DP IB Biology: SL

Your notes

6.5 Neurones & Synapses

Contents

6.5.1 Neurones: Function & Structure

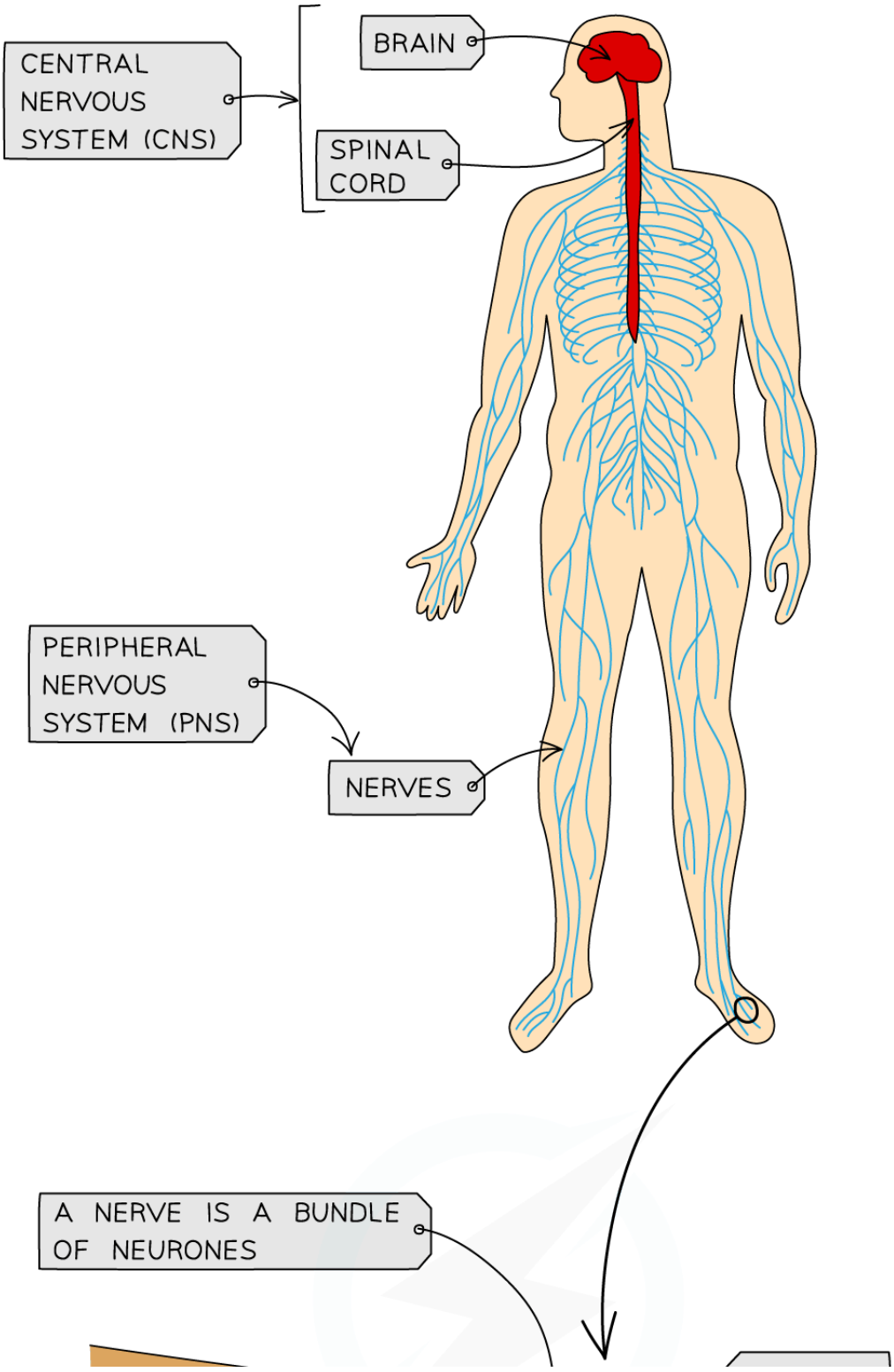
Your notes

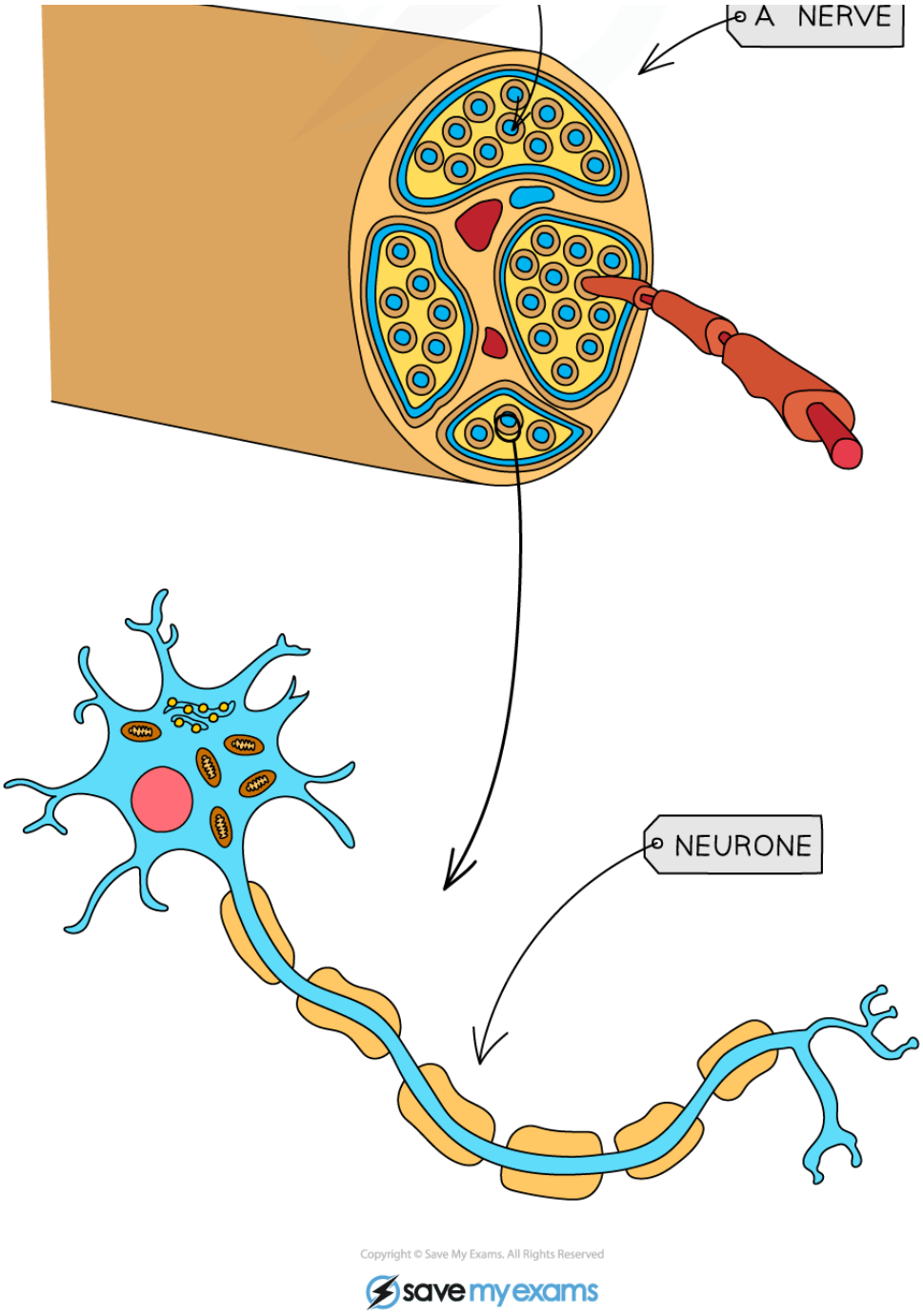
Function & Structure of Neurones

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

Your notes





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

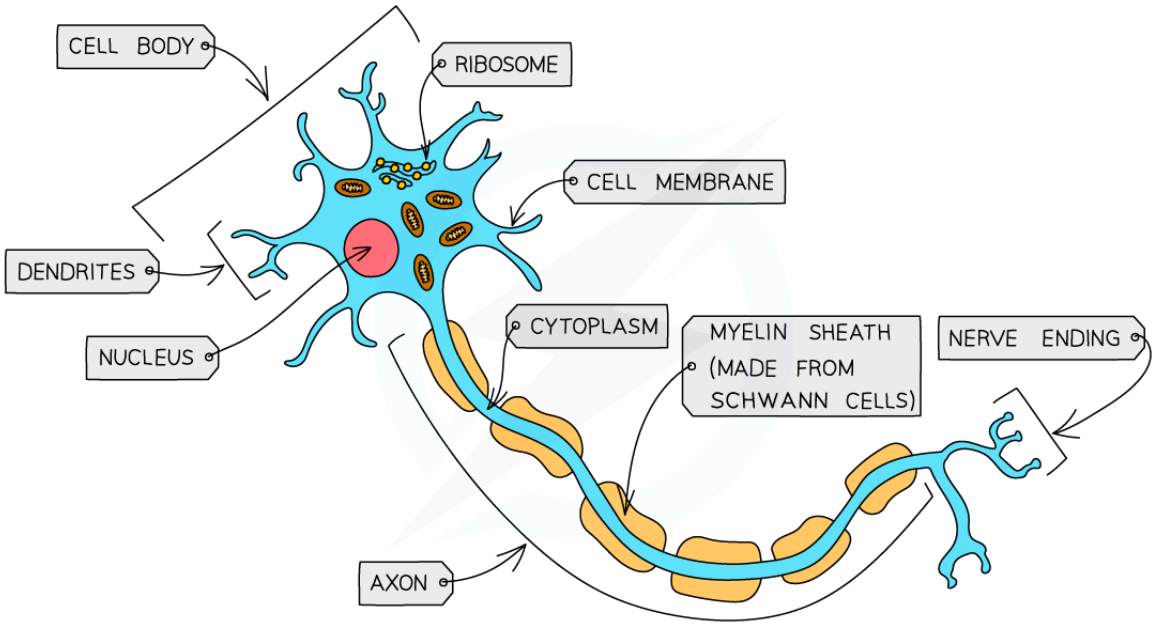
Your notes

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**

Your notes



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

Research


Your notes

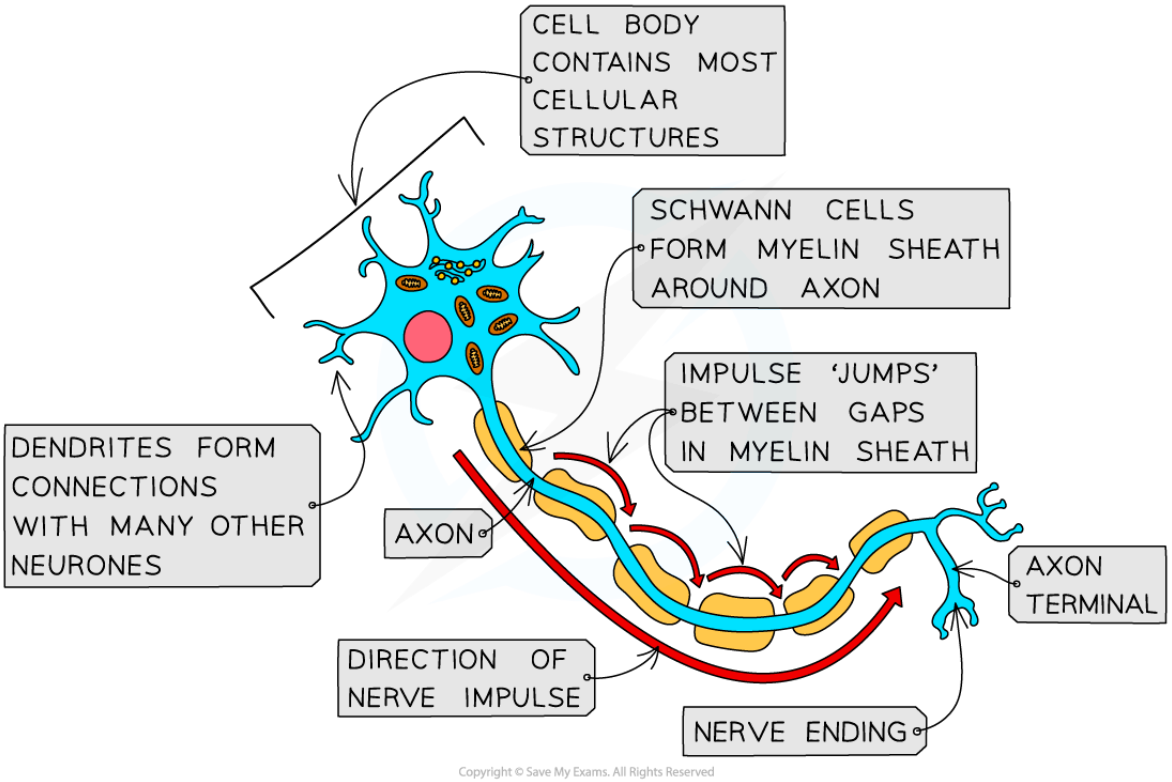
NOS: Cooperation and collaboration between groups of scientists; biologists are contributing to research into memory and learning

- 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**

Myelination

Your notes

- 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

6.5.2 Nerve Impulses

Your notes

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

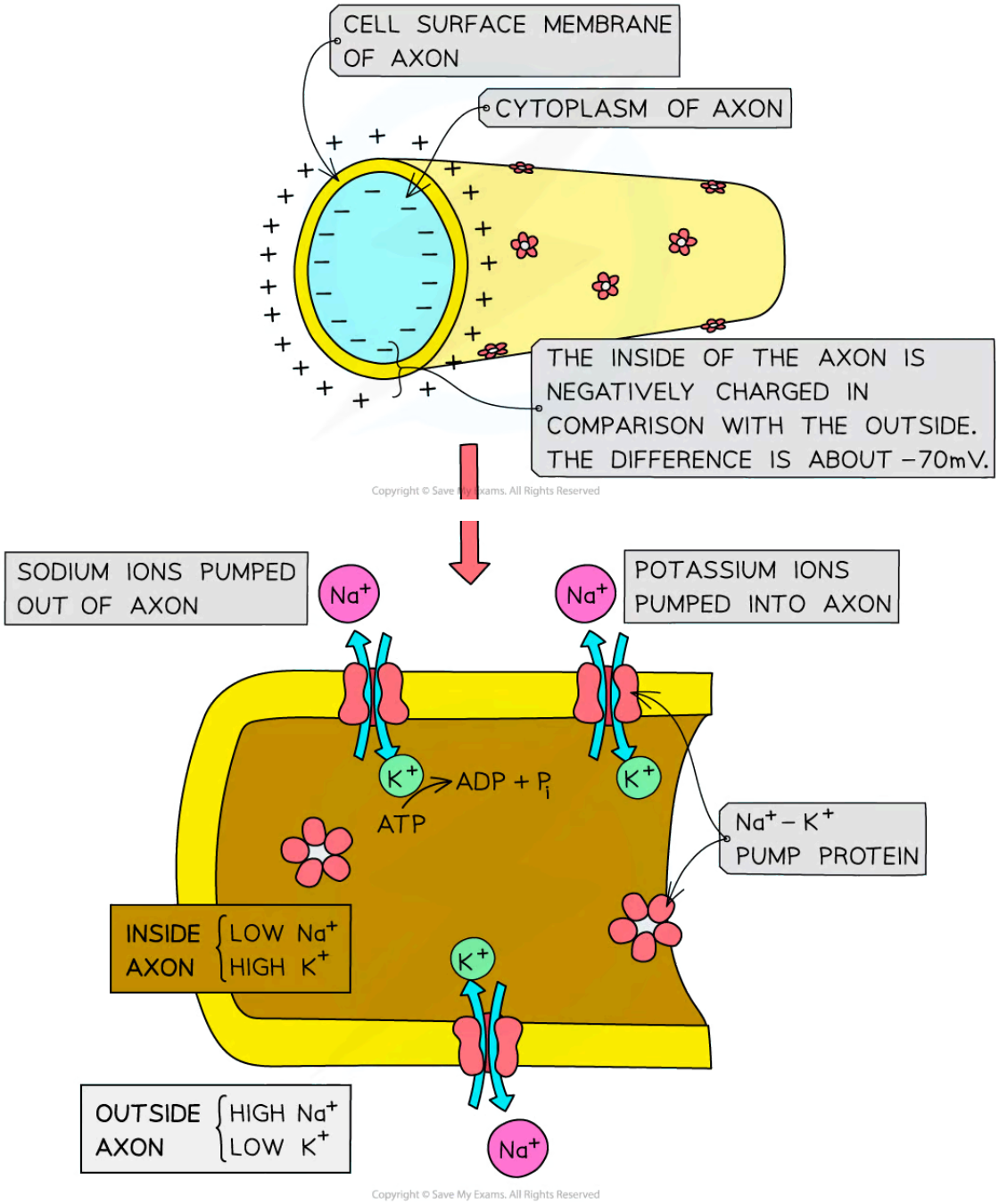
- Carrier proteins called sodium-potassium pumps are present in the cell surface membranes of neurones
- These pumps use **ATP** to actively transport **sodium ions** (Na^+) **out** of the axon and **potassium ions** (K^+) **into** the axon
- The two types of ion are pumped at an unequal rate; for every **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**

- 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)**

Your notes



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

Action Potential


Your notes

- 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

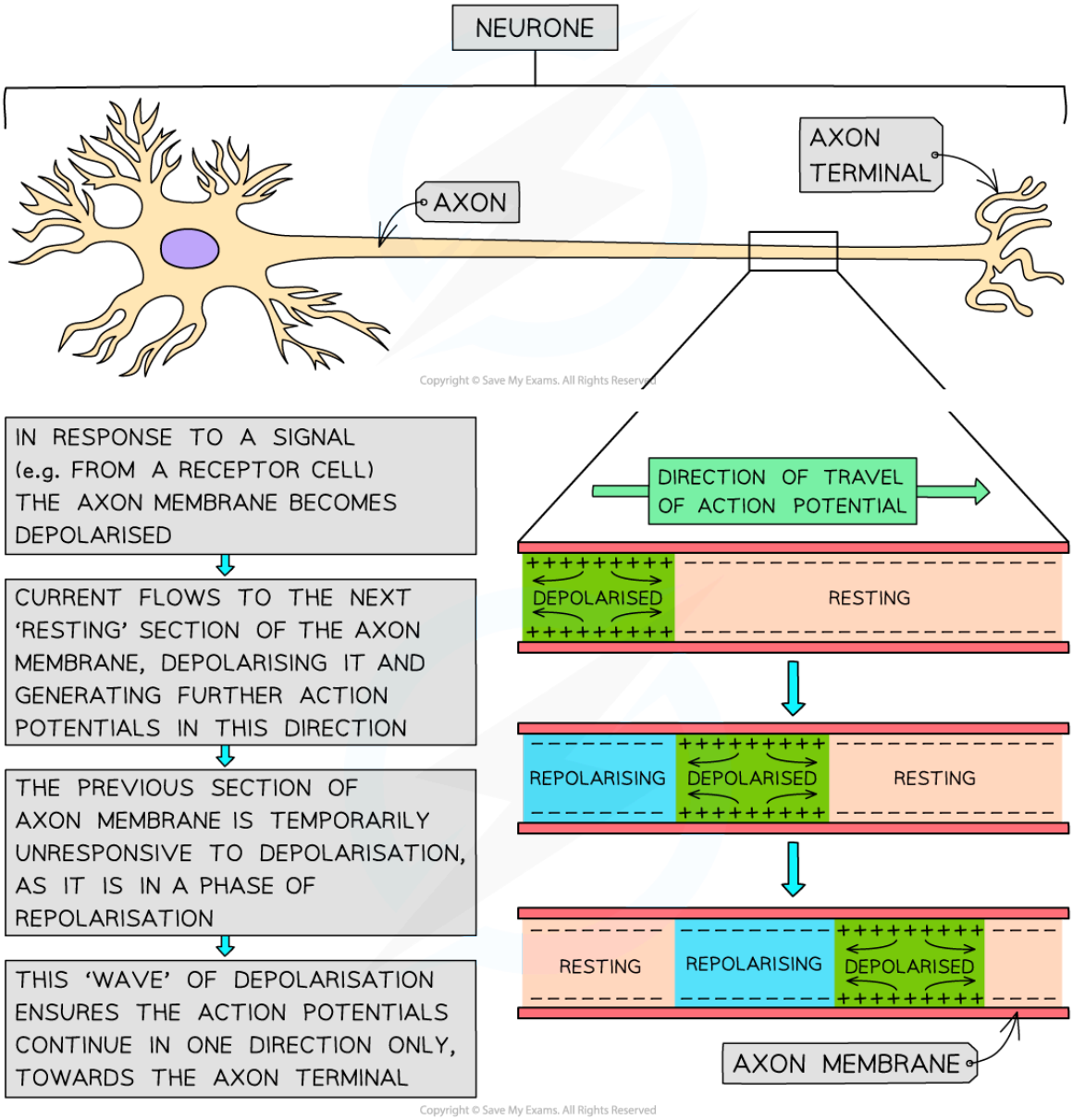
- Some of the ion channels in the membrane of a neurone are **voltage gated**, meaning that they open and close in response to changes in the **electrical potential** across the membrane
  - Voltage gated ion channels are **closed** when the membrane is at rest, but they are involved in the generation 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

Your notes



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

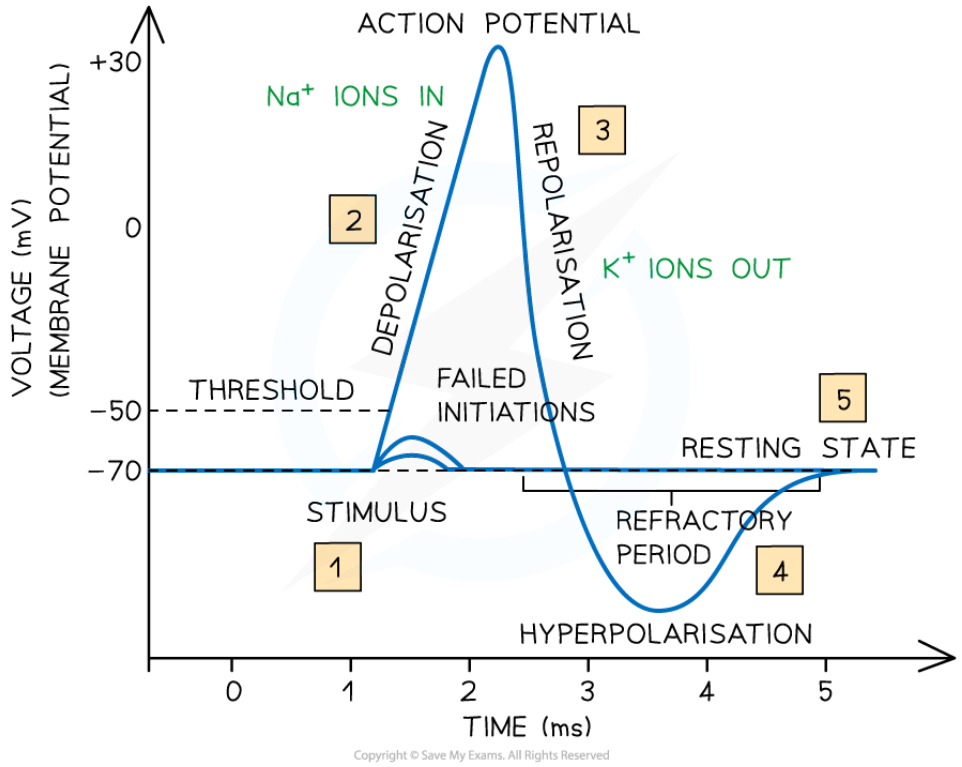
Repolarisation

Your notes

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

Your notes

Threshold Potential

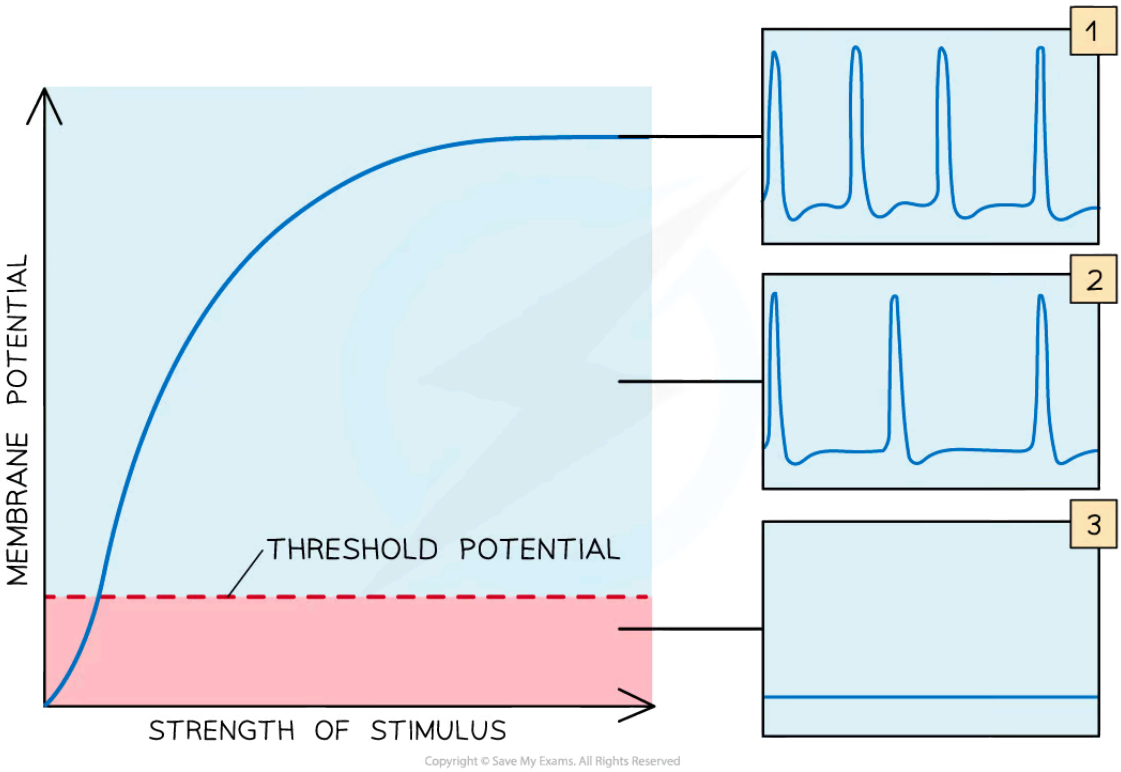

Your notes

- 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



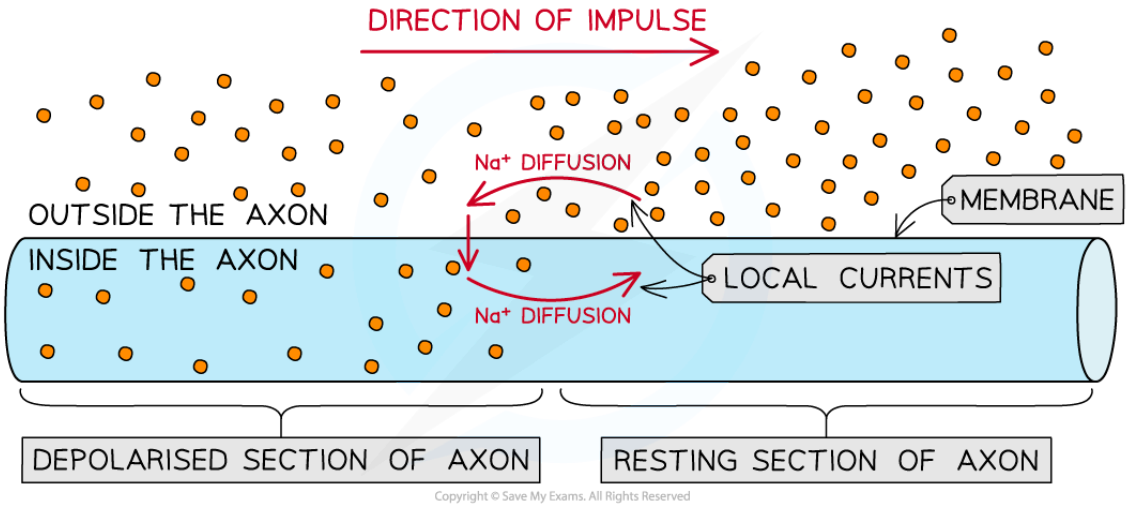
1	THE MEMBRANE IS GIVEN A STRONG STIMULUS WHICH GENERATES A HIGH FREQUENCY OF ACTION POTENTIALS
2	THE MEMBRANE IS GIVEN A WEAK STIMULUS WHICH GENERATE A LOW FREQUENCY OF ACTION POTENTIALS
3	THE MEMBRANE IS GIVEN A VERY WEAK STIMULUS WHICH FAILS TO GENERATE AN ACTION POTENTIAL

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

Local Currents

Your notes

- 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**



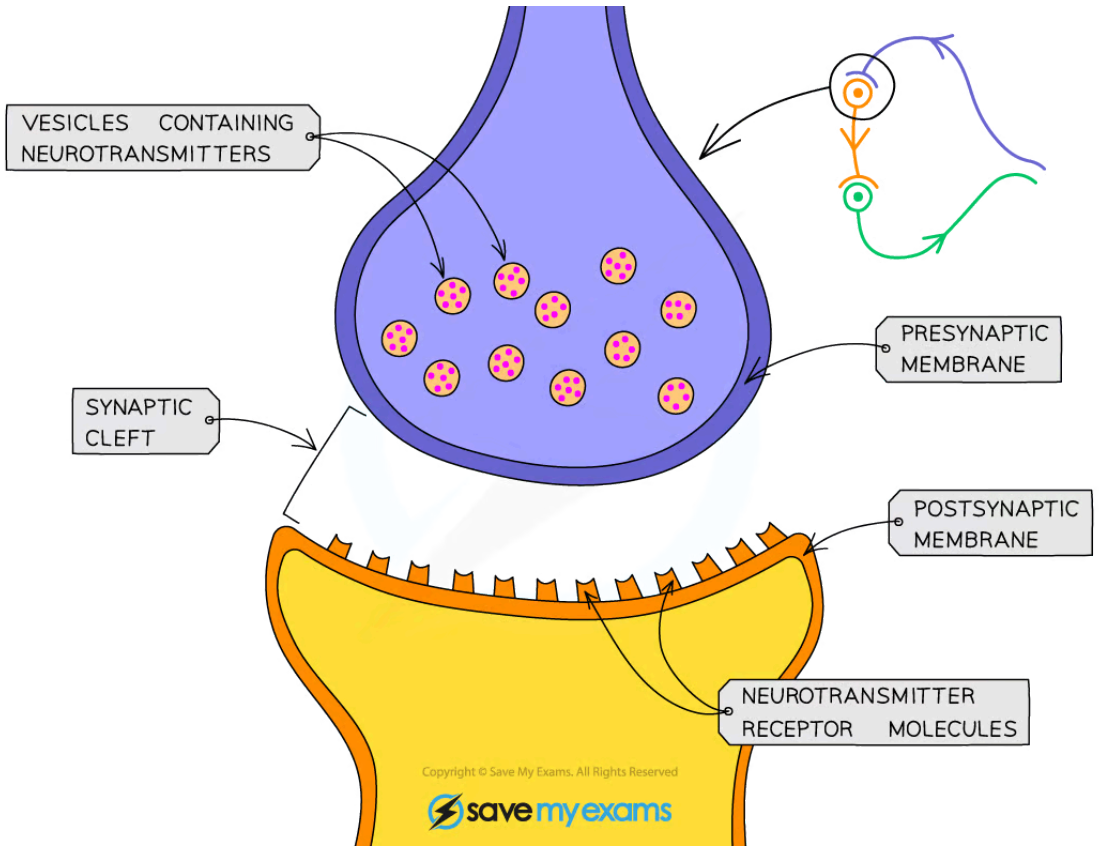
The propagation of nerve impulses along axons occurs due to local currents created by the diffusion of sodium ions

6.5.3 Synapses

Your notes

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

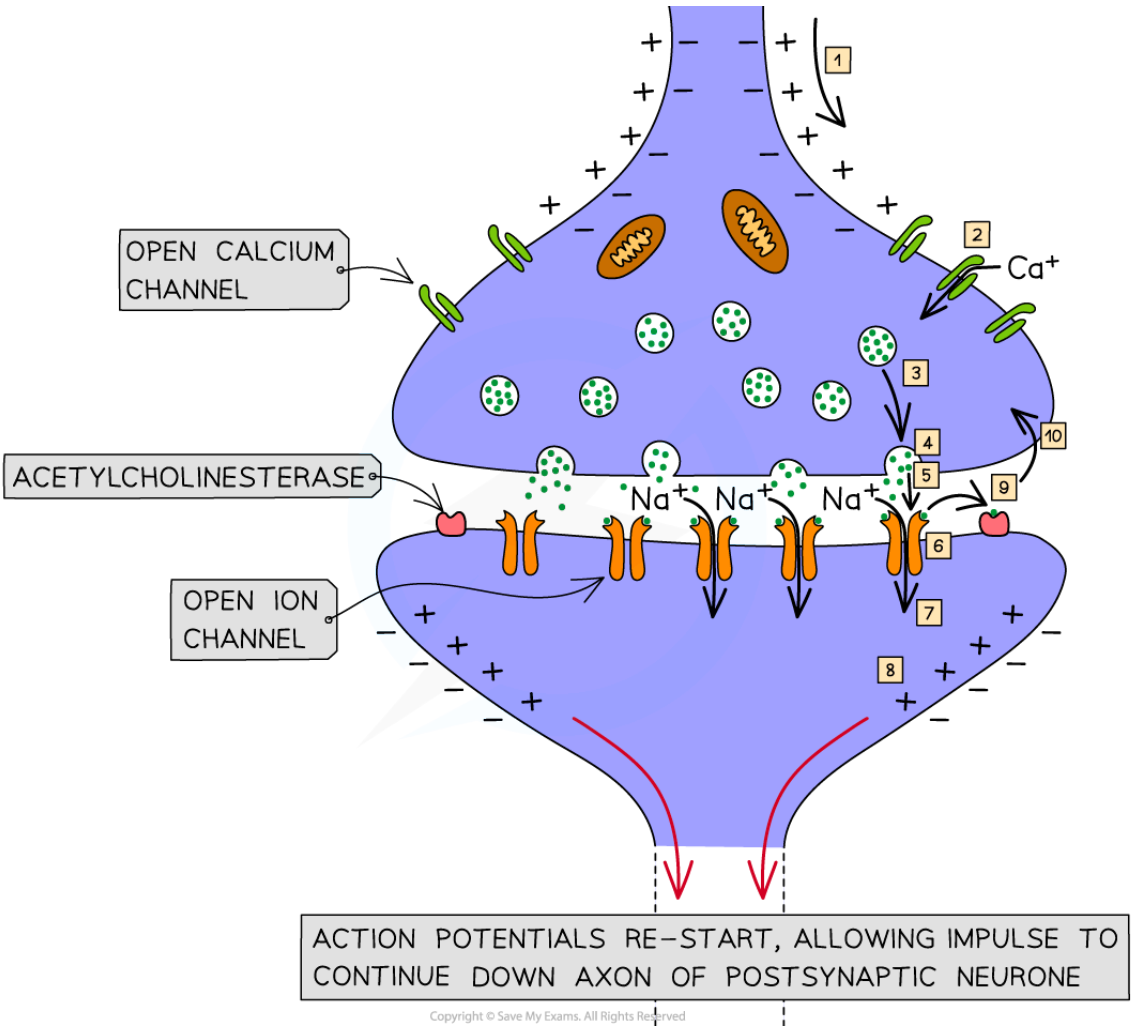
Synaptic transmission

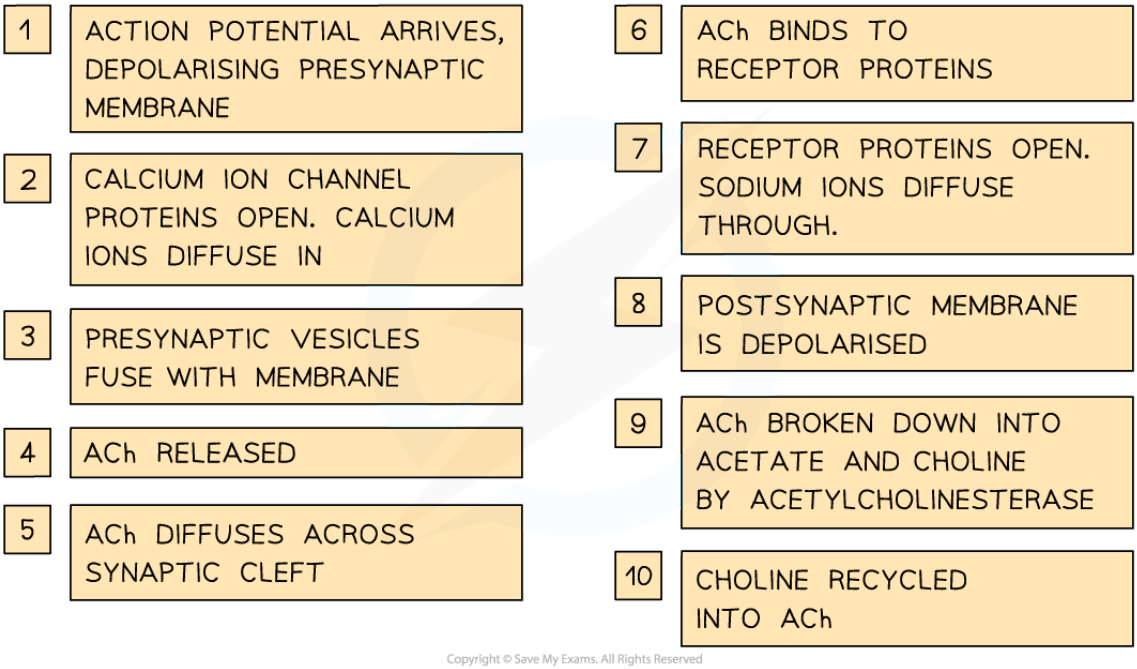
- Electrical impulses cannot 'jump' across the synaptic cleft

- 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
- 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**


Your notes

Your notes





Synaptic transmission using the neurotransmitter acetylcholine

Your notes

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

Acetylcholine

Your notes

- 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 combing **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

6.5.4 Skill: Neurones & Synapses

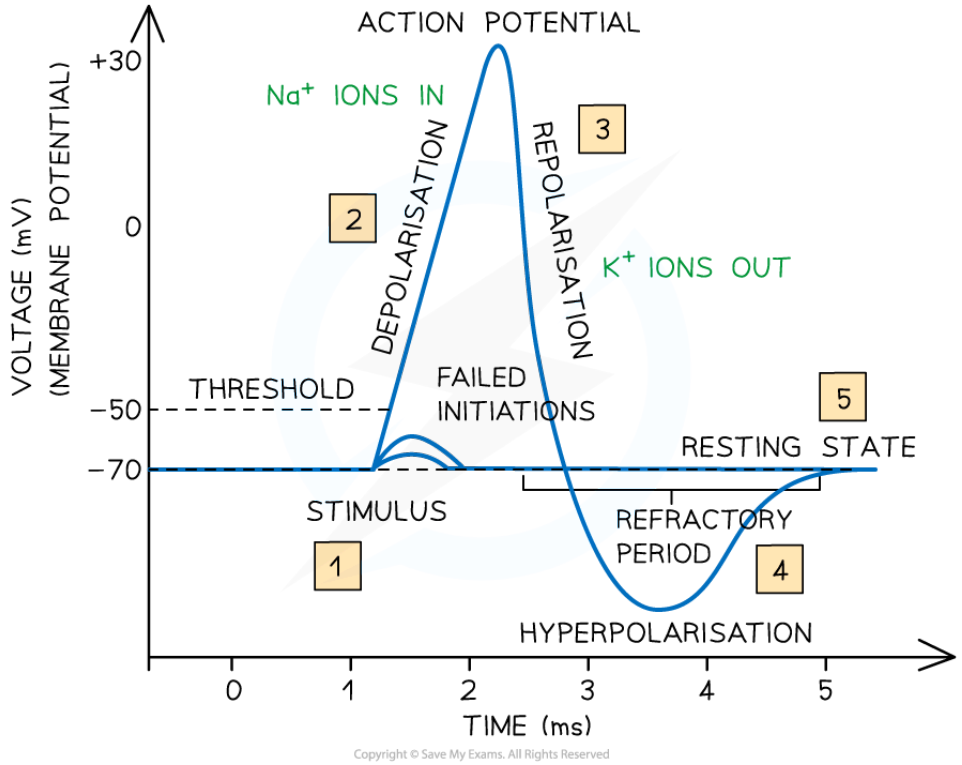
Your notes

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



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

Your notes