Lecture 15

**Magnetism**
- Source of magnetism
- Magnetic field
- Magnetic force
- Electromagnetic Induction
- Applications

**Electric shock**
- Physiological effects

**Bioelectricity**
- Cell potentials
- Resting potential
- Action Potential
Magnetism

Historical

First magnets were pieces of iron-bearing rock called **loadstone** (magnetite, Fe$_3$O$_4$) found originally in Asia (magnesia)

Materials

**Iron** is one of a few materials (also **Nickel, Cobalt**) that can be permanently magnetised.

These are called **ferromagnetic materials**
Magnets and Magnetic Force

All magnets have two poles, **North and South**, named with reference to alignment in Earth’s magnetic field.

**Magnetic pole** that points to Earth’s geographic north pole is called the **north pole** of the magnet.
Magnets and magnetic force

A magnetic field surrounds the magnet.

Lines indicate **direction and magnitude** of magnetic field

When **two magnets** are near to each other or in contact, they **exert a force on one another**, in a manner similar to electrical charges. This force is the **magnetic force**.

Like poles repel, unlike poles attract.
Earth’s magnetic field pattern similar to that of a bar magnet.

North Geographic Pole is approximately 2,000km from the south magnetic pole
The motion of electrical charges (current) is the only source of magnetism.

Permanent magnets are not the only items with magnetic properties.

Example:
When a current passes through a simple wire, a magnetic field is created around the wire, this is due to the flow of the electrons.

What about permanent magnets?
The microscopic origin of the magnetism in magnets;

Orbiting Electrons
Electrons are moving around the nucleus, electrons orbiting constitute a circular current loop, (moving charge) so each electron generates a tiny magnetic field.

Spinning Electrons
Electrons also act as though they are spinning about an axis through their centres.

Spinning electron also act like a current loop and so creates a tiny magnetic field.

Both these electron motions in atoms, orbital and spins create magnetic fields.
In most atoms the magnetic effect of the electrons cancel each other out, atoms then are like tiny magnets.

Ferromagnetic materials consists of small regions (called domains) in which all the magnetic effects of atoms are aligned.

Externally applied magnetic field can align the domains so that the material becomes magnetised.
Some metals (iron for example), can be magnetised under the influence of an external magnetic field.

**Uses**

**Electromagnet**

When the magnetic field is switched off, the magnetization disappears.
A wire carrying a current in an external magnetic field. Current and magnetic field are perpendicular to each other as shown.

**Force** on the wire:
- Perpendicular to the plane containing the wire
- Perpendicular to the line of the magnetic field.

i.e. into the page
Force \((F)\) on the wire is proportional to the current \((I)\) and the length \((L)\) of the wire in the magnetic field \((B)\):

\[ F \propto IL \quad \text{or} \quad F = B \times I \times L \]

- \(B\) is the magnetic field strength.
- \(B = \frac{F}{IL}\) (\(B\) perpendicular to \(I\)).
- **Units of** \(B\) **are** Newtons per metre per ampere (SI unit) of magnetic field strength **Tesla**.

**Nikola Tesla** (1856—1943) Croatia

\[ 1 \text{T} = 1 \text{N}.\text{m}^{-1}.\text{A}^{-1} \]
Magnetic Induction

Moving charges (current) cause a magnetic field

A **changing** magnetic field in the vicinity of a wire or coil will induce a voltage in the wire or coil.

This effect is used in generators to produce AC current (power plants, bikes, cars)
Electromagnetic Induction

A **changing** magnetic field in the vicinity of a wire or coil will induce a current in the wire or coil.

**Induced voltage is proportional to the rate of change of magnetic flux** through the coil.

**magnetic flux** $\phi = \text{Magnetic field strength} \times \text{area}$

$\phi = B \cdot A$

$$emf = -N \frac{\Delta \Phi}{\Delta t}$$  

$N = \text{number of turns in coil}$

**Faraday’s law of magnetic induction**
Electromagnetic Induction

Application

Transformer

<table>
<thead>
<tr>
<th>Primary circuit</th>
<th>Secondary circuit</th>
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<tbody>
<tr>
<td>ac Voltage in</td>
<td>ac Voltage out</td>
</tr>
<tr>
<td>Iron</td>
<td></td>
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</tbody>
</table>

Voltage out is proportional to the number of turns $N_s$ in the secondary coil

\[
\frac{V_p}{V_s} = \frac{N_p}{N_s}
\]

X-ray machine—high voltage

Charger:
- mobile phone
- I pod
- etc

Electric toothbrush
- Charges sitting on base unit
- No metal to metal contact
- Only plastic to plastic.

How does it charge??
Medical uses of Magnetic fields

Recently developed magnets
- small
- exceptional strength

Dentistry: Magnets not routinely used

- Orthodontics
- Dental prostheses retention—jaw implant

Orthodontics
Magnets
- alternative to elastics & wires

Magnetic Force
- constant
- Directional
- Biologically safe
Medical uses of Magnetic fields

Magnetic fields can penetrate tissue with little or no adverse effects ---can be used to probe the body

Main medical application

Nuclear Magnetic Resonance  NMR
Magnetic Resonance Imaging   MRI

Like electrons, protons (positively charged) in the nucleus also act as though they are spinning about an axis through their centres. **Spinning protons act like a current loop and so creates a tiny magnetic field**

Nuclei of some atoms (particularly Hydrogen) have small magnetic fields

In strong magnetic field they align with the field.
Medical uses of Magnetic fields MRI

Patient in strong magnetic field. Radio frequency signal applied (reoriented the proton spin). Absorption and re-emission measured and computer image generated showing the types of tissue present.

MRI uses superconducting magnet;

Earth’s magnetic field ≈ 0.5 x10^{-4} tesla.
fridge magnet ≈ 10^{-3} tesla.
MRI scanner magnet ≈ 3 tesla
– 6 x10^4 times the Earth’s magnetic field.

Non-invasive imaging technique that discriminates between body tissues.

diagnostic tool for soft tissue – organs, ligaments, the circulatory system, spinal column, brain.
A wire placed in magnetic field such that its length is perpendicular to the field which is of strength 10 milliTesla. If the current in the wire is 15 milliamps and the magnitude of the force on the wire is $30 \times 10^{-6}$ N, what is the length (in cm) of the wire in the magnetic field?

$$B = \frac{F}{IL}$$

Therefore

$$L = \frac{F}{BI} = \frac{30 \times 10^{-6}}{10 \times 10^{-3} \text{ T} \cdot 15 \times 10^{-3} \text{ A}}$$

$$L = 2 \times 10^{-1} \text{ m} = 0.2 \text{ m} = 20 \text{ cm}.$$
An **electrical shock** happens when one’s body provides an “**accidental**” circuit completion to “**earth**”.

A current then flows through the body, resulting in **tissue burn or muscle affect**

Current disrupts central nervous system

Nerves controlling muscles use electric currents

Muscles involuntarily contract in response to external electric currents

**“Can’t let go effect”**

Essentially because contractor muscles which close the hand are stronger than the extensor muscles which are used to open it
Main factors and Physiological effects

The effects of the electrical shock depends on 4 main factors:

1. magnitude of current
2. DC or AC (frequency)
3. duration
4. path in body

Voltage
Resistance of body
Ohm’s law
Effects of the electrical current at 50/60 Hz, for 1 second, through the trunk:

<table>
<thead>
<tr>
<th>Current (mA)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>threshold of sensation*</td>
</tr>
<tr>
<td>100-300</td>
<td>ventricular fibrillation possible</td>
</tr>
<tr>
<td>300</td>
<td>onset of burns, depends on concentration of current</td>
</tr>
<tr>
<td>6000 (6A)</td>
<td>onset of sustained ventricular contraction and respiratory paralysis</td>
</tr>
</tbody>
</table>

**Ventricular Fibrillation**
Hearts electrical activity becomes disordered. Pumping becomes unsynchronized. Little or no blood pumped. Death within minutes unless medical help is provided----- Defibrillation
Frequency:

frequencies in the ≈ 50 Hz region are most detrimental. Possibly related to the firing rate of many nerves.

Both curves have lowest current thresholds ≈ 50Hz

Higher currents can be tolerated at higher frequencies, effects mostly thermal

Application: Electrosurgery uses high frequency currents (>100kHz): dermatological procedures

At these frequencies (100kHz) energy can pass through the patient with minimal neuromuscular stimulation and no risk of electrocution.
Effects of other parameters

Path: >>>heart

Primary cause of death by electrical shock is ventricular fibrillation

100mA to 300mA path dependant >>>heart

Path: Skin has higher resistance than tissues.

Humidity is important:
- dry skin: resistance $\sim 10^4$-$10^6$ ohm,
- wet skin: resistance $\sim 10^3$ ohm

Duration:
- lengthy breathing interruption is dangerous.
- lengthy heart beat interruption is fatal.

(short-term heart interruption potentially beneficial: (defibrillation))
Bioelectricity

Voltages are created by nearly all types of animal cells.

Largest in nerve and muscle cells.

Creation and maintenance of bioelectricity requires 25% of energy used by cells.

Cell potentials (voltages)

• may be constant for long periods
• may be changed by internal/external stimuli

Nerve cells use these changing potentials or voltage pulses for many purposes including for example, vision and muscle control.
Bioelectricity: Cell Potential

Electrical potential across cell boundaries:

- **ionic concentration difference** in fluids inside and outside of cells
- **permeability of cell membrane** to these ions, Na⁺, K⁺ and Cl⁻

**Inactive (resting potential)**

Cell membrane
≈ 8 nanometres thick

Outside - thin layer of positive charge
Inside – thin layer of negative charge

Dipole layer

Layer of protein

Lipid bilayer
Two features explain the formation of cell potentials
1. Ion diffusion across membrane
2. Coulomb force Like charges repel & unlike charges attract
Bioelectricity: Cell Potential

Initially neutral cell. Total charge inside & outside is zero.

Outside

Inside

| Ion  | Concentration
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Na⁺</td>
<td>100 Moles/m³</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>100 Moles/m³</td>
</tr>
<tr>
<td>K⁺</td>
<td>100 Moles/m³</td>
</tr>
<tr>
<td>A⁻</td>
<td></td>
</tr>
</tbody>
</table>

Ionic concentration differences

Origin:
Cell membrane is semi-permeable: few ions can go through (K⁺, Cl⁻ in opposite directions)
Na⁺: 100 times less permeable.
Other ions—highly impermeable.
Direction, from high to low concentration.
Cell Potential Difference (2 states)

Repolarisation

2 distinct states: “resting” (inactive) and “action” (responsible for communication and muscle contraction)

Convention of polarity: inner relative to outer:

$\begin{align*}
+ &+ &+ &+ &+ \\
0 &mV & & & &
\end{align*}$

Cell Potential Difference (2 states)

**Origin:**

Nerve cell fires, cell membrane becomes 1000 times more permeable to Na$^+$ than normal (10 time more permeable than for K$^+$ and Cl$^-$)

The influx of sodium depolarises the cell, and the outflow of potassium repolarises...
This bio-electrical signal consists of a temporary reversal in the potential across the neuron membrane, and is called depolarisation—re-polarisation.

Voltage pulse
-nerve impulse
-action potential (AP)

In neurons it is a means of transmitting signals through the body

In muscles—initiates contraction
In a muscle, the Action Potential causes the contraction of the muscle.

The Action Potential can be stimulated from nerves on one side of the muscle and then spread inside the muscle.

Coordinated action of many thousands of muscle cells are involved

Large scale electrical activity easy to measure

Monitoring electrical signals from the heart: Electrocardiogram (ECG). Complex signals

Spreading of the electrical activity (AP) in a muscle represented by arrow

Depolarisation
Exterior of cells positive → negative

Monitor the polarity of electrodes A & B
Electrocardiogram

Array of **electrodes** on the skin can measure the **timing, magnitude and direction** of these electrical patterns.

A **map of the muscle** areas undergoing depolarisation and re-polarisation can be made by placing **at least 3 electrodes** on the skin.

Each pair of electrodes measures one component of the voltage wave.

Einthoven triangle

Records problems with the heart’s rhythm
The resting potential inside a muscle cell is approximately -90mV and the potential outside is taken to be 0V. If the average thickness of the cell membrane is 8 nanometres, determine the strength of the electric field across the membrane.

\[ V = Ed \]

Units: \( V \) (volts) \( d \) (metres)

\[ E = \frac{V}{d} = \frac{-90 \times 10^{-3} V}{(8 \times 10^{-9} m)} \]

\[ E = -1.125 \times 10^6 V/m \]
Example
How many electrons must be removed from an object so that it is left with a charge of $8 \times 10^{-10} \text{ C}$

Total charge $= 8 \times 10^{-10} \text{ C}$
Charge on electron $= -1.6 \times 10^{-19} \text{ C}$

Therefore number of electrons removed

$$= \frac{8 \times 10^{-10} \text{ C}}{1.6 \times 10^{-19} \text{ C}} = 5 \times 10^9 \text{ electrons}$$
Examples

Determine the minimum distance apart two identical charges of 2 \times 10^{-3} \text{ C} must be in order that the Coulomb force between them is less than 500 \text{ N}. k = (9 \times 10^9) \text{ Nm}^2\text{C}^{-2}

\[ F = k \frac{q_1 q_2}{r^2} \]

\[ 500 = 9 \times 10^9 \frac{(2 \times 10^{-3})(2 \times 10^{-3})}{r^2} \]

\[ r^2 = 9 \times 10^9 \frac{(2 \times 10^{-3})(2 \times 10^{-3})}{500} \]

\[ r = 8.48 \text{ m} \]
Example

Current in a torch bulb is 0.2A. How many electrons flow through the bulb if it is on for 5 minutes?

\[
\text{Current} = \frac{\text{Charge}}{\text{time}}
\]

\[
I = \frac{Q}{t}
\]

\[
0.2\, \text{A} = \frac{Q}{(5\times60)}
\]

\[
Q = 5\times60\times0.2 = 60 \, \text{Coulombs}
\]

But charge on the electron \(= 1.6 \times 10^{-19}\)C

Therefore number of electrons

\[
= \frac{60}{1.6 \times 10^{-19}}
\]

\[
= 37.5 \times 10^{19} \, \text{electrons}
\]