Theories of Structure Versus Theories of Change

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Commentary on T. van Gelder, "The Dynamical Hypothesis in Cognitive Science."

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Abstract

The dynamics/computation debate recalls a similar debate in the evolutionary biology community concerning the relative primacy of theories of structure versus theories of change. I argue that a full account of cognition will require a rapprochement between such theories, and will include both computational and dynamical notions. The key to making computation relevant to cognition is not making it analog, but rather understanding how functional information-processing structures can emerge in complex dynamical systems.

Is cognition about change or is it about structure? Van Gelder clearly thinks that change is the essence: he champions dynamical systems theory because "Dynamicists are interested, in the first instance, in how things change; states are the medium of change, and have little intrinsic interest. Computationalists, by contrast, focus primarily on states; change is just what takes you from one state to another....Computationalists focus on internal structure...." (p. 10)

Van Gelder's formulation of this opposition—between dynamics as focused on state change and computation as focused on state internal structure—brings to mind a similar debate that has gone on for years in the evolutionary biology community, and whose resolution will, I believe, be instructive for the dynamics/computation debate in cogntive science. What accounts for the particular biological phenomena that we observe in the world? The predominant explanatory framework has been neo-Darwinism, a theory of change *par excellence* (inherited random change from one generation to the next leads to adaptation via natural selection). But some evolutionary theorists have questioned the adequacy of classical neo-Darwinism as either an explanatory or a predictive theory, and argue instead for the primacy of historical contingency (Gould, 1989a) or the self-organization of biological structure not due to natural selection (Fontana & Buss, 1994; Goodwin, 1990; Kauffman, 1993). These "historicists" and "structuralists" are the connectionists of the evolutionary biology community—the people questioning the classical orthodoxy. The selectionist/historicist/structuralist debate was summarized by Seilacher in his triangle of causal determinantes of form (Seilacher, 1991), and has been discussed at length by Gould (1989b), among others. It is becoming increasingly clear, however, that the stark oppositions posited among these three frameworks are not only false oppositions, but are hindering progress in evolutionary theory. The purely structuralist theories don't explain how structures can be significantly changed in evolution, and the purely selectionist theories don't explain what intrinsic driving forces and constraints there are on the formation of biological structures. What's needed is a theory that incorporates both change and structure[1].

Similarly, in cognitive science, we have theories of change and movement ("dynamical" approaches): how robots walk in a stable manner (Beer, 1995), how babies reach and grasp (Thelen & Smith, 1994), how people move from a condition of uncertainty to making a decision (Busemeyer & Townsend, 1993). These theories, however, do not explain the information-processing content of the states over which change is occurring; they either address tasks that don't require complex information processing or assume high-level information-related primitives *a priori*. For example, in Busemeyer and Townsend's Decision Field Theory, described in the target article, information-loaded notions such as "positive and negative consequences", "attention and shift of attention", "preferences", and "motivation" are atomic primitives (Busemeyer & Townsend, 1993), and the theory does not attempt to explain how these are implemented or why a particular decision-maker might have one version of them instead of another.

Likewise, in cognitive science we have theories of structure ("computational" approaches) that make statements about the information processing structure of concepts, representations, and beliefs (e.g., semantic networks, neural networks, schemata, Bayesean belief networks, fuzzy logic, theorem provers). As van Gelder points out, most of these theories assume that information processing consists of the manipulation of explicit, static symbols rather than the autonomous interaction of emergent, active ones (Hofstadter, 1985). Such theories typically cannot explain what driving forces and constraints there are on how the system in question can change, what trajectories it can take, and how the high-level symbols can emerge from a lower-level substrate.

Thus, as in evolutionary biology, cognitive science needs rapprochements between theories of change and theories of structure. Attempts at such rapprochements are coming from many sectors, in particular from research on "complexity," in which dynamics, computation, and adaptation are beginning to be viewed in a more unified framework. For example, in our work on emergent computation in cellular automata, my colleagues and I have shown how active representations and functional information processing can emerge from interactions among dynamical systems, an environment, and an adaptive evolutionary process (Crutchfield & Mitchell, 1995; Das, Crutchfield, Mitchell, & Hanson, 1995; Das, Mitchell, & Crutchfield, 1994). This work is a preliminary step in understanding how useful computation can be

[1]This formulation of the evolution debates was given to me by evolutionist Daniel McShea, personal communication. McShea's formulation was elaborated by Crutchfield (1994), who proposes a particular computation-theoretic notion of structure ("computational mechanics of nonlinear processes") and a related mechanism for the transformation of structure ("hierarchical machine reconstruction"). Crutchfield suggests that a unified theory of these two processes might be termed "evolutionary mechanics", which he proposes as a general theory of "emergence".

embedded in a complex dynamical system; it is one attempt to, as van Gelder puts it, "dramatically reconceive how [complex internal structures] might be instantiated" in such a system. In the end, van Gelder seems to agree that computational notions—albeit of a non-traditional kind—might be important for cognitive science: "the DH can embrace the idea that cognitive processes can be computational." (p. 15) However, unlike van Gelder, I don't believe that it is the digital/analog distinction that is key for making computation relevant for cognition; instead, I think progress will come from understanding how functional information-processing structures can emerge in spatially extended dynamical systems with no central control, with no globally accessible memory, and with limited communication among components. Computer science is gradually moving in this direction, and I believe that many useful synergies between computation theory and cognitive science will arise in the near future.

Van Gelder's answer to objection 6.7 ("Not As Cognitive") is that the Dynamical Hypothesis "asserts that cognitive agents are dynamical systems of quite special kinds." (p. 17) I will venture to say that they are dynamical systems in which the states and state trajectories can and must be interpreted in functional, informational, and information-processing terms, and that computational notions will be necessary as well as dynamical notions for constructing a full account.

References

Beer, R. D. (1995). A dynamical systems perspective on agent-environment interaction. *Artificial Intelligence*, 72: 173–215.

Busemeyer, J. R. & Townsend, J. T. (1993). Decision field theory: A dynamic-cognitive approach to decision-making in an uncertain environment. *Psychological Review* 100: 432–459.

Crutchfield, J. P. (1994). Is anything ever new? Considering emergence. In G. Cowan, D. Pines, & D. Meltzer (Eds.), *Complexity: Metaphors, Models, and Reality*, 515–537. Reading, MA: Addison-Wesley.

Crutchfield, J. P. & Mitchell, M. (1995). The evolution of emergent computation. *Proceedings of the National Academy of Sciences, USA*, 92 (23): 10742.

Das, R., Mitchell, M, and Crutchfield, J. P. (1994). A genetic algorithm discovers particle-based computation in cellular automata. In Y. Davidor, H.-P. Schwefel, and R. Männer (editors), *Parallel Problem Solving from Nature—PPSN III.* Berlin: Springer-Verlag.

Fontana, W. & Buss, L. W. (1994). What would be conserved if 'the tape were played twice'? In G. Cowan, D. Pines, and D. Meltzer (Eds.), *Complexity: Metaphors, Models, and Reality*, 223–244. Reading, MA: Addison-Wesley.

Gould, S. J. (1989a). *Wonderful Life: The Burgess Shale and the Nature of History.* New York: W. W. Norton.

Gould, S. J. (1989b). A developmental constraint in *Cerion*, with comments on the definition and interpretation of constraints in evolution. *Evolution*, 43(3): 516–539.

Goodwin, B. C. (1990). Structuralism in biology. *Sci. Prog.*, 74: 227.

Hofstadter, D. R. (1985). Waking up from the Boolean dream, or, subcognition as computation. Chapter 26 of *Metamagical Themas*. New York: Basic Books.

Kauffman, S. A. (1993). *The Origins of Order: Self-Organization and Selection in Evolution.* New York: Oxford University Press.

Seilacher, A. (1991). Self-organizing mechanisms in morphogenesis and evolution. In N. Schmidt-Kittler and K. Vogel (Eds.), *Constructional Morphology and Evolution.* New York : Springer-Verlag.

Thelen, E. & Smith, L. B. (1994). *A Dynamic Systems Approach to the Development of Cognition and Action.* Cambridge, MA: MIT Press.