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.

End that points to Earth’s geographic north pole is called the north pole of the magnet.
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.
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 do not fully 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.

Disorder non-magnetic

Externally applied magnetic field can align the domains so that the material becomes magnetised.
Magnetization

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.
Magnetic force

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 is perpendicular to the plane containing the line of the wire and the line of the magnetic field. i.e. into the page
**Magnetic force**

\[ F \propto I \times L \]

\[ F = B \times I \times L \]

- **Force** \((F)\) on the wire is proportional to the current \((I)\) and the length \((L)\) of the wire in the magnetic field \((B)\).
- **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**

\[ 1 \text{T} = 1 \text{N.m}^{-1} \cdot \text{A}^{-1} \]
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 voltage in the wire or coil.

Faraday’s law of magnetic Induction

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

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

$\phi = B.A$

Application

Transformer

AC voltage

Iron

Voltage in

Voltage out

Charger:

mobile phones

Electric toothbrush
Charges sitting on base unit
No metal to metal contact
Only plastic to plastic.
How does it charge??

X-ray machine—high voltage
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

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

Magnet material
Biological safety ????
Medical uses of Magnetic fields

MRI

Non-invasive imaging technique that discriminates between body tissues.

diagnostic tool for soft tissue – organs, ligaments, the circulatory system, spinal column, brain

MRI uses superconducting magnet;

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

A wire placed in magnetic field such that its length is perpendicular to the field which is of strength 10 milliTeslas. 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 \[ L = \frac{F}{BI} = \frac{30 \times 10^{-6} \text{ N}}{10 \times 10^{-3} \text{ T} \times 15 \times 10^{-3} \text{ A}} \]

\[ L = 2 \times 10^{-1} \text{ m} = 0.2 \text{ m} = 20 \text{ cm}. \]
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
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
## Significant levels of current

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><strong>1</strong></td>
<td><strong>threshold of sensation</strong>*</td>
</tr>
<tr>
<td>100-300</td>
<td>ventricular fibrillation possible</td>
</tr>
<tr>
<td><strong>300</strong></td>
<td>onset of burns, depends on concentration of current</td>
</tr>
<tr>
<td><strong>6000 (6A)</strong></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
**Effects of other parameters**

**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

Heart functions normally by use of controlled electrical impulses

If these impulses are disrupted by an external current, heart beat is affected - becomes random and ineffectual - may be fatal

However, ventricular fibrillation may be remedied by passing a much larger current (6A) through the chest using a defibrillator

Effect of a large current for a short period is such that normal beating resumes after shock.
Effects of other parameters

**Path:** Skin has higher resistance than tissues.

**Humidity is important:**
dry skin: $10^4$-$10^6$ ohm, wet skin: $10^3$ 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)**

- Outside: thin layer of positive charge
- Inside: thin layer of negative charge
- Dipole layer

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

**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)

2 distinct states: “resting” (inactive) and “action” (responsible for communication and muscle contraction)
Convention of polarity: inner relative to outer:

**Nerve cell fires >> temporary reversal in potential across cell membrane**

**Depolarisation**
- Cell contracts
- Inaction: -90mV
- Action: +50mV

**Repolarisation**
- Inaction: -90mV

**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 $\rightarrow$ negative

Monitor the polarity of electrodes A & B
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 \(-90\text{mV}\) and the potential outside is taken to be \(0\text{V}\). If the average thickness of the cell membrane is 8 nanometres, determine the strength of the electric field across the membrane.

\[E = \frac{V}{d} = \frac{-90 \times 10^{-3} \text{V}}{8 \times 10^{-9} \text{m}} = 1.125 \times 10^6 \text{V/m}\]