Al-Mustaqbal University.

College of Engineering and Engineering Technologies.

Biomedical Engineering Department.

Subject: Biomedical Instrumentation Design.

Class (code): 5th (BME515)

Lecture: *1*

BME 515

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What is Engineering Design?

- According to The Accreditation Board for Engineering and Technology (**ABET**), Engineering design is the process of devising a system, component, or process to meet desired needs.
- It is a decision-making process (often iterative), in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective.
- Among the fundamental elements of the design process are establishing objectives and criteria, synthesis, analysis, construction, testing and evaluation.

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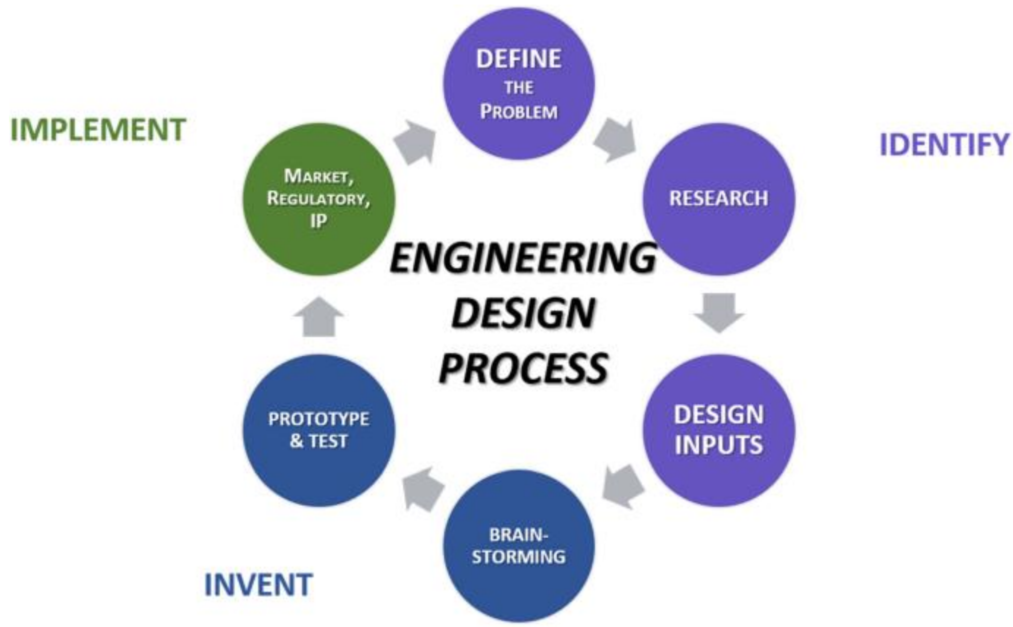
What is Engineering Design?



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What is Engineering Design?

- In Bio/biomedical engineering;
- In Applying principles of engineering, biology, human physiology, chemistry, calculus-based physics, mathematics and statistics;
- Solving bio/biomedical engineering problems, including those associated with the interaction between living and non-living systems;
- Analyzing, modelling, designing, and realizing bio/biomedical engineering devices, systems, components, or processes; and
- Making measurements on and interpreting data from living systems.

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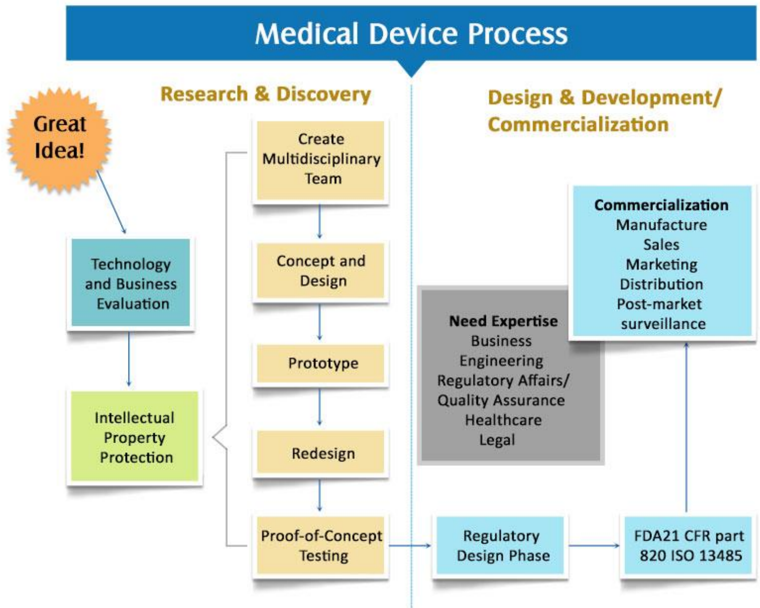
What is engineering Design?



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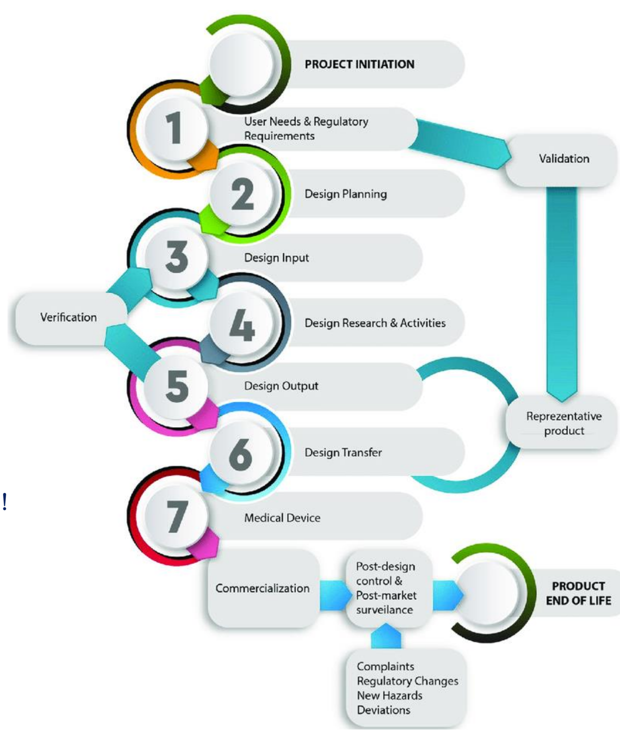
The life cycle of medical devices

Q: What is meant by customer-focused design and manufacturing partner?

Note: you can answer with a diagram !!!



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MRI Design: Magnetism and electromagnetism

Magnetic susceptibility:

- The **magnetic susceptibility** of a substance is the ability of external magnetic fields to affect the nuclei of a particular atom, and is related to the electron configurations of that atom.
- The nucleus of an atom, which is surrounded by paired electrons, is more protected from, and unaffected by, the external magnetic field than the nucleus of an atom with unpaired electrons.
- There are three types of magnetic susceptibility:

➢ **paramagnetism**,

➢ **Diamagnetism**; and

➢ **ferromagnetism**.

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MRI Design: Magnetism and electromagnetism

Paramagnetism

- Paramagnetic substances contain unpaired electrons within the atom that induce a small magnetic field about themselves known as the **magnetic moment**.
- With no external magnetic field, these magnetic moments occur in a random pattern and cancel each other out.
- In the presence of an external magnetic field, paramagnetic substances align with the direction of the field and so the magnetic moments add together.
- Paramagnetic substances affect external magnetic fields in a positive way, resulting in a local increase in the magnetic field.
- An example of a paramagnetic substance is oxygen.

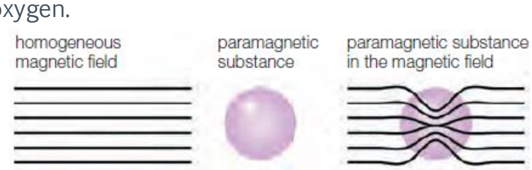

Figure 1.1 Paramagnetic properties.

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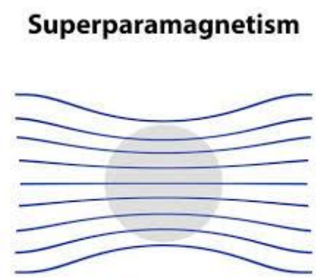
MRI Design: Magnetism and electromagnetism

Super-paramagnetism

- Super-paramagnetic substances have a positive susceptibility that is greater than that exhibited by paramagnetic substances, but less than that of ferromagnetic materials.
- Examples of a super-paramagnetic substance are iron oxide contrast agents.



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MRI Design: Magnetism and electromagnetism

Diamagnetism

- With no external magnetic field present, diamagnetic substances show no net magnetic moment, as the electron currents caused by their motions add to zero.
- When an external magnetic field is applied, diamagnetic substances show a small magnetic moment that opposes the applied field.
- Substances of this type are therefore slightly repelled by the magnetic field and have negative magnetic susceptibilities.
- Examples of diamagnetic substances include water and inert gasses.

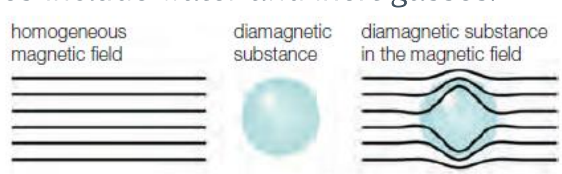

Figure 1.2 Diamagnetic properties.

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MRI Design: Magnetism and electromagnetism

Ferromagnetism

- When a ferromagnetic substance comes into contact with a magnetic field, the results are strong attraction and alignment.
- They retain their magnetization even when the external magnetic field has been removed.
- Ferromagnetic substances remain magnetic, are permanently magnetized and subsequently become permanent magnets.
- An example of a ferromagnetic substance is iron.
- Magnets are **bipolar** as they have two poles, north and south.
- The magnetic field exerted by them produces magnetic field lines or lines of force running from the magnetic south to the north poles of the magnet.

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MRI Design: Magnetism and electromagnetism

Ferromagnetism

- Magnetic field lines are called **magnetic lines of flux.** The number of lines per unit area is called the **magnetic flux density**.
- The strength of the magnetic field, expressed by the notation **(B).** In the case of more than one field, the primary field **(B_0)** and the secondary field **(B_1)** and measured in one of three units: **gauss (G)**, **kilogauss (kG)** and **tesla (T)**.
- If two magnets are brought close together, there are forces of attraction and repulsion between them depending on the orientation of their poles relative to each other.
- Like poles repel and opposite poles attract.

Q: What is the magnitude of the earth's magnetic field?

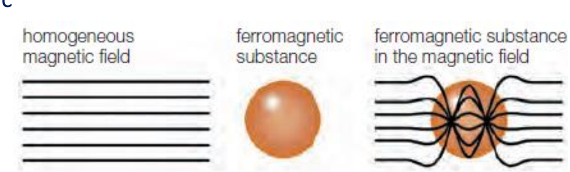

Figure 1.3 Ferromagnetic properties.

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MRI Design: Magnetism and electromagnetism

Electromagnetism

- A magnetic field is generated by a moving charge (electrical current). The direction of the magnetic field can either be cw or ccw with respect to the direction of flow of the current.
- **Ampere's law** determines the magnitude and direction of the magnetic field due to a current.
- *Just as moving electrical charge generates magnetic fields, changing magnetic fields generate electric currents.*
- When a magnet is moved in and out of a closed circuit, an oscillating current is produced, which ceases the moment the magnet stops moving. Such a current is called an **induced electric current**.

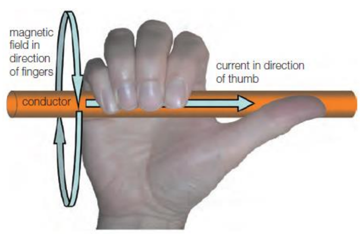

Figure 1.4 The right-hand thumb rule.

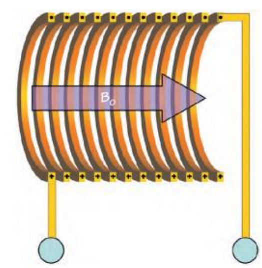

Figure 1.5 A simple electromagnet.

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MRI Design: Magnetism and electromagnetism

Electromagnetism

- **Faraday's law of induction** explains the phenomenon of an induced current.
- The change of magnetic flux through a closed circuit induces an **electromotive force (emf)** in the circuit.
- The emf is defined as the energy available from a unit of charge travelling once around a loop of wire.
- The emf drives a current in the circuit and is the result of a changing magnetic field inducing an electric field.
- The laws of electromagnetic induction (Faraday) state that the induced emf:
  - is proportional to the rate of change of magnetic field and the area of the circuit;
  - is proportional to the number of turns in a coil of wire;
  - is in a direction so that it opposes the change in magnetic field which causes it (**Lenz's law**).

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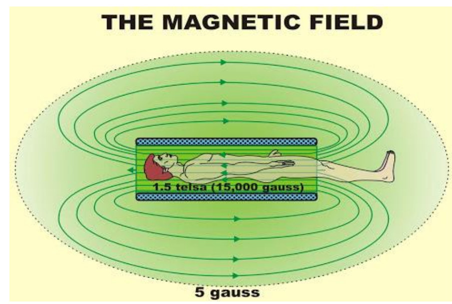
MRI Design: Magnetism and electromagnetism

Electromagnetism

› Electromagnetic induction is a basic physical phenomenon of MRI, but is specifically involved in the following:

➢the spinning charge of a hydrogen proton causes a magnetic field to be induced around it;

➢the movement of the **net magnetization vector (NMV)** across the area of a receiver coil induces an electrical charge in the coil.



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MRI Design: Magnetism and electromagnetism

Key points

› Paramagnetic substances add to (increase) the applied magnetic field.

› Super-paramagnetic substances have a magnetic susceptibility that is greater than paramagnetic substances but less than that of ferromagnetic materials.

› Diamagnetic substances slightly oppose (decrease) the applied magnetic field.

› Diamagnetic effects appear in all substances. However, in materials that possess both diamagnetic and paramagnetic properties, the positive paramagnetic effect is greater than the negative diamagnetic effect, and so the substance appears paramagnetic.

› Ferromagnetic substances are strongly attracted to, and align with, the applied magnetic field. They are permanently magnetized even when the applied field is removed.

› Moving a conductor through a magnetic field induces an electrical charge in it.

› Moving electrical charge in a conductor induces a magnetic field around it.

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MRI Design: Atomic structure

Introduction

- There are approximately 7 octillion (7 x 10 27) atoms in the average 70 kg person. Most of the human body (96%) is made up of four elements: hydrogen, oxygen, carbon and nitrogen. Hydrogen is the most common element in the universe and in humans.
- The atom consists of the following particles:
- **Protons:** in the nucleus, and positively charged
- **Neutrons:** in the nucleus, and have no charge
- **Electrons:** orbit the nucleus, and are negatively charged.
- The following terms are used to characterize an atom:
- **Atomic number:** number of protons in the nucleus and determines the type of element the atoms make up.
- **Mass number:** sum of the neutrons and protons in the nucleus.

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MRI Design: Atomic structure

Introduction

- Atoms of the same element having a different mass number are called **isotopes** .
- In a stable atom the number of negatively charged electrons equals the number of positively charged protons.
- Atoms with a deficit or excess number of electrons are called **ions**

and the process of removing electrons from the atom

is called **ionization.**

- Only certain types of atoms are available to us in

Magnetic Resonance Imaging (MRI).

- These are atoms whose charged nuclei move or spin.

This is because a moving electrical charge produces a magnetic field.

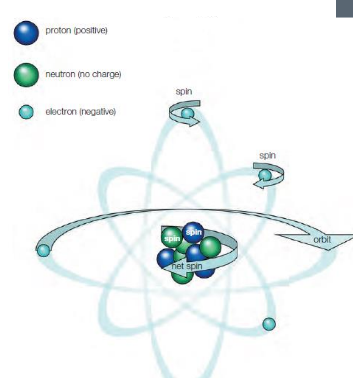

Figure 2.1 The atom.

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MRI Design: Atomic structure

Motion within the atom

› There are three types of motion of particles in the atom:

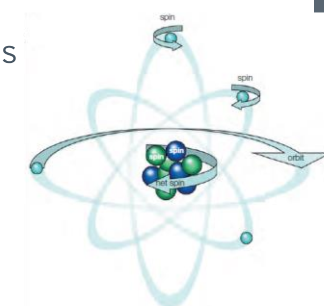
➢Negatively charged electrons spinning on their own axis.

➢Negatively charged electrons orbiting the nucleus.

➢Particles within the nucleus spinning on their own axes.

› Each type of motion produces a magnetic field.

› In MRI, we are concerned with the motion of particles within the nucleus and the nucleus itself.



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MRI Design: Atomic structure

MR active nuclei

› Protons and neutrons spin about their own axis within the nucleus.

› The direction of spin is random, so that some particles spin cw and others ccw.

› When a nucleus has an *even mass number* , the spins cancel each other out so the nucleus has *no net spin.*

› When a nucleus has an *odd mass number,* the spins do not cancel each other out and the *nucleus spins.*

› As protons have charge, a nucleus with an odd mass number has a net charge as well as a net spin.

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MRI Design: Atomic structure

MR active nuclei

- Due to the laws of electromagnetic induction, a moving unbalanced charge induces a magnetic field around itself.
- The direction and size of the magnetic field are denoted by a magnetic moment.
- The total magnetic moment of the nucleus is the vector sum of all the magnetic moments of protons in the nucleus.
- The length of the arrow represents the magnitude of the magnetic moment. The direction of the arrow denotes the direction of alignment of the magnetic moment.

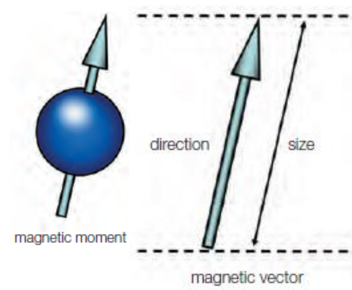

Figure 2.2 The magnetic moment of the hydrogen 1 nucleus.

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MRI Design: Atomic structure

MR active nuclei

- Nuclei with an odd number of protons are said to be **MR active**. They act like tiny bar magnets.
- There are many types of elements that are MR active. They all have an odd mass number.
- The common MR active nuclei, together with their mass numbers, are:
  - hydrogen 1, carbon 13, nitrogen 15, fluorine 19, sodium 23, oxygen 17.
- The spin characteristics of the commonest MR active nuclei are shown in the next table.

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MRI Design: Atomic structure

MR active nuclei

Table 2.1 Constants of selected MR active nuclei.

Element	Protons	Neutrons	Nuclear spin	% Natural abundance
^{1}H (protium)	1	0	1/2	99.985
^{13}C (carbon)	6	7	1/2	1.10
^{15}N (nitrogen)	7	8	1/2	0.366
^{17}O (oxygen)	8	9	5/2	0.038

MRI Design: Atomic structure

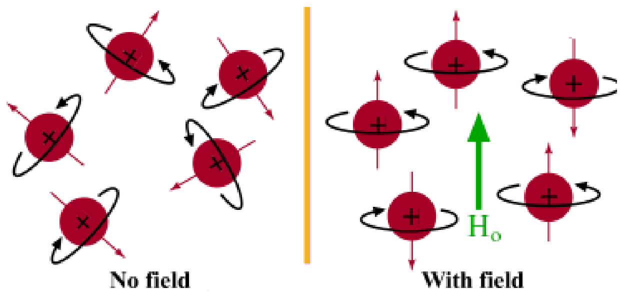
MR active nuclei

- The isotope of hydrogen called **protium** is the MR active nucleus used in MRI, as it has a mass and atomic number of 1.
- The nucleus of this isotope consists of a single proton and has no neutrons.
- It is used for MR imaging because:
  - it is abundant in the human body (e.g. in fat and water);
  - the solitary proton gives it a relatively large magnetic moment because there are no neutrons present in this type of nucleus.
  - Neutrons tend to decrease the relative size of the nuclear magnetic field, so if they are not present, the magnetic field is maximized.
- To the end of this course, MR active nuclei, and specifically protium, are referred to as *spins*.

MRI Design: Atomic structure

Key points

- Hydrogen is the most abundant element in the human body.
- The nuclei available for MRI exhibit a net spin (because their mass number is an odd number).
- As all nuclei contain at least one positively charged proton, those that also spin have a magnetic field induced around them.
- An arrow called a magnetic moment denotes the magnetic field of a nucleus.



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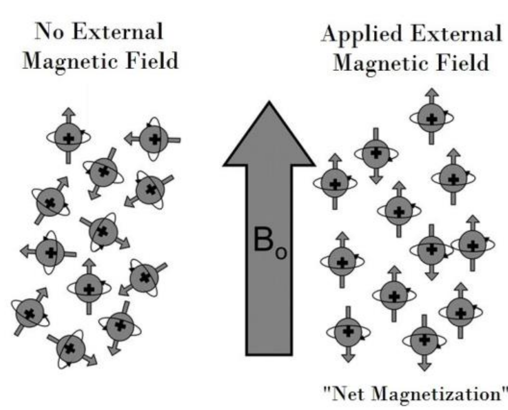
MRI Design: Alignment

Introduction:

- in a normal environment the magnetic moments of MR active nuclei (spins) point in a random direction, and produce no overall magnetic effect.
- When spins are placed in an external magnetic field, their magnetic moments line up with the magnetic field flux lines.
- This is called **alignment** .
- Alignment is described using two theories:
  - The classical theory.
  - The quantum theory.



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MRI Design: Alignment

The classical theory

› This uses the direction of the magnetic moments to illustrate alignment.

➢ **Parallel alignment** : alignment of magnetic moments in the *same* direction as the main field.

➢ **Antiparallel alignment** : alignment of magnetic moments in the *opposite* direction to the main field.

› At room temperature there are always more spins with their magnetic moments aligned parallel than anti-parallel.

› The net magnetism of the patient (termed the **net magnetization vector**; **NMV**) is therefore aligned parallel to the main field.

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MRI Design: Alignment

The classical theory

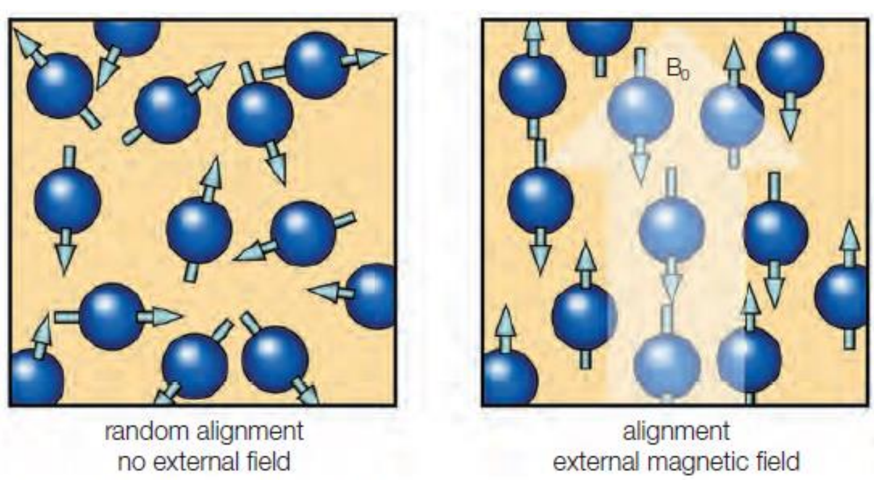

Figure 3.1 Alignment: classical theory.

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MRI Design: Alignment

The quantum theory

- This uses the energy level of the spins to illustrate alignment.
- According to the quantum theory, protons of hydrogen nuclei interact with the external magnetic field of the scanner (Zeeman interaction) and cause a discrete number of energy states.
- For hydrogen nuclei, there are only two possible energy states.
- **Spinup** nuclei have low energy and do not have enough energy to oppose the main field. These are nuclei that align their magnetic moments parallel to the main field in the classical description.
- **Spindown** nuclei have high energy and have enough energy to oppose the main field. These are nuclei that align their magnetic moments anti-parallel to the main field in the classical description.
- The difference in energy between these two states is proportional to the strength of the external magnetic field (B_0).
- The magnetic moments of the spins actually align at an angle to B_0 due to the force of repulsion between B_0 and the magnetic moments.

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MRI Design: Alignment

What do the quantum and classical theories tell us?

- Hydrogen only has two energy states – high or low. Therefore, the magnetic moments of hydrogen spins only align in the parallel or anti-parallel directions. The magnetic moments of hydrogen spins cannot orientate themselves in any other direction.
- The patient's temperature is an important factor that determines whether a spin is in the high- or low-energy population. In clinical imaging, thermal effects are discounted, as we assume the patient's temperature is the same inside and outside the magnetic field (thermal equilibrium).
- The magnetic moments of hydrogen spins are constantly changing their orientation because they are constantly moving between high- and low-energy states. The spins gain and lose energy and their magnetic moments therefore constantly alter their alignment relative to B_0.

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MRI Design: Alignment

What do the quantum and classical theories tell us?

- The number of spins in each energy level can be predicted by the Boltzmann distribution.
- In thermal equilibrium, at any moment there are a greater proportion of spins with their magnetic moments aligned with the field than against it. This excess aligned with B_0 produces a net magnetic effect called the NMV that aligns with the main magnetic field.

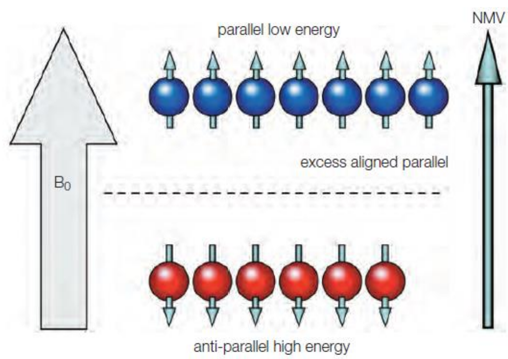

Figure 3.3 The net magnetization vector (NMV).

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MRI Design: Alignment

What do the quantum and classical theories tell us?
Boltzmann distribution

Table 3.1 Common equations of alignment.

Equations (if you like them)		
$N^+/N^- = e^{-\Delta E/kT}$	N^+ and N^- are the number of spins in the high- and low-energy populations respectively ΔE is the energy difference between the high- and low-energy populations in Joules (J) k is Boltzmann's constant (1.381×10^{-23} J/K) T is the temperature of the tissue in Kelvin (K)	This equation enables prediction of the number of spins in the high- and low-energy populations and how this is dependent on temperature. In MRI, thermal equilibrium is presumed in that there are no significant changes in body temperature in the scan room.

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MRI Design: Alignment

What do the quantum and classical theories tell us?

› As the magnitude of the external magnetic field increases, more magnetic moments line up in the parallel direction, because the amount of energy the spins must possess to align their magnetic moments in opposition to the stronger field and line up in the anti-parallel direction is increased. As the field strength increases, the low-energy population increases and the high energy population decreases. As a result, the NMV increases.

MRI Design: Alignment

Key points

› When placed in an external magnetic field, the magnetic moments of hydrogen either align in a spin-up, low-energy or spin-down, high-energy orientation.

› At thermal equilibrium, there are more spin-up, low-energy than spin-down, high-energy spins, so the net magnetization of the patient (NMV) is orientated in the same direction as B_0.

› The difference in energy between these populations is determined by the strength of B_0 .

› As B_0 increases the energy difference between the two populations also increases, as the number of spin-up, low-energy spins increases relative to the number of spin-down, high-energy spins.

› The signal to noise ratio (SNR) increases at higher values of B_0.

Thank you