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Book Review

Computing with Lipids, Proteins, and Ions

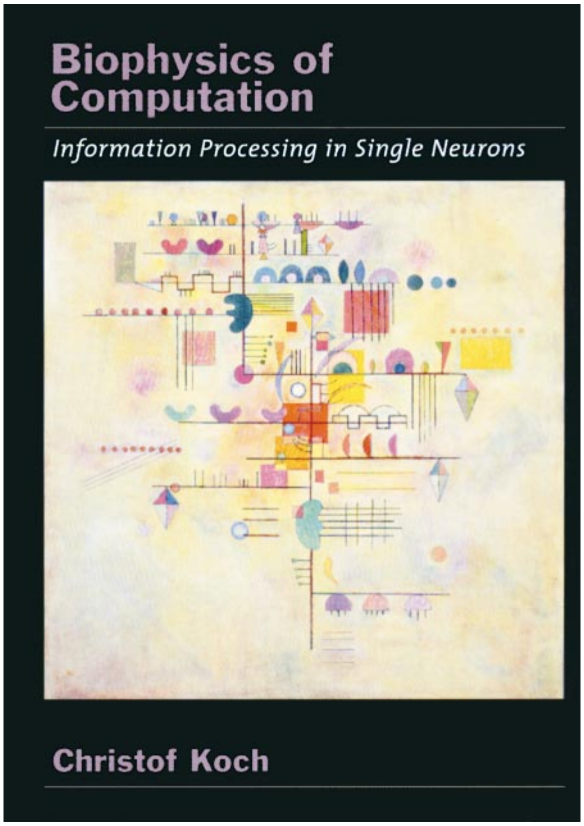
Biophysics of Computation
By Christof Koch
New York: Oxford University Press (1999). 562 pp., $59.95.

What are the building blocks of computation in the nervous system, and how do they influence how the brain computes? This question forms the basis of Christof Koch's new book, *Biophysics of Computation*. Many phenomena that could serve as computational mechanisms within the nervous system have been discovered in the past 10 years; the most striking example is the nonlinear properties of dendrites. Koch's book summarizes our current understanding of dendrites and axons, with an emphasis on how their biophysical properties can implement elementary computations, like multiplication and division, from which more complex computations can be built. The focus of the book is almost exclusively on the computational potential of subcellular mechanisms; this focus permits the book to be concrete and well grounded in established biophysical properties. This bottom-up approach to computation complements the more traditional top-down systems neuroscience approach (e.g., *The Computational Brain*, Churchland and Sejnowski, 1992, MIT Press), where the focus is on what computation needs to be done to explain a particular behavior rather than on how a particular computation is implemented.

How important are the biophysical properties of ion channels, synapses, and the like for understanding high-level computation in the brain? Koch argues convincingly that these computational building blocks may determine the types of computations the nervous system does well and those it does poorly, and, as a result, may influence the approach the brain takes to computation. As an example, he points out that the physical properties of the elementary semiconductor circuits found in modern computers dictate that the basic computational element is an inverter: a device that converts 1s to 0s and vice versa. The conventional logical operations AND and OR turn out to require more of these inverters than do the inverted logical operations NOT AND (NAND) and NOT OR (NOR). Thus, a simple physical property of the basic semiconductor devices used in computers plays an important role in what computations can be done efficiently. Koch describes several ways in which the basic computational elements in the nervous system differ significantly from those in digital computers—for example, the ubiquitous ability of synapses and neurons to adapt to the past history of their input signals. We have essentially no understanding, however, of how these differences influence high-level computational strategies in the nervous system. *Biophysics of Computation* represents an important step in this direction as it explores what elementary computations are easily implemented by known biophysical mechanisms.

One theme running throughout the book is the potential computational properties of dendrites. Dendrites have gained tremendous respect in recent years, as a wealth of experimental evidence has shifted our view of the "typical" dendritic tree from a passive structure that sums its inputs to an active, nonlinear device that potentially is where much of the computation in the nervous system takes place. Koch begins by describing analytical approaches to passive dendrites, following Rall's classic treatment of this topic. With this foundation in place, Koch turns to the properties of dendritic spines and active conductances in dendrites. Koch does a good job of keeping this enormous increase in the complexity of the dendritic tree from becoming overwhelming by pointing out conditions where the added complexity doesn't matter. For example, he describes conditions under which spines have little effect on synaptic potentials and thus can be ignored from a computational standpoint.

A second theme is the discussion of models for spike generation. Again, Koch begins at the beginning—with the classic description of Hodgkin and Huxley. He works from the Hodgkin-Huxley framework to a discussion of simplified models that nevertheless possess the same essential features—action potentials and periodic and chaotic spike trains, for example. These models permit



mathematical analyses that lead to an intuitive understanding of some aspects of the original Hodgkin-Huxley equations. For example, Koch provides a nice description of why there is a nonzero minimum firing rate in the Hodgkin-Huxley equations, and shows how adding a conductance—the A current—permits arbitrarily low firing rates. Finally, Koch describes integrate-and-fire models that, while less faithful to details of the biology, permit exploration of the computational importance of the threshold for spike generation. These methods are clearly and succinctly described.

There are a couple of areas Koch mentions only briefly that I think deserve more attention. One is how behavioral performance can be used to constrain the underlying computational mechanisms. This is particularly clear for sensory tasks like visual motion detection or sound localization. For example, the barn owl's ability to localize sound sources constrains the temporal comparison of signals originating from the two ears. Possible biophysical implementations of the computations at the heart of these tasks can be discarded unless they explain the measured behavioral precision. A related issue is how noise, either cellular noise or noise in the input signals themselves, influences computational strategies. One computation that is very susceptible to noise is division, as noise can easily cause the dreaded "division by zero" or more generally large random errors. There are approximations to division that, though systematically wrong, can provide a more accurate estimate of the ratio of two noisy signals. For example, adding a constant to the denominator can often suppress random errors at the cost of a systematically biased result. These considerations of noise robustness may help choose among different potential computational mechanisms.

The neurobiology community has a (probably deserved) distrust of theoretical approaches, in large part due to the small number of theories that are subject to experimental test. Thus, a critical aspect of the approach Koch advocates is that it makes testable predictions. For example, Koch describes several ways that a cell could multiply two inputs, and each method places specific requirements on the cell's biophysical properties. One mechanism relies on local interactions between excitatory and inhibitory inputs on a single branch of the dendritic tree. As Koch points out, this mechanism requires precise localization of the synapses and can be discarded if this localization is found not to exist. Another mechanism for multiplication uses the threshold for spike generation to detect coincidences in two presynaptic spike trains; this method requires that the two inputs individually do not exceed threshold but together they do. Thus, these different possible implementations of multiplication rely on very different biophysical mechanisms. Koch's clear discussion of these differences should lead to focused experiments.

Koch's informal writing style and the numerous figures help make the book a pretty easy read. Particularly helpful are figures illustrating many of the more mathematical concepts. The material systematically builds upon itself, making the book self-contained with a minimum of assumptions about the reader's background. This quality will make *Biophysics of Computation* a good textbook for a graduate or advanced undergraduate computational neuroscience course, especially if someone writes an accompanying set of problems! The systematic progression of the material makes the book a little difficult to use as a reference, as issues brought up early in the book are often not resolved until much later. This is offset, however, by the division of the book into many short, well-titled sections and the extensive bibliography.

There are a number of excellent books that describe the biophysical properties of ion channels and synapses (*Ionic Channels of Excitable Membranes*, Hille, 1992, Sinauer; *Foundations of Cellular Neurophysiology*, Johnstone and Wu, 1995, MIT Press). Koch's book provides a set of tools to bridge this understanding of basic biophysical mechanisms and higher-level computational studies. This is an ambitious task, largely because our understanding of computation in the nervous system is not mature enough to have many widely agreed upon success stories. The value of this book, instead, is to provide the methods to place detailed studies of biophysical mechanisms in a computational framework; we can only hope that this work will pay off in providing answers to some of the open questions Koch poses at the end of the book.

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