Chapter 1
Introduction to Education as a Complex Dynamical System

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This book seeks to introduce educational researchers, practitioners, and policy makers to the theory of Complex Dynamical Systems (CDS), a novel perspective that has gained considerable ground in many scientific disciplines, but whose applicability to education remains underappreciated. The theory of complex dynamical systems (CDS) is concerned with the analysis of systems irrespective of how the unit of analysis of those systems is defined. These systems could be molecules, cells, words, people, or human organizations. In recent years, there has been a growing interest in the use of a complexity perspective in social science research as well as policy and practice, as the perspective provides a rich and widely applicable vocabulary to capture processes of change and the interaction between individuals and larger organizational constellations. This book focuses on educational processes in human systems.

Let us begin with a clarification of the terminology. When we say *complex*, we mean that the behavior of a larger systemic constellation cannot be readily reduced to that of its individual members. Consequently, the perspective inspires a holistic view where the behavior of individuals is understood in its larger context. For example, we can understand student learning in terms of collaborative behavior in the classroom in which it takes place, while a classroom climate conducive to learning cannot be readily reduced to the learning or interactive behavior of individual teachers and students. In other words, the whole is greater than the sum of its parts. When we say *dynamical*, we mean that current behavior is understood in terms of deviations from past behavior. As a result, the perspective focuses on behavioral change and its

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determinants, rather than on outcomes frozen in time. Thus, we might take an interest in the learning trajectories of individuals rather than whether students meet certain benchmarks or performance goals as a group. When we say *systems*, we refer to a constellation of individual members who are in a position to interact with each other as a coherent entity. In this sense, schools, districts, classrooms, and parent–teacher conferences are all examples of systems, and when we would like to understand the behavior of individuals within such systems, we also need to look at the behavior of other units at the same level of description within the same system.

This book seeks to provide a conceptual and methodological introduction to the use of complex dynamical systems (CDS) approaches in education, covering most of the basic dynamical concepts that can be found in the literature, such as emergence, complexity, self-organized criticality, attractors, catastrophe theory, chaos theory as well as recent innovations to the complexity field such as fractional differencing and power laws. As a field of inquiry, education has been slow to catch on to complex dynamical systems approaches, whereas, in other disciplines, such as psychology, econometrics, and theoretical biology, dynamical approaches have by now been largely integrated into the theoretical and empirical research agenda. Psychology, for example, has produced several edited volumes about the application of dynamical systems approaches to various subspecialties in the field (Abraham & Gilgen, 1995; Guastello, Koopmans, & Pincus, 2009; Robertson & Combs, 1995; Sulis & Combs, 1996; Tschacher & Dauwalder, 1999), but there is no similar book that is specific to the field of education. This book seeks to address this gap.

In education, work from a complexity perspective tends to be theoretical, and covers such topics as the exploration of the interface between dynamical systems, education, and post-modernism (e.g., Doll, 1993; Truiet, 2012), the use of complexity to characterize the political process in education (Osberg & Biesta, 2010), the implications for practice of complexity as a paradigm shift (Davis & Sumara, 2006), or it consists of retrospective interpretations in terms of complexity of research findings from studies utilizing conventional research paradigms (Morrison, 2006). While this work is valuable in its own right, it does not have the level of conceptual and methodological specificity that is required to capture the dynamical processes hypothesized in the dynamical literature, such as emergence, second order change, and sensitive dependence on initial conditions, nor does it speak to the specific gaps in our knowledge that result from the relative absence of dynamical perspectives in empirical research in education.

There needs to be greater clarity about how research into the dynamical aspects of the educational process can inform and supplement our knowledge obtained through more traditional research paradigms such as randomized control trial studies, quasi-experimental designs, and qualitative research. Recent progress in the field of dynamical systems includes significant empirical work to study the dynamical underpinnings of the educational process. A first inventory of this work was a special issue in *Nonlinear Dynamics, Psychology and Life Sciences* on education (Stamovlasis & Koopmans, 2014), which brought together significant new empirical studies in education that explicitly utilize a complexity perspective. This book further capitalizes on these developments by presenting some of the most recent path-breaking advances in this area.

The six chapters immediately following this introduction discuss the conceptual framework of complex dynamical systems and its applicability to educational processes. Chapters 8–10 translate some of these concepts into coherent research methodology. Chapters 11–17 report the results of empirical research illustrating the use of CDS research methods. This work aims to help the reader appreciate what we can learn about dynamical processes in education when this angle is taken. In Chap. 2, Fleener appreciates, at a theoretical level, the implications of CDS as a paradigm shift in education and its ability to address long-standing issues to which conventional research paradigms have failed to produce satisfying answers, such as how the complexities of school environment and individual differences contribute to learning outcomes, and to forge a new kind of link between research and practice. In Chap. 3, Bloom further explores the historical affinity between qualitative research and complexity research that dates back to the work of Gregory Bateson in the 1930s. Qualitative transformation is one of the central concerns in CDS, and the fine-grained observation that qualitative research permits make it possible to bring the dynamical underpinnings of causal processes to the surface in a way that randomized control trial studies cannot (Maxwell, 2004, 2012).

Currently, it is difficult to imagine how one can talk about change in dynamical terms without talking about *emergence*, the appearance of radical novelty in systemic behavior and the search for the origins of such novelty. Goldstein discusses the construct of emergence in Chap. 4 and points to the failure of most current dynamical literature to explain such novelty. He presents *self-transcending constructions* as one possible way to distinguish spontaneous transformation that may occur without any theoretically interesting antecedents from a change process where the propensity toward transformation is already built into the system. The identification of such propensities is both of theoretical and pragmatic interest to the field of education, because it will help us understand why change does occur or fails to transpire. This knowledge may, in turn, place findings of existing research into clearer perspective. It may even help us penetrate deeper into the metaphysical realm of questions about the origins of complex dynamical systems.

In Chap. 5, Jörg appreciates the magnitude of the paradigm shift produced in the field if a complexity perspective is taken, and he introduces the term generative complexity as a new way of looking at systemic behavior in terms of the processes through which systems maintain their integrity in the ongoing interrelationship with their constituent components. His contribution is unique in that it is grounded in a combination of the philosophical and early developmental literature (Vygotsky), rather than in the accomplishments in mathematics, physics, and chemistry (e.g., Bak, 1996; Prigogine & Stengers, 1984; Thom, 1975), engineering (Ashby, 1957; Wiener (1961), or anthropology (Bateson, 1972) as has been more common in the field of complexity.

Chapters 6 and 7 analyze, respectively, the dynamical processes underlying the acquisition of motor skills and children's play, which both require description of how integrated behavioral patterns occur over and above the individual elements that make up those patterns. In Chap. 6, Corrêa, Correia and Tani describe the complex processes that constitute psychomotor behavior, such as the fluency of movement based on identifiable behavioral elements, as well as the dynamical components of that

behavior: consistency and flexibility are both present in the behavior. They address the question on motor skills acquisition as the main goal for teaching and coaching, based on a nonequilibrium model of motor learning, where psychomotor behavior can be understood as adaptive behavior in its spatiotemporal context. Likewise, in Chap. 7 Fromberg analyzes the contextual, transformative aspects of children's play as well as the complex relationship of the individual play episodes with the larger developmental outcomes to which the play activities bear a generative relationship. Play is the means through which children acquire their adaptive skills in the interface with the external environment, and the relationship between these developmental outcomes and individual play episodes illustrates complexity.

Koopmans in Chap. 8 focuses on an important methodological implication of taking a dynamical approach, namely the need to augment our knowledge grounded in rigorously sampled cross-sectional studies with an equally rigorous collection information about the behavior of individuals observed frequently over extended time periods. This focus on the changes in systemic behavior over time addresses a potentially very important aspect of cause and effect relationships in education, namely the extent to which behavior can be understood in terms of its own previous manifestations.

Complex dynamical systems approaches are grounded in a wide variety of mathematical models. One of the most important ones is a family of models known as catastrophe theory, a formulation of discontinuous changes based on sets of predictors that model the conditions under which discontinuity occurs. Stamovlasis in Chap. 9 provides a complete presentation of catastrophe theory starting with a brief history of its mathematical foundation and continuous with its mathematical formalism in deterministic and stochastic forms. Subsequently, he reviews all the current statistical methodologies that apply catastrophe theory to real data, focusing on cusp model, and discusses central epistemological issues associated with nonlinear dynamics in social and behavioral sciences. Furthermore, he demonstrates the applicability of catastrophe theory in educational research by presenting nonlinear models within the neo-Piagetian framework and science education. Marion and Schreiber in Chap. 10 discuss the recent advances in the use of network analysis and provide a primer of how these methods can be used in educational research. The main interest is to study networks of agents who share work-related experiences. For example, students and teachers in a given school, or informal leaders in a school community might constitute a relevant network. Network analysis has strong grounding in the mathematics of graph theory and it has a specific terminology in describing the system under consideration, associated with various network-level and agent-level measures. It is therefore a particularly useful approach to provide an empirical basis for our descriptions of how systems are organized.

A set of empirical studies follows in Chaps. 11–17. Each of these chapters provides examples of methodologies that are specific to the description of complex dynamical process and the exploration and confirmation of the hypotheses it generates. The section showcases several standard methodological approaches that are currently used in CDS: time series analysis, state space grid modelling, orbital decomposition, network analysis, and catastrophe theory, as well as

simulation models. In addition, problem-specific approaches are discussed as well, such as van Vondel's macro-dynamical description of student reasoning skills and the temporal sequencing of types of teacher responses in Chap. 11. Van Vondel and her coworkers rightly argue that understanding development requires, at a minimum, a detailed understanding of how behavioral changes occur over time and what the environmental contingencies are of these changes. The authors developed a unique approach, and demonstrate the surplus value that a complex dynamic systems approach offers, based on new tools designed to answer questions about how the underlying processes affect students' performance and provide insights into how teachers can optimize their lessons.

The potential of CDS approaches to capture classroom interaction processes has been appreciated in the literature on at least several occasions recently. Pennings and Mainhart take the obvious next step in Chap. 12 by collecting and analyzing teacher interactions with students and the social climate in classrooms using a rigorous real-time data collection process as well as rigorous modelling practices, State Space Grids (SSG), to identify the attractors underlying these interactions. SSG is a powerful tool to examine the moment-to-moment nature of classroom interactions that could be correlated with teacher and teaching process characteristics. The authors in this chapter are making a remarkable contribution towards the new paradigm establishing classrooms as complex dynamical systems.

Two papers illustrate the use of orbital decomposition analysis (ODA), a method designed to study interaction processes and specifically to analyze time series measured at the nominal level. Stamovlasis in Chap. 13 illustrates the utility of the symbolic dynamics approach when looking at collaborative learning processes, where it is shown that discourse analysis of students' verbal interactions can reveal those dynamical characteristics that might have a decisive impact on outcomes; this exemplifies how to look closer, and thus, sheds light into the 'black box' of educational interventions; moreover it demonstrates that small group processes, under certain circumstances, behaves as a complex dynamical system driven by self-organization mechanisms, finding that is important for the theory of education regarding the emergent phenomena, such as learning and creativity. In Chap. 16, Garner and Russell demonstrate the use of the same approach to better understand self-regulated learning by looking at the interaction between learners and the learning materials they use. They use ODA to investigate the nature of gaze sequences during a self-regulated learning episode. They aimed to investigate research questions regarding the presence and the nature of patterned sequences in relation to global task strategies, and furthermore the degree to which these patterns of acting, responsible for directing attentional guidance during learning, are the fingerprints of an underling nonlinear dynamical system.

Scrutinizing ordered observations over a long period of time permits the detection of dynamical processes that otherwise remain hidden. Koopmans illustrates this point in Chap. 14 when discussing recent advances in time series analysis, such as fractional differencing and spectral power analysis to detect long-range dynamical features in high school daily attendance over a 7-year period (e.g., pink noise, self-organized criticality, self-similarity). Guevara and Porta in Chap. 15 reexamine

the persistence of inequality in society and the questions it raises about the instrumentality of the educational system in perpetuating it. The authors build simulation models to better understand the relationships between critical variables and triangulate them against data compiled from the educational system of Nicaragua. It is important to note that simulation techniques are infrequently used in educational research, while they are particularly useful to address questions about the temporal evolution and dynamical complexity of the relationship between variables pertaining to educational outcomes. Within the CDS framework, simulation models track down the complex interactions of social inequalities that educational systems generate in the context of global trends, and permit the investigation of more complex causal models than those typically documented in studies using traditional linear methods.

Lastly, in Chap. 17 Sideridis and Stamovlasis discuss the complex interrelationships between motivation, arousal and achievement and they use a cusp catastrophe model to illuminate that relationship as well as providing empirical confirmation of the nonlinear character of the relationships between these variables. They combined nonlinear dynamics and self-organization theory in order to explain instabilities in arousal level in educational settings and thus they built bridges between psychology and physiology within the nonlinear dynamics and complexity framework.

In conjunction, we believe that these chapters illustrate the potential of CDS in providing a new perspective on some old and newer problems in education, as well as providing a new set of interests and priorities for the field to address. The book also presents a set of methodological innovations that are specifically tailored to the analysis of processes of stability and transformation in educational systems in particular, and they demonstrate how these new approaches can be used on real educational data collected in real educational settings.

The advent of chaos and complexity theory in the late 1980s and early 1990s (e.g., Gleick, 1987; Waldrop, 1992; West & Deering, 1995) has created a need among scientists as well as practitioners, policy makers and the business community for a deeper understanding about how these new perspectives can help them address the most persistent questions of their respective fields. Considering the enormous variety of disciplines in which these perspectives have been utilized (e.g., biology, organizational theory, physics and chemistry, psychology, education, art medicine), it is not hard to appreciate the difficulty in trying to find consistency in the language that we use when talking about complex dynamical processes. In the field of CDS, there has been some serious discussion about its terminological consistency, or the lack thereof (Abraham, 1995; Goldstein, 1995), resulting in the realization that we need to get our house in order regarding the definition of our critical constructs. In that spirit, this book provides a glossary of terms based on their use in its chapters. These definitions are not meant to be written in stone, but they provide explicitness about how we used our terms, and may help bring clarity to the field of complexity in education.

We hope that the contributions presented here will facilitate our discussions of education as a complex dynamical system and inspire the generation of new types of questions about educational processes and what makes them effective. The work presented in this book seeks to take a meaningful first step in that direction.

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