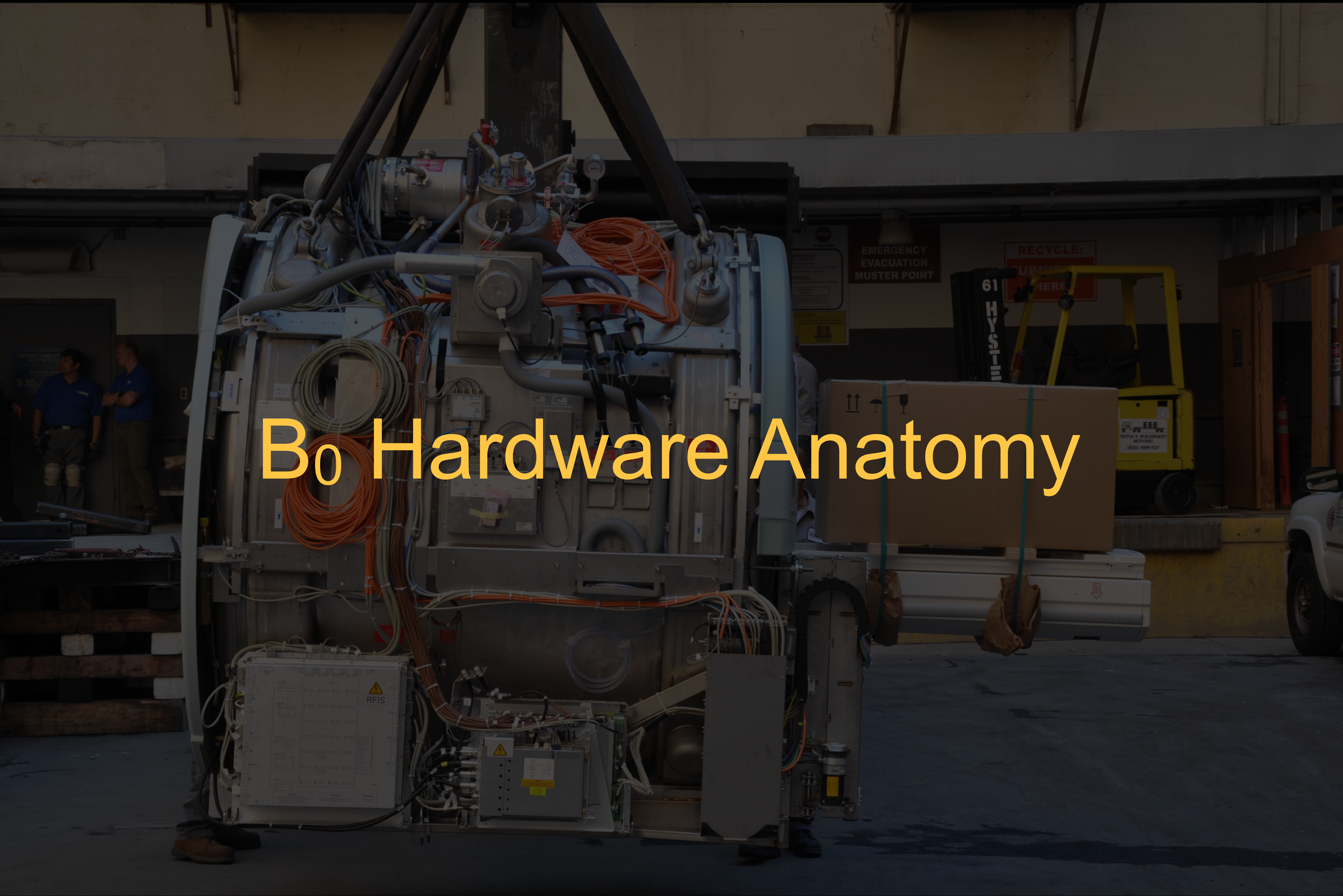
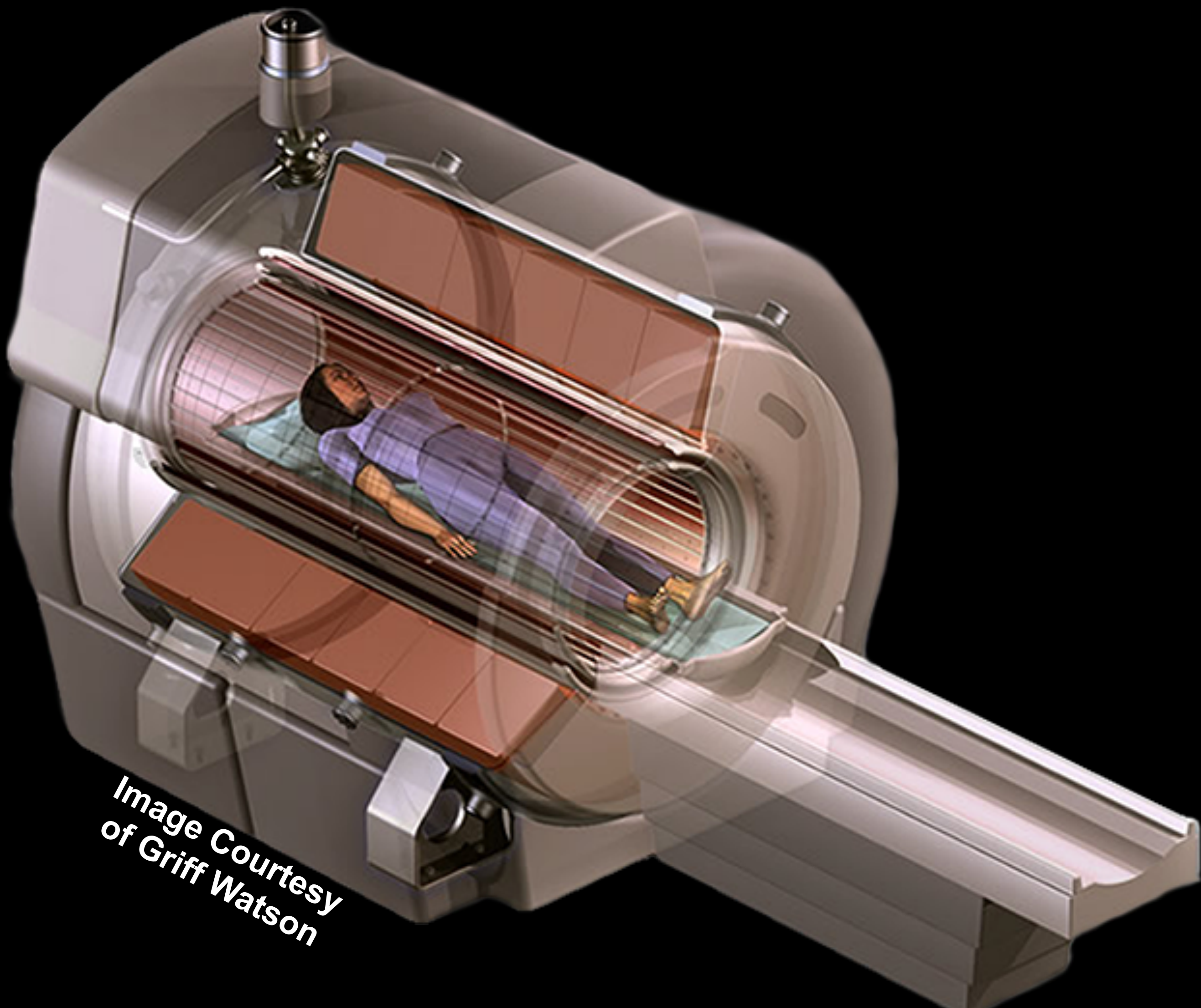
B_0 Hardware Anatomy

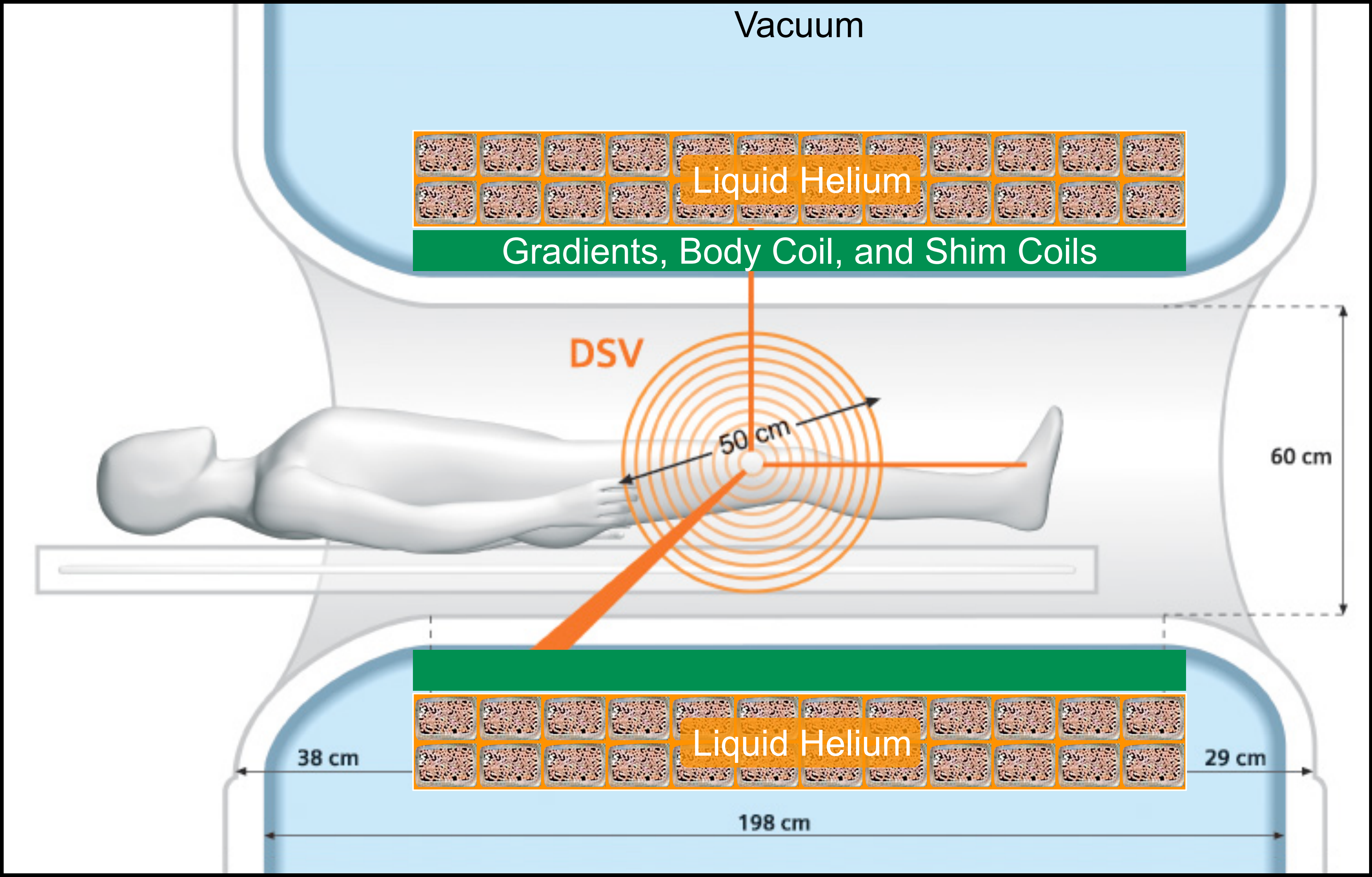


Superconducting Electromagnets

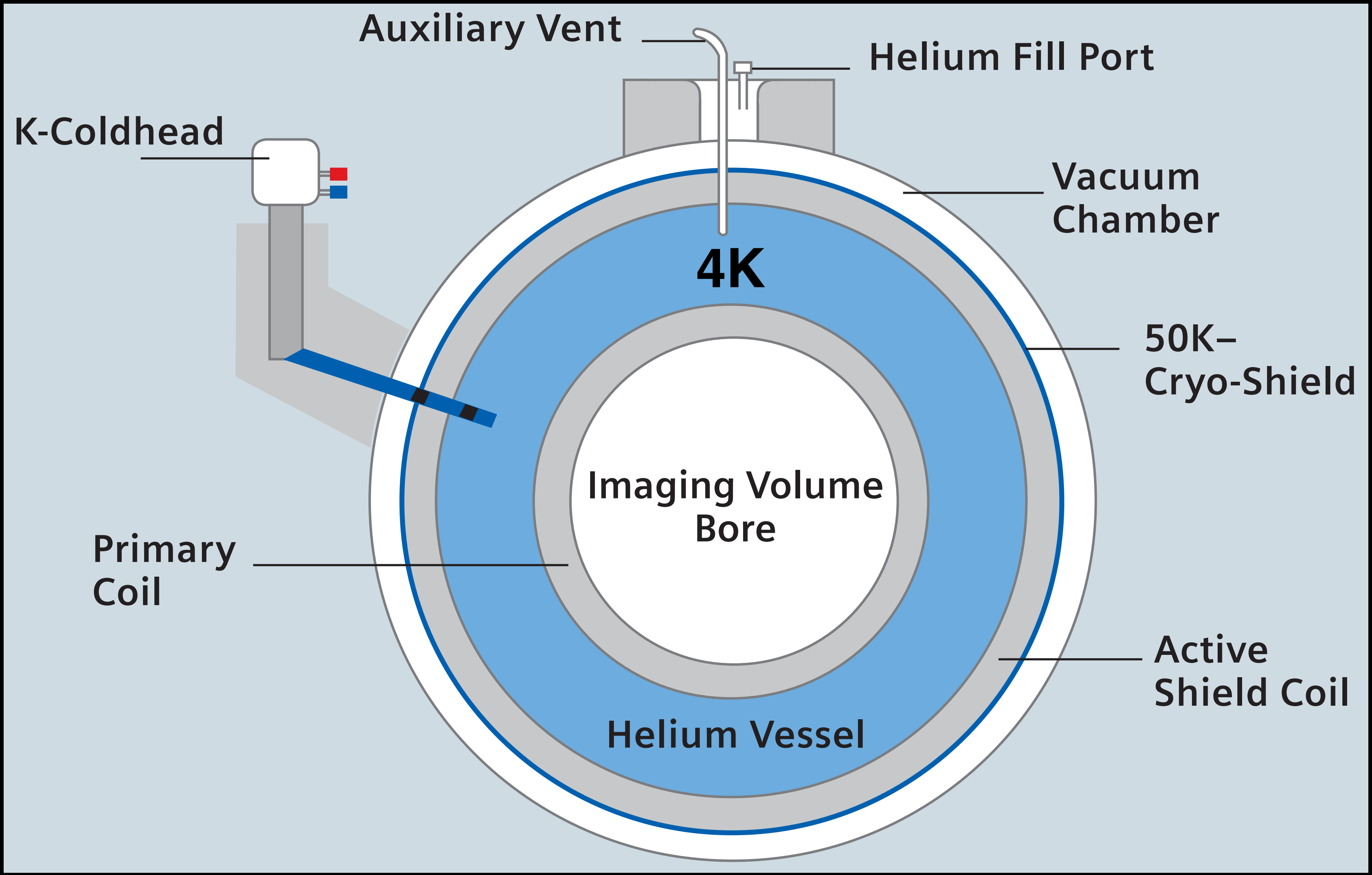
- MRI scanners are superconducting electromagnets
  - B-field is generated by flowing electricity
  - Permanent magnet MRI are uncommon



Superconducting Magnet

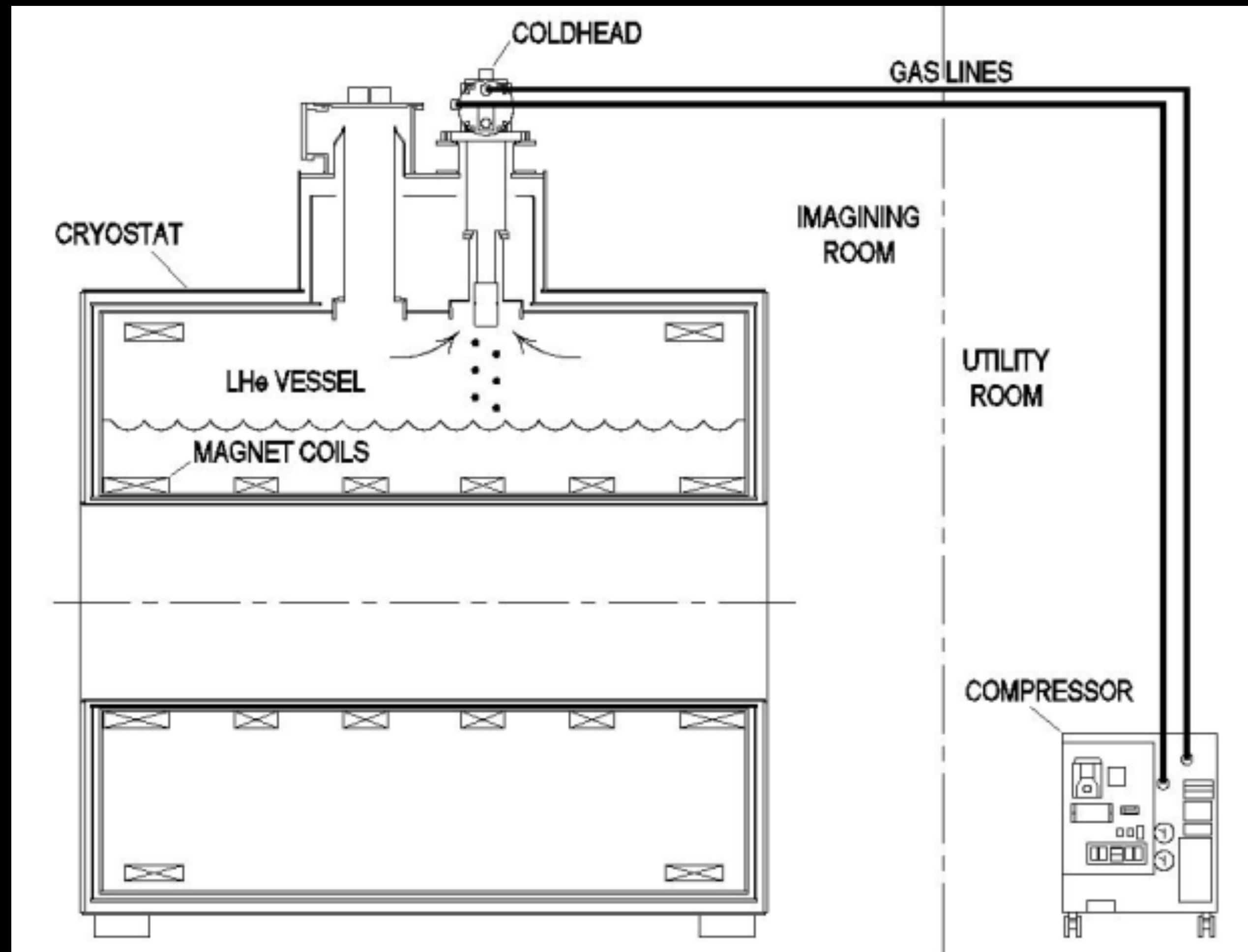


Superconducting Electromagnets



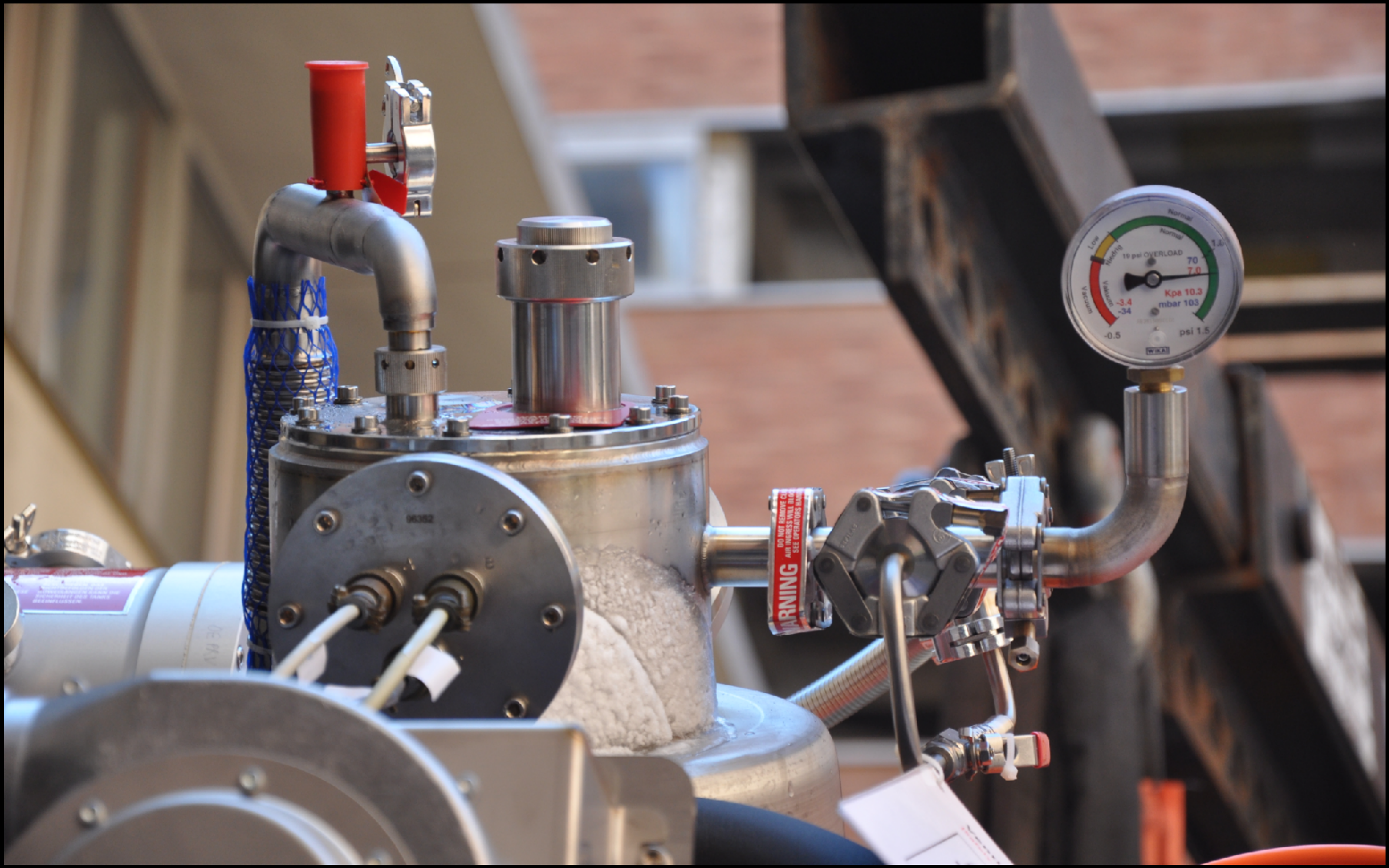
www.siemens.com/magnetom-world (Magnetom Flash 2/2008)

Coldhead (Cryocooler)



Re-condenses helium vapor and returns liquid helium to vessel.

Helium Fill Port



Helium boils off at 0 to 0.03 L/hour.
$10-$25 per liter of liquid Helium.

Zero Boil-off and Low Volume (~20L vs 2000L) systems are emerging.

Liquid Helium

- **Where does helium come from?**
  - **Extracted from natural gas**
  - **Strategic helium reserve**
  - **Helium that escapes to atmosphere is lost *forever*.**
- **Zero boil-off design**
  - **Captures and re-compresses cryogen**
  - **Saves 700-1300L per year**

Main Field (B_0) - Principles

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

$$\vec{B}_0 = B_0\vec{k}$$

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

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

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

$$\omega = \gamma B$$

Main Field (B_0) - Principles

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- B_0 generates bulk magnetization ($\vec{M}$)
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$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$ Eqn. 3.26

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

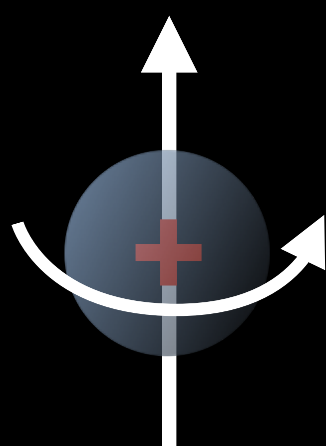
$$\omega = \gamma B$$ Eqn. 3.18

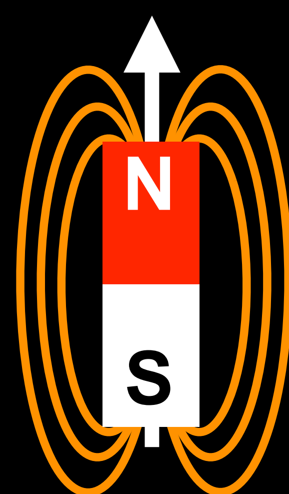
Magnetic Dipole Moments

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

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

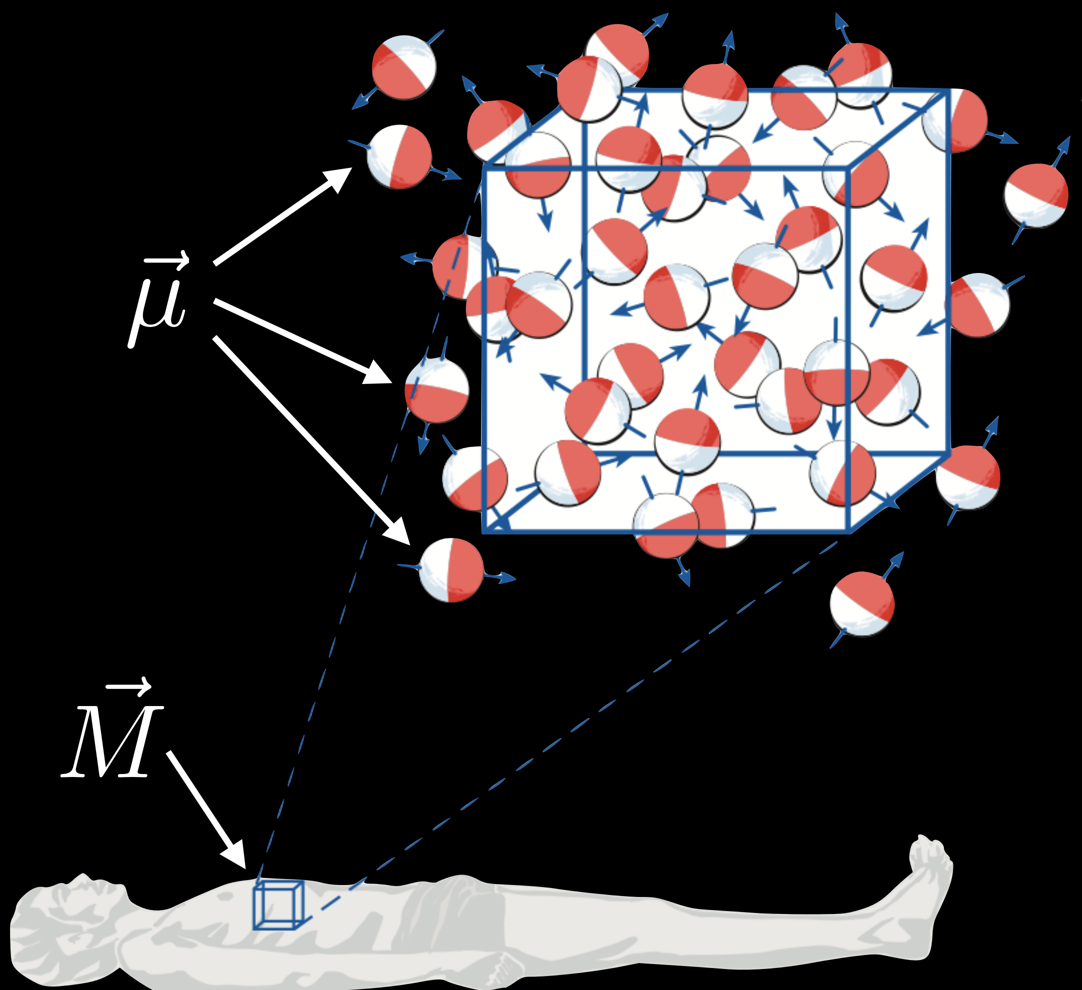
$\vec{\mu}$ $\vec{\mu}$





Hydrogen nuclei have magnetic dipole moments.

Bulk Magnetization

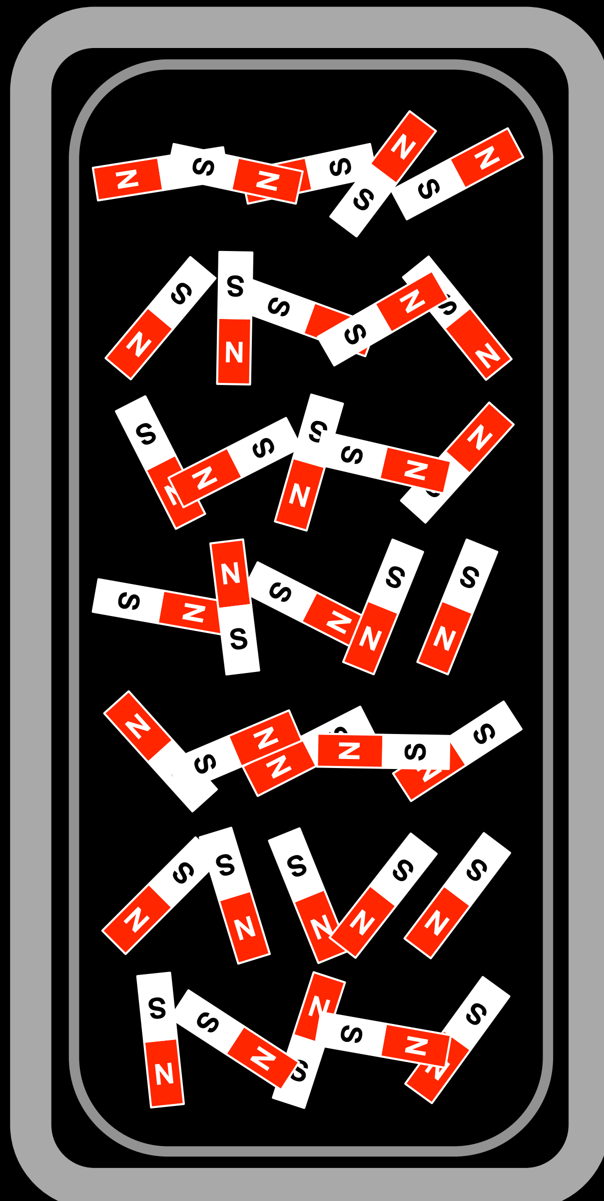


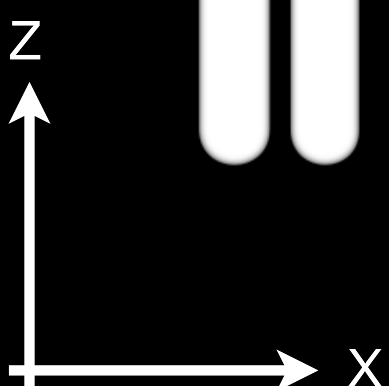
$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$

N_{total}=0.24x10^{23} spins in a 2x2x10mm voxel

But not all spins contribute to our measured signal...

B_0 Field OFF

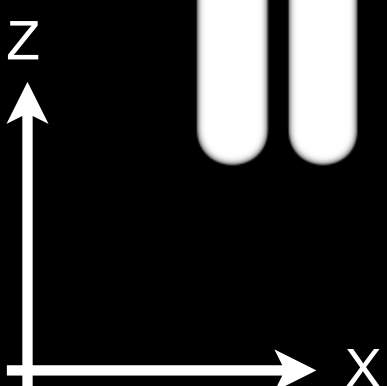


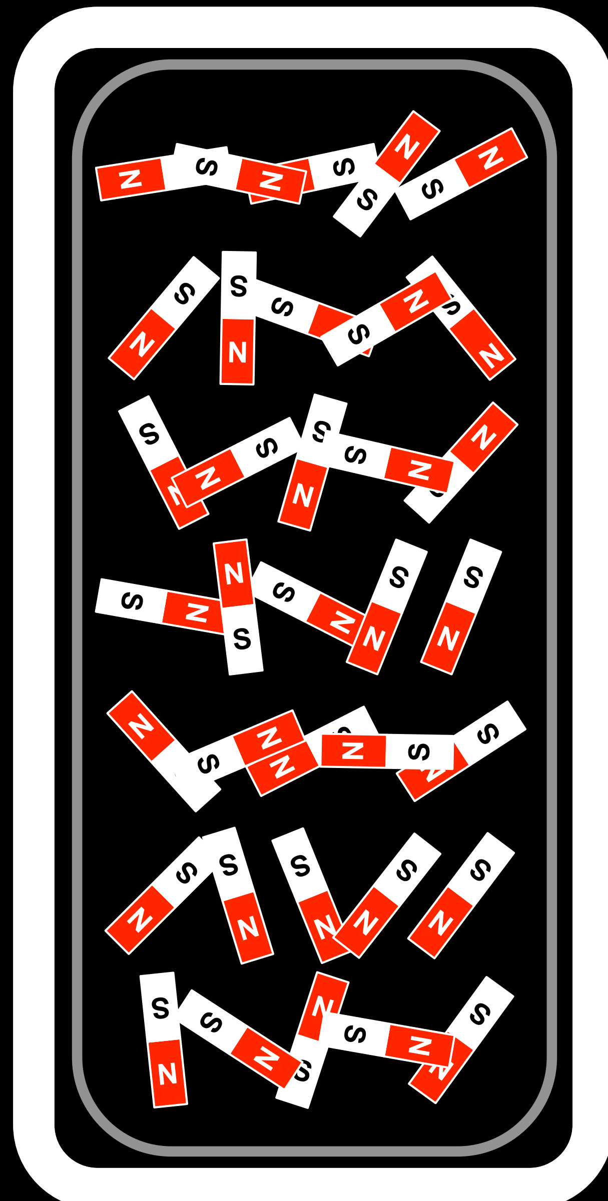


$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n = 0$$

Spins point in all directions.

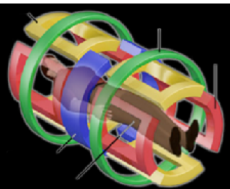
B_0 Field ON



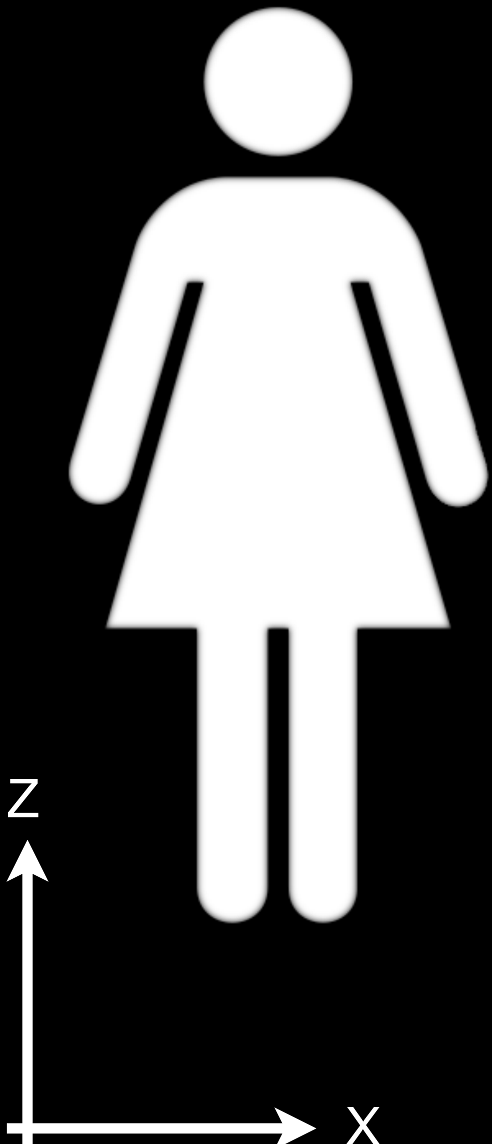


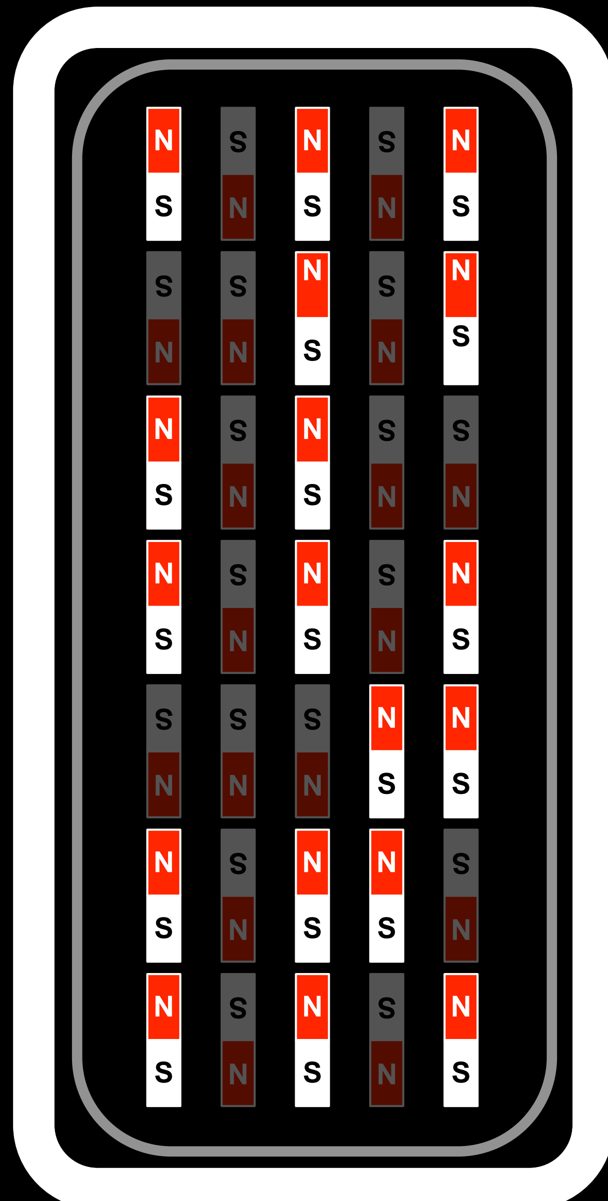
$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n = M_z$$

B_0 polarizes the spins and generates bulk magnetization.

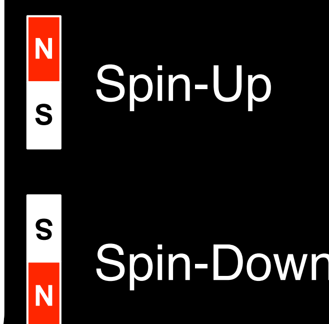


B_0 Field ON





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

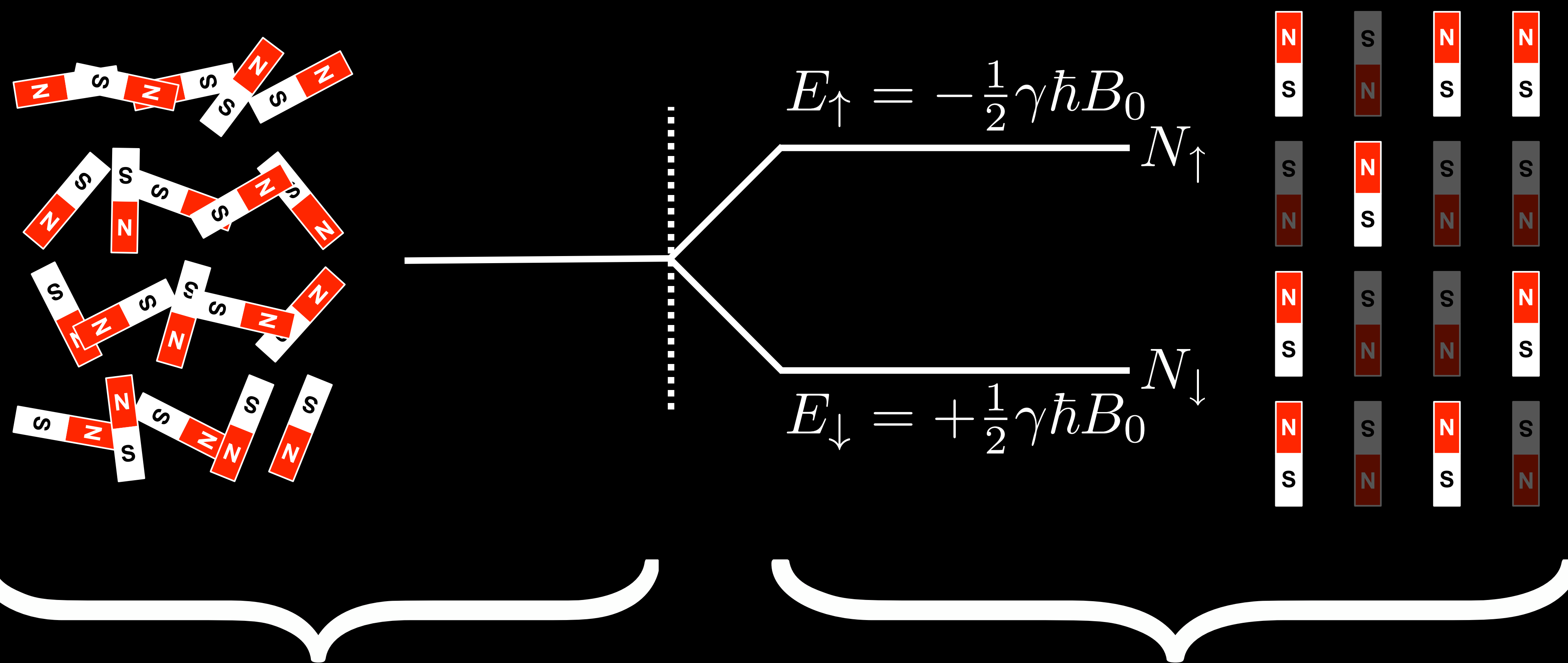


Only a very small number are spin-up relative to spin-down.

David Geffen School of Medicine

UCLA Radiology

Zeeman Splitting



B_0 is off

B_0 is on

$N_{\uparrow}$ = Spin-Up State, Low Energy

$N_{\downarrow}$ = Spin-Down State, High Energy

Zeeman Splitting

- The spin population difference in the two spin states is related to their energy difference. According to the well-known Boltzmann distribution:

$$\frac{N_{\uparrow}}{N_{\downarrow}} = e^{-\Delta E/\kappa T}$$

$\Delta E = \gamma \hbar B_0$

$\kappa =$ Bolzmann constant

$T =$ Absolute temperature of the spin system

- At 1.5T, $\frac{N_{\uparrow}}{N_{\downarrow}}$ = 0.999993
  - All imaging is based on weak polarization (enough for clinical)

Main Field (B_0) - Principles

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$$\vec{B}_0 = B_0\vec{k}$$

Eqn. 3.5

- B_0 generates bulk magnetization ($\vec{M}$)
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$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$

Eqn. 3.26

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

$$\omega = \gamma B$$

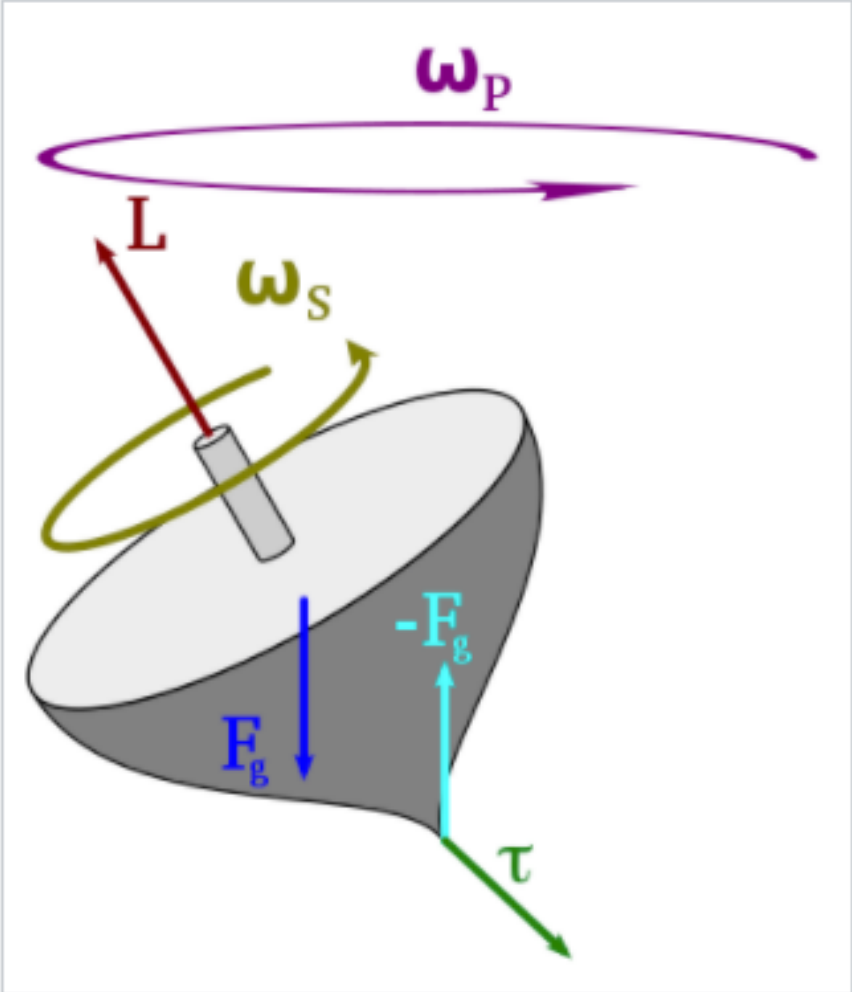
Eqn. 3.18

Spin vs. Precession

- **Spin**
  - Intrinsic form of angular momentum
  - Quantum mechanical phenomena
  - No classical physics counterpart
    - Except by hand-waving analogy…

- **Precession**
  - Spin+Mass+Charge give rise to precession

Precession

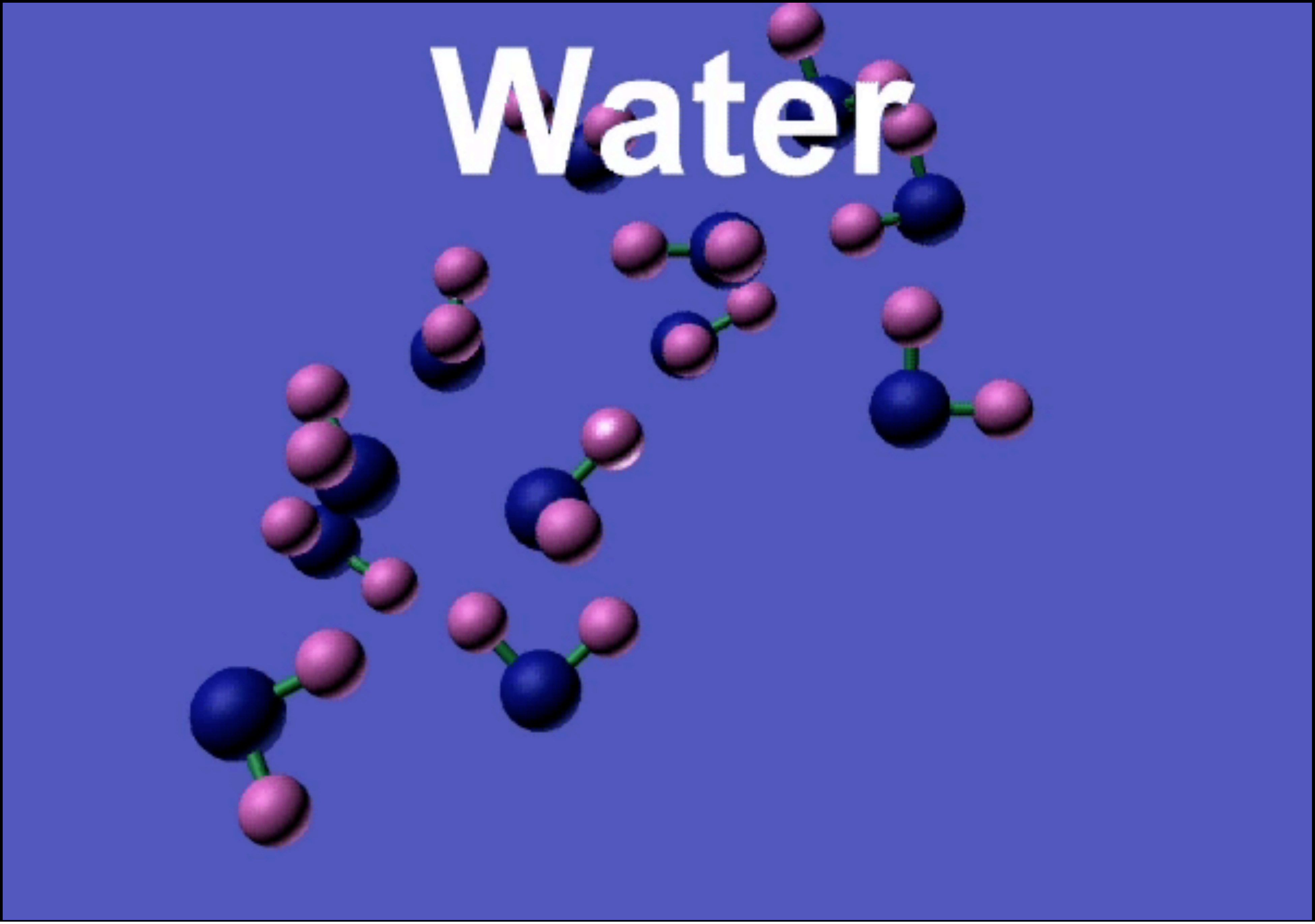


The torque caused by the normal force $-\mathbf{F}_g$ and the weight of the top causes a change in the angular momentum $\mathbf{L}$ in the direction of that torque. This causes the top to precess.

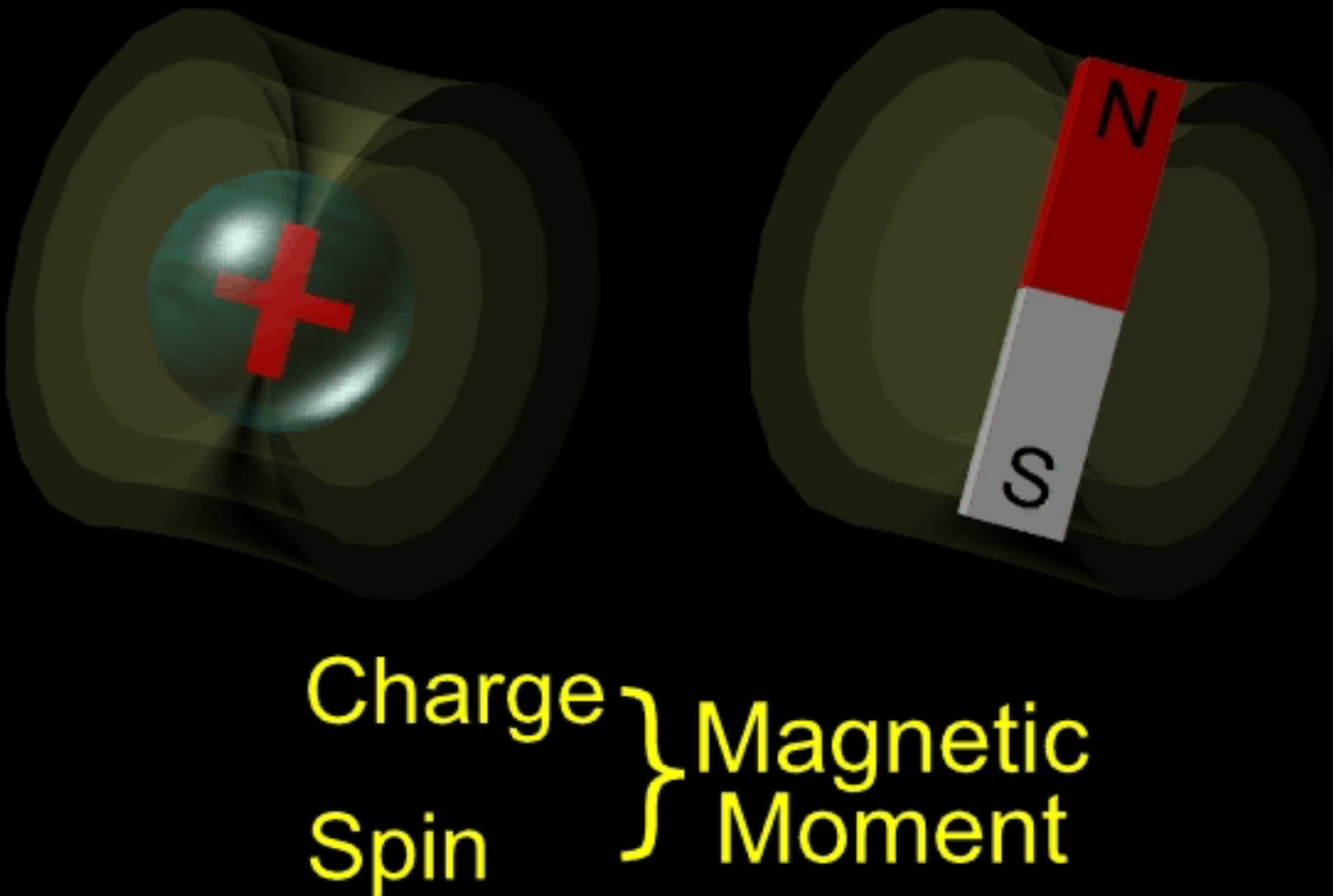
https://en.wikipedia.org/wiki/Precession

Nuclear Magnetic Resonance

NMR Phenomena

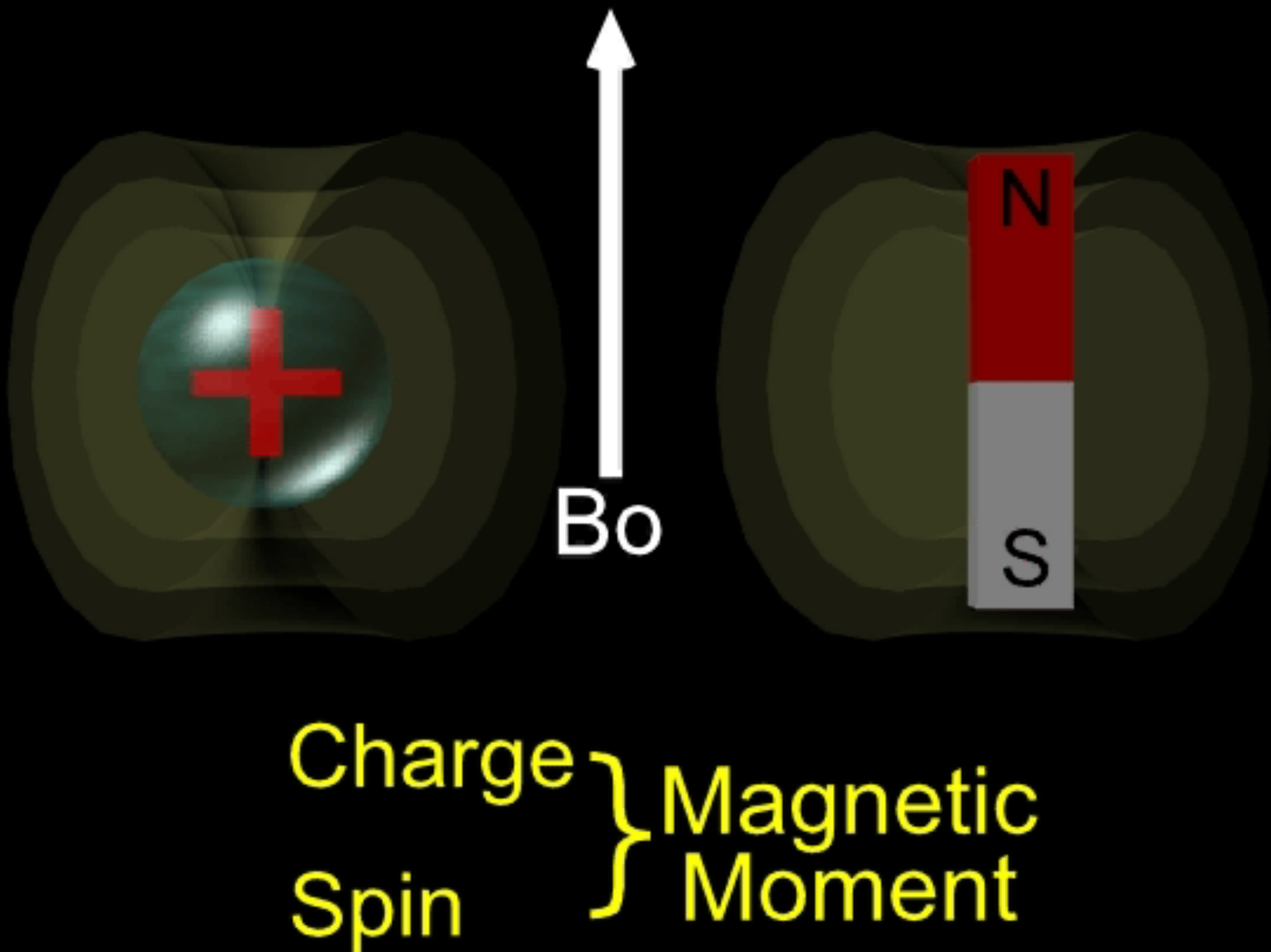


Magnetic Moment



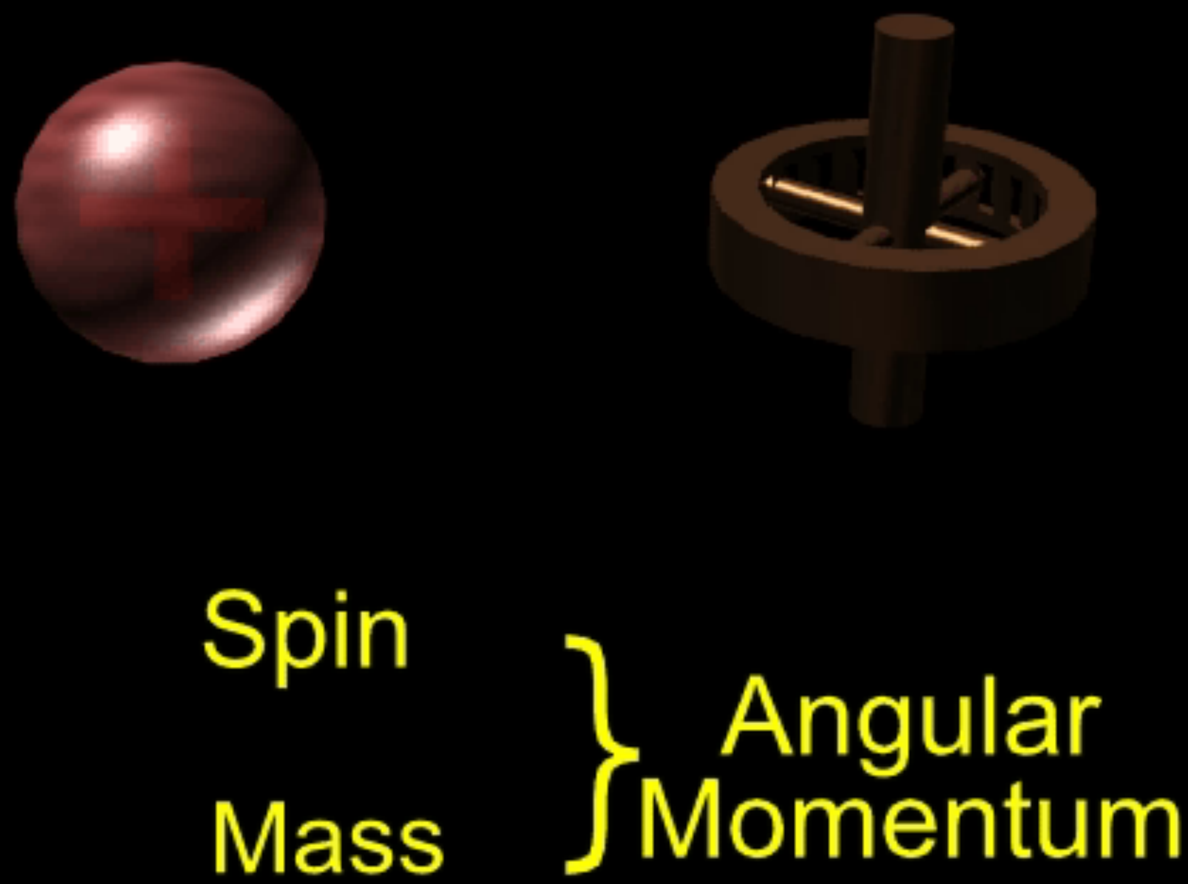
Protons behave like small magnets because of spin and charge.

Magnetic Moment



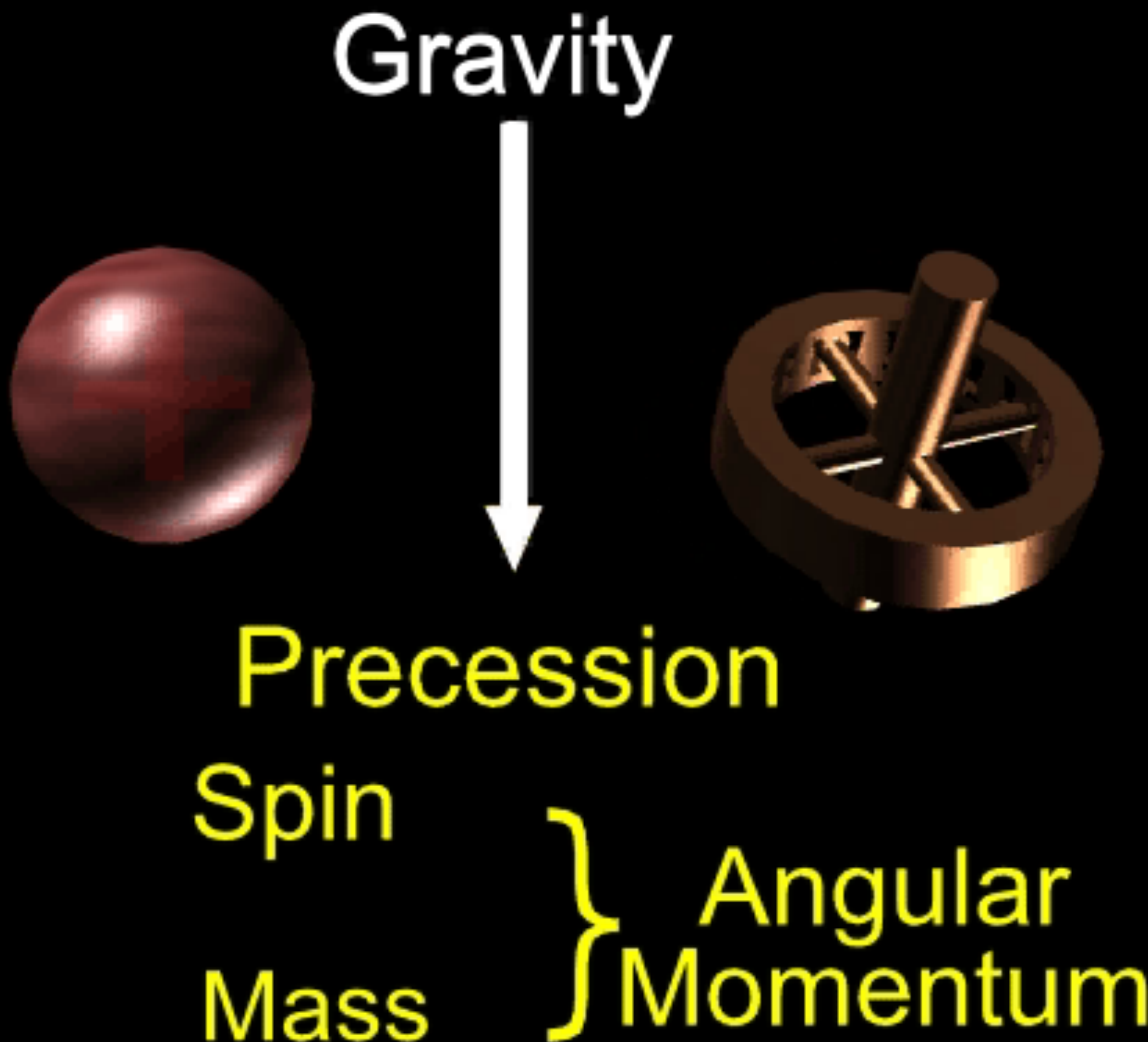
Protons (small magnets) align with an external magnetic field (B_0).

Angular Momentum



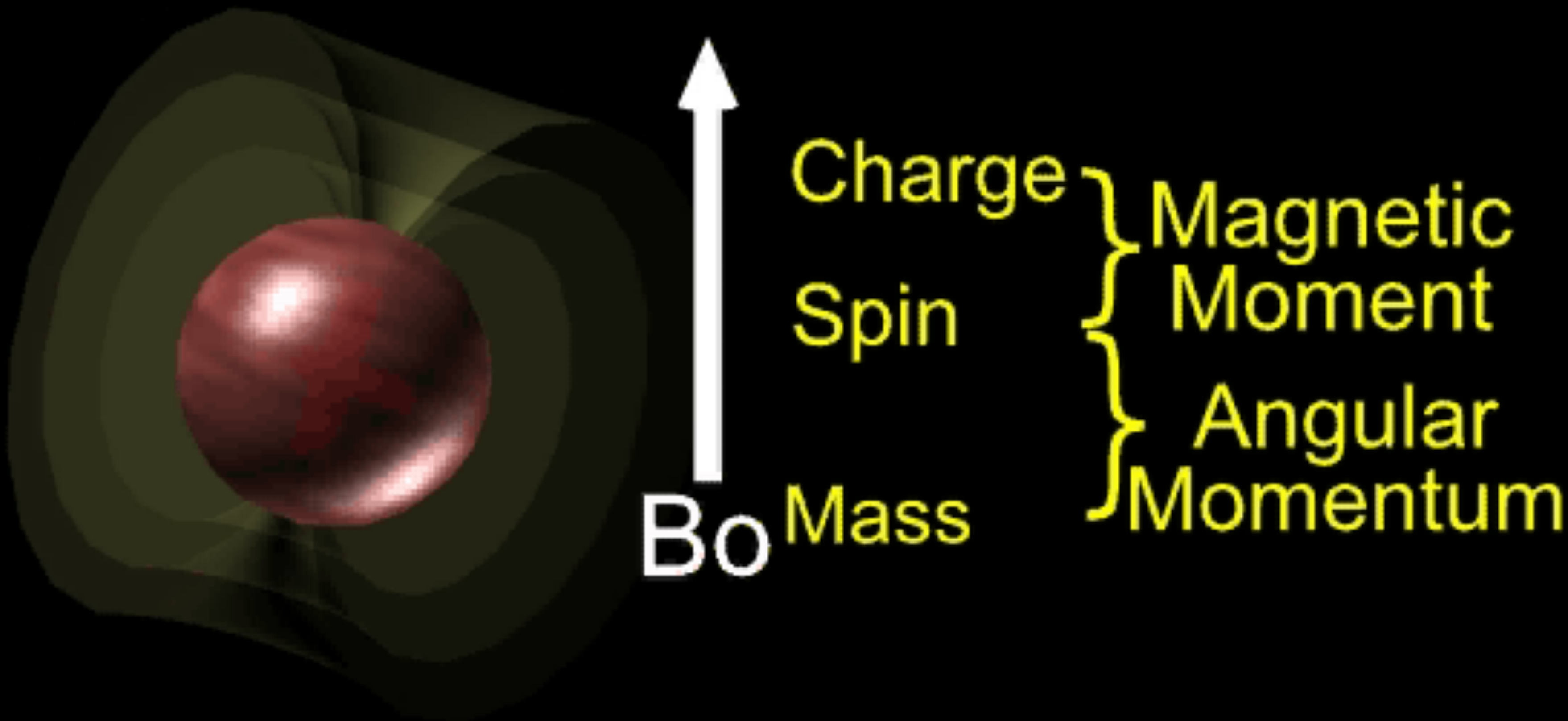
Protons have angular momentum because of spin and mass.

Precession (Top Analogy)



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

Larmor Frequency



$$\text{Larmor Frequency} = \omega = \gamma\, Bo$$

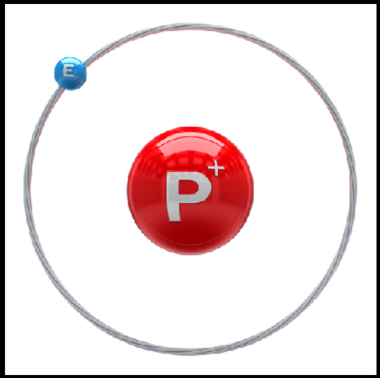
The frequency of precession is the Larmor frequency.

NMR Active Nuclei

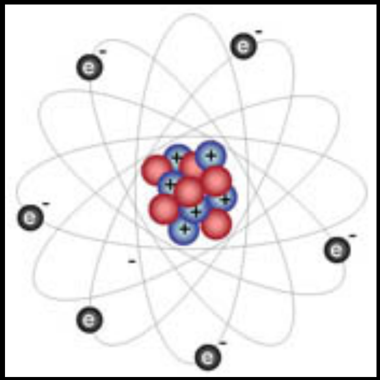
- Spin + Charge + Mass $\Longrightarrow$ NMR Active
  – Spin? ***Intrinsic*** form of angular momentum.
- Nuclei have spin angular momentum if:
  – Odd atomic mass (# protons+neutrons)

    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)
    – Physical constant
    – Unique for each NMR active nuclei



Hydrogen


Carbon-13

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

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...

$$\omega = \gamma B_0$$

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

Quiz: NMR - True or False?

1. Electron spin is the key to NMR
2. MRI is *nothing* without spin, charge, and mass
3. All atomic nuclei are NMR active.
4. Spin and precession are the same.
5. Higher fields lead to faster precession

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 precesses at the same Larmor frequency.

Questions?

- Related reading materials
  - Nishimura Chap 3 and 4

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