Non-additive processing of synchronous inputs yields enhanced memory storage

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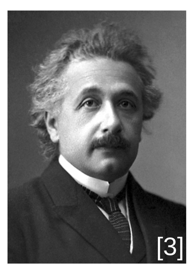
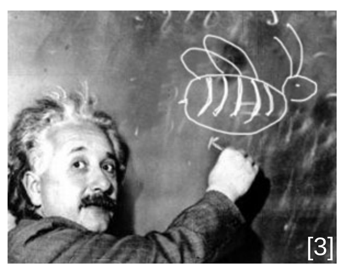
Motivation

How is the memory capacity of the brain ...

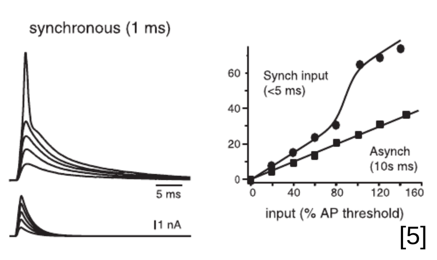
Every day we experience that we are (i.e. our brain is) **good at remembering** a large number of facts, faces and other things. Furthermore, we are able, e.g., **to associate** different facts and recognize faces of friends even under complicating conditions. **Simple neural network models** can grasp these capabilities and explain the storage capacity and robustness of memory retrieval [1,2]. The following pictures demonstrate both aspects of our memory:

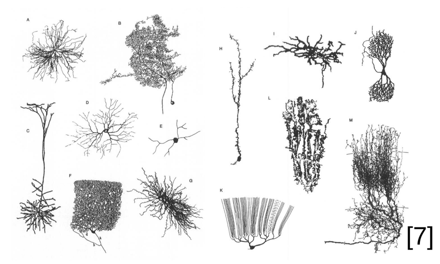




... influenced by the complexity of the brain?

The collective dynamics of neural circuits centrally relies on how individual neurons process their inputs [4]. Despite a vast literature on neural network dynamics, almost all theoretical studies so far have **assumed linear summation of inputs**. Experimental works, however, have shown that temporally synchronous and spatially close inputs yield a soliton-like excitation and thereby a **supralinear enhancement of the inputs** [5,6]. Moreover, commonly studied point-neuron models ignore the richness and **complexity of dendritic arbors** as present in many regions of the brain [7,8].





- How do complex biological features of the brain, such as **non-additive input processing** in **multiple dendritic branches**, influence its **performance as an associative memory?**

Dendrites provide effective neuronal input

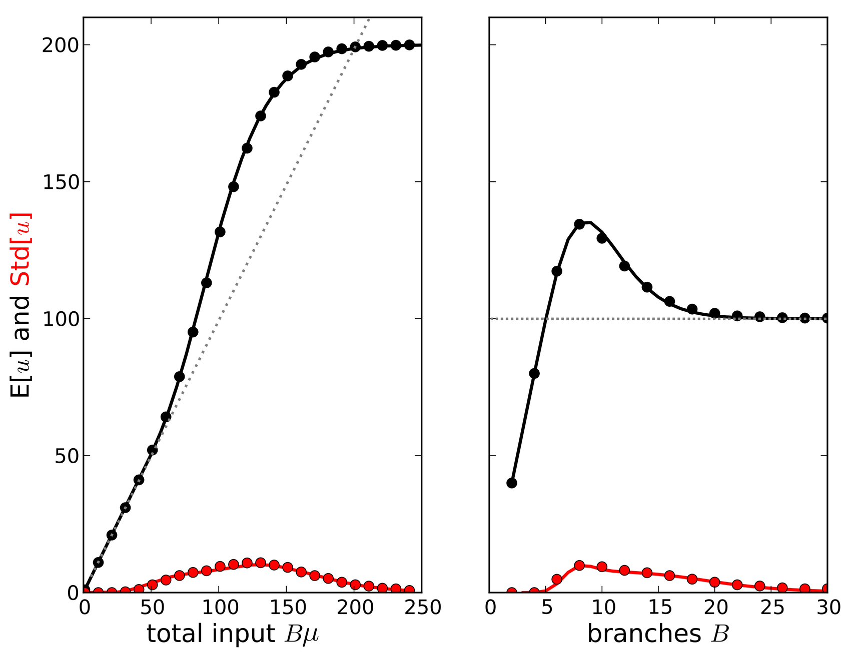
effective input *u* to neuron in presence of non-additive dendrites

- the neuronal input is split into **two contributions** of linear and saturated dendrites, respectively

B number of branches
D fraction of non-add. branches
P_{NL} strength of dendritic non-add.
θ onset of dendritic non-add.
μ mean input to branch
σ^2 variance of input to branch

$$P_{\mathrm{NL}} = \frac{1}{2}\mathrm{erfc}\left(\frac{\theta-\mu}{\sqrt{2\sigma^2}}\right)$$

$$\mathrm{E}[u] = BP_{\mathrm{NL}}D + B\left(1-P_{\mathrm{NL}}\right)\mu - B\sqrt{\frac{\sigma^2}{2\pi}}\exp\left(-\frac{(\theta-\mu)^2}{2\sigma^2}\right)$$

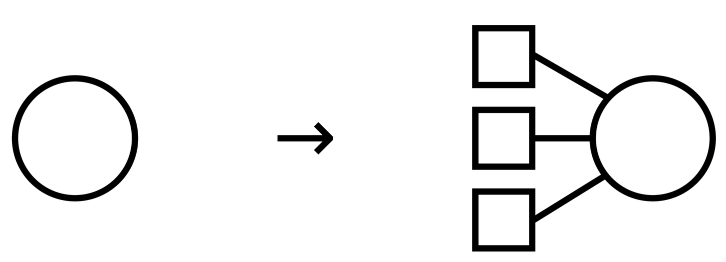


- Non-additive **dendrites alter input** *u* to neuron in a non-trivial but **predictable** manner with small deviations Std[*u*] ≪ E[*u*] [9].

Neuron Model

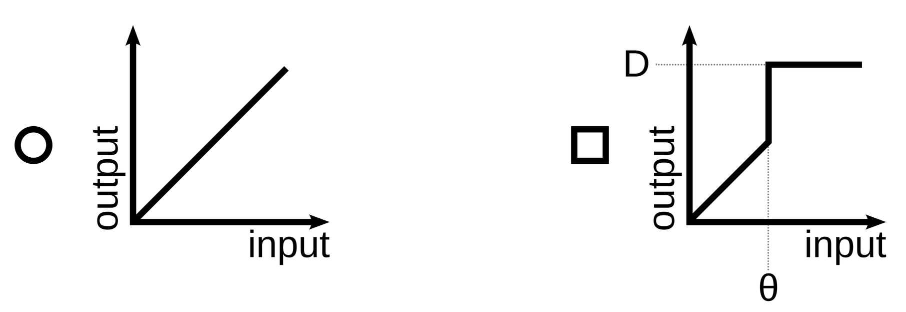
extended point neurons to two-layer structures

- each independent **dendritic branch** is modeled as a seperate compartment



non-additive dendritic input processing

- input summation in dendrites is **non-additive** (see Motivation) but remains linear in neuron



Conclusion & Outlook

take home messages

- Hopfield networks provide a **simple model** for associative memories.
- The complexity of the brain covers, i.a., **non-additive input processing** and dendritic arbors.
- Dendritic non-additivities **increase the robustness** of the model against fluctuations.

work in progress

- How can the couplings w_{nbm} be adjusted to optimize storage capacity?
- Do similar gains in memory performance persist in networks of biologically plausible neurons?

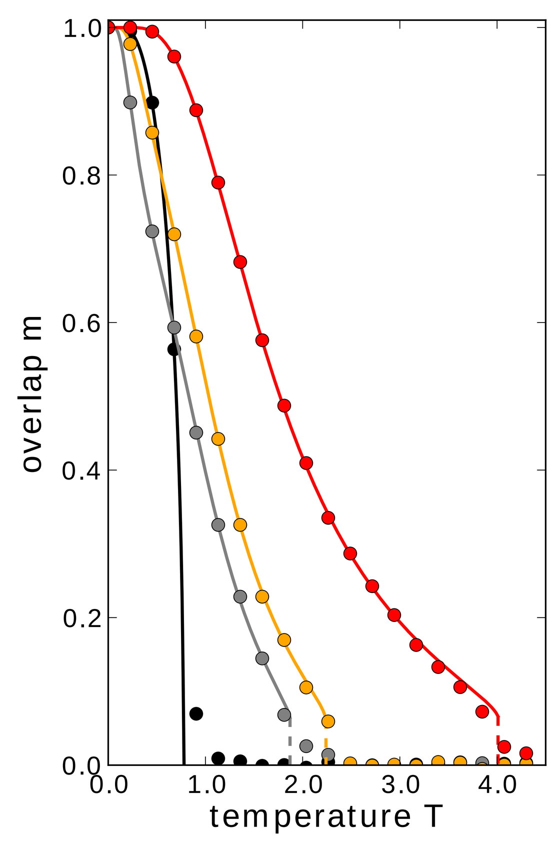
Dendrites improve robustness of memory

dendritic non-additivities stabilize memorized patterns

- **quality of retrieval is measured by the overlap** m of the network state with pattern p = 1, w.l.o.g.

$$m = N^{-1}\sum_{n=1}^{N} x_n^1 \langle v_n \rangle$$

- overlap in the limit $PN^{-1} \to 0$ for the standard Hopfield model (black) and increasingly strong non-additivites (gray, orange, red)



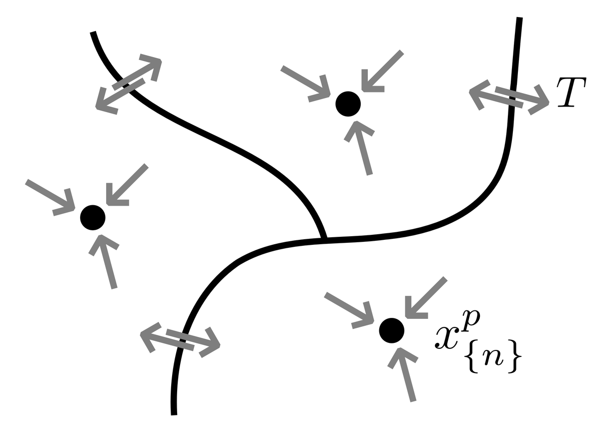
- Non-additive dendrites allow successful **memory retrieval at higher noise levels** [9].

Extended Hopfield Model

network architecture

- due to the dendritic branches, **neurons are coupled to branches** of neurons w_{nbm}
- the Hebbian **connectivity stores patterns** x_n^p as attractors into the network [1]
- this provides the network with the **capability to recall and associate memories**

$$w_{nm} = N^{-1}\sum_{p=1}^{P} x_n^p x_m^p = N^{-1}\sum_{b=1}^{B} w_{nbm}$$



neuronal dynamics

- the **binary neurons** are updated stochastically, modeling **noise** [2]
- the non-additive dendrites provide the neuron with an **effective input** *u* (see Effective Input)

$$v_n(t+1) = \begin{cases} +1, & \text{with probability } p_n \\ -1, & \text{otherwise} \end{cases}$$

$$p_n(T, u_n) = \left(1 + \exp\left(-2T^{-1}u_n\right)\right)^{-1}$$

v_n state of neuron n
t time
T temperature
u_n effective input to neuron n

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