Cognitive Development 27 (2012) 326–348

Contents lists available at SciVerse ScienceDirect

Cognitive Development

The past, present, and future of computational models of cognitive development

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ARTICLE INFO

Keywords:
Computational models
Cognitive development
History

ABSTRACT

Does modeling matter? We address this question by providing a broad survey of the computational models of cognitive development that have been proposed and studied over the last three decades. We begin by noting the advantages and limitations of computational models. We then describe four key dimensions across which models of development can be organized and classified. With this taxonomy in hand, we focus on how the modeling enterprise has evolved over time. In particular, we separate the timeline into three overlapping historical waves and highlight how each wave of models has not only been shaped by developmental theory and behavioral research, but in return also provided valuable insights and innovations to the study of cognitive development.

The year 1986 saw the Challenger shuttle disaster, the Chernobyl nuclear accident, the Iran-Contra affair, and the publication of Rumelhart and McClelland's 2-volume set, *Parallel distributed processing: Explorations in the microstructure of cognition*. While the last event would not make most people's top-10 list, the *PDP* volumes have exerted an enormous influence on developmental science and their impact continues nearly three decades later (Elman, 2005; Elman et al., 1996; Karmiloff-Smith, 1992; Mareschal & Thomas, 2007; McClelland, 1995; Munakata & McClelland, 2003; Plunkett & Sinha, 1992; Quinlan, 2003; Schlesinger & Parisi, 2004; Shultz, 2003; Spencer, Thomas, & McClelland, 2009).

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http://dx.doi.org/10.1016/j.cogdev.2012.07.002

Although computational models of learning and development existed before 1986, the *PDP* "bible" not only made *connectionism* a household word (among psychologists), but also catalyzed the emergence of modern developmental science. It restored learning as a core topic in cognitive science by introducing more powerful learning rules that enabled the development of internal representations. This evolution cogently illustrated the concept of *emergence*: Connectionist networks could, in some ways, develop themselves (McClelland, 2010). Perhaps most importantly, the PDP volumes illustrated the power of computational modeling as a tool for inquiry into the mechanisms of development.

Historically, most work in developmental science has combined careful observation/description of children and their environments (in all their glorious complexity) with well-controlled experiments attempting to distill some of these factors. In this context, what can a handful of equations or a simple algorithm offer, beyond what these methods already provide? The 25th anniversary of *PDP* presents the developmental community with an opportune moment to address this question by raising a series of important issues about the computational modeling enterprise (and not just connectionism): Why do we construct models? How has this enterprise changed? What can they teach us? And what have they taught us?

Our goal is to address these questions by surveying the history of computational models of cognitive development to highlight three themes. First, the array of modeling approaches available to developmental scientists has grown to cover a broad landscape of timescales, domains, and theoretical perspectives. But the consequence is not simply better or more diverse computing devices; rather, this diversity reflects increasingly creative and subtle theoretical development. Second, computational models have not only provided tests for theoretical accounts, but also generated insights and predictions that transcend the models themselves. Third, and perhaps most importantly, the very nature of the computational enterprise has evolved, as researchers have migrated from computational models as a tool for description and implementation of theory to models as a tool for inquiry and experimentation about theory.

We begin by describing the modeling enterprise, offering principles for evaluating and interpreting models. These have evolved along with more specific modeling approaches, and it is useful to bear them in mind. We next present a taxonomy of modeling paradigms. Here, our objective is to illustrate the complementarity between particular approaches and specific developmental domains and timescales. We then shift to a chronological perspective, describing three major waves since the mid-1980s. We highlight not only how computational models have improved, but also how this refinement is the result of interaction between model-testing, empirical research and theoretical development. Finally, we return to our three themes, to reflect on the progress of the last 25 years and to consider the future of developmental models.

1. (Why) does modeling matter?

Oakes, Newcombe, and Plumert (2009) asked, "Are dynamic systems and connectionist approaches an alternative to Good Old-Fashioned Cognitive Development?" The outcome of their analysis is optimistic, but the question is reasonable, particularly as dynamic systems and connectionism are not just theories of development, but particular ways of using modeling to understand it. Although many who study development are open-minded about the use of models, they are not yet convinced that computation adds value to the research enterprise.

Computational modeling will never supplant conventional behavioral methods. Rather, it *complements* such methods by answering questions about mechanism that are not immediately accessible to experimentation. Braitenberg (1984) offers an example. He describes a series of mechanical "creatures" (see Fig. 1) and uses them to illustrate both the power of simple mechanisms working in concert over time and the unique contribution of computational models:

> It is pleasurable and easy to create little machines that do certain tricks. It is also quite easy to observe the full repertoire of behavior of these machines—even if it goes beyond what we had originally planned, as it often does. But it is much more difficult to start from the outside and try to guess internal structure just from the observation of behavior. It is actually impossible in theory to determine exactly what the hidden mechanism is without opening the box, since there