Dynamical Embodiments of Computation in Cognitive Processes

James P. Crutchfield

Physics Department, University of California, Berkeley, CA 94720-7300

and Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501

Electronic Address: chaos@santafe.edu

URL: http://www.santafe.edu/~jpc

Abstract

Dynamics is not enough for cognition nor is it a substitute for information processing aspects of brain behavior. Moreover, dynamics and computation are not at odds, but are quite compatible. They can be synthesized so that any dynamical system can be analyzed in terms of its intrinsic computational components.[1]

It is hard to argue with the hypothesis that time underlies cognition [1]. From our current vantage point it's now simply curious that "static" conceptions of cognitive processes have held so much sway over alternatives during the last two decades, even at cognition's lowest levels. Models of early visual processing that view the flow of information only from the environment inward ignore the strong and numerous neural pathways from visual and higher cortex that reach back to early stages. Predispositions to such feedforward architectures essentially ignore time—time which is intrinsic to the behavior of neural systems and which supports the storage, transmission, and manipulation of information. Numerous similar examples provide enough justification to make a case for time underlying cognition.

[1] Submitted as Open Peer Commentary on article [1].

One can conclude then that time is one of the substrates of cognition. But what kind of substrate is it? One of the central ways in which a natural process embodies time is in an architecture with feedback pathways between its components. Feedback, in turn, enables a system to exhibit a vastly richer range of dynamical behaviors than systems without it. That the temporal aspects of a process are well-modeled by a mathematical abstraction called a "dynamical system" has been appreciated since the turn of the century. At that time the French mathematician Henri Poincaré, through pure insight and hard hand calculation—that is, without the benefit of fast simulation on computers, discovered the essential mechanisms that lead to complicated and rich behaviors in dynamical systems. Much of the theoretical development since then has been the elaboration, extension, and adaptation of his basic insights.

Dynamical systems theory views a process's behavior as a sequence of states in a state space, guided by equations of motion that take the current state to the succeeding, future one. In this framework time is made implicit and one employs a geometric view of how structures in the state space generate as well as constrain behavior and the emergence of spatio-temporal patterns. In this way kinds of temporal behavior are translated into geometric objects of varying topologies. As has been noted many times before, dynamics is the geometry of behavior [2,3]. The benefits of this geometric analysis over previous approaches, such as purely statistical or linear analysis, are now well known. The production of deterministic unpredictability (chaos), sudden changes in system behavior as control parameters are varied (bifurcations), and a rich taxonomy of nonlinear behaviors, are a few of the phenomena that have been qualitatively and quantitatively analyzed.

So one can argue that, to the extent it allows us to understand nature's complex nonlinear processes, dynamics is involved, at least partly, in cognition. But it is an entirely different question to ask, How do dynamical systems support information processing and computation? This question leads to my main point: Though I can't argue against time and dynamics in cognition, any hypothesis connecting them to cognition has to be, and at this time can be, more concrete.

Dynamics is not a substitute for information processing and computation in cognitive processes. Given this, how can we synthesize dynamics and computation? The approach of computational mechanics is to analyze dynamical systems in terms of how geometric state space structures support computation [4,5]. How much memory of the past is stored in the system's current state? How is this information transmitted between the system's degrees of freedom? How is it manipulated to produce the system's future behavior? What is the causal structure of this information flow? Building on a notion of the "effective" causal states embedded in a dynamical system these questions can be answered both quantitatively and architecturally.

One consequence of such a synthetic framework is that it renders entirely moot arguments between symbolic and dynamical approaches to cognition and also debates about discrete versus analog embodiments of computation. In short, there simply is no antagonism between a dynamical view and a computational view, as long as one is willing to fairly assess where each field is and be willing to extend the notions each brings to the problems of cognition.

Are dynamical systems theory and our notions of computation ready to form a foundation for cognitive science? There are such fundamental limitations at present to both that I don't think so. Dynamics, for example, is in need of serious modification and extension to be made directly relevant to cognitive processing. Over its century-long history dynamical systems theory has been (i) deterministic, (ii) low dimensional, and (iii) time asymptotic. Neural and cognitive systems, in stark contrast, are (i) stochastic, (ii) distributed and so high dimensional, and (iii) must react quickly, that is, over transient, not asymptotic time scales. The theory must be extended in just these ways.

Equally important, we need to greatly soften the digital hegemony that conflates "computation" with "discrete computation". The history of mathematical logic's dominance in computation theory is well appreciated, but nature is structured in many other and quite different ways, as just noted. To the extent that these alternatives are the substrates out of which cognitive systems are built then we need to investigate those kinds of information processing supported by natural systems.

So far all of the issues raised concern intrinsic computation and its possible dynamical embodiments, but even if a dynamical system can store information and manipulate it, how does such computational behavior become useful? What is the functional or even semantic content of a dynamical cognitive process having a fractal separatrix between three limit cycle, one fixed point, and two chaotic attractors? Typically, questions like these are answered by an analyst interpreting them in light of knowledge outside the system—knowing what the designed stimulus is, for example, and interpreting the resulting behavior in light of it and the desired range of responses.

This is certainly a necessary, even difficult and tedious, form of analysis. But in important ways it doesn't address the fundamental issues that arise in understanding the spontaneous appearance of cognition in a natural system. Even if we agree with the dynamical embodiment of computation, how do dynamical structures take on meaning and functionality in and of themselves? This is the notion of intrinsic emergence, in which a dynamical system generates behaviors and patterns that take on functionality within itself, in particular without reference to an a posteriori analysis by an external observer [6]. To my mind this is one of the key open issues currently precluding a mathematical theory of cognition. It helps to have a view, such as afforded by computational mechanics, that in principle lets one extract a system's causal information processing architecture. But how do semantics and functionality arise in the interrelation of the architectural components and between them and the environment?

In summary, I agree that time is central to cognition. It is embodied in architectures that include feedback pathways. Feedback opens up qualitatively new regimes of dynamical behavior. The current best way to analyze the mechanisms that produce these behaviors is dynamical systems theory, which gives a geometric view of state space structures. But to say that dynamics underlies cognition is not enough.

It is very important to distinguish the dynamical hypothesis from questions about how any given dynamical system supports computation—that is, how it stores historical information, transmits it internally, and manipulates it to produce its future behavior and output responses. One approach to this that avoids artificial dichotomies, such as symbolic versus connectionist or discrete versus analog embodiments, is computational mechanics. Computational mechanics allows one to identify the dynamical mechanisms that support intrinsic computation and so to lay out a system's embedded information processing architecture. Yet another, different and higher level, question is how the behavior of a dynamical system that supports intrinsic computation takes on functionality and cognitive import in an environment. As we look to the future it will be increasingly important that the limitations of our current conceptions of dynamics and of computation be identified so that extensions and new frameworks, invented in the spirit that has brought us to the threshold of synthesizing them, can form the foundations for understanding how cognition works.

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