Magnetism and Nuclear Magnetization

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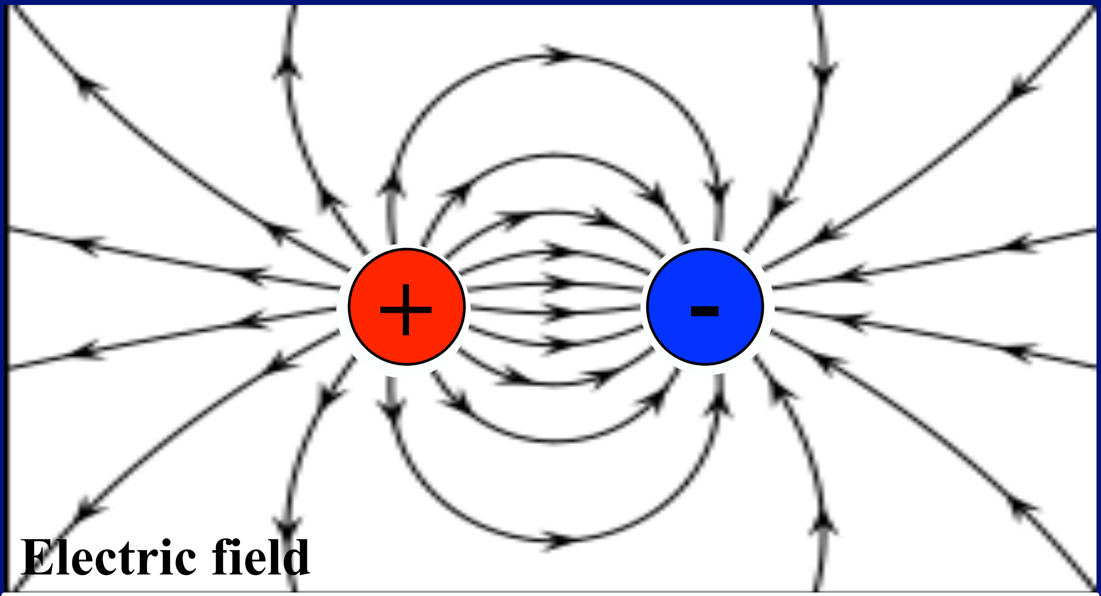
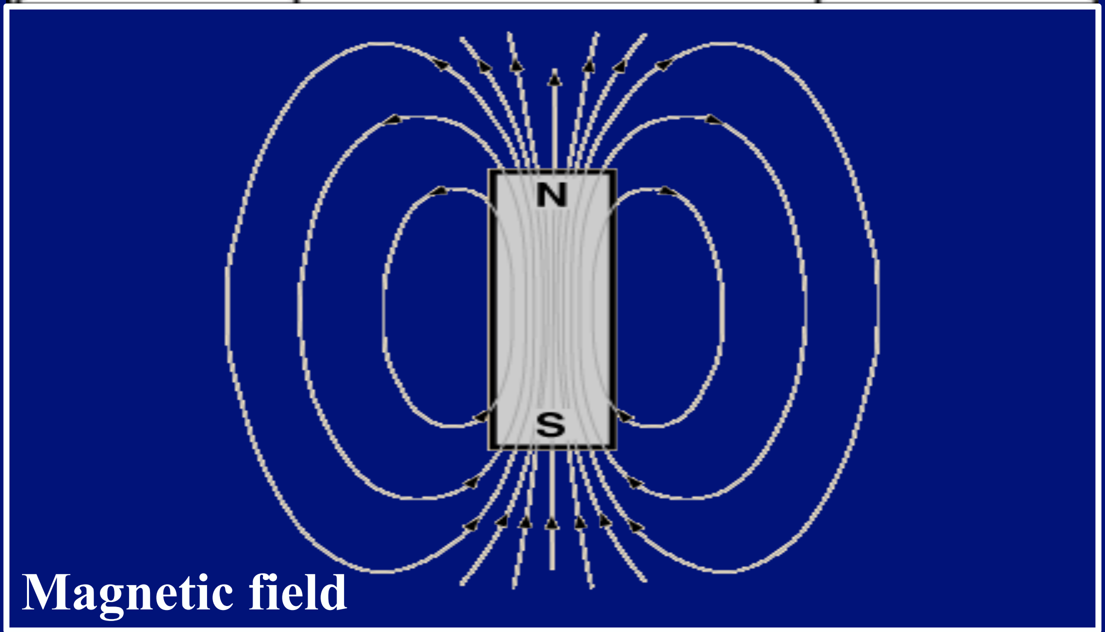
Main Areas Covered in Lecture

- Magnetic fields
- Magnetic susceptibility
- Types of magnetic materials
- Nuclear magnetism
- Net magnetization due to field strength
- Precession
- Nuclear magnetic resonance and excitation

Magnetic Fields





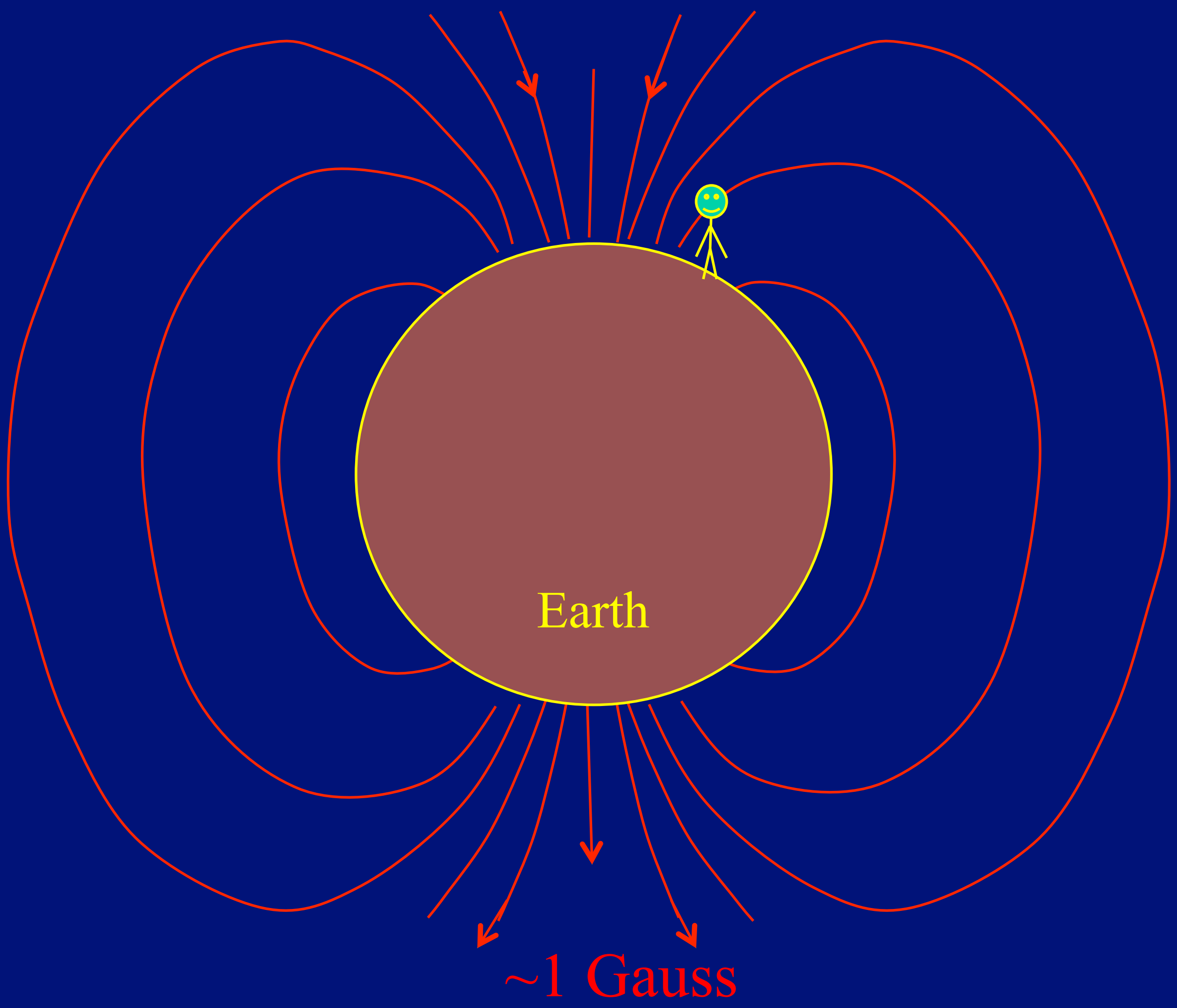
Electric and magnetic fields are defined in terms of the interaction with electric charge.

Stationary charges will produce an electric field and only an electric field in the surrounding space.

A magnetic field is always associated with the motion of charged particles.

This is true also for the magnetic properties of materials – the fields generated in these materials are due to the motion of charged particles (electrons and protons).

The Earth's Magnetic Field



We live our lives in a magnetic field on the surface of a large magnet that is the Earth.

The Earth's magnetic field is thought to be created by currents circulating in its core.

Although the Earth is big, the strength of it's magnetic field is small, only ½ to 1 Gauss at the surface.

The earth's magnetic field at the surface is only about 1/100th the strength of a refrigerator magnet.

Gauss and Tesla are measures of magnetic field strength.
1 Tesla = 10,000 Gauss.

Strongest Human-Made Magnetic Fields

World's Strongest Magnet: 91.4T

Press release published by Helmholtz-Zentrum Dresden-Rossendorf on June 28, 2011

In order to examine as closely as possible the electric charge in the materials of tomorrow, researchers need higher magnetic fields with, for example, 90 or 100 Tesla. "At 100 Tesla, though, the Lorentz force inside the copper would generate a pressure which equals 40,000 times the air pressure at sea level," calculates Joachim Wosnitza. These forces would tear copper apart like an explosion. That is why researchers use specific copper alloys which can withstand ten thousand times the atmospheric pressure. They then add a corset made from a special fiber that is

914,000 Gauss

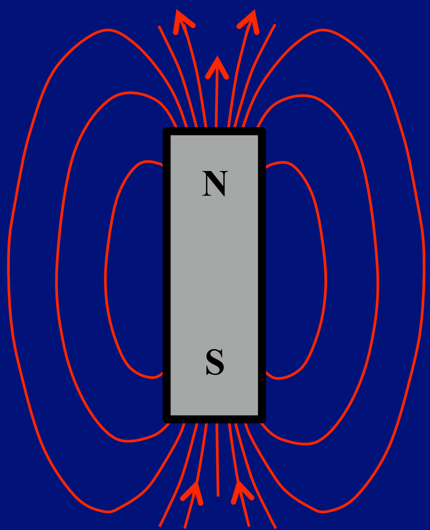
The strongest magnetic field created by humans, as of 2011, is a 91.4 Tesla electromagnet.

It is very difficult to make magnets of this strength. One problem is the force of the magnetic field on the conductors containing the currents that produce the field. Such strong magnets tend to rip themselves apart.

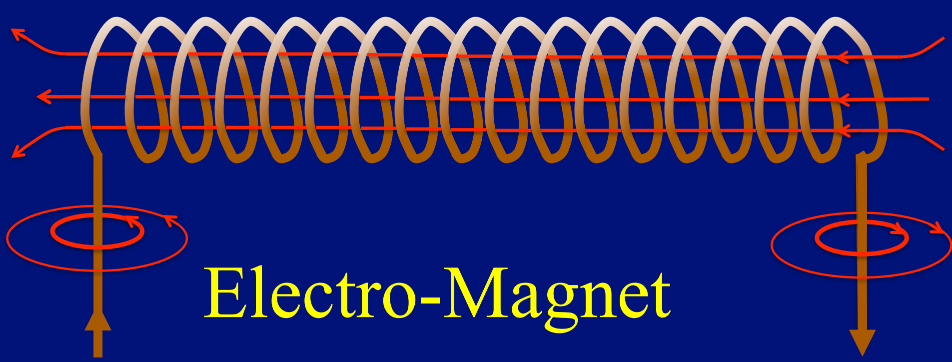
The strongest MRI magnet to date is 21.1 Tesla. It has a bore diameter of only 10.5 centimeters.

The strongest human MRI is 11.7 Telsa.

Creating Magnetic Fields



Permanent Magnet



Electro-Magnet

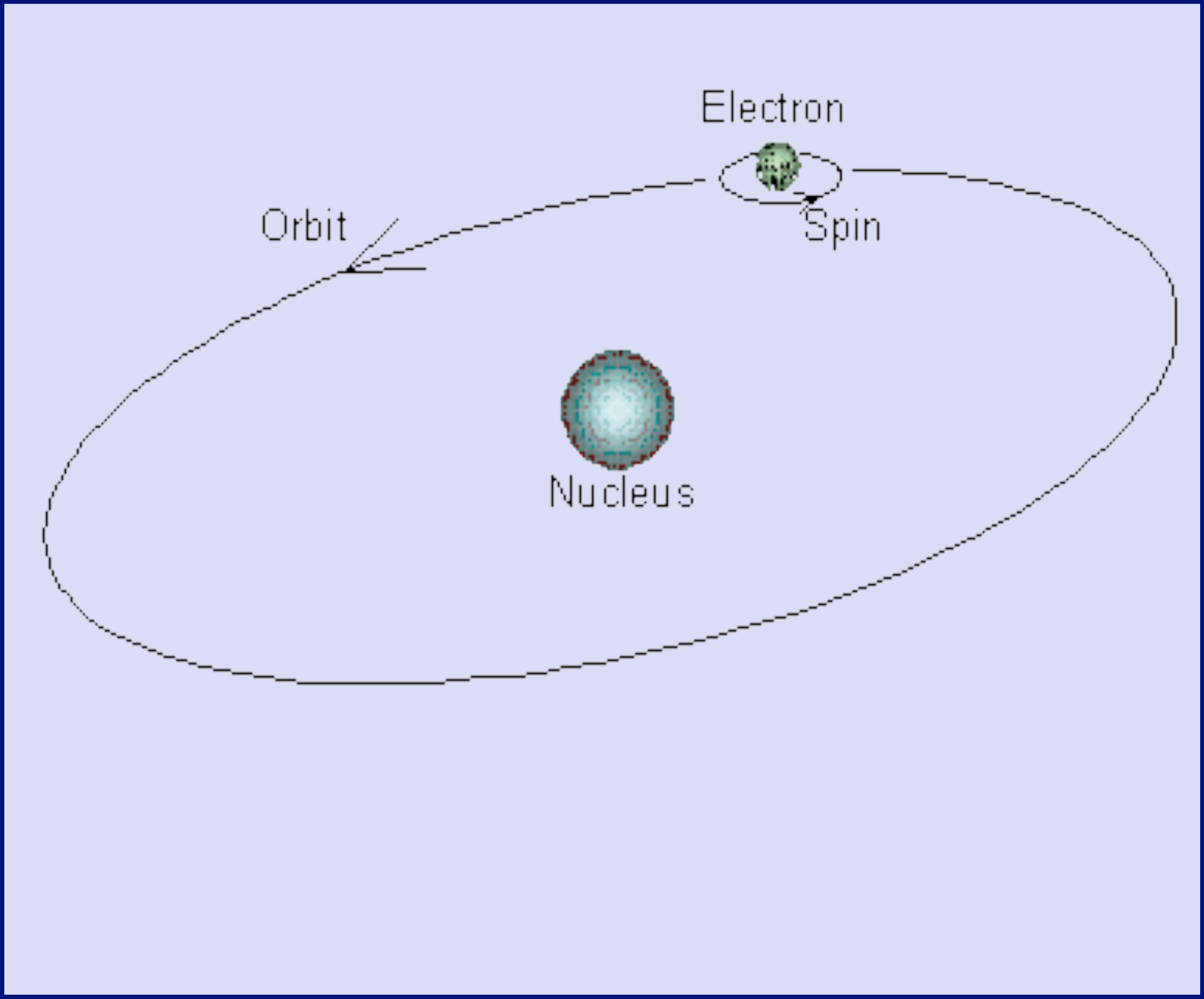
The magnets made by humans are either permanent magnets or electro-magnets.

Permanent magnets are made from ferromagnetic materials. The magnetic field is generated by the movement of electric charge – by electrons – in the atom.

Electro-magnets are made by winding conducting wire in loops. The strength of the magnetic field increases with the number of loops.

In a modern MRI there are thousands of loops carrying 100 amps or more of current.

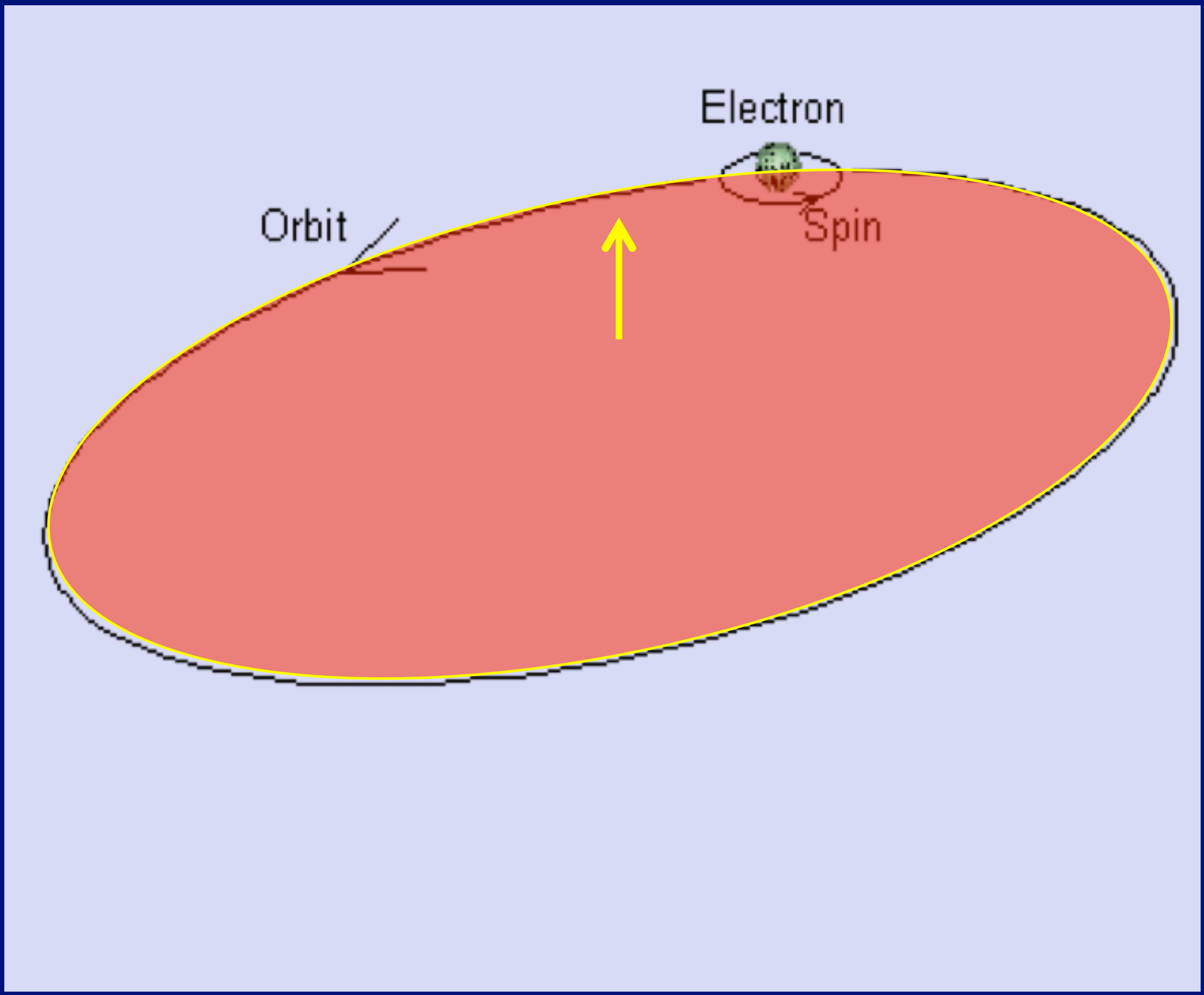
Magnetic Fields in Materials



Magnetic fields are always generated by electrical charge in motion.

In materials, the primary source of the magnetic fields is the motion of the electrons within the atom.

Magnetic Fields in Materials

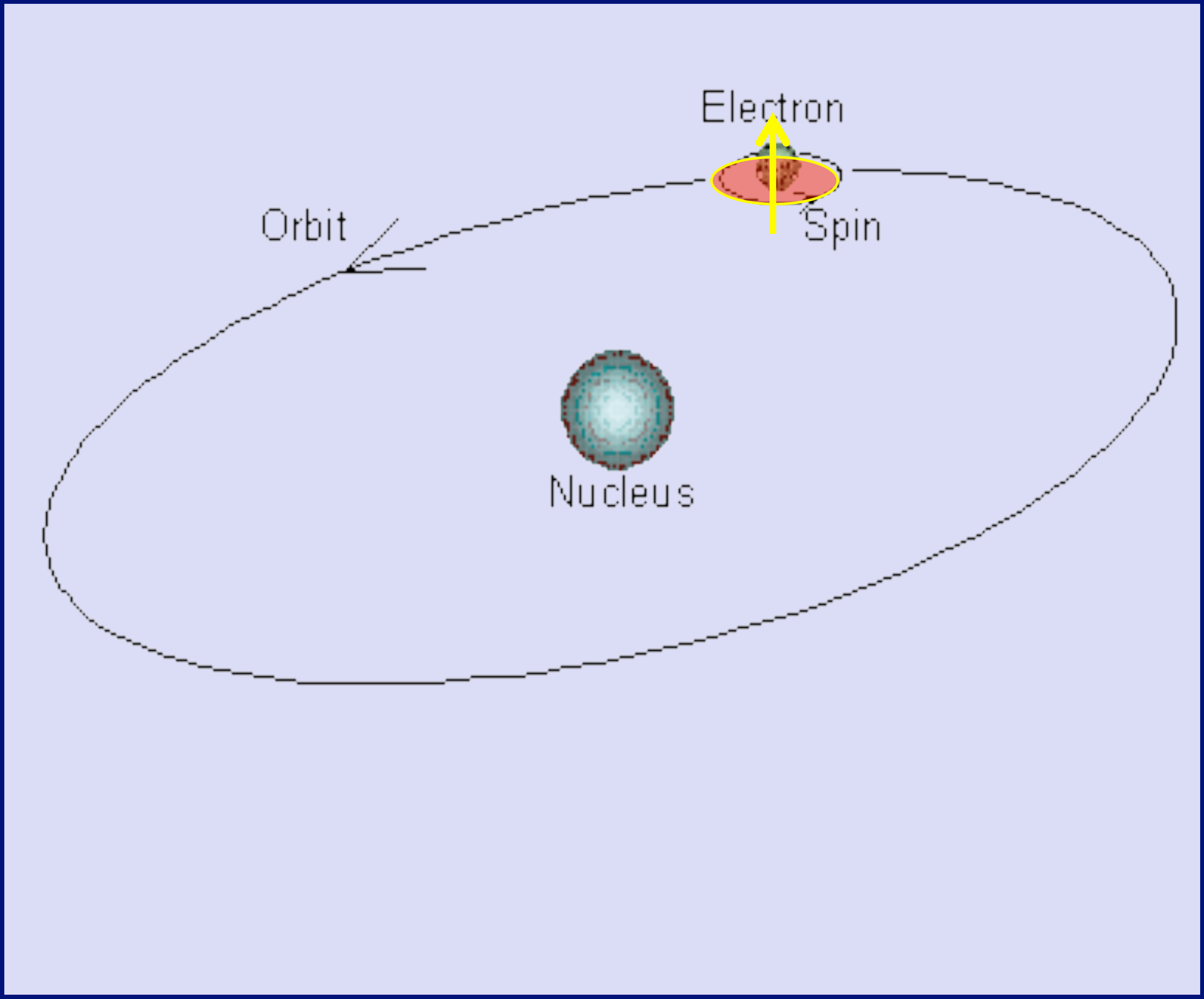


Magnetic fields are always generated by electrical charge in motion.

In materials, however, the source of the magnetic fields is the motion of the electrons in the atom.

The orbital motion of the electron generates a magnetic dipole moment.

Magnetic Fields in Materials



Magnetic fields are always generated by electrical charge in motion.

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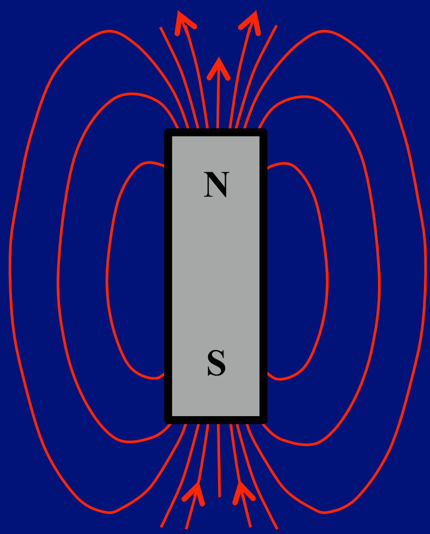
The orbital motion of the electron generates a magnetic dipole moment.

The spin of the electron also generates a magnetic dipole moment.

Magnetic Fields in Materials



Magnetic fields are always generated by electrical charge in motion.

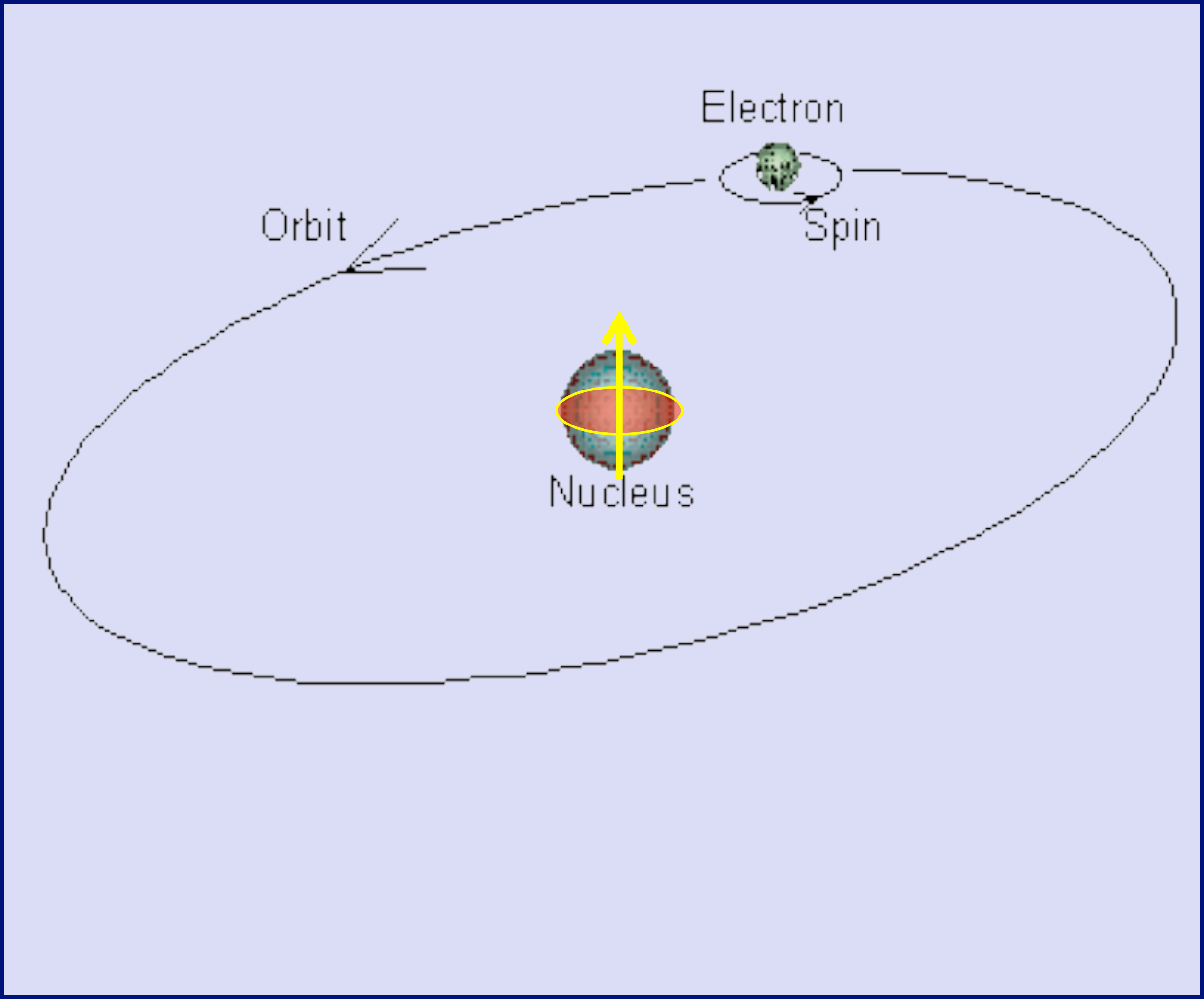
In materials, however, the source of the magnetic fields is the motion of the electrons in the atom.

The orbital motion of the electron generates a magnetic dipole moment.

The spin of the electron also generates a magnetic dipole moment.

It is useful to think of these magnetic dipole moments like little bar magnets.

Magnetic Fields in Materials



There is also a magnetic dipole moment generated in the nucleus of the atom.

The effect of nuclear magnetism is very small compared to the magnetism due to the electron.

Nuclear magnetism is not important when considering the bulk magnetic properties of materials – for example, in making industrial magnets, or considering safety issues in MRI.

Nuclear magnetism is very important, however, in probing the characteristics of molecules and the molecular environment in materials - including in tissue.

Nature of Magnetic Materials

Magnetic Properties:

1. Diamagnetic
2. Paramagnetic
3. Ferromagnetic
4. Antiferromagnetic
5. Ferrimagnetic
6. Superparamagnetic

Materials are classified in terms of their magnetic properties into six different categories.

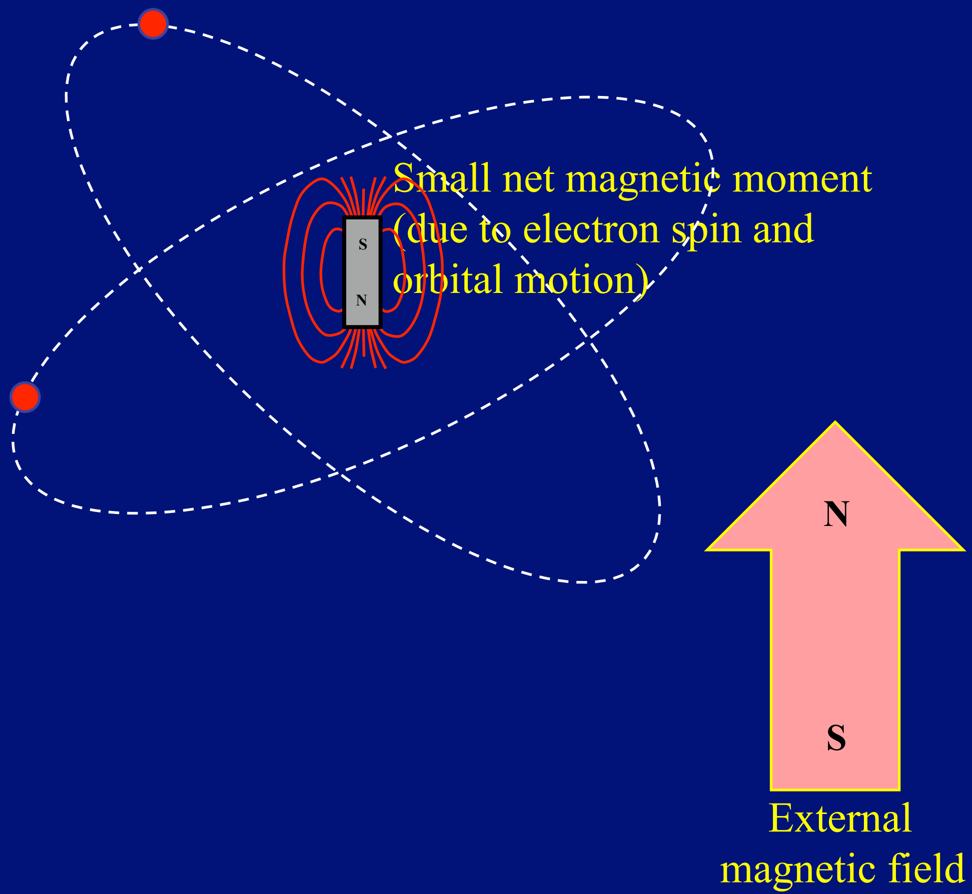
Types of materials most relevant for the purposes of MRI are diamagnetic, paramagnetic and ferromagnetic.

Most tissues in the body are DIAMAGNETIC.

MRI contrast agents are PARAMAGNETIC.

Iron, nickel and cobalt are FERROMAGNETIC.

1. Diamagnetic Materials



Diamagnetic atoms have NO inherent magnetic moment.

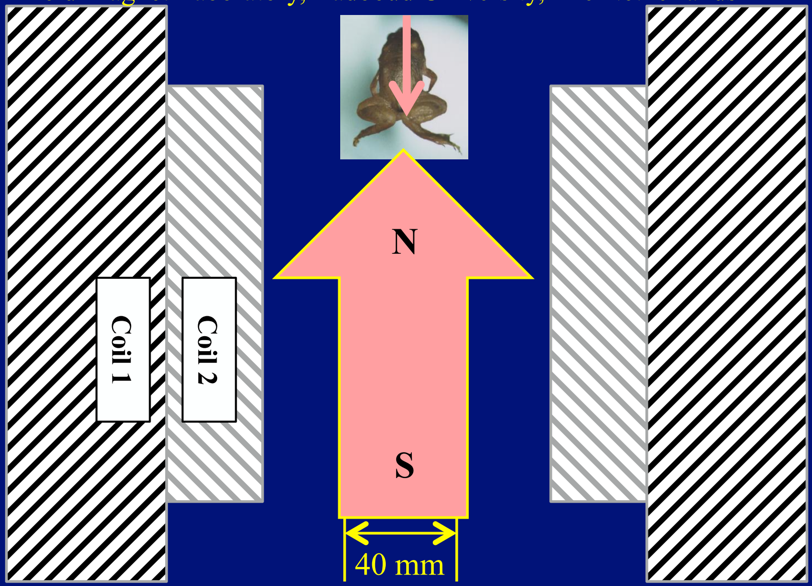
In the presence of an external magnetic field the electron motion is altered resulting in a small net magnetic moment.

The magnetic moment of diamagnetic atoms in an external magnetic field is oriented opposite to the direction of the external magnetic field.

1. Diamagnetic Materials

http://www.ru.nl/hfml/research/levitation/diamagnetic/
High Field Magnet Laboratory, Radboud University, The Netherlands

16.5 Tesla
vertical bore
Bitter
electromagnet.



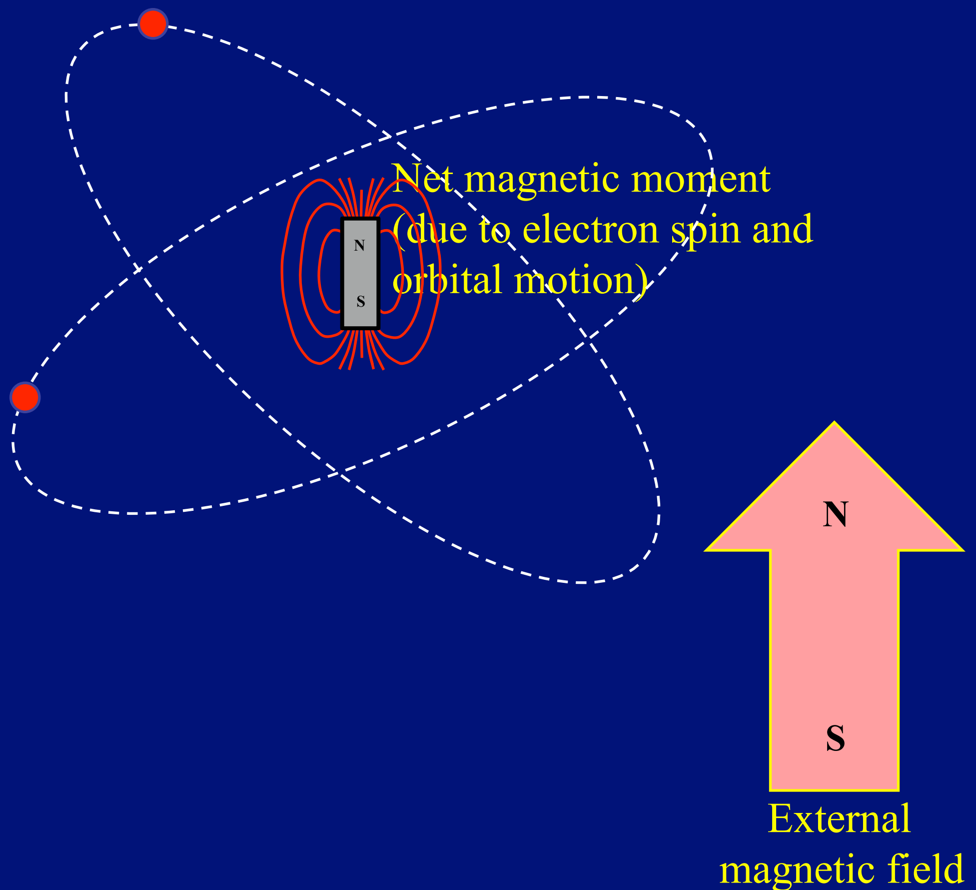
Biological tissue is diamagnetic.

Although the magnetism induced in tissue by a magnetic field is very small, if the field is strong enough, the force on the tissue from the field can be significant.

Frogs have been levitated at 16.5T in a small-bore electromagnet.

Though the strongest human MRI at present is 11.7T, there are initial plans to go as high as 20T.

2. Paramagnetic Materials



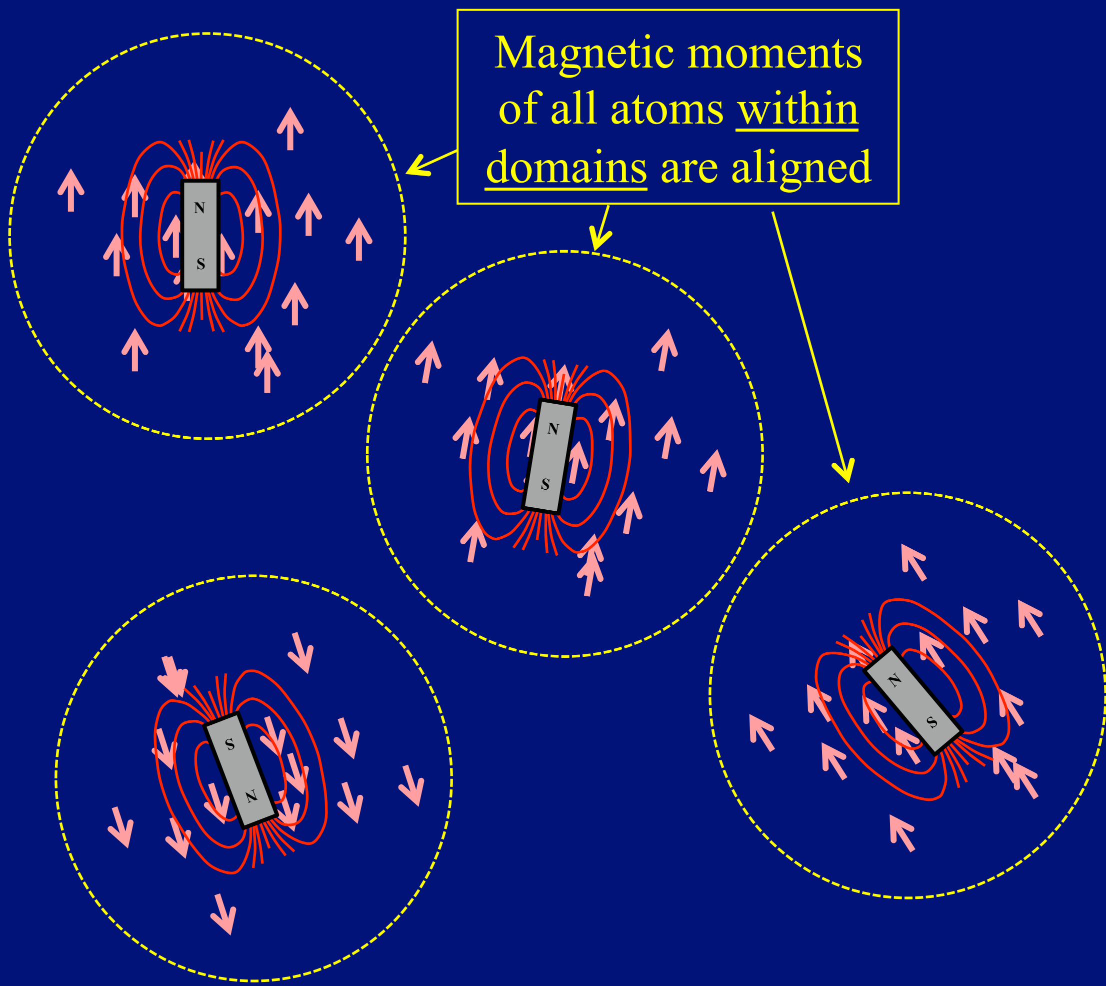
Paramagnetic atoms have an inherent magnetic moment.

In the absence of an external magnetic field the magnetic moments are randomly aligned and there is no net magnetic moment in the material.

When placed in an external magnetic field a small majority of the paramagnetic atoms align with the magnetic field and there is a small net magnetic moment.

The net magnetic moment of paramagnetic atoms in an external magnetic field is aligned in the direction of the external magnetic field.

3. Ferromagnetism

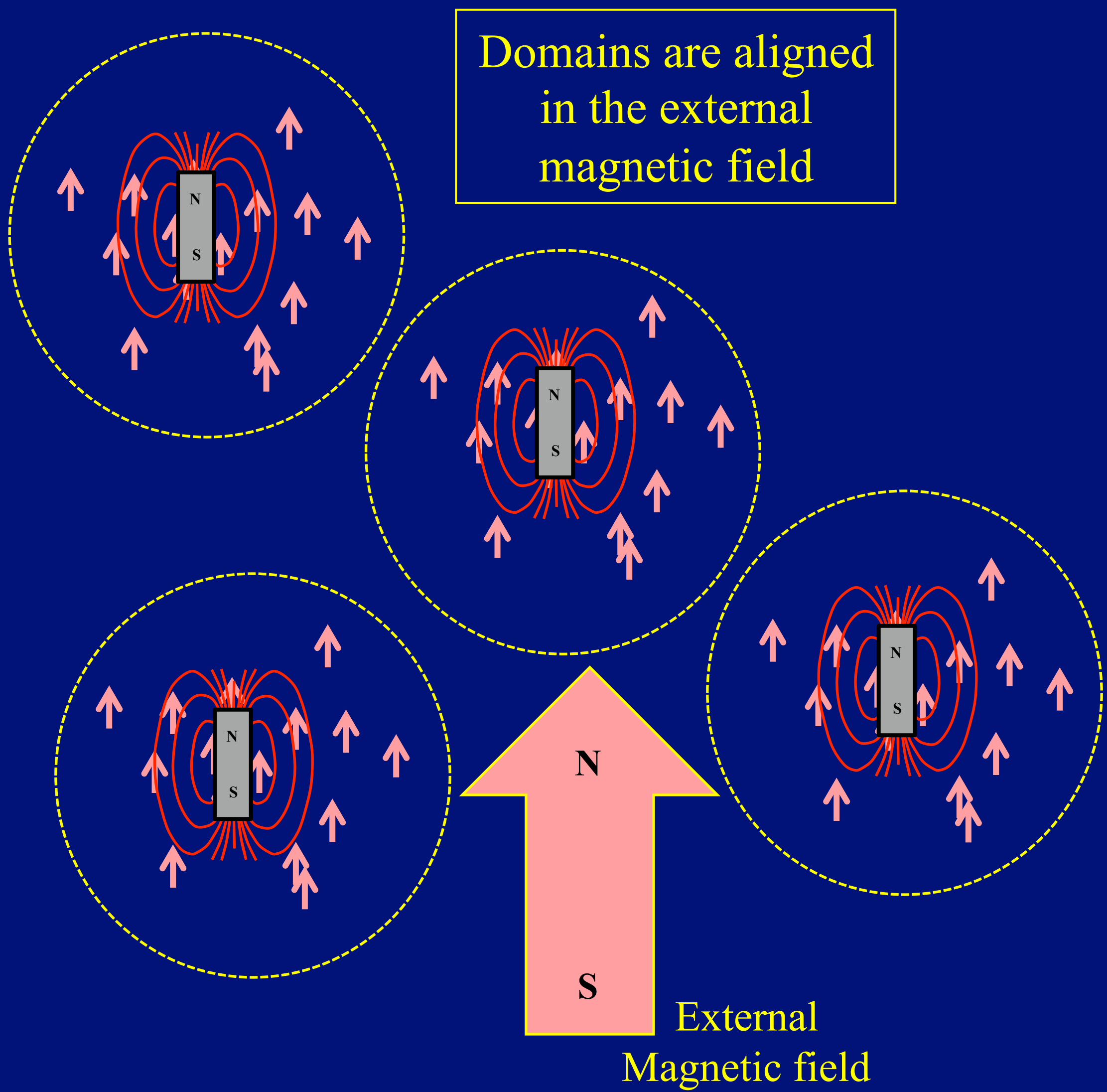


Ferromagnetic atoms have an inherent magnetic moment that is much larger than it is for paramagnetic atoms.

Due to magnetic coupling between atoms, collections of ferromagnetic atoms align their magnetic moments over large regions called domains.

In the absence of an external magnetic field the domains tend to be randomly aligned and there is no net magnetic field in the material.

3. Ferromagnetism

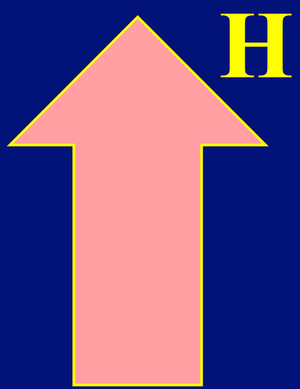


In the presence of an external magnetic field, the domains now tend to align parallel to the external field.

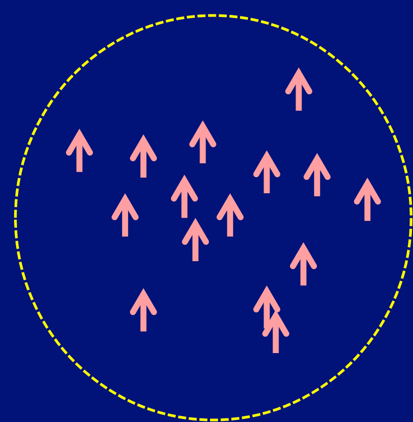
Eventually, all domains will be aligned so that the magnetic moments of all atoms point in the same direction. A very large internal field results – typically between 0.2 and 2 Tesla.

Permanent magnets are made from ferromagnetic material in processes where the domains remain aligned even when the external magnetic field is removed.

Magnetic Susceptibility



External magnetic field



Magnetized Sample, Net magnetization = M

$$\mathbf{M} = \chi_m \mathbf{H}$$

Material	χ_m
Iron (99.8%)	150
Iron (99.95%)	10,000
Permalloy	8,000
Super Permalloy	100,000

The magnetic susceptibilty, χ_m , is a measure of the degree to which a material is magnetized.

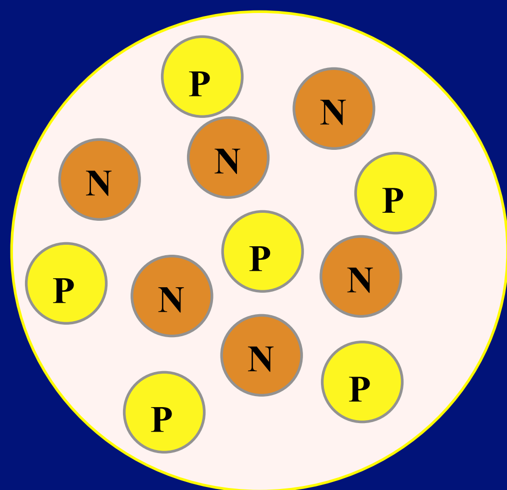
$$M = \chi_m H$$

Diamagnetic materials have a very small negative susceptibility while paramagnetic materials have a small positive susceptibility.

Ferromagnetic materials such as iron and nickel have magnetic susceptibilities that are >>1.

There is also nuclear susceptibility, χ_{nuc} , related to nuclear magnetism. But it is several orders of magnitude lower than typical values of electronic susceptibility.

Nuclear Magnetism and Nuclear Spin



Carbon nucleus

^{12}C

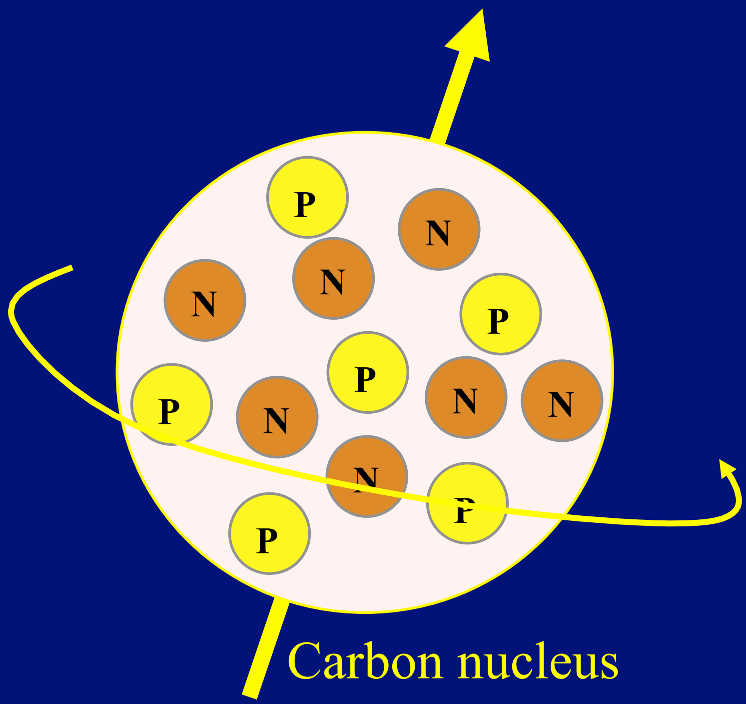
(6 protons and 6 neutrons)

Nuclei of all elements contain protons and neutrons and they each have the property of "spin".

The protons and neutrons in the atomic nucleus combine to give a net spin.

If there is an even number of protons and an even number of neutrons, then the net spin of the nucleus is zero.

Nuclear Magnetism and Nuclear Spin



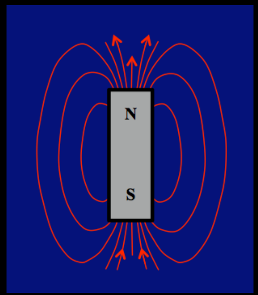
Carbon nucleus

^{13}C

(6 protons and 7 neutrons)

If there is an odd number of protons OR there is an odd number of neutrons in the nucleus of the atom, then the net spin of the nucleus is not zero.

The circulating electric charge in the nucleus due to the net spin gives the nucleus a *magnetic dipole moment*.



Nuclei in the Human Body with MR Signal

Nucleus	Abundance in the Body	Abundance of Isotope	Percent of All Atoms in the Body
^{13}C	9.4%	1.11%	0.1%
^{23}Na	0.04%	100%	0.04%
^{31}P	0.24%	100%	0.24%
^{1}H	63%	99.985%	63%

A number of elements in the human body have stable isotopes that have a non-zero net nuclear spin.

If an element is naturally abundant in the body AND its isotope with non-zero spin is also abundant – the potential for giving a detectable MRI signal is maximized.

Nuclei in the Human Body with MR Signal

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^{1}H	63%	99.985%	63%

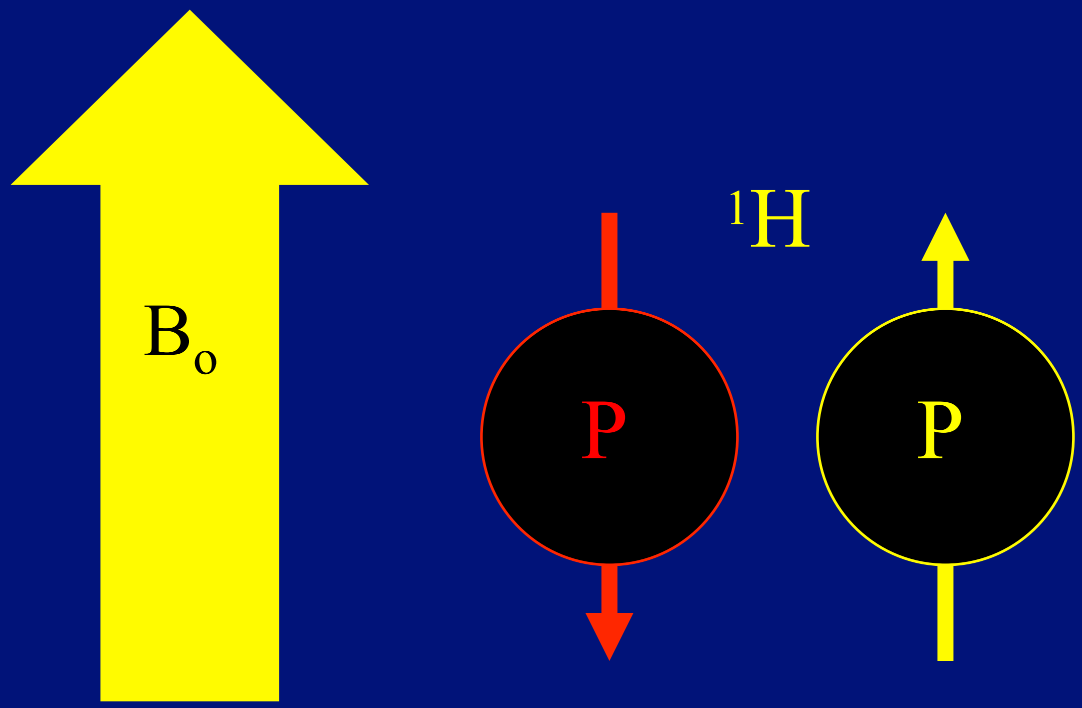
Hydrogen containing a single proton, ^{1}H, is a very good candidate nucleus for MRI because:

- there is a lot of hydrogen in the body,
- ^{1}H is the most common isotope of hydrogen
- the magnetic moment of ^{1}H is relatively strong compared to other nuclei

In medical imaging we deal almost exclusively with the signal ^{1}H.
Because ^{1}H consists of a single proton, MRI is often referred to as proton imaging.

Hydrogen atoms in the body are primarily in water and fat.

Quantum States in NMR

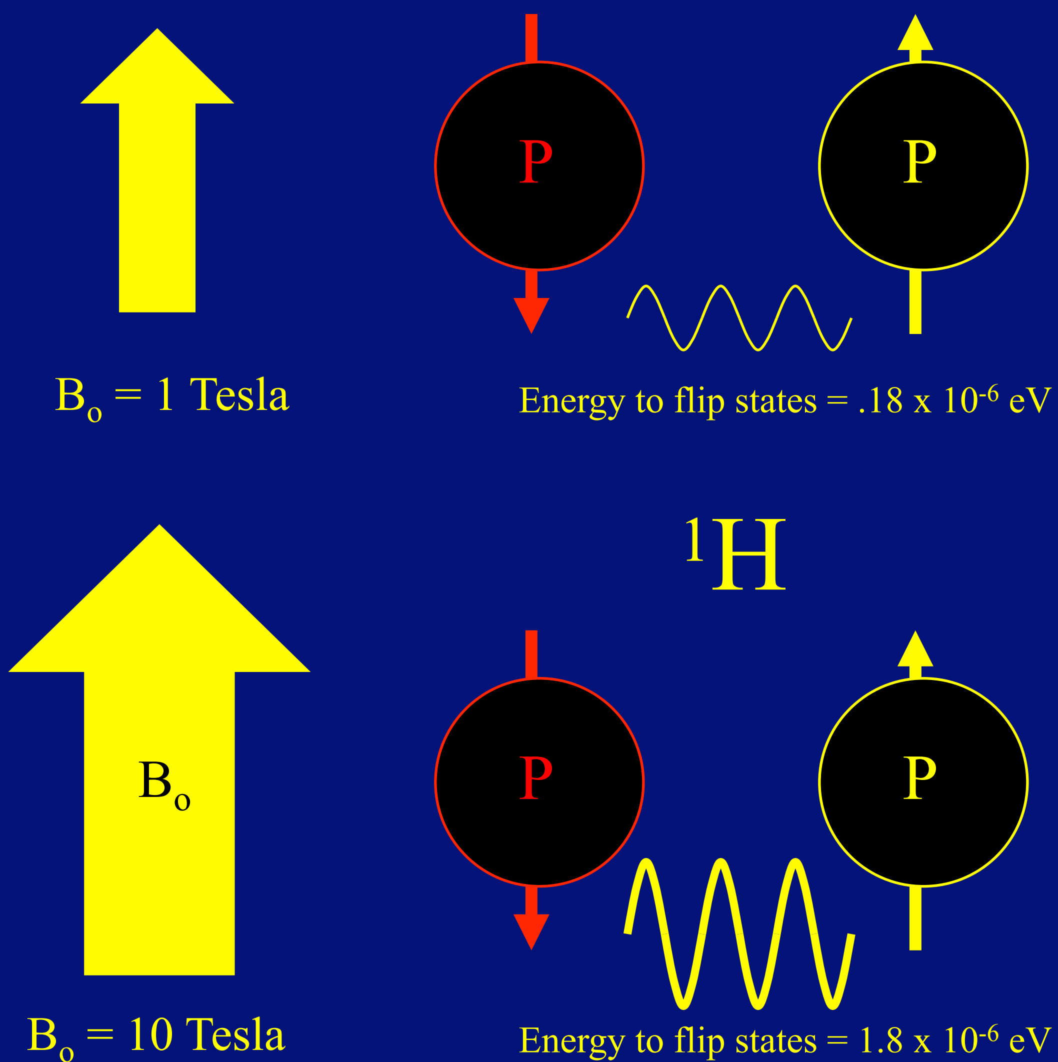


In a background magnetic field, B_o, the states of the nuclear magnetic moments are quantized – that is, there are fixed number that are allowable.

For the hydrogen atom, there are only two allowable states.

The nuclear magnetic moments must either align with the field or against it.

Quantum States in NMR

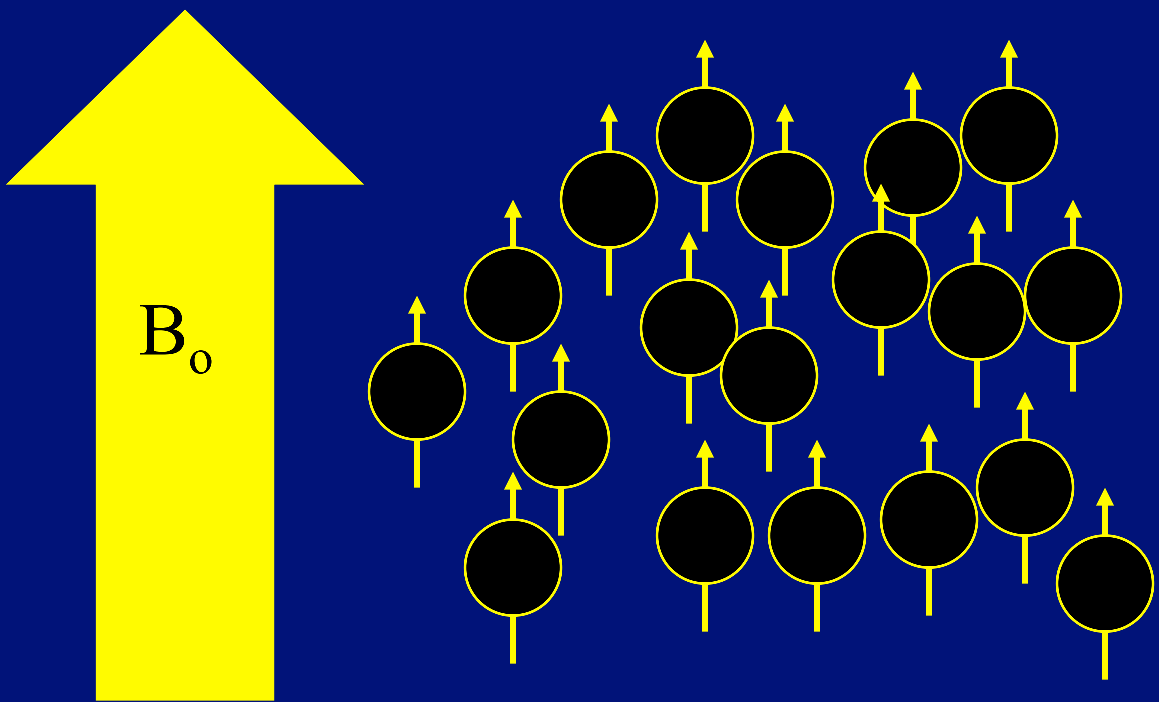


The energy needed to change state from aligned to not-aligned depends on how strong the background magnetic field is.

In a strong magnetic field, more energy is needed to change the state of alignment of the nuclear magnetic moment than in a weak field.

The energy needed to ‘flip spins’ in a 10 Tesla field is ten times that needed to flip spins in a 1 Tesla field.

Alignment of Nuclear Spins

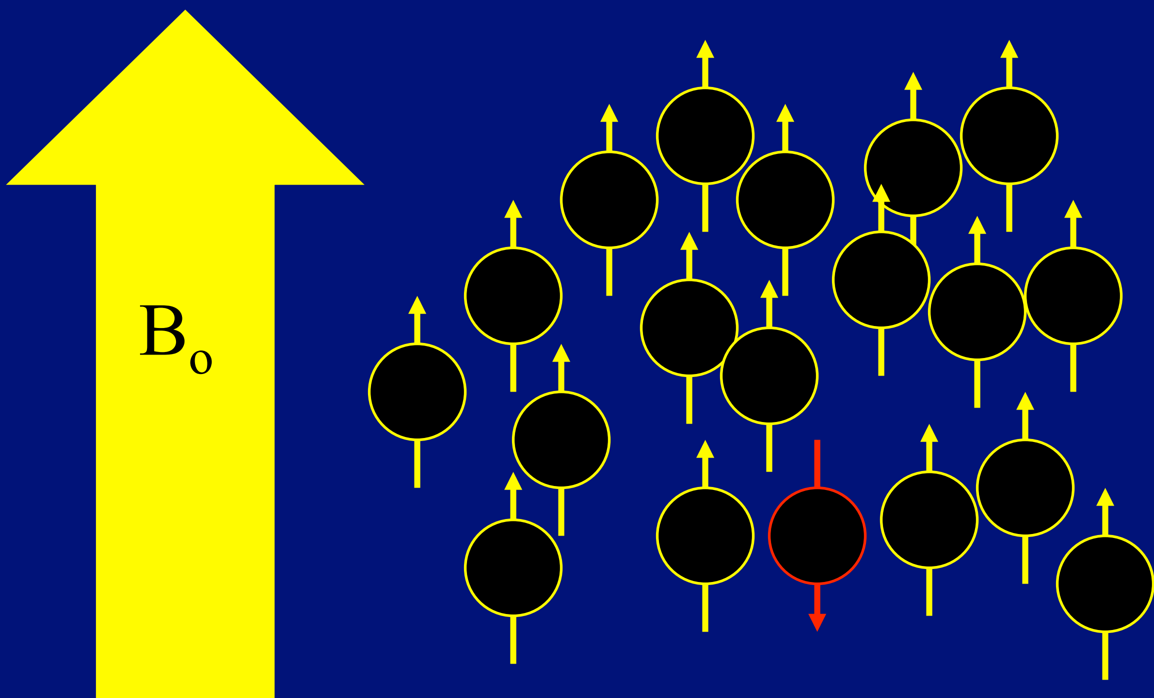


The preferred state of the ^1H nuclear magnetic moments is to align with the external magnetic field.

This is because it is the lowest energy state.

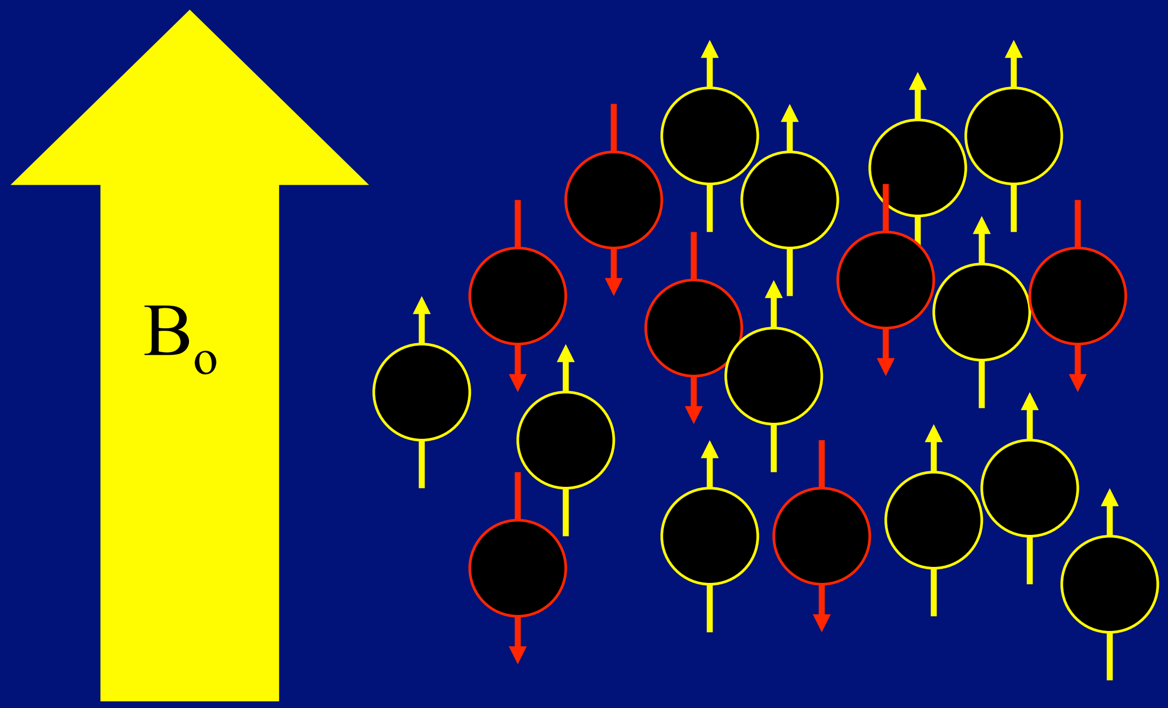
We might expect, therefore, that all the ^1H nuclei in our body will be aligned with any external magnetic field.

Alignment of Nuclear Spins



Although the preferred, low-energy state is to align with the field, due to thermal fluctuations, some spin moments may occasionally align opposite to the field in the higher energy state.

Alignment of Nuclear Spins



Although the preferred, low-energy state is to align with the field, due to thermal fluctuations, some spin moments may occasionally align opposite to the field in the higher energy state.

At high-temperatures the moments constantly flip back and forth and only a small net magnetic moment is aligned with the field.

At body temperature, given 1 million hydrogen spins at 1.5T, only about 5 more spins on average are aligned with the field than against the field.

Distribution of States - Nuclear Polarization

Net number of protons aligned with a 1.5T field in 1 mm^3 of water:

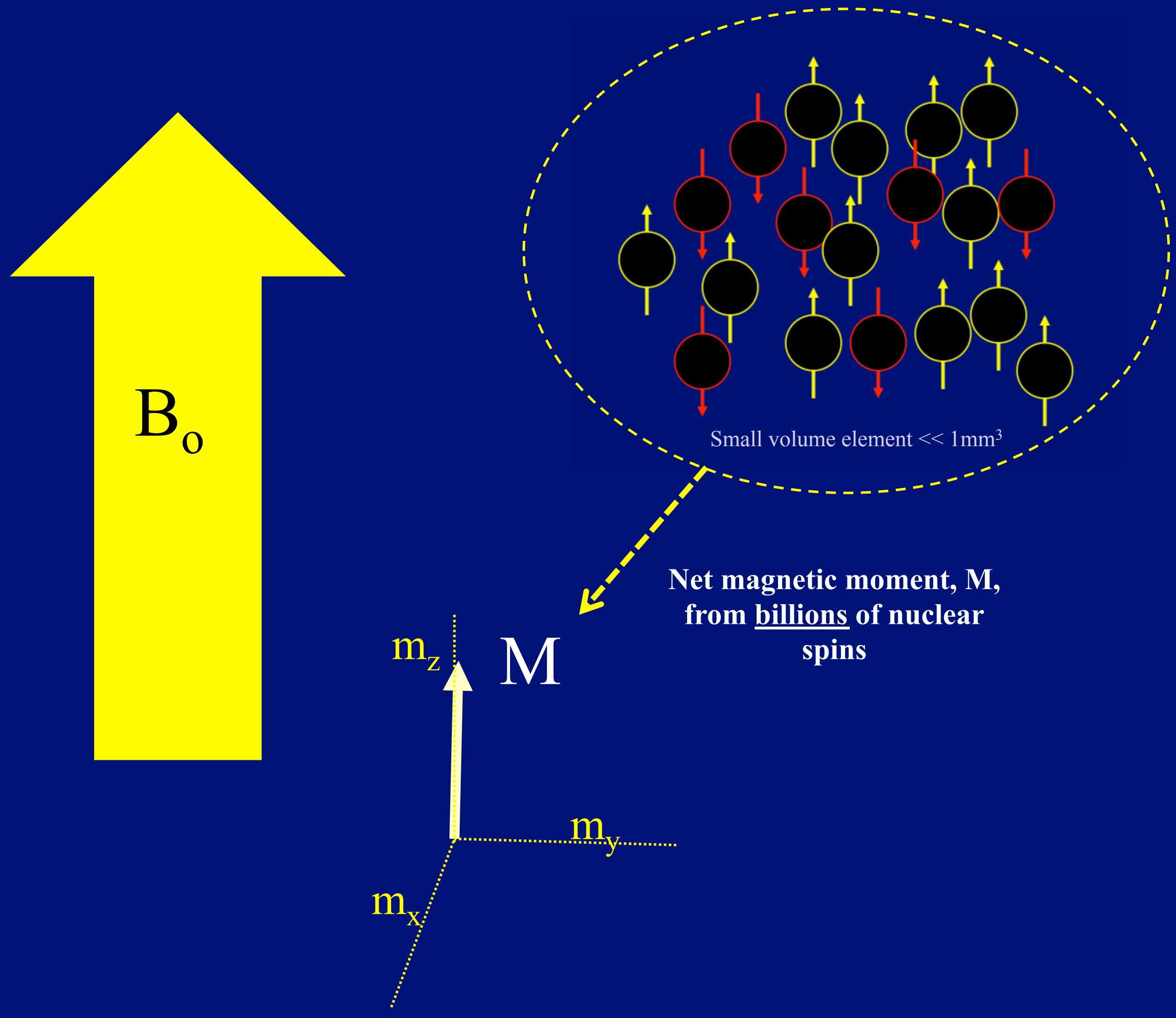
330 trillion

The percentage of magnetic moments aligned with the external field is referred to as the nuclear polarization of a sample.

The polarization is dependent on the field strength and on temperature. It increases with field strength and decreases with temperature.

Although, at body temperature and in a typical MRI magnet, the polarization is very very low, the net number of moments aligned with the field, even in a small volume, is substantial because there are so many atoms.

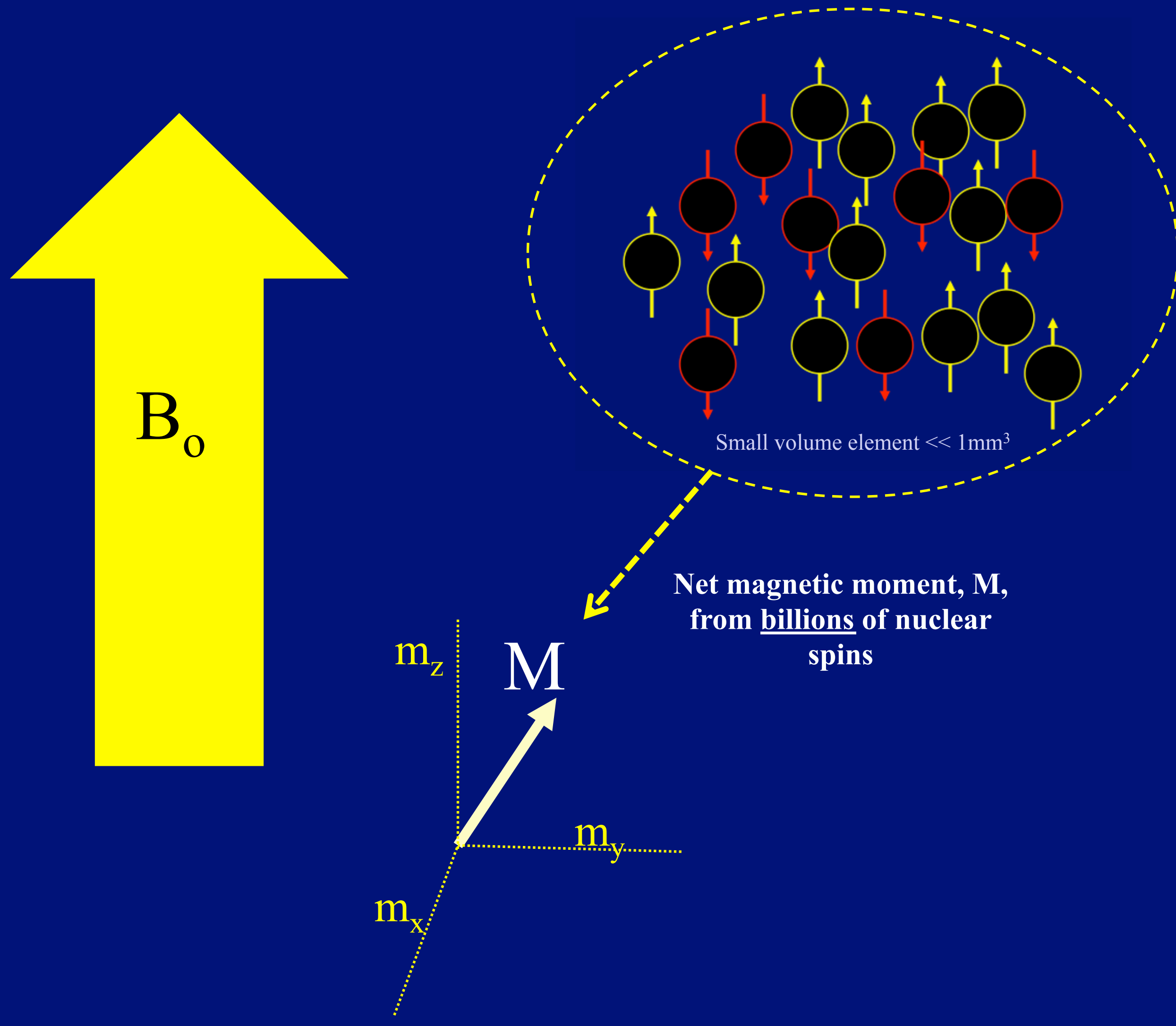
Magnetization Vector



Most of MRI can be explained using a <u>magnetization vector</u>, M, that represents the net moment from a very large number of atoms.

The net magnetization in small volumes << 1mm3 can be represented by such a magnetization vector.

Magnetization Vector

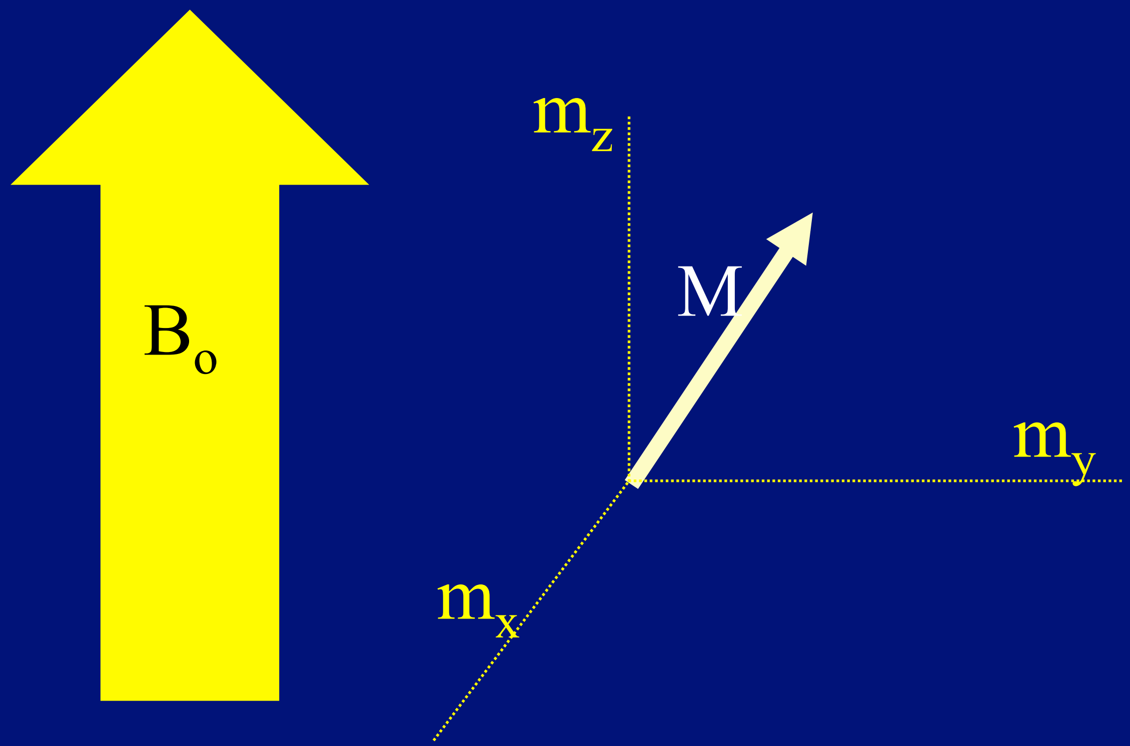


Most of MRI can be explained using a magnetization vector, M, that represents the net moment from a very large number of atoms.

Small volumes << 1mm3 are each represented by such a magnetization vector.

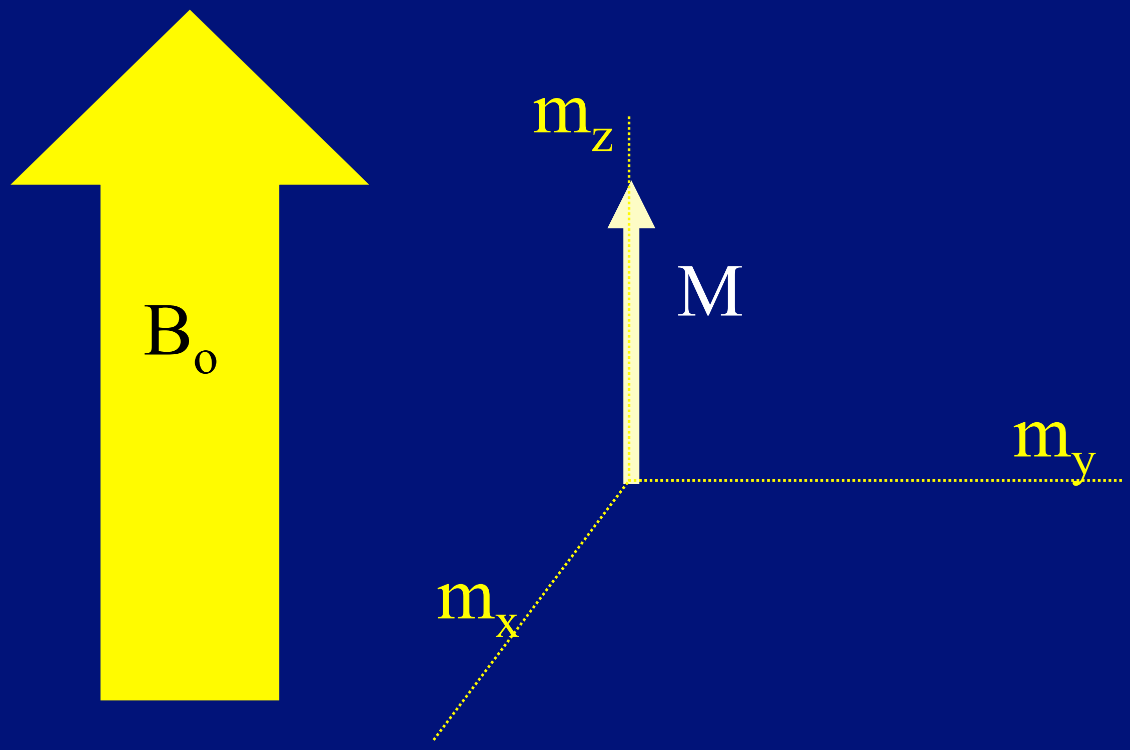
The magnetization, M, interacts with the external field according to the laws of classical physics.

Magnetization Vector



Unlike the individual spin magnetic moments, M can have any orientation - NOT just with or against the B_o field orientation.

Magnetization Vector

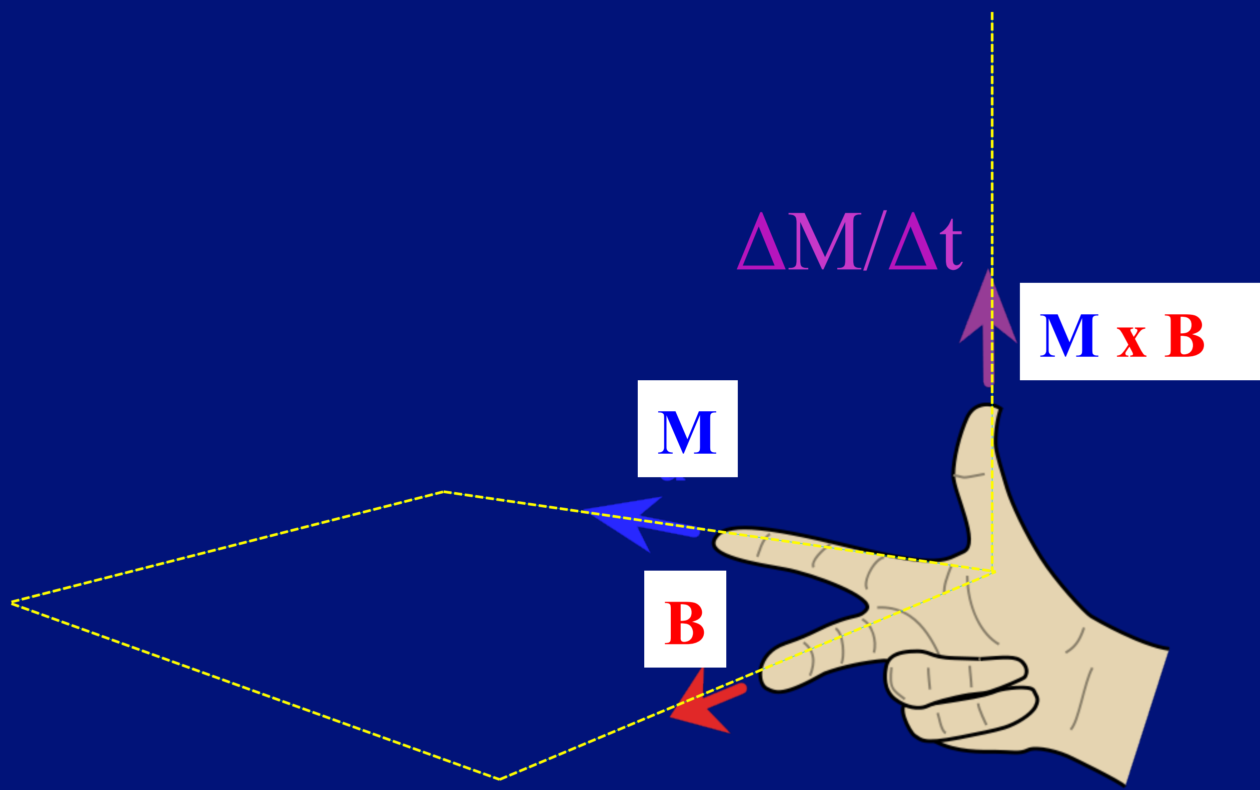


Unlike the individual spin magnetic moments, M can have any orientation - NOT just with or against the B_o field orientation.

Although the magnetization vector, M, can have any orientation, in the resting state, it is aligned with the field - along the m_z axis - also known as the longitudinal axis.

When M is oriented along the m_z axis, there is very little potential for making measurements – or images.

Dynamics of the Magnetization Vector



$\Delta M/\Delta t$ is orthogonal to the plane containing M and B

The magnetization (M) interacts with the external magnetic field (B) or any other magnetic field.

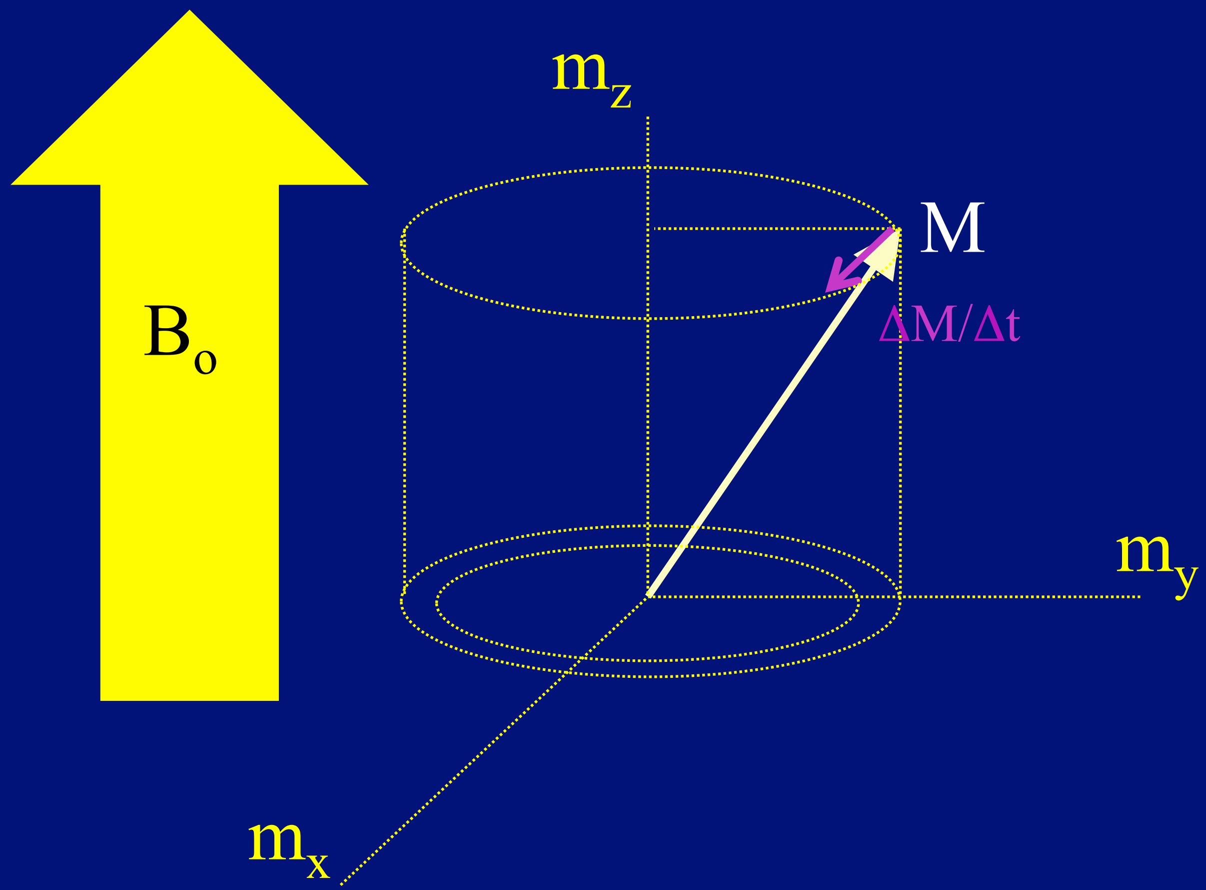
The rate of change of M due to B is proportional to the cross product, M x B.

The orientation of the magnetization vector changes in a direction that is orthogonal to the plane containing both M and B.

The magnitude of the change in M depends on the angle between M and B.

The magnitude of the change is maximum if M and B are orthogonal and is 0 if they are parallel.

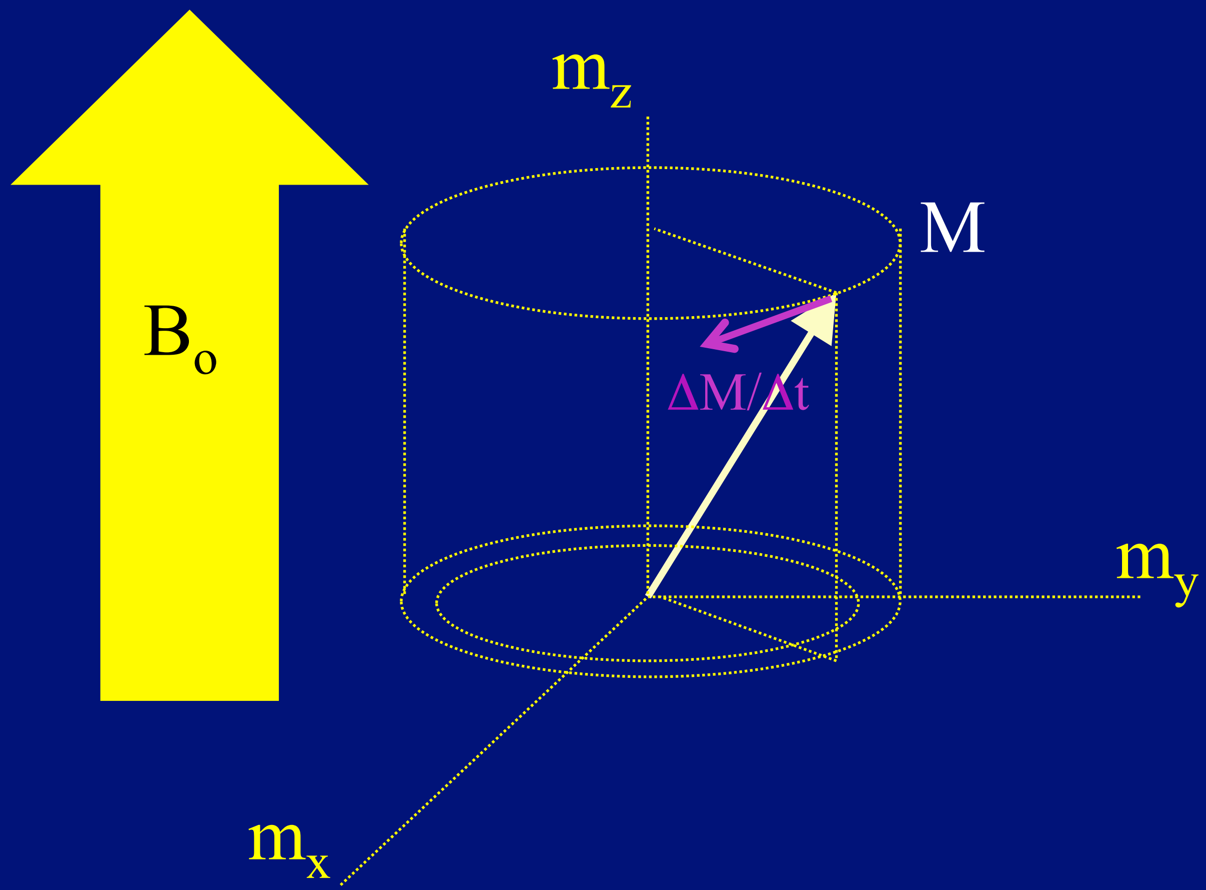
Dynamics of the Magnetization Vector



When M is not in its equilibrium state - it is not parallel with B_o - its orientation will be altered due to the interaction with B_o.

M will tend to be pushed out of the M-B_o plane.

Dynamics of the Magnetization Vector

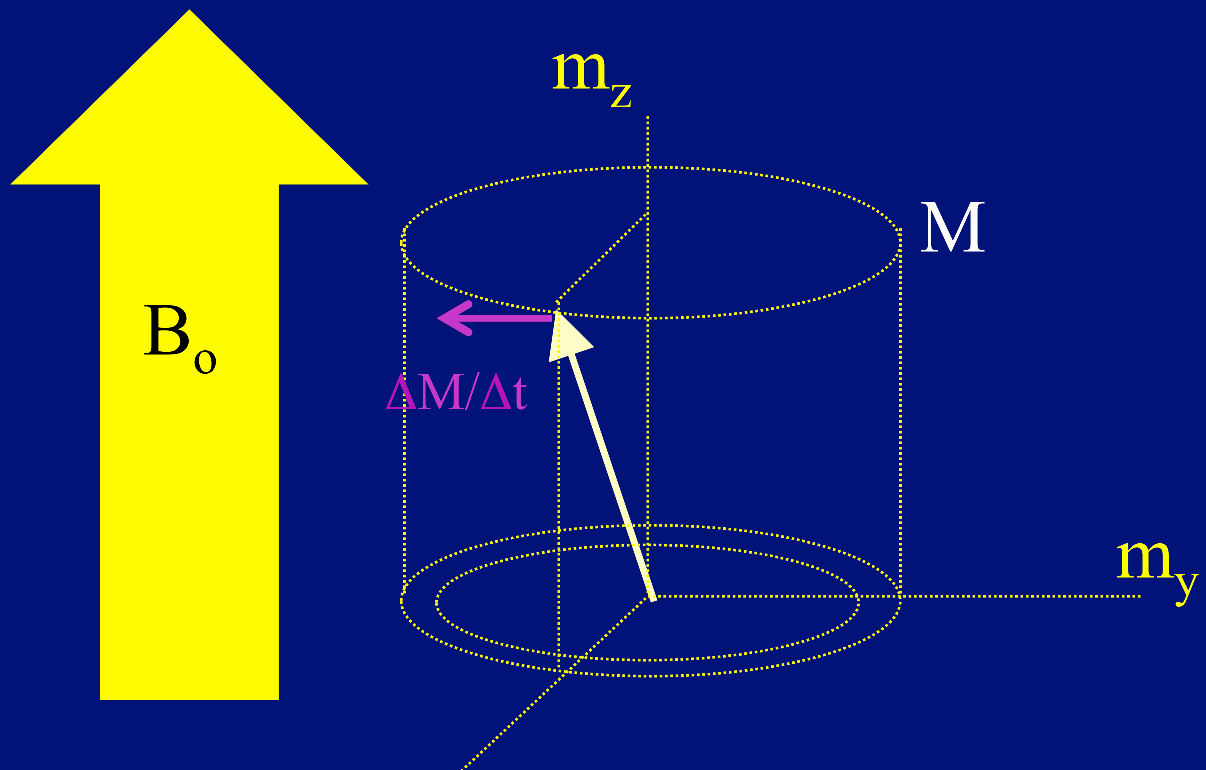


When M is not in its equilibrium state - it is not parallel with B_o - its orientation will be altered due to the interaction with B_o.

M will tend to be pushed out of the M-B_o plane.

As long as M is not parallel to Bo, it will continue to be pushed away from its current orientation.

Precession



Precession frequency, $f_o = \gamma B_o$ = Larmor frequency.

γ = gyro-magnetic ratio for proton = 42.58 Mz / Tesla.

f_o for B_o of 1.5 Tesla = 42.58 x 1.5 = 63.87 Mhz

When M is not in its equilibrium state - it is not parallel with B_o - its orientation will be altered due to the interaction with B_o.

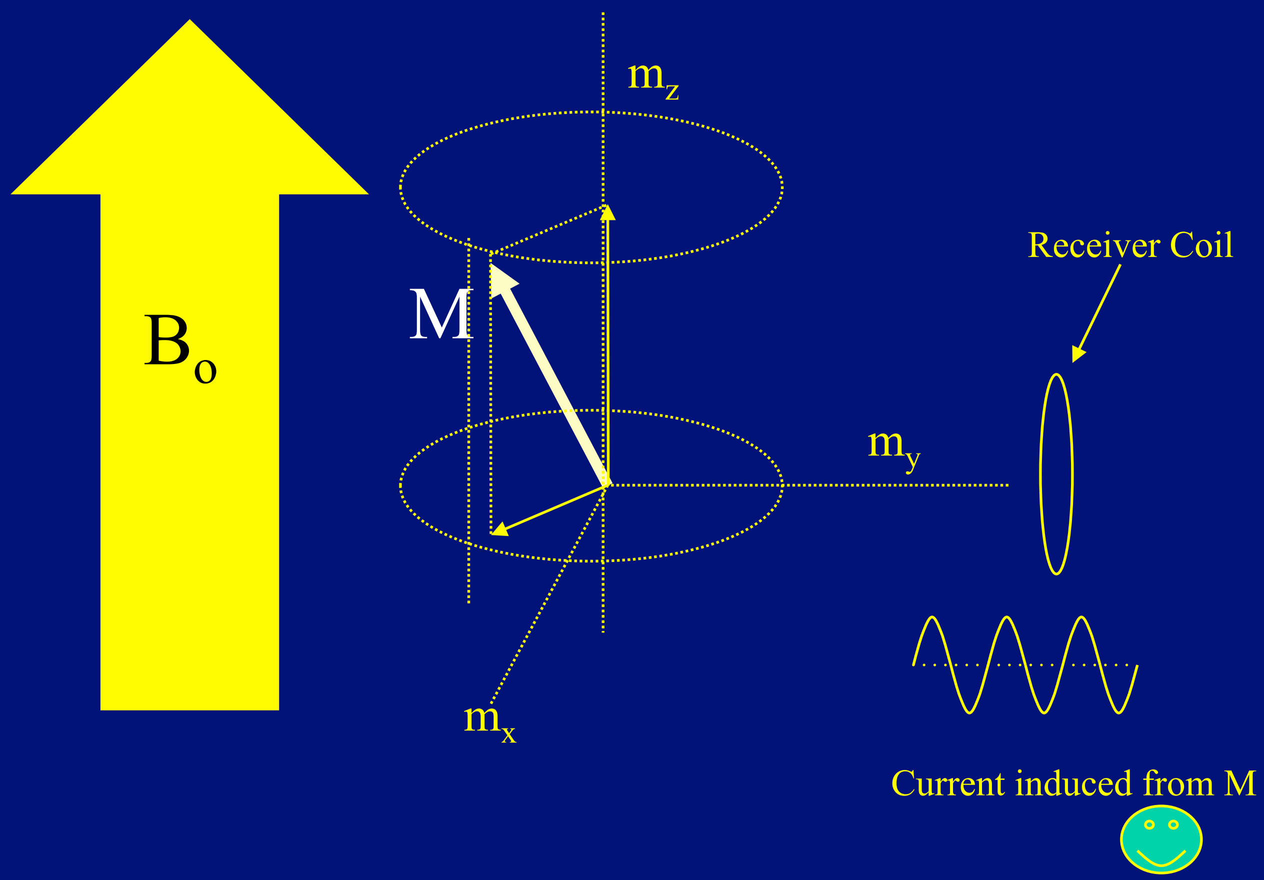
M will tend to be pushed out of the M-B_o plane.

As long as M is not parallel to Bo, it will continue to be pushed away from its current orientation.

The continual change in the orientation of M is a precession about the direction of Bo.

The frequency of the precession is proportional to the strength of B_o. It is called the Larmor frequency.

MRI Signal Detection

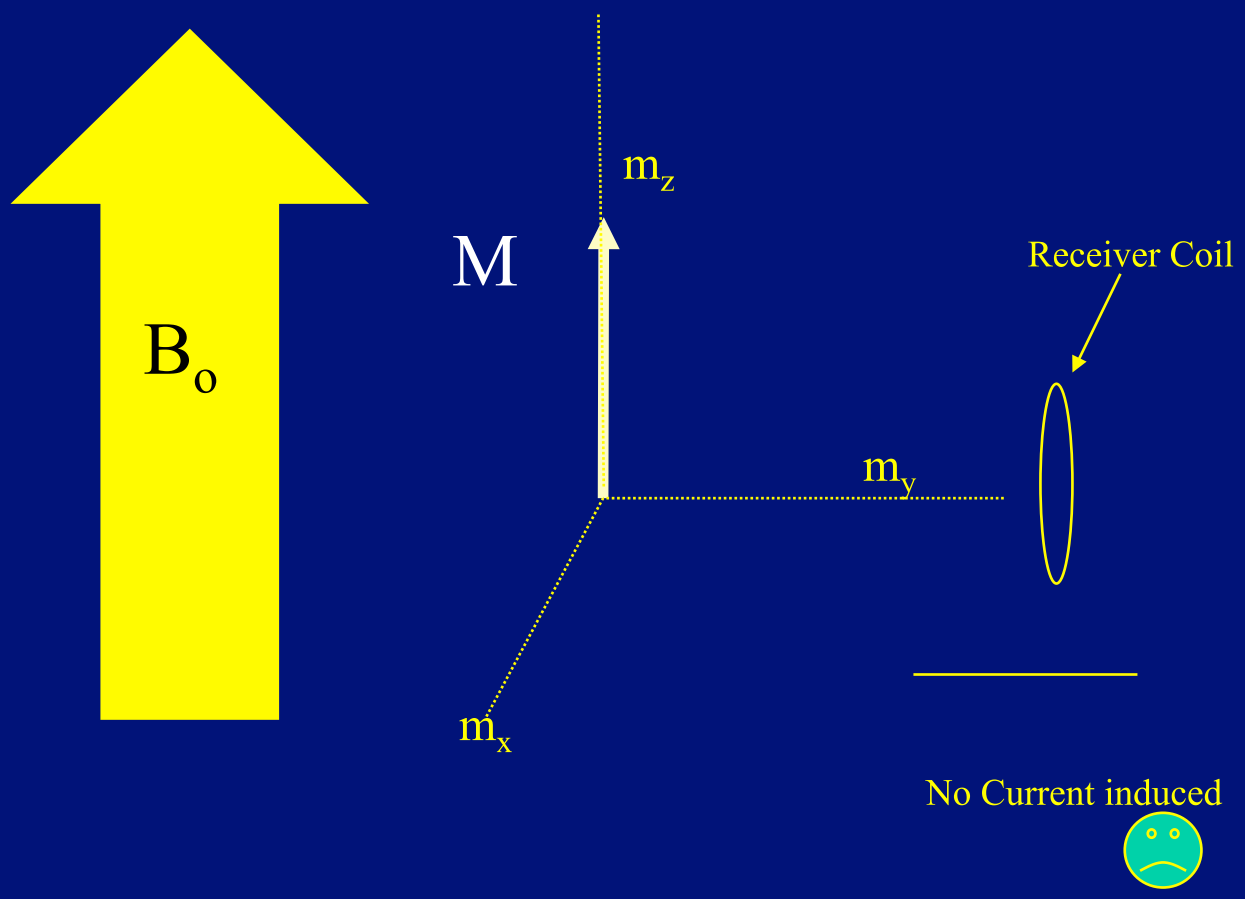


In MRI, a signal is detected only when M precesses about the longitudinal axis (m_z).

The precessing magnetic moments result in a time varying magnetic field. If a conducting loop (coil) is placed in this changing field, a current is generated.

The frequency of the detected signal is equal to the Larmor frequency. This is in the radio frequency (RF) range.

MRI Signal Detection

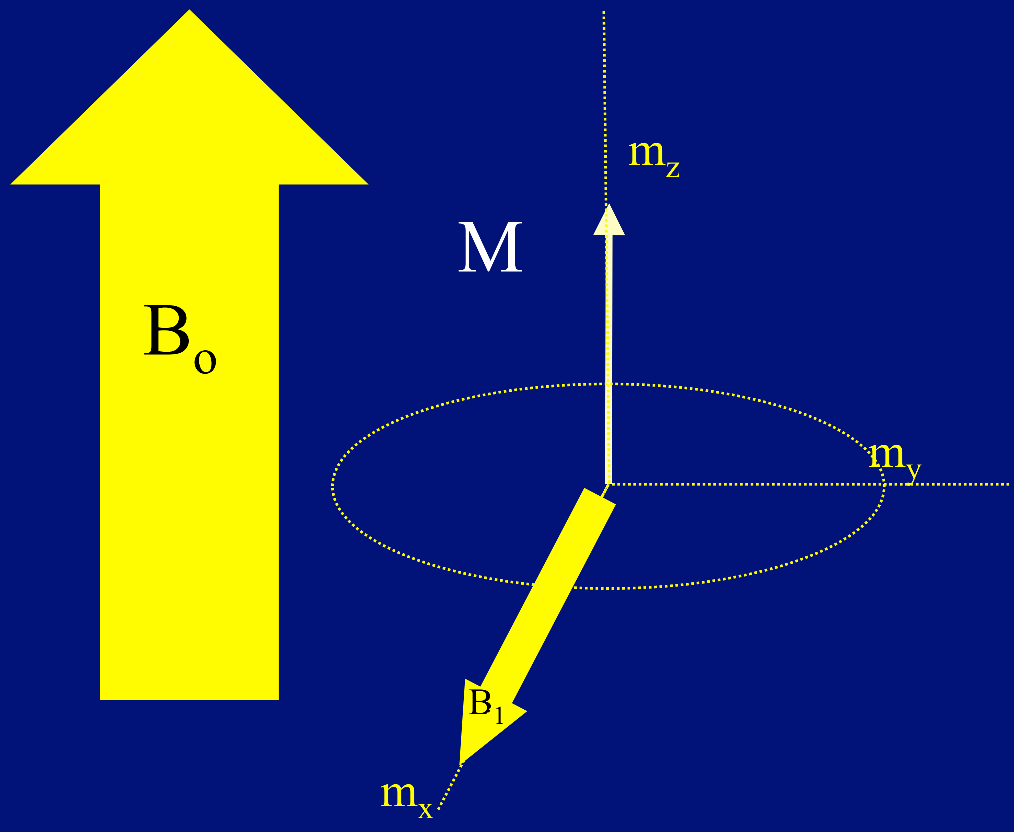


To obtain a signal, M must precess - there needs to be a component in the m_x-m_y or <u>transverse plane</u>.

But, in equilibrium, M is parallel to m_z and there is no transverse component of the magnetization - and no precession.

To get a signal, first, M needs to be tilted away from m_z.

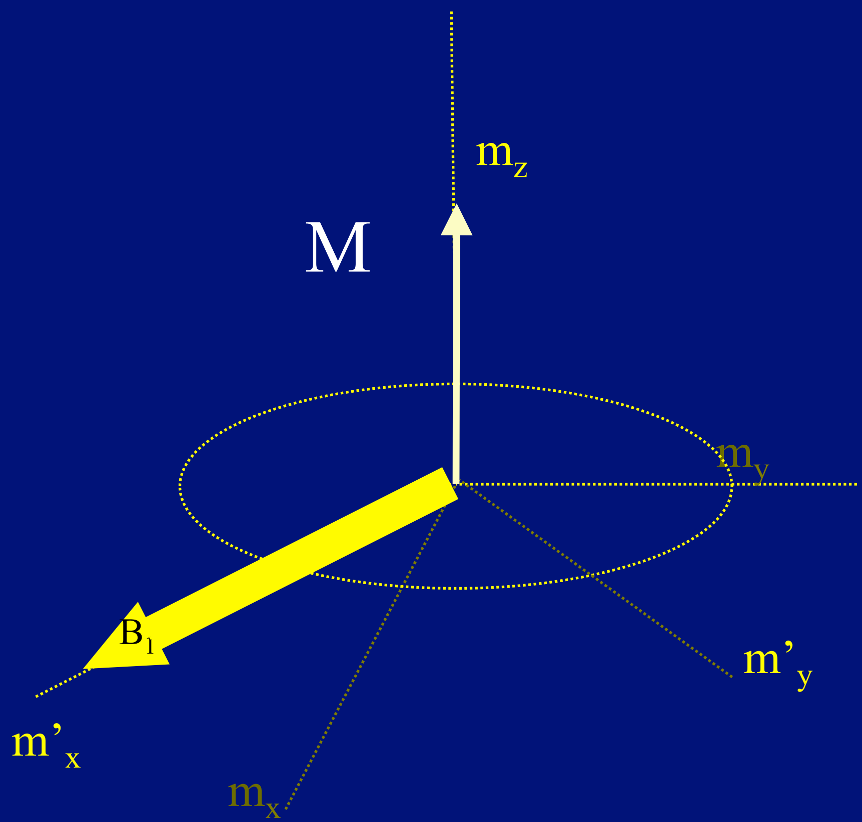
RF Excitation – The B1 Field



Applying a second magnetic field, B_1, that is perpendicular to m_z could be used to cause M to precess so as to tilt away from m_z.

But, to be effective, the B_1 field must rotate about m_z at the Larmor frequency.

RF Excitation – The B1 Field

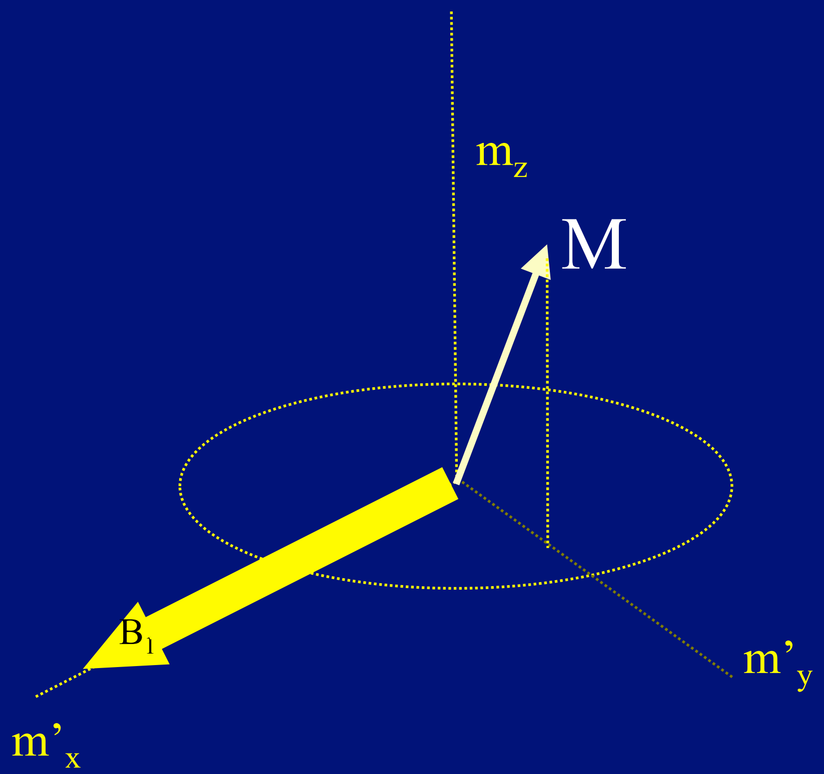


Applying a second magnetic field, B_1, that is perpendicular to m_z could be used to cause M to precess so as to tilt away from m_z.

But, to be effective, the B_1 field must rotate about m_z at the Larmor frequency.

In a reference frame that rotates about m_z at the Larmor frequency, B_o effectively disappears and, since B1 rotates at the Larmor frequency, it is stationary.

RF Excitation – The B1 Field



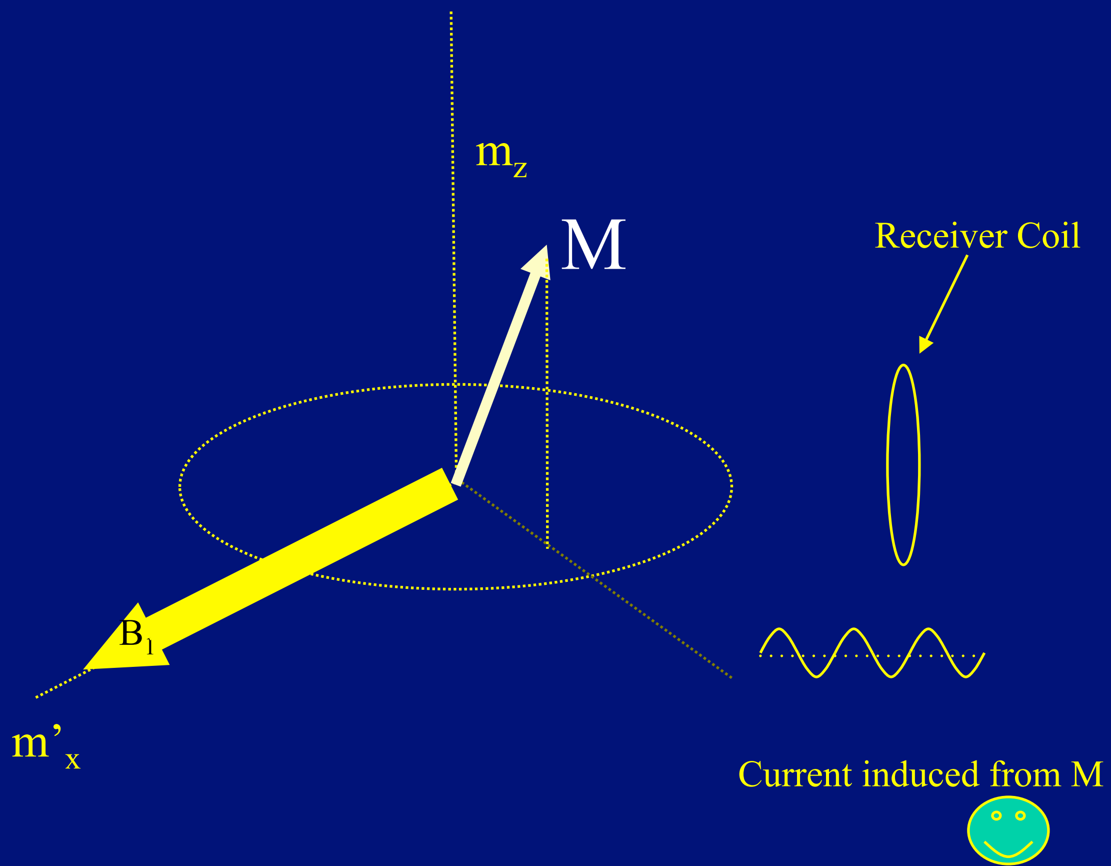
Applying a second magnetic field, B_1, that is perpendicular to M will cause M to precess and tilt away from m_z.

But, to be effective, the B1 field must rotate about m_z at the Larmor frequency.

In a reference frame that rotates about m_z at the Larmor frequency, B_o effectively disappears and, since B1 rotates at the Larmor frequency, it is stationary.

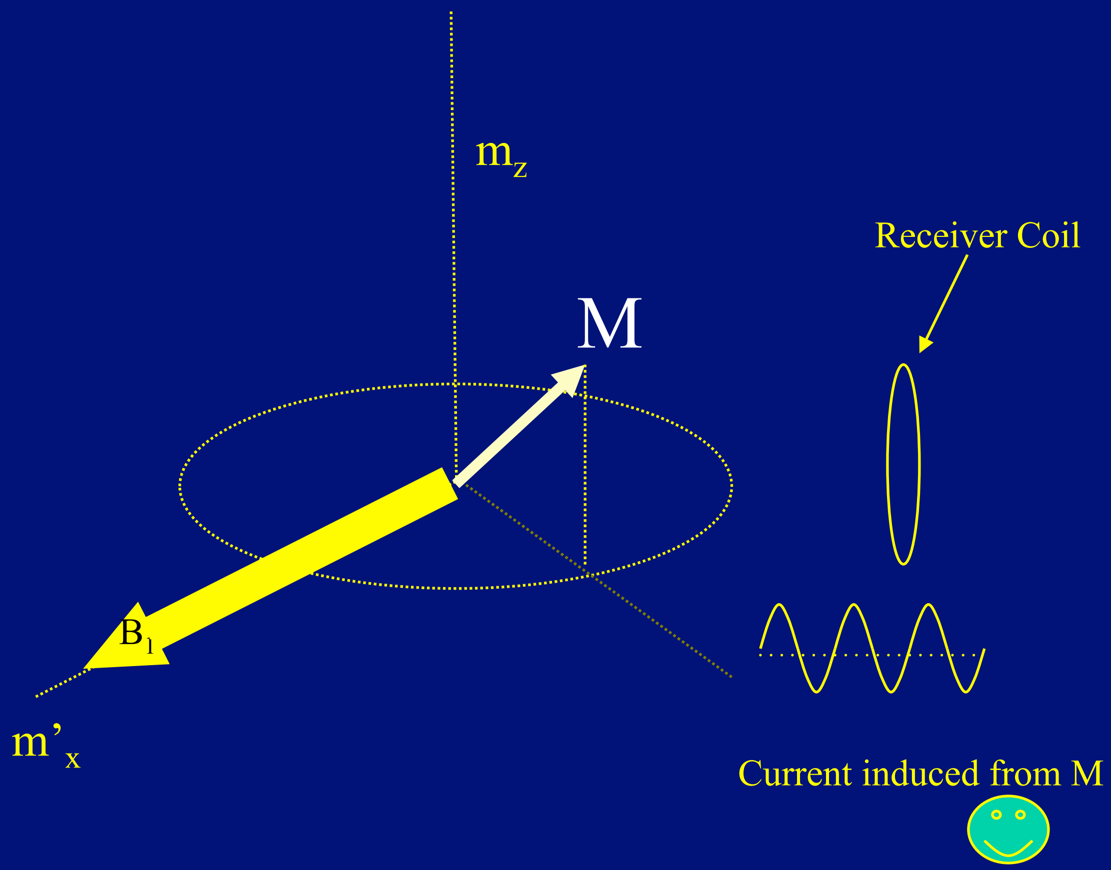
In the rotating reference frame, M precesses only about B_1 and is able to tilt away from the m_z axis.

RF Excitation – The 90° Pulse



Now that there is a component of M in the transverse plane, a signal is generated in the receiver coil.

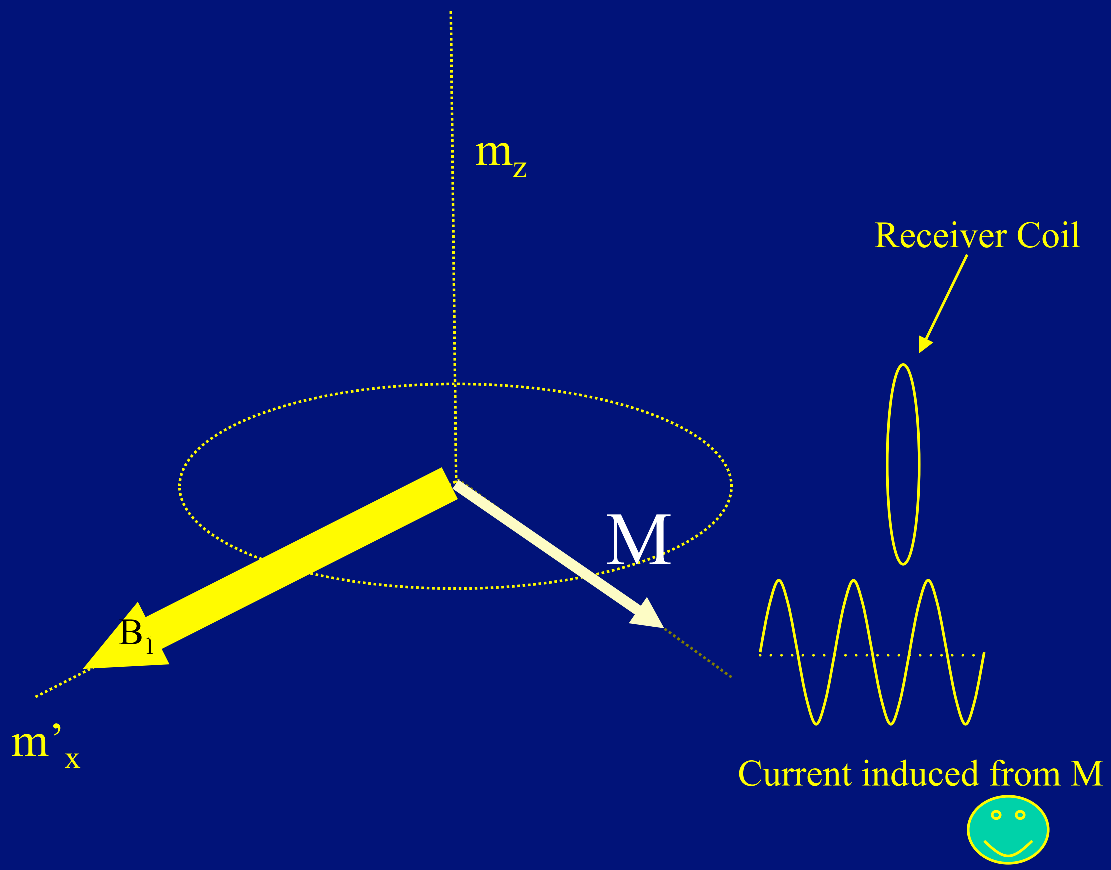
RF Excitation – The 90° Pulse



Now that there is a component of M in the transverse plane, a signal is generated in the receiver coil.

The signal grows as M is tilted further from the m_z axis and the transverse component of M is increased.

RF Excitation – The 90° Pulse

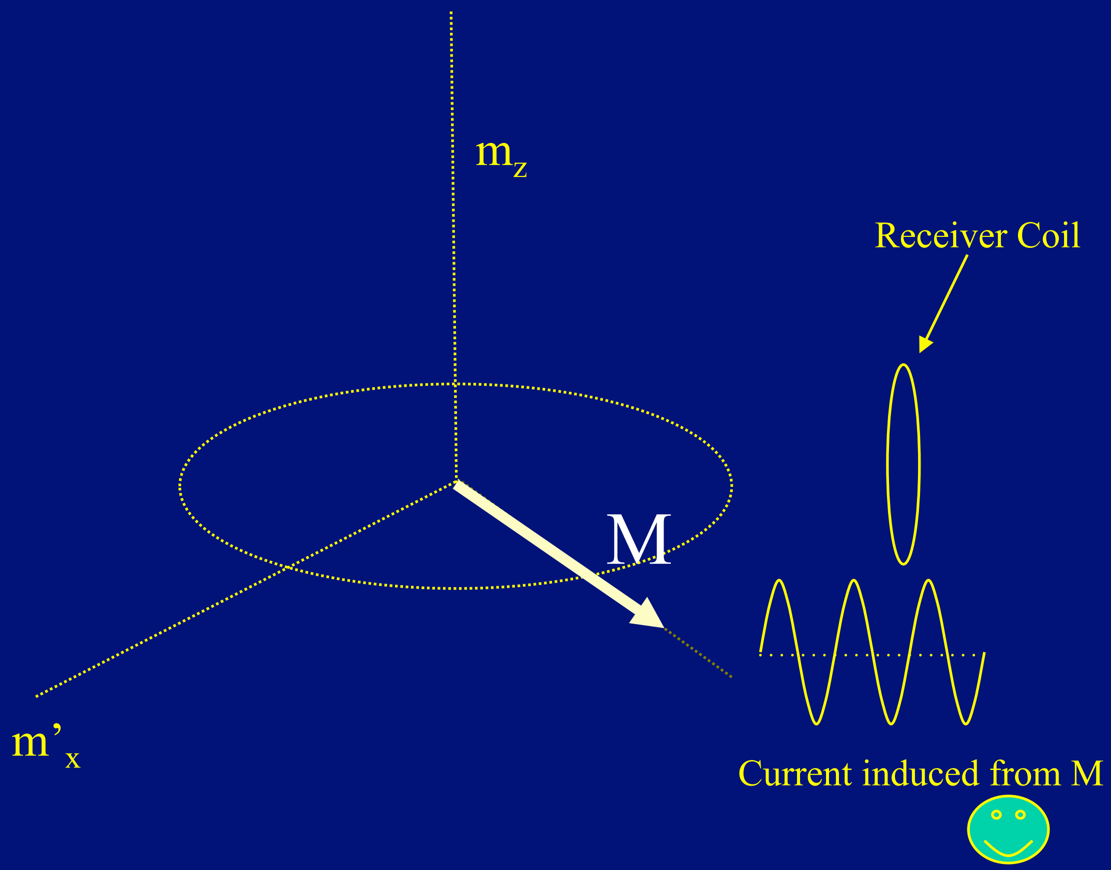


Now that there is a component of M in the transverse plane, a signal is generated in the receiver coil.

The signal grows as M is tilted further from the mz axis and the transverse component is increased.

When M is tilted completely into the m'_x-m'_y plane, the induced signal will reach a maximum.

RF Excitation – The 90° Pulse



Now that there is a component of M in the transverse plane, a signal is generated in the receiver coil.

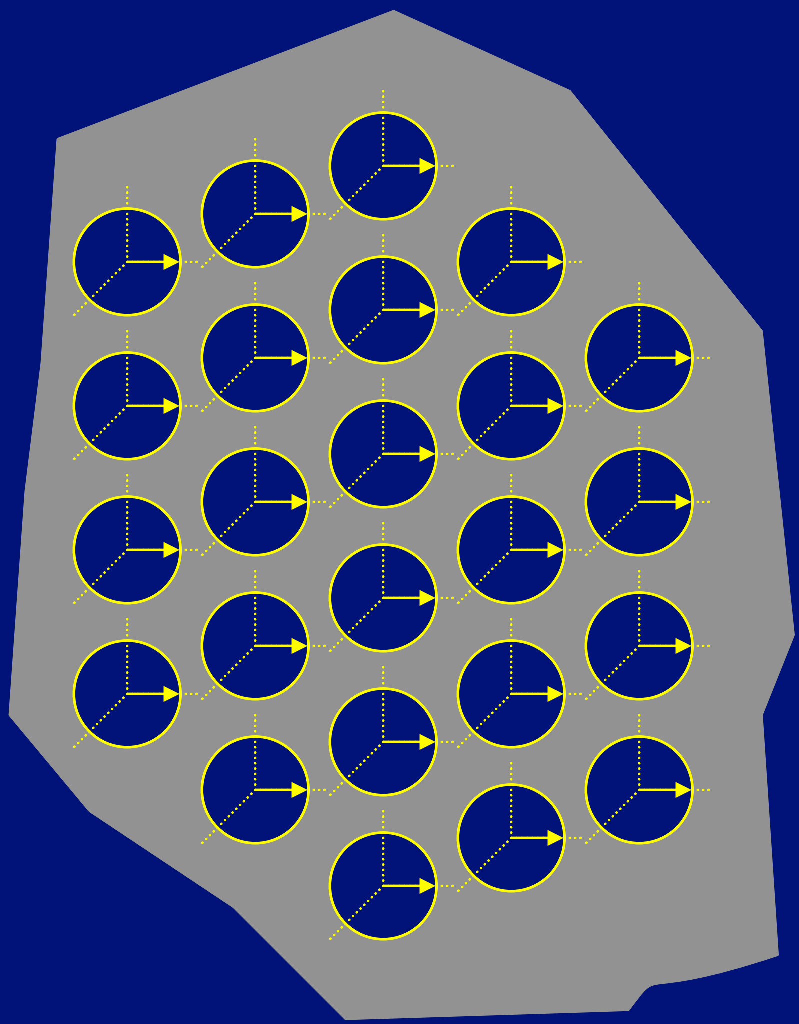
The signal grows as M is tilted further from the mz axis and the transverse component is increased.

When M is tilted completely into the m'_x-m'_y plane, the induced signal will reach a maximum.

The B1 field is then removed.

The short application of the RF field is called a 90° pulse due to its action in tilting M by 90° into the transverse plane.

RF Excitation – The 90^o Pulse



With the magnetization vectors throughout the body now 'excited', we are ready to acquire the signal that is used to make images.

MRI consists of probing the behavior of the precessing M's in an enormous number of tiny volumes located in tissues throughout the body.

Main Areas Covered in Lecture

- ✓Magnetic fields
- ✓Magnetic susceptibility
- ✓Types of magnetic materials
- ✓Nuclear magnetism
- ✓Net magnetization due to field strength
- ✓Precession
- ✓Nuclear magnetic resonance and excitation