



DP IB Biology: HL



6.5 Neurones & Synapses

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6.5.1 Neurones: Function & Structure



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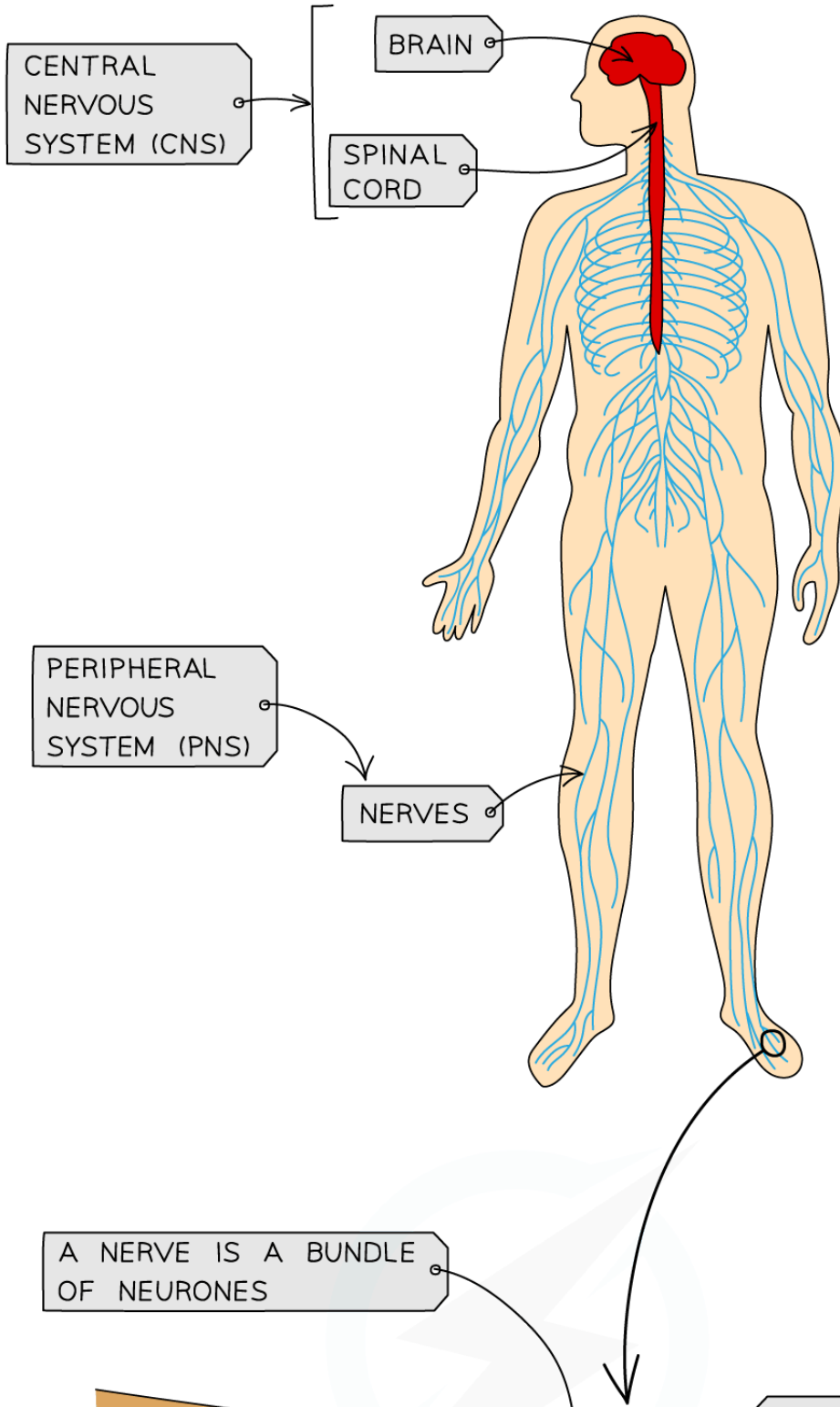
Function & Structure of Neurones

The nervous system

- The human nervous system consists of:
 - **Central nervous system (CNS)** – the **brain** and **spinal cord**
 - **Peripheral nervous system (PNS)** – all of the **nerves** in the body
- It allows us to make sense of our surroundings and respond to them, and to **coordinate and regulate body functions**
- Information is sent through the nervous system in the form of **electrical impulses** – these are electrical signals that pass along **nerve cells** known as **neurones**
 - A **bundle of neurones** is known as a **nerve**
- The nerves spread out from the central nervous system to **all other regions of the body** and importantly, to all of the **sense organs**
 - The **CNS** acts as a **central coordinating centre** for the impulses that come in from, and are sent out to, any part of the body

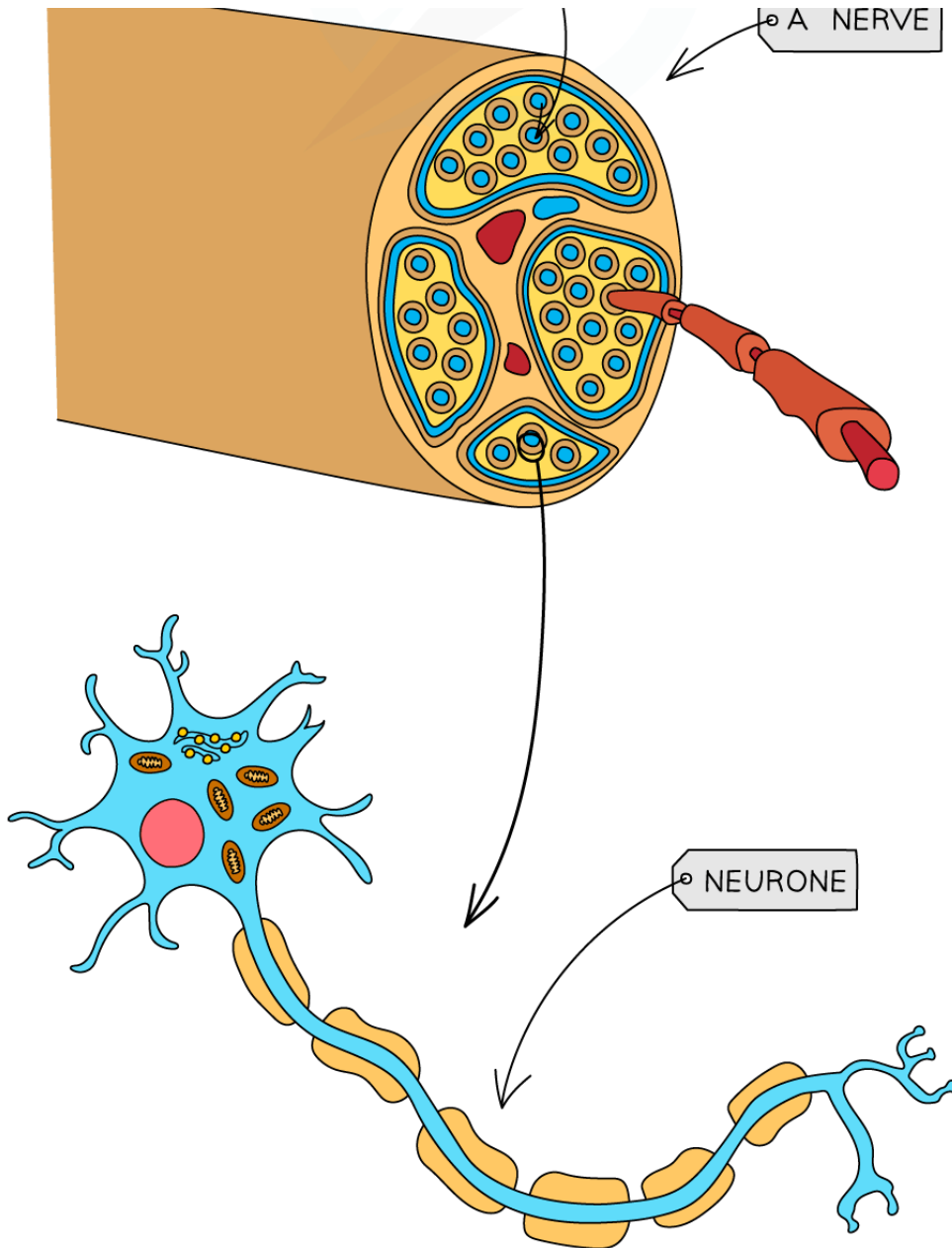


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The human nervous system is comprised of the CNS and the PNS

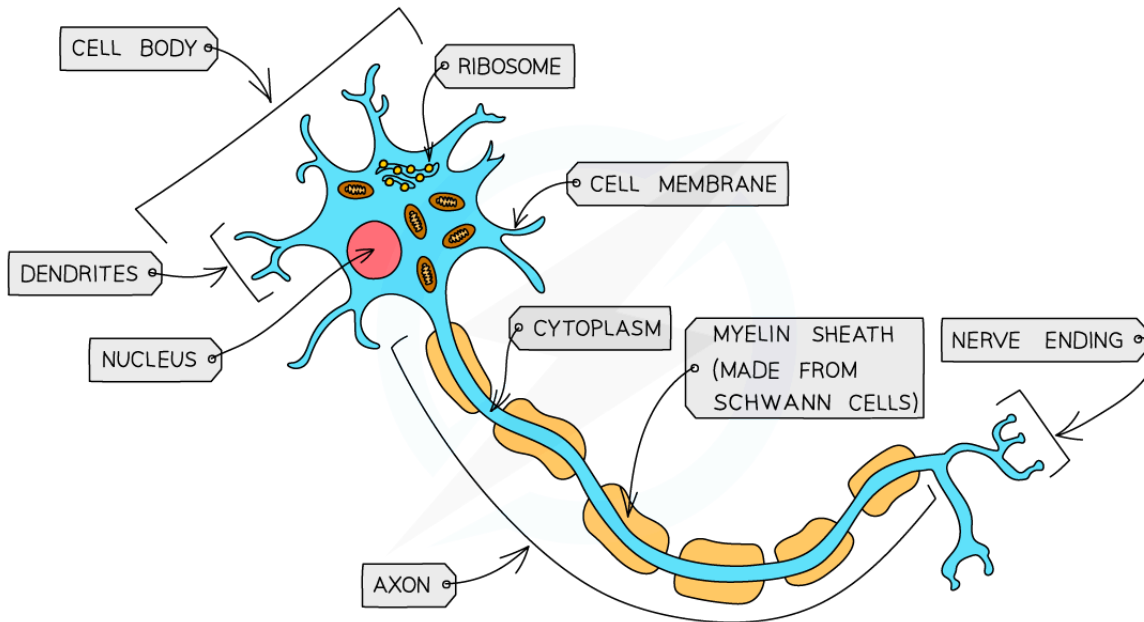
Neurones

- The following features are found in neurones:
 - Neurones have a **main, long, fibre** known as an **axon**

- They have a **cell body** that contains the **nucleus** and other cellular structures
- Their **cell bodies** and **axon terminals** contain many extensions called **dendrites**
- These **dendrites** allow them to **connect to many other neurones** and receive **impulses** from them, forming a **network** for easy **communication**



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Neurones have a characteristically elongated structure which allows them to transfer information between the central nervous system and the rest of the body

Research

NOS: Cooperation and collaboration between groups of scientists; biologists are contributing to research into memory and learning

- Some of the so-called '**higher**' **functions of the brain** e.g., memory and learning, are still not fully understood and are the focus of much **current research**
- **Biologists are becoming increasingly involved** in this research, which uses techniques from the fields of **neurobiology**, **molecular biology**, and **biochemistry** to understand the mechanisms behind these brain functions
- The Centre for Neural Circuits and Behaviour (CNCB) at the University of Oxford is a good example of an institution in which scientists with different areas of expertise **collaborate**, or work together, with a **common research goal**
 - The research team at the CNCB contains experts in various fields of biological science, including medicine, physiology, genetics, molecular biology, neurobiology, and neurogenetics
- Research into functions of the brain such as memory and learning not only involves **collaboration** between scientists from **different specialities**, but also from **different countries**



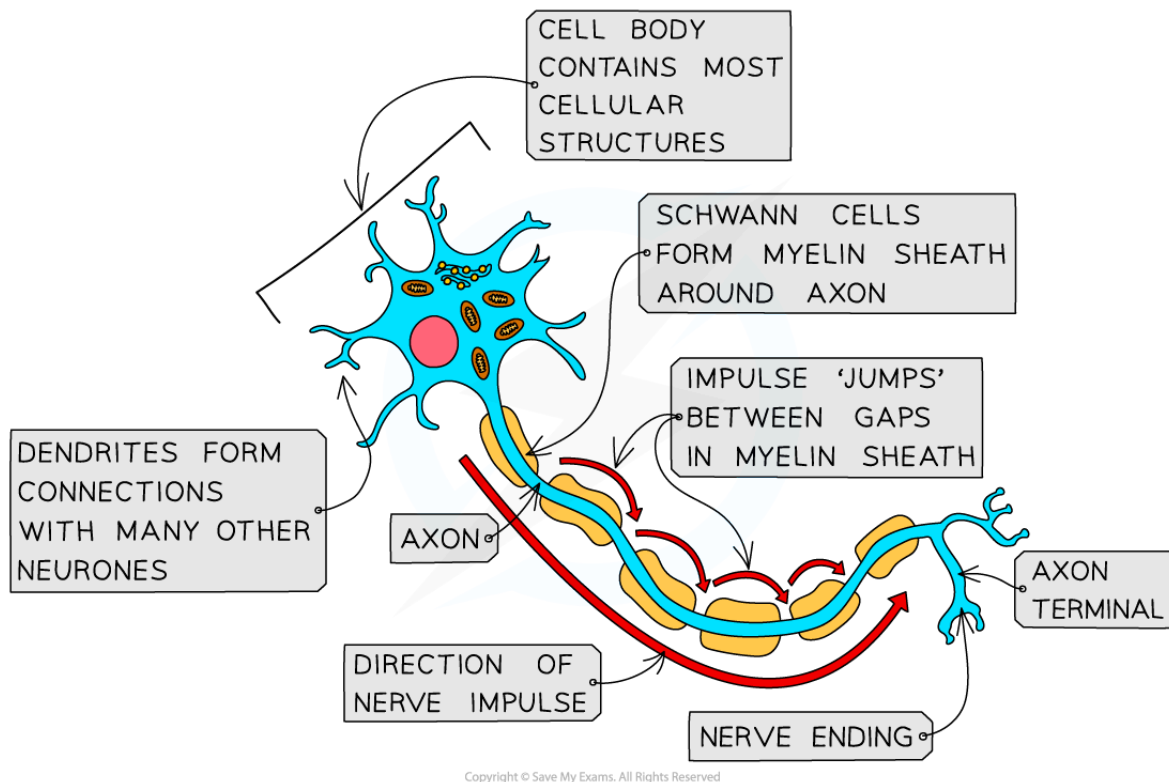
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Myelination

- Neurones have a **main, long, fibre** known as an **axon**
- The axons of neurones are **surrounded** by specialised cells called **Schwann cells**
- Schwann cells **wrap themselves around the axon**, forming a structure known as a **myelin sheath**
 - Myelin** contains the **phospholipids** of the **Schwann cell membranes**; it is built up in layers as the Schwann cells grow around the axon
 - The **lipid** content of the myelin sheath gives it a **high electrical resistance**
- The myelin sheath acts as an **electrical insulator**; impulses cannot pass through the myelin sheath
- The myelin sheath has **small, uninsulated sections** in the gaps between the individual Schwann cells
 - These gaps are called **nodes of Ranvier**
- Electrical impulses effectively **jump** from one node of Ranvier to the next
 - This process is known as **saltatory conduction**
 - It greatly **speeds up the rate of transmission of impulses** along myelinated neurones
 - In non-myelinated neurones the axon is not insulated by myelin, so the impulse travels **more slowly**



An impulse travels down a neurone via saltatory conduction



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6.5.2 Nerve Impulses

Resting Potential

- **Neurones** transmit information in the form of **impulses**, which travel extremely quickly along the neurone from one end to the other
 - Note that an impulse is **not** an electrical current that flows along neurones as if they were wires
 - Instead, an impulse is a **momentary reversal in the electrical potential difference** across the **neurone cell surface membrane**
 - The electrical potential difference across a membrane can also be described as the **voltage** across a membrane, the **difference in charge** across a membrane, or the **membrane potential**
- In an axon that is **not transmitting an impulse** the **inside** of the axon always has a **negative electrical potential**, or charge, compared to **outside** the axon, which has a **positive electrical potential**
 - This membrane potential in a resting neurone is known as **resting potential**
- The **resting potential** is usually about **-70 millivolts (mV)**
 - This means that the **inside** of the resting axon has a **more negative** electrical charge than the **outside** by about 70 mV
- Two main processes contribute to establishing and maintaining resting potential:
 - **The active transport of sodium ions and potassium ions**
 - **A difference in rates of diffusion of sodium ions and potassium ions**
- In addition to these two main processes, **negatively charged proteins** inside the axon also contribute to the negative resting potential

The active transport of sodium ions and potassium ions

- Carrier proteins called sodium-potassium pumps are present in the cell surface membranes of neurones
- These pumps use **ATP** to actively transport **sodium ions** (Na^+) **out** of the axon and **potassium ions** (K^+) **into** the axon
- The two types of ion are pumped at an unequal rate; for every **3 sodium ions that are pumped out** of the axon, only **2 potassium ions are pumped in**
- This creates a concentration gradient across the membrane for both sodium ions and potassium ions

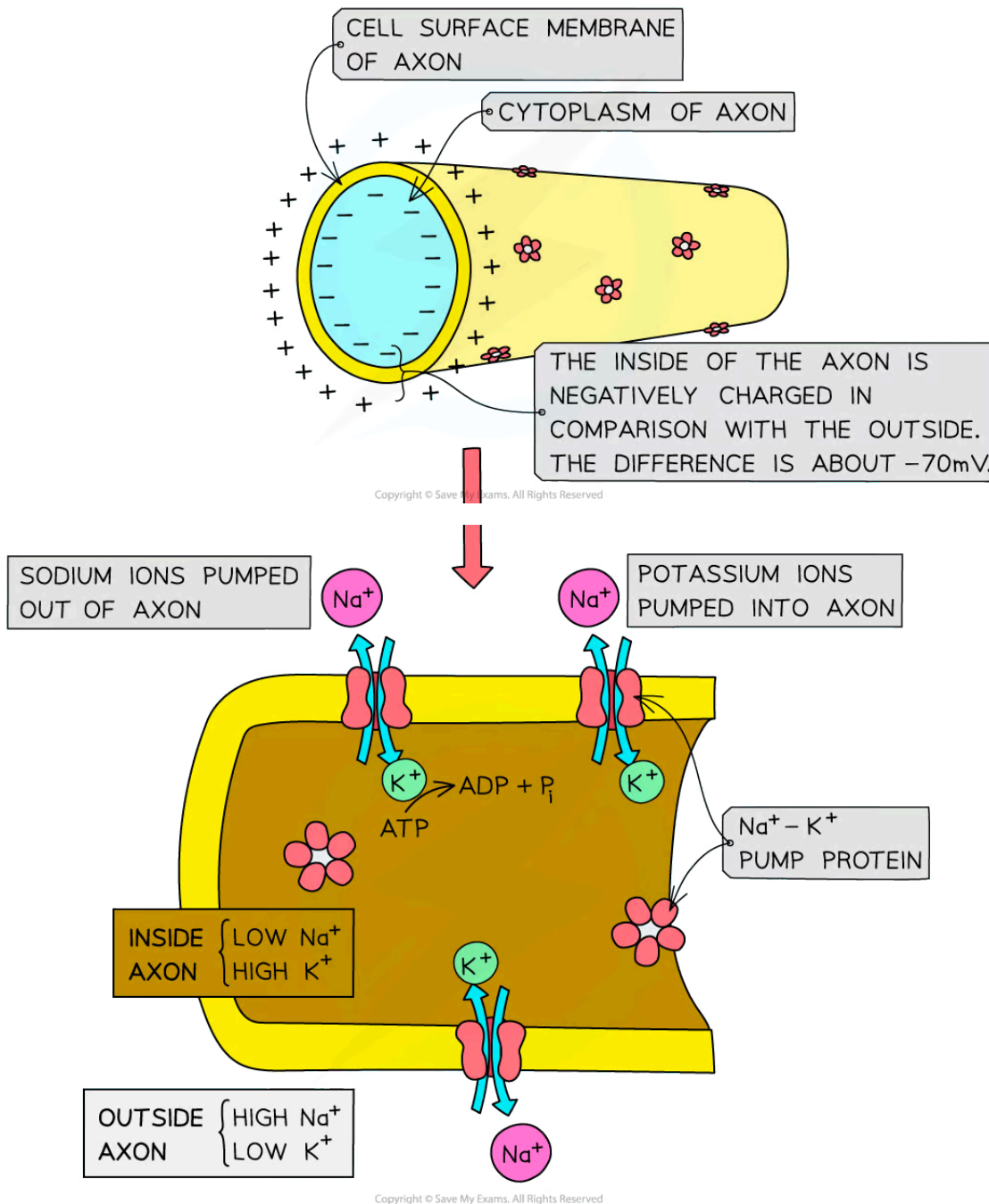
Difference in rates of diffusion of sodium ions and potassium ions

- Because of the concentration gradient generated by the **sodium-potassium pumps**, both sodium and potassium ions will diffuse back across the membrane
 - The neurone cell surface membrane has **sodium ion channels** and **potassium ion channels** that allow sodium and potassium ions to move across the membrane by **facilitated diffusion**
- The neurone membrane is much **less permeable** to sodium ions than potassium ions, so potassium ions inside the neurone can diffuse **out** at a **faster rate** than **sodium ions** can diffuse **back in**



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- This results in **far more positive ions** on the **outside** of the neurone than on the inside, generating a **negative charge inside** the neurone in relation to the outside
- The result of this is that the neurone has a **resting membrane potential** of around **-70 millivolts (mV)**



Sodium-potassium pumps in the membrane of a resting neurone generate a concentration gradient for both sodium ions and potassium ions. This process, together with the facilitated diffusion of potassium

ions back out of the cell at a faster rate than sodium ions diffuse back into the cell, generates a negative resting potential across the membrane.



Your notes



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Action Potential

- Once resting potential is reached, the neurone membrane is said to be **polarised**
- To initiate a nerve impulse in a neurone, the neurone membrane needs to be **depolarised**
 - Depolarisation is the **reversal of the electrical potential difference** across the membrane
- The depolarisation of the membrane occurs when an **action potential** is generated
 - Action potentials lead to the reversal of resting potential from around **-70 mV** to around **+40 mV**
- Action potentials involve the **rapid movement** of **sodium ions** and **potassium ions** across the **membrane** of the **axon**
- An action potential is the **potential electrical difference** produced across the axon membrane when a neurone is **stimulated** e.g. when an environmental stimulus is detected by a receptor cell

How an action potential is produced

- Some of the ion channels in the membrane of a neurone are **voltage gated**, meaning that they open and close in response to changes in the **electrical potential** across the membrane
 - Voltage gated ion channels are **closed** when the membrane is at rest, but they are involved in the generation and transmission of action potentials
 - Note that not all of the channels in a neurone membrane are voltage gated e.g. some types of potassium ion channel are open when a neurone is at rest to enable potassium ions to diffuse out of the axon and generate resting potential
- When a neurone is stimulated, the following steps occur:
 - A small number of **sodium ion channels** in the axon membrane **open**
 - Sodium ions** begin to move **into the axon** down their **concentration gradient**
 - There is a greater concentration of sodium ions outside the axon than inside due to the action of sodium-potassium pumps
 - This **reduces** the **potential difference** across the axon membrane as the **inside** of the axon becomes **less negative**
 - If enough sodium ions enter the axon and the potential difference is reduced enough, **voltage gated sodium ion channels** open, leading to a further, large influx of sodium ions
 - Once the charge has been reversed from -70 mV to around +40 mV, **an action potential** is said to have been **generated**

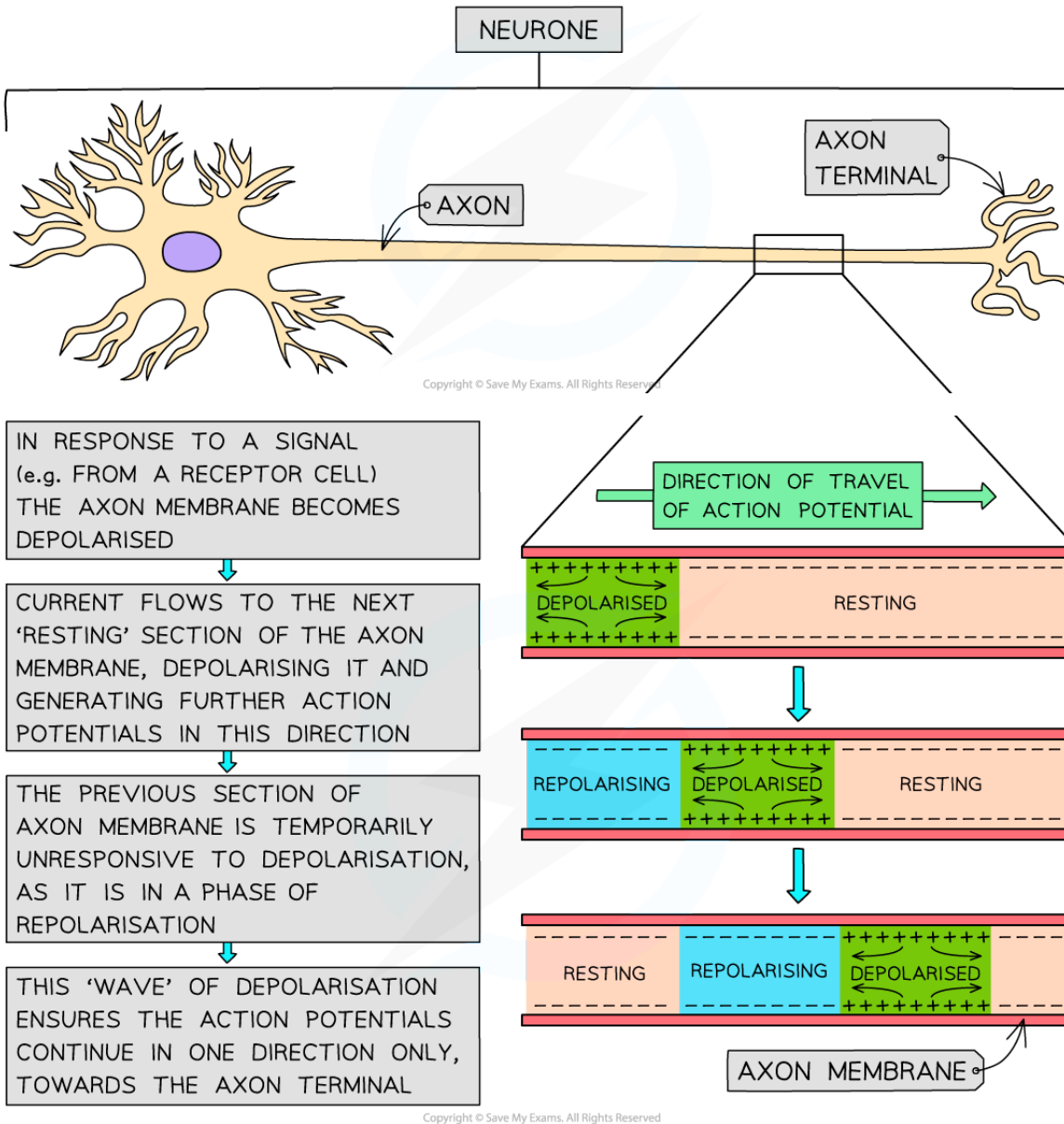
How an action potential is propagated

- Once an action potential has been generated, it can be **propagated**, or transmitted, along the length of the axon
 - The depolarisation of the membrane at the site of the first action potential causes **sodium ions** to diffuse along the cytoplasm into the next section of the axon, **depolarising** the membrane in this new section, and causing voltage gated sodium channels to open
 - This triggers **another action potential** in this section of the axon membrane
 - This process then repeats along the length of the axon

- In the body, this allows action potentials to begin at one end of an axon and then pass along the entire length of the axon membrane



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How an impulse is propagated in one direction along the axon of a neurone

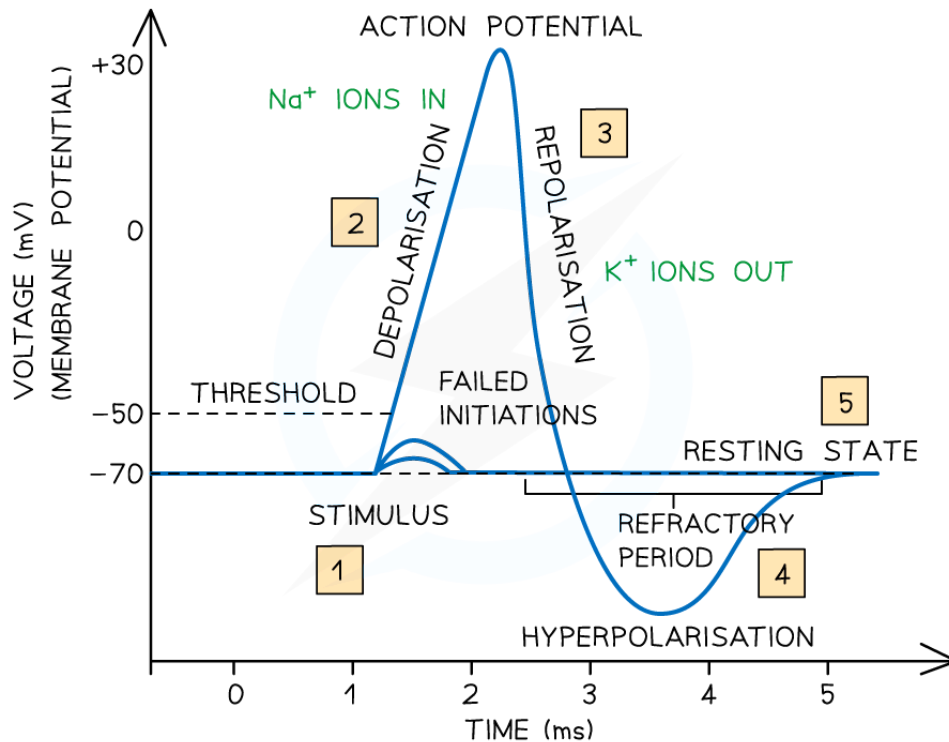
Repolarisation

- About 1 ms after an action potential is generated, all the **voltage gated sodium channels** in this section of membrane **close**



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- **Voltage gated potassium channels** in this section of axon membrane now **open**, allowing the diffusion of potassium ions **out of the axon**, down their concentration gradient
 - Remember that the sodium-potassium pumps have not stopped working during the action potential; hence the potassium ion gradient is still present
- This movement of potassium ions causes the inside of the axon to become negatively charged again, a process known as **repolarisation**
 - There is a short period during which the membrane potential is more negative than resting potential; this is known as **hyperpolarisation**
 - The period during which the membrane is hyperpolarised is known as the **refractory period**
 - The membrane is unresponsive to stimulation during the refractory period, so a new action potential cannot be generated at this time
 - This makes the action potentials **discrete** events and means the impulse can **only travel in one direction**
 - This is essential for the successful and efficient transmission of nerve impulses along neurones
- The voltage gated potassium channels then **close**, and the **sodium-potassium pumps** work to restore **resting potential**
 - Only once resting potential is restored can the membrane be stimulated again



The depolarisation and repolarisation of an action potential can be clearly seen in a graph of membrane potential against time



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Threshold Potential

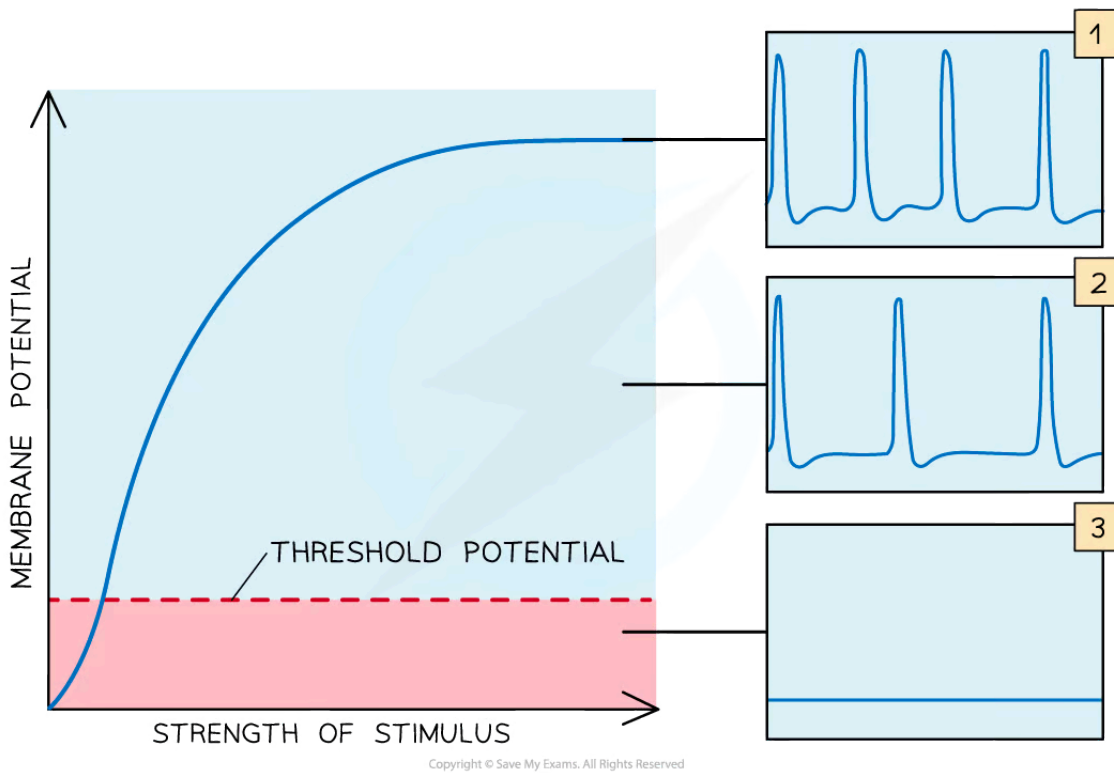
- An **action potential** is only **initiated** if the **threshold potential** is reached
- When a neurone is stimulated, sodium ion channels in the axon membrane open and sodium ions pass into the axon down their concentration gradient
- This causes the inside of the axon to become **less negative**, but exactly how much less negative it becomes is dependent on the number of sodium ion channels that open
 - A large stimulus will cause more channels to open than a small stimulus
 - If more channels open, then more sodium ions will enter the axon, causing it to become less negative
- If the potential difference reaches around **-50 mV**, known as the **threshold potential**, voltage gated sodium ion channels open and **many more** sodium ions enter the axon
 - This causes the membrane potential to reach around +40 mV
- Once the charge has been reversed from -70 mV to +40 mV, an action potential is generated

The all-or-nothing principle

- Action potentials are either generated or not generated depending on whether the threshold potential is reached; there is **no such thing as a small or large action potential**
 - If a stimulus is **weak**, only a few sodium ion channels will open and the membrane won't be sufficiently depolarised to reach the **threshold potential**; an action potential will not be generated
 - If a stimulus is **strong enough** to raise the membrane potential above the **threshold potential** then an action potential will be generated
- This is the **all-or-nothing principle**
 - An impulse is **only transmitted** if the **initial stimulus is sufficient** to increase the membrane potential above a **threshold potential**
- Stimulus size can be detected by the brain because as the **intensity of a stimulus increases**, the **frequency** of action potentials transmitted along the neurone **increases**
 - This means that a small stimulus may only lead to one action potential, while a large stimulus may lead to several action potentials in a row



Your notes



1 THE MEMBRANE IS GIVEN A STRONG STIMULUS WHICH GENERATES A HIGH FREQUENCY OF ACTION POTENTIALS

2 THE MEMBRANE IS GIVEN A WEAK STIMULUS WHICH GENERATE A LOW FREQUENCY OF ACTION POTENTIALS

3 THE MEMBRANE IS GIVEN A VERY WEAK STIMULUS WHICH FAILS TO GENERATE AN ACTION POTENTIAL

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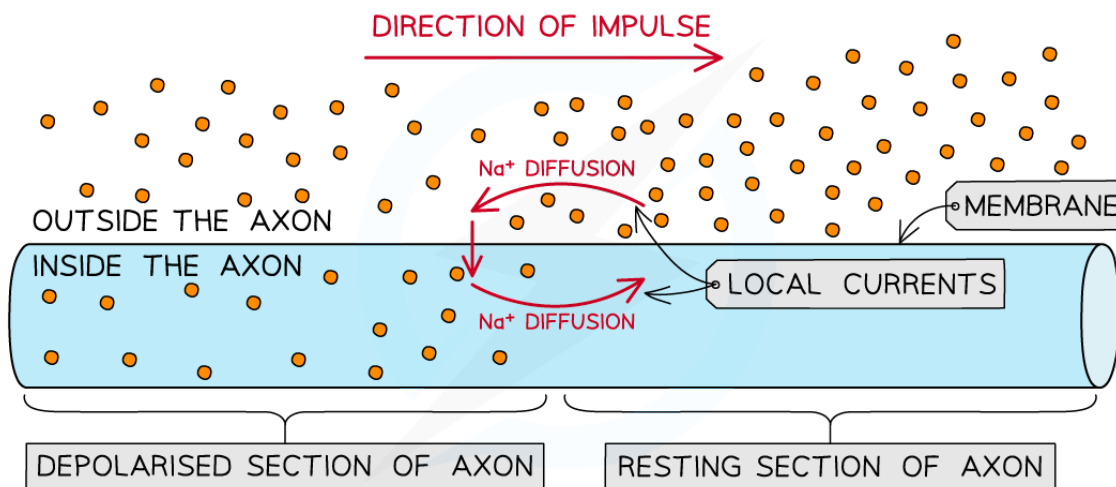
As the strength of a stimulus increases beyond the threshold potential, the frequency of action potentials increases



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Local Currents

- The propagation of nerve impulses along axons occurs due to **local currents** that cause each successive section of the axon to reach the **threshold potential**
- **Inside** the **depolarised** section of the axon
 - There is a **high concentration** of sodium ions due to their recent **influx**
 - This creates a **concentration gradient** between the section of the axon that has depolarised and the section next to it
 - Sodium ions diffuse along **inside** the axon to the neighbouring section of axon that has not yet become depolarised
 - This reduces the negative membrane potential in the new section of axon and, if a threshold is reached, begins the initiation of an action potential
 - This enables the original action potential to be propagated
- On the **outside** of the axon
 - There is a higher concentration of sodium ions outside the section of axon that has **not yet become depolarised** due to the diffusion of sodium ions into the depolarised section
 - Sodium ions diffuse from here along the outside of the axon to the section of axon that has just become depolarised
- These movements of sodium ions are known as **local currents**
- These local currents cause a **wave of depolarisation** and **repolarisation** to travel along the axon, resulting in the **propagation of a nerve impulse**



The propagation of nerve impulses along axons occurs due to local currents created by the diffusion of sodium ions

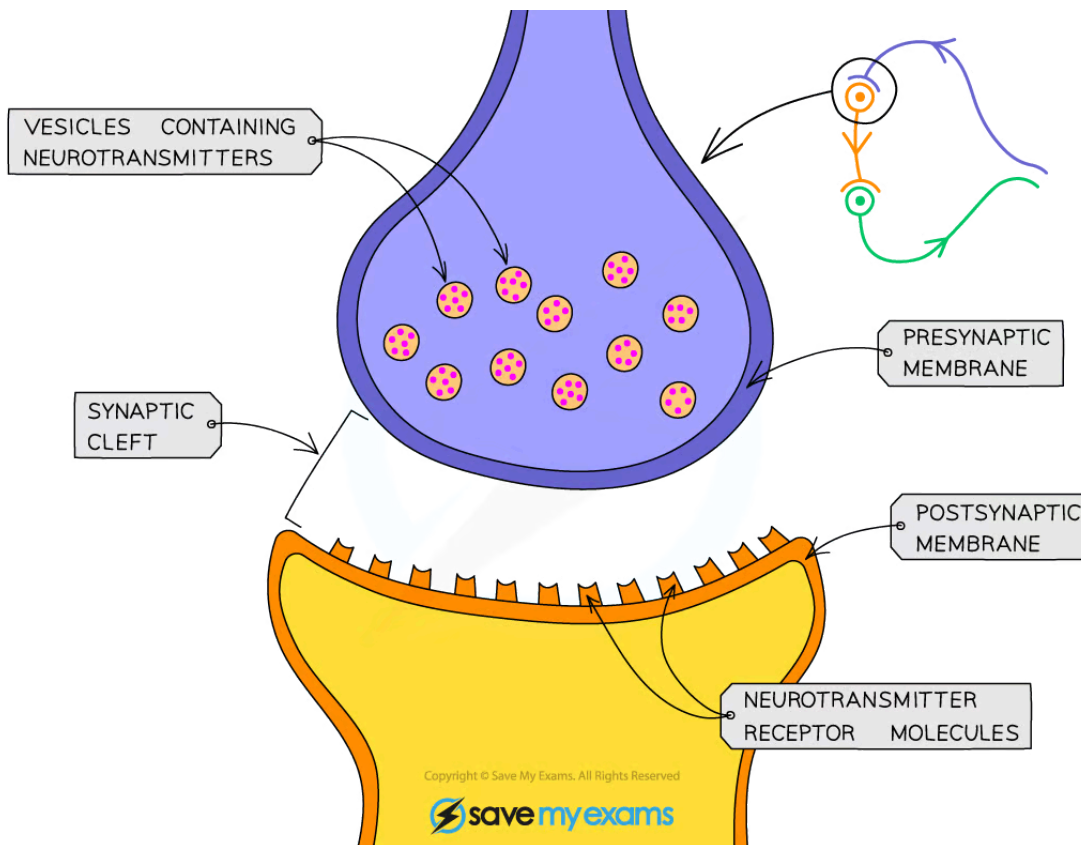


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6.5.3 Synapses

Synapses

- Where two neurones meet, they do not actually come into **physical contact** with each other
- Instead, a very small gap, known as the **synaptic cleft**, separates them
- The ends of the two neurones, along with the synaptic cleft, form a structure known as a **synapse**
- Synapses act as the junctions **between any cells in the nervous system**, e.g.
 - In the sense organs, there are synapses between **sensory receptor cells** and **sensory neurones**
 - In muscles, there are synapses between **motor neurones** and **muscle fibres**



A synapse

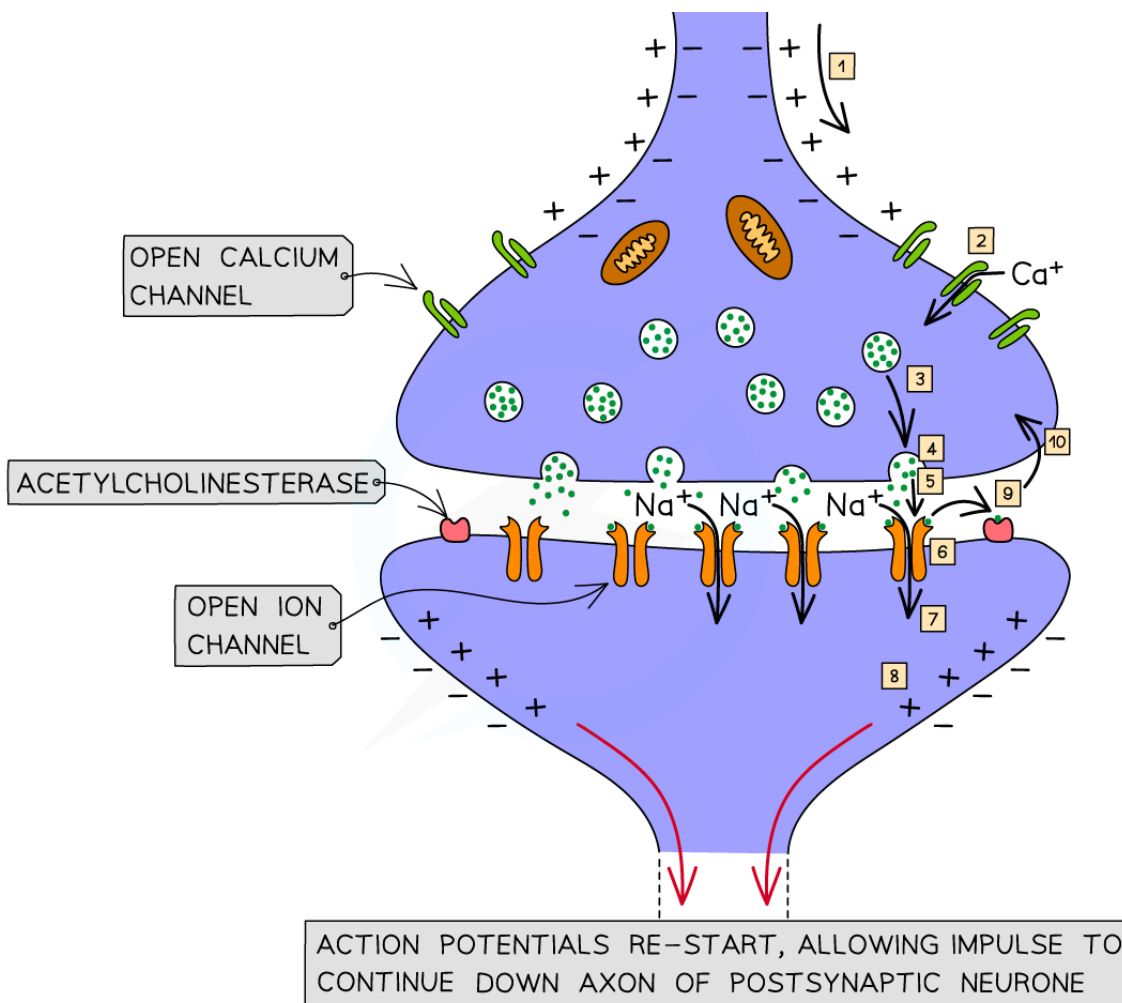
Synaptic transmission

- Electrical impulses cannot 'jump' across the synaptic cleft
- When an electrical impulse arrives at the end of the axon on the **presynaptic neurone**, the **membrane** of the presynaptic neurone becomes depolarised, triggering an influx of **calcium ions** into the presynaptic cell via **calcium ion channels** in the membrane



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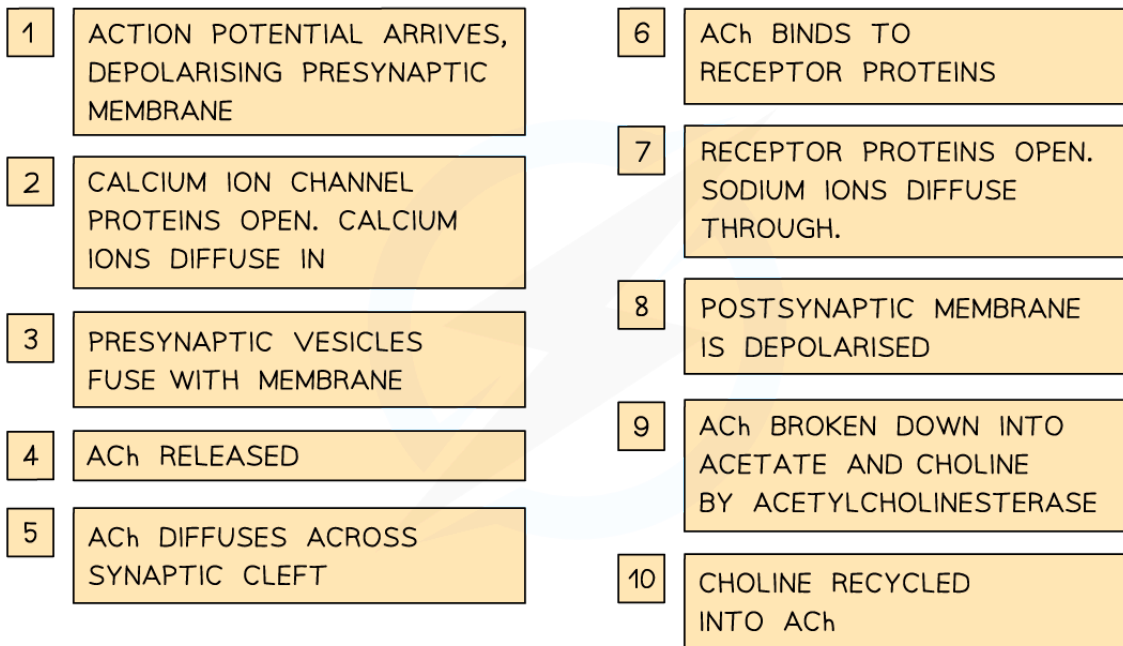
- The calcium ions cause vesicles in the presynaptic neurone to move towards the presynaptic membrane where they fuse with it and **release chemical messengers** called **neurotransmitters** into the synaptic cleft
 - A common neurotransmitter is **acetylcholine**, or **ACh**
- The neurotransmitters **diffuse** across the **synaptic cleft** and **bind with receptor molecules** on the **postsynaptic membrane**; this causes associated **sodium ion channels** on the postsynaptic membrane to open, allowing **sodium ions** to diffuse into the postsynaptic cell
- If enough neurotransmitter molecules bind with receptors on the postsynaptic membrane then an **action potential** is generated, which then travels down the **axon** of the **postsynaptic neurone**
- The neurotransmitters are then **broken down** to prevent continued stimulation of the postsynaptic neurone
 - The enzyme that breaks down acetylcholine is **acetylcholinesterase**



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Synaptic transmission using the neurotransmitter acetylcholine

Unidirectionality

- Synapses ensure the **one-way transmission** of impulses
- Impulses can only pass in **one direction** at synapses because **neurotransmitter is released on one side** and its **receptors are on the other** – chemical transmission cannot occur in the opposite direction
- This prevents impulses from travelling the wrong way



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Acetylcholine

- There are over 40 different known **neurotransmitters**
 - Examples include dopamine and noradrenaline
- One of the key neurotransmitters used throughout the nervous system is **acetylcholine (ACh)**
 - ACh is produced in the **presynaptic neurone** by combining **choline** with an **acetyl group**
 - Synapses that use the neurotransmitter ACh are known as **cholinergic synapses**
- Acetylcholine is released into the **synaptic cleft** when **ACh-containing vesicles** fuse with the **presynaptic membrane**, releasing ACh molecules into the **synaptic cleft**
- ACh **binds to specific receptors** on the postsynaptic membrane, where it can **generate an action potential** in the postsynaptic cell by opening **associated sodium ion channels**
- To prevent the sodium ion channels staying permanently open and to stop permanent depolarisation of the postsynaptic membrane, the **ACh molecules are broken down and recycled**
 - The enzyme **acetylcholinesterase** catalyses the **hydrolysis** of ACh molecules into **acetate** and **choline**
 - The products of hydrolysis are then **absorbed back into the presynaptic neurone**, and the **active neurotransmitter ACh** is reformed

Inhibition of Acetylcholine Receptors

- Neonicotinoids** are synthetic compounds similar to nicotine that are commonly found in **pesticides**
- Neonicotinoids can **block** synaptic transmission at **cholinergic synapses** in **insects** by binding to **acetylcholine receptors**
 - This binding is **irreversible**, as **acetylcholinesterase** cannot break down neonicotinoids
 - As the acetylcholine receptors are blocked, **acetylcholine is unable to bind**, which **stops impulses** from being transmitted across synapses
 - This leads to **paralysis** and **death** in insects
- Neonicotinoids are considered to be especially suitable as pesticides because they're **not toxic to humans and other mammals**
 - A much larger proportion of synapses in insects are cholinergic compared to mammals
 - Neonicotinoids bind much more strongly to acetylcholine receptors in insects
- There is a great deal of controversy over the use of neonicotinoid pesticides because of the impact that they are thought to have on essential pollinators such as bees



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6.5.4 Skill: Neurones & Synapses

Analysis of Oscilloscope Traces

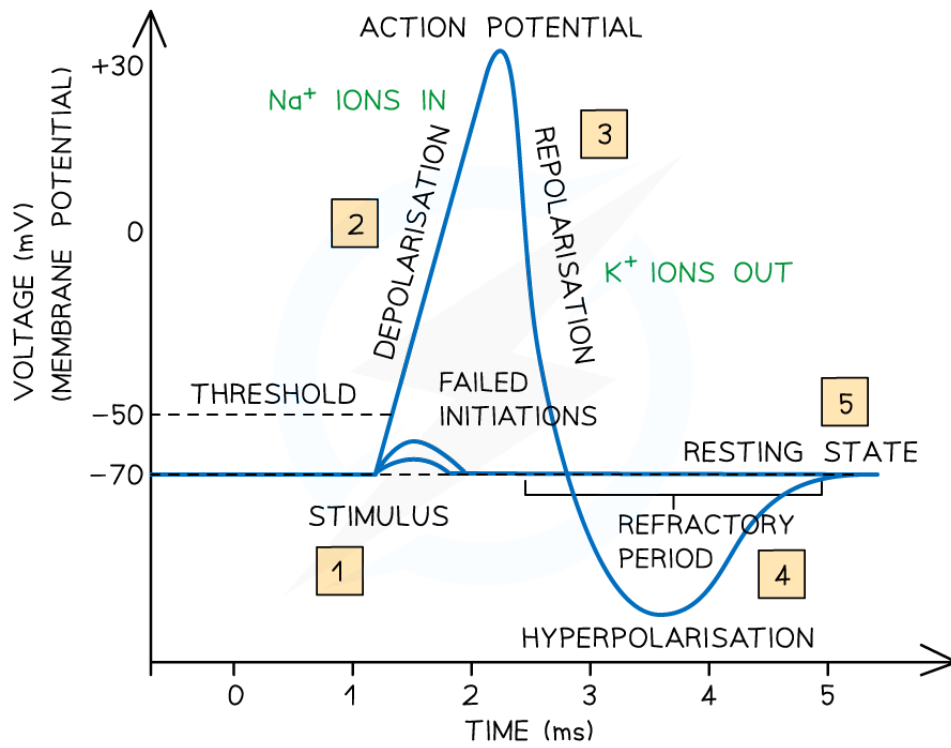
- It is possible to **measure membrane potentials** in neurones by placing electrodes on each side of the membrane
 - A membrane potential is the **difference in charge** between one side of a membrane and the other, sometimes described as the potential difference, or the voltage
- The membrane potential can then be **visually represented** and **displayed** using an **oscilloscope**
- An oscilloscope is a type of **electronic test instrument** that **graphically displays varying signal voltages**
- The display produced is **like a graph** with **time** in milliseconds on the **x-axis** and the membrane **potential** in millivolts on the **y-axis**

How to analyse oscilloscope traces showing resting potentials and action potentials

- If there is a **resting potential**, a **straight, horizontal line** should be shown on the display screen of the oscilloscope at a level of **-70 mV**
- If an **action potential** occurs a **spike**, rising up to a maximum voltage of **between +30 and +40 mV**, should be shown on the display
 - The **rising phase** of the spike shows depolarisation
 - The **falling phase** of the spike shows repolarisation
- Often not shown on an action potential graph is the gradual rise in membrane potential just before the membrane rapidly depolarises
 - Before threshold potential is reached, only a small number of sodium channels in the membrane are open, so the membrane depolarises slowly, but when the threshold is reached many more sodium channels open
- Instead of repolarisation causing the membrane potential to return **immediately** to the normal resting potential of -70 mV, the trace often shows a **short period of hyperpolarisation**
 - This is when the membrane potential briefly becomes **more negative** than resting potential



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An example of an oscilloscope trace showing resting potential and an action potential