BS-CS Double major

2024 seminar, Lecture 2:

Computational Neuroscience

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Computer Science and Neuroscience

- Computer science → Neuroscience

Modeling neuronal activity (classic computational neuroscience)

- Neuroscience → Computer science

Inspiration for algorithms based on neural solutions

- Analysis of neuroscience data (classic data science)

Modeling – Why?

- Understand – gain new knowledge (e.g., attention)
- Emulate - develop new algorithms (e.g., learning algorithms)
- Heal – develop new therapies (e.g., deep brain stimulation)

Models

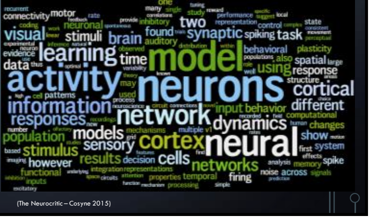
The fundamental truth about models:

"All models are wrong, but some are useful"

George E. P. Box (1987)

Computational neuroscience – definition I

Highly diverse and ill-define research field including a large array of computational methods for **understanding** the **brain**



(The Neurocritic – Cosyne 2015)

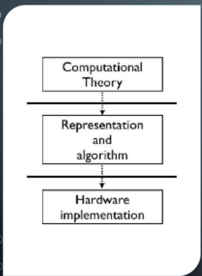
Computational neuroscience – definition II

The version of the "Organization for Computational Neuroscience":

Computational neuroscience (CNS) is an **interdisciplinary field** for development, simulation, and analysis of multi-scale models and theories of neural function from the level of molecules, through cells and networks, up to cognition and behavior.

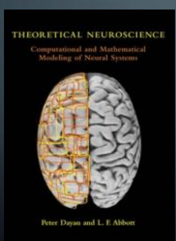
(www.cnsorg.org)

David Marr (1982)
Tri-Level Hypothesis



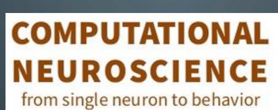
- **Computational level:** what does the system do (e.g.: what problems does it solve or overcome) and similarly, why does it do these things
- **Algorithmic (representational) level:** how does the system do what it does, specifically, what representations does it use and what processes does it employ to build and manipulate the representations
- **Implementational (physical) level:** how is the system physically realized (in the case of biological vision, what neural structures and neuronal activities implement the visual system)

Dayan and Abbott



- **Mechanistic models** - how nervous systems operate based on known anatomy and physiology.
- **Descriptive models** - summarize large amounts of experimental data, accurately describing and quantifying the behavior of neurons and neural circuits.
- **Interpretive models -** explore the behavioral and cognitive significance of nervous system function, often connecting explaining experimental data in terms of certain theoretical principles.

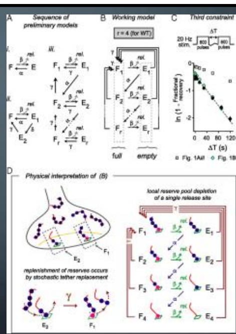
Hierarchical multi-level approach



- (Sub-cellular models)
- Single neuron models – biophysical models
- Neural network models – connectionist models
- Behavioral models – cognitive models

Sub-cellular models

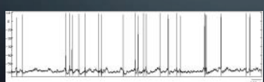
- Protein kinetics
- Vesicle kinetics
- Synapse growth/pruning
- …

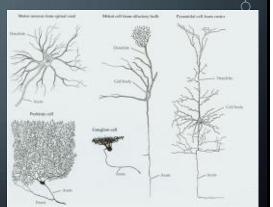


(Gabriel et al., JNS, 2011)

Single neurons

- A neuron is an electrically excitable cell consisting a cell body, dendrites and an axon.
- There is a large variety of neurons.





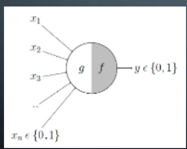
Single neuron models

- What is the amount of detail required for generating a useful model?

- A formal neuron
- Rate based neurons
- Leaky integrate and fire
- Hodgkin Huxley model
- Compartmental detailed neuron

The formal neuron

- The McCulloch-Pitts model (1943) is an extremely simple artificial neuron. The inputs are (0,1) and so it the output.



$$g(x_1, x_2, x_3, \ldots, x_n) = g(\mathbf{x}) = \sum_{i=1}^{n} x_i$$

$$\begin{aligned} y = f(g(\mathbf{x})) &= 1 \quad if \quad g(\mathbf{x}) \geq \theta \\ &= 0 \quad if \quad g(\mathbf{x}) < \theta \end{aligned}$$

Rate based models

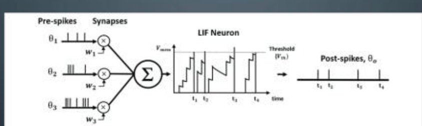
- The neurons are represented by their firing rate:

  Y = f(WX+b)

- A common example is the perceptron:

$$f(\mathbf{x}) = \begin{cases} 1 & \text{if } \mathbf{w} \cdot \mathbf{x} + b > 0, \\ 0 & \text{otherwise} \end{cases}$$

Leaky integrate and fire (LIF)



Leaky integration

$$\tau_m \frac{dv(t)}{dt} = -(v(t) - E_L) + RI(t)$$

$$I(t) = \sum_j \sum_{t_j^f} w_j \alpha(t - t_j^f)$$

Fire (spike)

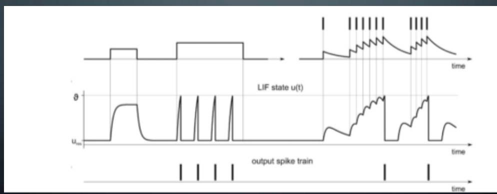
If the potential reaches the threshold voltage, $v(t^f) = V_{th}$

then, add a spike and reset the potential to the reset voltage.

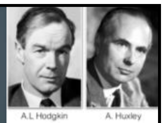
$v(t^f) \leftarrow V_{reset}$.

Implementation →

LIFs are one example of threshold-based models



The Hodgkin & Huxley model (1952)

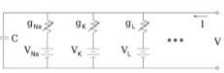


The empirical work lead to the development of a coupled set of differential equations describing the ionic basis of the action potential.

The ionic current is subdivided into three distinct components, a sodium current I_{Na}, a potassium current I_K, and a small leakage current I_L (chloride ions).

Based on the experiments, they were able to accurately estimate all parameters.

$$I = C_m\frac{dV_m}{dt} + \bar{g}_K n^4(V_m - V_K) + \bar{g}_{Na} m^3 h(V_m - V_{Na}) + \bar{g}_l(V_m - V_l),$$
$$\frac{dn}{dt} = \alpha_n(V_m)(1-n) - \beta_n(V_m)n$$
$$\frac{dm}{dt} = \alpha_m(V_m)(1-m) - \beta_m(V_m)m$$
$$\frac{dh}{dt} = \alpha_h(V_m)(1-h) - \beta_h(V_m)h$$



Biophysically detailed models (NEURON and others)

Large number of compartments (typically hundreds), each compartments has a few dozen free parameters.

$$I = C_m\frac{dV_m}{dt} + \bar{g}_K n^4(V_m - V_K) + \bar{g}_{Na} m^3 h(V_m - V_{Na}) + \bar{g}_l(V_m - V_l),$$
$$\frac{dn}{dt} = \alpha_n(V_m)(1-n) - \beta_n(V_m)n$$
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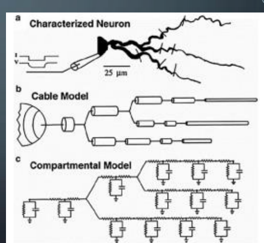
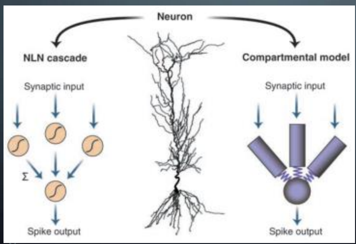
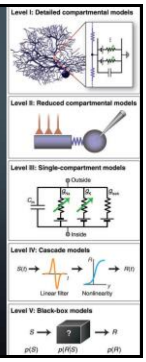


Stamatiaids et al., 2016)

Complex cascade models





(Herz et al., Science, 2016)

Model complexity

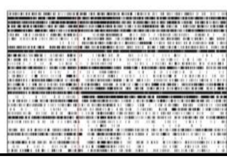
"A good theoretical model of a complex system should be like a good caricature: it should emphasize those features which are most important and should downplay the inessential details. Now the only snag with this advice is that one does not really know which are the inessential details until one has understood the phenomena under study" (M.E. Fisher, 1983)

SYSTEMS NEUROSCIENCE

- Neural circuits
- Distributed representations

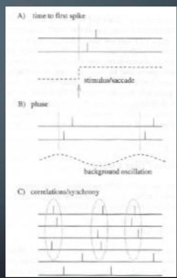
Neurons never function in isolation; they are organized into ensembles or circuits that process specific kinds of information.

Afferent neurons, efferent neurons and interneurons are the basic constituents of all neural circuits.



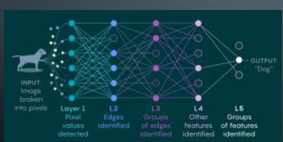
The neural code

- Rate coding
- Temporal Coding
  - Latency Coding
  - Phase Coding
  - Correlations and Synchrony
- Population Coding
- Local vs. Distributed Codes
- Synfire Chains

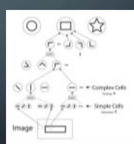


Neural networks (connectionist models)

Information is encoded by a network of neurons that collectively represent the object.

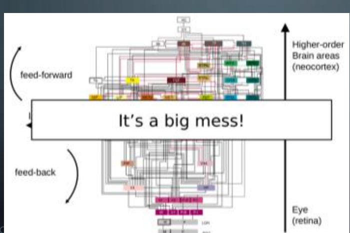


Lucy Reading-Ikkanda/Samuel Velasco/Quanta Magazine



- Machine Learning applications:
  - Neocognitron
  - Convolutional neural networks (CNNs)

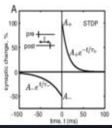
REAL networks - vision



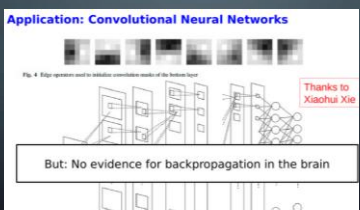
Plasticity and learning

- Hebb rule:
  - Neurons that fire together, wire together
- Short-term plasticity:
  - Weight changes depending on recent firing history of neurons
- Spike-timing dependent plasticity (STDP):
  - Weight changes depending on the degree of correlated firing
- Dopamine-modulated STDP:
  - Weight changes according to STDP only if dopamine present

Donald O. Hebb
1905-1985



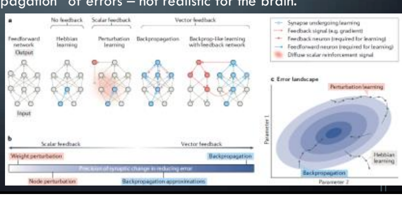
Neural network – machine learning



Neural network models

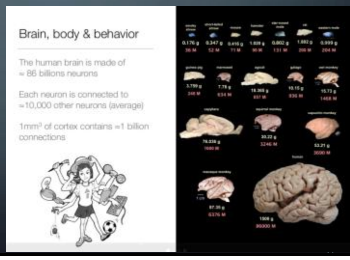
- Extremely active field in machine learning.
- Based upon "backpropagation" of errors – not realistic for the brain.

Backpropagation and the brain

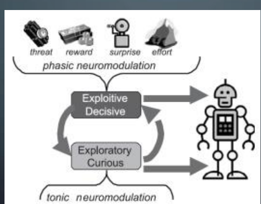


Behavioral models

- Addressing whole brain areas instead of individual elements (neurons) within it.

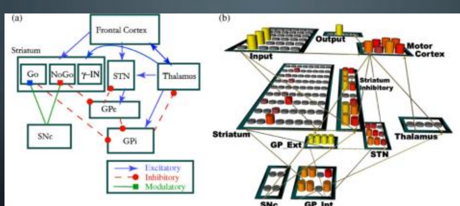


Neurotransmitters and neuromodulation

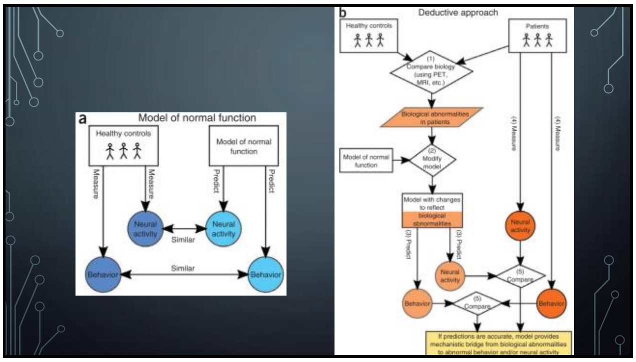


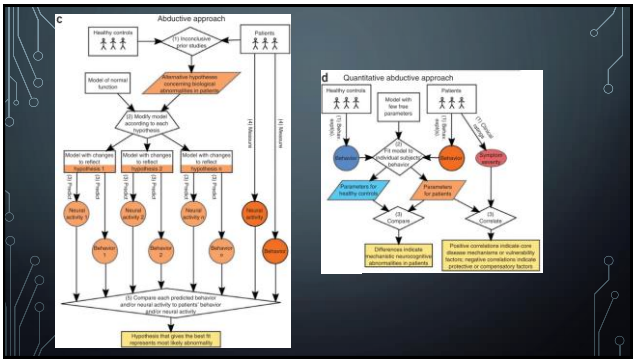
(Krichmar 2008)

Behavioral models



(Frank et al., 2007)





Summary

- Computational neuroscience focuses on modeling the brain.
- Modeling traverses multiple levels from sub-cellular activity to whole organisms.
- At each level, the complexity of representation varies greatly.
- Bridging between computational neuroscience and machine learning is a major field of research.