MRI Systems I: B0 and Bulk Magnetization

M219 - Principles and Applications of MRI

Kyung Sung, Ph.D.

1/8/2025

Department of Radiological Sciences
David Geffen School of Medicine at UCLA

Course Overview

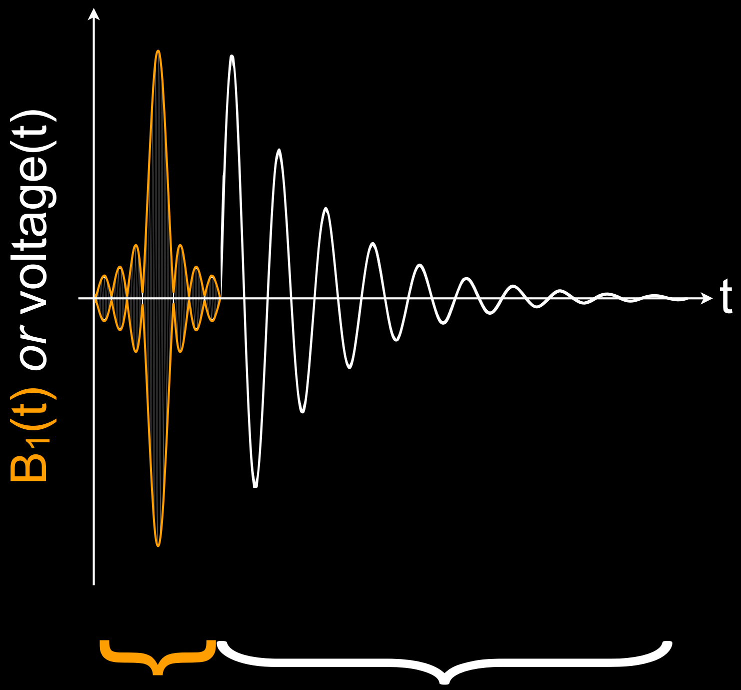
- Course website
  - https://mrrl.ucla.edu/pages/m219
- 2025 course schedule
  - https://mrrl.ucla.edu/pages/m219_2025
- TA - Raymi Ramirez, RaymiRamirez@mednet.ucla.edu
- Assignments
  - Homework #1 will be out on 1/13 (due on 1/29)
- Office hours, Fridays 10-11pm
  - In-person (Ueberroth, 1417B) or Zoom

What is MRI?

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

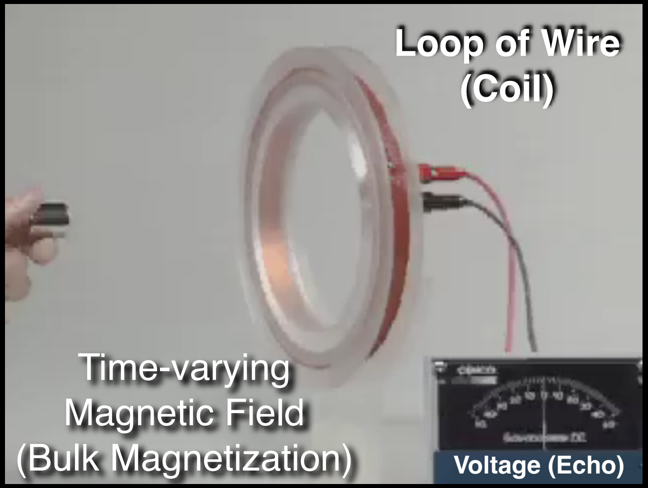
What is MRI?

MRI follows a classic excitation-reception paradigm.



Excitation
(RF Pulse)

Reception
(FID or **Echo**)



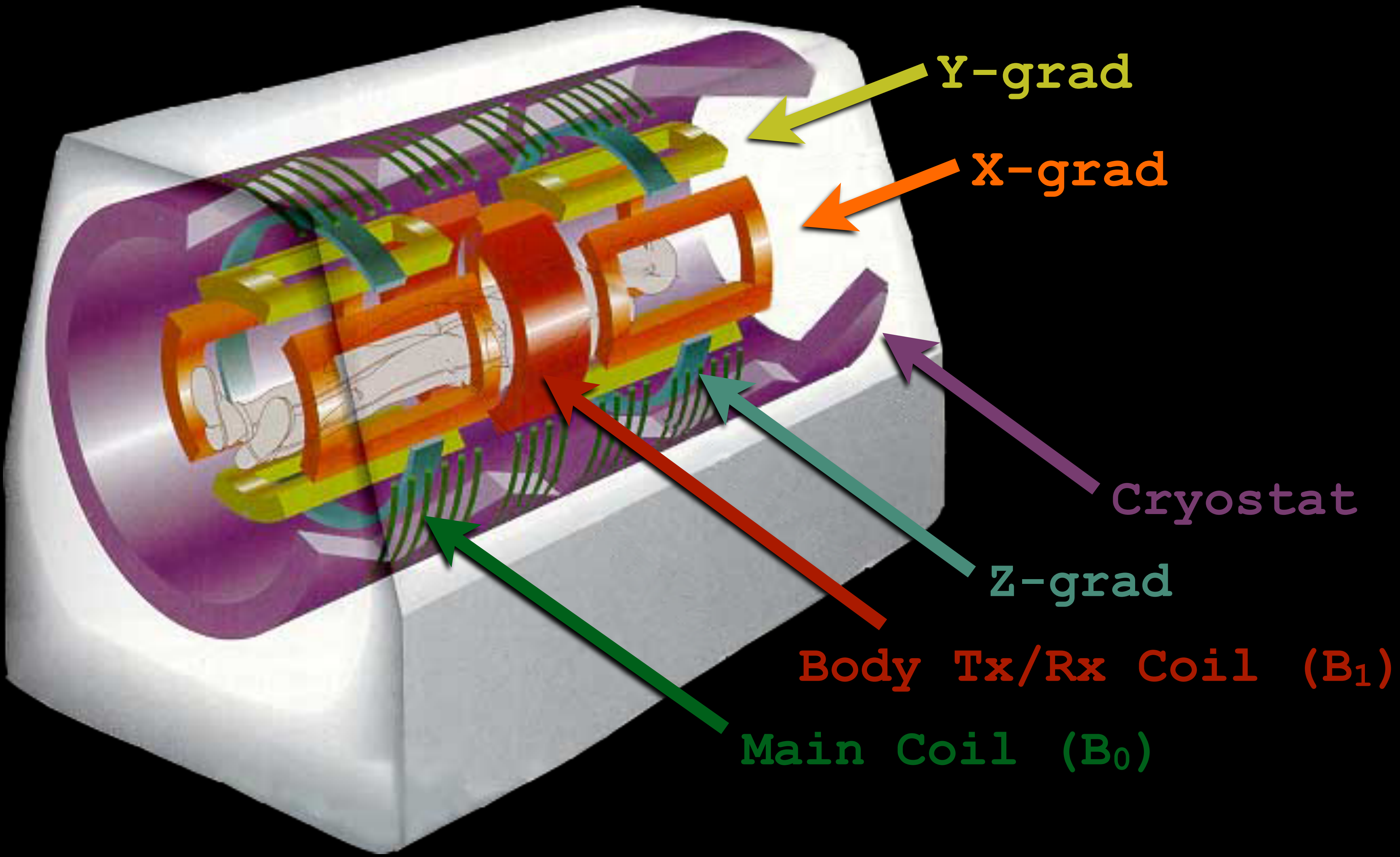
Faraday’s Law of Induction

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



Y-grad

X-grad

Cryostat

Z-grad

Body Tx/Rx Coil (B_1)

Main Coil (B_0)

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

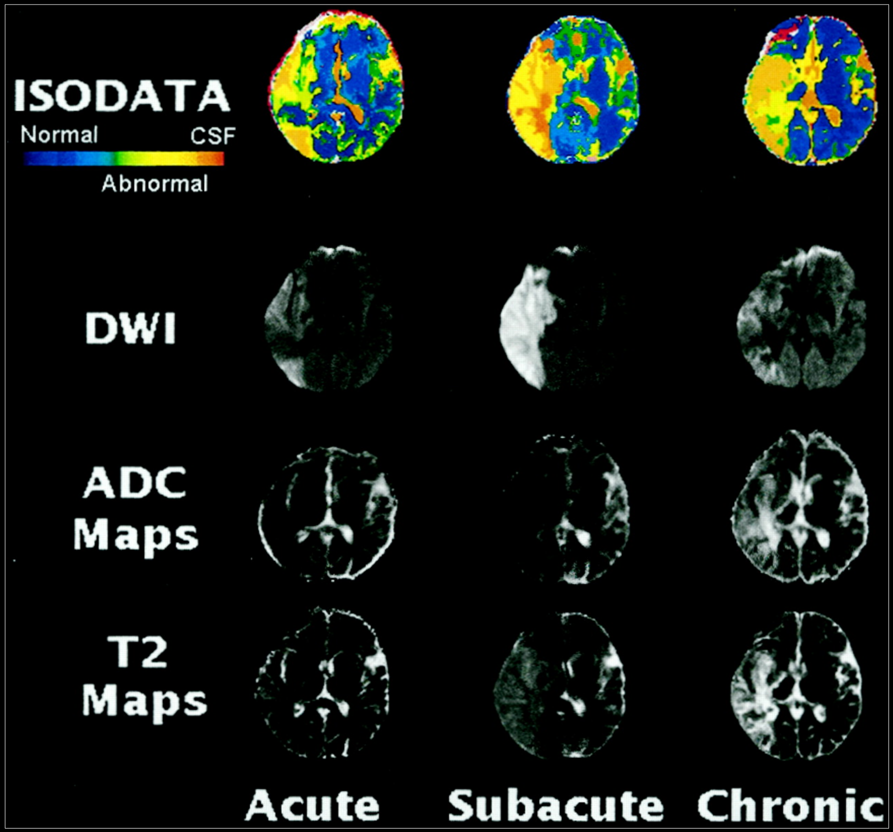
MRI Advantages

Soft Tissue Contrast

Tissue Characterization

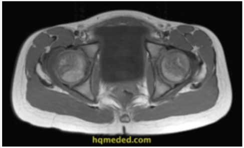
- **Routine**
  - T_1, T_2, T_2^*, proton weighted
  - Perfusion
  - Diffusion
  - Contrast enhancement
    - Tumor evaluation

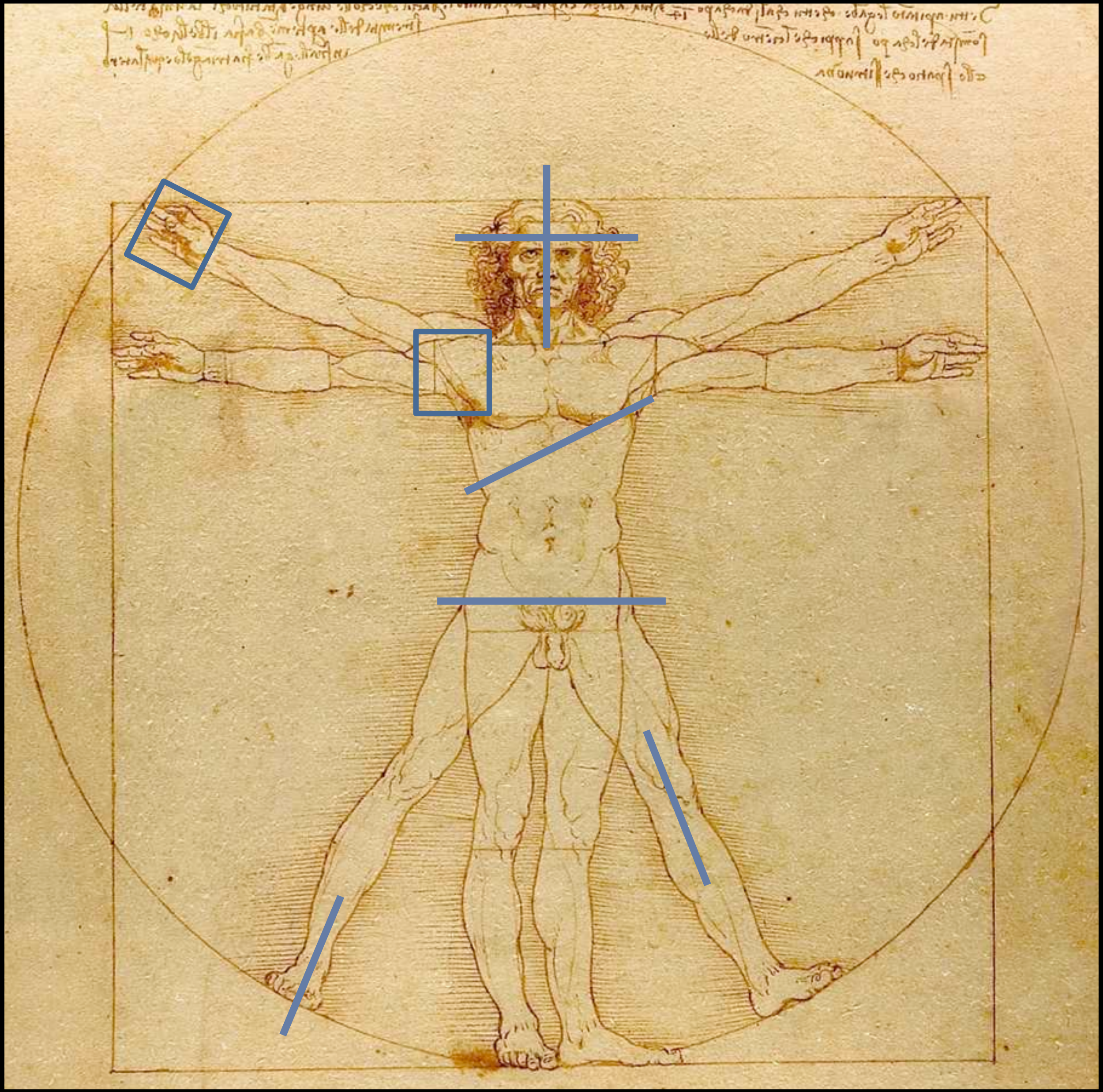
- **Advanced**
  - T1- and T2-mapping
  - Fat/Water & Iron quantification
  - Spectroscopy (molecular)
  - Susceptibility weighted imaging (SWI) for blood products and calcium
  - Non-contrast angiography

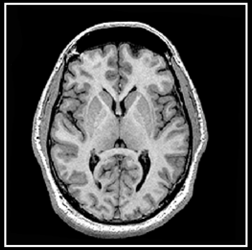


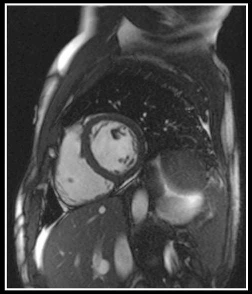
Demonstration of the multiparametric ISODATA segmentation methodology and corresponding DWI (b=1000 s/mm2), ADC map, and T2 map at different times after stroke. *Jacobs M A et al. Stroke. 2001;32:950-957*

Arbitrary Imaging Planes









No Ionizing Radiation

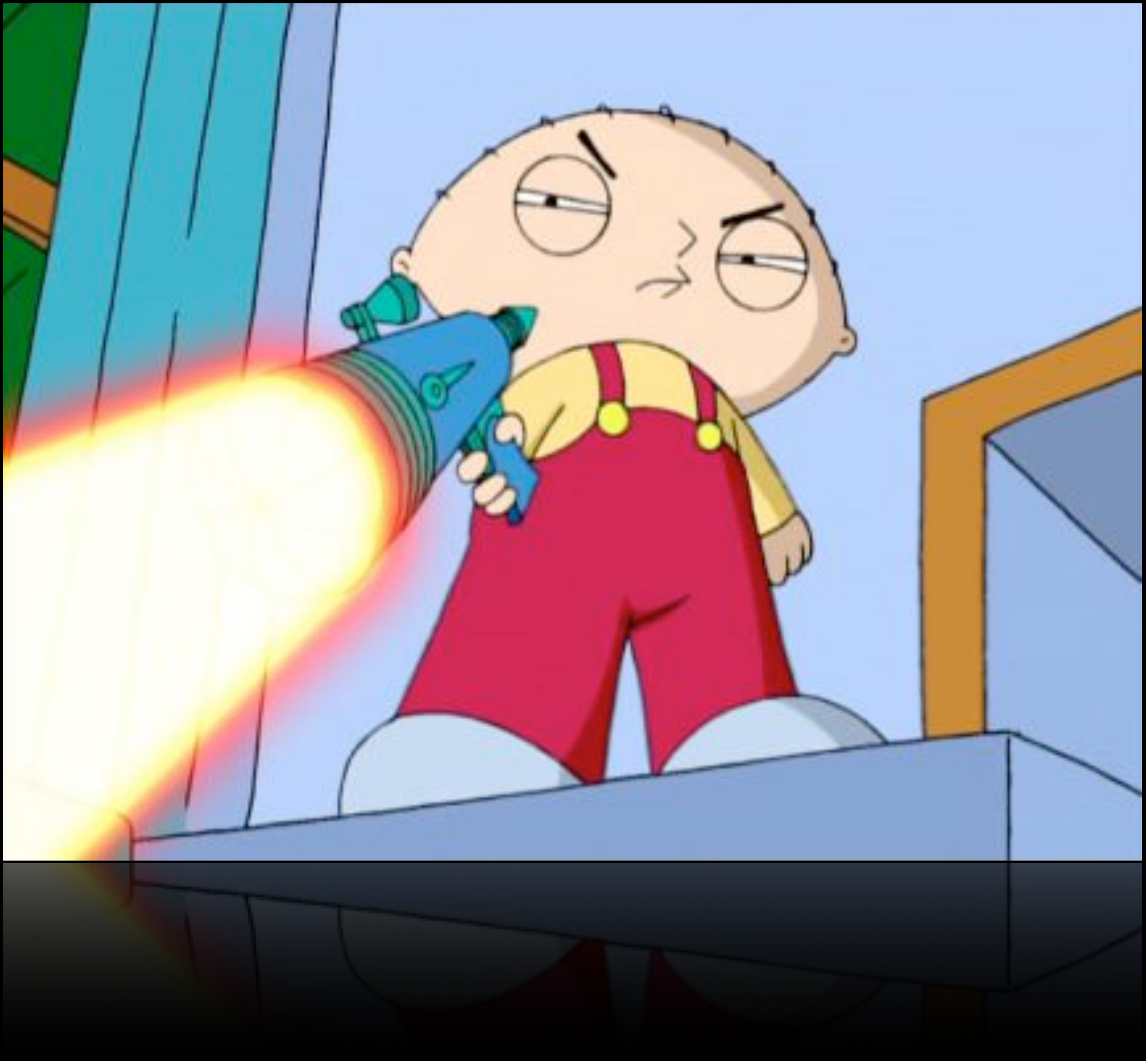
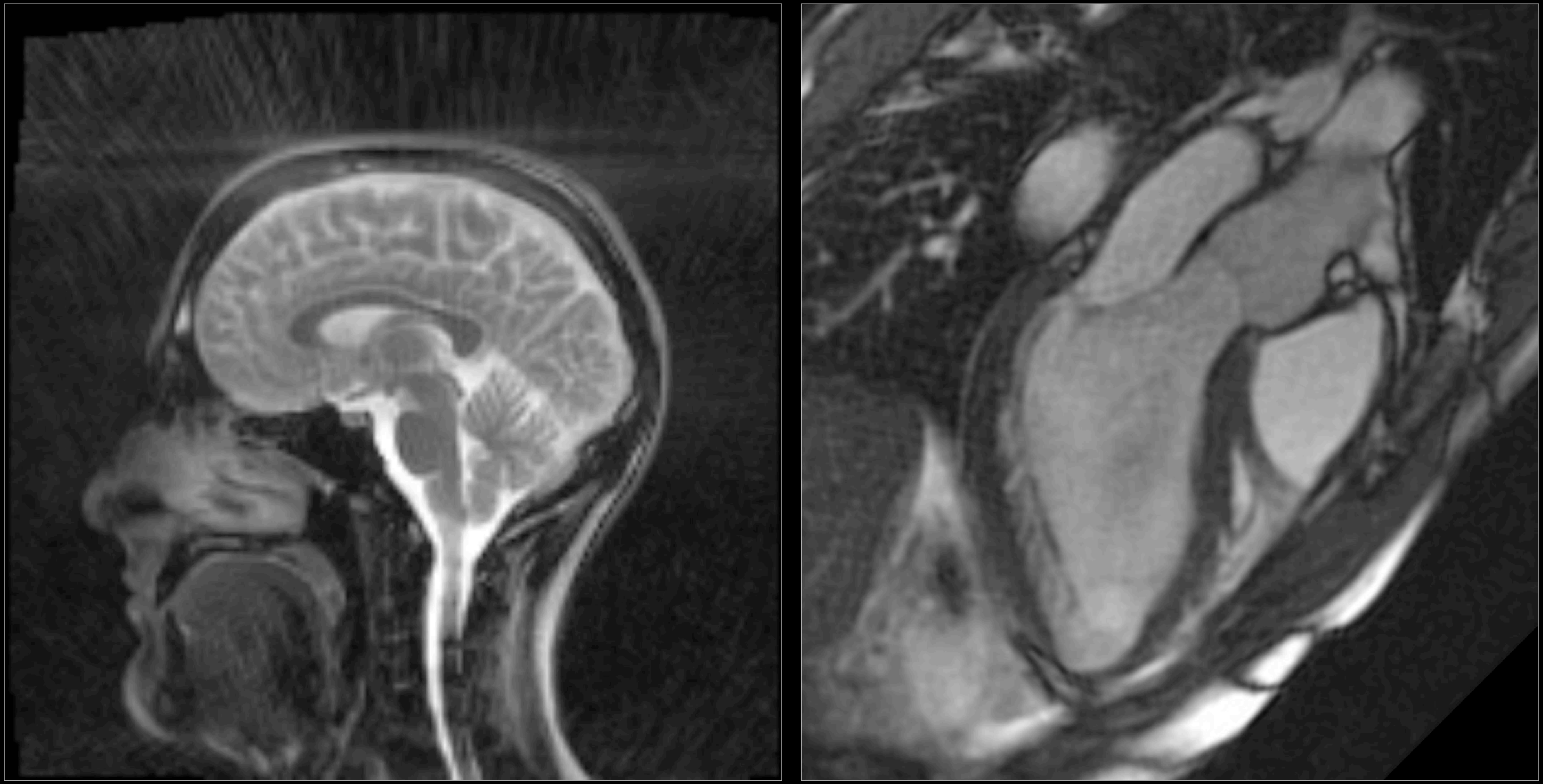
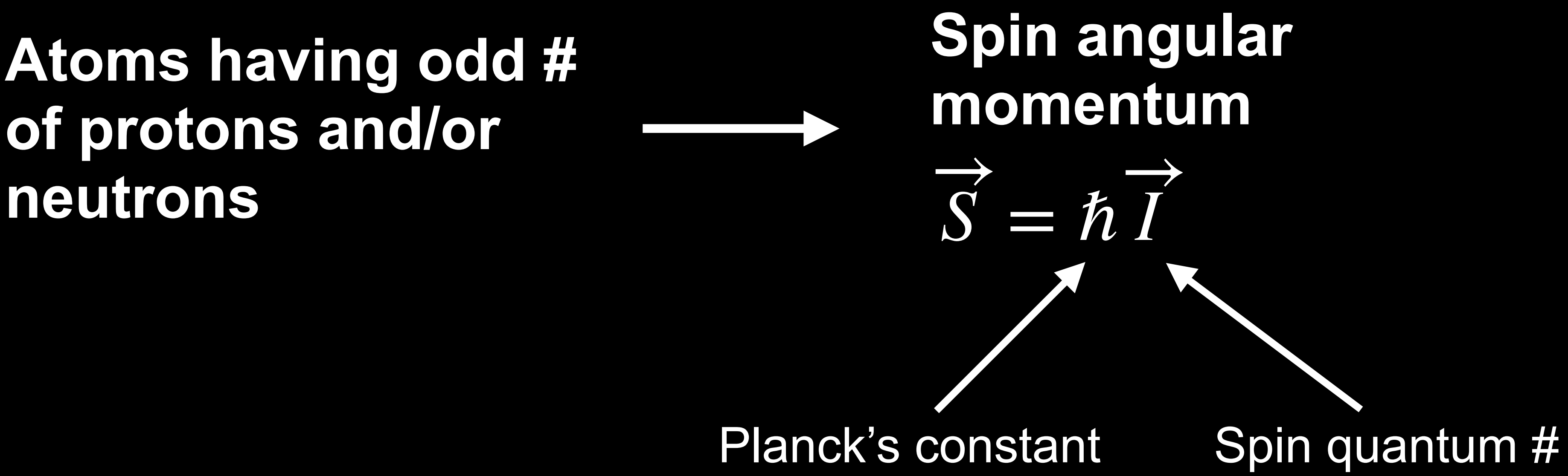


Image Physiologic Motion



Nuclear Spin

Classical View



Atoms having odd # of protons and/or neutrons

Spin angular momentum

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

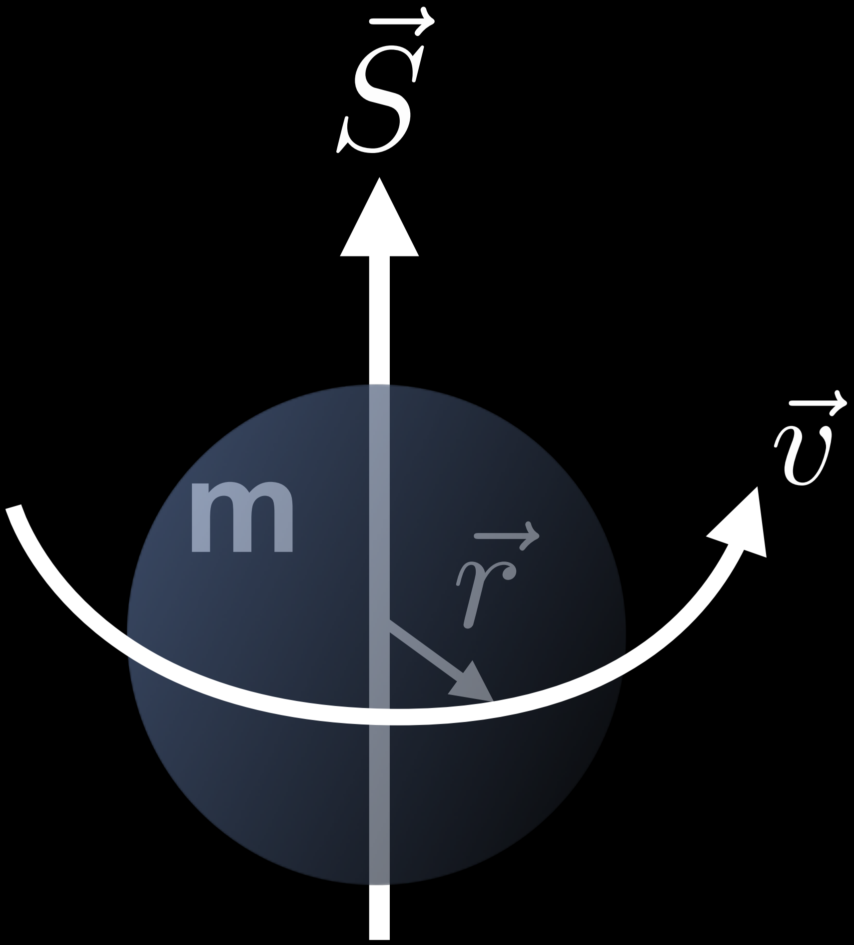
Planck's constant

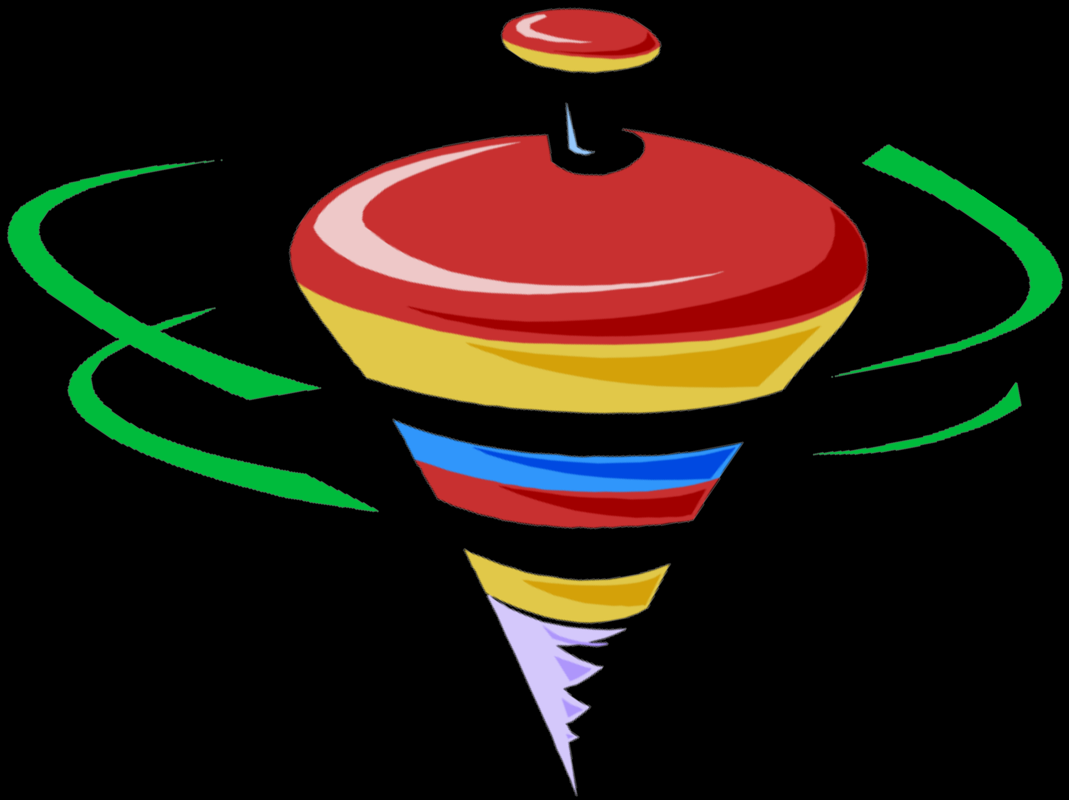
Spin quantum #

- 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 ➟ $\vec{S}$ [$\mathrm{kg \cdot m^2 s^{-1}}$]

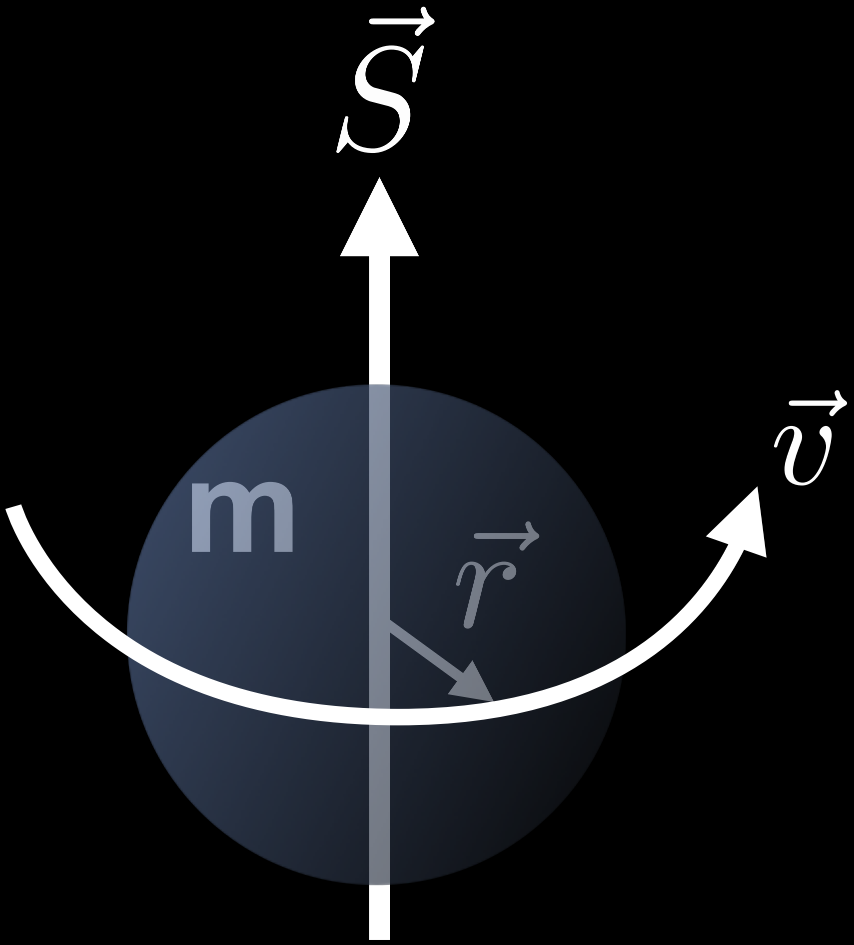




Hydrogen nuclei have spin angular momentum.

Spin Angular Momentum

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



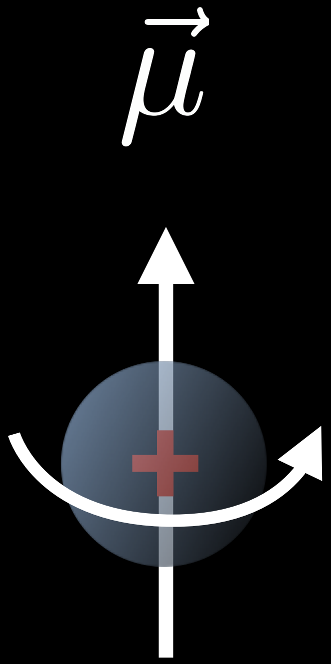
$$\vec{S} = \vec{r} \times \vec{p}$$
$$= \vec{r} \times m\vec{v}$$

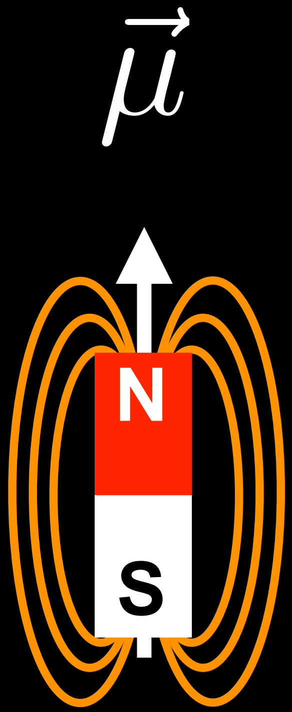
Hydrogen nuclei have spin angular momentum.

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**

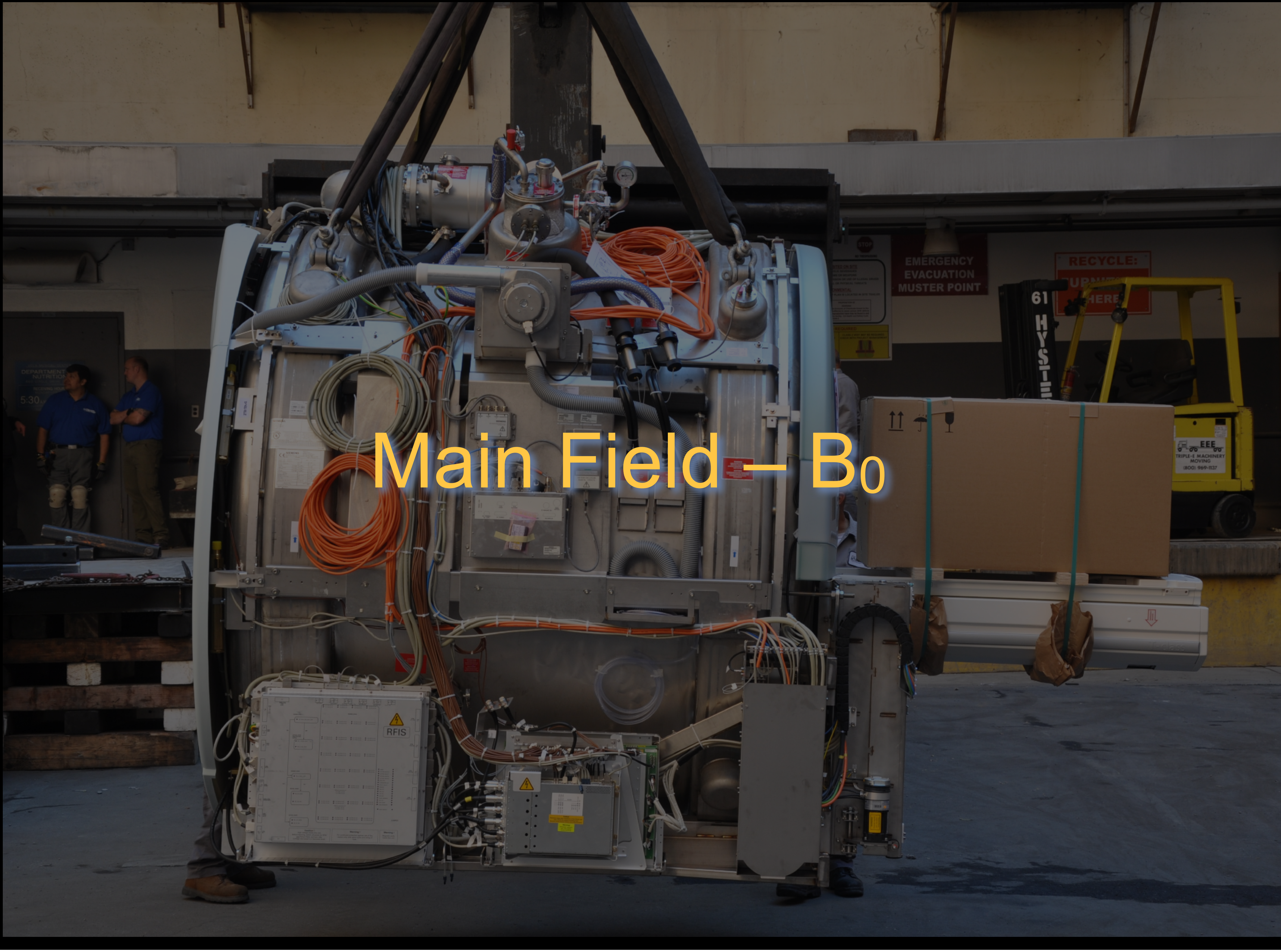
The ***relative*** sensitivity is at constant magnetic field and equal number of nuclei.

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

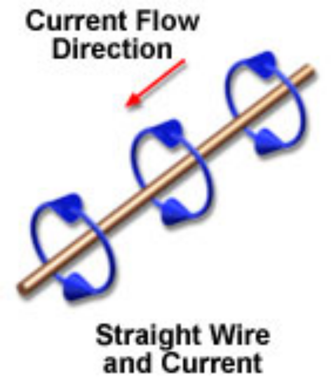
The ***absolute*** sensitivity is the relative sensitivity multiplied by natural abundance.

P. Callaghan & http://www.cryst.bbk.ac.uk/PPS2/projects/schirra/html/nuclei.htm

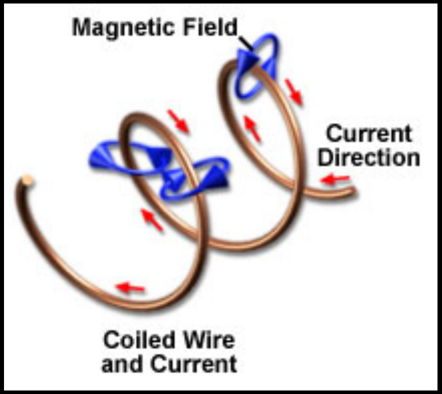
Main Field – B_0

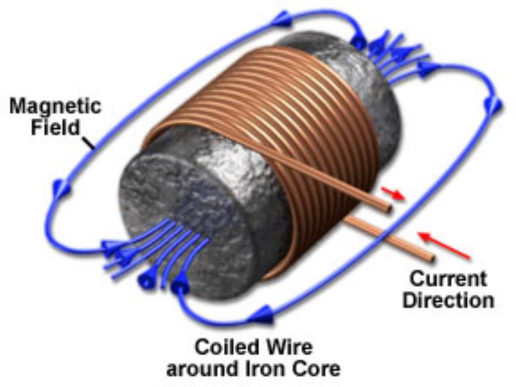


Currents & Magnetic Fields



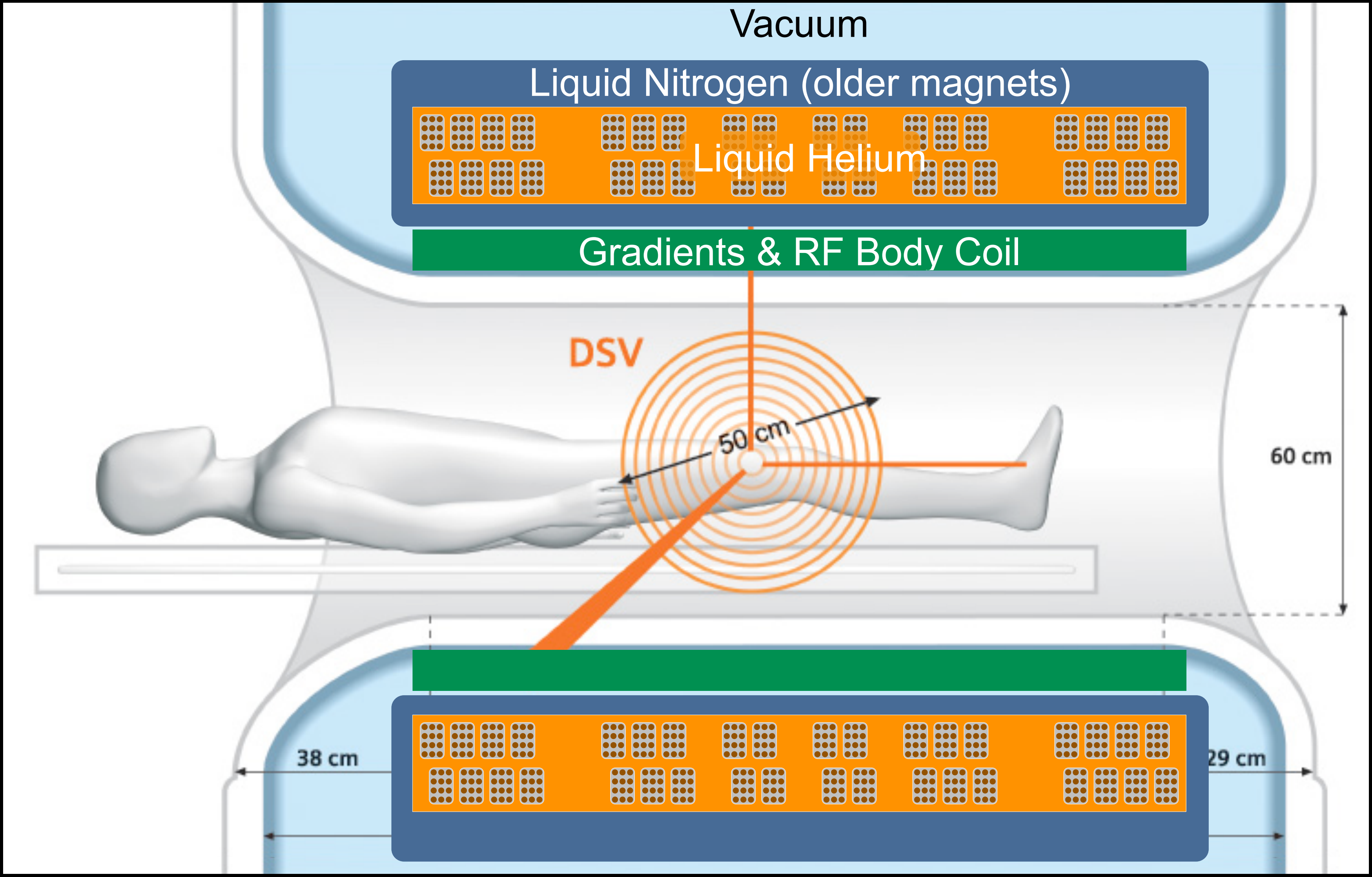
Left-hand Rule





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

Superconducting Electromagnet



MRI scanners are superconducting electromagnets.

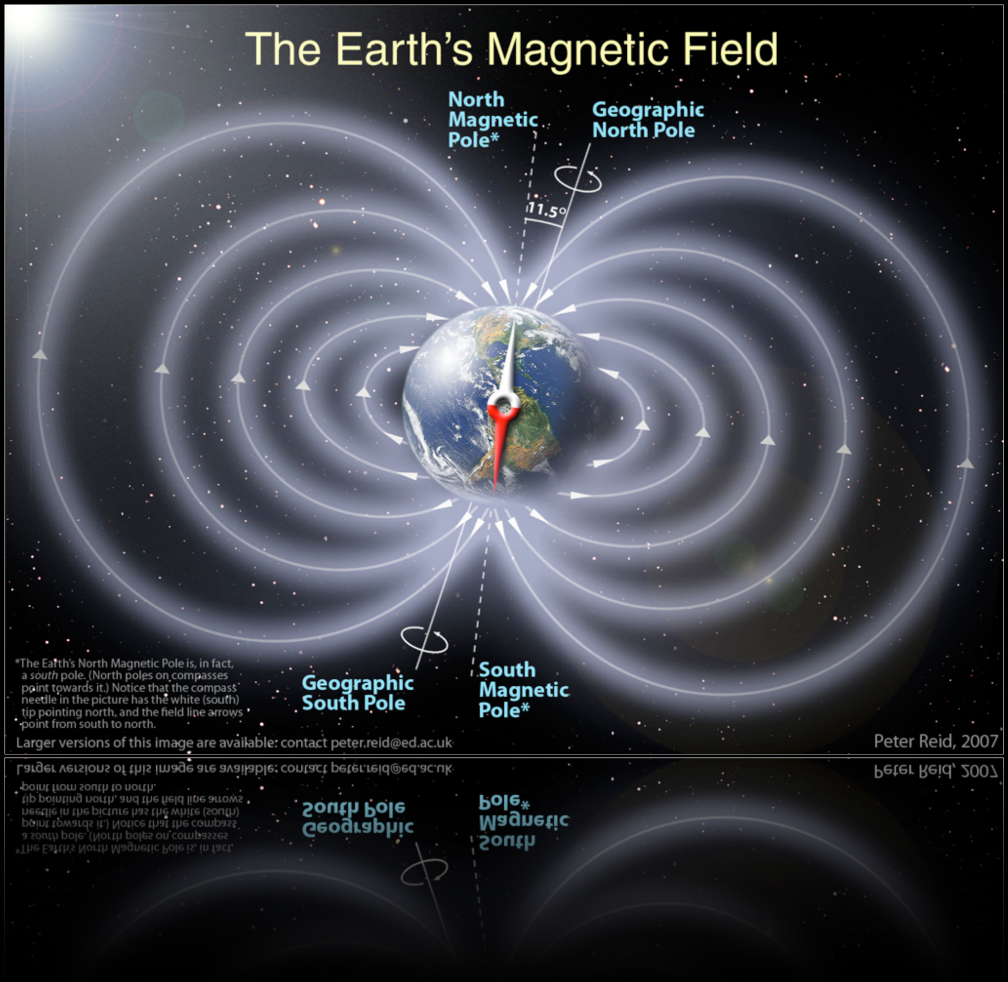
B_0 Field

- 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



*The Earth's North Magnetic Pole is, in fact, a *south* pole. (North poles on compasses point towards it.) Notice that the compass needle in the picture has the white (south) tip pointing north, and the field line arrows point from south to north.

Larger versions of this image are available: contact peter.reid@ed.ac.uk

Peter Reid, 2007

B_0 Strength - Advantages

- ⬆ $B_0 \Longrightarrow$ ⬆ 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

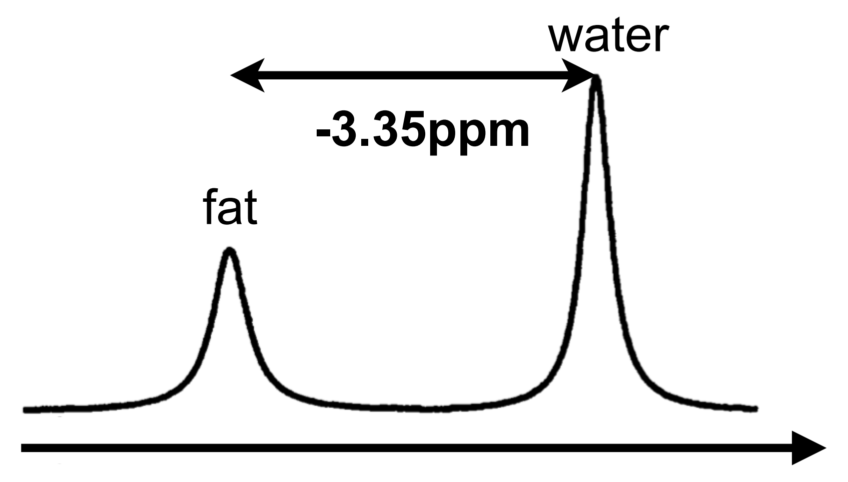
B_0 Strength - Disadvantages

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



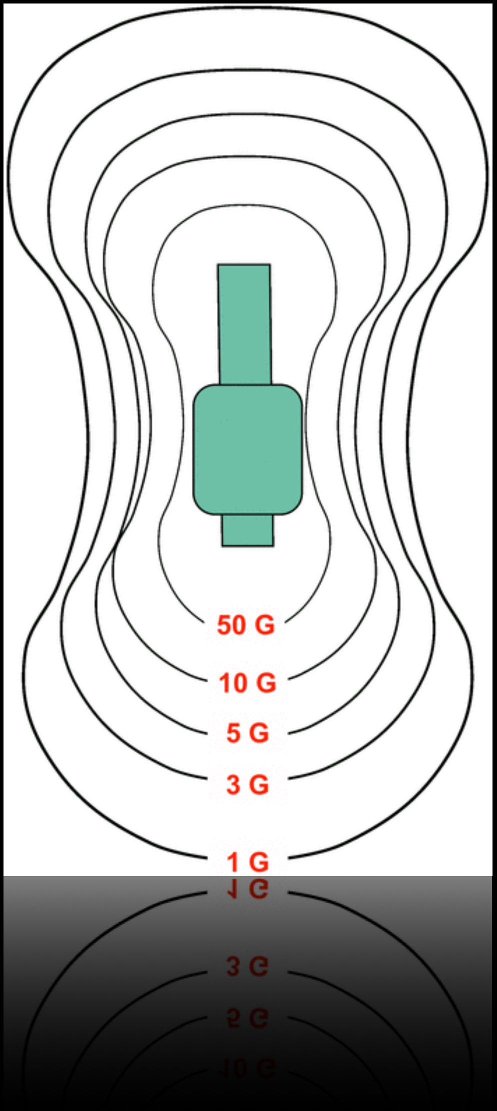
$$B = B_0 (1 - \delta)$$

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

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

Main Field (B_0) – Shielding

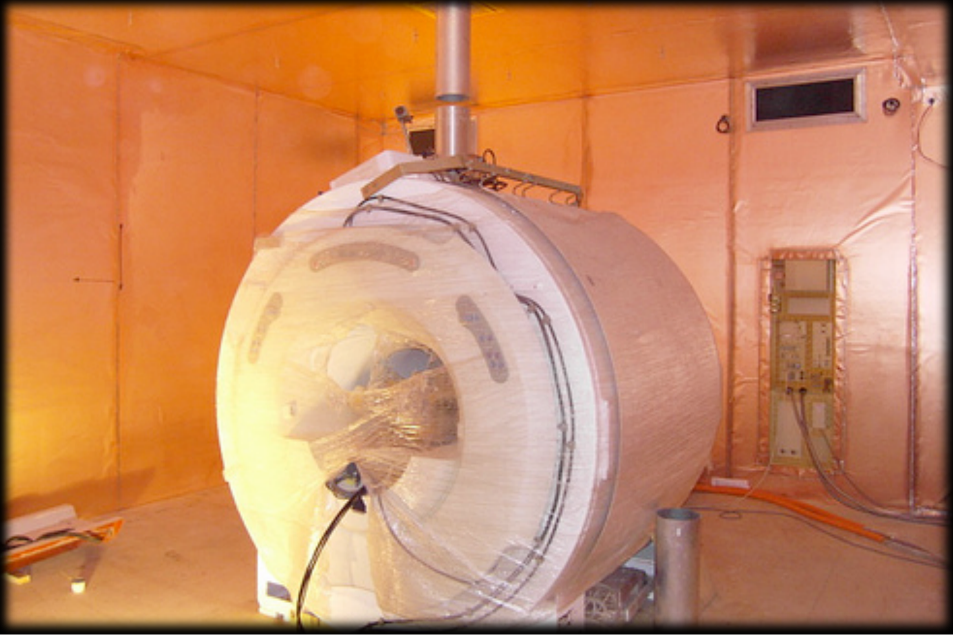
- **Problem**: The B_0 field extends well beyond the scanner.
- **Shielding** reduces B_0 foot print
  - Reduces install cost
  - Reduces interference
- **Passive Shielding**
  - Iron room shielding
  - Heavy, not cheap
- **Active Shielding**
  - Super-conducting coils that oppose (shield) B_0 fringe 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 ⇒ 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



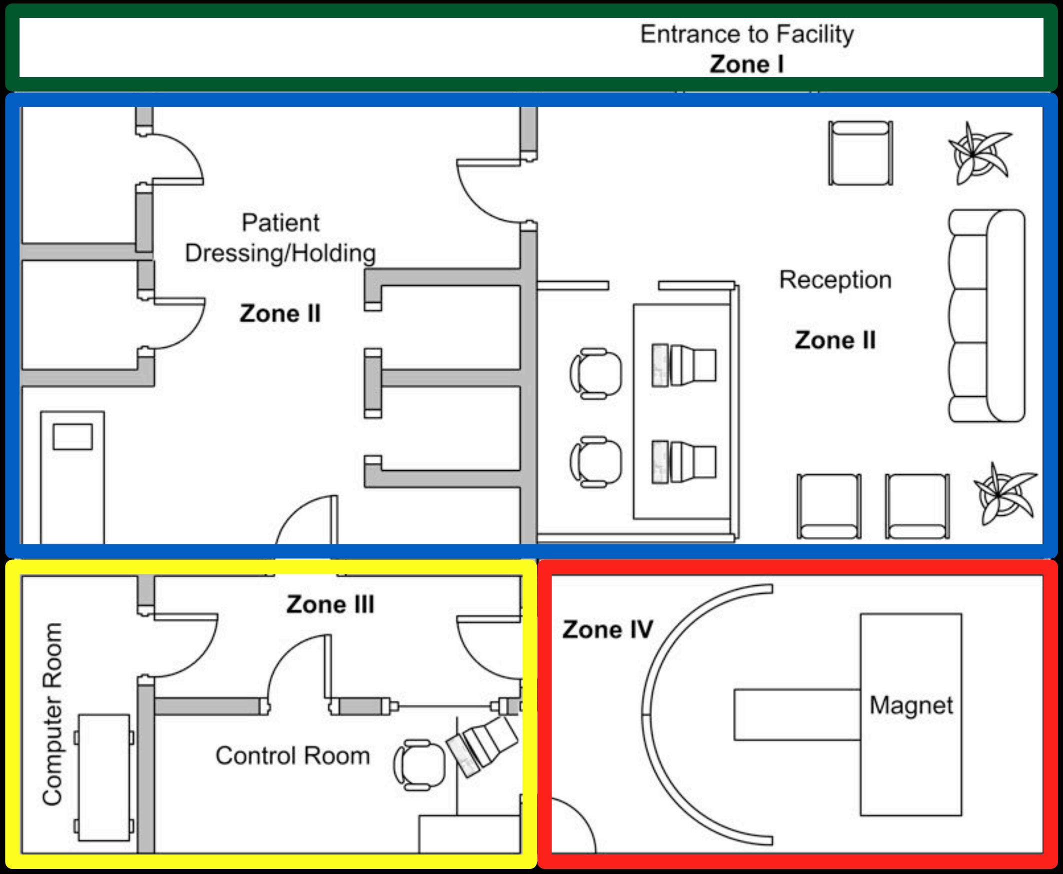
MRI Zones

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

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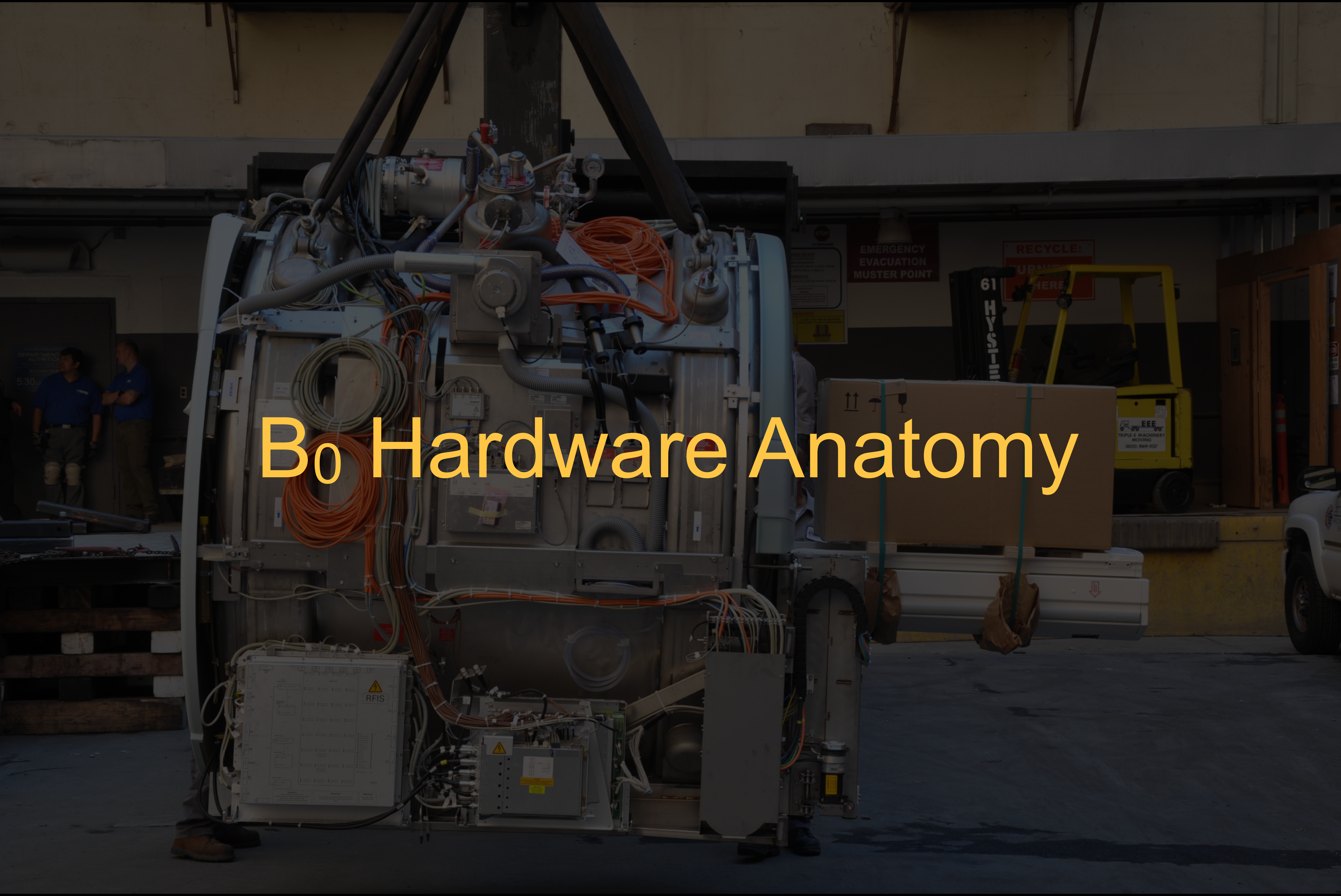
B_0 Hardware Anatomy



Superconducting Electromagnets

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

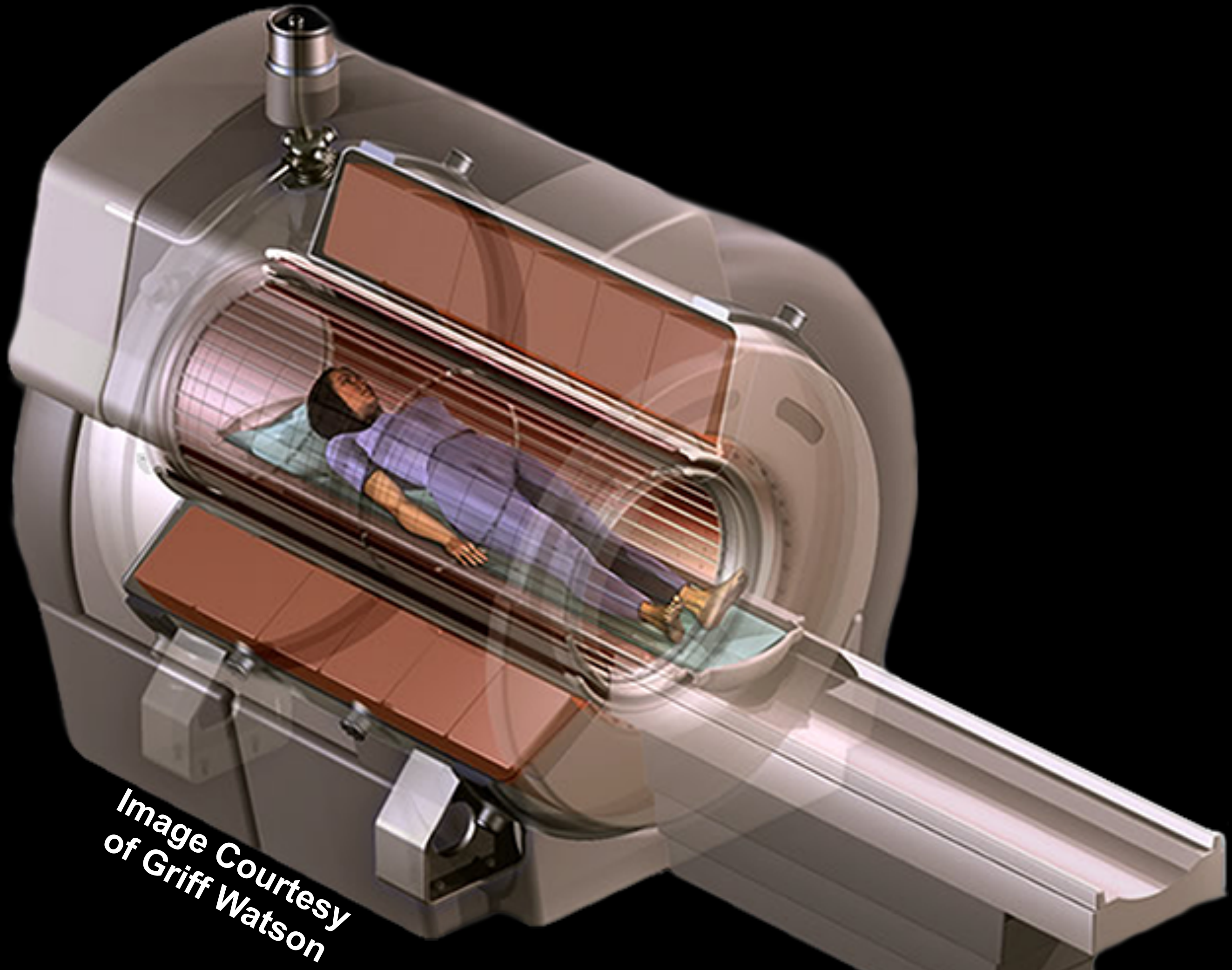
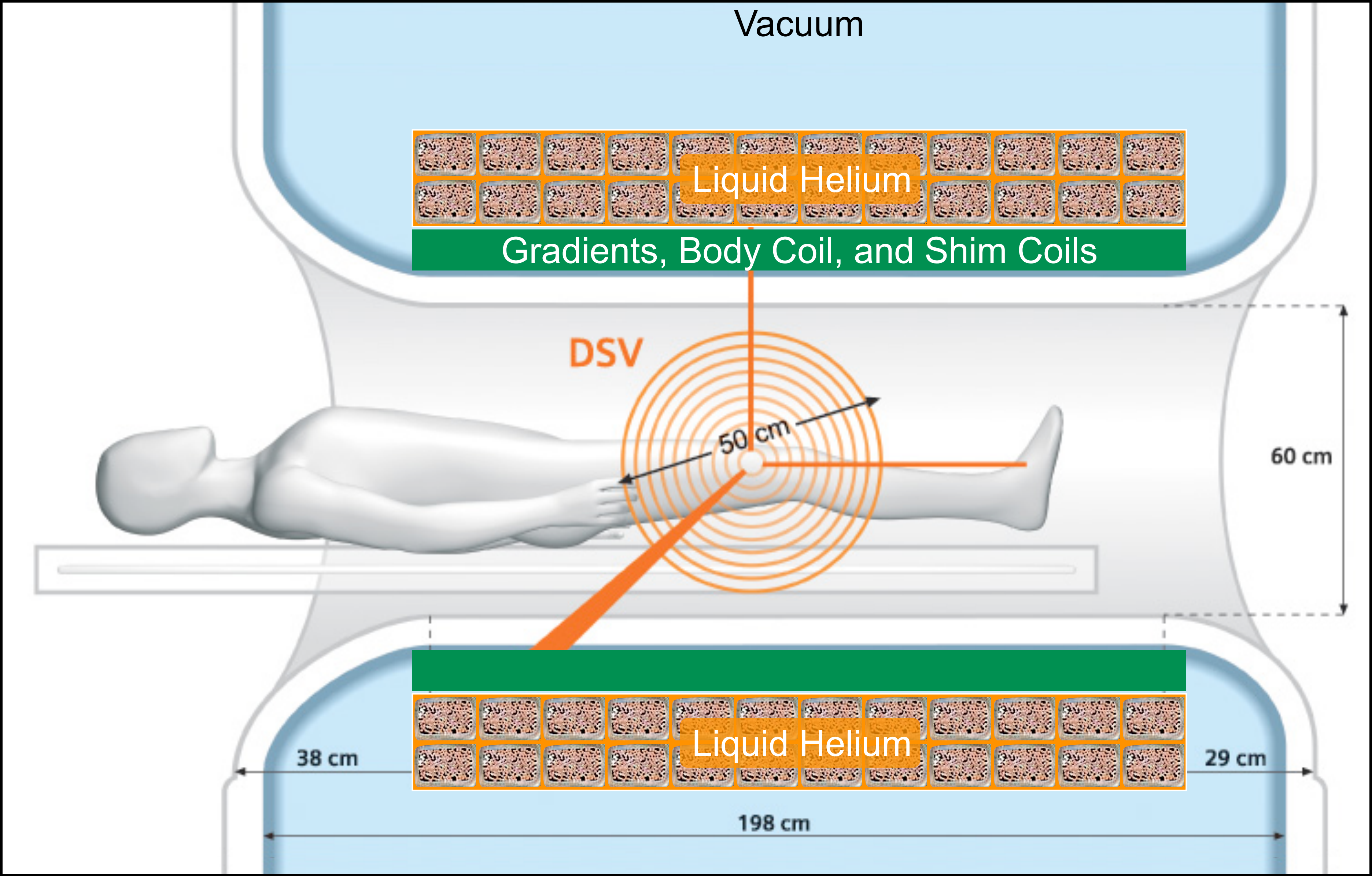


Image Courtesy of Griff Watson

Superconducting Magnet



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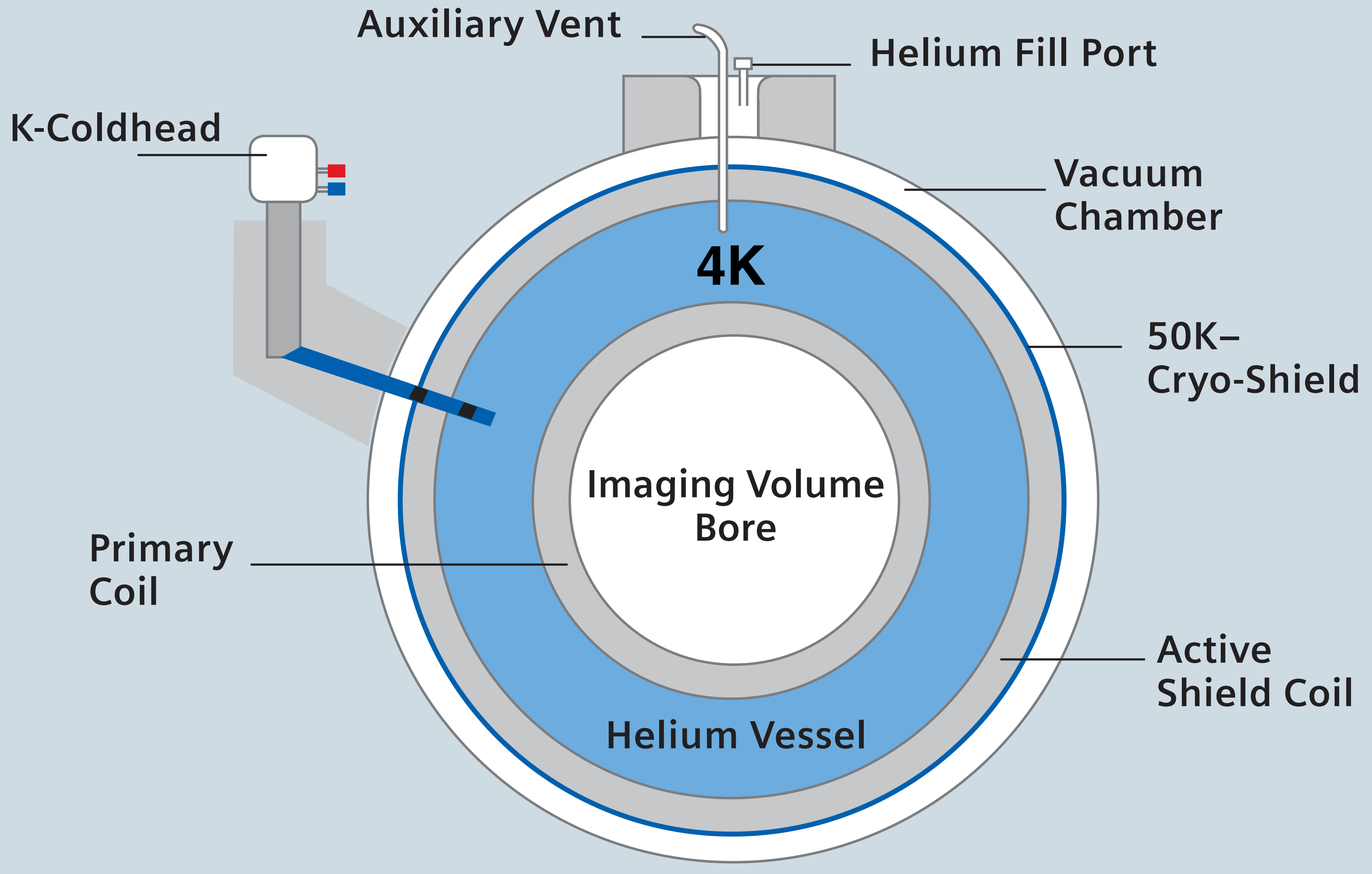
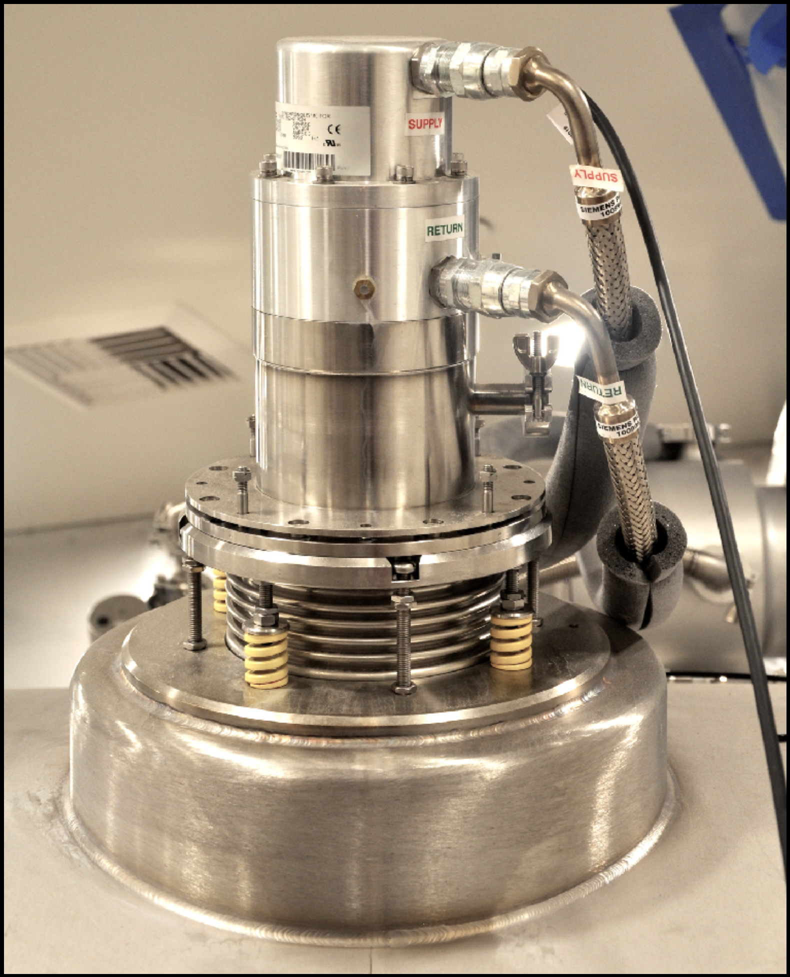
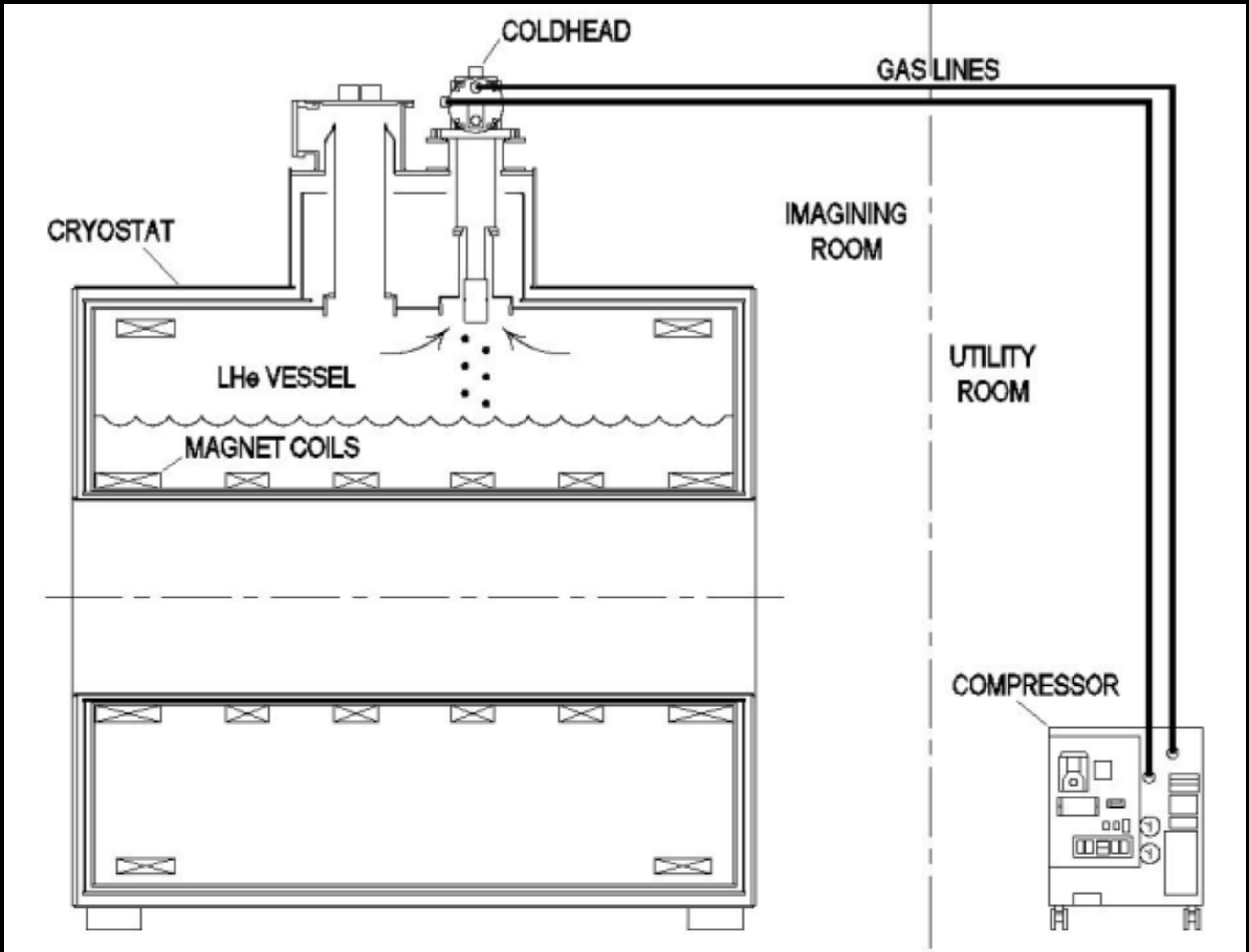


www.siemens.com/magnetom-world (Magnetom Flash 2/2008)

Coldhead (Cryocooler)





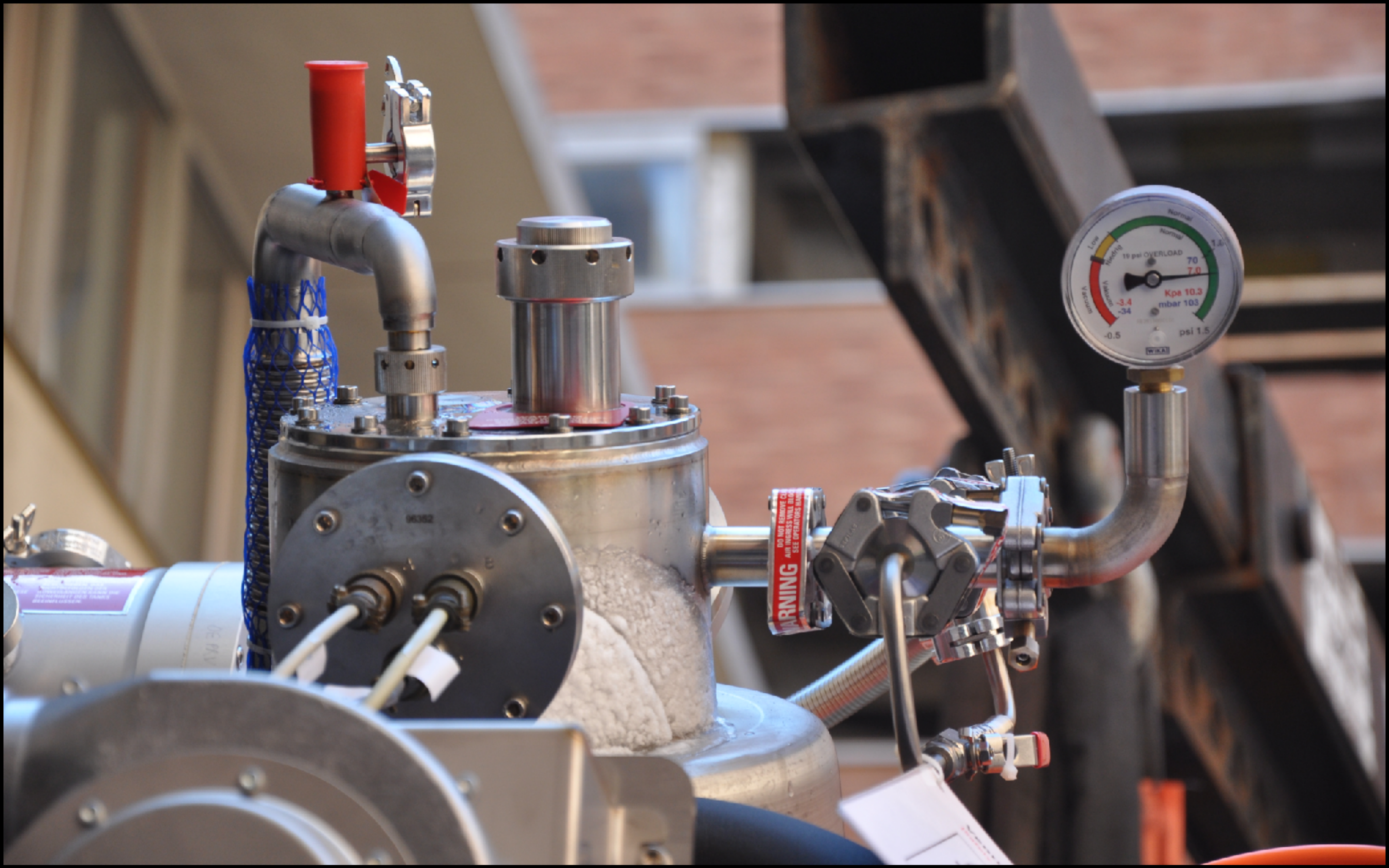
Re-condenses helium vapor and returns liquid helium to vessel.

David Geffen School of Medicine

Advances in Whole-Body MRI Magnets by Thomas C. Cosmus and Michael Parizh

UCLA Radiology

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

$$\omega = \gamma B$$

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Magnetic Dipole Moments

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“a measure of the strength of the system's net magnetic source”
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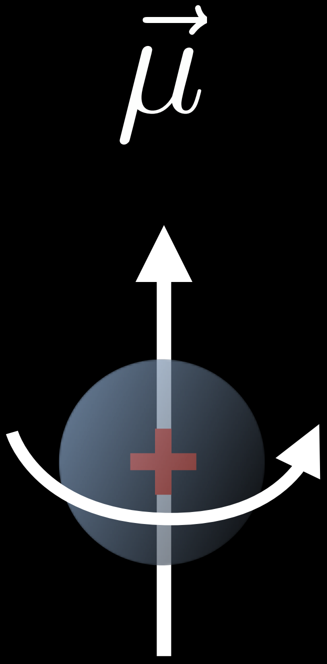
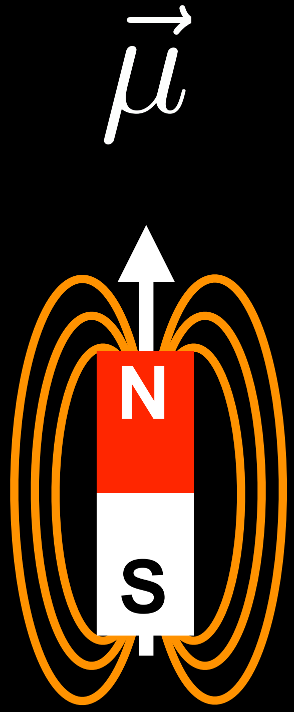
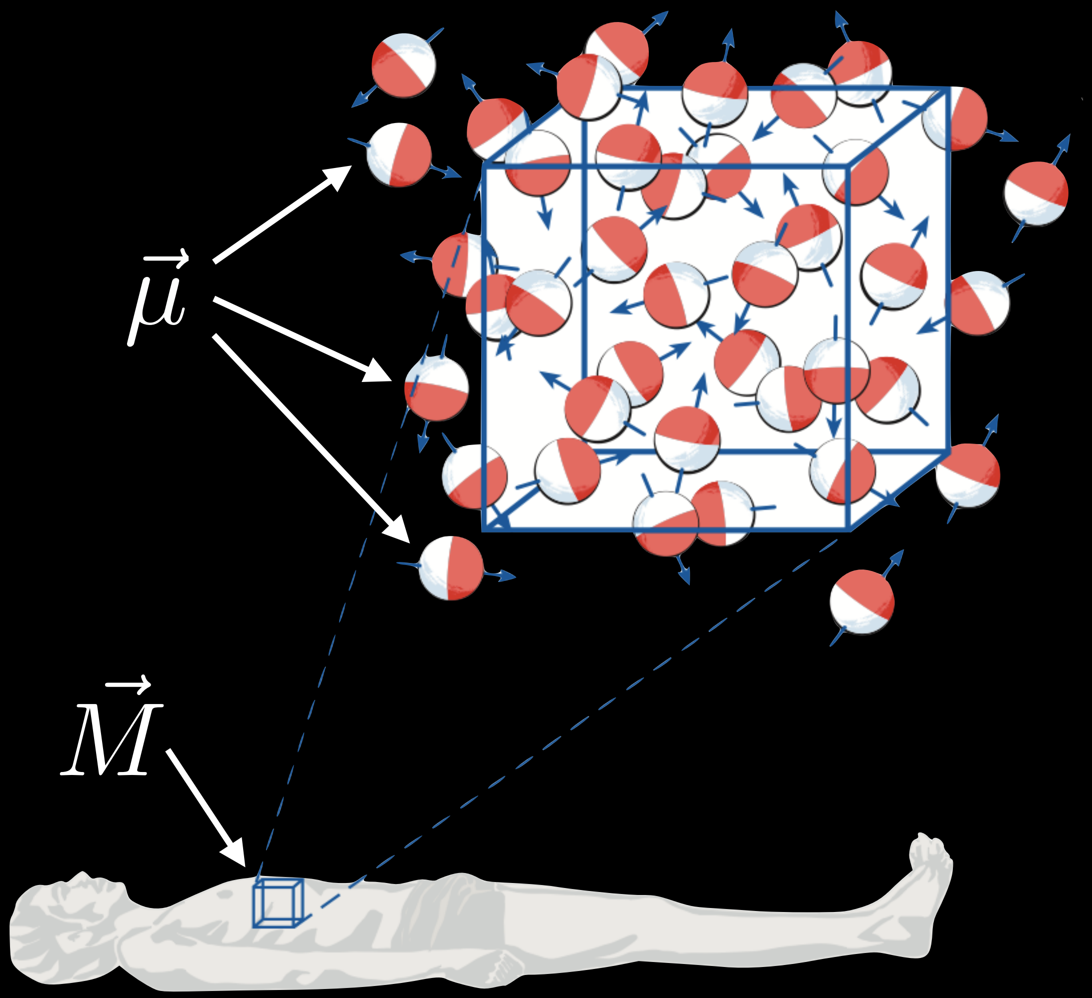




Hydrogen nuclei have magnetic dipole moments.

Bulk Magnetization

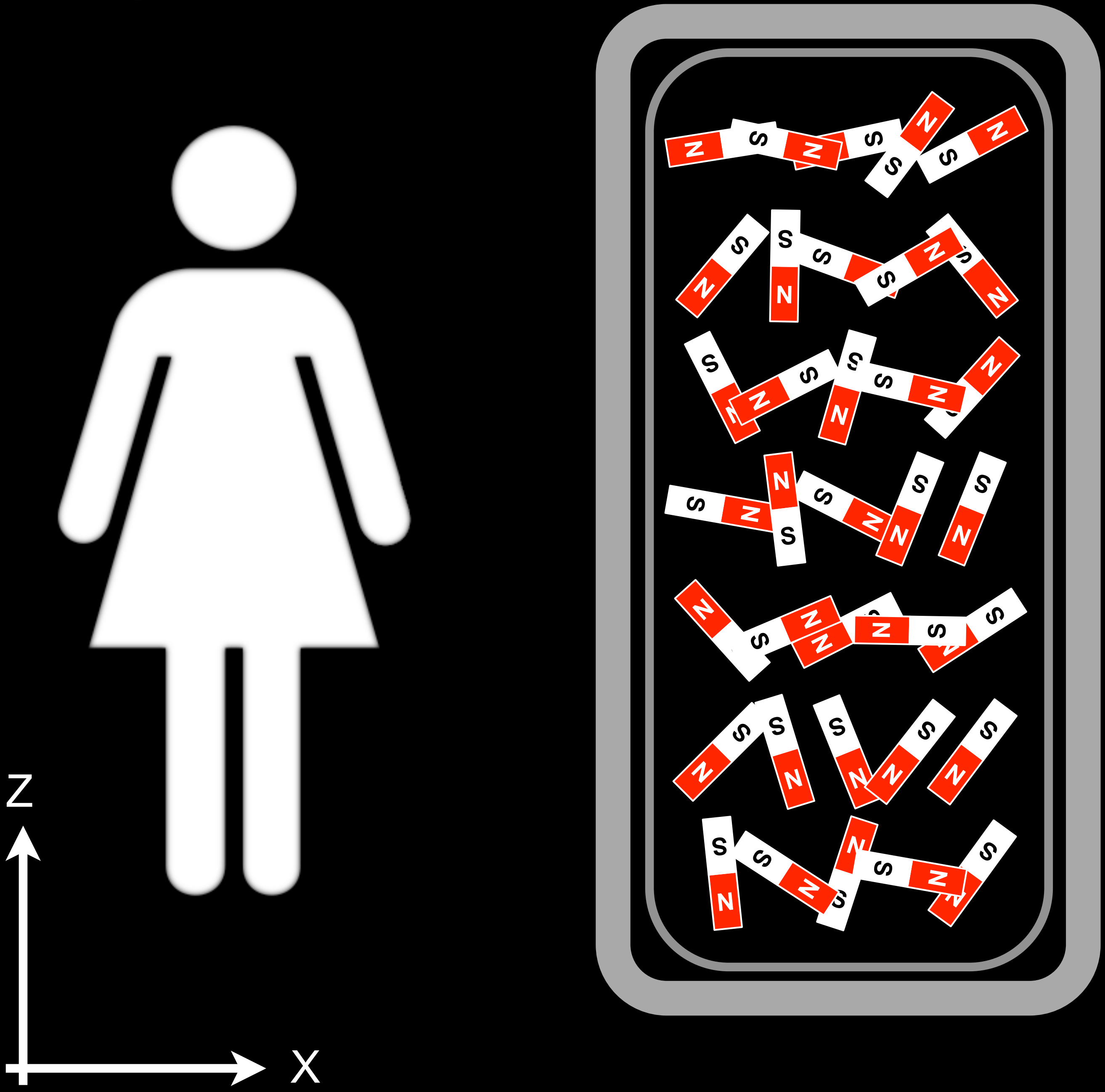


$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n$$

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

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

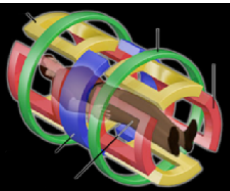
B_0 Field OFF

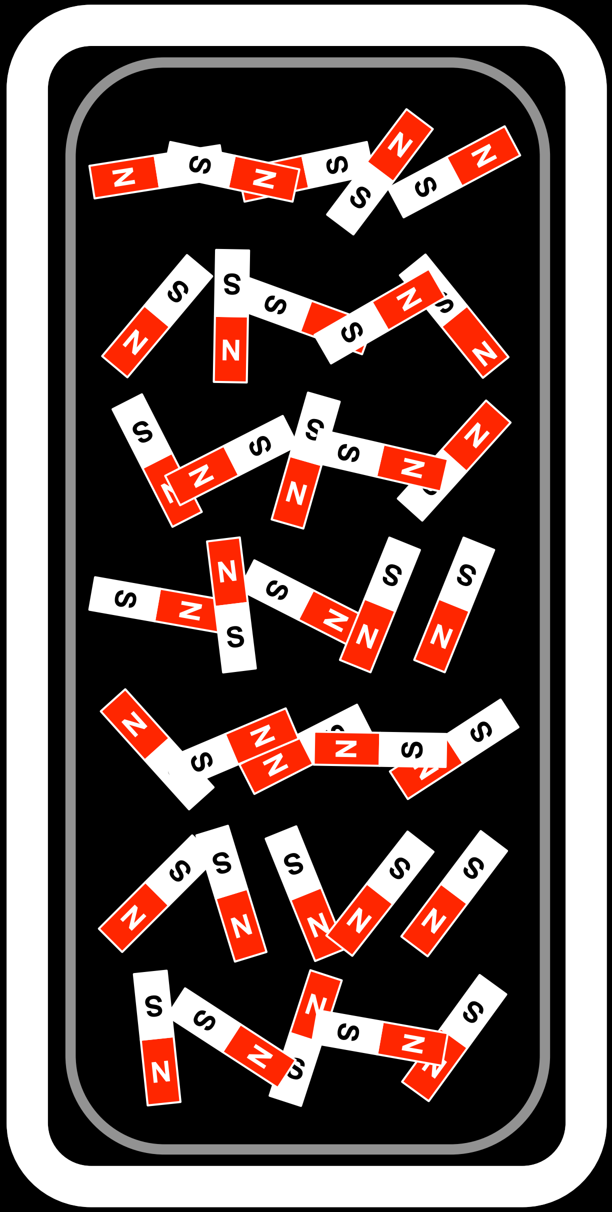


$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n = 0$$

Spins point in all directions.

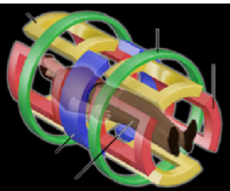
B_0 Field ON



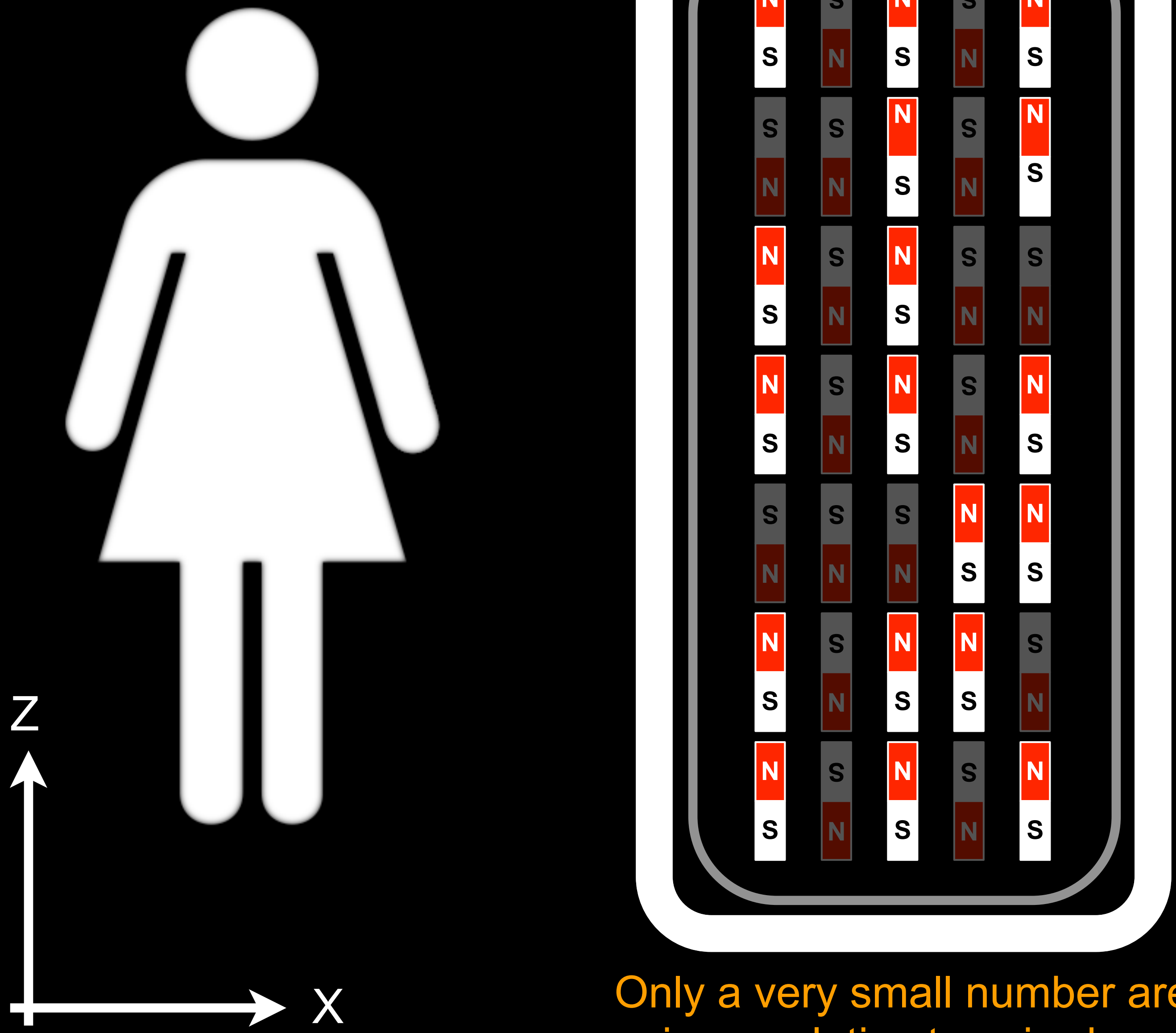


$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n = M_z$$

B_0 polarizes the spins and generates bulk magnetization.



B_0 Field ON



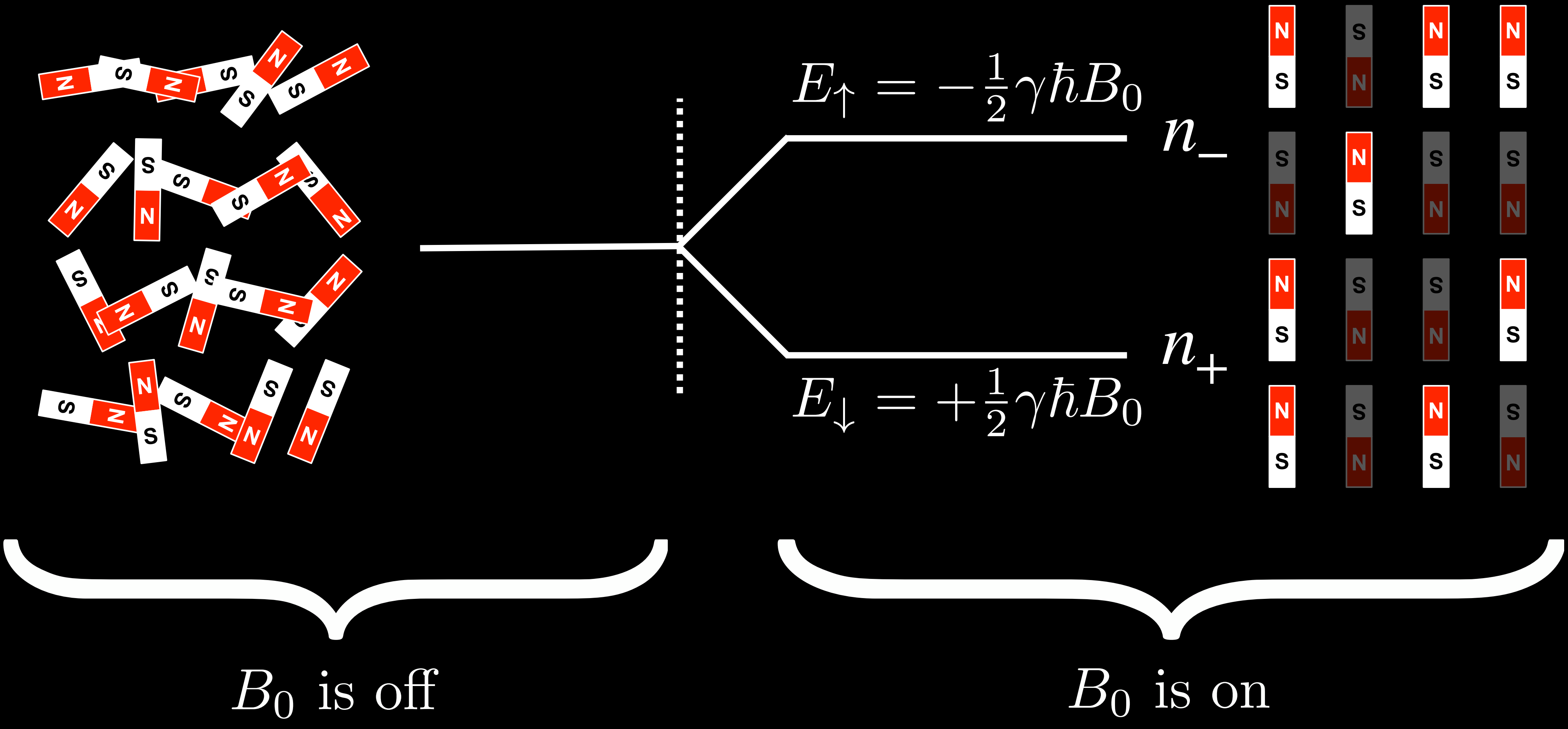
$$\vec{M} = \sum_{n=1}^{N_{total}} \vec{\mu}_n = M_z$$

Spin-Up

Spin-Down

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

Zeeman Splitting



$$E_{\uparrow} = -\tfrac{1}{2}\gamma\hbar B_0$$

$$E_{\downarrow} = +\tfrac{1}{2}\gamma\hbar B_0$$

$n_+ =$ Spin-Up State, Low Energy N S

$n_- =$ Spin-Down State, High Energy S N

Zeeman Splitting

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

$$\frac{n_-}{n_+} = e^{-\Delta E/\kappa T}$$

$\Delta E = \gamma \hbar B_0$

$\kappa =$ *Bolzmann constant*

$T =$ *Absolute temperature of the spin system*

- **At 1.5T, $\frac{n_-}{n_+}$ = 0.999993**
  - Imaging is based on weak polarization (enough for imaging)

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

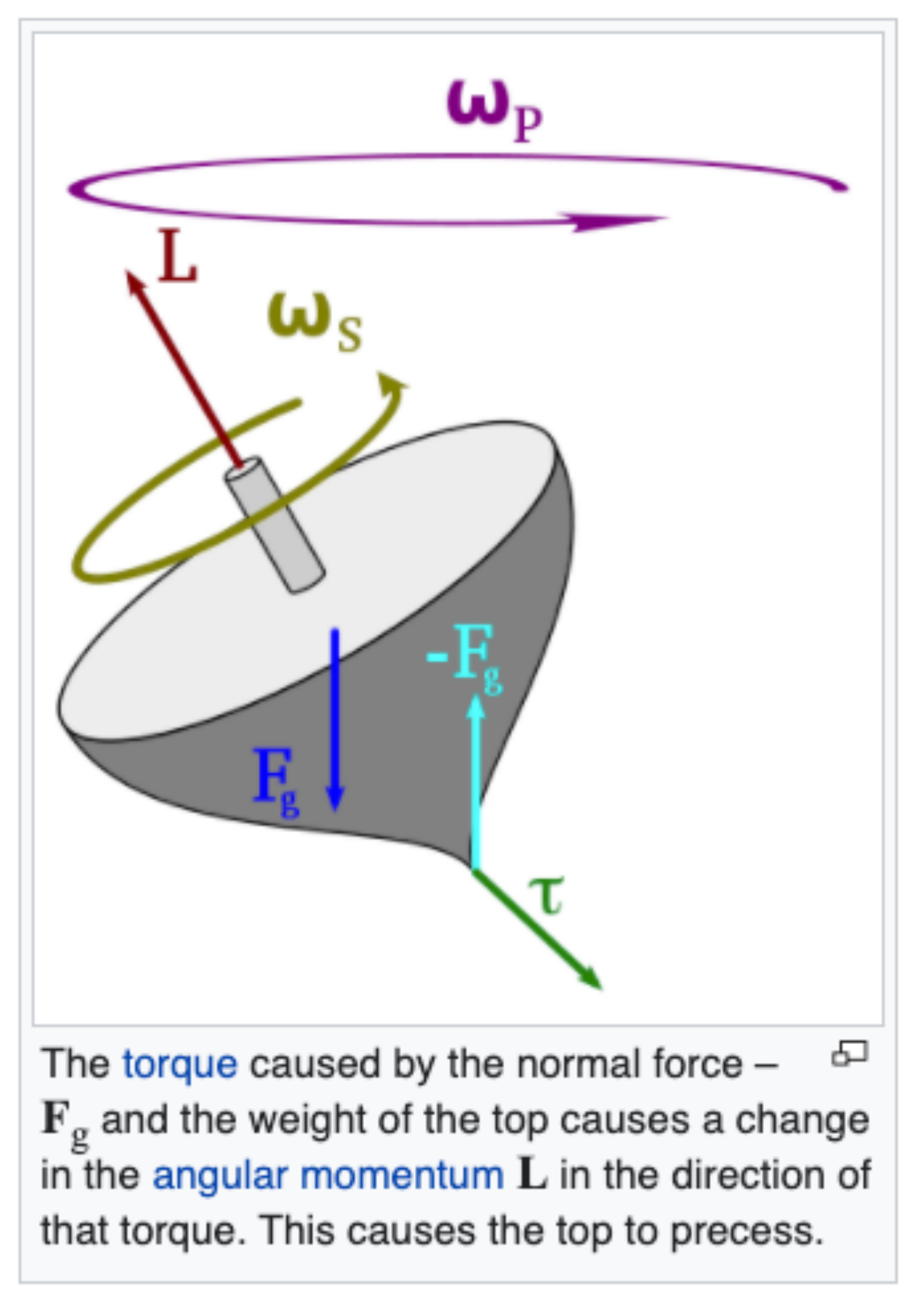
$$\omega = \gamma B$$

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

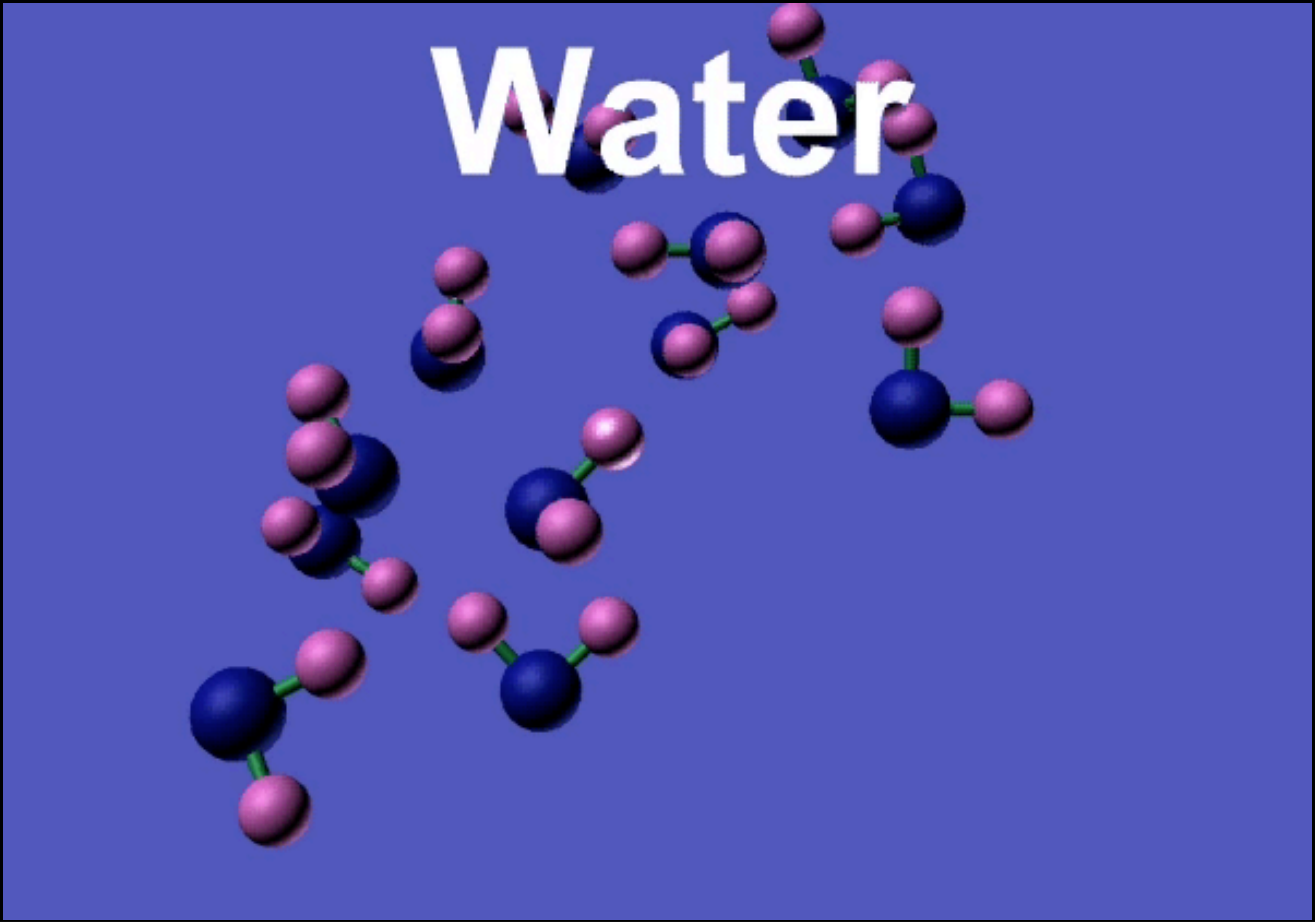


The torque caused by the normal force $-\mathbf{F}_g$ and the weight of the top causes a change in the angular momentum $\mathbf{L}$ in the direction of that torque. This causes the top to precess.

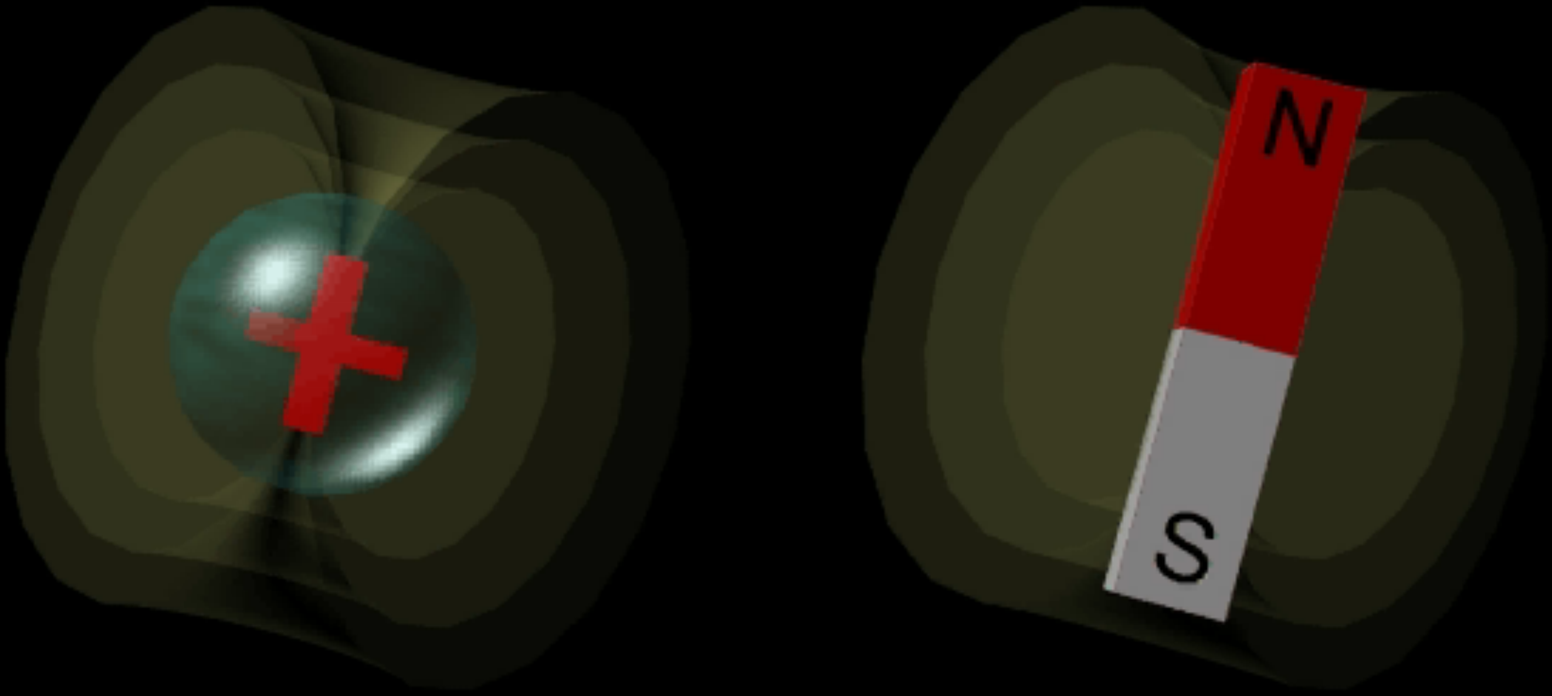
https://en.wikipedia.org/wiki/Precession

Nuclear Magnetic Resonance

NMR Phenomena



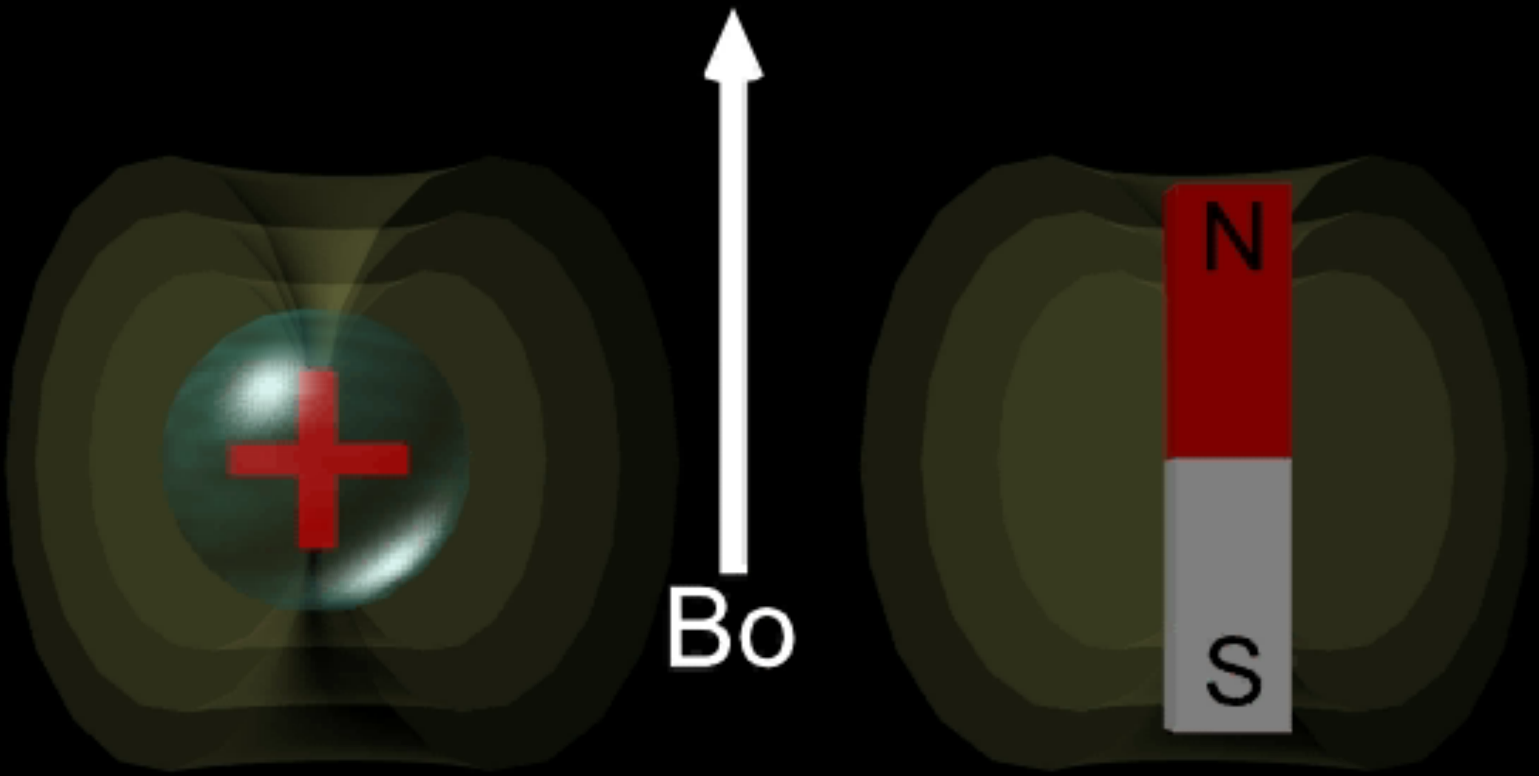
Magnetic Moment



Charge } Magnetic Moment
Spin

Protons behave like small magnets because of spin and charge.

Magnetic Moment

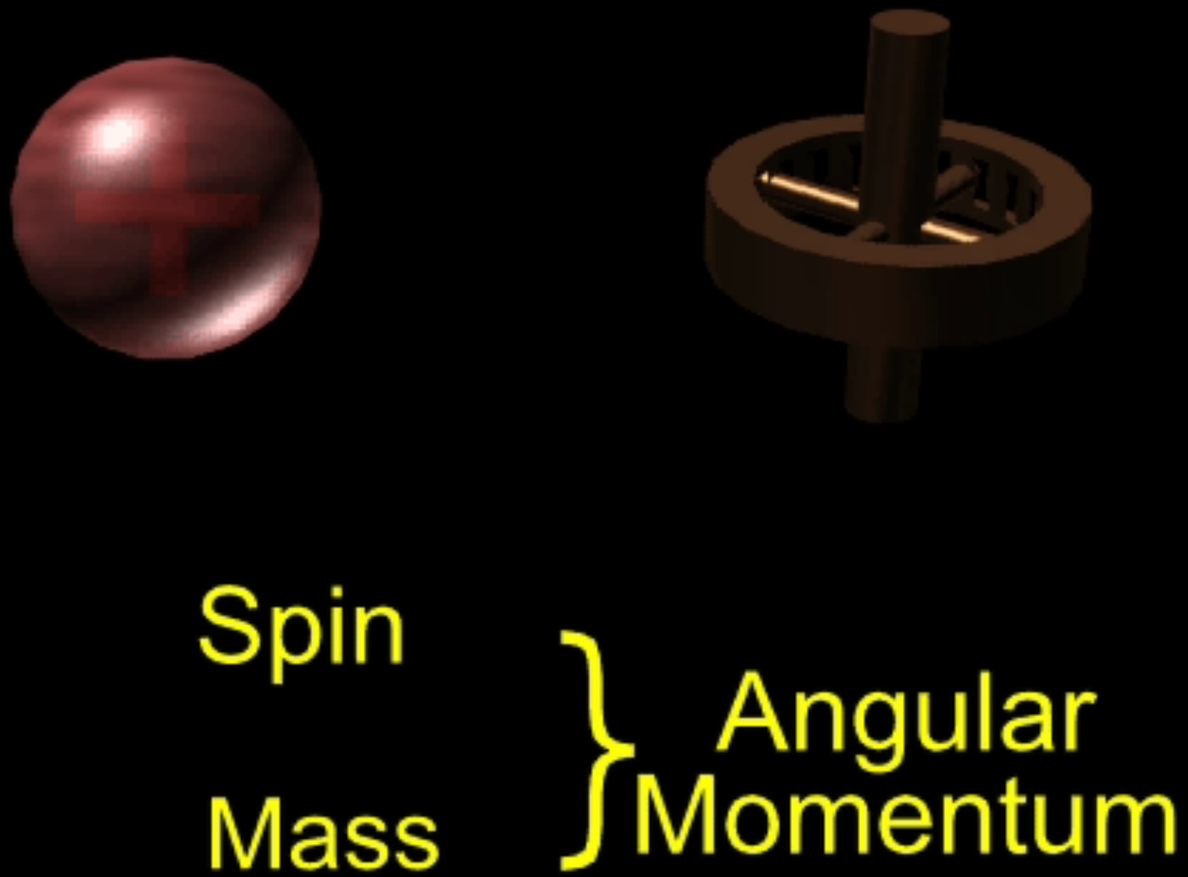


Charge
Spin

Magnetic Moment

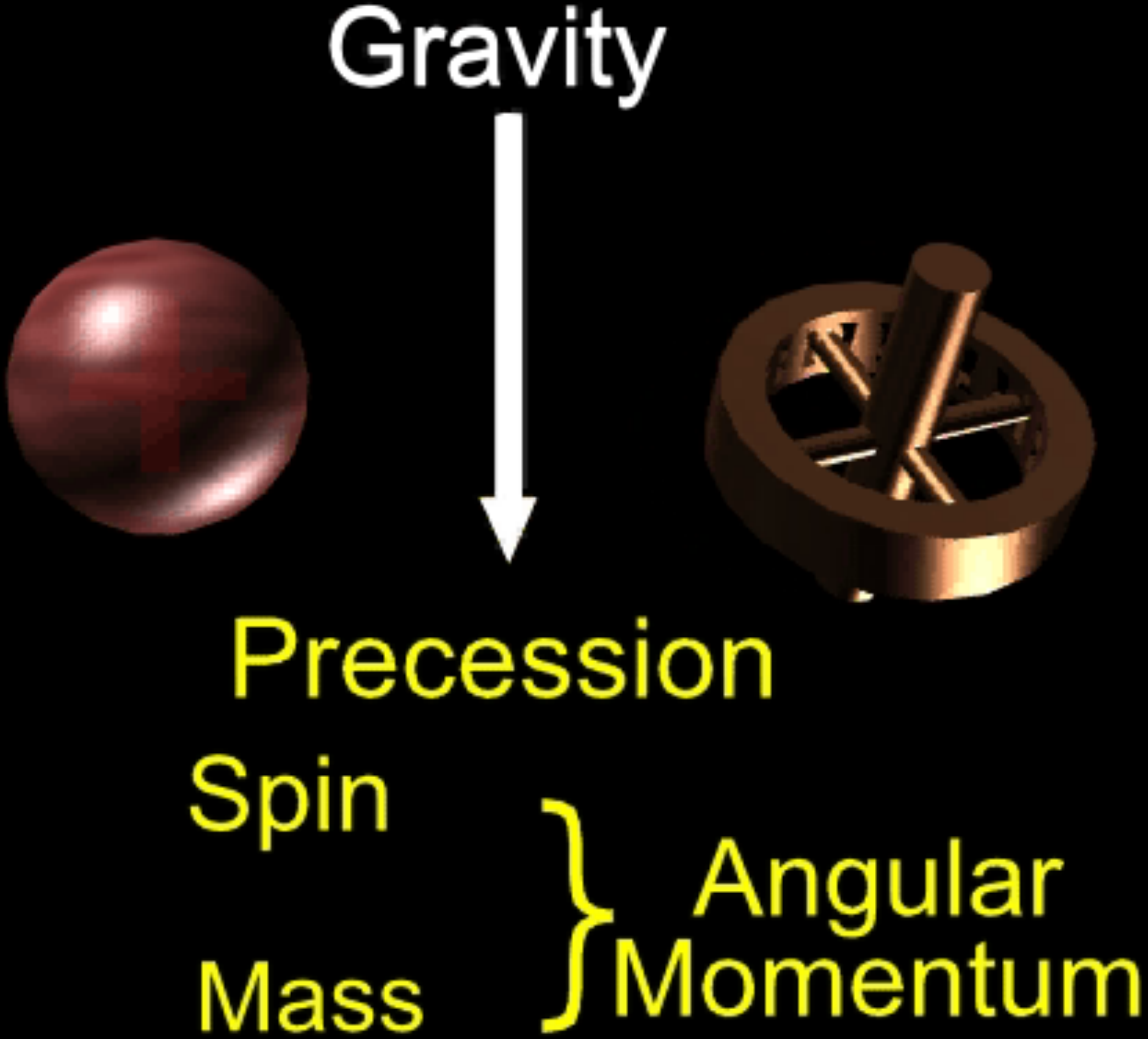
Protons (small magnets) align with an external magnetic field (B_0).

Angular Momentum



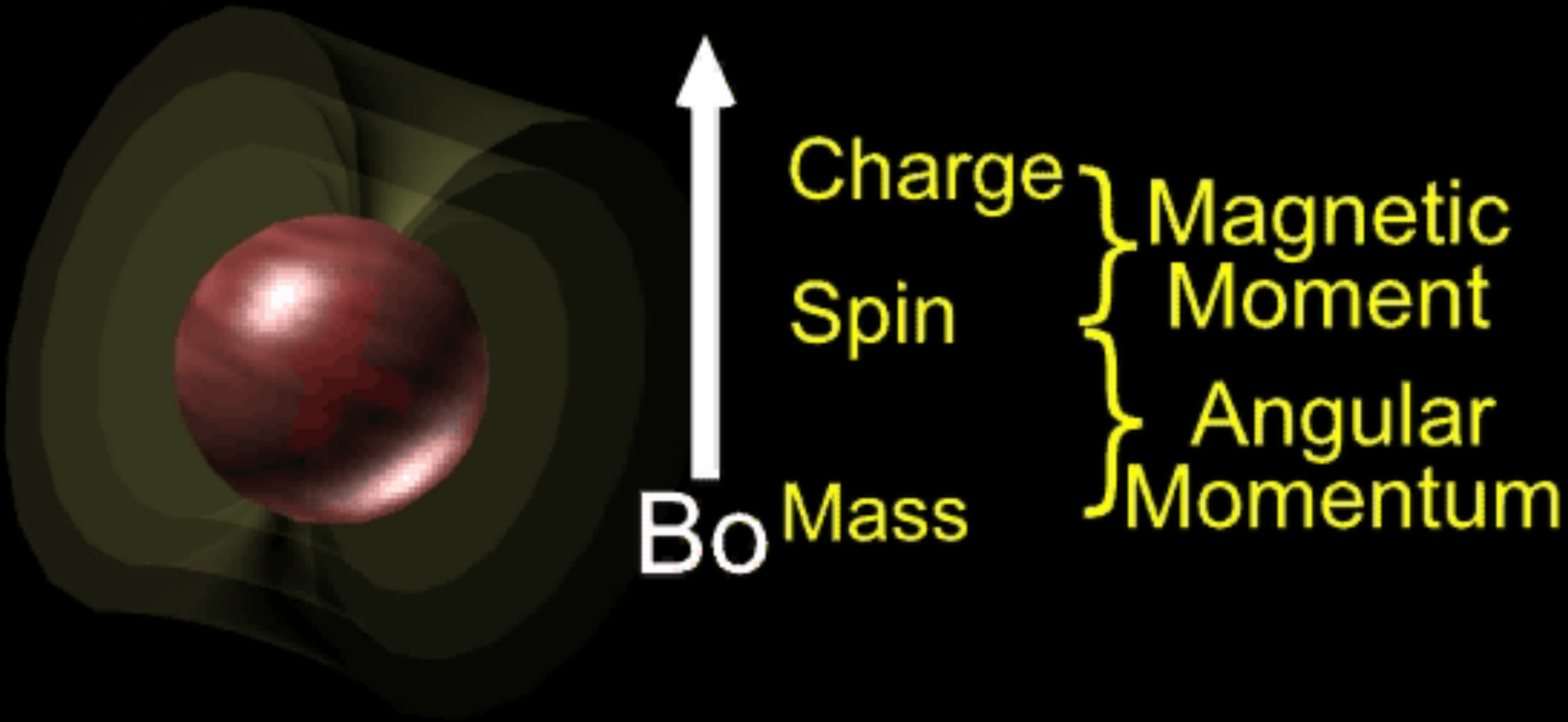
Protons have angular momentum because of spin and mass.

Precession (Top Analogy)



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

Larmor Frequency



Bo

Charge
Spin
Mass

Magnetic Moment

Angular Momentum

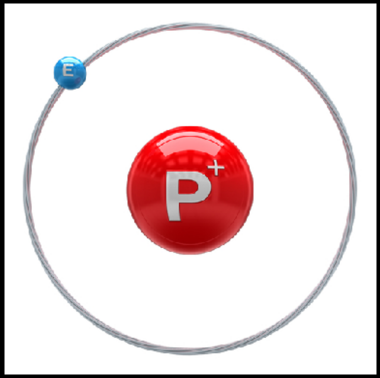
Larmor Frequency $=\omega=\gamma Bo$

The frequency of precession is the Larmor frequency.

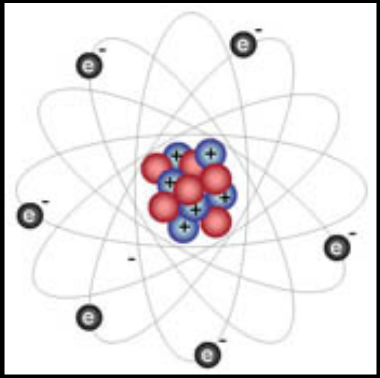
NMR Active Nuclei

- Spin + Charge + Mass ⟹ 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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