A principled procedure for designing brain-derived SWaP optimized neuronal units for low-power neuromorphic analog computation and digital communication.

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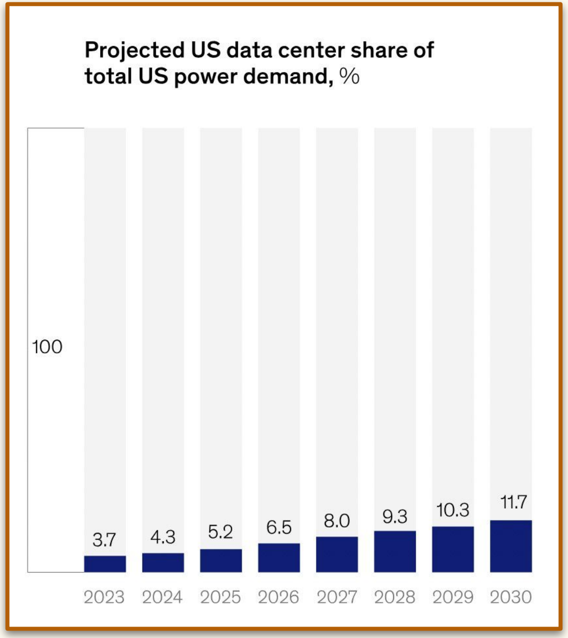
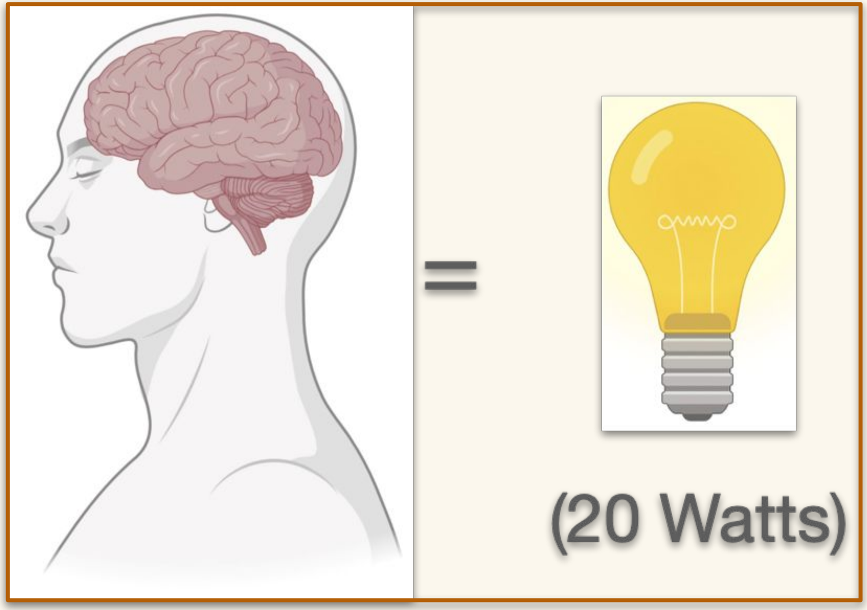
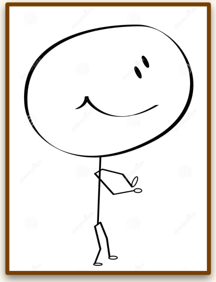
Brain has evolved under Space Weight and Power (SWaP) Constraints

"…the brain manages to produce poetry, design spacecraft, and create art on an energy budget of 20 W, a paltry sum given that the computer on which this article is being typed requires 80 W."
-Balasubramanian, Brain Power, PNAS

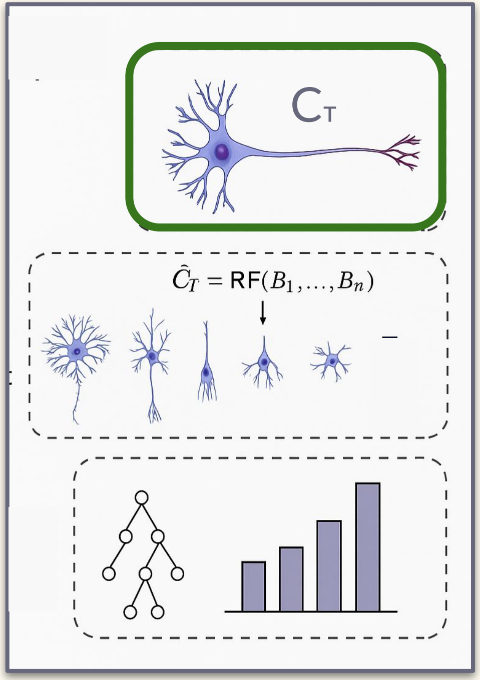


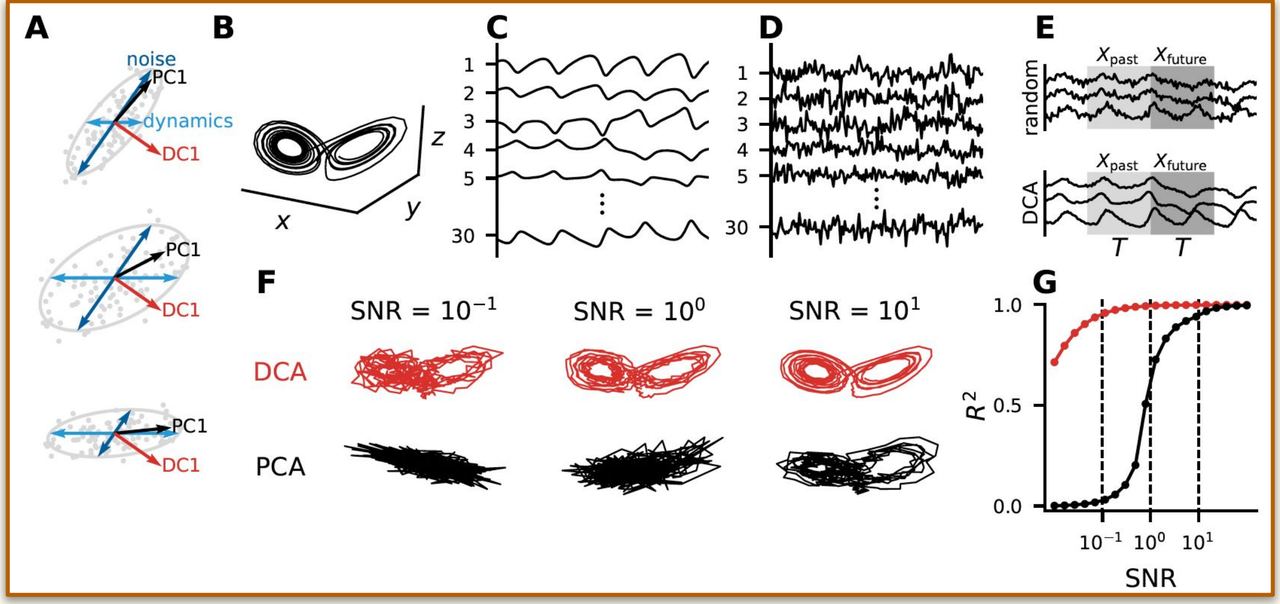




Dynamical Component Analysis allows us to differentiate noise from dynamics

David G. Clark, Jesse A. Livezey, Kristofer E. Bouchard **NeurIPS 2019**



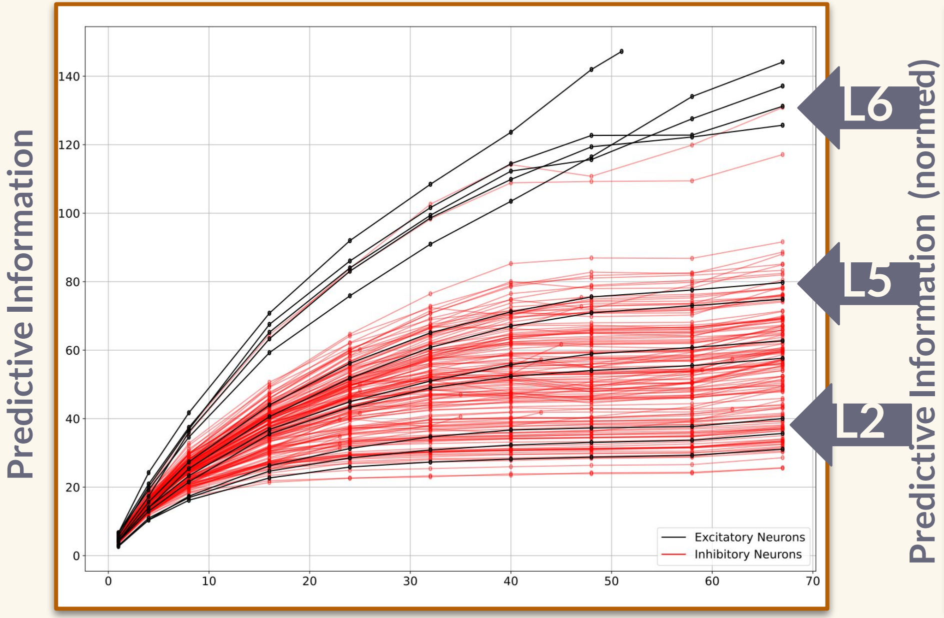


$$I_T^{pred}(X) = \log|\Sigma_T(X)| - \frac{1}{2}\log|\Sigma_{2T}(X)|$$

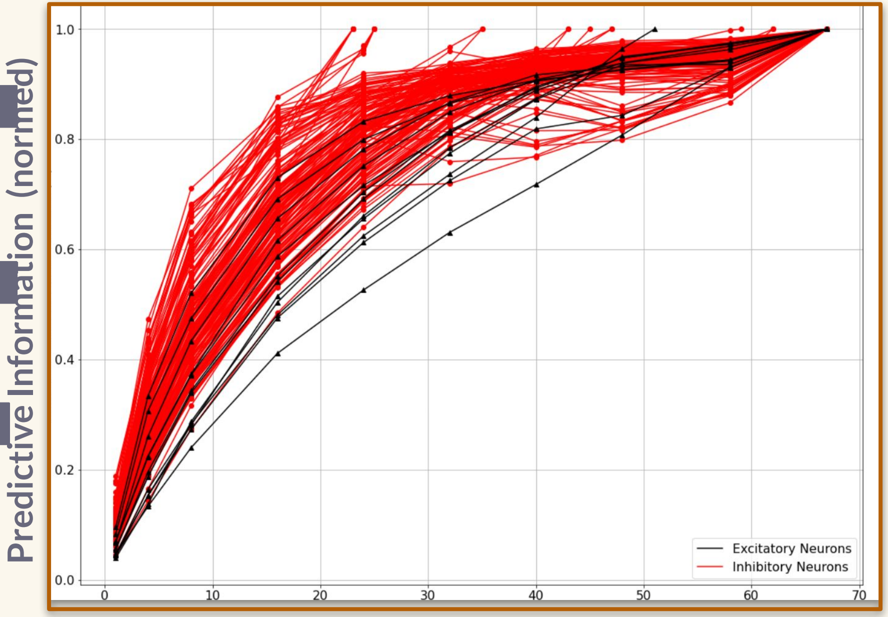
The complexity of a neuron is the minimum number of dynamical components needed to achieve a maximum of predictive information

From data alone PI can differentiate ‘kinds’ of neurons

Different behavior across the cortical column

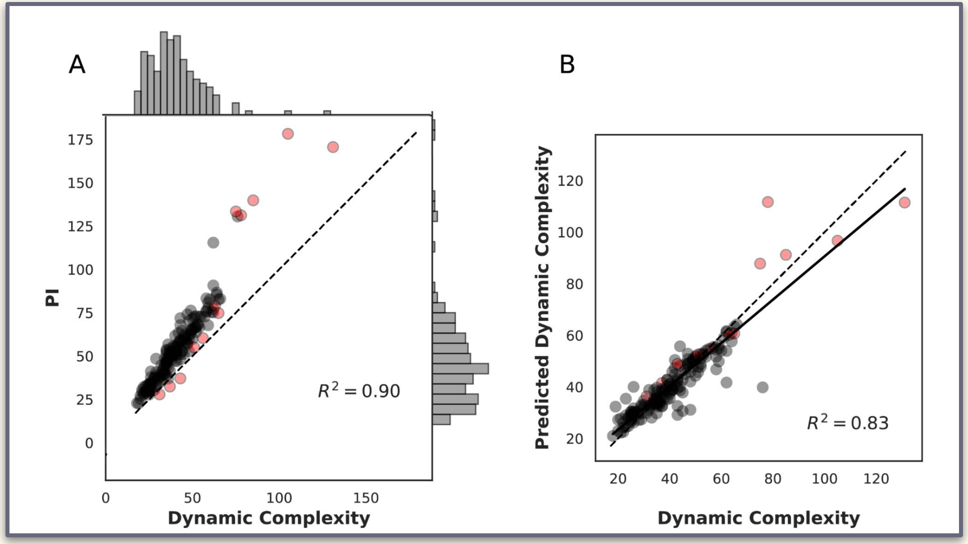


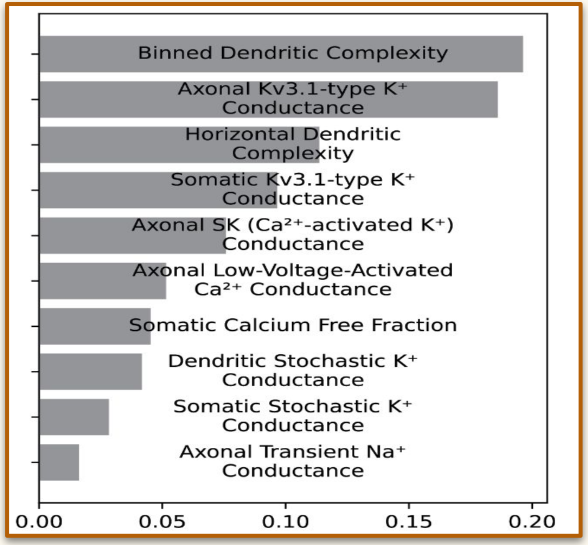
Differentiates between Neuron Transmitter Types



Simulations by Roy Ben-Shalom at UC Davis

Biological determinants of intrinsic neuronal complexity





dendrites have been thought to potentially be semi-independent computational subunits

Axonal v3.1-type K^+ conductance facilitates rapid action potential repolarization

Stochastic K^+ somatic Conductance influences action potential threshold variability

CA_LVAst

ODEs

$$v = v + 10$$

$$m_{\text{Inf}} = \frac{1}{1 + e^{-(v+30)/6}}$$

$$h_{\text{Inf}} = \frac{1}{1 + e^{(v+80.0)/6.4}}$$

$$\frac{dm}{dt} = \frac{m_{\text{Inf}} - m}{m_{\text{Tau}}}$$

$$\frac{dh}{dt} = \frac{h_{\text{Inf}} - h}{h_{\text{Tau}}}$$

$$m_{\text{Tau}} = \frac{5 + \frac{20}{1+e^{(v+25)/5}}}{QT}$$

$$h_{\text{Tau}} = \frac{20 + \frac{50}{1+e^{(v+40)/7}}}{QT}$$

SWaP Cost Information

FPGA

- ~500 LUTs
- ~500 FFs3–6 DSP slices ~1 BRAM18/36~1–5 mW at 100 MHz

Outlook

Outstanding opportunities for interdisciplinary research include:

1) expand analysis and dataset to identify biophysical principles of input-output complexity,
2) determine if networks of more complex neurons require less neurons to complete task,
3) determine SWaP-costs of important ODEs under various technologies (e.g., CMOS),
4) utilize importance of features (ODEs, dendritic features) as primitives and constraints in neuromorphic hardware design search that also incorporate hardware constraints,
5) create new neuron models with maximal computational capacity under SWaP constraints.

Outlook: This work provides a principled procedure for designing brain-derived SWaP optimized neuronal units, setting the stage for co-design of neuromorphic systems towards deployment in future HPC systems, at the edge, or in robotic systems.

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Thanks

Collaborators: Kristofer Bouchard, Kailin Zhunang , Dilip Vasudevan

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