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Computational modeling of neuro-biological systems and its impact on neuromorphic engineering

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Introduction

When modeling biological systems, humans have often relied on real world devices to place such complex processes in context. A kidney is replaced by a filtering device; the heart becomes a simple pump. Most recently, and perhaps the least of all accurate, the brain is being compared to a computer. Several distinctions and flaws in this comparison become immediately apparent to even the most fledgling of neurobiologists. Computers are digital, serial, cold devices that have not come close to approaching the processing tasks of the continuous, parallel human mind. Since when has a computer solved a second order non-linear differential equation? And yet, this fallacious metaphor of man and machine might be approaching reality thanks to recent advances in computational modeling and innovative methods of neuromorphic engineering. Admittedly, a sensational feat such as artificial intelligence is still a long way off, if even possible, but the present and future applications of these endeavors are quite relevant to the scientific community and society as well. Research in this field has led to life changing medical devices in addition to furthering knowledge about neurobiological systems. This paper seeks to explicate the process by which neural systems are modeled and subsequently engineered into devices, while highlighting prominent advances in the field along with several biophysically fabricated instruments.

Modeling neural communication

The earliest models of electrical signal communication in neural systems were primarily mathematical. Starting with the Nernst equation [1], established over 100 years ago, a cell's equilibrium membrane potential, in volts, for a specific ion can be calculated. For the entire spectrum of ions, this is expanded into the Goldman equation [2] which takes into account the said ions' permeability. Once it was known how neuron's electrochemical properties were governed, it was discovered that these cells communicate by propagating an electrical pulse down their elongated cell bodies; this flow of currents is described quantitatively using cable theory [3]. Further defining this propagation model, known as an action potential, was the Hodgkin and Huxley squid axon experiment, which accurately modeled [4] the fast-sodium action potential in all its phases via an abstraction known as ion channel gating. Combining these governing mathematical equations with recorded electrophysiological parameters, such as signal conduction, modelers can form simple differential equations that, when calculated with the aid of a computer, are able to reliably predict the type of neural communication that is observed in biological systems. Furthermore, the adaptive nature of this communication is modeled by several proposed learning models [5], such as Hebbian theory and spike time dependent plasticity (STDP).

Computational representation

Using computer programming environments, a user can artificially create a cell that follows all of these archetypes. This is a powerful tool because numerous different cell types can be modeled with differing topologies, geometries and biophysics. Once the basic cell template has been made, an entire artificial network of neurons can be created that models the structural and functional properties of a biological network. The development and analysis of these networks is a vast topic in itself with applications mainly stemming from the fact that they can be used to infer a function from observation. Various software is available that allows researchers to simulate and develop these adaptive biological systems, such as NEURON, SNNS, Neural Lab, and even Matlab can be used to design a biological network simulator.

Blue Brain Project

Perhaps the most publicly recognizable application of artificial neural networks is the Blue Brain Project. It seeks to reverse engineer the mammalian brain by using dissected sections of rat somatosensory cortex and modeling this data computationally. The software environment used is Michael Hine's NEURON, and the project utilizes the Blue Gene supercomputer. Initially, goals were set at modeling a single neocortical column which consists of over 10,000 neurons and 10^8 synapses. This was completed back in December 2006 and now researchers have moved on to introducing smaller scale biological concepts that would encompass phenomena in the genetic realm and gene expression, as well as attempting to replicate the single column into a million connected columns, forming a wholly functional cortex. A more long term goal is to construct a detailed, operative simulation of the physiological processes in the human brain, which should, if built correctly, “speak and have an intelligence and behave very much as a human does.” (Markram 2009)

Other than providing a model for consciousness and revealing how the brain perceives the world, the Blue Brain Project could help shed light on cognitive disorders and how they develop from a molecular level. Such disorders include schizophrenia, depression, Alzheimer’s and other forms of psychosis.

Neuromorphic Engineering (*in silico*)

The most impressive implementation technologies that are attempting to duplicate the analog nature of biological systems are the neuromorphic devices employed on analog very large scale integrated (VLSI) silicon chips. These information processing systems operate on completely different principles from those which most engineers are familiar with (Mead 1990). An ideal application would be to map neuromorphic computing strategies onto advanced computational architectures. Additionally, such medical devices as neural prostheses could also be developed from neuromorphic chips (Van Schaik et al 1999), examples of these are discussed in detail in later sections. The majority of neuromorphic research is being done on sensory systems, motor control, and cognition as these provide the best representations of mammalian brain computing abilities.

These analog correlates are no more than models based on existing electronic technology. Neuromorphic chips can be summarized as interconnections of electrical elements such as resistors, capacitors and inductors, and sometimes transformers and active amplifiers. Emphasis is placed on replicating the morphology of biological systems circuits and overall architecture, so as to harness the parallel processing and extremely efficient computing power of said systems (Elliot 2002).

Neuroprosthetics

The design and use of neuroprosthetics is a field encompassing neuroscience and biomedical engineering that pursues the development of neural prostheses. Neural prostheses are a class of devices that attempt to replace a motor, sensory or cognitive function that has been damaged. A prime example of such devices is the cochlear implant. This device is engineered so that sound can be perceived while simultaneously replicating and bypassing the functions performed by the ear drum, stapes, frequency analysis in the cochlea and finally stimulates the auditory nerves directly. Sensory neuroprosthetics usually involve an external unit that gathers environmental stimuli and processes it, the processed signal is then transferred to an implanted unit that stimulates the sensory nerves through a microelectrode array. The development of such instruments has a pronounced impact on the quality of human life, and research in this discipline aims to mitigate, if not cure disabilities.

These devices typically take the form of sensory prosthetics, motor prosthetics, and prosthetics for pain relief. Major examples of these devices are provided with in depth analysis of their functional properties.

Sometimes referred to as a bionic ear, this device restores semi-normal hearing capabilities to profoundly deaf or severely hard of hearing individuals. The device consists of two basic parts, external and internal. The external components are responsible for picking up sound waves from the environment, processing these signals via filtering and transducing them into electrical signals that are sent to a transmitter. The transmitter then sends the processed signals via electromagnetic induction to an internal receiver implanted in the patient. The receiver converts the signal into electrical impulses that are conducted down an internal cable to a microelectrode array embedded in the cochlea which directly stimulates the auditory nerve. Due to the brain’s advanced evolutionary ability to adapt signals coming from afferent inputs, patients who were exposed to some form of auditory development in their younger years are able to learn and interpret sounds and voices in a reasonable manner.

Similar in design to the cochlear implant are visual prostheses, which typically take the form of an externally-worn camera that is attached to an electronic stimulator on the retina, optic nerve, or in the visual cortex, thereby producing perceptions in the visual cortex. As with the cochlear implant, the way in which individuals lost their vital sense is an important factor in determining the effectiveness of these devices. Also common to both these devices is the use of fast Fourier transforms (FFTs) in the signal processing component to analyze spectral data.

Automatons (robotics)

The construction of autonomous robots and artificially intelligent neural systems, also known as behavior-based robotics, is a branch of robotics that bridges artificial intelligence (AI), engineering and cognitive science. The field seeks to develop methods for synthesizing artificial systems, ranging from physical robots to autonomous software agents, and use robotics to model and analyze natural systems, ranging from insects to humans (Mataric 1998). Domains of application have included mobile robots, underwater vehicles, space robotics (Mars Sojourner), as well as robots capable of manipulation, grasping, walking and running. Eerily, an autonomous robot receiving wireless signals recorded from a section of cultured rat brain cells, that in turn receives input from the robot’s ultrasound distance sensor, can navigate its way around the floor. The robot has an actual, living brain consisting of rat neurons. The cells are removed from rat fetuses and then disentangled from each other with an enzyme bath. Finally, the cells are spread over a multi-electrode array (MEA) bathed in a nutrient-rich medium. Impulses from its robotic part are received; the neurons organize themselves and fire electrical signals back (Christensen 2009).

Discussion and further research

This paper presents a brief review of the process by which neural systems are modeled, mathematically, computationally, and biosynthetically. Included were various hardware applications that can be implemented using biological models of cognitive processes. It isn’t difficult to imagine what future tools might come out of artificial neural network research, devices like neural prostheses, autonomous robots; and what obstacles need to be overcome to reach these goals, such as modeling genetic phenomena on the molecular level. The only limit is our functional mind.

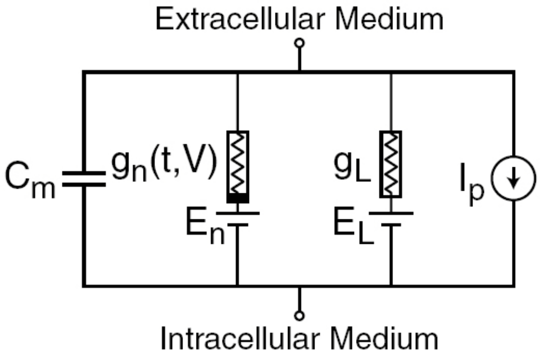
Appendix

[1]
$$E_{eq,K^+} = \frac{RT}{zF} \ln \frac{[K^+]_o}{[K^+]_i},$$

[2]
$$E_m = \frac{RT}{F} \ln \left(\frac{P_{\mathrm{K}}[\mathrm{K}^+]_{\mathrm{out}} + P_{\mathrm{Na}}[\mathrm{Na}^+]_{\mathrm{out}} + P_{\mathrm{Cl}}[\mathrm{Cl}^-]_{\mathrm{in}}}{P_{\mathrm{K}}[\mathrm{K}^+]_{\mathrm{in}} + P_{\mathrm{Na}}[\mathrm{Na}^+]_{\mathrm{in}} + P_{\mathrm{Cl}}[\mathrm{Cl}^-]_{\mathrm{out}}} \right)$$

[3]
$$\lambda^2 \frac{\partial^2 V}{\partial x^2} = \tau \frac{\partial V}{\partial t} + V$$

[4]



[5]
$$y_j = \phi \left(\sum_i w_{ij} x_i \right)$$

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