Neural signalling

C2.2 · SL and HL

Electrical impulses and chemical junctions form one pathway

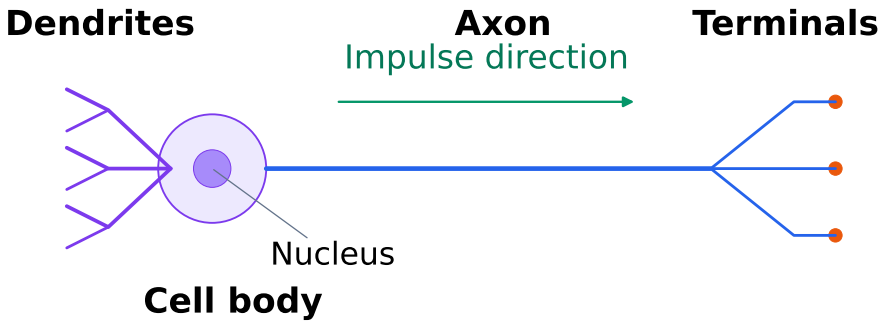
Follow a signal within a cell and between cells

Common C2.2: neuron structure, resting potential, impulses, conduction speed, correlation skills and chemical synapses.

Prerequisites: membrane transport, ion gradients and ATP. All numerical data and voltage traces are invented teaching models.

Use supplied traces or simulations rather than electrical stimulation of people.

Identify one cell before tracing its communication



An axon connects distant regions of one neuron.

Connect the regions with their functions

Region	Function and limit
Cell body	Nucleus, cytoplasm and machinery for maintaining the cell
Dendrites	Usually several branching receiving processes
Axon and terminals	One axon may branch and communicate with several targets
Nerve	Bundle of nerve fibres with support tissues; not one neuron

Ion movement makes neural signals electrical

A neuron is not a metal wire

Charged ions move in aqueous fluids and across selectively permeable membranes.

An impulse does not require one sodium ion to travel from cell body to terminal.

A long axon supports directed communication; supporting cells and metabolism also matter.

Explain a negative interior using both gradients and permeability

1. **Reference.** Membrane potential compares inside with outside. A representative resting value is -70 mV, not a universal constant.
2. **Maintain gradients.** ATP-dependent pumps export three sodium and import two potassium per standard cycle; sodium is higher outside, potassium inside.
3. **Selective movement.** Potassium leak permits outward diffusion; charge separation increasingly opposes further positive-ion loss. Low sodium permeability and intracellular anions contribute.

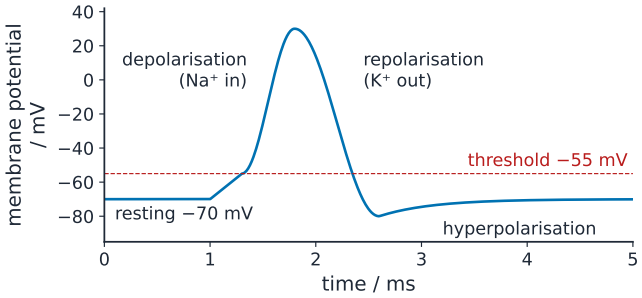
Distinguish a maintained gradient from a measured voltage

Feature	Interpretation
Pump	Uses ATP to maintain gradients; unequal charge transfer also contributes
Leak channels	Passive flow depends on electrochemical gradients
Bulk fluids	Both contain positive and negative ions; charge separation is small and near the membrane
At rest	No local impulse does not mean no transport or metabolism

Keep pump bookkeeping separate from voltage prediction

1. **Eight standard cycles.** 24 sodium out, 16 potassium in, eight ATP used.
2. **Net charge.** $24 - 16 =$ eight positive charges outward.
3. **Limit.** Counts alone do not determine -70 mV. Area, capacitance, concentrations and relative permeabilities are also needed.

An action potential



A brief undershoot, all within about 3 ms

Threshold distinguishes a local input from a travelling action potential

Regeneration prevents a long-distance signal simply fading away

An action potential is a brief self-propagating membrane-potential change.

Under stable conditions in one healthy fibre, threshold-crossing input triggers an approximately full impulse; subthreshold input does not produce a smaller travelling impulse.

Waveforms can differ between fibres or physiological conditions; all-or-none does not mean one universal trace.

Encode stimulus strength without making every spike taller

1. **Frequency.** A stronger sustained stimulus can increase impulses per second in a fibre.
2. **Recruitment.** Additional sensory neurons can become active; a nerve compound signal can therefore grow.
3. **Count example.** 30 impulses/0.50 s = 60 Hz. A count window differs from the first-to-last peak interval; specify the convention.

A propagation speed needs distance and travel time

1. **Invented recording.** Distance along the fibre 0.80 m; travel time 0.016 s.
2. **Equation.** Speed = distance/time = 0.80/0.016 = 50 metres/second.
3. **Limit.** A complete skin-to-muscle response includes receptor, synaptic and muscle delays; its total time does not isolate one axon.

Compare diameter and insulation without confounding them

Comparison	Explanation and control
Larger unmyelinated axon	Lower internal resistance can support faster conduction
Giant squid axon	Diameter supports fast conduction compared with small unmyelinated fibres
Myelinated fibre	Insulation can give high speed at smaller diameter
Fair test	Control temperature, species and myelination; body size alone is not a universal speed rule

Plot four invented comparable fibres before fitting a line

Diameter / micrometres	Speed / metres per second
10	1
20	2
30	2
40	5

Calculate Pearson correlation from paired deviations

1. **Means.** Diameter mean 25; speed mean 2.5.
2. **Supplied/recomputed sums.** Sum of paired deviation products 60; diameter squared deviations 500; speed squared deviations nine.
3. **Coefficient.** $r = 60/\sqrt{(500 \times 9)} \approx 0.894$: a strong positive linear association in these four pairs.

Interpret the coefficient of determination in its model

A fitted relationship is not a percentage causal contribution

For simple linear regression with an intercept, $R^2 = r^2 = 0.80$: 80% of sample speed variation is accounted for by the fitted diameter relationship.

This does not mean diameter causes 80% of every neuron's speed or predicts every new observation exactly.

A coefficient of -0.70 has $R^2 = 0.49$: squaring loses direction, so report the sign of r separately.

A coefficient cannot replace experimental design

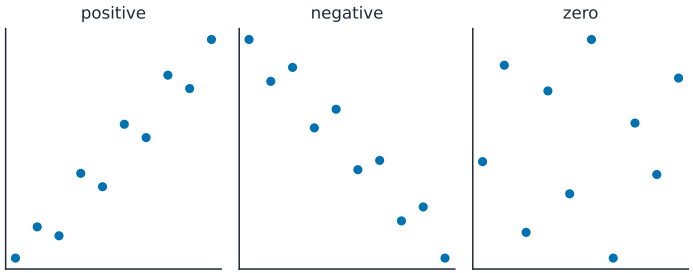
Linear strength, mechanism and sampling are separate issues

Near-zero Pearson correlation does not rule out a curved association. Plot the pairs and inspect outliers.

Standardize conditions and use independent fibres. Repeated timings of one fibre are not independent fibres.

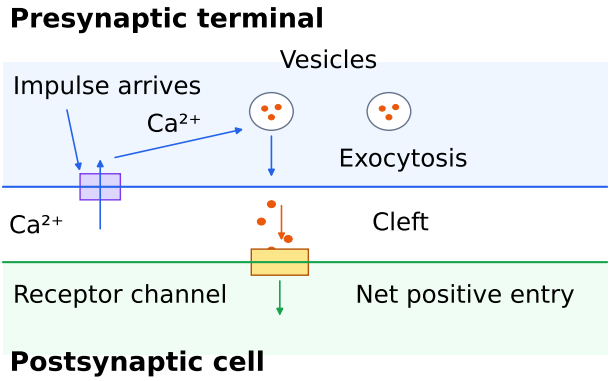
Four pairs, measurement uncertainty, confounding and a narrow sampled range restrict inference.

Positive and negative correlation



> Correlation does not show the mechanism

Separate terminal calcium entry from target receptor activation



Calcium triggers release; transmitter binds the target.

Trace the presynaptic sequence in causal order

1. **Arrival.** An **action potential** depolarizes the terminal and opens voltage-gated calcium channels.
2. **Internal signal.** Calcium enters down its electrochemical gradient; raised cytosolic calcium promotes vesicle fusion.
3. **Release.** Exocytosis releases neurotransmitter into the cleft; it diffuses to compatible target receptors.

Typical one-way transmission has a structural explanation

Random diffusion operates within an organized junction

Vesicles and release machinery are presynaptic; receptors for that signal are postsynaptic.

The target may be another neuron or an effector, such as a muscle cell at a neuromuscular junction.

Release, diffusion and receptor activation introduce delay. An action potential does not jump intact across the liquid gap.

Distinguish a graded EPSP from a new action potential

1. **Binding.** Acetylcholine opens nicotinic ligand-gated cation channels.
2. **Voltage.** Near rest, net positive current enters, with sodium entry important; the membrane depolarizes.
3. **Consequence.** An EPSP may remain below threshold. A new **action potential** needs sufficient depolarization in an excitable region; at a neuromuscular junction the target is muscle.

End a message so that the next one can be distinguished

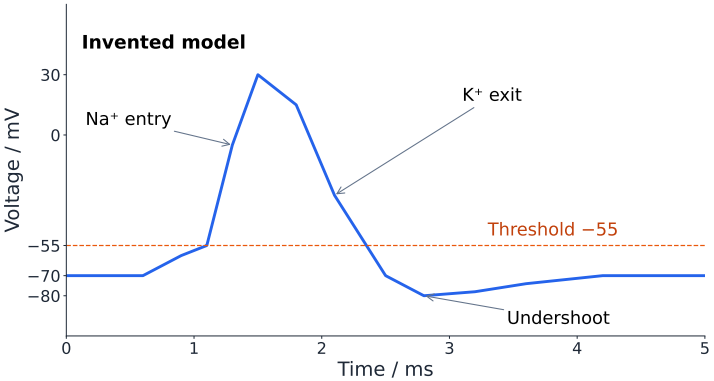
Removal mechanisms differ between transmitters

Acetylcholinesterase hydrolyses acetylcholine into choline and acetate.

Choline can be taken back for reuse; this differs from reuptake of every acetylcholine molecule intact.

Other transmitters can be removed by reuptake. Nicotinic channels also pass potassium; not every acetylcholine receptor is a sodium-only channel.

Read the voltage phases before assigning ion movements



Sodium entry dominates the rise; potassium exit supports the fall.

Explain threshold, rise and fall with channel behaviour

1. **Threshold and rise.** At -55 mV in this model, regenerative sodium-channel opening increases sodium entry and further depolarization.
2. **Fall.** Sodium-channel inactivation reduces entry; delayed potassium-channel opening increases potassium exit.
3. **Undershoot.** Persisting potassium conductance can take voltage below rest. Model peak $+30$ minus rest $-70 = 100$ mV; values are illustrative.

Pumps maintain gradients while channels produce rapid phases

Refractoriness begins during a spike

Each spike moves a small fraction of available ions. The pump does not suddenly reset every ion to cause the rapid downstroke.

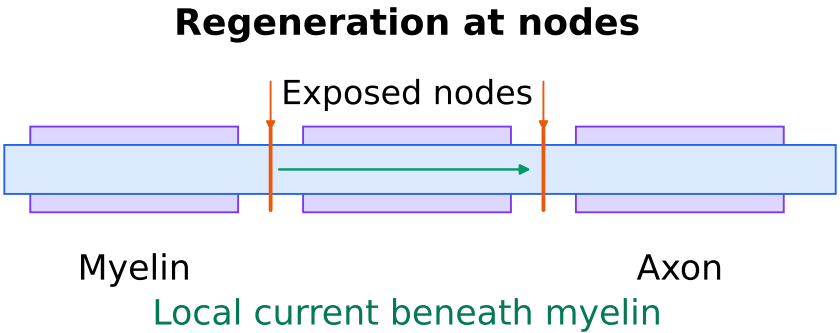
Sodium-channel inactivation prevents a second full spike during absolute refractoriness, including part of the ongoing spike.

Recovery and elevated potassium conductance can produce a relative refractory period requiring stronger excitation.

Local current brings adjacent excitable membrane to threshold

1. **Current spread.** Entering positive charge produces currents through nearby cytoplasm and extracellular fluid.
2. **Regeneration.** Adjacent membrane reaches threshold and opens its own voltage-gated channels; one group of sodium ions does not run the axon's length.
3. **Direction.** Recent membrane is refractory. Normal initiation/connectivity favour forward signalling; artificial middle-axon stimulation can propagate both ways.

Locate regenerated impulses at exposed nodes



Local current spreads beneath myelin; nodes regenerate the impulse.

Saltatory conduction changes where regeneration occurs

Insulation reduces internodal current loss and charging requirements

Myelin covers internodes; exposed nodes of Ranvier have concentrated voltage-gated channels and gradient-maintaining pumps.

Local current spreads continuously through fluids beneath myelin and brings the next node to threshold.

Node-to-node regeneration is described as jumping; ions do not fly across myelin or an empty gap.

Read time calibration before calculating firing frequency

1. **Scale.** 0.50 ms/division $\times$ four divisions $=$ 2.0 ms.
2. **Regular intervals.** A 10 ms peak interval is a period of 0.010 s; frequency $=$ $1/\text{period} = 100$ Hz.
3. **Different quantity.** A count in a stated window gives average firing frequency. Neither method alone supplies propagation speed.

Identify the target before describing disruption

Chemical	Target and mechanism
Neonicotinoids	Insect nicotinic receptors; persistent agonist activation can cause depolarization block
Cocaine	Dopamine transporter inhibition reduces dopamine reuptake
Important distinction	A receptor activating a response differs from a transporter removing a signal
Scope	Compound, receptor and exposure affect outcomes; these examples are not every possible drug action

A cellular experiment supports a mechanism within stated limits

Persistent activation can disrupt transmission

Palmer and colleagues studied isolated honeybee brain cells and found depolarization block and inhibited nicotinic responses with imidacloprid/clothianidin.

This supports a cellular mechanism under the studied conditions; it does not alone quantify population decline.

Cocaine can prolong extracellular dopamine availability by inhibiting removal; this is not acetylcholinesterase breakdown or nicotinic-receptor agonism.

Graded inputs combine at an impulse-initiation region

Inhibition can move the membrane farther from threshold

In a hyperpolarizing model, chloride entry or potassium exit makes the inside more negative; receptor and ion gradients determine the effect.

Temporal summation combines closely timed inputs from one source; spatial summation combines different input locations.

EPSPs and IPSPs are graded and decay. Some inhibition shunts excitation without a large voltage fall; real inputs need not sum linearly.

State an additive model before predicting threshold crossing

1. **Assumptions.** Rest -70 mV, threshold -55 mV; overlapping EPSPs $+8$ mV each.
2. **Excitation.** $-70 + 8 + 8 = -54$ mV: threshold crossed.
3. **With inhibition.** Add -6 mV: -60 mV, below threshold. Timing, location and conductance can alter real summation.

Trace a capsaicin stimulus without sending capsaicin to the brain

1. **Reception.** Free skin endings can have positive-ion channels responding to heat, acidity or capsaicin.
2. **Transduction.** Positive-ion entry depolarizes the ending; reaching threshold initiates action potentials.
3. **Perception.** Sensory pathways engage brain processing, where pain is perceived. Detection at an ending and conscious experience are distinct.

Consciousness concerns interactions among neuronal networks

An emergent property requires more than listing isolated cells

Individual neurons generate electrical responses, but one action potential is not itself a conscious thought.

Interactions among neurons and networks support integrated functions that cannot be read from one isolated cell part.

The detailed neural basis of conscious experience remains an active research question; emergence does not mean every mechanism is solved.

Attempt the common questions before checking

Keep voltage, frequency and propagation speed distinct

Explain neuron regions, resting gradients, all-or-none signals, frequency and recruitment.

Calculate pump transfers, count frequencies, travel speeds, Pearson r and R^2 with appropriate limits.

Trace calcium-dependent release, typical one-way synaptic transmission, acetylcholine EPSPs and removal.

Check the common calculations and their meanings

1. **Pump / impulses.** 12 cycles: 36 sodium out, 24 potassium in, 12 ATP and 12 net positive charges outward. $24/0.40 = 60$ Hz.
2. **Speed.** $1.20/0.020 = 60$ metres/second; a full reflex time includes extra delays.
3. **Correlation.** $60/\sqrt{4{,}500} \approx 0.894$; $R^2 = 0.80$. At $r = -0.70$, $R^2 = 0.49$. Linear fit does not prove causation.

AHL answers: trace scale, targets and summation

1. **Trace.** Six $\times$ 0.50 ms $= 3.0$ ms; $1/0.0030 \approx 333$ Hz. Model peak-minus-rest voltage is 100 mV.
2. **Targets.** Neonicotinoids act at insect nicotinic receptors; cocaine inhibits dopamine-transporter removal.
3. **Additive example.** $-70 + 9 + 9 = -52$ mV crosses -55 mV; adding -7 gives -59 mV, below threshold.

Check yourself

Use the named membrane, channel and measured quantity

A pump maintains gradients; passive channels allow ion current. Electrical signalling does not require electron flow along a metal wire.

An EPSP is graded and may be subthreshold. A typical synapse has presynaptic release machinery and postsynaptic receptors.

Impulse frequency is not speed, correlation is not causation, and a nerve is not one neuron.