Informatics 1 Cognitive Science

Lecture 5: Neurons

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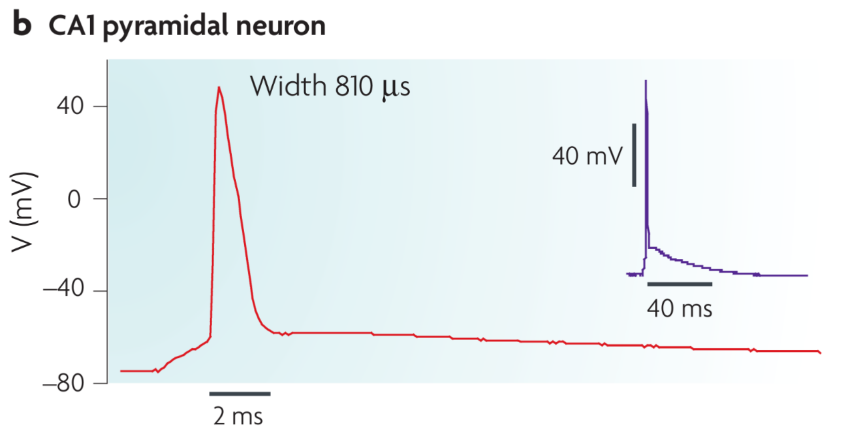
Overview

The Action Potential

Listening to a Neuron

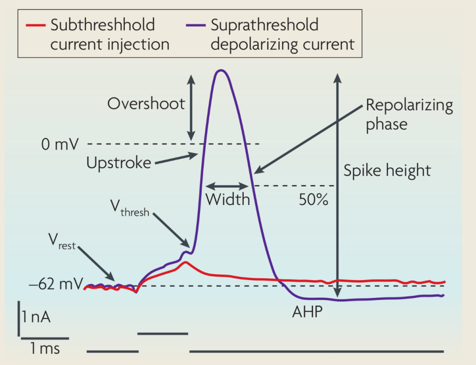
With tiny electrodes (micropipettes filled with electrolyte and containing an electrode) we can record electrical activity in single neurons.

The Action Potential (Spike)



- An inward current pulse depolarises the cell membrane.
- When the depolarisation exceeds a threshold, the neuron fires a spike.

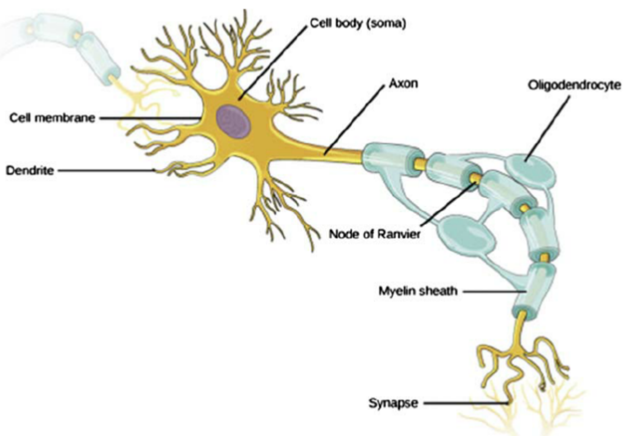
The Action Potential (Spike)



- An all-or-none electrical event in a neuron.
- A weak stimulus does not produce a weaker spike, but no spike.
- After a spike, the neuron is refractory for a short period and cannot spike again.
- The refractory period is a short hyperpolarisation of the membrane potential.

Anatomy of Neurons

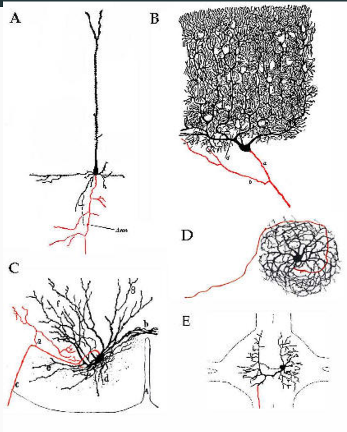
A Neuron



Neurons collect inputs through *dendrites*, and send signals (spikes) to other neurons via their *axons*.

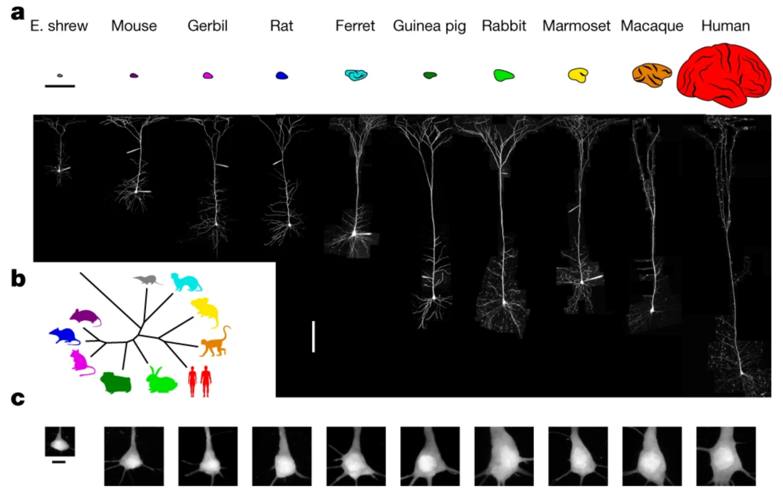
Anatomical Diversity of Neurons

- Neurons differ markedly in anatomy and physiology.
- Dendrites can be extensive, but are usually confined to 100s of micrometers (μm).
- Axons may transmit signals over long distances (up to meters), and to multiple targets.
- Communication in axons is fast with around 100 m/s.



A: Pyramidal cell, cortex; B: Purkinje cell, cerebellum; C: Motorneuron, spinal cord; D: Inferior olivary nucleus cell, E: Leech sensory neurons (red: axon, black: dendrites)

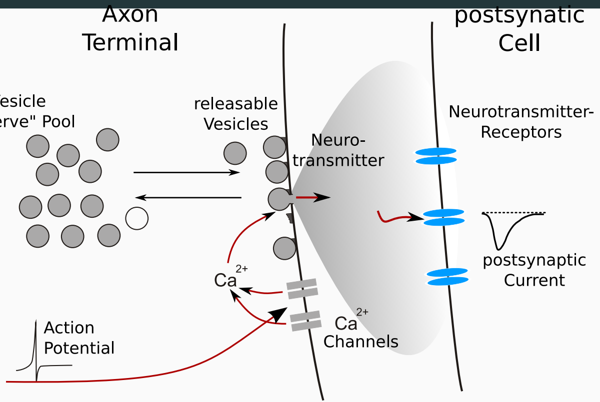
Neuron anatomy across species (Cortex)



Scale bars: 5cm top, 200 μm bottom. Beaulieu-Laroche et al. (2021). Nature, 600(7888), 274-278.

Communication between Neurons

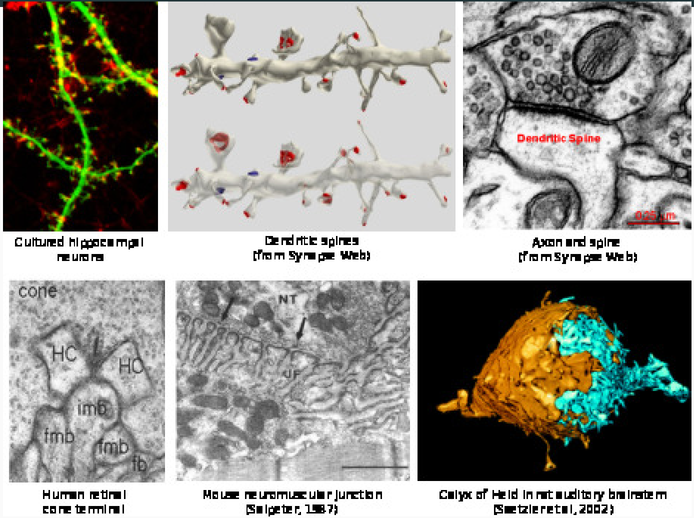
Synaptic Transmission between Neurons



A *synapse* is a specialised contact between axon and dendrite of two neurons. A spike causes *neurotransmitter release* at the synapse, which in turn changes the potential of the receiving neuron.

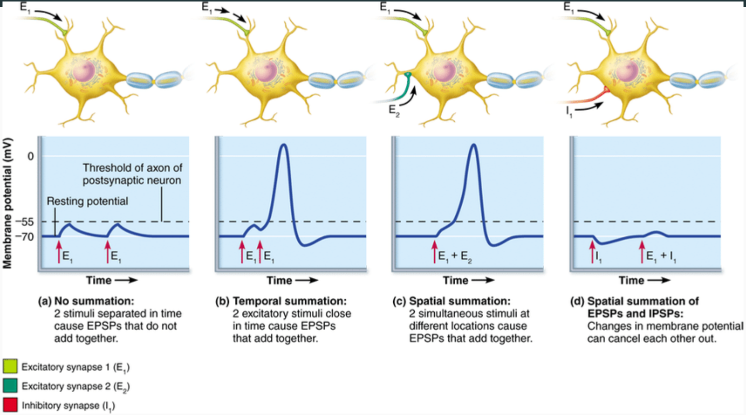
The strength of a synapse can vary: it depends on amount of transmitter released and number of postsynaptic receptors.

Anatomical Diversity of Synapses



A neuron may receive anywhere between 1 and 100,000 synaptic inputs.

Excitatory and Inhibitory Synapses

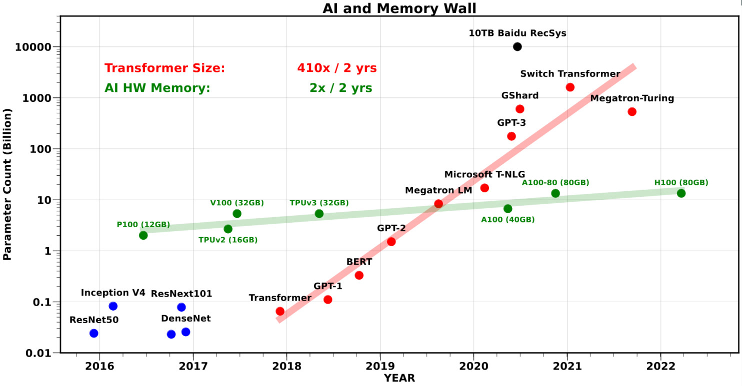


Synapses can *excite* (bring closer to spiking threshold), or *inhibit* the receiving neuron.

Dale's principle: Each neuron can *make* only either excitatory or inhibitory synapses.

A neuron will usually receive *both* excitatory and inhibitory inputs.

More synapses, better brains?



- Deep learning models (esp. LLMs): 1+ trillion parameters (weights).
- The human brain: 100 trillion synapses (weights).

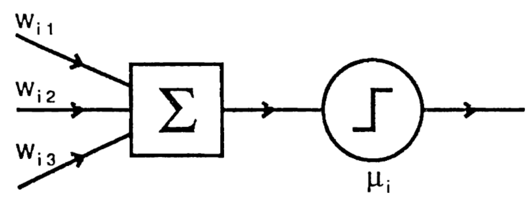
image from https://medium.com/riselab/ai-and-memory-wall-2cb4265cb0b8

The brain creates and eliminates synapses.

- A typical adult cortical neuron has around 10,000 synapses.
- During early development (synaptogenesis) and beyond, neurons and synapses are overproduced and eliminated.
- Cell loss: 25-40% or more (Finlay & Pallas, 1989).
- Collateral/synapse loss: ubiquitous (Purves & Lichtmann, 1980); in primate visual cortex alone around 5000 synapses/second are eliminated during adolescence (Bourgeois & Rakic, 1993).
- This is called pruning and has been linked to circuit refinement and specification.

Two Simple Neuron Models

The McCulloch-Pitts Neuron



- Activity is computed as: $n_i(t+1) = \Theta\left(\sum_j W_{ij} n_j(t) - \mu_i\right)$
- Threshold function: $\Theta(x) = (1 \text{ if } x \leq 0; 0 \text{ otherwise})$

Original publication: McCulloch, W. S., Pitts, W. H., 1943. Bull. Math. Biophys. 5, 115–133.

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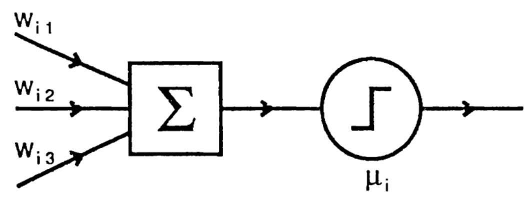

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- The weight w_{ih} determines the type/strength of each synapse. Dale's principle is not respected.

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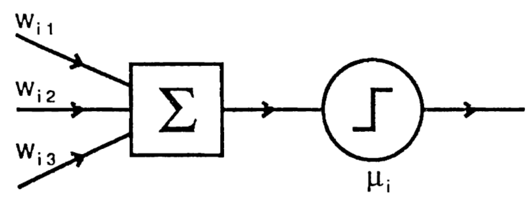

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- The neuron fires if the weighted sum $\sum_j W_{ij} n_j$ of the inputs reaches or exceeds the threshold μ_i.

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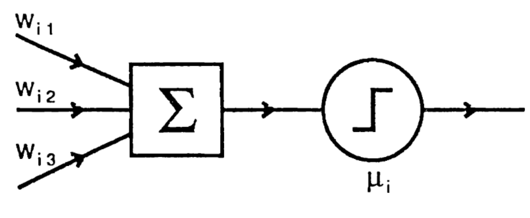

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- The weight w_{ih} determines the type/strength of each synapse. Dale's principle is not respected.
- The neuron fires if the weighted sum $\sum_j W_{ij} n_j$ of the inputs reaches or exceeds the threshold μ_i.
- This neuron has no memory of its past activity.

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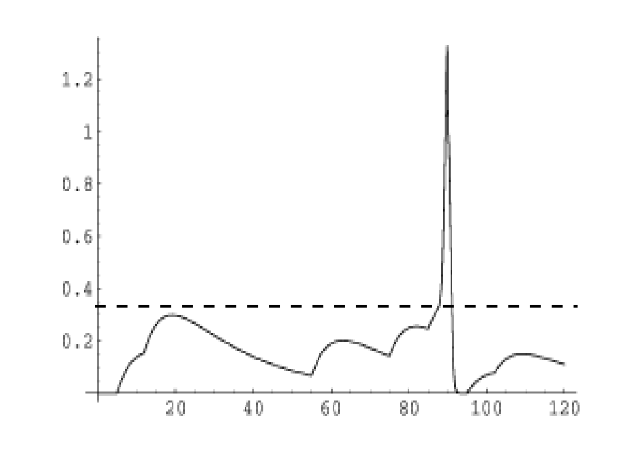
The Integrate and Fire Neuron



$$V(t) = V(t-1) + \frac{\Delta}{\tau}\left[-V_m(t-1) + I_{ext}(t)\right]$$

Integrate-and-Fire: step by step

$$\begin{aligned}
\textbf{(1) Leak:} \quad & V(t) \;\leftarrow\; V(t-1) + \frac{\Delta}{\tau}\left[-V(t-1)\right] \\
\textbf{(2) Add input:} \quad & V(t) \;\leftarrow\; V(t) + \frac{\Delta}{\tau} I_{ext}(t) \\
\textbf{(3) Threshold:} \quad & \text{if } V(t) > V_{thr} \text{ then emit a spike} \\
\textbf{(4) Reset:} \quad & \text{if spike then set } V(t+1) = V_{reset} \text{ (else keep integrating)}
\end{aligned}$$

- The term $-V(t-1)$ makes the voltage decay back toward baseline (a *leaky* integrator).
- Δ/τ controls how much the voltage changes per step (Euler update).
- Intuition: input pushes V up/down; the leak pulls V back; spikes happen when V crosses V_{thr}.

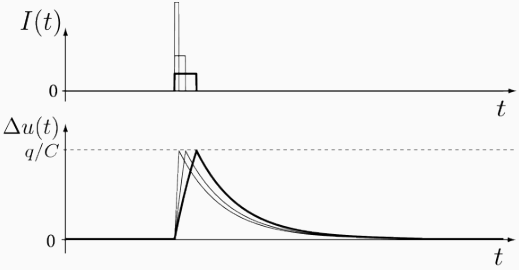
The Integrate and Fire Neuron

$$V(t) = V(t-1) + \frac{\Delta}{\tau}\left[-V_m(t-1) + I_{ext}(t)\right]$$

$$\text{if } \; V(t) > V_{thr} \quad \text{then} \quad \text{Spike} \quad \text{and} \; V(t+1) = V_{reset}$$

- $I(t)$ is the external input from synapses.
- $V(t)$ without input tends towards zero, the *resting potential*.
- τ is the *membrane time constant*, determines how fast the potential changes (10-40ms).
- V_{reset} is the reset potential after a spike, usually below the resting potential.
- Δ is a parameter that determines the simulation time step (as small as possible).

The Integrate and Fire Neuron



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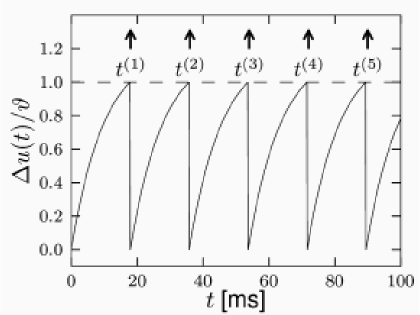
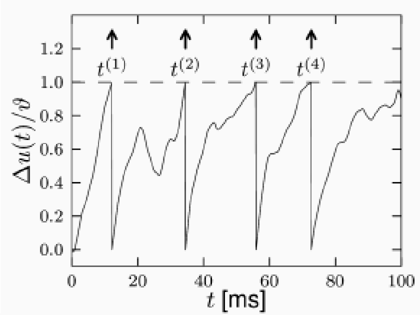
This neuron integrates its past activation and hence has some memory (τ=10-20 ms).

The Integrate and Fire Neuron





$$V(t) = V(t-1) + \frac{\Delta}{\tau}\left[-V_m(t-1) + I_{ext}(t)\right]$$

$$\text{if } \; V(t) > V_{thr} \quad \text{then} \quad \text{Spike} \quad \text{and} \; V(t+1) = V_{reset}$$

Fluctuations in the input current $I_{ext}(t)$ lead to irregular spiking.

Summary

- Neurons transmit information through spikes: electrical all-or-non events.
- Synapses mediate communication between neurons through chemical neurotransmitters.
- Synapses have either an excitatory or inhibitory effect.
- Synapses have different strength or weight, which quantifies their influence on the receiving neuron.
- We can use highly simplified neuron models to investigate neural computations.