REVISION GUIDE

How a *nerve* says go

Neural signalling

Touch something hot and the news reaches your brain in a fraction of a second, as a string of identical electrical blips running along your nerve cells. Where one cell meets the next, each blip becomes a puff of chemical that crosses a gap and starts the next cell's signal.

17 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-c2-2-neural-signalling

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By the end you can

- [ ] Describe a neuron and say what its cell body, axon and dendrites are for C2.2.1
- [ ] Explain how pumping sodium and potassium ions across the membrane makes the resting potential, and why the inside is negative C2.2.2
- [ ] Explain a nerve impulse as an action potential that moves along a nerve fibre, and why that is electrical C2.2.3
- [ ] Explain how a threshold and voltage-gated sodium and potassium channels depolarize and repolarize the membrane C2.2.8
- [ ] Explain how local currents make an action potential travel along an axon C2.2.9
- [ ] Read resting potentials, action potentials and impulses per second off an oscilloscope trace C2.2.10
- [ ] Compare the speed of impulses in giant squid axons, small unmyelinated fibres and myelinated fibres, and use r and R squared on speed data C2.2.4
- [ ] Explain how saltatory conduction from node to node makes impulses faster C2.2.11
- [ ] Describe a chemical synapse and say why a signal crosses it one way only C2.2.5
- [ ] Explain how an impulse makes calcium enter a presynaptic terminal and neurotransmitter leave it C2.2.6
- [ ] Explain how acetylcholine crossing the cleft generates an excitatory postsynaptic potential C2.2.7
- [ ] Explain how neonicotinoids and cocaine change synaptic transmission C2.2.12
- [ ] Explain how an inhibitory neurotransmitter hyperpolarizes the postsynaptic membrane C2.2.13
- [ ] Explain how excitatory and inhibitory inputs add up to an all-or-nothing response C2.2.14
- [ ] Explain how free nerve endings in the skin start the signal that the brain perceives as pain C2.2.15
- [ ] Explain consciousness as a property that emerges from many interacting neurons C2.2.16

Tick each one when you can do it without the book.

C2.2.1 NEURONS AS CELLS WITHIN THE NERVOUS SYSTEM THAT CARRY ELECTRICAL IMPULSES

01 One cell, *built to signal*

Before you read on, sketch a nerve cell from memory and label what you can. Then check it against the figure.

A **neuron** is a single cell, with a nucleus and cytoplasm like any other, but drawn out into long thin threads. The part with the nucleus is the **cell body**. From it run **nerve fibres** of two kinds: many short, branched **dendrites**, and one long **axon**.

KEY POINTS

- **Dendrites receive.** Signals from other neurons arrive on the dendrites and the cell body.
- **The axon sends.** It carries **impulses** away from the cell body, as far as a metre, and branches at its end into terminals that pass the signal to the next cell.
- **The signal is electrical.** Impulses are conducted along the fibres as electrical changes in the membrane, which is what the next few chapters are about.

Why so long and thin? A signal has to cross the body in a fraction of a second, and one cell that reaches the whole way can carry it without a single hand-over. Neurons come in three kinds, by where they carry the signal: sensory neurons bring it in from the sense organs, relay neurons in the brain and spinal cord pass it between neurons, and motor neurons take it out to the muscles and glands. C3.1 puts them together into a reflex. A *nerve*, the cord you can see in a dissection, is a bundle of hundreds or thousands of these fibres from many neurons, wrapped together.

KEY TERMS

neuron
A nerve cell: a cell of the nervous system that carries electrical impulses along its fibres.

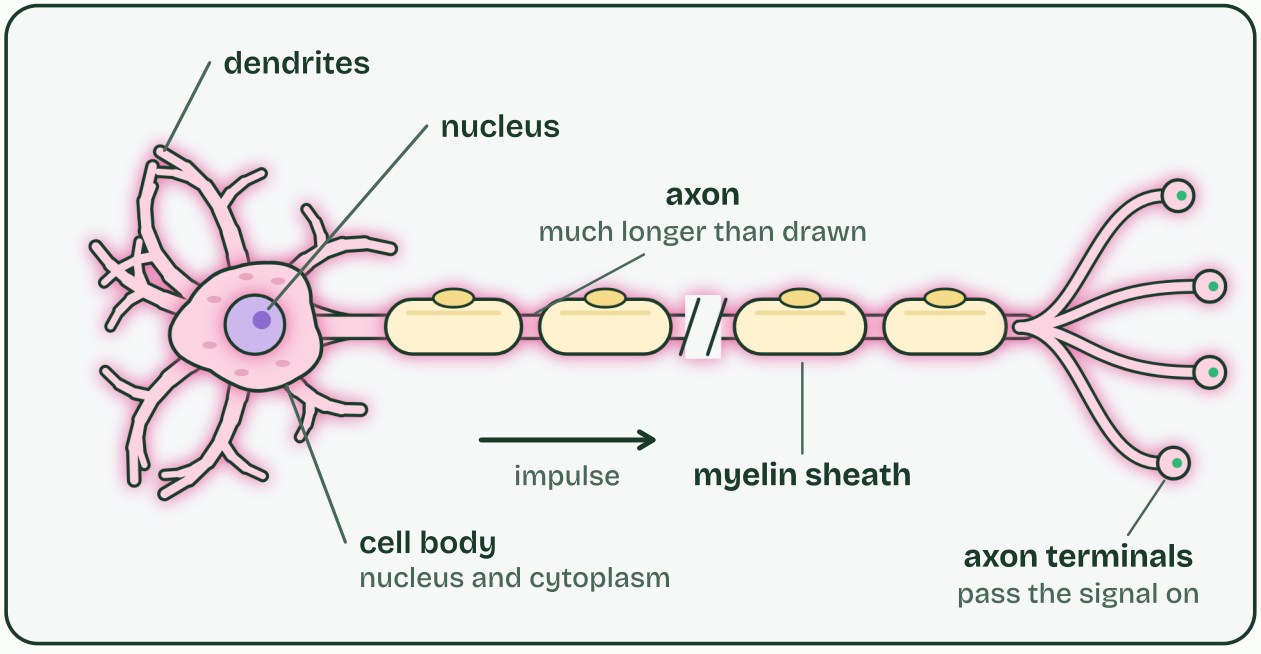
cell body
The part of a neuron that holds the nucleus and most of the cytoplasm and organelles. The nerve fibres project from it.

nerve fibres
Long thin projections of a neuron, along which impulses are conducted: its axon and its dendrites.

dendrites
The short, branched fibres of a neuron, which receive signals from other cells.

axon
The single long fibre of a neuron, which carries impulses away from the cell body to its terminals.

impulses
An electrical signal conducted along a nerve fibre: an action potential.



Dendrites Many short, branched fibres that receive signals from other neurons and carry them in towards the cell body.

Cell body The part of the neuron with the nucleus and most of the cytoplasm and organelles. The fibres project from it.

Myelin sheath A fatty wrapping round many axons, made by other cells, which makes impulses faster (chapter 7). The short bare gaps between the wrappings are nodes.

Axon The one long fibre that carries impulses away from the cell body. It can be very long: it is much longer than drawn here.

Nucleus In the cell body, as in any cell: it holds the neuron's DNA.

Axon terminals The ends of the axon's branches, which pass the signal to the next cell at a synapse (chapter 9).

PREDICT

The motor neuron that moves a toe muscle has its cell body in the lower spinal cord. Where is its axon?

(A) In a chain of short neurons that hand the signal on, one after another, from the cord to the foot

(B) Inside the spinal cord, where it passes the signal to a different cell that runs to the foot

(C) Running all the way from the cord to the toe muscle, one thread about a metre long in a tall adult

(D) In the spinal cord too: a short axon stays in the cord, and long dendrites reach down the leg to the toe

Decide before you look. Answer on page 72.

WATCH OUT

"A neuron is a nerve." A nerve is a bundle of fibres from many neurons; a neuron is one cell. "An axon is made of many cells." It is part of one cell. "Dendrites carry the impulse away." Dendrites receive; the axon sends.

C2.2.2 GENERATION OF THE RESTING POTENTIAL BY PUMPING TO ESTABLISH AND MAINTAIN CONCENTRATION GRADIENTS OF SODIUM AND POTASSIUM IONS

02 A battery *before any signal*

A neuron that is not sending an impulse is not idle. Across its membrane there is a voltage, the **membrane potential**, of about −70 mV: the inside is 70 thousandths of a volt more negative than the outside. That is the **resting potential**, and a membrane with a voltage across it is **polarized**. (This guide uses British spelling, but follows the IB's own *z* in polarized, depolarization, repolarization and hyperpolarized.)

The voltage comes from a pump. The **sodium-potassium pump** uses the energy of one ATP to push three sodium ions (Na^+) out and bring two potassium ions (K^+) in, both against their **concentration gradients** (B2.1 has the pump's cycle). Millions of pumps on every neuron, working all the time, leave:

KEY POINTS

- **Sodium high outside**, about ten times as concentrated as inside.
- **Potassium high inside**, twenty to forty times as concentrated as outside.
- **More positive charge outside.** Three positive ions go out for every two that come in, so each turn of the pump leaves the inside a little more negative.
- **Negative charges that cannot leave.** The inside is full of large negatively charged molecules, proteins and others, that are far too big to cross the membrane.

The membrane also lets potassium leak back out through channels that stay open, far more easily than it lets sodium leak in. Each K^+ that leaves takes a positive charge out and leaves a negative one behind. In most neurons this leak sets most of the −70 mV; the pump's own uneven 3 for 2 adds a few millivolts, and its real job is to keep the gradients that the leak and every impulse run down. Exam answers can give the pump's account and the leak: it uses ATP, it moves three Na^+ out and two K^+ in, K^+ leaks back out far more easily than Na^+ leaks in, and the inside is left negative.

KEY TERMS

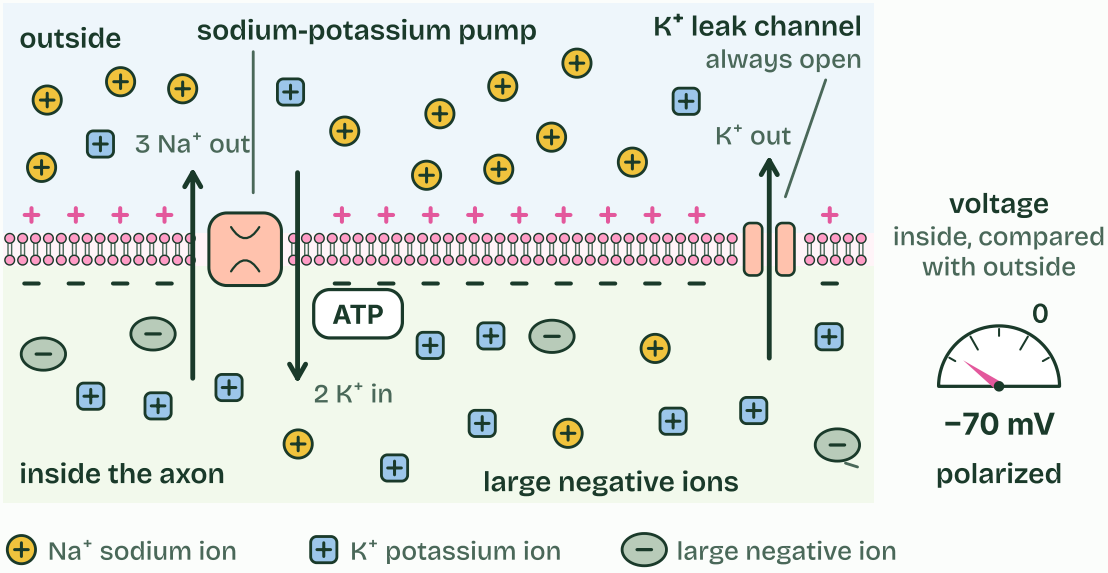
membrane potential
The voltage across a cell's plasma membrane: the inside compared with the outside, in millivolts (mV).

resting potential
The membrane potential of a neuron that is not sending an impulse: about -70 mV, the inside negative.

polarized
Having a difference in charge across it, one side more positive than the other. The IB spells it with a z.

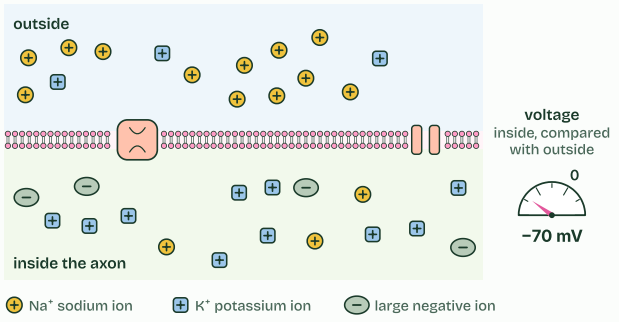
sodium-potassium pump
A protein in the plasma membrane that uses the energy of one ATP to move three sodium ions out of the cell and two potassium ions in, both against their concentration gradients.

concentration gradients
A difference in concentration between two places. Ions diffuse down it, from where they are more concentrated to where they are less, if they can cross.


outside
sodium-potassium pump
K⁺ leak channel
always open
3 Na⁺ out
K⁺ out
ATP
2 K⁺ in
inside the axon
large negative ions
voltage
inside, compared with outside
0
−70 mV
polarized
Na⁺ sodium ion
K⁺ potassium ion
large negative ion

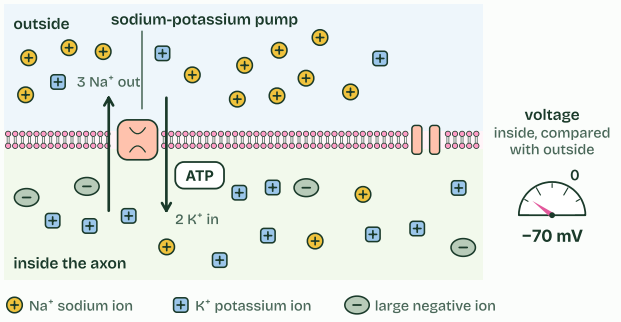
STEP BY STEP
5 STEPS

1



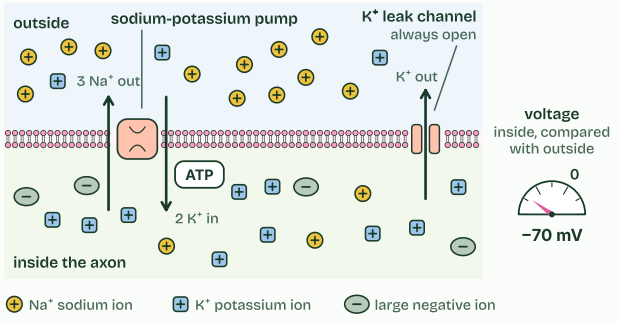
A resting neuron's membrane, much enlarged: **sodium** ions crowd the fluid outside, **potassium** ions the cytoplasm inside, and the dial reads about −70 mV.

2



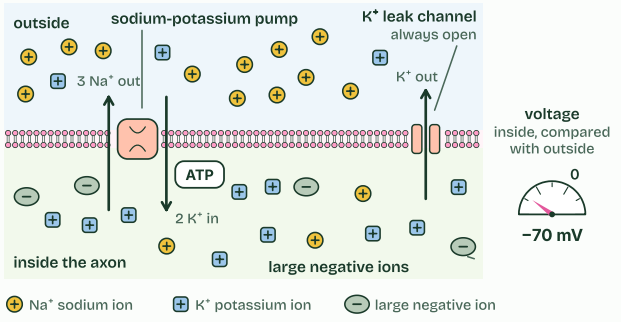
The **sodium-potassium pump** uses one ATP to move three Na^+ out and two K^+ in, both against their gradients. It never stops.

3



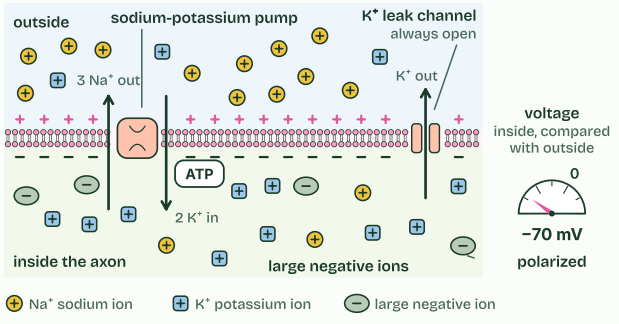
Potassium **leaks** back out through channels that are always open; sodium can barely leak in. Each K^+ that leaves takes a positive charge out.

4



Large **negative ions**, mostly proteins, are trapped inside: they are far too big to cross the membrane.

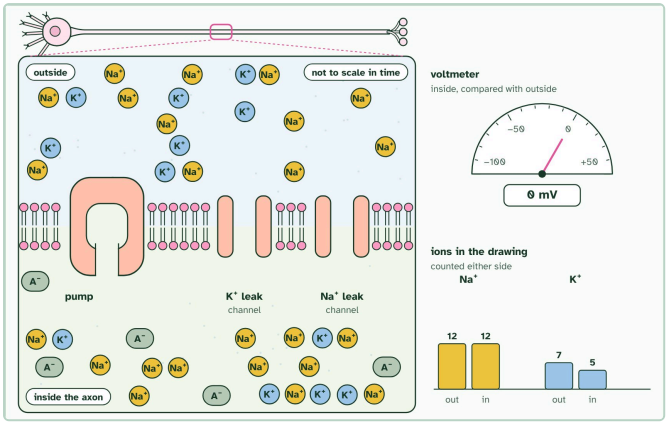
5



The result: more positive charge outside, more negative inside. The membrane is **polarized**, at about −70 mV: the resting potential.

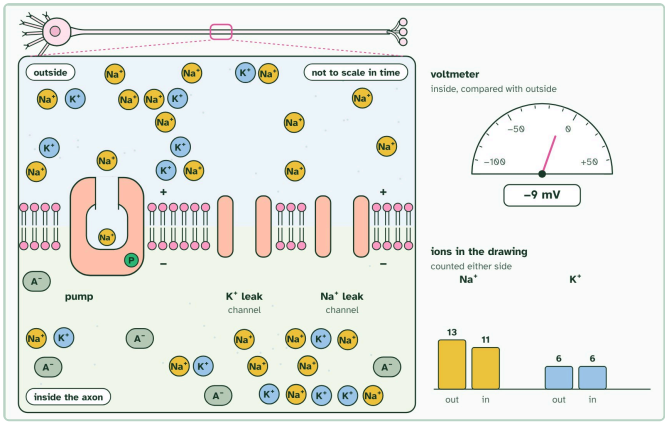
ANIMATION · A BATTERY BEFORE ANY SIGNAL
5 MOMENTS

1 0 MV



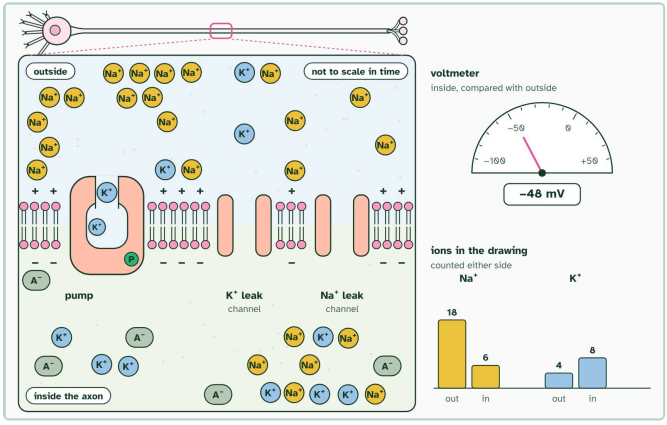
A patch of an axon's membrane, zoomed in. Suppose Na^+ and K^+ were spread the same on both sides: ions cross both ways, and there is no voltage across it.

2 −9 MV



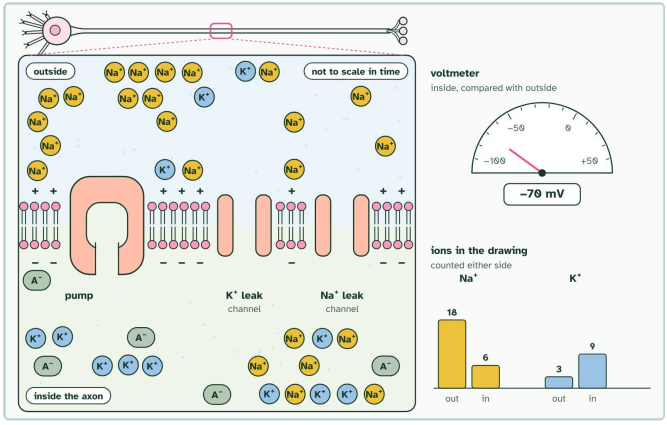
The **sodium-potassium pump** uses one ATP to move 3 Na^+ out and 2 K^+ in, against their gradients. Each turn moves more positive charge out than in.

3 −48 MV



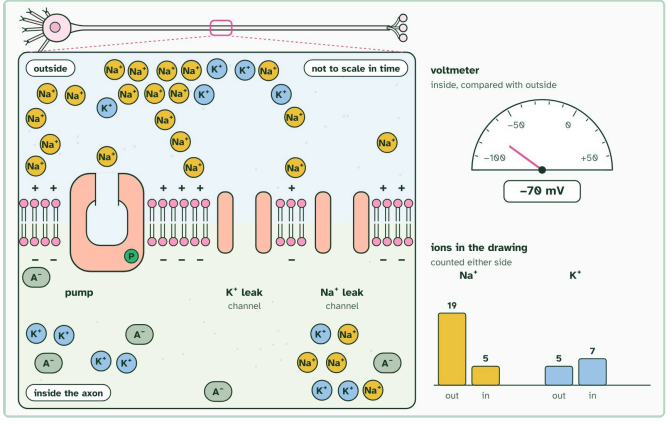
K^+ leaks back out through open **leak channels** far more easily than Na^+ leaks in. The large anions inside cannot follow, so the inside is left negative.

4 −70 MV



About **−70 mV** inside: the **resting potential**. The membrane is **polarized**, and only a tiny share of the ions had to cross to make it.

5 −70 MV



At rest a little Na^+ still leaks in and K^+ leaks out, so the pump keeps working, using ATP, and the resting potential holds.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#resting

PREDICT

A neuron's pumps are all switched off and it is left alone. What happens to the voltage across its membrane over a long time?

(A) It jumps straight to +70 mV, because sodium floods in with nothing at all to stop it

(B) It stays at −70 mV for good, because the charge is fixed by the lipids in the membrane

(C) It grows more negative, because potassium keeps leaking out and nothing brings it back in

(D) It runs slowly down towards zero, as the ions leak across and the gradients fade away

Decide before you look. Answer on page 72.

WATCH OUT

"The pump moves ions down their gradients." It moves both against them, which is why it needs ATP. "The inside is negative because it has extra electrons." No electrons cross: the negative charge is on large molecules that cannot leave. "A membrane potential is the same as a concentration difference." The gradients cause it, but the potential is a voltage, a difference in charge.

03 A blip *that travels*

C2.2.3 NERVE IMPULSES AS ACTION POTENTIALS THAT ARE PROPAGATED ALONG NERVE FIBRES

A nerve impulse is an **action potential**: for about a millisecond, one short stretch of membrane flips its voltage, the inside turning positive, then flips back. While it is reversed, that stretch sets off the same reversal in the stretch next to it, and so the impulse is **propagated** along the fibre.

Why is it electrical? Because the ions that move are charged. When a stretch fires, positively charged sodium ions rush in across the membrane, and that reverses the voltage; then positively charged potassium ions flow out and the voltage goes back to rest. Moving charge is an electric current, so a nerve impulse is electrical even though no electrons run along the axon. Turning the inside less negative is called **depolarization**.

KEY POINTS

- **Ions cross, they do not travel.** Each sodium ion moves a few millionths of a millimetre, through the membrane, near where it started. What travels is the reversal.
- **It does not fade.** Each stretch makes a full impulse of its own, so a signal from your toe reaches your spine as big as it set off.
- **Every impulse is alike.** One neuron's impulses are all the same size; a strong stimulus sends more of them each second, not bigger ones.

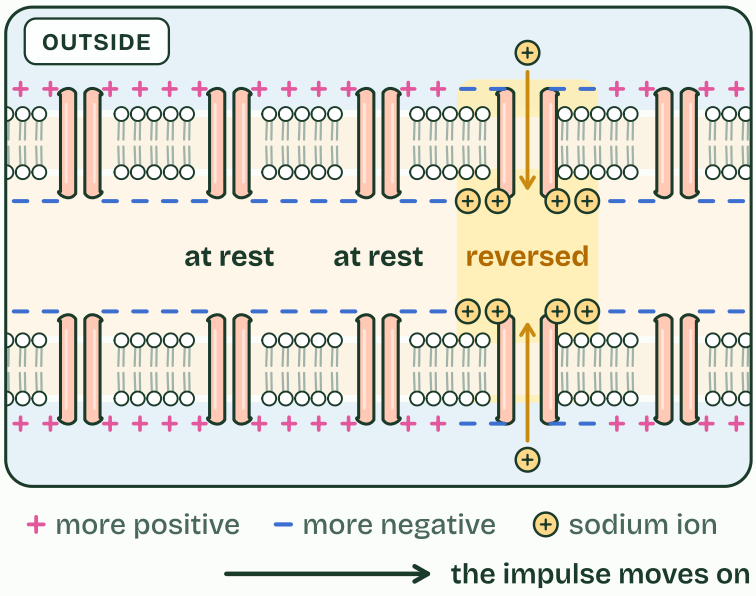
How the membrane flips and flips back, through channels that open at a certain voltage, is higher level (chapter 4). So is the current that carries the reversal from one stretch to the next (chapter 5).

KEY TERMS

action potential
A brief reversal of the membrane potential at one place on a nerve fibre, which sets off the same reversal in the next stretch of membrane: a nerve impulse.

propagated
Passed on along a nerve fibre, each stretch of membrane setting off the next.

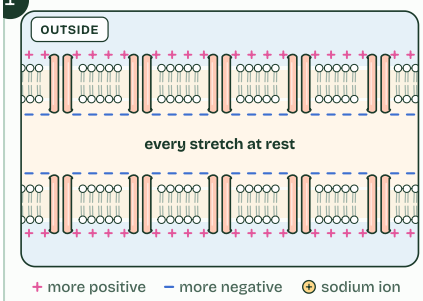
depolarization
A change in membrane potential that makes the inside less negative than at rest, and in an action potential positive.



STEP BY STEP

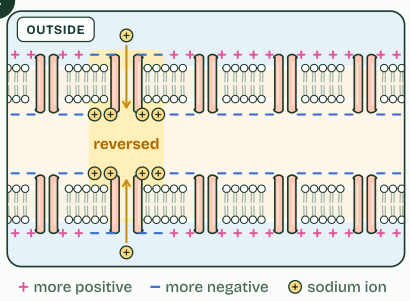
4 STEPS

1



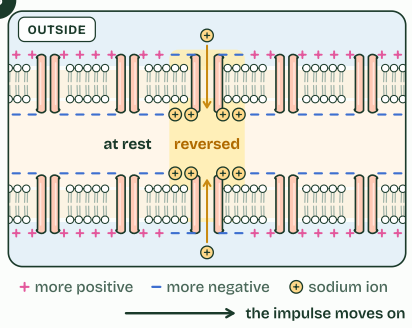
A resting axon, cut along its length: **positive** outside the membrane and **negative** inside, all the way along.

2



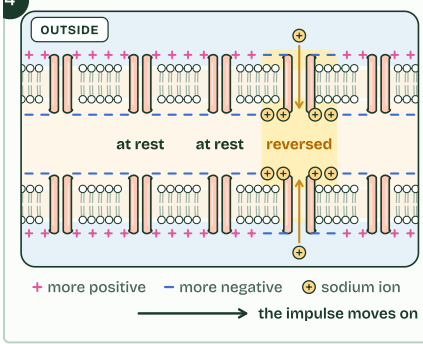
A stimulus: sodium ions rush **in** at one stretch, and its charge is **reversed**, positive inside.

3



That stretch sets off the next one, and goes **back to rest** itself. The reversal has moved on.

4

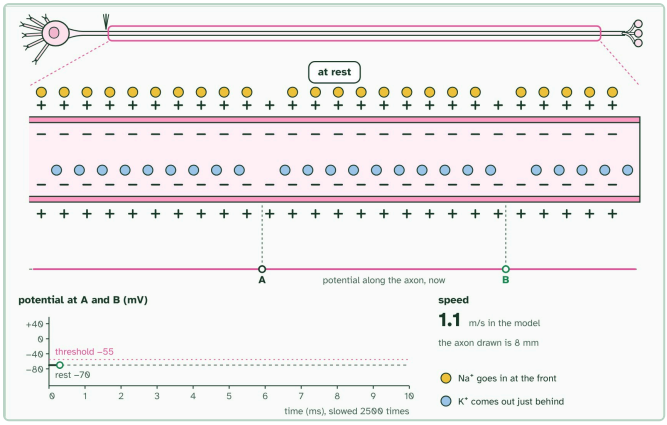


And the next, and the next: the reversal **travels** along the axon, stretch by stretch.

ANIMATION · AN IMPULSE TRAVELS

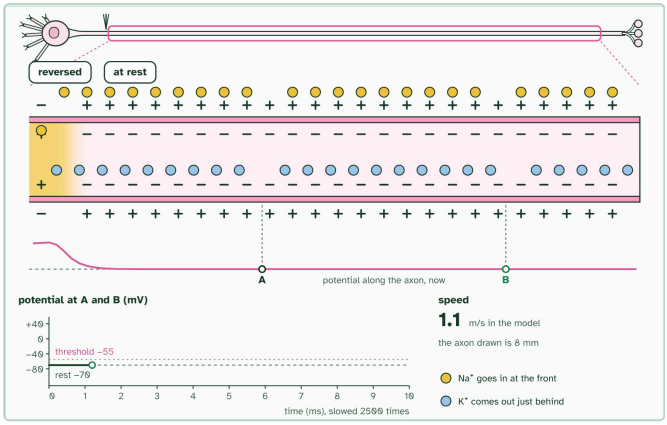
7 MOMENTS

1 AT REST



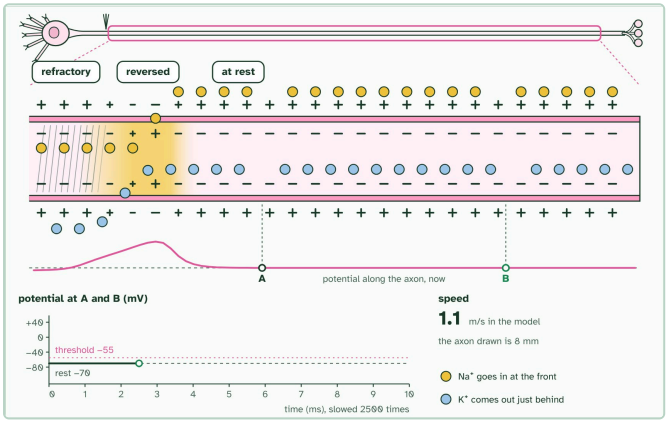
An axon at rest. Along its whole length the outside is positive and the inside negative: the membrane is polarized.

2 IMPULSE 3% ALONG



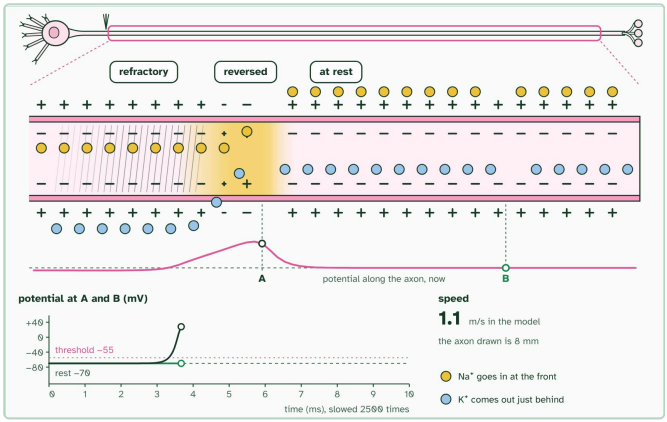
A stimulus at the left end. There the membrane **reverses**: Na^+ ions enter, and the inside becomes positive. This is an **action potential**.

3 IMPULSE 19% ALONG



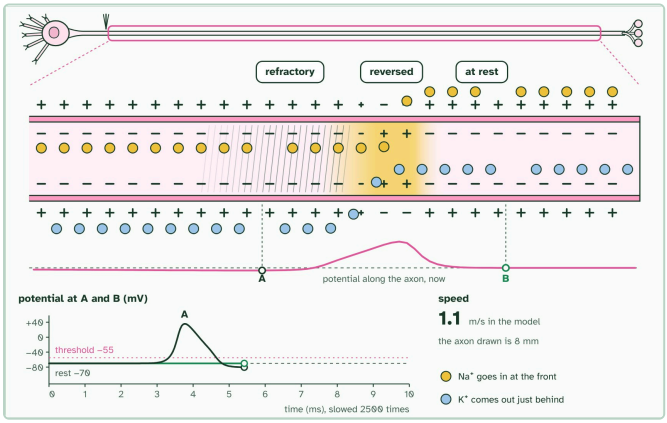
Na^+ that has entered spreads along inside the axon, and positive charge outside flows back towards it: these **local currents** depolarizing the next stretch to its threshold, and it fires in turn.

4 IMPULSE 35% ALONG



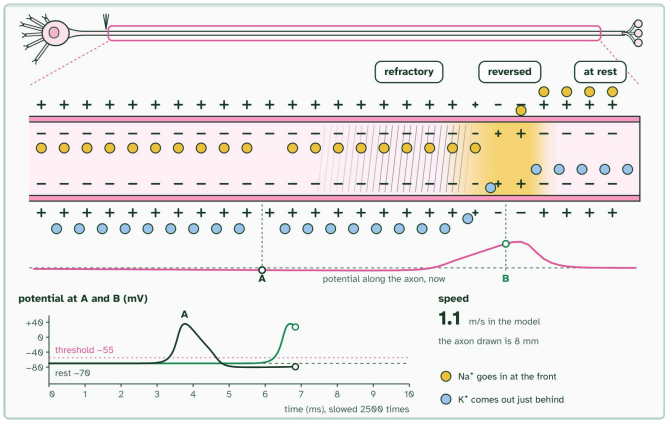
The front reaches A: Na^+ rushes in there, the charges turn over and the potential at A shoots up. Just behind the front, K^+ flows out and the inside turns negative again.

5 IMPULSE 59% ALONG



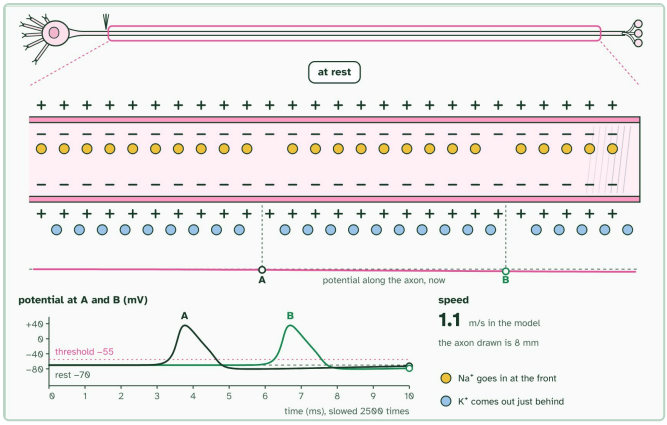
Behind the impulse the membrane recovers, but for a moment it cannot fire again: it is **refractory** (hatched). So the impulse only goes forward.

6 IMPULSE 79% ALONG



At B, further along, the same action potential happens again, later: the same rise and fall at every point of the axon, one after another.

7 PASSED



The impulse reaches the end of the axon just as big as it started, because each stretch of membrane makes a fresh one.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#impulse

PREDICT

An impulse sets off along an axon a metre long. Compared with where it started, how big is it when it reaches the far end?

(A) Much smaller, because it loses energy all the way along, as a current does in a long wire

(B) Just as big, because every stretch of membrane it reaches makes a fresh impulse of its own

(C) Larger, because more and more of the axon has joined in by the time it reaches the far end

(D) Smaller only in a thin axon, because a thin membrane leaks more of the charge along the way

Decide before you look. Answer on page 72.

WATCH OUT

"An impulse is electrons flowing along the axon, as in a wire." It is ions crossing the membrane, a fresh change at every stretch. "The sodium ions travel the length of the axon." They cross the membrane where they are; only the reversal moves along.

04 The shape of *an action potential*

C2.2.8 HL DEPOLARIZATION AND REPOLARIZATION DURING ACTION POTENTIALS

An action potential has a shape, and two kinds of channel make it. Both are **voltage-gated channels**: they open when the membrane potential reaches a certain value, and they let only one kind of ion through.

KEY POINTS

- **To threshold.** A stimulus makes the inside a little less negative. If it reaches the **threshold potential**, about −55 mV, the voltage-gated sodium channels open. Below it they stay shut and the membrane falls back to rest.
- **Depolarization.** Na^+ rushes in down its concentration gradient, and towards the negative inside. Each ion that enters makes the inside less negative, which opens more sodium channels, so the potential shoots up to about +30 to +40 mV in under a millisecond.
- **Repolarization.** At the peak the sodium channels shut and cannot open again for a moment, and the slower voltage-gated potassium channels open. K^+ flows out, down its gradient, and the inside is negative again.
- **A dip, then rest.** The potassium channels close slowly, so the potential falls a little below −70 mV before it settles back.

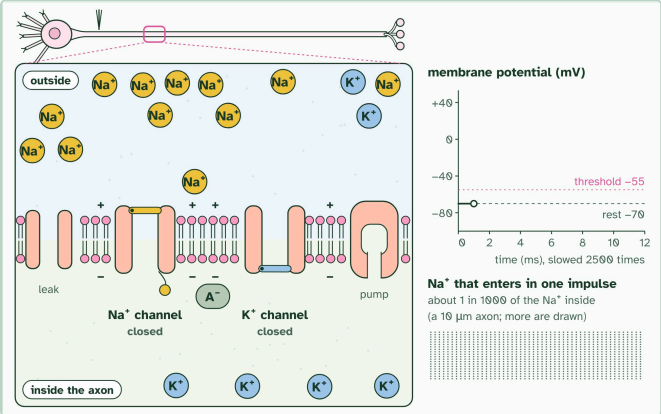
The whole spike takes one to two milliseconds. For a few milliseconds afterwards the membrane cannot fire again, or needs a much bigger stimulus, because its sodium channels are still resetting: the *refractory period* (a term you need not learn, though chapter 5 uses the idea). Very few ions cross in one impulse, far too few to change the concentrations you could measure, so a neuron can fire thousands of times before its gradients run down; the pump keeps restoring them in the background, but it plays no part in the spike itself.

KEY TERMS

voltage-gated channels
A channel protein in the membrane that opens or closes when the voltage across the membrane changes.

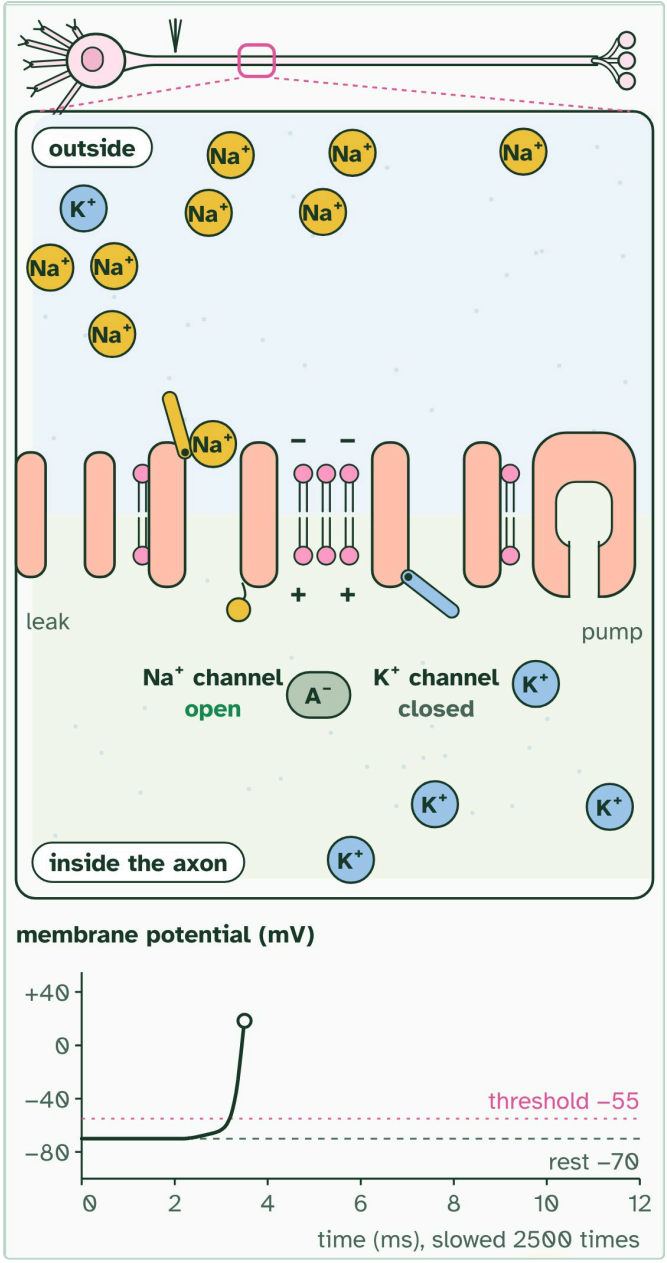
threshold potential
The membrane potential at which voltage-gated sodium channels open and an action potential starts: about -55 mV.

1 CHANNELS CLOSED



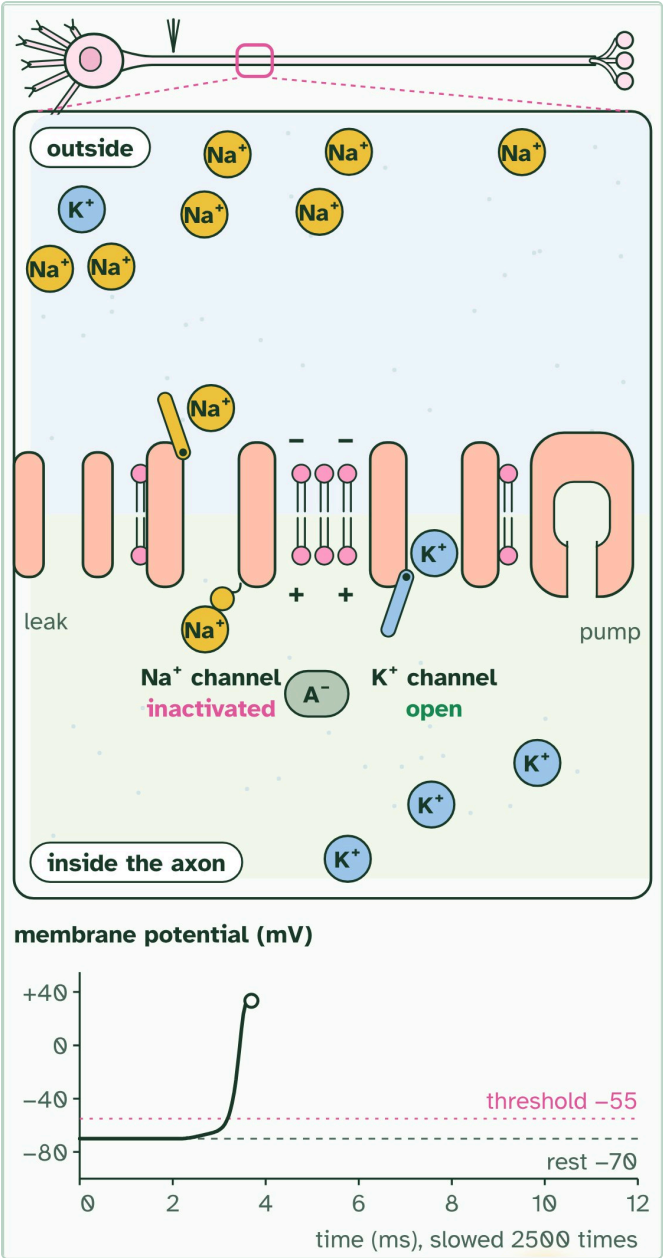
A patch of axon membrane at rest, −70 mV inside. Its **voltage-gated** Na^+ and K^+ channels are closed. A stimulus electrode sits a little way along the axon.

2 NA^+ CHANNELS OPEN



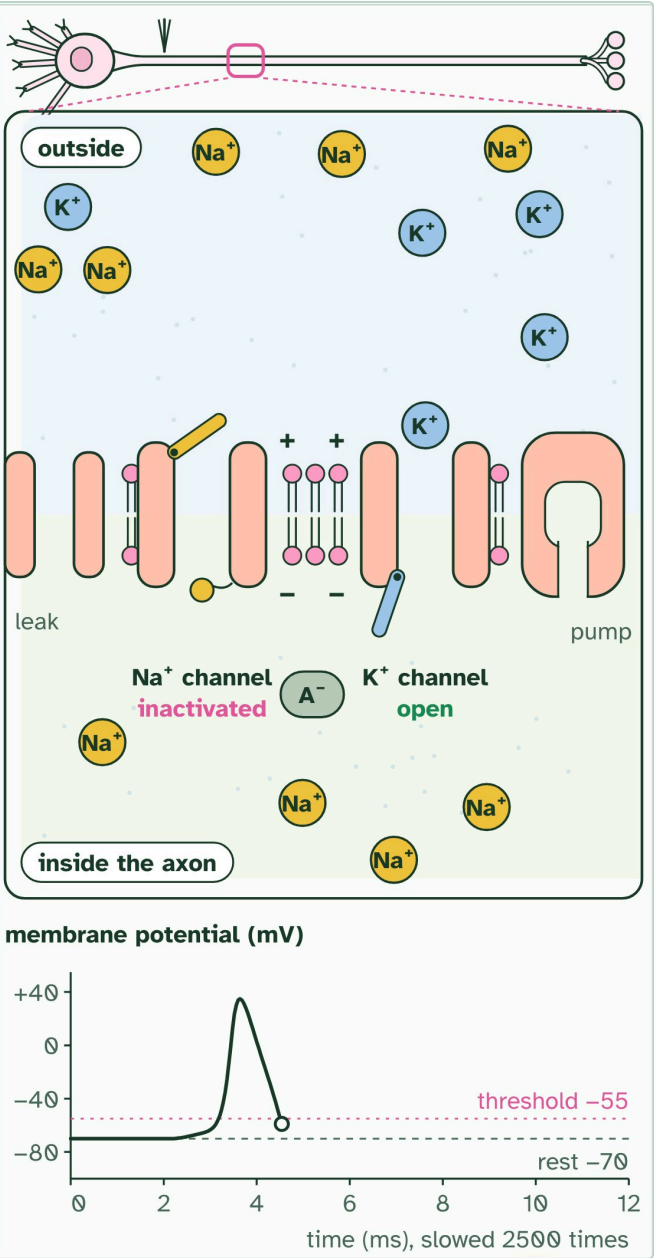
At the **threshold**, about −55 mV, the voltage-gated **Na^+ channels open**. Na^+ rushes in down its gradient, and the inside becomes positive.

3 K⁺ CHANNELS OPEN



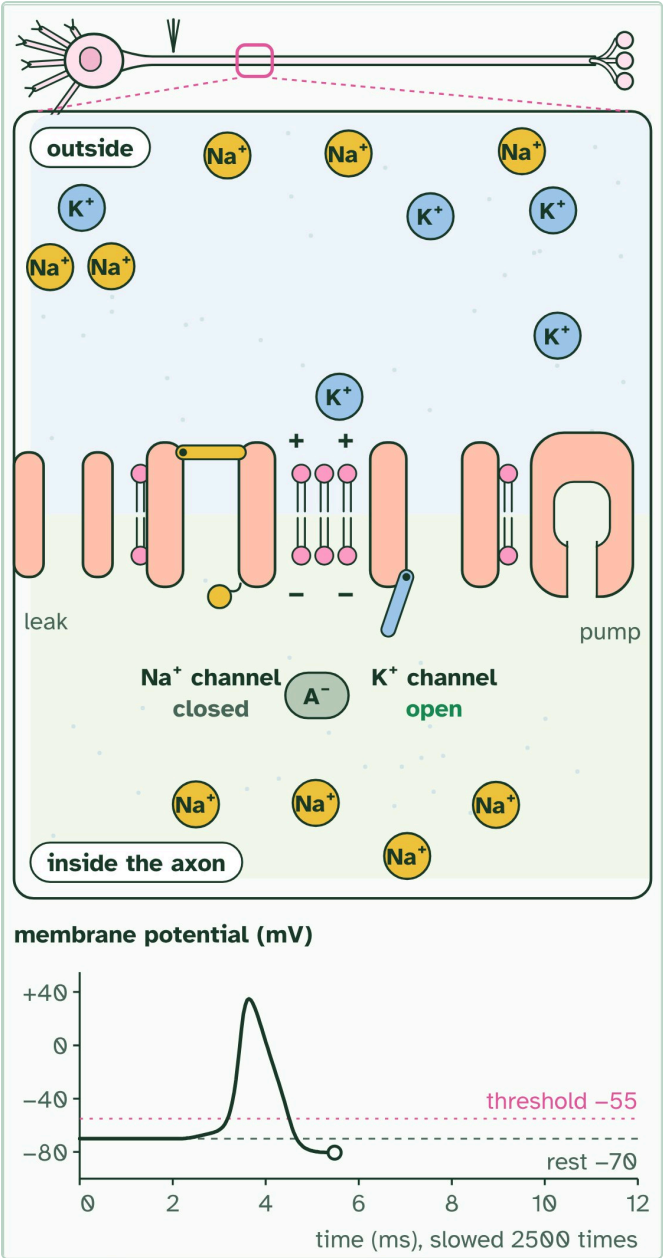
At about +35 mV the Na^+ channels close and are **inactivated**: they cannot open again at once. The voltage-gated **K^+ channels open**.

4 K⁺ CHANNELS OPEN



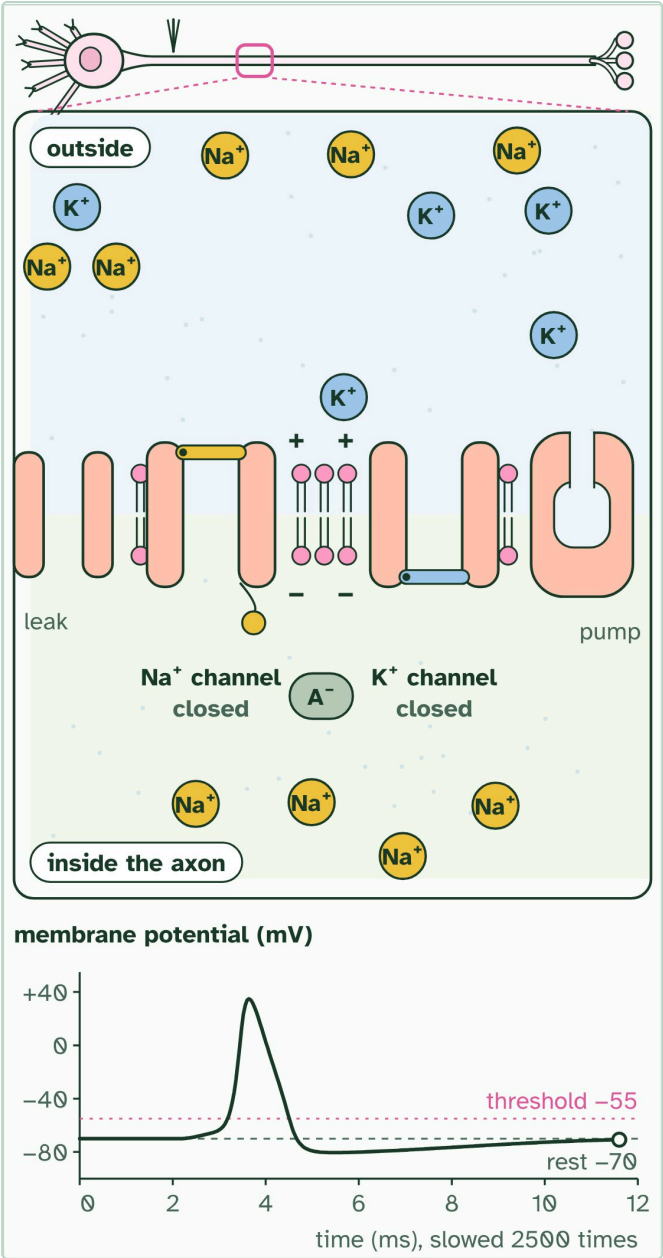
K^+ flows out down its gradient, and the inside becomes negative again: **repolarization**.

5 K⁺ CHANNELS OPEN



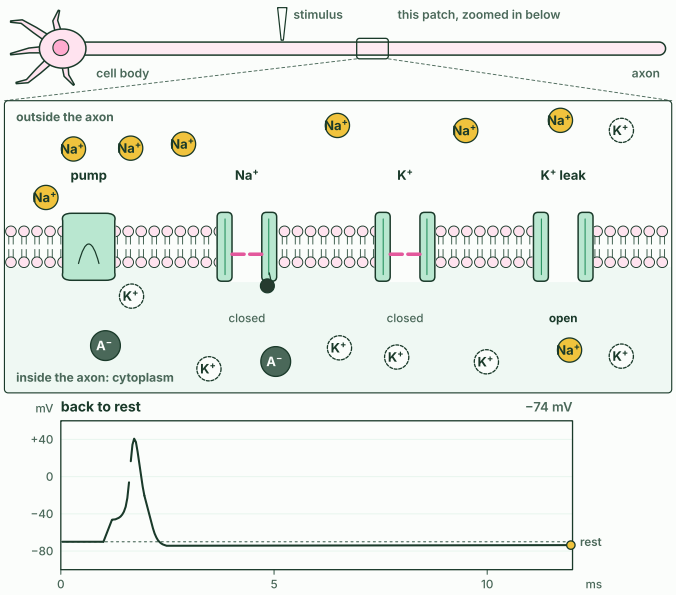
The K⁺ channels are slow to close, so for a moment the inside is more negative than at rest.

6 CHANNELS CLOSED



The K⁺ channels close and the Na⁺ channels are ready again: back to −70 mV. The pump puts back the few ions that crossed, over time.

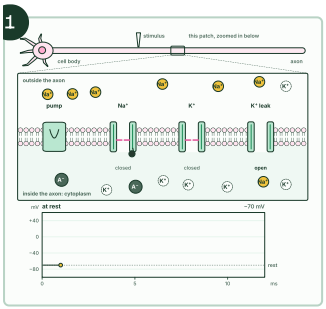
Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#threshold



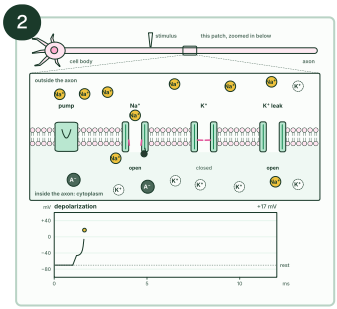
Now you are the stimulus. Find the weakest pulse that fires it, fire it twice close together, and hold a steady stimulus to count the impulses each second.

STEP BY STEP

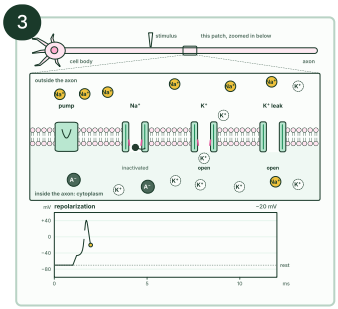
4 STEPS



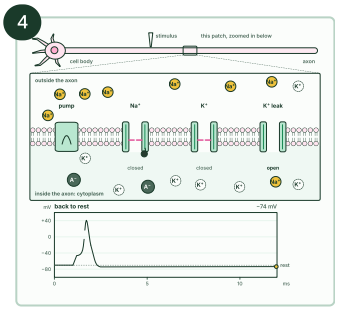
At rest the inside of the axon is about −70 mV against the outside: the **resting potential**. The pump has made sodium (Na^+) many times more concentrated outside and potassium (K^+) more concentrated inside; potassium leaks out through its leak channels.



A stimulus opens a few voltage-gated **sodium channels**. Sodium rushes in down its gradient, which opens more: the inside becomes positive, about +39 mV. This is **depolarization**.



The sodium channels close (inactivated) and the slower voltage-gated **potassium channels** open. Potassium flows out, and the inside goes negative again: **repolarization**, overshooting to about −76 mV.



The potassium channels close and the membrane settles back to −70 mV within a few milliseconds. The **sodium-potassium pump** keeps the gradients, moving three Na^+ out for two K^+ in with each ATP.

PREDICT

A stimulus just strong enough fires a neuron. A second stimulus, twice as strong, then reaches the same neuron. What does its action potential look like?

(A) Twice as tall, because twice as many sodium channels open and twice as much sodium rushes in through them

(B) The same height but twice as long, because the stimulus holds the sodium channels open longer

(C) The same size and shape, because once threshold is passed the channels make the same spike every time

(D) A little smaller, because the stronger stimulus uses up the sodium outside the membrane faster than it is replaced

Decide before you look. Answer on page 72.

REMEMBER IT

The order of one action potential

T Tickle	S Salty	P Pickles	D Dance
Threshold about −55 mV is reached	**Sodium in** depolarization, up to about +35 mV	**Potassium out** repolarization	**Dip** below rest, then back to −70 mV

WATCH OUT

"Potassium rushes in at the start." Sodium comes in first; potassium goes out. "The pump makes the spike, or pushes the sodium back out to repolarize." Channels make both halves; the pump only tops up the gradients over time. "Depolarization means the inside becomes more negative." It means the opposite: less negative, then positive.

C2.2.9 HL PROPAGATION OF AN ACTION POTENTIAL ALONG A NERVE FIBRE/AXON AS A RESULT OF LOCAL CURRENTS

05 The current that *pulls the wave on*

How does one firing stretch of axon set off the next? Through the ions it has just let in.

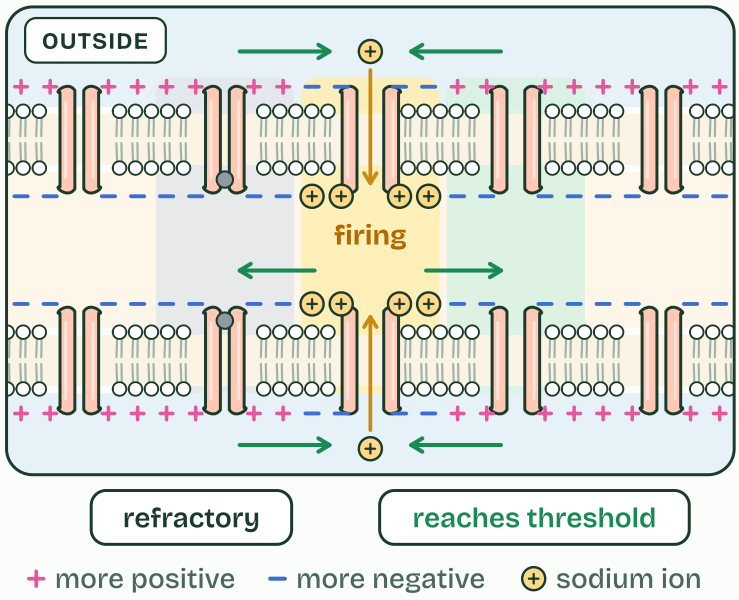
KEY POINTS

- **Sodium spreads inside.** The Na^+ that has rushed into the firing stretch diffuses along the inside of the axon towards the more negative stretches next to it.
- **And outside, the other way.** Outside the membrane, positive ions move from the resting stretches beside it towards the firing stretch, where the outside has lost its positive charge.
- **That is a local current.** Together these flows of charge make a small loop of current, a **local current**, which makes the resting membrane next door less negative.
- **Next door reaches threshold.** When that stretch reaches about −55 mV its sodium channels open and it fires in turn, and so on along the axon.

The current also spreads backwards from the firing stretch, but the stretch behind has just fired and cannot fire again yet. So the impulse moves forwards only, at the same size all the way, and each stretch fires once as it passes.

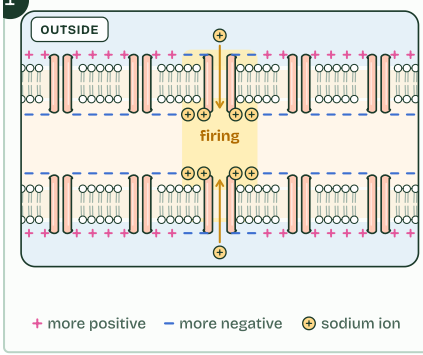
KEY TERMS

local current
The flow of ions inside and outside an axon between a stretch that is firing and the resting stretches next to it, which depolarizes them towards threshold.



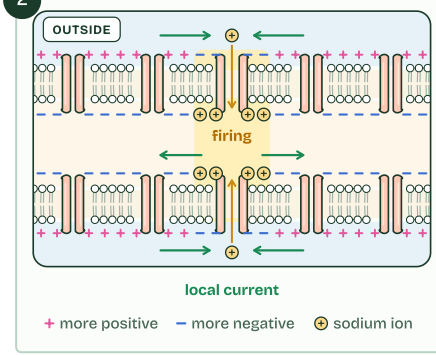
STEP BY STEP
4 STEPS

1



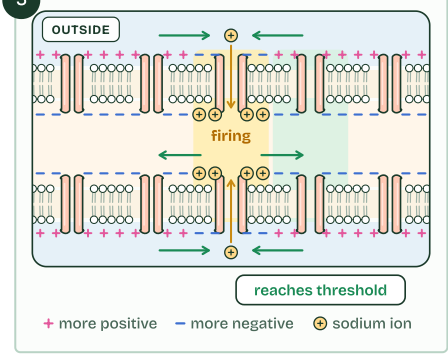
One stretch of axon is **firing**: sodium ions have rushed in, and its inside is positive.

2



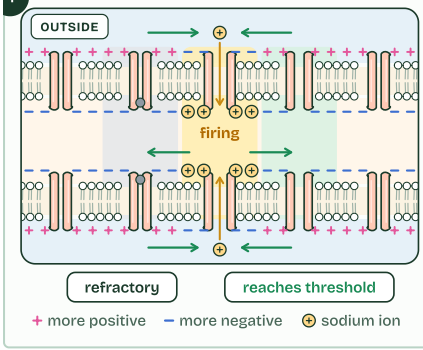
The sodium ions **diffuse along the inside**, both ways, and positive charge outside moves back towards the firing stretch: a **local current**.

3

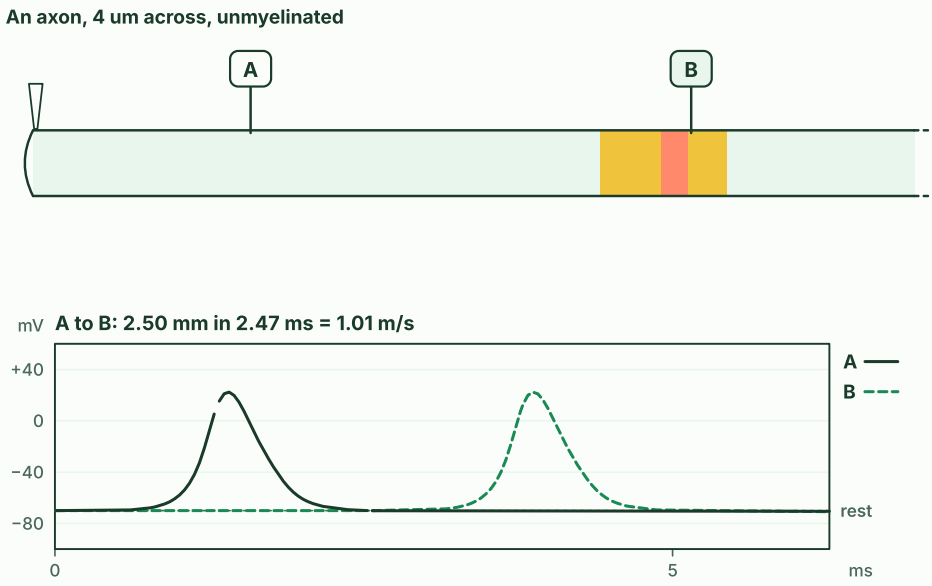


The resting stretch ahead is depolarized by it until it **reaches threshold**, about −55 mV. Its sodium channels open, and it fires.

4



The stretch behind has just fired: it is **refractory**, its sodium channels still resetting, so the impulse cannot go back.

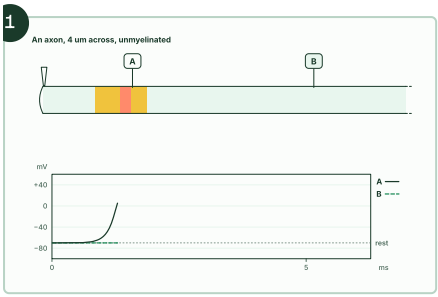


Stimulate the axon and watch the impulse travel, then switch on Local currents. Click anywhere along the axon to start an impulse there, and drag the two electrodes to time it.

STEP BY STEP

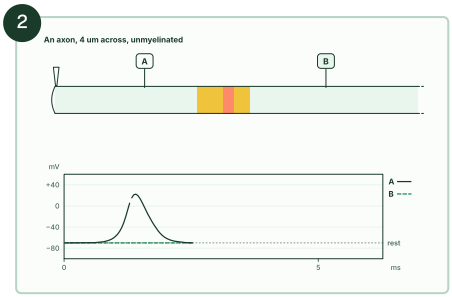
3 STEPS

1



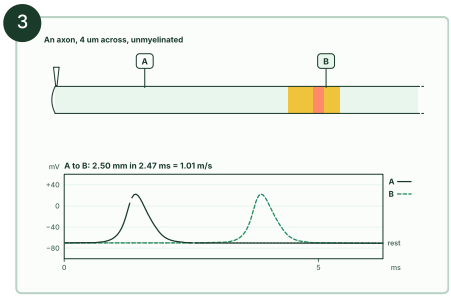
A stimulus at the left end starts an impulse. It has reached electrode **A**: the inside there is positive for a moment, and A's trace rises.

2



Positive ions spread inside the axon from the stretch firing to the stretch ahead, and outside the other way: these **local currents** bring the stretch ahead to the threshold.

3



At **B** the trace is the same impulse, 2.47 ms later. The speed is the distance from A to B over that time: 1.01 m/s for this unmyelinated axon, 4 µm across.

PREDICT

An axon is stimulated in its middle, not at one end. Which way does the impulse go?

(A) Only on towards the terminals, because an axon can only ever carry impulses in one direction, away from the cell body

(B) Both ways at once, away from the stimulus, and neither wave can turn back on itself

(C) Only back towards the cell body, because the membrane there sits a little closer to the threshold

(D) Nowhere: it stays where it started, because there is no pump in the middle to send it on its way

Decide before you look. Answer on page 72.

WATCH OUT

"The impulse moves because sodium ions flow along the whole axon." They diffuse a short way, just far enough to bring the next stretch to threshold. "An impulse only goes one way because the axon is built that way." Stimulated in the middle, an axon carries impulses both ways; one way comes from where it starts and the refractory stretch behind it.

06 Reading *the oscilloscope*

C2.2.10 HL OSCILLOSCOPE TRACES SHOWING RESTING POTENTIALS AND ACTION POTENTIALS

To record an impulse, a very fine electrode goes inside one axon and another sits in the fluid outside it. An **oscilloscope** then draws the membrane potential against time, as a line across its screen: a *trace*. Read it as a story of what the channels are doing at one place on the axon.

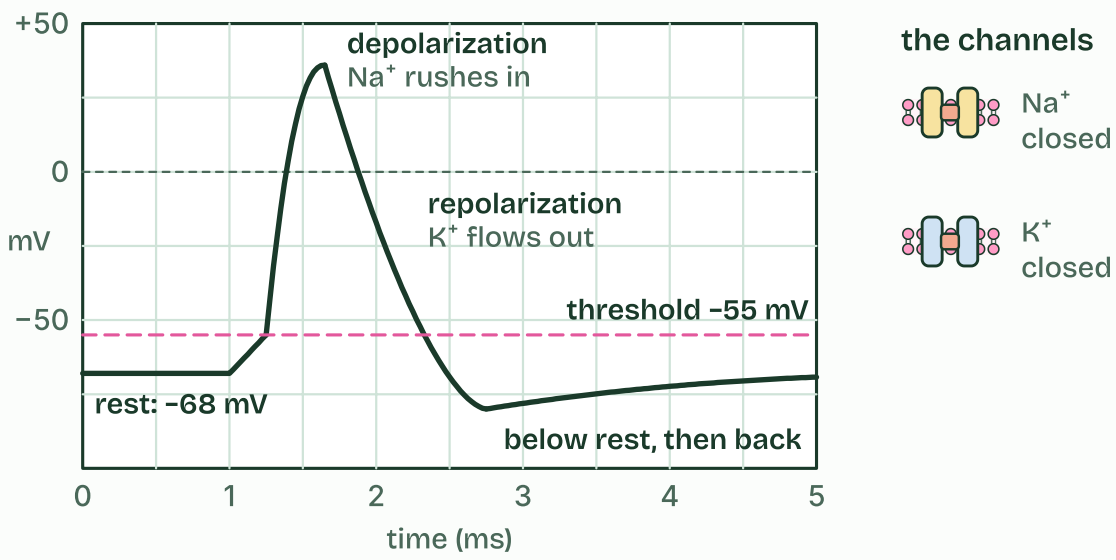
KEY POINTS

- **Flat at the bottom.** The resting potential, read off the vertical axis in millivolts. Nothing is open but the leak channels.
- **A small rise that stops.** A stimulus that never reached threshold: no sodium channels opened.
- **The steep rise.** Voltage-gated sodium channels open, Na^+ rushes in: depolarization.
- **The peak and the fall.** The sodium channels shut, potassium channels open, K^+ flows out: repolarization.
- **The dip and the return.** Potassium channels close slowly, so the trace undershoots rest, then settles.

Two numbers come off any trace. The **time** along the bottom gives how long one impulse lasts, and how far apart the spikes are; count the spikes in a stretch of trace and divide by its time for the **impulses per second**. The **voltage** up the side gives the resting potential, the peak and the depth of the dip. Always read the scale first: a scope's screen is ruled in squares, and the settings say how many milliseconds and millivolts each square is worth.

KEY TERMS

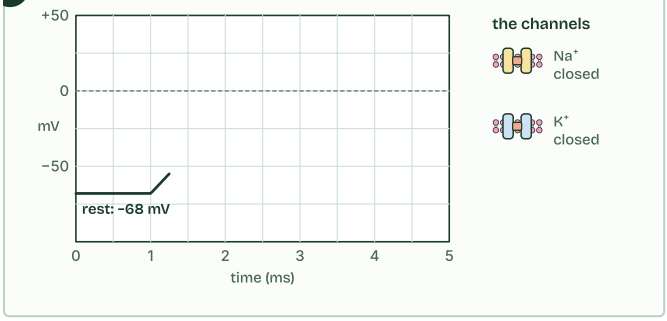
oscilloscope
An instrument that draws a voltage against time as a line across a screen.



STEP BY STEP

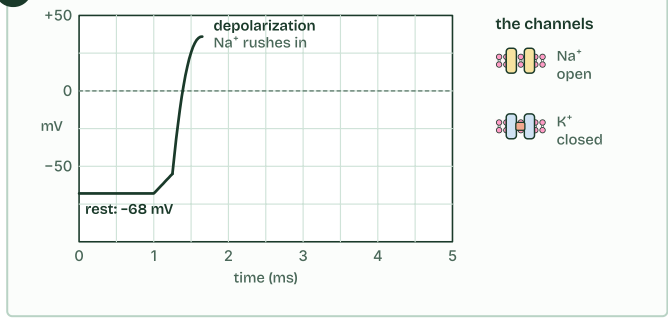
5 STEPS

1



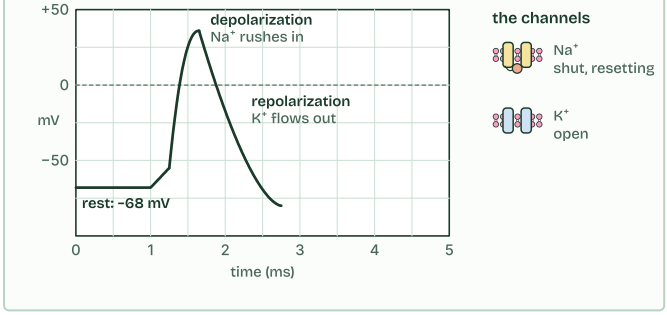
One electrode inside the axon, one outside: the screen draws the membrane potential against time. Before anything happens it sits at the **resting potential**, here −68 mV.

2



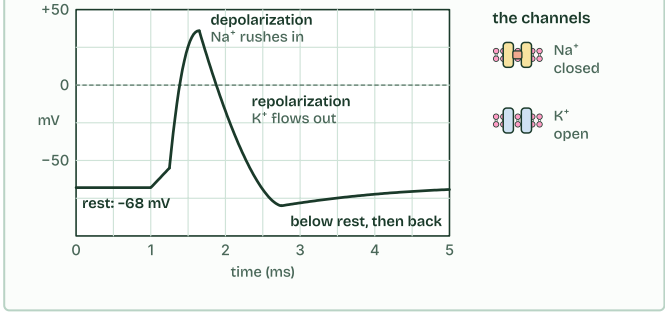
A stimulus takes it to threshold and the sodium channels open: Na^+ rushes in and the trace shoots up, past zero: **depolarization**.

3



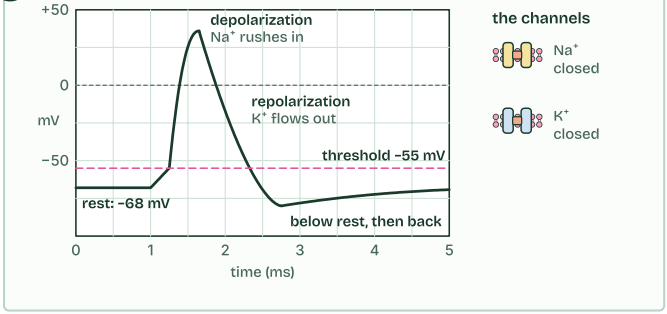
At the peak the sodium channels shut and the potassium channels open: K^+ flows out and the trace falls: **repolarization**.

4

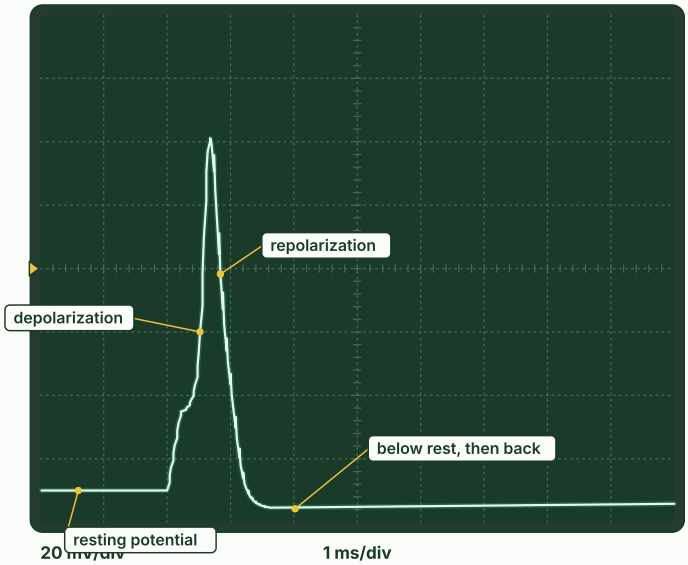


The potassium channels close slowly, so the trace **dips below rest**, then creeps back.

5



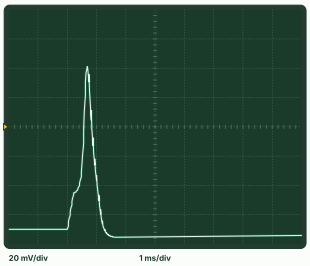
The **threshold**, here about −55 mV, is where the steep rise starts. Read the scale: the whole impulse takes about 2 ms, the return to rest a few more.



An oscilloscope with six recordings to read. Set the time and voltage per square, place the cursors to read the resting potential, the peak and the gap between spikes, and drag each label onto the part of the trace it names.

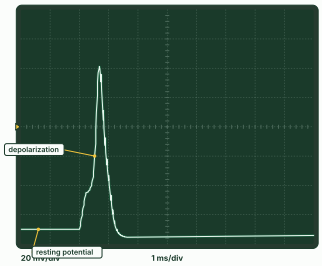
STEP BY STEP 3 STEPS

1



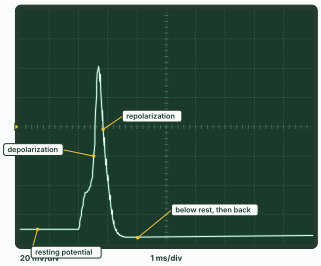
An oscilloscope trace: the potential inside a neuron against an electrode outside it, up the screen, and time across it. Each square is 1 ms across and 20 mV up; the yellow mark is 0 mV.

2



The flat start is the **resting potential**, about −70 mV (3.5 squares below 0). A stimulus takes it to the threshold, and it shoots up: **depolarization**, to about +41 mV.

3



Then **repolarization**: the potential falls, dips below the resting potential and returns to it. The impulse is over in about 2 ms.

PREDICT

A trace shows 12 identical spikes in 3 seconds. What was the rate of impulses, and what would a stronger, steady stimulus have changed?

(A) 12 impulses a second, because the number of spikes on the trace is the number each second; the rate would rise

(B) 4 impulses a second, and a stronger stimulus would have made every one of the spikes taller than before

(C) 36 impulses a second, because there are 12 spikes in each of the 3 seconds; the spikes would be taller

(D) 4 impulses a second, and a stronger stimulus would have raised that rate, with spikes of the same height

Decide before you look. Answer on page 72.

WATCH OUT

"The horizontal axis is distance along the axon." It is time, at one place. "A taller spike means a stronger signal." Spikes from one neuron are all the same height; strength is in how many come each second.

C2.2.4 VARIATION IN THE SPEED OF NERVE IMPULSES

07 Why some impulses *are quicker*

Not every impulse travels at the same speed. In the thinnest bare fibres, the ones that carry a dull ache, an impulse creeps along at about a metre a second. In the fastest, which move your muscles and tell you where your limbs are, it covers over a hundred metres a second. Many vertebrate axons are wrapped in a fatty **myelin sheath**, broken by short bare gaps; others are bare.

Two things set the speed:

KEY POINTS

- **A wider axon.** The wider the axon, the faster the impulse. A wide axon has more room inside for the local current to flow, so the current spreads further along it and brings the next stretch to threshold sooner. The squid's **giant axon**, up to about a millimetre across, carries an impulse at roughly 20 to 25 metres a second. That is twenty to forty times as fast as a small unmyelinated fibre a micrometre or so across, and it fires the squid's escape jet.
- **A myelin sheath.** A mammal's myelinated axon a hundredth of a millimetre across, at body temperature, conducts at about 50 to 60 metres a second: faster than the squid's giant one, a hundred times wider. How it does that is higher level (chapter 8).

Temperature matters too. A frog's fibres at 20 °C conduct more slowly than a mammal's of the same width at 37 °C, as the dry lab at the end of this chapter shows.

Why does it matter? A reflex, a fast run or a catch needs signals in milliseconds over a metre of nerve. A squid gets speed by making one axon enormous, which works for a few axons but would not fit a nervous system of millions. Myelin gives the same speed or more in a fibre a hundred times thinner, so a human nerve the width of a pencil can hold thousands of fast fibres.

To see the two together, race some axons of your own in *Race the impulse* under this chapter: set each one's width, wrap it in myelin or leave it bare, and watch the impulses go. The dry lab after it measures speeds the way a physiologist does, with electrodes and a stopwatch on the screen.

Reading speed data. Plot speed against axon diameter for a set of fibres and the points rise together: a *positive correlation*, where one goes up as the other does (a *negative* one would fall as the other rises). The **correlation coefficient**, r, says how strong it is: +1 is a perfect straight line rising, 0 no straight-line link at all, −1 a perfect line falling. Square it for the **coefficient of determination**, R^2: the share of the spread in speed that goes with diameter. An r of 0.9 gives $R^2 = 0.81$, so 81 per cent of the variation in speed goes with diameter, and the other 19 per cent with something else, such as temperature or the thickness of the sheath. Neither number shows that diameter causes the speed; the local current explains why it might. The IB guide's own example says conduction speed is negatively correlated with animal size and positively correlated with axon diameter. Across animals the first depends on

KEY TERMS

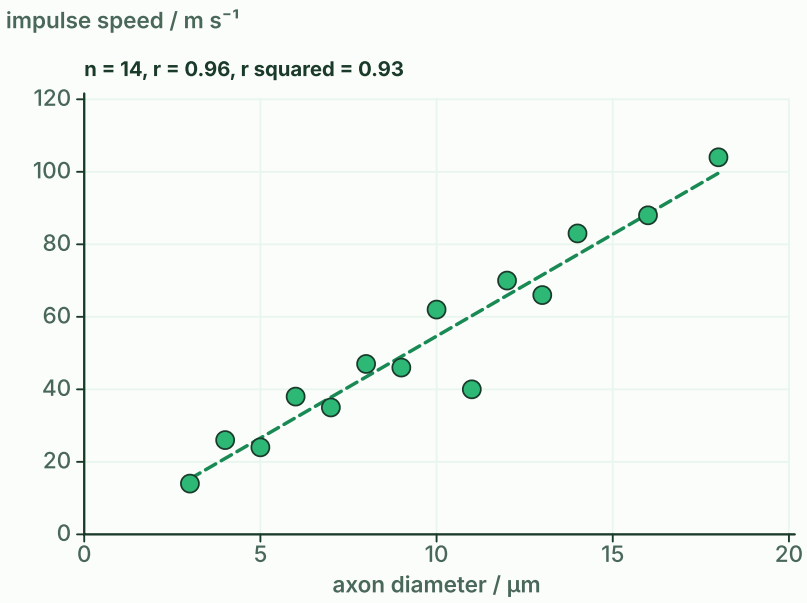
myelin sheath
Layers of a supporting cell's membrane wound tightly round an axon, which stop ions crossing the axon membrane under them.

giant axon
A very wide unmyelinated axon, up to about a millimetre across in a squid, which carries the impulse for the squid's escape jet.

correlation coefficient
Pearson's r: a number from -1 to +1 for how closely points on a scatter graph follow a straight line. The sign is the direction; the size is the strength.

coefficient of determination
R squared: the share of the variation in the dependent variable that goes with the independent variable along a straight line. 0.81 means 81 per cent.

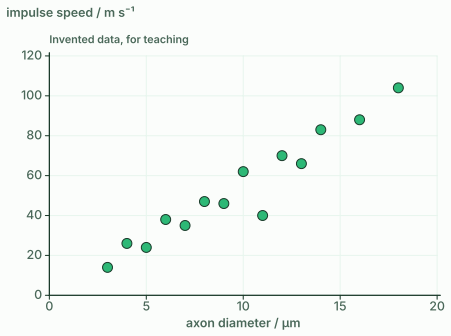
which animals are in the sample (small squid and insects rely on giant fibres), so in an exam describe the correlation shown by the data you are given, not this example.



Fourteen invented myelinated fibres: drag a point and watch r and R^2 follow, then take one out and see how much one fibre can change them.

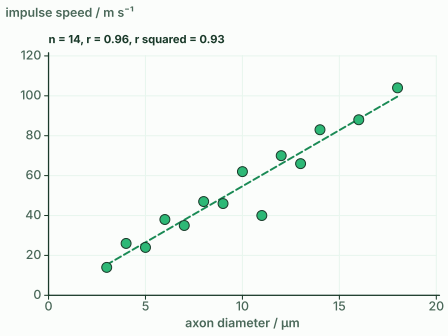
STEP BY STEP 2 STEPS

1

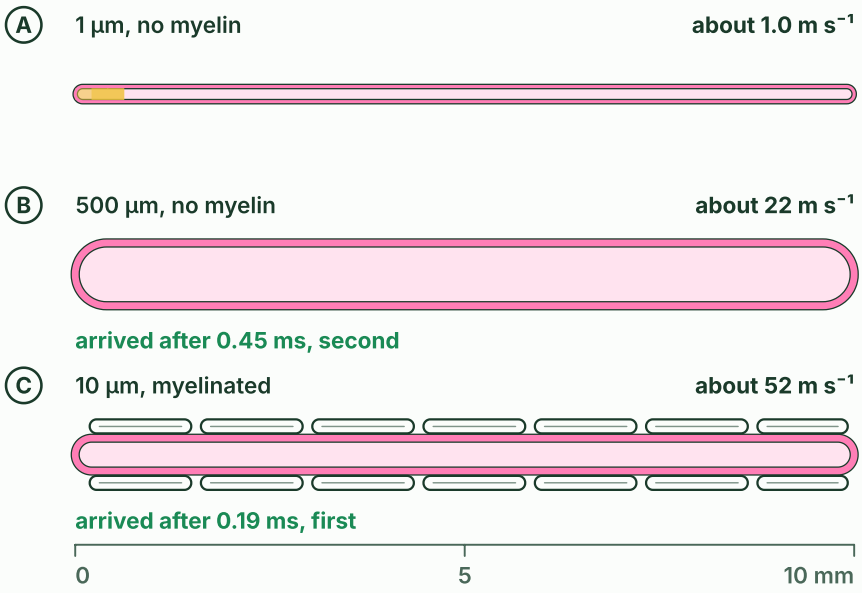


Invented data: Fourteen myelinated fibres from one invented nerve at 37 °C, each timed between two electrodes. Every number is invented for teaching. Each point is one of the 14 fibres. Describe the pattern before you calculate anything.

2



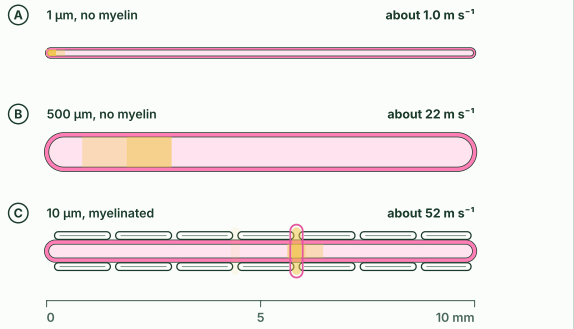
The trend line and the **correlation coefficient**: r = 0.96, a strong positive correlation. r squared = 0.93: about 93% of the variation in impulse speed goes with axon diameter. That says nothing about which, if either, is the cause.



Up to three axons, one stimulus. Answer each prediction first, then race it; after that, drag the diameter, tick Myelin sheath and add axons of your own, and watch each point land on the graph.

STEP BY STEP

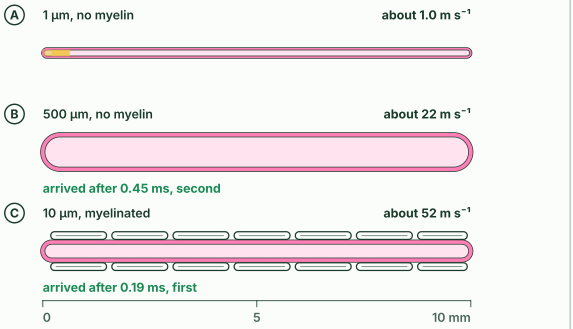
1



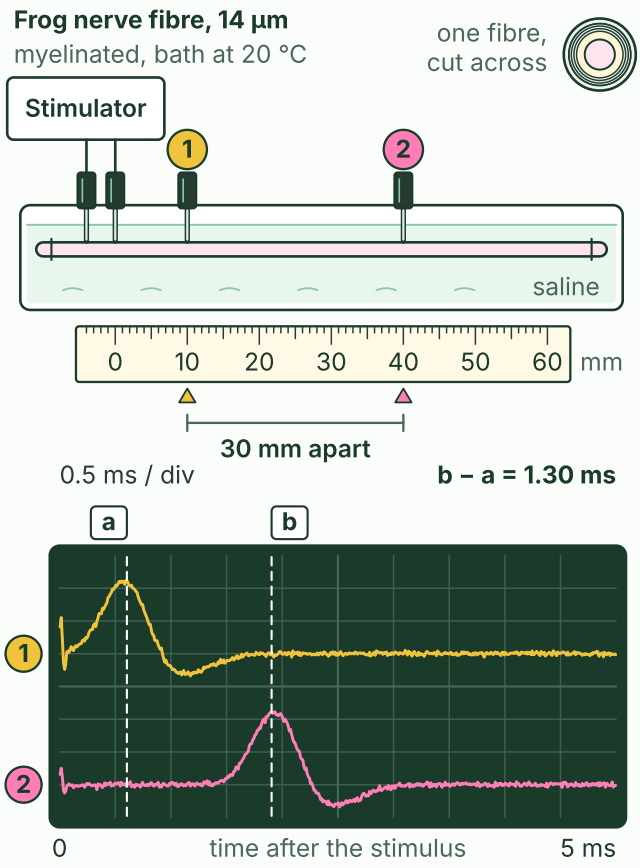
Three axons, one stimulus, 0.12 ms later. On C, the myelinated one, the impulse hops from node to node and is most of the way along. B, a giant bare axon 500 µm across, glows smoothly; A, a bare axon 1 µm across, has barely started.

2 STEPS

2



After 0.5 ms: C arrived first, after about 0.19 ms (about 52 m s⁻¹), and B second, after about 0.45 ms. A, at about 1 m s⁻¹, needs about 10 ms for the same 10 mm.



Frog nerve fibre, 14 µm, 30 mm apart

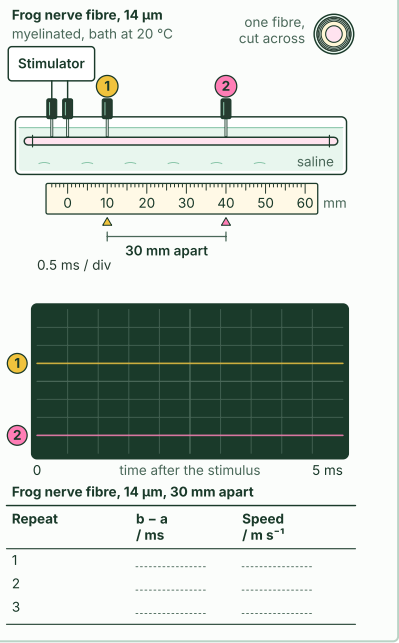
Repeat	b – a / ms	Speed / m s^{-1}
1	----------	----------
2	----------	----------
3	----------	----------

Conduction speed. A frog nerve fibre lies across the pins of a chamber of saline at 20 °C. The stimulator starts an impulse at 0 mm; recording electrodes 1 and 2 sit at 10 mm and 40 mm, 30 mm apart. Stimulate: each electrode records the impulse as a blip as it passes, electrode 1 first. The time from the stimulus to one electrode includes a short delay before the impulse sets off, so the lab uses the time between the two. Two cursors on the peaks of the blips read the delay b – a. Speed = distance between the electrodes / delay: repeat three times and fill in the table.

STEP BY STEP

3 STEPS

1

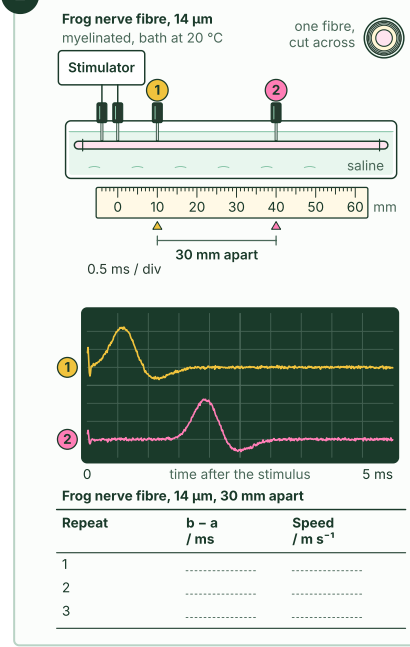


Frog nerve fibre, 14 µm, 30 mm apart

Repeat	b − a / ms	Speed / m s^{-1}
1	.....	.....
2	.....	.....
3	.....	.....

Conduction speed. A frog nerve fibre lies across the pins of a chamber of saline at 20 °C. The stimulator starts an impulse at 0 mm; recording electrodes 1 and 2 sit at 10 mm and 40 mm, 30 mm apart.

2

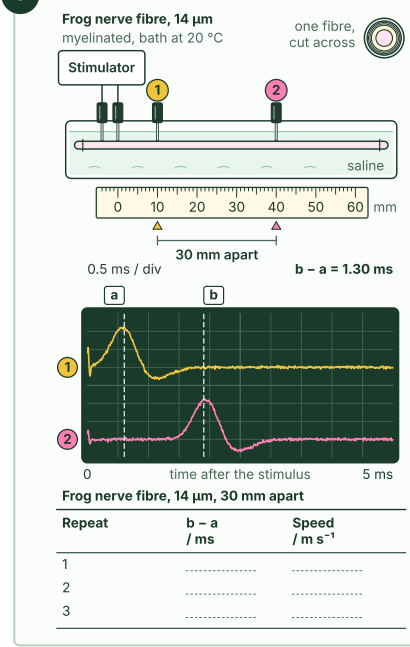


Frog nerve fibre, 14 µm, 30 mm apart

Repeat	b − a / ms	Speed / m s^{-1}
1	.....	.....
2	.....	.....
3	.....	.....

Stimulate: each electrode records the impulse as a blip as it passes, electrode 1 first. The time from the stimulus to one electrode includes a short delay before the impulse sets off, so the lab uses the time between the two.

3



Frog nerve fibre, 14 µm, 30 mm apart

Repeat	b − a / ms	Speed / m s^{-1}
1	.....	.....
2	.....	.....
3	.....	.....

Two cursors on the peaks of the blips read the delay b − a. Speed = distance between the electrodes / delay: repeat three times and fill in the table.

PREDICT

Two axons are the same diameter. One has a myelin sheath and the other has none. Which carries impulses faster?

(A) The bare one, because the sheath insulates the axon, and an insulated axon holds back the signal running along it

(B) Neither: they go at the same speed, because the speed of an impulse depends only on the diameter of the axon

(C) The myelinated one, because the sheath insulates the axon, so its impulses are conducted far faster than in a bare one

(D) The bare one, because ions can cross every part of its bare membrane, so each stretch is ready to fire again much sooner

Decide before you look. Answer on page 72.

REMEMBER IT

The two things that make an impulse faster

W Wide	**W** Wrapped
Wider axon	**Myelin sheath**
faster: more room for the local current	insulates: far faster, as the impulse fires only at the gaps

WATCH OUT

"A faster impulse is a bigger one." Speed and size are separate: every impulse is the same size, fast or slow. "A high r proves that diameter causes speed." A correlation shows the two go together; the cause needs a mechanism or an experiment. "Myelin is the only thing that matters." Diameter matters in both kinds of fibre.

08 Jumping *from node to node*

C2.2.11 HL SALTATORY CONDUCTION IN MYELINATED FIBRES TO ACHIEVE FASTER IMPULSES

A myelin sheath is made by supporting cells that wrap themselves round and round the axon, layer on layer of fatty membrane. Ions cannot cross the axon's membrane under the sheath. Between one wrapping cell and the next is a short bare gap, a **node of Ranvier**, about a micrometre long and every millimetre or so along the axon.

KEY POINTS

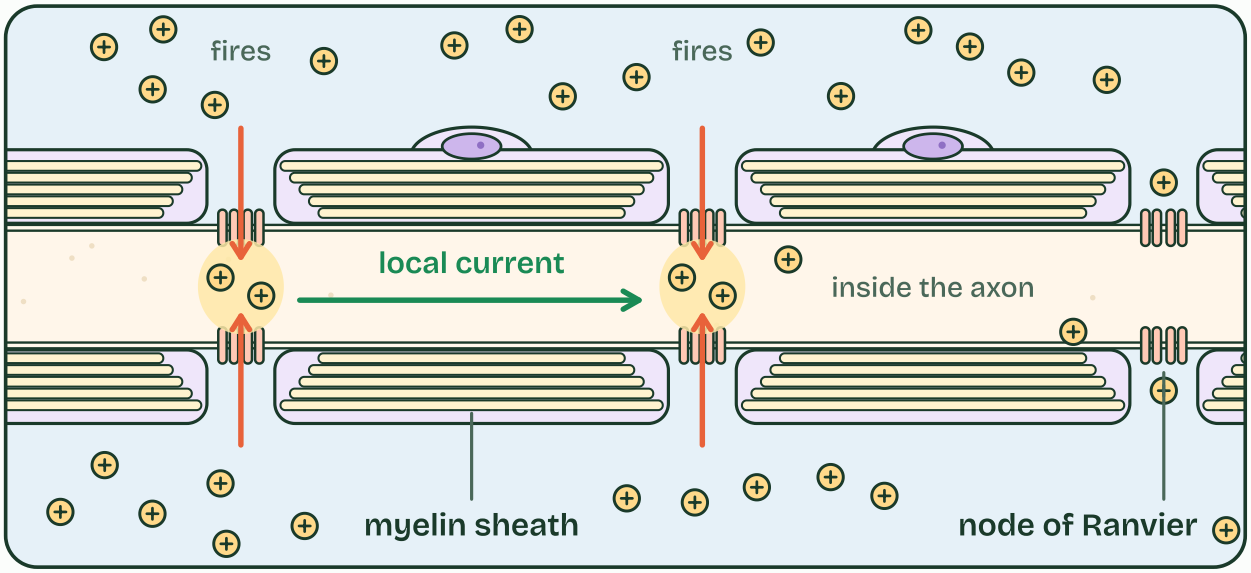
- **Fire at a node.** The voltage-gated sodium channels, and the pumps, are clustered at the nodes; under the sheath there are almost none. An action potential at one node lets Na^+ in there.
- **The current runs under the sheath.** The local current flows along the inside of the axon, under the myelin, to the next node. The sheath stops it leaking out on the way, so it reaches a millimetre or more.
- **The next node fires.** It reaches threshold and fires in turn. The impulse leaps from node to node: **saltatory conduction**, from the Latin for to leap.

Why is that faster? Making an action potential is the slow part, and here the axon makes one every millimetre instead of at every patch of membrane along it. It is also cheaper. Ions cross only at the nodes, a tiny share of the membrane, so far fewer ions cross in each impulse and the pumps have far less to put back afterwards. That saves ATP in a nervous system that fires all day.

KEY TERMS

node of Ranvier
A short gap in the myelin sheath, about a micrometre long, where the axon membrane is bare. Gaps come every millimetre or so along a myelinated axon.

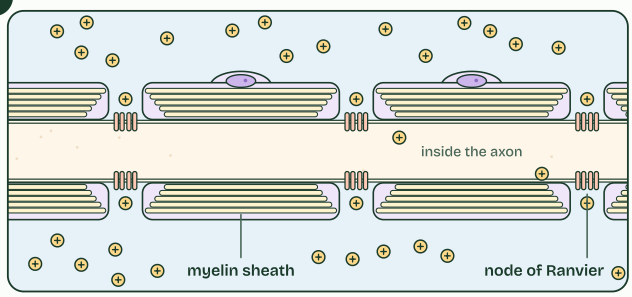
saltatory conduction
Conduction of an impulse along a myelinated axon by action potentials at the nodes of Ranvier only, the impulse jumping from node to node.



STEP BY STEP

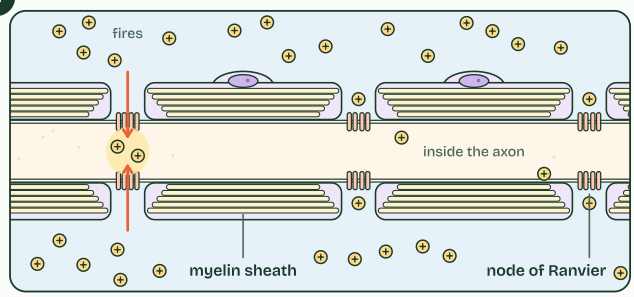
4 STEPS

1



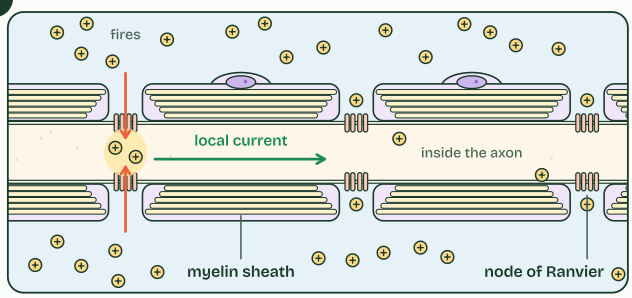
A myelinated axon: the **myelin sheath** wraps the membrane, broken every millimetre or so by a bare **node of Ranvier**.

2



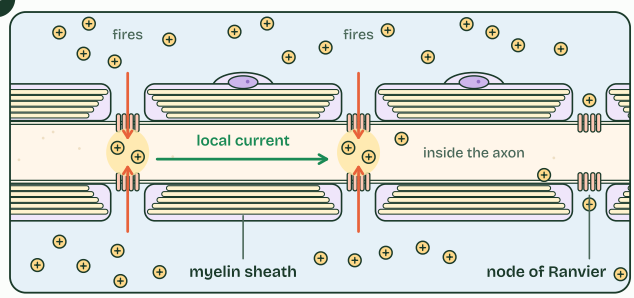
An action potential at one **node**: sodium ions rush in there, where the membrane is bare.

3



The **local current** flows along the inside of the axon, under the sheath, without leaking out, as far as the next node.

4

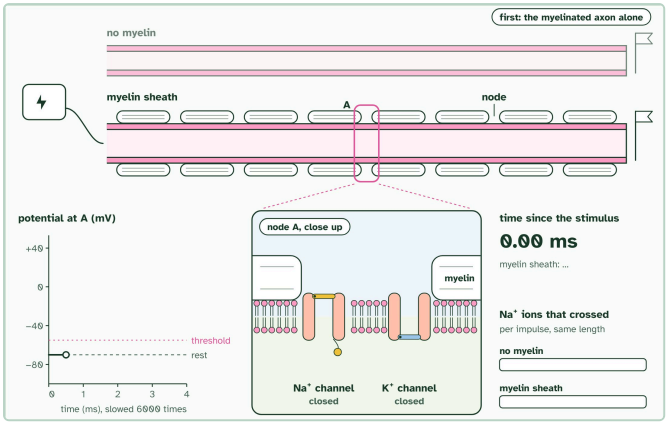


The next node reaches threshold and **fires**. The impulse leaps from node to node: saltatory conduction.

ANIMATION · NODE TO NODE

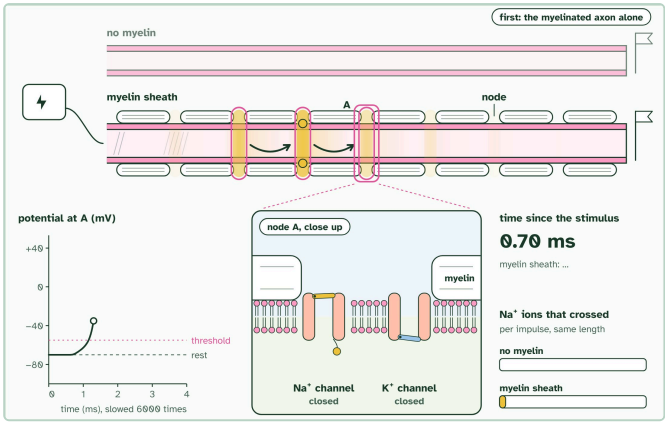
8 MOMENTS

1 MYELINATED, READY



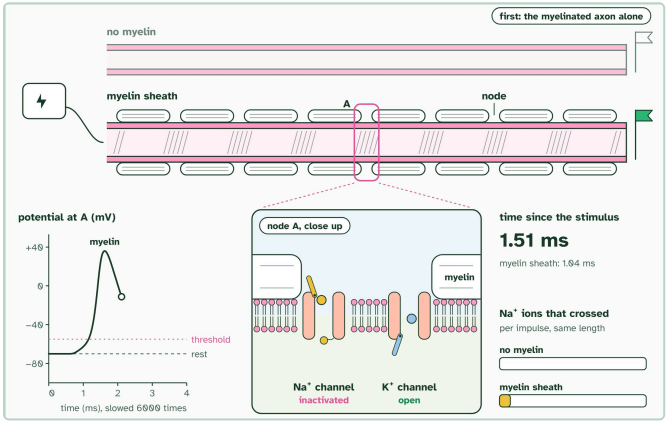
A myelinated axon on its own first, slowed 6000 times. The **myelin sheath** wraps it, and between the wraps are gaps, the **nodes of Ranvier**, where the membrane is bare.

2 NODE TO NODE



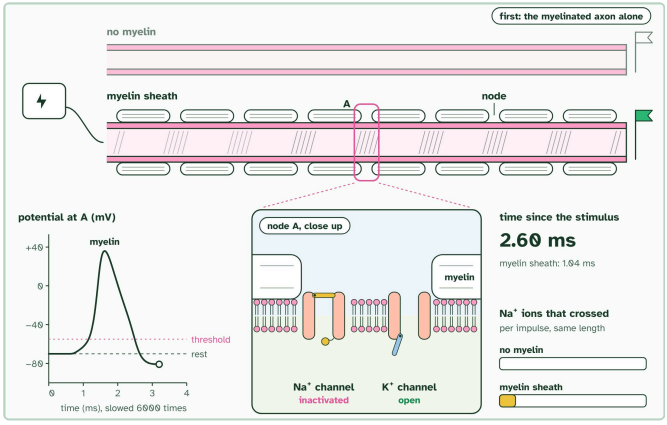
The first node fires. Na^+ that enters spreads on inside the axon, under the sheath, to the next node: a **local current**. That node reaches its threshold and fires, and so on: the impulse **jumps**, node to node.

3 NODE A RECOVERS



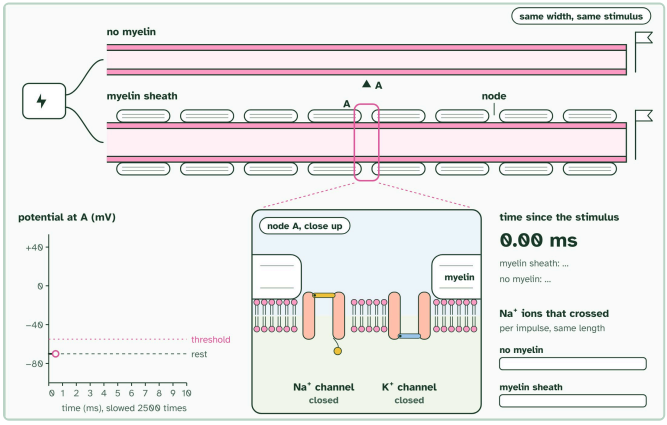
Node A close up: its Na^+ channels opened and Na^+ rushed in as the potential at A shot up. Now its K^+ channels open and K^+ flows out, and node A returns to rest.

4 NODE A RECOVERS



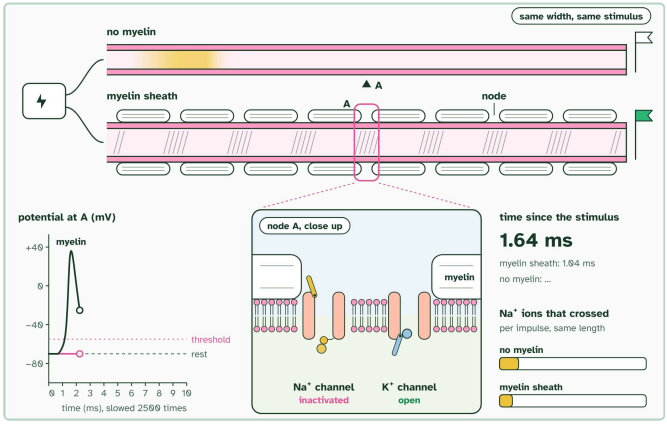
Ions crossed only at the nodes: this is **saltatory conduction**. Next, a race: an unmyelinated axon of the same width, the same stimulus into both.

5 RACE: READY



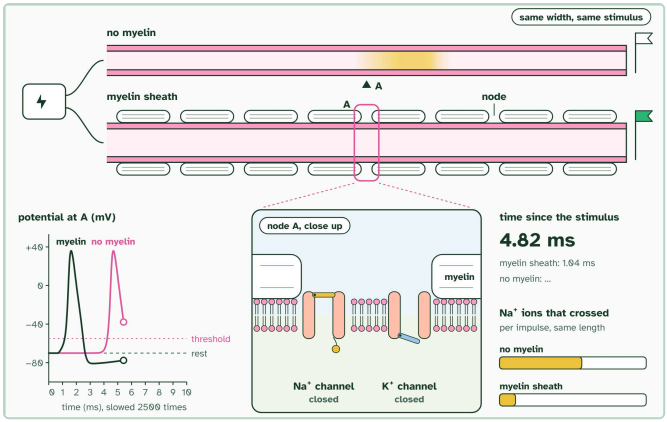
The race, slowed 2500 times. The same stimulus starts an impulse in both axons at the same moment.

6 MYELINATED FIRST



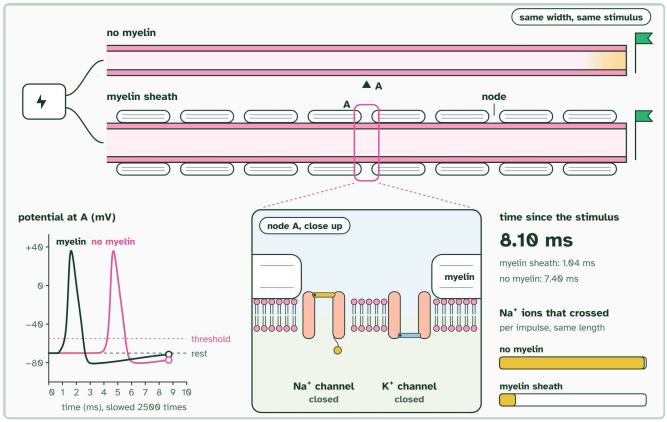
The myelinated axon's impulse is already at the end.

7 MYELINATED FIRST



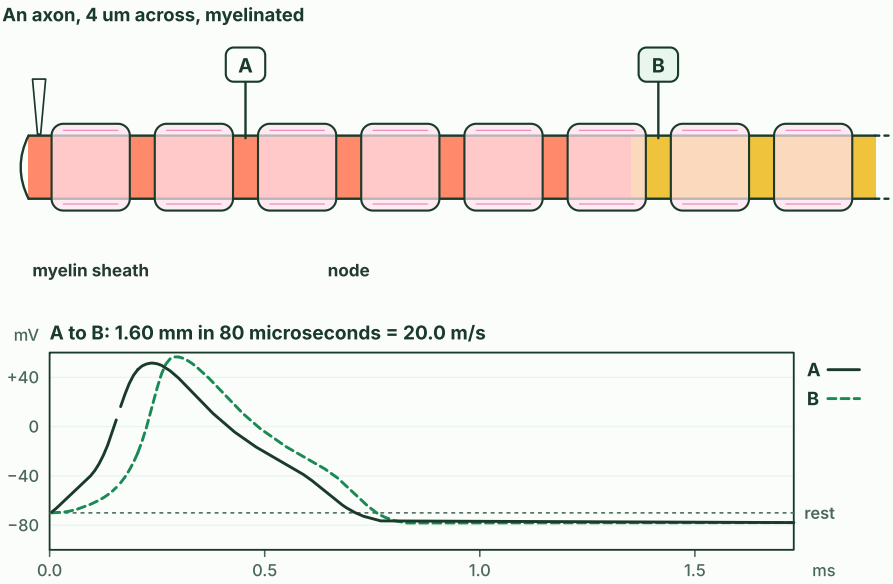
Without myelin, every stretch of membrane must fire in turn, so the impulse is far slower: see the trace at A for each.

8 BOTH ARRIVED



Far fewer ions cross the myelinated axon too, so there is less for its pumps to put back afterwards.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#saltatory

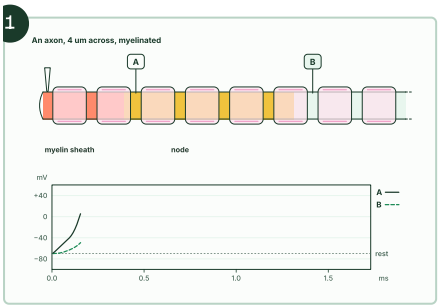


The same axon tool, with Myelin on. Time the impulse between the electrodes, then switch Myelin off at the same diameter, and try a wider axon.

STEP BY STEP

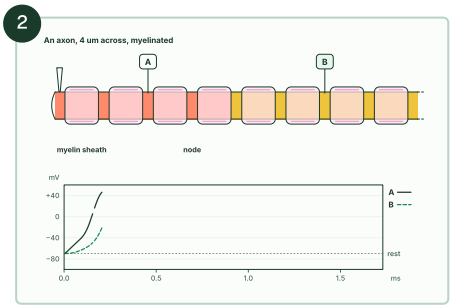
3 STEPS

1



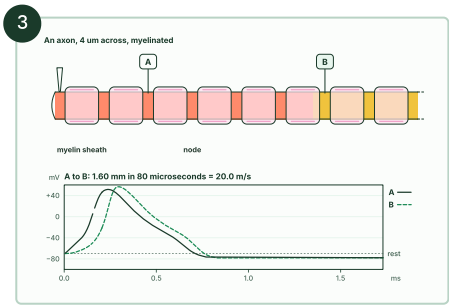
A stimulus at the left end starts an impulse. It has reached electrode **A**: the inside there is positive for a moment, and A's trace rises.

2



The impulse jumps from **node** to node: ions cross the membrane only in the gaps in the myelin, where the channels are clustered. This is **saltatory conduction**.

3



At **B** the trace is the same impulse, 80 microseconds later. The speed is the distance from A to B over that time: 20.0 m/s for this myelinated axon, 4 µm across.

PREDICT

In a myelinated axon the nodes are about a millimetre apart. Imagine an axon whose nodes were ten centimetres apart instead. What would happen to an impulse?

(A) It would stop, because the local current fades before it can bring the next node to threshold

(B) It would go a hundred times faster, because it would make a hundred times fewer leaps on its way

(C) Nothing would change, because the speed is set by the axon's diameter and not by its myelin

(D) It would carry on, but each action potential would get smaller at every node it came to

Decide before you look. Answer on page 73.

WATCH OUT

"The impulse jumps through the air between nodes." The current flows through the cytoplasm inside the axon. "Myelin conducts the impulse." Myelin insulates: it is what stops the current leaking, and it carries nothing. "The sheath is one long cell." Each stretch is a separate cell, and the nodes are the gaps between them.

GO FURTHER

In the nerves of your limbs and body the sheath is made by Schwann cells, each wrapping one stretch of one axon; in the brain and spinal cord by oligodendrocytes. In multiple sclerosis the sheath in the brain and spinal cord is damaged, and impulses slow or fail. Neither is needed for the exam.

09

C2.2.5 SYNAPSES AS JUNCTIONS BETWEEN NEURONS AND BETWEEN NEURONS AND EFFECTOR CELLS

A gap that *works one way*

An impulse reaches the end of an axon and stops. To go on, the signal has to cross to the next cell, at a **synapse**. There are synapses between one neuron and another, and between a neuron and an **effector** cell: a muscle fibre that contracts, or a gland cell that secretes.

At a synapse the two cells do not touch. A gap about 20 nanometres wide, the **synaptic cleft**, separates the end of the axon, the **presynaptic** terminal, from the **postsynaptic** cell. The signal crosses as a chemical, a **neurotransmitter**, stored in tiny sacs, the vesicles, in the terminal.

Why a gap and a chemical, not a wire? Because a chemical step can be changed. A synapse can pass a signal on, make it weaker, stop it, or add it to others (chapters 13 and 14), and drugs can act on it (chapter 12). It also makes the signal one-way: the whole nervous system runs in one direction, from the senses through the brain to the muscles.

KEY POINTS

- **Presynaptic terminal.** Vesicles full of neurotransmitter, and mitochondria to make the ATP they need.
- **Synaptic cleft.** A gap of about 20 nm, filled with tissue fluid.
- **Postsynaptic membrane.** Receptor proteins that bind the neurotransmitter.

KEY TERMS

synapse
A junction where a neuron passes a signal to another neuron or to an effector cell, by releasing a chemical across a small gap.

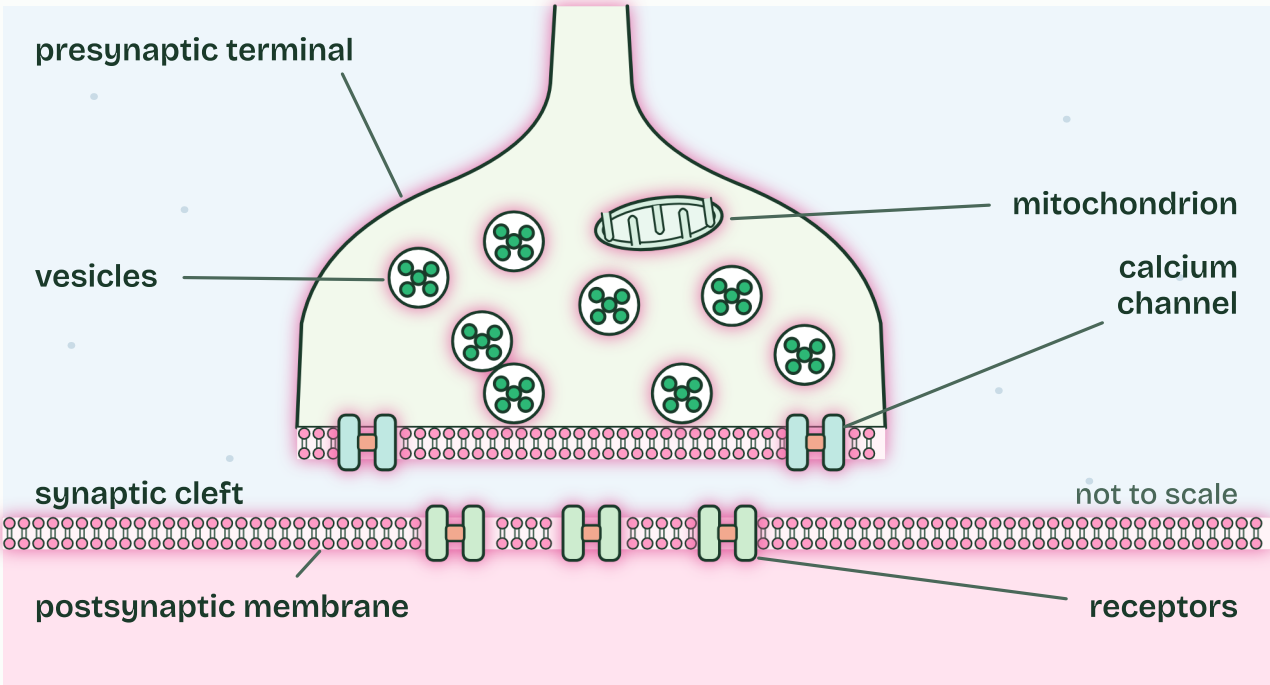
effector
A cell that carries out the body's response to a signal: a muscle fibre that contracts, or a gland cell that secretes.

synaptic cleft
The narrow gap, about 20 nm wide, between the presynaptic membrane and the postsynaptic membrane at a synapse.

presynaptic
Before the synapse: the neuron whose terminal releases the neurotransmitter.

postsynaptic
After the synapse: the cell whose membrane carries the receptors for the neurotransmitter.

neurotransmitter
A chemical released from a presynaptic terminal that crosses the synaptic cleft and binds to receptors on the postsynaptic cell.



Presynaptic terminal The swollen end of the axon, where the impulse arrives and the neurotransmitter is released.

Mitochondrion Makes the ATP the terminal needs to make neurotransmitter, refill its vesicles and pump ions.

Synaptic cleft The gap between the two cells, about 20 nanometres wide in life (drawn far wider here), filled with tissue fluid.

Receptors Proteins in the postsynaptic membrane that bind the neurotransmitter.

Vesicles Tiny membrane sacs, each full of neurotransmitter, made and filled before any impulse arrives. Some wait docked against the membrane.

Calcium channels Channels in the presynaptic membrane that open when the impulse arrives (chapter 10).

Postsynaptic membrane The membrane of the next cell, a neuron, a muscle fibre or a gland cell.

Presynaptic terminal The swollen end of the axon, where the impulse arrives and the neurotransmitter is released.

Mitochondrion Makes the ATP the terminal needs to make neurotransmitter, refill its vesicles and pump ions.

Synaptic cleft The gap between the two cells, about 20 nanometres wide in life (drawn far wider here), filled with tissue fluid.

Receptors Proteins in the postsynaptic membrane that bind the neurotransmitter.

Vesicles Tiny membrane sacs, each full of neurotransmitter, made and filled before any impulse arrives. Some wait docked against the membrane.

Calcium channels Channels in the presynaptic membrane that open when the impulse arrives (chapter 10).

Postsynaptic membrane The membrane of the next cell, a neuron, a muscle fibre or a gland cell.

PREDICT

A neurotransmitter carries a signal across a synapse. Why can the postsynaptic cell not send a signal back the same way?

(A) The impulse is too weak once it has crossed the gap, so there is not enough of it left over to make the long journey back the other way

(B) Only the presynaptic terminal has vesicles of the transmitter to release, and only the postsynaptic membrane has the receptors that respond

(C) The postsynaptic cell releases its own transmitter into the cleft, but the presynaptic membrane is far too thick for any of it to bind there

(D) The neurotransmitter is destroyed the moment it reaches the receptors, so none of it is left to carry a signal back

Decide before you look. Answer on page 73.

WATCH OUT

"The impulse jumps the gap." The impulse stops at the terminal; a chemical crosses. "At a synapse the two neurons are joined." At the synapses in this course they are not: the cleft separates them (a few synapses in the body are joined directly, and they are not in the course).

10 Calcium *opens the stores*

C2.2.6 RELEASE OF NEUROTRANSMITTERS FROM A PRESYNAPTIC MEMBRANE

The neurotransmitter is made beforehand and waits in vesicles, some of them docked against the presynaptic membrane. What makes them let it go?

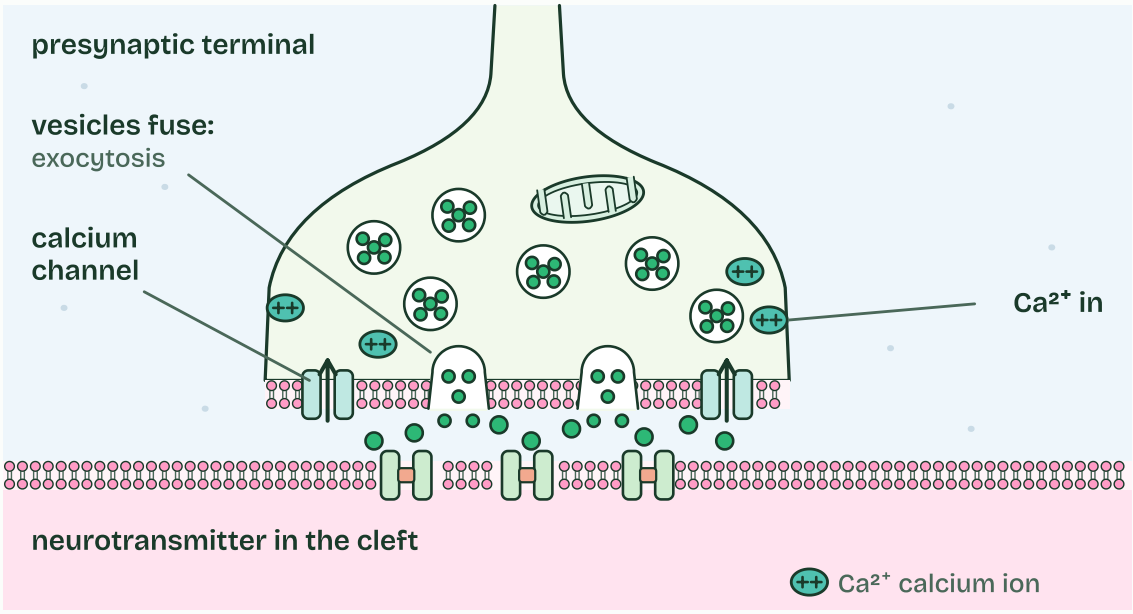
KEY POINTS

- **The impulse arrives.** The action potential depolarizes the membrane of the terminal.
- **Calcium channels open.** They are voltage-gated, and the depolarization opens them.
- **Calcium diffuses in.** Ca^{2+} is thousands of times more concentrated in the fluid outside than in the cytoplasm, so it rushes in down its gradient.
- **Vesicles fuse.** Inside the terminal calcium acts as a signal: it makes the vesicles fuse with the presynaptic membrane, and their neurotransmitter spills into the cleft by **exocytosis**.

Calcium here is not crossing to the next cell: it is a messenger inside one neuron, turning an electrical signal, the impulse, into a chemical one, the release. More impulses a second let in more calcium, so more vesicles empty and the next cell gets a stronger signal. Afterwards the calcium is pumped back out, and the vesicle membrane is taken back into the terminal by endocytosis to be filled again (B2.1).

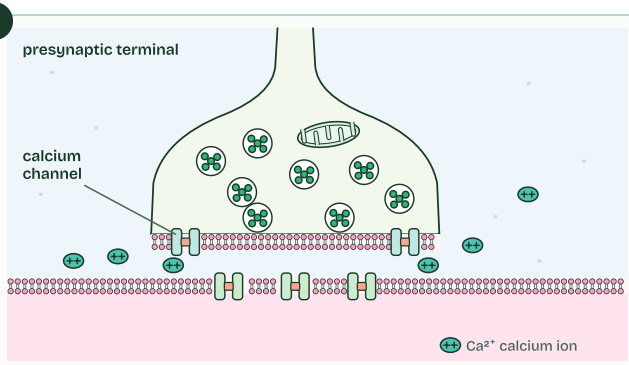
KEY TERMS

exocytosis
Release of a vesicle's contents from a cell: the vesicle fuses with the plasma membrane and opens to the outside.



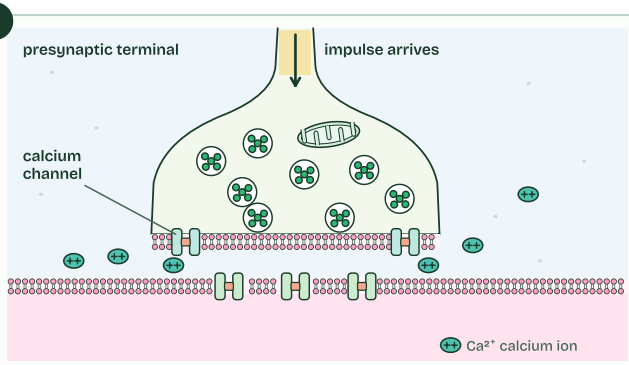
STEP BY STEP
5 STEPS

1



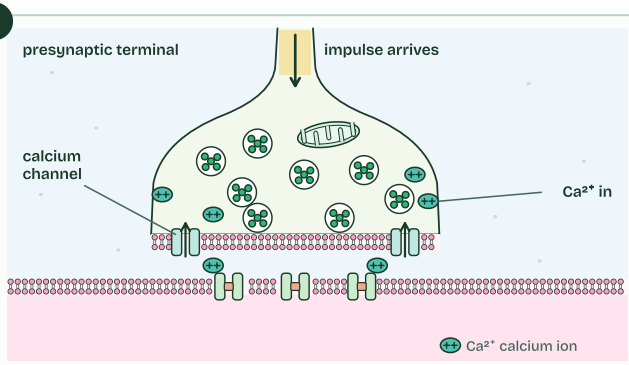
The terminal at rest: vesicles full of neurotransmitter, two of them **docked** at the membrane, and calcium ions in the fluid outside.

2



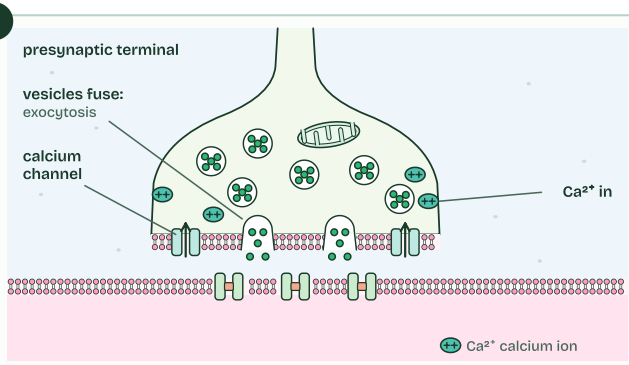
An **impulse arrives** down the axon and depolarizes the membrane of the terminal.

3



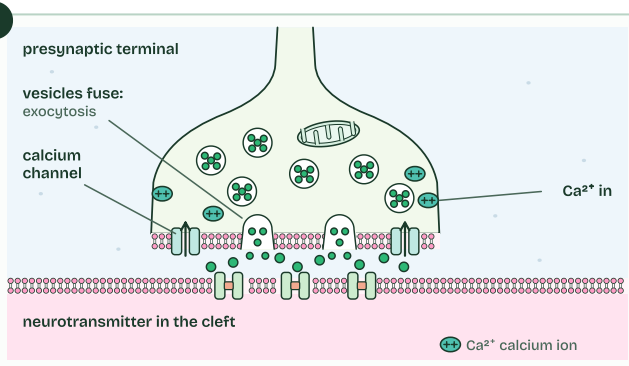
The depolarization opens voltage-gated **calcium channels**. Ca^{2+}, far more concentrated outside, diffuses in.

4



Calcium inside makes the docked vesicles **fuse** with the membrane and open into the cleft: **exocytosis**.

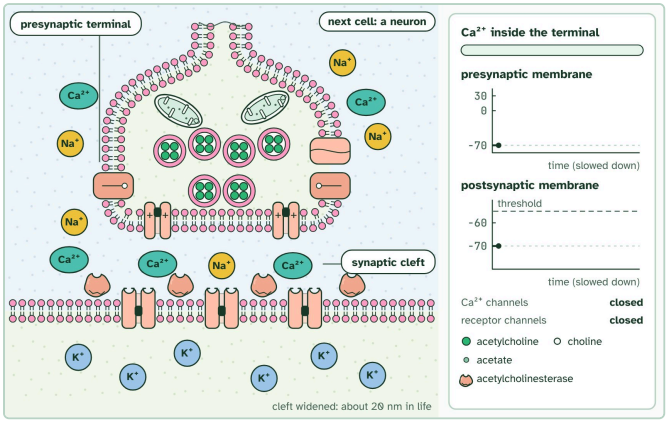
5



The **neurotransmitter** spills into the cleft, ready to cross to the next cell.

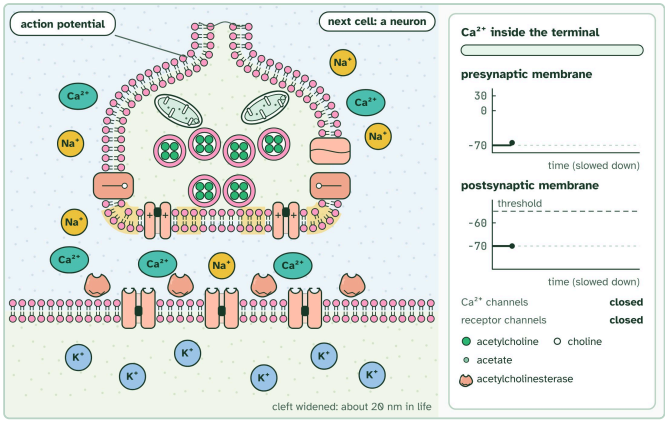
ANIMATION · ACROSS THE SYNAPSE
8 MOMENTS

1 AT REST



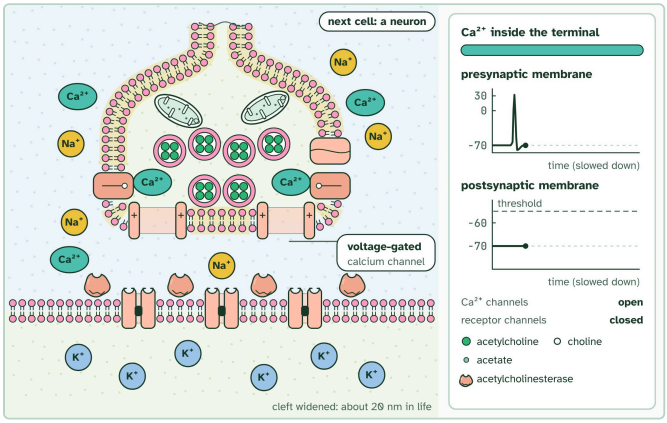
A synapse: the **presynaptic terminal** at the end of a neuron, a narrow gap (the **synaptic cleft**) and the membrane of the next cell. The terminal holds **vesicles** of acetylcholine, a neurotransmitter.

2 IMPULSE ARRIVES



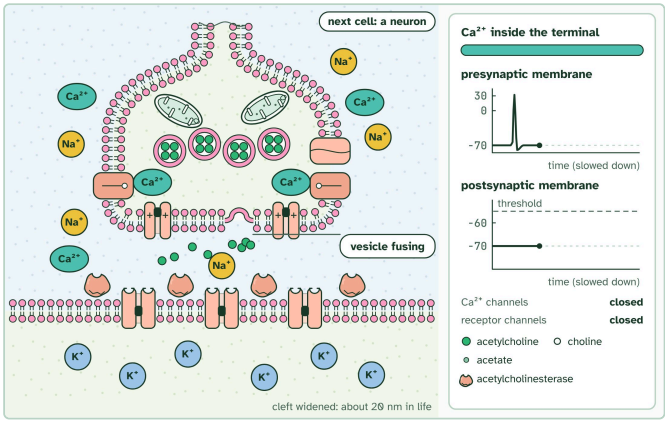
An **action potential** arrives along the axon and depolarizes the membrane of the terminal.

3 CALCIUM IN



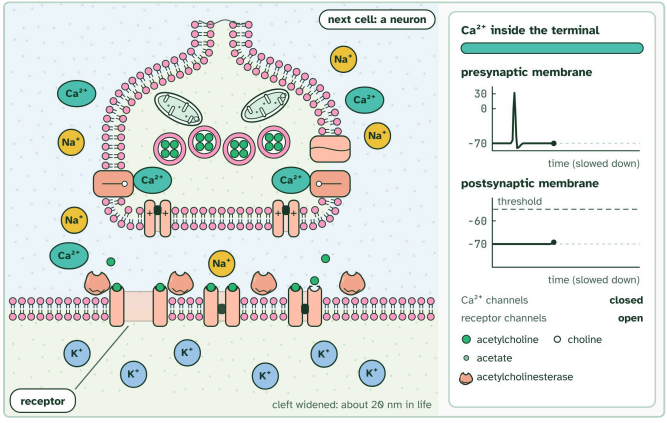
The depolarization opens **voltage-gated calcium channels**. Calcium ions, far more concentrated outside, diffuse in.

4 EXOCYTOSIS



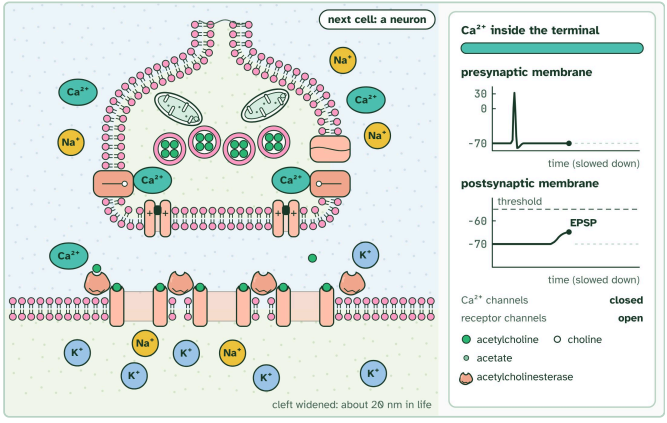
Calcium is a signal inside the neuron: it makes the vesicles fuse with the membrane and release acetylcholine into the cleft (**exocytosis**).

5 BINDING



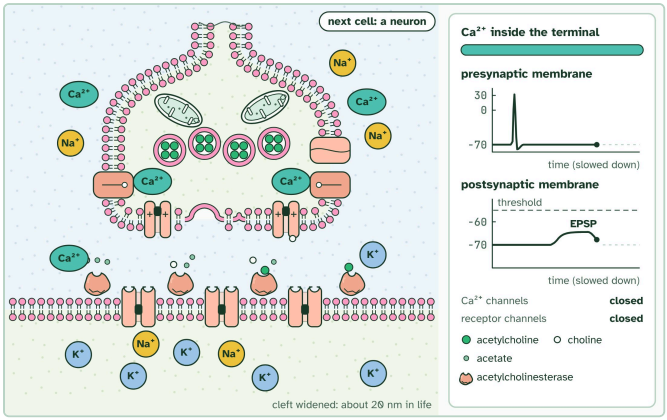
Acetylcholine **diffuses** across the cleft and binds to **receptors** in the postsynaptic membrane, two to each receptor.

6 POSTSYNAPTIC POTENTIAL

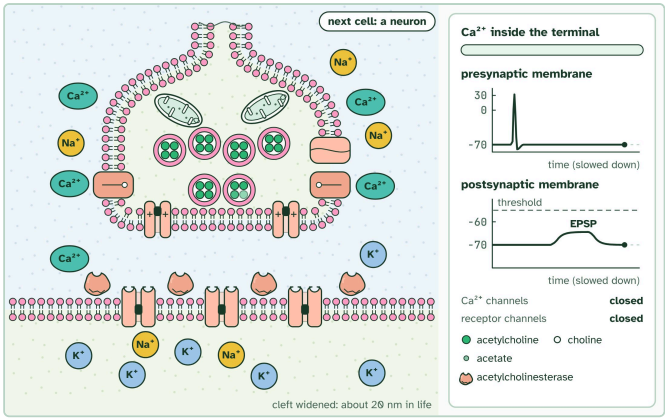


Binding opens the channel in each receptor. Sodium ions flow in (and a few potassium ions out), so the membrane depolarizes.

7 CLEAR-UP 8 READY AGAIN



Acetylcholinesterase in the cleft breaks acetylcholine into choline and acetate. The receptors are freed and their channels close.



Choline is taken back into the terminal and made into acetylcholine again; vesicle membrane is taken back in and calcium is pumped out. The synapse is ready for the next impulse. (The film is slowed down: in life this takes a few milliseconds.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#release

PREDICT

A toxin blocks the calcium channels in a presynaptic terminal. An impulse arrives. What happens at the synapse?

(A) The impulse cannot reach the terminal at all, so none of the events at the synapse begins

(B) Neurotransmitter still leaks out slowly, so a weaker signal crosses to the next cell anyway

(C) The vesicles never fuse, no neurotransmitter is released, and the next cell gets no signal

(D) The next cell fires all the same, because the impulse itself jumps across the gap to reach it

Decide before you look. Answer on page 73.

REMEMBER IT

Across a synapse, in order (this chapter and the next)

A	C	V	R	B
All	Cats	Very	Rarely	Bark
Action potential	**Calcium**	**Vesicles**	**Receptors**	**Breakdown**
arrives at the terminal	channels open, Ca2+ in	fuse and release	bind it, channels open	the enzyme clears the cleft

WATCH OUT

"The neurotransmitter is made when the impulse arrives." It is made in advance and stored in vesicles. "Calcium is the neurotransmitter." Calcium triggers the release and stays in the terminal. "Sodium entering the terminal releases the vesicles." It is calcium.

11 Acetylcholine *across the cleft*

C2.2.7 GENERATION OF AN EXCITATORY POSTSYNAPTIC POTENTIAL

Many synapses use the same neurotransmitter, **acetylcholine**. It is the one at every *neuromuscular junction*, where a motor neuron meets a muscle fibre, and at many synapses between neurons too. Follow it from the vesicle to the next cell.

KEY POINTS

- **It diffuses across.** Released into the cleft, acetylcholine diffuses across the 20 nm in a fraction of a millisecond.
- **It binds a receptor.** On the postsynaptic membrane are **transmembrane receptors** that fit it. At this synapse the receptor is itself an ion channel, opened when acetylcholine binds to it (C2.1 has this receptor among its examples).
- **Positive ions flow in.** The open channel lets Na^+ into the cell (and a little K^+ out), so the inside of the postsynaptic membrane becomes less negative.
- **An EPSP.** That small depolarization is an **excitatory postsynaptic potential**, EPSP. If it is big enough, an action potential starts in the next cell.

A signal has to stop as well as start. In the cleft is the enzyme **acetylcholinesterase**, which breaks acetylcholine into choline and acetate within milliseconds. The receptors let go, their channels close, and the membrane returns to rest, ready for the next impulse. The choline is taken back into the presynaptic terminal and made into new acetylcholine.

Not every EPSP fires the next cell. At a neuromuscular junction one impulse releases enough acetylcholine to fire the muscle fibre every time; at most synapses between neurons a single EPSP is small, and the cell fires only when several add up (chapter 14).

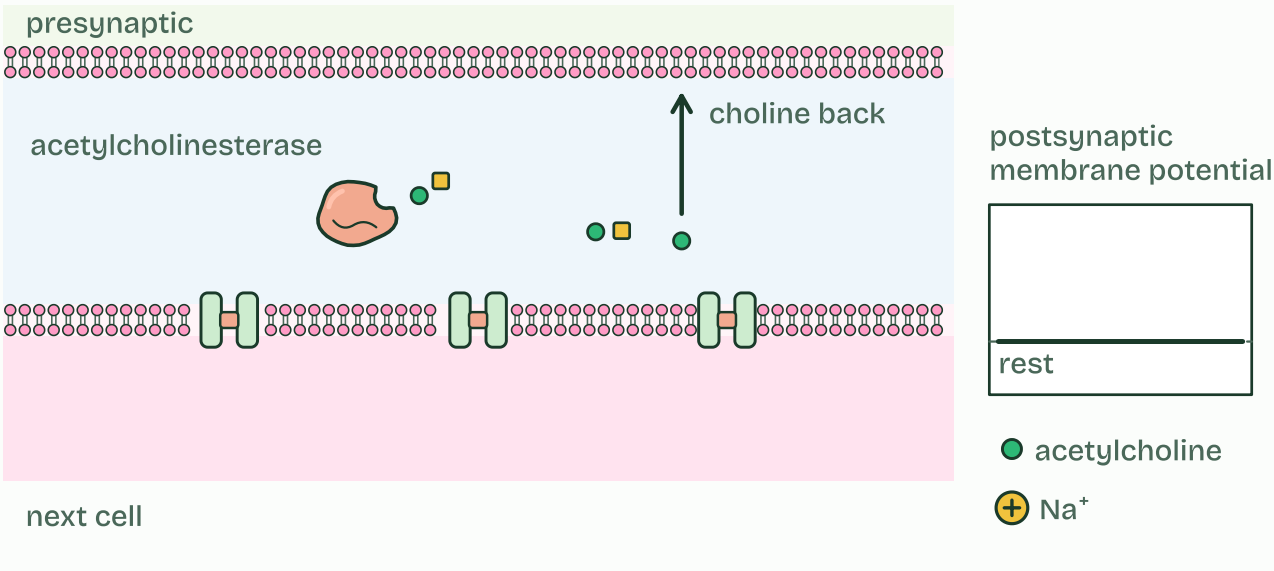
KEY TERMS

acetylcholine
A neurotransmitter used at many synapses, including every neuromuscular junction, where motor neurons meet skeletal muscle fibres.

transmembrane receptors
A protein that binds a particular signalling chemical. A transmembrane receptor spans the membrane, so what binds outside changes what happens inside.

excitatory postsynaptic potential
A small depolarization of a postsynaptic membrane, caused by an excitatory neurotransmitter, that makes the cell more likely to fire.

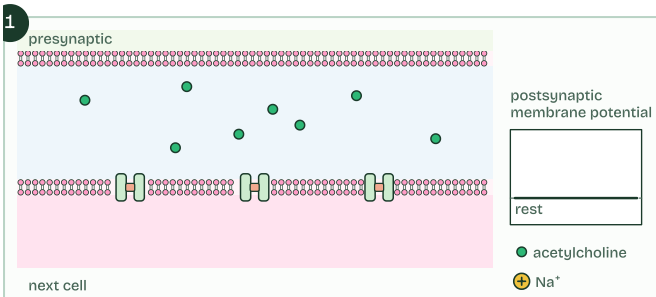
acetylcholinesterase
An enzyme in the synaptic cleft that breaks acetylcholine into choline and acetate, ending its signal.



STEP BY STEP

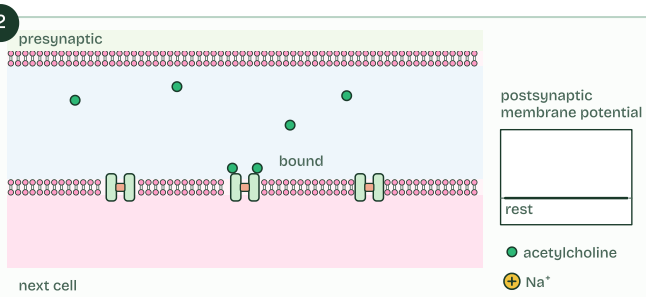
4 STEPS

1



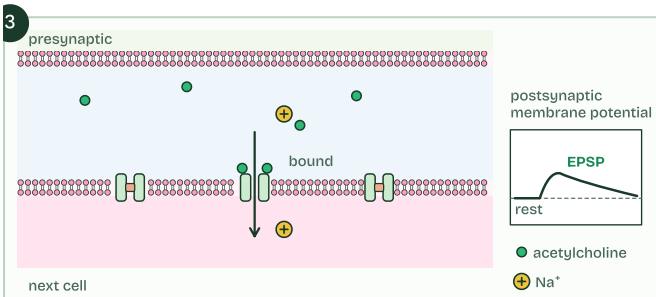
Acetylcholine released from the terminal diffuses across the cleft towards the receptors.

2



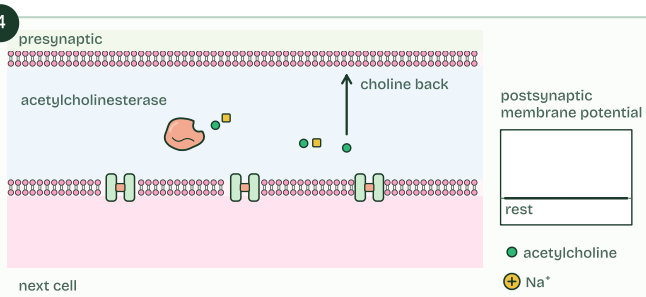
Two molecules **bind** one receptor, which is itself a channel in the postsynaptic membrane.

3



The channel **opens**: Na^+ flows in, the membrane depolarizes a little, and the trace shows an **EPSP**.

4

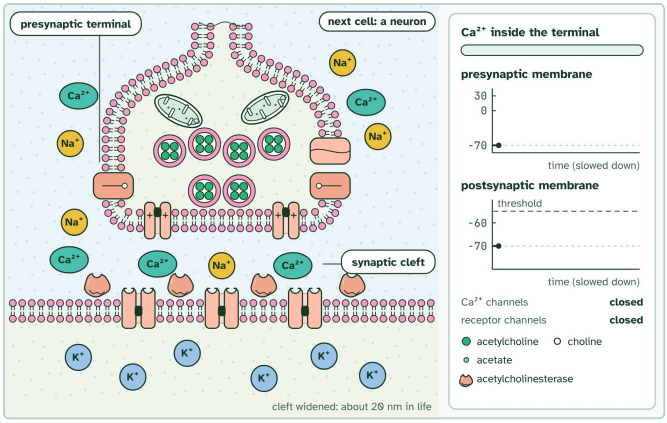


Acetylcholinesterase, an enzyme in the cleft, splits acetylcholine into choline and acetate, and is not used up. The receptor lets go, its channel closes, and the choline is taken back into the terminal.

ANIMATION · CLEARING THE SYNAPSE

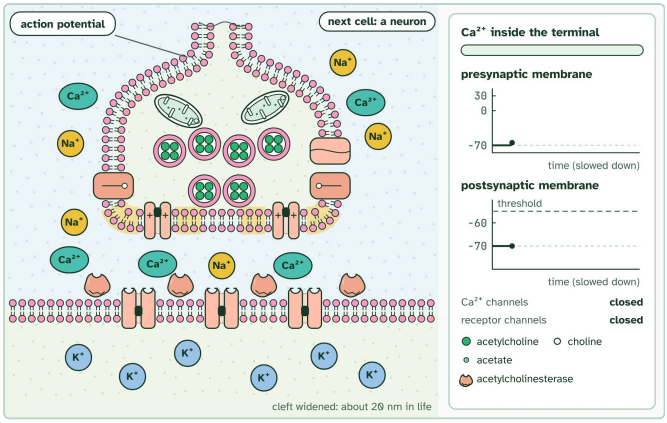
8 MOMENTS

1 AT REST



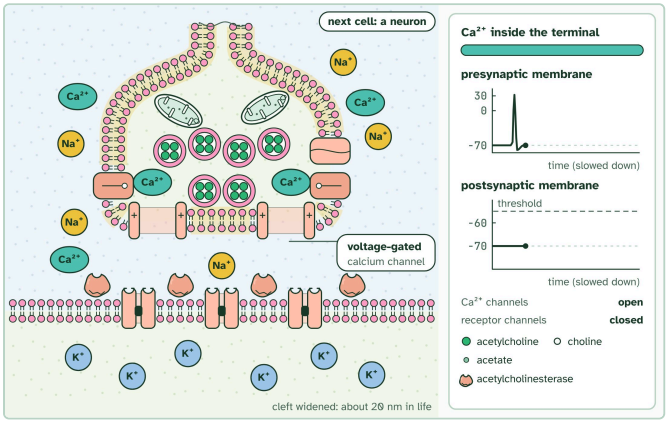
A synapse: the **presynaptic terminal** at the end of a neuron, a narrow gap (the **synaptic cleft**) and the membrane of the next cell. The terminal holds **vesicles** of acetylcholine, a neurotransmitter.

2 IMPULSE ARRIVES



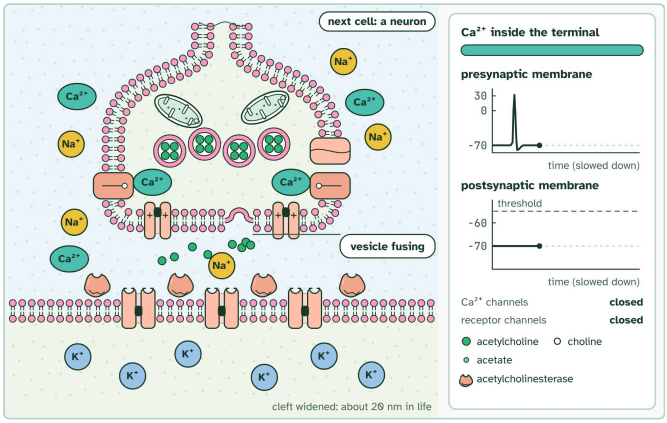
An **action potential** arrives along the axon and depolarizes the membrane of the terminal.

3 CALCIUM IN



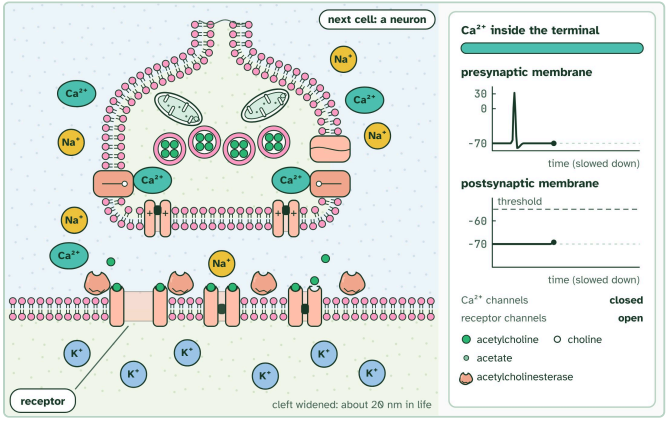
The depolarization opens **voltage-gated calcium channels**. Calcium ions, far more concentrated outside, diffuse in.

4 EXOCYTOSIS



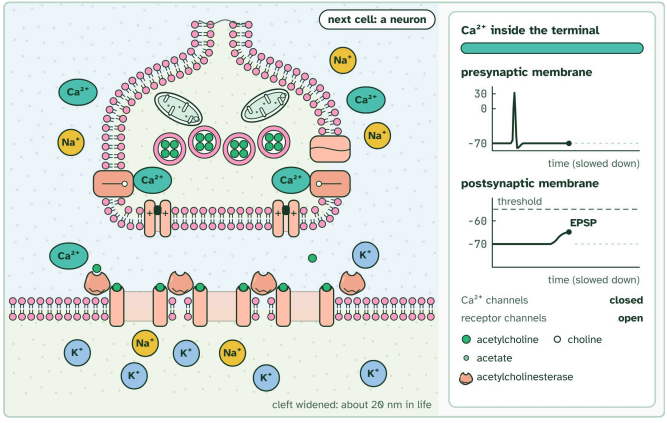
Calcium is a signal inside the neuron: it makes the vesicles fuse with the membrane and release acetylcholine into the cleft (**exocytosis**).

5 BINDING



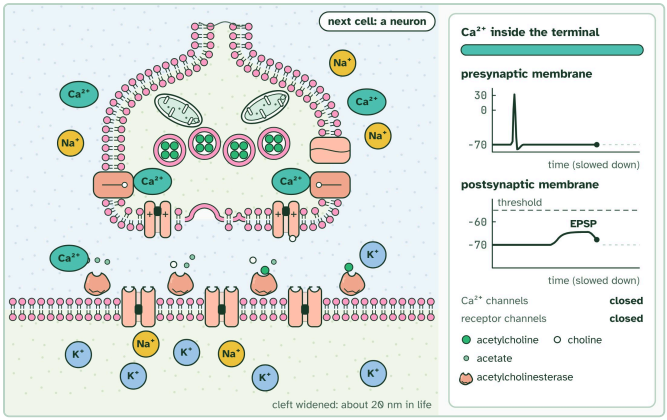
Acetylcholine **diffuses** across the cleft and binds to **receptors** in the postsynaptic membrane, two to each receptor.

6 POSTSYNAPTIC POTENTIAL



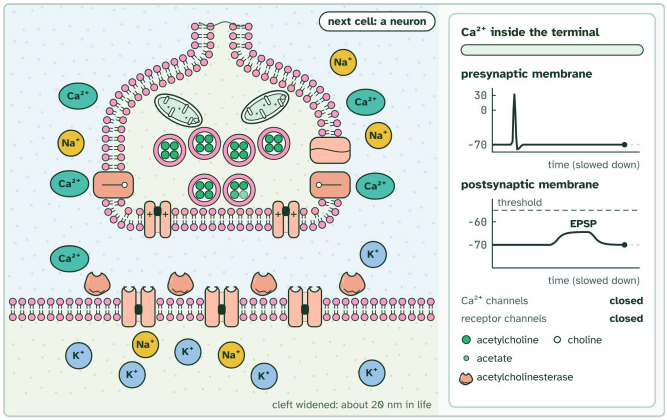
Binding opens the channel in each receptor. Sodium ions flow in (and a few potassium ions out), so the membrane depolarizes.

7 CLEAR-UP



Acetylcholinesterase in the cleft breaks acetylcholine into choline and acetate. The receptors are freed and their channels close.

8 READY AGAIN



Choline is taken back into the terminal and made into acetylcholine again; vesicle membrane is taken back in and calcium is pumped out. The synapse is ready for the next impulse. (The film is slowed down: in life this takes a few milliseconds.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#epsp

PREDICT

The enzyme that breaks down acetylcholine in the cleft stops working. What happens to the postsynaptic membrane after one impulse?

(A) It goes back to rest sooner, because the extra acetylcholine in the cleft switches the receptors off

(B) It stays depolarized, because acetylcholine keeps binding and the receptors stay open, so it cannot reset

(C) The presynaptic neuron makes less acetylcholine, so the signal fades away over the next few impulses it sends

(D) It becomes hyperpolarized, because the receptors close on their own once they have been open for long

Decide before you look. Answer on page 73.

WATCH OUT

"Acetylcholine goes back into the presynaptic neuron whole." It is broken down in the cleft; only the choline goes back. "An EPSP is an action potential." An EPSP is small, and only starts an action potential if it is large enough. "The receptors are in the cleft." They sit in the postsynaptic membrane.

12 When a chemical *gets in the way*

C2.2.12 HL EFFECTS OF EXOGENOUS CHEMICALS ON SYNAPTIC TRANSMISSION

Every step at a synapse is done by a protein: a channel, a receptor, an enzyme, a carrier. So a chemical from outside the body, an **exogenous** chemical, can change what a synapse does by fitting one of those proteins. The IB's two examples act at different steps.

KEY POINTS

- **Neonicotinoids block transmission.** These pesticides are like nicotine. In an insect they bind to the acetylcholine receptors at its synapses. Acetylcholinesterase cannot break them down, so they stay bound. The receptors are first held open, then stop responding, and acetylcholine released by the next impulses has nowhere to bind. Synaptic transmission is blocked, and the insect is paralysed and dies. They bind insect receptors far more strongly than ours, which is why they are used on crops. They also harm bees and other pollinators, which have the same kind of receptors.
- **Cocaine blocks reuptake.** At some synapses in the brain the neurotransmitter is dopamine. Dopamine is cleared mainly by reuptake rather than broken down in the cleft: carrier proteins in the presynaptic membrane take it back in whole, which is **reuptake**. Cocaine binds the carrier and blocks it. Dopamine builds up in the cleft and keeps stimulating the postsynaptic neurons.

The contrast is worth keeping. Acetylcholine is cleared by an enzyme in the cleft; dopamine is cleared by reuptake. A neonicotinoid takes the place of the neurotransmitter on its receptor and cannot be cleared; cocaine leaves the neurotransmitter alone and stops it being cleared. One silences a synapse, the other turns it up.

KEY TERMS

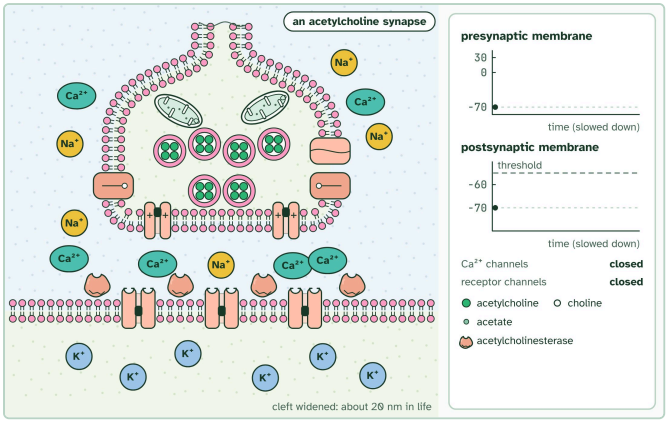
exogenous
Made outside the body: a drug, a pesticide or a poison that enters it.

reuptake
Taking a neurotransmitter back into the presynaptic neuron from the cleft, by a carrier protein in its membrane.

ANIMATION · CHEMICALS AT THE SYNAPSE

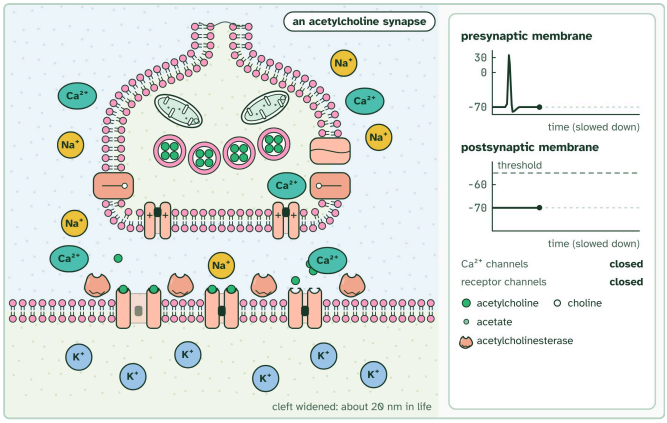
4 MOMENTS

1 NORMAL TRANSMISSION



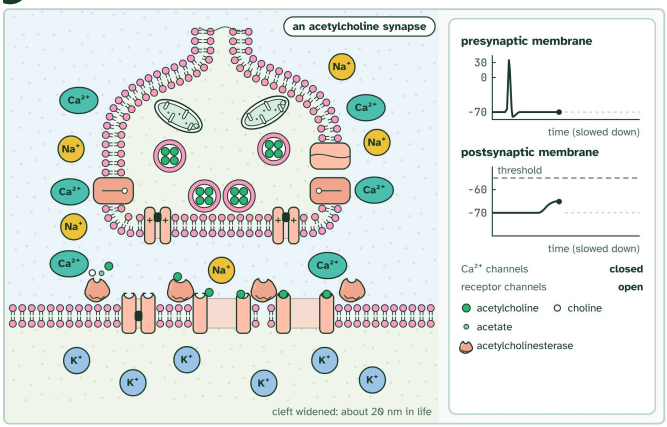
A synapse that uses **acetylcholine**. Two impulses will arrive, one after the other.

2 NORMAL TRANSMISSION



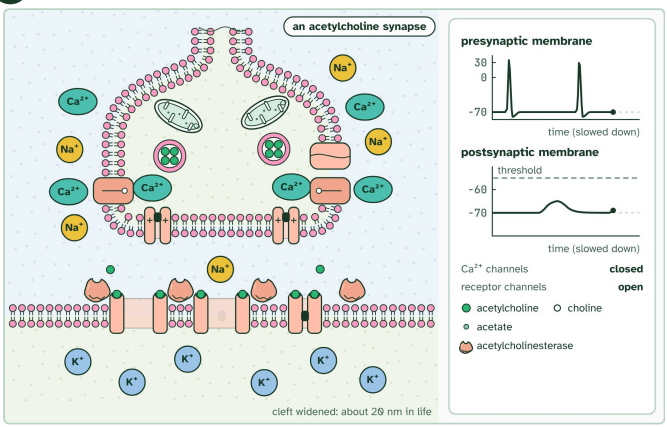
Each impulse releases acetylcholine, which binds to the receptors and opens their channels: the membrane depolarizes.

3 NORMAL TRANSMISSION



Acetylcholinesterase breaks the acetylcholine down, so the receptors are freed and the membrane returns to rest.

4 NORMAL TRANSMISSION



The second impulse gives the same response again. Choose a chemical to see what changes. (The film is slowed down: in life this takes a few milliseconds.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#drugs

PREDICT

A drug blocks the carrier protein that takes a neurotransmitter back into the presynaptic neuron. What happens to the neurotransmitter?

(A) It is broken down faster in the cleft, so the signal to the next cell fades away sooner than usual

(B) It is carried across the cleft faster than before, so the signal it gives the next cell is shorter than usual

(C) It binds to receptors on the presynaptic membrane instead, which makes the terminal release more of it with each impulse

(D) It stays in the cleft for longer, so it keeps binding the receptors, and the signal is stronger and longer

Decide before you look. Answer on page 73.

GO FURTHER

Cocaine also blocks the reuptake of noradrenaline and serotonin. That is not needed for the exam.

WATCH OUT

"Cocaine stops dopamine being made." It stops dopamine being taken back. "Neonicotinoids and cocaine both block reuptake." Only cocaine does; a neonicotinoid binds the receptor. "These chemicals only act in the brain." A neonicotinoid acts at an insect's synapses wherever they are.

C2.2.13 HL INHIBITORY NEUROTRANSMITTERS AND GENERATION OF INHIBITORY POSTSYNAPTIC POTENTIALS

13 Telling a neuron *not to fire*

Not every synapse says go. At an inhibitory synapse the neurotransmitter makes the postsynaptic membrane more negative than at rest, further from threshold: the membrane is **hyperpolarized**. That small change is an **inhibitory postsynaptic potential**, IPSP.

KEY POINTS

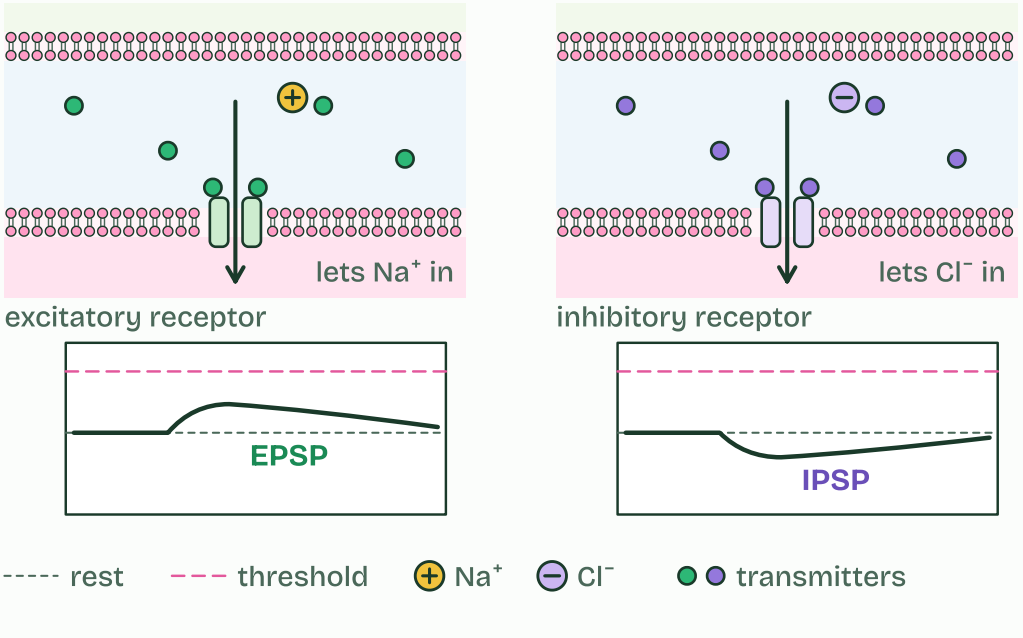
- **A different receptor.** The receptors at an inhibitory synapse open channels for negative ions, or for positive ions that leave the cell.
- **Chloride in, or potassium out.** Cl^- is more concentrated outside, so it flows in and adds negative charge; or K^+ flows out and takes positive charge away. Either way the inside becomes more negative.
- **Further from threshold.** The cell now needs a bigger excitatory input than before to reach −55 mV.

GABA is the brain's main inhibitory neurotransmitter: many of its receptors are chloride channels. So one neuron can carry both kinds of synapse on it, some pushing it towards threshold and some holding it back.

KEY TERMS

hyperpolarized
Made more negative inside than at rest, so further from the threshold potential.

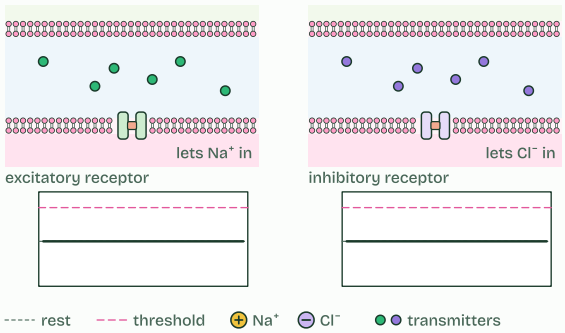
inhibitory postsynaptic potential
A small hyperpolarization of a postsynaptic membrane, caused by an inhibitory neurotransmitter, that makes the cell less likely to fire.



STEP BY STEP

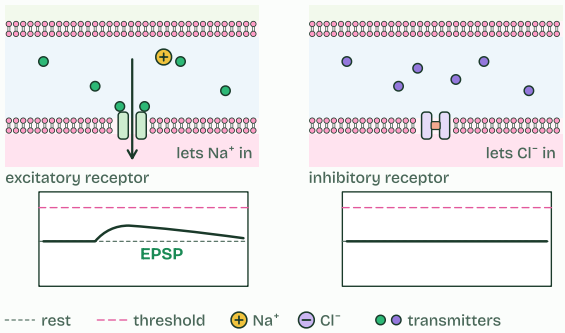
3 STEPS

1



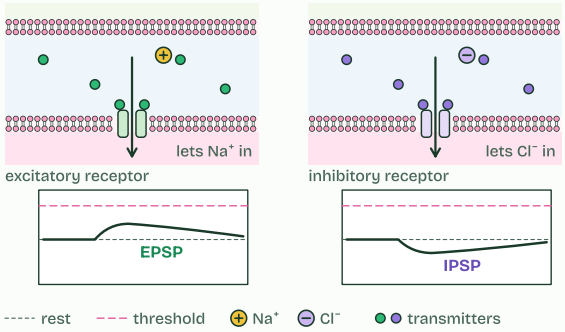
Two synapses on the same kind of cell, each named by what its receptor's channel lets through: an **excitatory** one (acetylcholine here) and an **inhibitory** one (GABA here). Both membranes sit at rest.

2



Acetylcholine binds: its channel lets **Na^+ in**, and the membrane moves towards threshold: an **EPSP**.

3



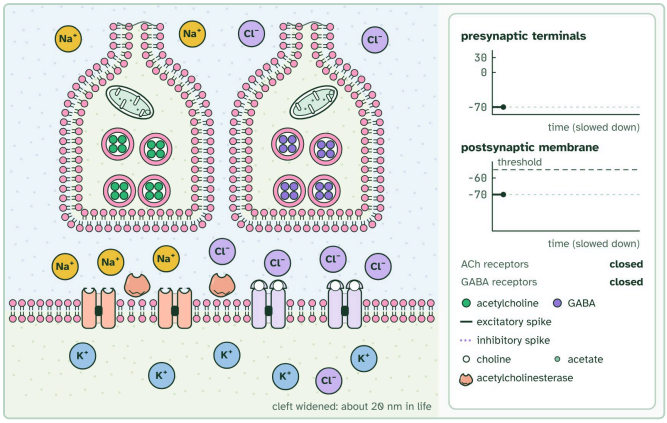
GABA binds: its channel lets **Cl^- in**, and the membrane moves the other way, below rest: an **IPSP**. It is **hyperpolarized**.

ANIMATION · AN INHIBITORY SYNAPSE

4 MOMENTS

1

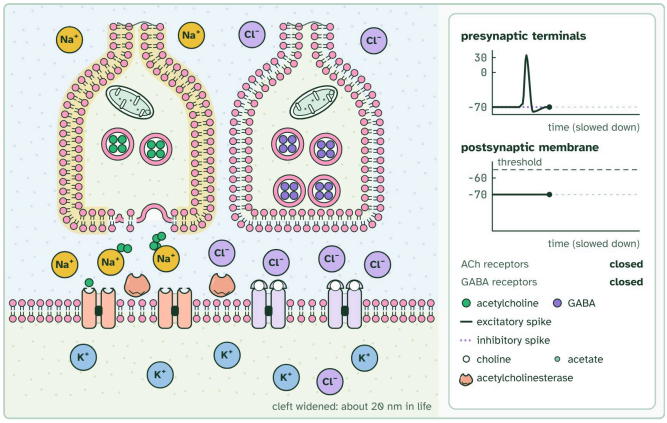
EXCITATORY INPUT



Two terminals end on one postsynaptic neuron. The left one releases acetylcholine; the right one releases GABA.

2

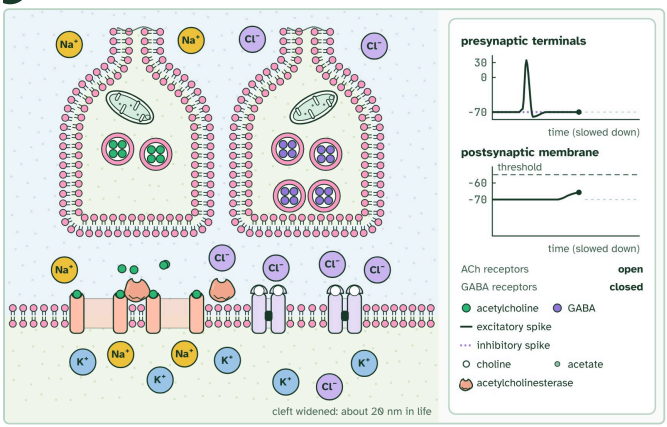
EXCITATORY INPUT



An impulse arrives at the left terminal. Acetylcholine crosses the cleft and opens its receptors: sodium ions flow in.

3

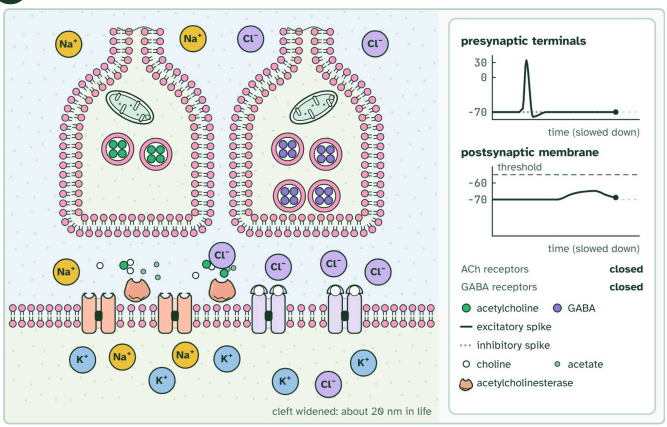
EXCITATORY INPUT



The membrane depolarizes a little: an **excitatory postsynaptic potential** (EPSP), still below the threshold.

4

EXCITATORY INPUT



The acetylcholine is broken down and the membrane returns to rest. Now choose **Inhibitory**: what will the GABA terminal do? (The film is slowed down: in life this takes a few milliseconds.)

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#ipsp

PREDICT

Acetylcholine makes a skeletal muscle fibre contract, yet the same chemical, released by a nerve onto the heart, slows it down. How can one neurotransmitter do both?

(A) The heart cells have a different receptor for it, one that opens channels making their membrane more negative

(B) It is broken down much faster in the heart, so it has too little time to depolarize the heart cells it reaches

(C) The heart has no synapses, so acetylcholine reaches its cells in the blood and acts as a hormone

(D) Heart muscle receives a much larger dose of it, and above a certain amount every transmitter turns inhibitory

Decide before you look. Answer on page 73.

WATCH OUT

"Inhibition stops the neurotransmitter being released." The inhibitory neurotransmitter is released as any other is; it is what it does to the next cell that differs. "An IPSP is a small action potential." It goes the other way, more negative. "Hyperpolarized means depolarized a lot." It means more negative than rest.

C2.2.14 HL SUMMATION OF THE EFFECTS OF EXCITATORY AND INHIBITORY NEUROTRANSMITTERS IN A POSTSYNAPTIC NEURON

14 Adding up *the votes*

A neuron in the brain may have thousands of synapses on its dendrites and cell body, from many presynaptic neurons, some excitatory and some inhibitory. Each one moves the membrane a little: an EPSP up, an IPSP down. They spread to where the axon leaves the cell body, and there they add together: **summation**.

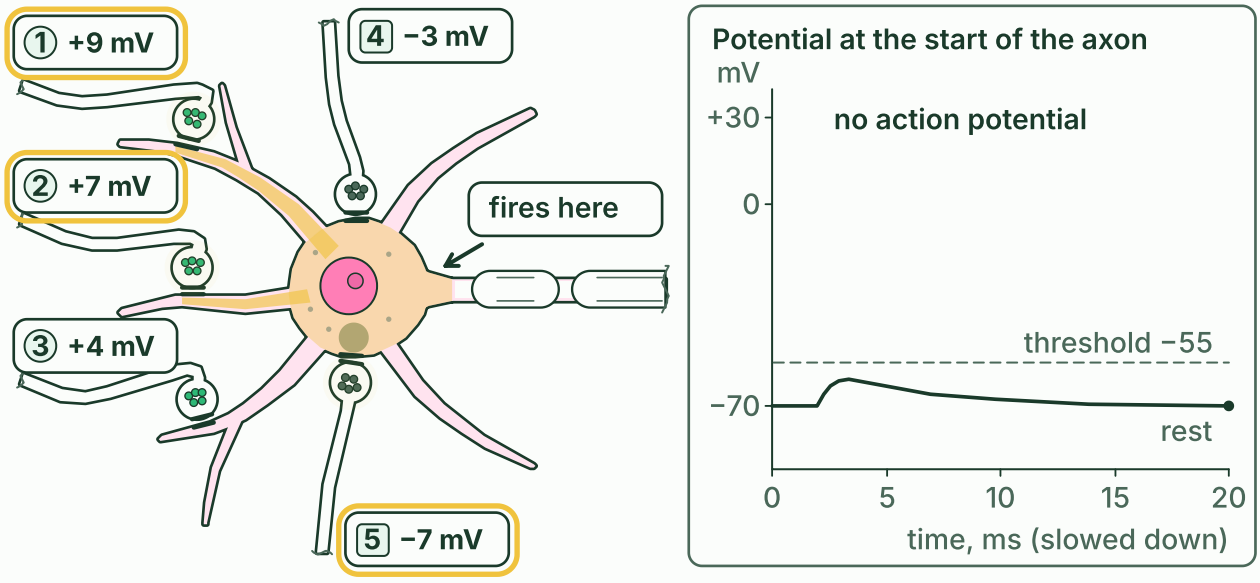
KEY POINTS

- **Graded in, all or nothing out.** The inputs come in any size and any mix; the output is one of two things: an action potential of the full size, or none.
- **Inhibition subtracts.** An IPSP takes away from the EPSPs arriving with it, so the same excitation can fire a cell on its own and fail with an inhibitory input beside it.
- **Several at once, or in quick succession.** EPSPs from several synapses add when they arrive together; impulses arriving rapidly at one synapse add too, because each EPSP has not faded before the next comes.

This is how a single neuron makes a decision. It weighs every input against every other, and fires only when the excitation wins by enough. Inhibition is not a fault in the system; it is how the brain stops signals spreading where they should not, and how it picks one action out of many.

KEY TERMS

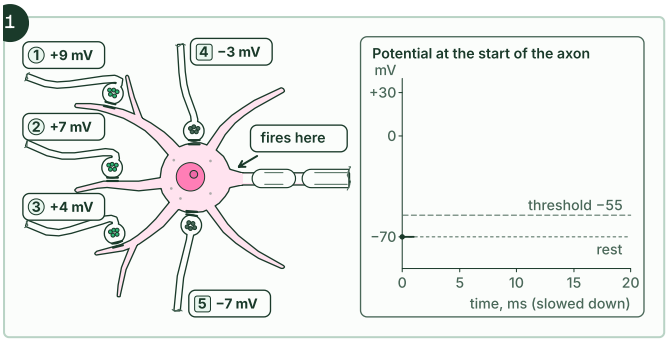
summation
Adding together the effects of all the excitatory and inhibitory inputs arriving at a postsynaptic neuron.



Five inputs onto one neuron: three excitatory and two inhibitory, each with its own millivolts. Answer the question above, then make it fire with two inputs, and stop it again with one inhibitory input. Fill in the table as you go.

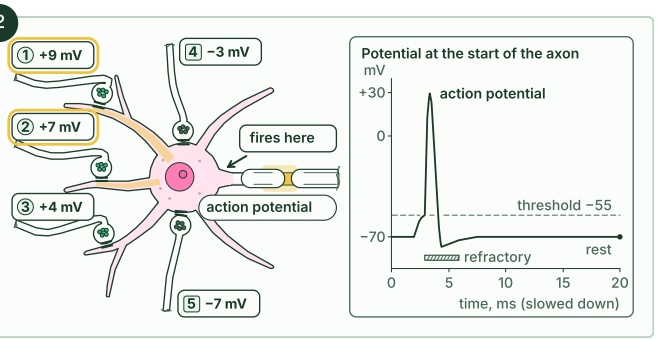
STEP BY STEP
3 STEPS

1



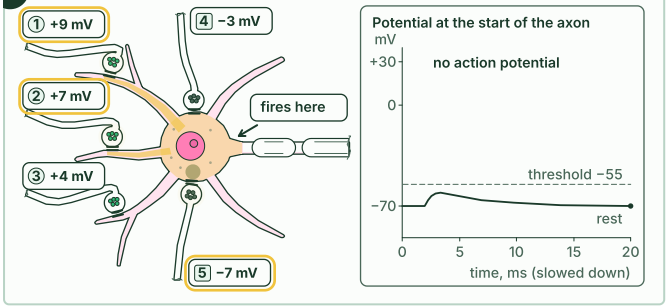
One neuron, 5 inputs. The excitatory ones (+9, +7 and +4 mV) and the inhibitory ones (−3 and −7 mV) each change the potential at the start of the axon, which is −70 mV at rest.

2



Inputs 1 and 2 fire together: +9 and +7 add to +16 mV, taking the start of the axon past the threshold (−55 mV). An action potential fires and leaves along the axon.

3



Add input 5 (−7 mV): the total is only +9 mV, below the threshold, so no action potential fires. The response is all or nothing.

PREDICT

A neuron at −70 mV fires at −55 mV, so it needs +15 mV. Three excitatory inputs give +6 mV each and one inhibitory input gives −4 mV. All four arrive together. Does it fire?

(A) Yes, it fires, because the three excitatory inputs outnumber the one inhibitory input arriving

(B) Yes, but with a smaller impulse than usual, because the total falls short of the full amount needed

(C) No: three times +6 is +18, less 4 is +14, which is short of the +15 the neuron needs to fire

(D) No, because a single inhibitory input arriving at the same time cancels all of the excitatory ones

Decide before you look. Answer on page 73.

WATCH OUT

"The biggest input decides." All of them add. "More input makes a bigger impulse." Once threshold is reached the impulse is always the same size. "Neurons count the inputs." They add the voltages: a large EPSP counts for more than a small one.

GO FURTHER

The place where the inputs are added is the axon hillock, the cone where the axon leaves the cell body. Inputs from several synapses at once add by *spatial summation*; repeated impulses at one synapse add by *temporal summation*. None of the three terms is needed for the exam.

15 A *burning* hand

C2.2.15 HL PERCEPTION OF PAIN BY NEURONS WITH FREE NERVE ENDINGS IN THE SKIN

Pain starts in the skin, at the bare tips of sensory neurons. A **free nerve ending** is just that: the neuron's fibre branching among the cells of the skin, with no special structure round it.

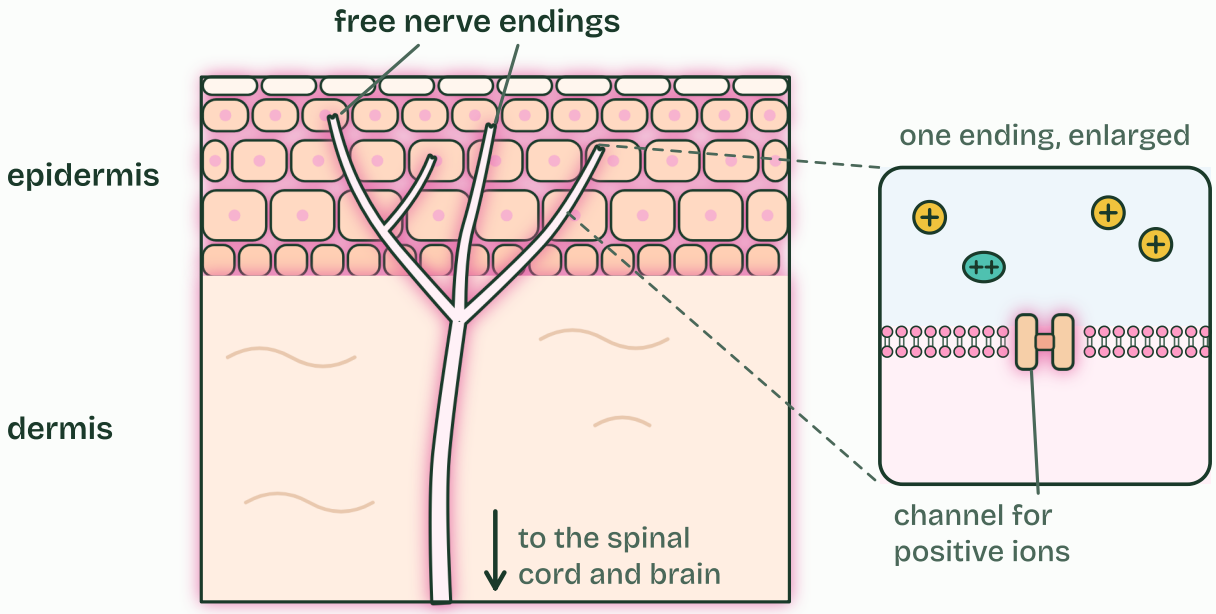
KEY POINTS

- **Channels that open to harm.** The membrane of the ending has channels for positively charged ions. They open in response to a stimulus that could damage the skin: a high temperature, an acid, or certain chemicals.
- **To threshold.** Positive ions flow in through the open channels and depolarize the ending. If it reaches threshold, action potentials start in the neuron.
- **To the brain.** The impulses pass along this neuron and then others, across synapses, to the brain. Only there is the pain perceived: felt, and placed in the hand.

A neuron cannot send a bigger impulse for a worse burn: impulses are all or nothing (chapter 4). A hotter stimulus opens more channels, holds the ending further above threshold, and fires it more times each second, so the brain reads strength from the rate. How the pain signal also triggers a reflex, pulling the hand away before you feel it, is in C3.1.

KEY TERMS

free nerve ending
The branched, bare end of a sensory neuron in the skin, with no special structure around it. Some detect pain.



Epidermis The outer layers of the skin: living cells below, flattened dead cells at the surface. It has no blood vessels, but nerve endings reach in among its cells.

Dermis The deeper layer of the skin, tough with fibres, where blood vessels and the fibres of sensory neurons run.

Free nerve endings The bare, branched tips of a sensory neuron among the cells of the epidermis. Some detect harm: heat, acid or certain chemicals.

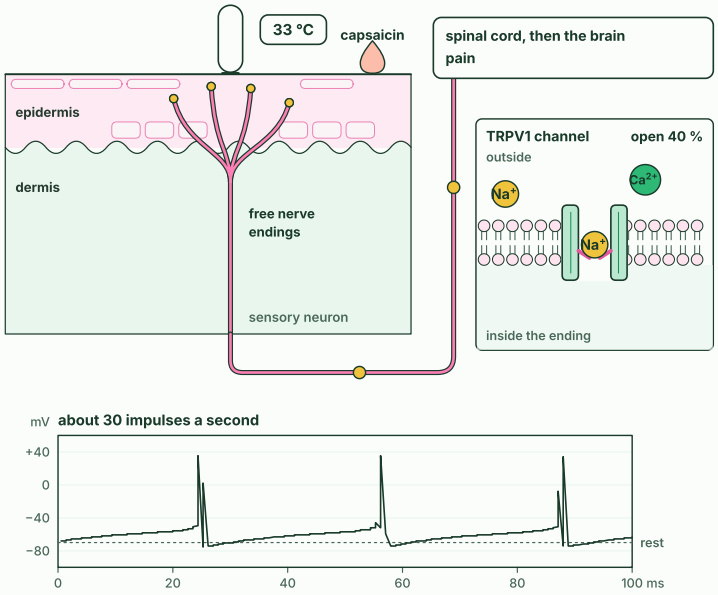
Epidermis The outer layers of the skin: living cells below, flattened dead cells at the surface. It has no blood vessels, but nerve endings reach in among its cells.

Free nerve endings The bare, branched tips of a sensory neuron among the cells of the epidermis. Some detect harm: heat, acid or certain chemicals.

A channel for positive ions A protein in the membrane of the ending. It is closed at rest and opens to a harmful stimulus; then positive ions flow in and depolarize the ending.

Dermis The deeper layer of the skin, tough with fibres, where blood vessels and the fibres of sensory neurons run.

A channel for positive ions A protein in the membrane of the ending. It is closed at rest and opens to a harmful stimulus; then positive ions flow in and depolarize the ending.

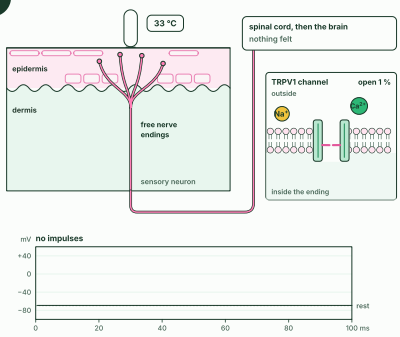


A free nerve ending in the skin. Raise the temperature until it fires, then add acid or capsaicin and find where it fires now. Count the impulses each second as you go.

STEP BY STEP

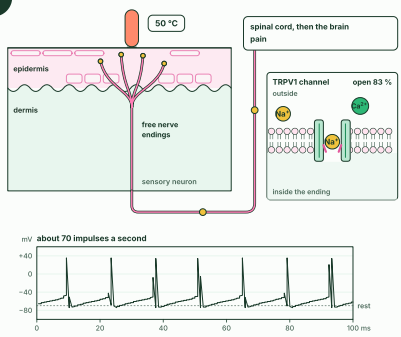
3 STEPS

1



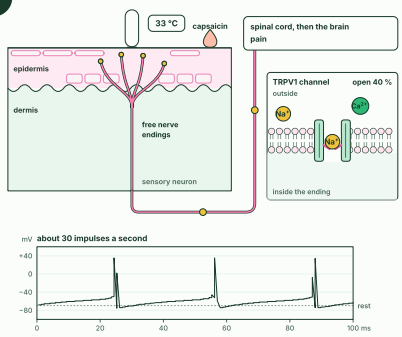
A **free nerve ending** in the skin, at skin temperature (about 33 °C). Its TRPV1 channels, which let positive ions in, are almost all closed: no impulses.

2



A probe at 50 °C. Heat opens the channels; sodium and calcium ions flow in, the ending reaches the **threshold**, and impulses travel along the sensory neuron, about 70 a second. In the brain, they are felt as **pain**.

3



Back at 33 °C, with **capsaicin**, from chilli peppers. It opens the same channels with nothing hot: impulses again, and the brain feels burning. Acid opens them too.

PREDICT

Chilli on a person's tongue feels hot, though nothing in their mouth is any warmer. Why?

(A) It warms the surface of the tongue by a few degrees, and the nerve endings there detect the rise in temperature

(B) It destroys cells on the tongue, and the damaged cells themselves send the pain signal to the brain

(C) It blocks the sodium-potassium pump in the endings, so the neurons fire without any real stimulus at all

(D) Its capsaicin opens the same channels that heat opens, so the endings fire and the brain reads it as heat

Decide before you look. Answer on page 74.

WATCH OUT

"Pain is felt in the hand." It is detected there and perceived in the brain. "A pain signal is a bigger impulse than a touch signal." Impulses are all the same size; pain comes from which neurons fire and how often. "Chilli burns the tongue." At the strength in food it only feels like a burn; nothing is warmer and nothing is damaged.

GO FURTHER

The heat and capsaicin channel is called TRPV1; it opens above about 43 °C, and acid makes it open at lower temperatures. Pain-sensing neurons are called nociceptors. Neither name is needed for the exam.

C2.2.16 HL CONSCIOUSNESS AS A PROPERTY THAT EMERGES FROM THE INTERACTION OF INDIVIDUAL NEURONS IN THE BRAIN

16 More than *the sum of its cells*

Every chapter so far has been about one neuron, or two. Each does something simple: it adds its inputs and fires or does not. Yet your brain, about 86 billion of them, is aware of the world and of itself.

That awareness, **consciousness**, is not in any single neuron. It is an **emergent property**: something the system has that none of its parts has, which arises from how the parts interact.

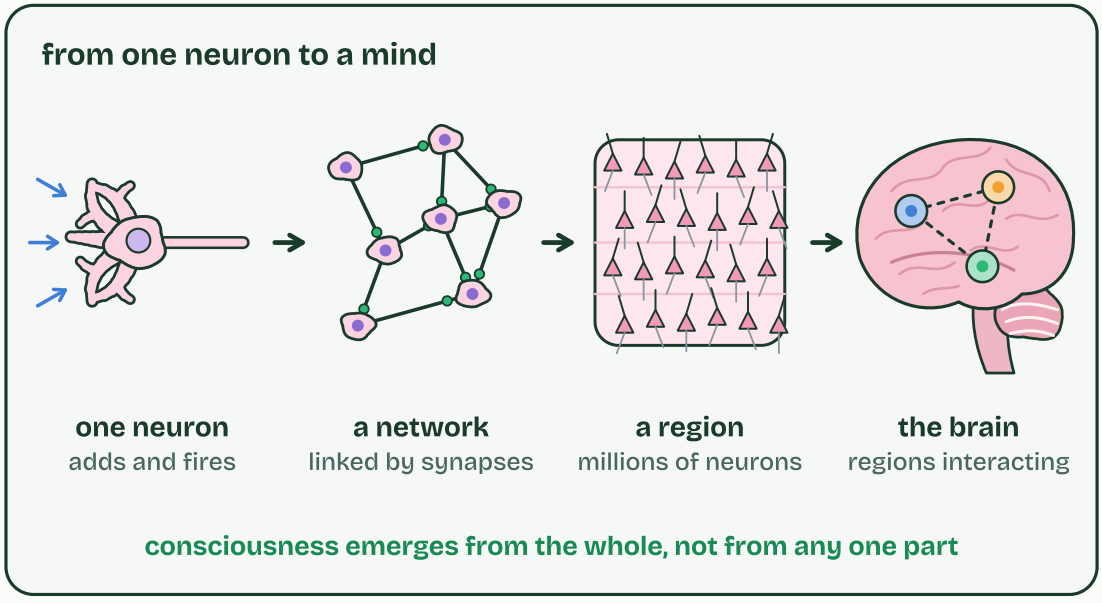
Emergent properties are everywhere in biology. One heart muscle cell twitches; billions of them, linked, make a heartbeat that pumps blood. One water molecule is not wet. One bird does not make the shape of a flock. In each case the property comes from the interactions, and you cannot find it by looking at a part alone. The same is true of the brain: neurons are linked into networks, networks into regions, regions into a brain, and at each level something new appears.

No one yet knows how consciousness arises from neurons, and the IB does not ask you to. What you can say is that it depends on interaction: on the synapses, the summing and the networks of the last few chapters, working together on an enormous scale.

KEY TERMS

consciousness
Being aware of yourself and your surroundings: a property of the brain as a whole, not of any one of its neurons.

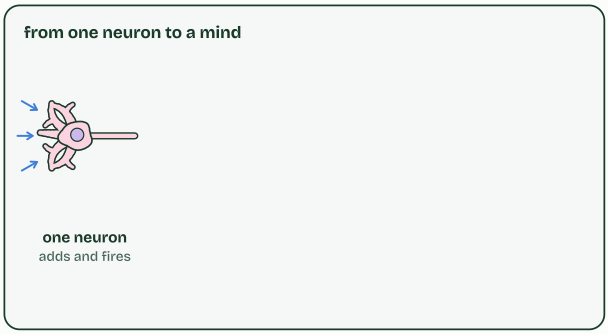
emergent property
A property that a system has, which comes from how its parts interact and which none of the parts has on its own.



STEP BY STEP

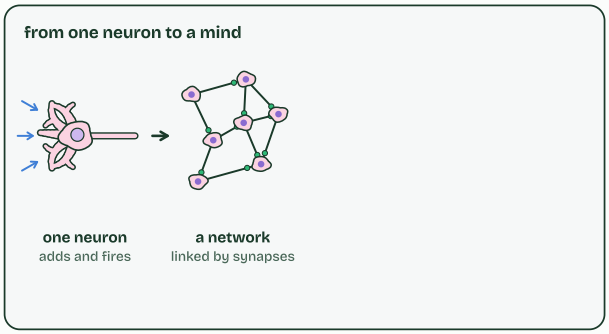
4 STEPS

1



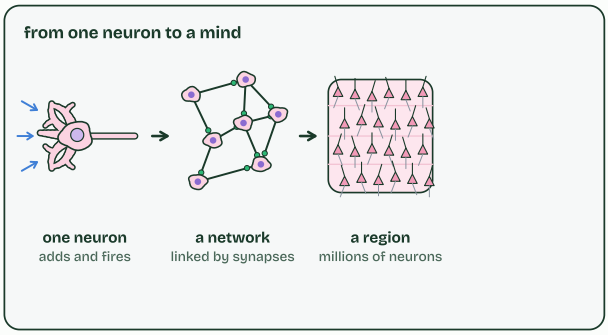
One neuron does something simple: it adds its inputs and fires, or it does not (chapter 14).

2



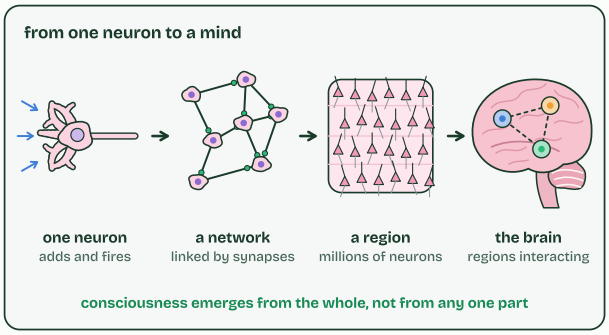
Neurons linked by synapses make a **network**. A network can do what no single neuron can, such as pick out a pattern in its inputs.

3

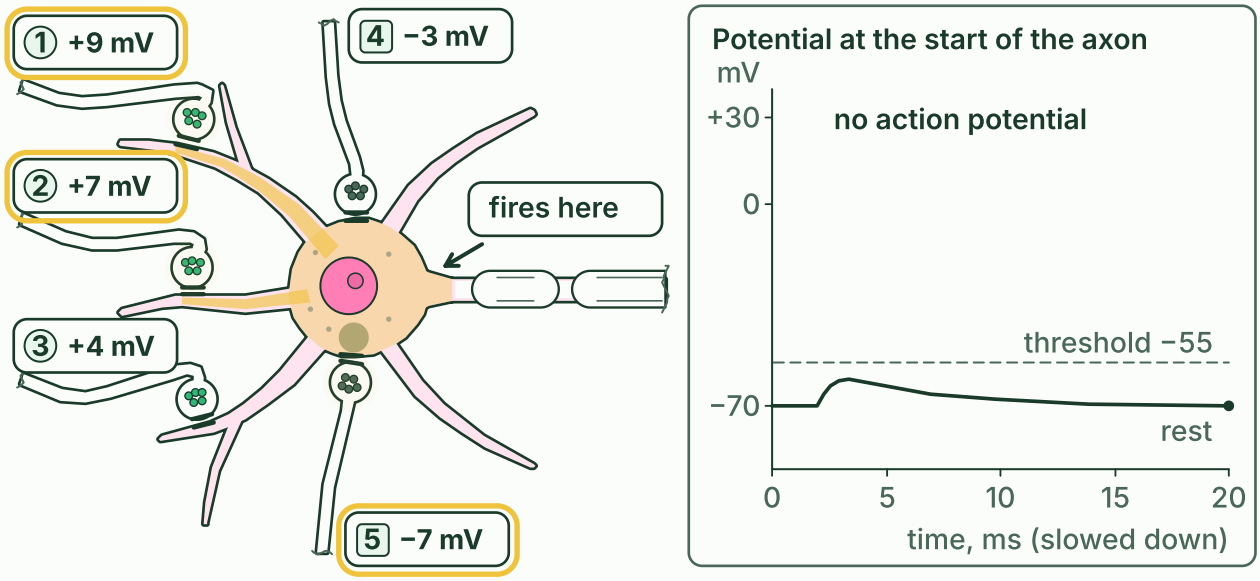


Millions of neurons and their networks make a **region** of the brain, which handles one kind of task, such as vision or movement.

4



Regions **interacting** make a brain that is aware of itself and its surroundings. Consciousness emerges from the interactions; it is in no one part.

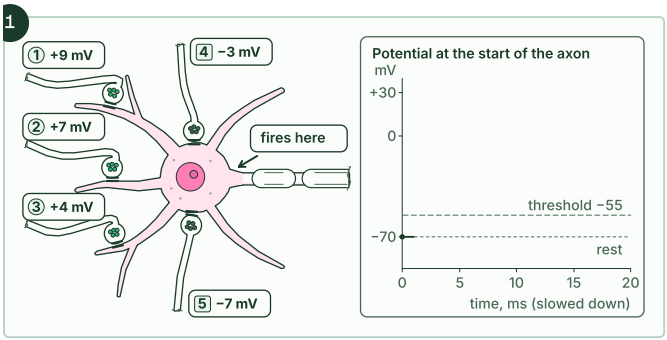


One neuron on its own: a single input fired again and again. Change the gap between impulses and see when they add. This is all one cell can do; the brain is billions of them doing it together.

STEP BY STEP

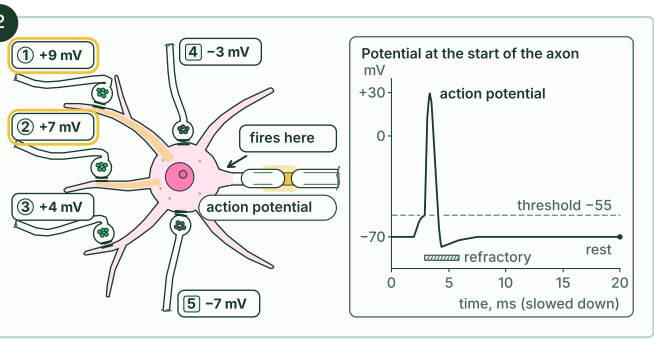
3 STEPS

1



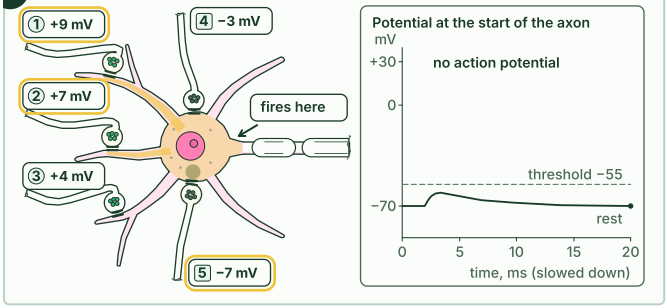
One neuron, 5 inputs. The excitatory ones (+9, +7 and +4 mV) and the inhibitory ones (−3 and −7 mV) each change the potential at the start of the axon, which is −70 mV at rest.

2



Inputs 1 and 2 fire together: +9 and +7 add to +16 mV, taking the start of the axon past the threshold (−55 mV). An action potential fires and leaves along the axon.

3



Add input 5 (−7 mV): the total is only +9 mV, below the threshold, so no action potential fires. The response is all or nothing.

PREDICT

Could you find the one neuron in a person's brain that holds their consciousness?

(A) Yes, in the oldest part of the brain, because every higher function starts in one control cell there

(B) No, because consciousness is a property of huge numbers of neurons interacting, not of any one

(C) Yes: it is the neuron with the most synapses, because that one adds together all of the inputs

(D) No, because consciousness is not physical at all, so it cannot be found anywhere in the body

Decide before you look. Answer on page 74.

WATCH OUT

"Consciousness is in one place in the brain." It depends on many regions interacting. "Scientists have explained consciousness." They have not: it is one of the great open questions in biology.

LONG ANSWERS: THE THREE THAT COME UP MOST

17 Three big ideas, *point by point*

The action potential, how an impulse moves along a fibre, and how a synapse passes it on are the long-answer questions this topic is best known for. Each is a sequence, and the marks go to the steps, in order, in the right words. Write one step per sentence, in the order below, and you will rarely miss a mark. The sentence under each list gives you the order: the first letter of each word is the first letter of a step. Tap a tile to turn it over.

AN ACTION POTENTIAL

1. **Rest:** the inside is negative, about −70 mV; the Na^+/K^+ pump uses ATP to move 3 Na^+ out and 2 K^+ in, keeping the gradients.
2. **Threshold:** a stimulus depolarizes the membrane to the threshold, about −55 mV.
3. **Open:** voltage-gated Na^+ channels open.
4. **Depolarization:** Na^+ diffuses in, down its gradient, and the inside becomes positive, about +30 mV.
5. **Switch:** the Na^+ channels close and voltage-gated K^+ channels open.
6. **Repolarization:** K^+ diffuses out and the inside becomes negative again.
7. **Hyperpolarization:** the K^+ channels close slowly, so the potential dips below −70 mV before it settles.
8. **Pump:** the Na^+/K^+ pump maintains the gradients, so the neuron can fire again.

Remember it Rabbits Tunnel Out, Dig, Sleep, Rise, Hop, PlayRabbits Dig, Rise, Play

AN IMPULSE MOVING ALONG A FIBRE, AND SALTATORY CONDUCTION

1. **Depolarized:** at the action potential Na^+ has diffused in, so that region of the axon is depolarized.
2. **Local current:** Na^+ diffuses along the inside to the next, resting region, and positive ions move the other way outside.
3. **Threshold:** the next region is depolarized to the threshold, about −55 mV.
4. **Fires:** the next region fires an action potential in turn, as its voltage-gated Na^+ channels open, so the impulse is propagated along the fibre at the same size.
5. **Refractory:** the region behind cannot fire again yet, as its Na^+ channels are still resetting, so the impulse travels one way.
6. **Myelin:** a myelin sheath insulates the axon between the nodes of Ranvier, so no ions cross the membrane there, so an impulse is far faster in a myelinated fibre than in an unmyelinated one.
7. **Nodes:** Na^+ channels and pumps are clustered at the nodes of Ranvier.
8. **Saltatory:** the local current reaches the next node, so the action potential jumps from node to node: saltatory conduction, far faster than in an unmyelinated fibre.

Remember it Dogs Like Treats, Fetch, Run, Munch, Nap, SnoreDogs Fetch, Munch

ACROSS A SYNAPSE

1. **Arrives:** an action potential arrives at the presynaptic terminal and depolarizes its membrane.
2. **Channels:** voltage-gated Ca^{2+} channels open.
3. **Calcium:** Ca^{2+} diffuses into the terminal, down its gradient.
4. **Vesicles:** vesicles of neurotransmitter fuse with the presynaptic membrane and release it into the cleft by exocytosis.
5. **Diffuses:** the neurotransmitter diffuses across the synaptic cleft.
6. **Binds:** it binds to transmembrane receptors on the postsynaptic membrane.
7. **Opens:** the receptor's channel opens, Na^{+} diffuses in and the postsynaptic membrane is depolarized: an excitatory postsynaptic potential.
8. **Removed:** the neurotransmitter is removed from the cleft: acetylcholinesterase breaks acetylcholine into choline and acetate; others, such as dopamine, are taken back by reuptake.

Remember it All Cats Can Very Delicately Balance On Rooftops

-
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Each list is the full story; a question worth fewer marks wants fewer steps, so match the number of points to the marks. Name the ion and the direction every time (Na^{+} in, K^{+} out, Ca^{2+} in), and say *diffuses*, not *is pumped*, for any ion moving through a channel.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

acetylcholine 11
A neurotransmitter used at many synapses, including every neuromuscular junction, where motor neurons meet skeletal muscle fibres.

acetylcholinesterase 11
An enzyme in the synaptic cleft that breaks acetylcholine into choline and acetate, ending its signal.

action potential 03
A brief reversal of the membrane potential at one place on a nerve fibre, which sets off the same reversal in the next stretch of membrane: a nerve impulse.

axon 01
The single long fibre of a neuron, which carries impulses away from the cell body to its terminals.

cell body 01
The part of a neuron that holds the nucleus and most of the cytoplasm and organelles. The nerve fibres project from it.

coefficient of determination 07
R squared: the share of the variation in the dependent variable that goes with the independent variable along a straight line. 0.81 means 81 per cent.

concentration gradients 02
A difference in concentration between two places. Ions diffuse down it, from where they are more concentrated to where they are less, if they can cross.

consciousness 16
Being aware of yourself and your surroundings: a property of the brain as a whole, not of any one of its neurons.

correlation coefficient 07
Pearson's r: a number from -1 to +1 for how closely points on a scatter graph follow a straight line. The sign is the direction; the size is the strength.

dendrites 01
The short, branched fibres of a neuron, which receive signals from other cells.

depolarization 03
A change in membrane potential that makes the inside less negative than at rest, and in an action potential positive.

effector 09
A cell that carries out the body's response to a signal: a muscle fibre that contracts, or a gland cell that secretes.

emergent property 16
A property that a system has, which comes from how its parts interact and which none of the parts has on its own.

excitatory postsynaptic potential 11
A small depolarization of a postsynaptic membrane, caused by an excitatory neurotransmitter, that makes the cell more likely to fire.

exocytosis 10
Release of a vesicle's contents from a cell: the vesicle fuses with the plasma membrane and opens to the outside.

exogenous 12
Made outside the body: a drug, a pesticide or a poison that enters it.

free nerve ending 15
The branched, bare end of a sensory neuron in the skin, with no special structure around it. Some detect pain.

giant axon 07
A very wide unmyelinated axon, up to about a millimetre across in a squid, which carries the impulse for the squid's escape jet.

hyperpolarized 13
Made more negative inside than at rest, so further from the threshold potential.

impulses 01
An electrical signal conducted along a nerve fibre: an action potential.

inhibitory postsynaptic potential 13
A small hyperpolarization of a postsynaptic membrane, caused by an inhibitory neurotransmitter, that makes the cell less likely to fire.

local current 05
The flow of ions inside and outside an axon between a stretch that is firing and the resting stretches next to it, which depolarizes them towards threshold.

membrane potential 02
The voltage across a cell's plasma membrane: the inside compared with the outside, in millivolts (mV).

myelin sheath 07
Layers of a supporting cell's membrane wound tightly round an axon, which stop ions crossing the axon membrane under them.

nerve fibres 01
Long thin projections of a neuron, along which impulses are conducted: its axon and its dendrites.

neuron 01
A nerve cell: a cell of the nervous system that carries electrical impulses along its fibres.

neurotransmitter 09
A chemical released from a presynaptic terminal that crosses the synaptic cleft and binds to receptors on the postsynaptic cell.

node of Ranvier 08
A short gap in the myelin sheath, about a micrometre long, where the axon membrane is bare. Gaps come every millimetre or so along a myelinated axon.

oscilloscope 06
An instrument that draws a voltage against time as a line across a screen.

polarized 02
Having a difference in charge across it, one side more positive than the other. The IB spells it with a z.

postsynaptic 09
After the synapse: the cell whose membrane carries the receptors for the neurotransmitter.

presynaptic 09
Before the synapse: the neuron whose terminal releases the neurotransmitter.

propagated 03
Passed on along a nerve fibre, each stretch of membrane setting off the next.

resting potential 02
The membrane potential of a neuron that is not sending an impulse: about -70 mV, the inside negative.

reuptake 12
Taking a neurotransmitter back into the presynaptic neuron from the cleft, by a carrier protein in its membrane.

saltatory conduction 08
Conduction of an impulse along a myelinated axon by action potentials at the nodes of Ranvier only, the impulse jumping from node to node.

sodium-potassium pump 02
A protein in the plasma membrane that uses the energy of one ATP to move three sodium ions out of the cell and two potassium ions in, both against their concentration gradients.

summation 14
Adding together the effects of all the excitatory and inhibitory inputs arriving at a postsynaptic neuron.

synapse 09
A junction where a neuron passes a signal to another neuron or to an effector cell, by releasing a chemical across a small gap.

synaptic cleft 09
The narrow gap, about 20 nm wide, between the presynaptic membrane and the postsynaptic membrane at a synapse.

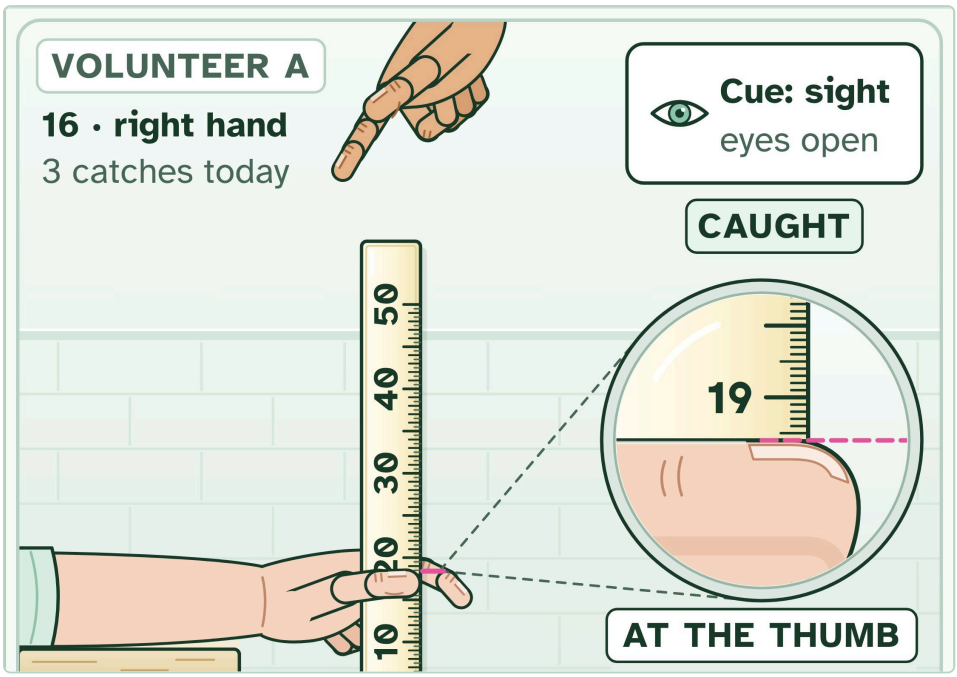
threshold potential 04
The membrane potential at which voltage-gated sodium channels open and an action potential starts: about -55 mV.

transmembrane receptors 11
A protein that binds a particular signalling chemical. A transmembrane receptor spans the membrane, so what binds outside changes what happens inside.

voltage-gated channels 04
A channel protein in the membrane that opens or closes when the voltage across the membrane changes.

Dry lab: *Reaction time*

A volunteer catches a falling ruler, and how far it drops tells you how long the catch took. Change what starts the catch, the hand, a distraction, a warning or practice, then plan and write it up as an investigation with the coach beside you.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-c2-2-neural-signalling#lab`

Your question

How does one condition change how quickly a person reacts? The bench starts with the stimulus: is a catch quicker when the volunteer sees the ruler go, hears a click, or feels a tap on the shoulder?

What you can change

One independent variable at a time: the stimulus (sight, sound or touch), the hand (the one they write with or the other), a distraction (none, or counting backwards in threes aloud), a warning before the drop, or the number of tries. Keep the rest the same: the same ruler, the same starting gap between the fingers, the same volunteer seated the same way, and the same warning before each drop.

What to record

The distance the ruler falls before it is caught, in cm, for every try; turn each into a time with the free-fall equation once, by hand, then with the strip. At least five tries at each value, a mean and a standard deviation, and a graph of the means with error bars. The volunteers are simulated profiles, never real people; in class, a volunteer agrees first and may stop at any time.

Find out

- **Sight, sound or touch?** The same volunteer catches with each cue: watching the ruler go, hearing “now” as it is let go, or feeling a tap on the shoulder. Five practised catches at each.
- **Does the hand matter?** The hand they write with against the other, everything else the same.
- **Does a second task slow it?** No distraction against counting backwards in threes aloud while they wait.
- **Warned or not?** A random wait before the drop against a spoken count with the drop on its beat. Watch the catches that come too soon.
- **Do they get faster?** Record every catch in order from the very first, and plot the time against the try number.

Record

- For every catch: the volunteer, the value of the variable you changed, and the settings you kept the same.
- The distance the ruler fell, read at the top of the thumb to the nearest millimetre.
- Turn it into a time once by hand: $t = \sqrt{(2d \div g)}$, with d in metres and $g = 9.81\ m\ s^{-2}$. A fall of 19.6 cm is 0.200 s. Then let the strip do the rest.
- At least five catches at each value, after a few practice catches, with a mean and its standard deviation. Leave out a false start or a miss, and say how many you left out and why.
- The table and the graph fill in as you record, or download the CSV and plot your own. When you are done, the IA coach below the dry lab helps you write it up as an investigation.

Your question How does one condition change how quickly a person reacts? The bench starts with the stimulus: is a catch quicker when the volunteer sees the ruler go, hears a click, or feels a tap on the shoulder?**What you can change**One independent variable at a time: the stimulus (sight, sound or touch), the hand (the one they write with or the other), a distraction (none, or counting backwards in threes aloud), a warning before the drop, or the number of tries. Keep the rest the same: the same ruler, the same starting gap between the fingers, the same volunteer seated the same way, and the same warning before each drop.**What to record**The distance the ruler falls before it is caught, in cm, for every try; turn each into a time with the free-fall equation once, by hand, then with the strip. At least five tries at each value, a mean and a standard deviation, and a graph of the means with error bars. The volunteers are simulated profiles, never real people; in class, a volunteer agrees first and may stop at any time.

Back to neurons

A catch takes about 0.2 s, yet impulses cross a metre of nerve in a few hundredths of a second. Use your results to explain where the rest of the time goes.

QUESTIONS ON THE LAB

QUESTION 1

A volunteer’s first two catches are clearly slower than the rest. What should you do with them?

(A) Keep them in the mean, because leaving out any reading at all makes the results less honest

(B) Treat them as practice and start recording after them, the same way for every volunteer

(C) Replace them with the class mean, so that every value of the variable has the same count

(D) Use only those two, because a first catch is the true reaction time before any learning

Answer on page 74.

QUESTION 2

With a spoken count and the drop on the beat, one volunteer sometimes catches the ruler only 2 cm down. What is going on?

(A) They have unusually fast neurons, and these are their true reaction times at their very best

(B) The ruler slipped from the partner's fingers early, so it had less far to fall each time

(C) They are guessing the moment from the count and closing their fingers before they see it fall

(D) Sound reaches the brain faster than light does, so a spoken count gives far quicker catches

Answer on page 74.

QUESTION 3

About a metre of nerve runs from the eye, through the brain, to the finger muscles, and impulses in these nerves go at tens of metres a second. A catch takes about 0.2 s. Where does most of that time go?

(A) Along the nerve fibres, because a metre at tens of metres a second takes most of a second

(B) In the ruler, because it takes a while to start falling once the partner's fingers open

(C) In the muscles alone, because a muscle can only contract a fixed time after the signal arrives

(D) At synapses and in the brain, because conduction along the fibres takes only a few hundredths

Answer on page 74.

WRITE IT UP AS AN INVESTIGATION

Your results from this dry lab can be written up the way an IB scientific investigation is: four criteria, each worth 6 marks. Tick each line as your write-up does it. The coach on the page checks these as you go; it never gives a mark.

1 Research design

A focused question set in its biology; your choices of what to measure, how, over what range and how often, explained rather than listed; what you kept the same and how; safety, ethics and the environment; a method someone else could follow and repeat.

- [ ] My question names what I changed.
- [ ] It gives the range I used, with units.
- [ ] It names what I measured and how.
- [ ] It names the organism or system.
- [ ] My background explains, with the biology, why the two should be linked.
- [ ] I cite my sources, and each reference can be traced.
- [ ] If I give a hypothesis, it predicts and explains.
- [ ] Every variable has its How, Why and Units.
- [ ] For each thing kept the same, I say how I kept it so.
- [ ] I list at least three things I kept the same.
- [ ] I name the apparatus that set what I changed, and the instrument that measured.
- [ ] I test enough values.
- [ ] My values spread wide enough.
- [ ] I run at least three trials at every value.
- [ ] I run a control.
- [ ] I explain why these values, this many and this often.
- [ ] Someone else could repeat my method.
- [ ] I deal with safety, ethics and the environment.

2 Data analysis

Raw data recorded clearly, with titles, units, uncertainties and the same decimal places down a column; what you saw as well as what you measured; processing that suits the question, shown with a worked example; the spread shown; a graph a reader can trust.

- [ ] Each table has a numbered title that says what it shows.
- [ ] Every heading has its quantity and its unit.
- [ ] Every raw data heading has its uncertainty.
- [ ] Each uncertainty is realistic for the instrument.
- [ ] Each uncertainty has the same decimal places as its readings.
- [ ] I record what I saw as well as what I measured.
- [ ] I show one worked example of my processing, and it is right.
- [ ] I say why I left out any trial.
- [ ] My error bars show a spread my repeats can support.
- [ ] My graph has a numbered title and labelled axes with units.
- [ ] I say what the error bars show.
- [ ] A straight line, if I draw one, has its R^2.
- [ ] A statistical test, if I run one, has its hypotheses and suits the data.

3 Conclusion

Your question answered from the processed data, with numbers quoted and the spread taken into account; the biology that explains the pattern; a comparison with published work; no claim bigger than the data.

- [ ] I answer my question in a sentence, naming both variables.
- [ ] I quote my processed numbers.
- [ ] I say how sure the spread lets me be.
- [ ] I say whether my hypothesis is supported.
- [ ] I explain the pattern with biology.
- [ ] I compare my result with published work, and cite it.
- [ ] I claim no more than my data show.

4 Evaluation

Weaknesses and limitations of this method (not slips in carrying it out), with evidence from your own data, the effect each had on the results, which mattered most and why, and a realistic improvement for each.

- [ ] I give at least three weaknesses or limitations.
- [ ] Every row is filled in.
- [ ] No slips in carrying it out: weaknesses of the method itself.
- [ ] Each improvement is specific: which instrument, how many, what changes.
- [ ] Each effect says what it did to my data.
- [ ] At least two rows point to evidence in my own data.
- [ ] At least one limitation: what this experiment cannot tell me.
- [ ] I say which mattered most, and why.
- [ ] I deal with what stands out in my data.
- [ ] My improvements improve this investigation, not a new one.

Variables

Variable	How?	Why?	Units
Independent: cue (stimulus)			
Dependent: reaction time			
Kept the same: hand used			
Kept the same: distraction			
Kept the same: warning			
Kept the same: practice			
Kept the same: the same volunteer			
Kept the same: the ruler and where its zero sits (level with the top of the thumb)			
Kept the same: the gap between finger and thumb at the start			
Kept the same: the forearm resting on the table, the hand over its edge			
Kept the same: the same partner dropping the ruler, the same way			
Kept the same: practice catches before the recorded ones			
Kept the same: the time of day and a quiet room			

Evaluation

Weakness or limitation	Which?	Evidence in my data	Effect on my results	Improvement

Data generated with the reaction time dry lab, biologybybradford.com (a simulation: the volunteers are invented profiles, not real people). These checks catch what is missing. They cannot judge how good it is: that is what your teacher does.

Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on C2.2 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=C2.2&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 The motor neuron that moves a toe muscle has its cell body in the lower spinal cord. Where is its axon?

C **Running all the way from the cord to the toe muscle, one thread about a metre long in a tall adult**

One axon runs the whole way. The cell body stays in the spinal cord and its axon reaches all the way down the leg to the muscle: about a metre in a tall adult, though the axon is only about a hundredth of a millimetre across. A neuron is one cell however long its axon is, and the impulse travels the whole length without being handed on.

02 A neuron's pumps are all switched off and it is left alone. What happens to the voltage across its membrane over a long time?

D **It runs slowly down towards zero, as the ions leak across and the gradients fade away**

It runs down towards zero. The pumps are what build the gradients and keep them: without them sodium slowly leaks in and potassium leaks out, the two sides become alike, and the voltage fades. It does not happen at once: the stores of Na^+ and K^+ on each side are so large that the leaks take a long time to even them out. The film below lets you switch the pump off.

03 An impulse sets off along an axon a metre long. Compared with where it started, how big is it when it reaches the far end?

B **Just as big, because every stretch of membrane it reaches makes a fresh impulse of its own**

Just as big. The impulse is not pushed along and does not run down: each stretch of membrane makes its own impulse, the full size, when the one next to it reverses. So it reaches the far end of a metre of axon exactly as big as it started.

04 A stimulus just strong enough fires a neuron. A second stimulus, twice as strong, then reaches the same neuron. What does its action potential look like?

C **The same size and shape, because once threshold is passed the channels make the same spike every time**

The same size and shape. Below the threshold there is no action potential at all; at or above it, the channels open and make the same spike each time. This is **all or nothing**. A stronger, steady stimulus does change something: it fires the neuron again and again, more times each second (chapter 6).

05 An axon is stimulated in its middle, not at one end. Which way does the impulse go?

B **Both ways at once, away from the stimulus, and neither wave can turn back on itself**

Both ways at once. The local currents spread both ways from the firing stretch, so two impulses run off in opposite directions. Neither can turn back, because the membrane each has just passed is in its refractory period, its sodium channels still resetting. In the body an impulse starts at one end, so it only ever goes one way, and the synapse at the far end (chapter 9) only passes signals one way too.

06 A trace shows 12 identical spikes in 3 seconds. What was the rate of impulses, and what would a stronger, steady stimulus have changed?

D **4 impulses a second, and a stronger stimulus would have raised that rate, with spikes of the same height**

4 impulses a second: 12 spikes ÷ 3 seconds. Spikes are all or nothing, so a stronger stimulus never makes them taller; it fires them more often, and the rate goes up. That rate is how a neuron tells the brain how strong a stimulus is.

07 Two axons are the same diameter. One has a myelin sheath and the other has none. Which carries impulses faster?

C **The myelinated one, because the sheath insulates the axon, so its impulses are conducted far faster than in a bare one**

The myelinated one, by a long way. At the same diameter a myelinated fibre is tens of times faster than a bare one. The sheath stops ions crossing under it, so the impulse fires only at the gaps and the local current jumps the stretch between them. How the sheath does it is higher level (chapter 8).

08 In a myelinated axon the nodes are about a millimetre apart. Imagine an axon whose nodes were ten centimetres apart instead. What would happen to an impulse?

A **It would stop, because the local current fades before it can bring the next node to threshold**

It would stop. The current that flows under the sheath fades with distance. With nodes about a millimetre apart it still brings the next node to threshold; ten centimetres on, it would be far too weak, and the impulse would die out between two nodes.

09 A neurotransmitter carries a signal across a synapse. Why can the postsynaptic cell not send a signal back the same way?

B **Only the presynaptic terminal has vesicles of the transmitter to release, and only the postsynaptic membrane has the receptors that respond**

The two sides are built differently. Only the presynaptic terminal has vesicles of the neurotransmitter, and only the postsynaptic membrane has receptors for it. A signal can only go from the side that releases to the side that receives, so a typical synapse works one way.

10 A toxin blocks the calcium channels in a presynaptic terminal. An impulse arrives. What happens at the synapse?

C **The vesicles never fuse, no neurotransmitter is released, and the next cell gets no signal**

Nothing crosses. The impulse still arrives and the terminal depolarizes, but with its calcium channels blocked no calcium comes in, and without calcium the vesicles do not fuse with the membrane. No neurotransmitter is released, so the signal stops at the synapse.

11 The enzyme that breaks down acetylcholine in the cleft stops working. What happens to the postsynaptic membrane after one impulse?

B **It stays depolarized, because acetylcholine keeps binding and the receptors stay open, so it cannot reset**

It stays depolarized. Acetylcholine left in the cleft keeps binding the receptors, so their channels keep opening and the membrane cannot return to rest. The synapse can no longer pass on separate signals, one for each impulse. At a muscle the result is a muscle that will not relax properly, which is how nerve agents and organophosphate insecticides kill. (Neonicotinoids work differently: chapter 12.)

12 A drug blocks the carrier protein that takes a neurotransmitter back into the presynaptic neuron. What happens to the neurotransmitter?

D **It stays in the cleft for longer, so it keeps binding the receptors, and the signal is stronger and longer**

It stays in the cleft. With its way back blocked, the neurotransmitter builds up and goes on binding the postsynaptic receptors, so the next cell is stimulated more strongly and for longer than one impulse should cause. That is what cocaine does.

13 Acetylcholine makes a skeletal muscle fibre contract, yet the same chemical, released by a nerve onto the heart, slows it down. How can one neurotransmitter do both?

A **The heart cells have a different receptor for it, one that opens channels making their membrane more negative**

The receptor decides. Heart cells carry a different acetylcholine receptor, which opens potassium channels: K^+ flows out, the membrane goes more negative, the cells fire less often and the heart slows. Whether a neurotransmitter excites or inhibits depends on the receptor it binds, not on the chemical itself.

14 A neuron at −70 mV fires at −55 mV, so it needs +15 mV. Three excitatory inputs give +6 mV each and one inhibitory input gives −4 mV. All four arrive together. Does it fire?

C **No: three times +6 is +18, less 4 is +14, which is short of the +15 the neuron needs to fire**

No. The inputs add: +6 + 6 + 6 − 4 = +14 mV, which takes the membrane to −56 mV, one millivolt short of threshold. So there is no action potential at all. Take away the inhibitory input and the total is +18 mV: the neuron fires a full-size impulse, exactly the same as it would for +30.

15 Chilli on a person's tongue feels hot, though nothing in their mouth is any warmer. Why?

D **Its capsaicin opens the same channels that heat opens, so the endings fire and the brain reads it as heat**

Capsaicin opens the heat channels. The chemical in chilli peppers binds to the very channel in the free nerve endings that opens at a harmful temperature. The endings fire as they would for heat, and the brain, which only receives impulses, perceives burning. At the strength in food it only feels like a burn: nothing is warmer and nothing is damaged.

16 Could you find the one neuron in a person's brain that holds their consciousness?

B **No, because consciousness is a property of huge numbers of neurons interacting, not of any one**

No. Each neuron only adds and fires; consciousness comes from billions of them interacting through trillions of synapses. Take one neuron away and nothing changes; damage a large region and some part of experience may go.

QUESTIONS ON THE DRY LAB

Q1 A volunteer's first two catches are clearly slower than the rest. What should you do with them?

B **Treat them as practice and start recording after them, the same way for every volunteer**

Treat them as practice. People get quicker over their first few tries as they settle to the task, so the first catches measure the learning as well as the reaction. Decide before you start how many practice catches everyone gets, give the same number at every value of the variable, and say so in your method. Leaving them out by a rule set in advance is a fair procedure, the same for everyone; leaving out readings you do not like after you see them is not.

Q2 With a spoken count and the drop on the beat, one volunteer sometimes catches the ruler only 2 cm down. What is going on?

C **They are guessing the moment from the count and closing their fingers before they see it fall**

They are anticipating. A 2 cm fall is under a tenth of a second, too quick for the eye, the brain and the muscles to have responded to the ruler moving. With a predictable beat, a volunteer can start to close on the count itself. That is why a random wait before each drop is the usual control: nobody can time it.

Q3 About a metre of nerve runs from the eye, through the brain, to the finger muscles, and impulses in these nerves go at tens of metres a second. A catch takes about 0.2 s. Where does most of that time go?

D **At synapses and in the brain, because conduction along the fibres takes only a few hundredths**

Mostly at synapses and in processing. A metre at, say, 50 m s^{-1} takes 0.02 s. The rest goes on the eye turning light into impulses, many synapses in the brain, the brain deciding to act, and the muscles starting to contract. Every synapse adds a short delay, and a reaction passes through a great many of them.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.