A classification of

Models for computational neuroscience

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# Introduction

Computational neuroscience is an out breaking field of research aims to decode the functions of the brain in terms of information processing properties of the structure that constitute our nervous system. It is an interdisciplinary science that links the field of neuroscience, psychology and cognitive studies with computer science, electrical engineering along with mathematics and physics. In short, computational neuroscience is a huge emerging field involving multiple disciples of science.

It is highly possible to understand the subject without any inference and practical implementation, given the enormity of the subject “neuroscience” how do we go about understanding the phenomenal functions of the brain? It is not easy for someone to understand something without knowing the practical approach. Various computational models are being implemented to understand the subject. Scientist named David Marr has divided the level of analysis into 3 different types, computational, algorithmic and the implementable levels.

# General criteria for evaluating models

* **Speed of information processing**

The rate of information processing in biological neural systems are comparatively faster than digital processing, the nervous system overwhelmingly prefers parallel computation over serial ones in time-critical applications.

* **Robustness**

A model is robust if it continues to produce the same set of outputs under variations of inputs or new parameters are introduced, nonetheless the model should be steady and robust no matter what.

* **Gain control**

The principle behind the response of a nervous system should stay within certain bounds even when the inputs from the environment change drastically. The producing outputs should follow the constraints provided while building the model.

* **Linearity vs nonlinearity**

A linear system is one type of modelling which follows specified unit of measure, the set of inputs will be considered at once. Linear systems are easier to analyze mathematically and are a persuasive assumption in many models. Whereas nonlinear models are generally assumed to be parametric and are described in a nonlinear equation.

# Modelling approaches

As mentioned David Marr’s work on levels on description/analysis of the brain as a complex system, he argued that neuroscience needs to start with studying the specific computation a system is trying achieve and his postulation that we need to study specific computations rather than theories of the brain. Different approaches/methods he mentioned a model can be used are:

* **Descriptive models** – often aims to capture a core phenomenon of interest, describes what is an understandable model that can quantitatively describe empirical observations?
* **Mechanistic models** – tries to determine how a functionality is implemented at a biophysical level? The challenge which this type of models has to overcome is to find the right level of abstraction.
* **Interpretive models** – it focuses on analyzing at circuitry level, it focuses on the question   
  *“why is the system set up a particular way? What is its role and function?”*

### Descriptive Models:

Descriptive models are mathematical and computational representations that aim to describe and replicate observed neural phenomena or data without focusing on underlying mechanisms. These models may not provide insights into the detailed biophysical processes occurring within neurons or neural networks. Instead they are used to capture and replicate specific features of neural activity or behavior.

Some descriptive models are:

* Neural firing rate models – these models describe the firing rates of neurons as a function of their inputs. They are used to capture the relationship between the input and output firing rate without modelling the underlying processes within the neuron. Models such as *Linear-Nonlinear-Poisson model* (LNP*)* and *Rectified Linear Unit model* (ReLU) are considered.
* Population rate models – these models focus on the aggregate activity of populations of neurons, often representing the firing rates of a neuron within a population or a brain region. Models such as *Rate-based models* and *Gaussian population models* are considered.
* Neural field models – these models describe the spatiotemporal dynamics of neural activity in continuous space, often are used to study activities of a specific region of interest (ROI). Models such as *Wilson-cowman model* and *Amari equation* are considered.

There are other models and modelling paradigms like the *Kuramoto model*, *point process models*, *hidden markov models*, *FitzHugh-nagumo oscillator*, etc., are being used under different use cases.

### Mechanistic Models:

Mechanistic models are essential for understanding the fundamental biological processes underlying neural function. They are used to simulate and predict neural activity and explore how neural mechanisms can lead to other. Unlike descriptive models, they delve into the details of how neurons are functioning.

Some mechanistic models are:

* Hodgkin-Huxley model – they describe the biophysical mechanisms of action potential generation in neurons by modeling the behavior of voltage-gated ion channels.
* Synaptic models – They entails a mathematical description of the transformation of a presynaptic action potential into a postsynaptic response, such as an ionic current. Models such as *Tsodyks-Markram* model and *STDP* models are considered.
* Biophysical models – These models simulate the interactions between neurons with detailed biophysical properties such as dendritic compartments and multiple ion channels. Models such as *Izhikevich model*, *Morris-Lecar models* and *multi-compartment models* are considered.

There are other types such as *neuromuscular models*, *cellular automata models*, *spiking neural network models*, *reaction-diffusion models*, etc., are being used.

### Interpretive Models:

Interpretive models focuses on explaining or interpreting specific neural phenomena. These models are designed and used to provide insights into the underlying mechanisms or principles governing neural processes, providing the relationships between neural activity and external stimuli. Though they provide insights, unlike mechanistic models they may not necessarily aim to capture all the intricate details of neural biology, they just prioritize conceptual understanding.

Some interpretive models are:

* Integrate-and-Fire models – These models represent neurons as passive electrical circuits that accumulate input currents and generate spikes when a threshold is reached. *Leaky integrate-and-fire model* is one of their kind.
* Generalized linear models – GLMs combine linear filters with a nonlinear transformation, often a Poisson spiking process. Models such as *temporal filtering model*, *Bernoulli GLM* and *Logistic regression models* are considered.

There are other models such as the *place cell models*, *population vector models*, *Bayesian models*, *information theory models*, etc., are being utilized

# Summary

In summary, The three types of models serves different purposes on computational neuroscience, researchers often choose the type of model that aligns with their specific research goals and the level of detail required to address their questions in computational neuroscience. These different types of models can also complement each other in advancing our understanding of the brain. Table1 is made to give an inference between the types of models.

Table 1: Tabulating difference between descriptive, mechanistic and interpretive models.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Descriptive Models | Mechanistic Models | Interpretive Models |
| Purpose | Replicate or predict observed neural phenomena or data without explaining the underlying biophysical mechanisms. | Seek to explain the underlying biophysical mechanisms of neural processes. | Aims to provide conceptual understanding and insights into specific neural phenomena or data. |
| Focus | They prioritize capturing specific features of neural activity. | They delve into the detailed mechanisms occurring within neurons, synapses and neural networks. | They prioritize explaining or interpreting neural processes while often simplifying certain aspects. |
| Examples | Rate-based models, population rate models, data-driven models and behavioral models. | Hodgkin-Huxley model, synaptic models, spiking neural networks and biophysical neural networks. | Linear-nonlinear models, population vector models, state-space models and information theory models. |

# Conclusion

Computational neuroscience models encompass a diverse set of mathematical and computational tools used to understand, simulate, and analyze neural processes and brain function. The models can range from simple, phenomenological representations to complex, biophysically detailed simulations. It is essential for a researcher to choose models based on their needs to explore and explain the workings of the brain at different levels of detail, from abstract descriptions to detailed simulations, helping advance our understanding of the nervous system and future technology advancements.

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