Neurons and Spikes

Informatics 1 Cognitive Science

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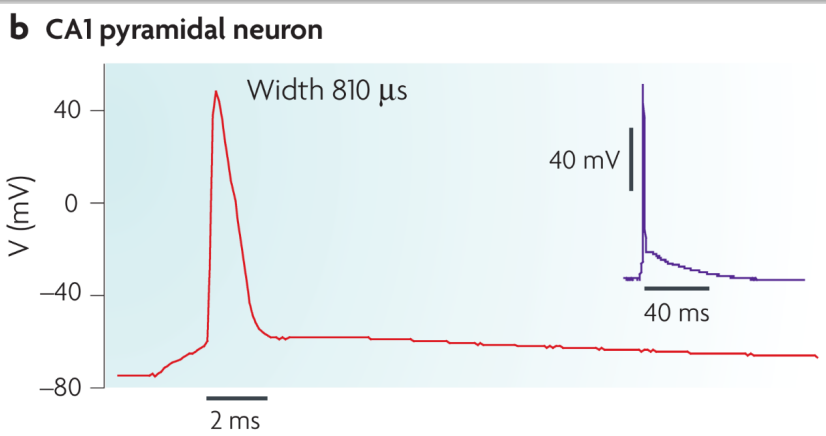
Listening to a Neuron

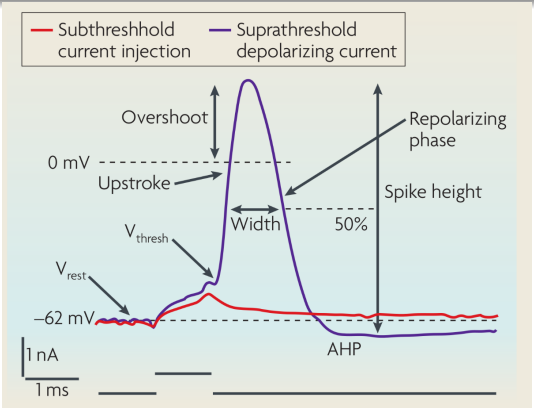
With tiny electrodes (micropipettes filled with electrolyte and containing an electrode) we can record electrical activity in single neurons.

The Action Potential (Spike)



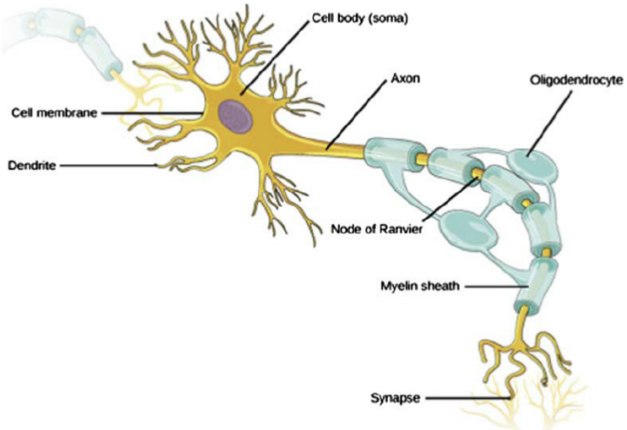
- An inward current pulse depolarises the cell membrane.
- When the depolarisation exceeds a threshold, the neuron fires a spike.

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.

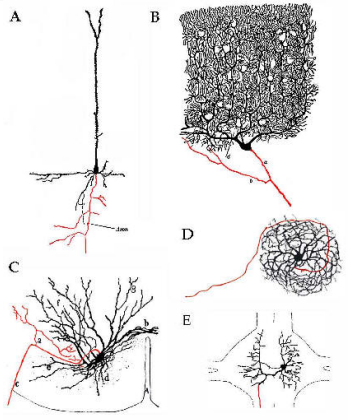
A Neuron



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

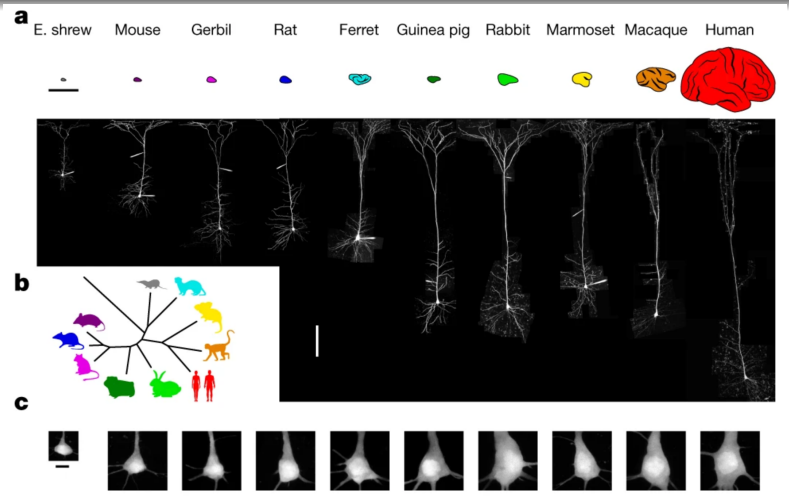
Anatomical Diversity of Neurons

- 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.



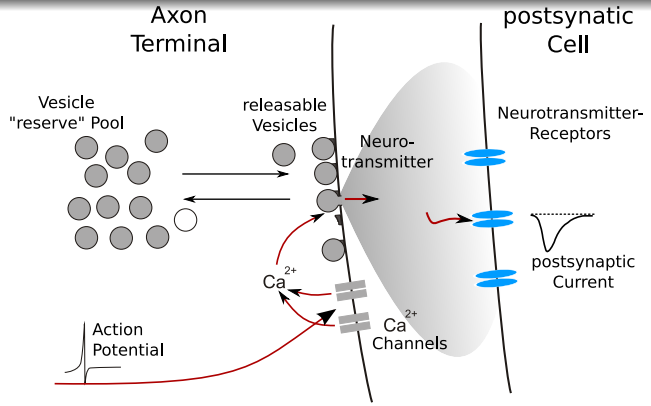
A: Pyramidal cell, cortex; B: Purkinje cell, cerebellum; C: Motorneuron, spinal cord; D: Inferior olivary nucleus cell, E: Leech sensory neurons (red: axon, black: dendrites)

Neuron anatomy across species (Cortex)



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

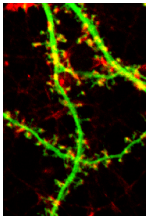
Synaptic Transmission between Neurons



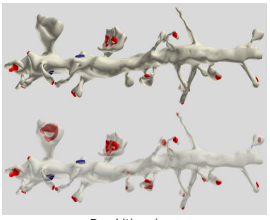
A *synapse* is a specialised contact between axon and dendrite of two neurons. A spike causes *neurotransmitter release* at the synapse, which in turn changes the potential of the receiving neuron.

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

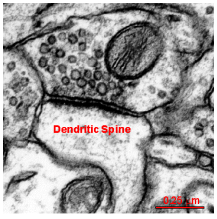
Anatomical Diversity of Synapses



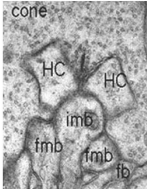
Cultured hippocampal neurons



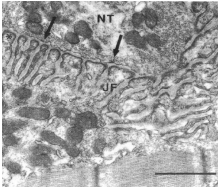
Dendritic spines (from Synapse Web)



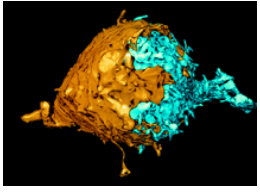
Axon and spine (from Synapse Web)



Human retinal cone terminal



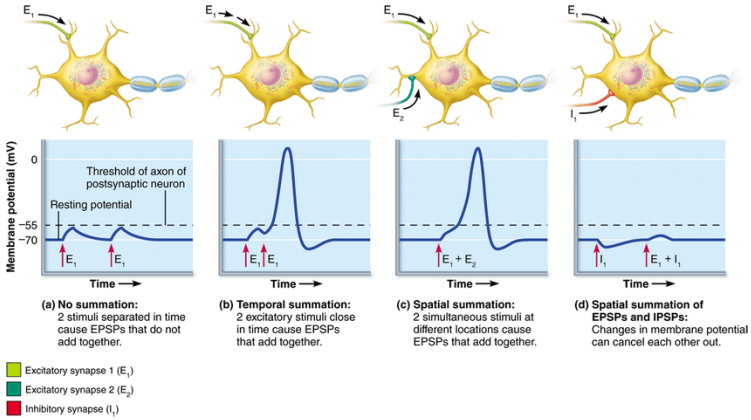
Mouse neuromuscular junction (Salpeter, 1987)



Calyx of Held in rat auditory brainstem (Saetzler et al, 2002)

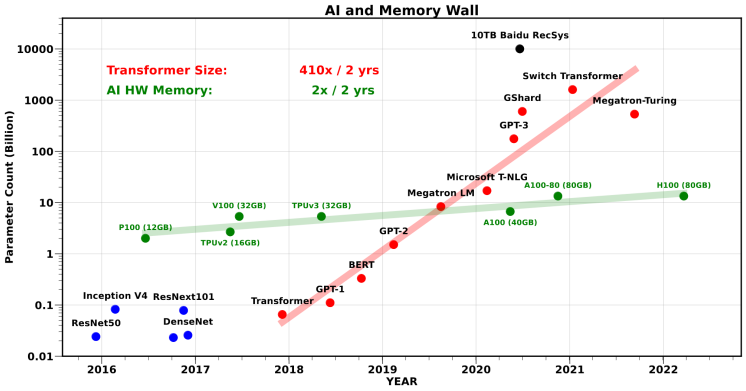
A neuron may receive anywhere between 1 and 100,000 synaptic inputs.

Excitatory and Inhibitory Synapses



Synapses can *excite* (bring closer to spiking thresold), 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.

How many synapses are useful?



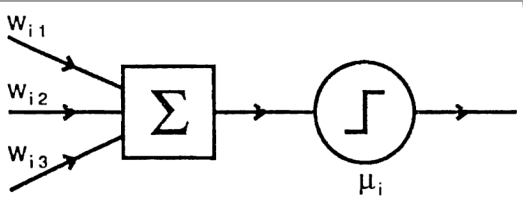
- Deep learning models (esp. LLMs): approaching 1 trillion parameters (weights).
- The human brain: perhaps 100 trillion synapses (weights).

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.

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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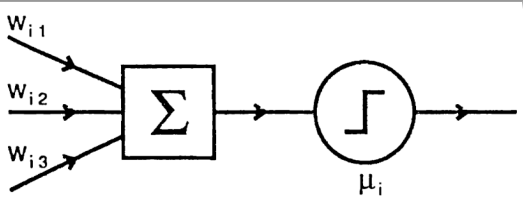

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- The weight w_{ih} determines the type/strength of each synapse. Dale's principle is not respected.

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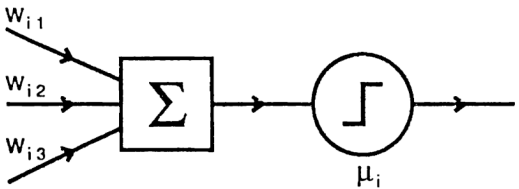

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- The neuron fires if the weighted sum $\sum_j W_{ij} n_j$ of the inputs reaches or exceeds the threshold μ_i.

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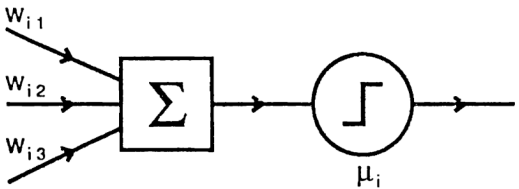

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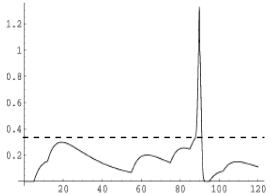
- The neuron fires if the weighted sum $\sum_j W_{ij} n_j$ of the inputs reaches or exceeds the threshold μ_i.
- This neuron has no memory of its past activity.

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

The Integrate and Fire Neuron

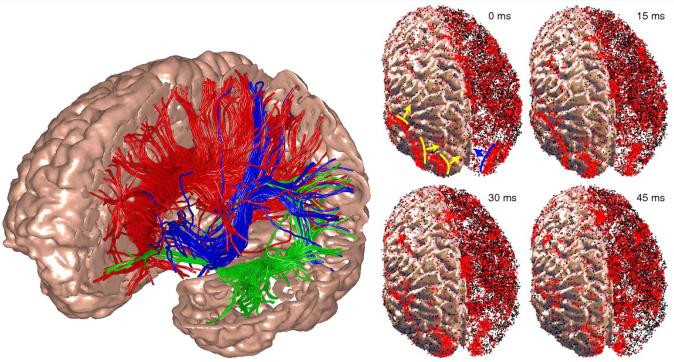


$$V(t) = V(t-1) + \frac{\Delta}{\tau}\left[-V_m(t-1) + I_{ext}(t)\right]$$

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

Membrane time constant: τ Reset potential (usually lower than resting): V_{reset}
External input from synapses: $I(t)$
Simulation parameter: time step Δ.
This neuron integrates its past activation and hence has some memory (20-40 ms).

Network models



A large scale model of the connections between thalamus and cortex (left), with about 500 million synapses. It exhibits spontaneous activity and emergence of waves and rhythms.

Original publication: MIzhikevich, E. M., & Edelman, G. M. (2008). Large-scale model of mammalian thalamocortical systems. Proceedings of the National Academy of Sciences, 105(9), 3593-3598.

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.