Chaos Theory and the Sciences of Complexity: Foundations for Transforming Educational Systems

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Contents

Abstract

Chaos theory and the sciences of complexity are branches of systems theory that were developed to help understand highly complex systems. This chapter begins with a summary of some key features of these theories that are particularly relevant to understanding educational systems: coevolution, disequilibrium, positive feedback, perturbation, transformation, fractals, strange attractors, self-organization, and dynamic complexity. Then it explores two major ways that these theories can inform systemic transformation (paradigm change) in

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K-12 education in the United States and other parts of the world. One way is to help people understand their present systems of education, how each is likely to respond to changes that people try to make, and the effects of those changes, to determine when a system is ready for transformation and identify the system dynamics that are likely to influence both the attempted changes and the effects of those changes. The other way is to help people understand and improve the transformation process, which is itself a complex system that educational systems can use to transform themselves. Strange attractors and leverage points are two particularly powerful tools for influencing the success of the transformation process.

Keywords
Chaos theory · Sciences of complexity · Complex systems · Educational systems · Systemic transformation process · Paradigm change in education

Public education in the United States is an array of highly complex systems whose behavior, or causal dynamics, has proven difficult to understand. Similarly, the process of transforming a school system is highly complex and difficult to predict or control. Chaos theory and the sciences of complexity (Gleick, 1988; Holden, 1986; Kellert, 1993; Lorenz, 1995; Nowotny, 2005; Wheatley 1999) are branches of systems theory that were developed to help understand highly complex systems. They recognize that beneath the apparently chaotic or unpredictable behavior of a complex system lie certain patterns that can help one to both understand, and especially influence the behavior of, the system. This chapter begins with a summary of some of the key features of chaos theory and the sciences of complexity and then explores the ways that these theories can inform systemic transformation (paradigm change) in K-12 education in the United States and other parts of the world.

What Are Chaos Theory and the Sciences of Complexity?

Some of the key features of chaos theory and the sciences of complexity include coevolution, disequilibrium, positive feedback, perturbation, transformation, fractals, strange attractors, self-organization, and dynamic complexity. Each of these is briefly discussed and related to school systems.

Coevolution

For a system to be healthy, it must coevolve with its environment: It changes in response to changes in its environment, and its environment changes in response to its changes. Wheatley says, “We inhabit a world that coevolves as we interact with it. This world is impossible to pin down, constantly changing . . .” (1999, p. 9). A K-12 educational system exists in a community and larger society that are constantly evolving. But how are they evolving?

Toffler (1980) has identified three major waves of societal evolution. Each has been accompanied by a fundamental change of paradigm in all a society's systems, and they provide examples of coevolution between educational systems and their respective environments. During the agrarian age, the one-room schoolhouse was the predominant paradigm of education, with its focus on tutoring and apprenticeship. During the industrial age, the factory model of schools became the predominant paradigm of education, with its focus on standardization and teacher-centered learning. Now, as societies evolve ever deeper into the information age, they are undergoing just as dramatic a change as during the industrial revolution, and this is putting greater pressure on educational systems to coevolve through a similarly fundamental shift in paradigm.

As communities and society evolve deeper into the information age, in which knowledge work is rapidly replacing manual labor and more and more children are being raised in poverty and single-parent or dual-income households, the need for coevolution in education has become ever more urgent (Reigeluth, 1994; Reigeluth & Karnopp, 2013). Banathy (1991) has pointed to a large coevolutionary imbalance between education and society, which places society in ill-health and peril. Schlechty (1990), Caine and Caine (1997), and others have pointed out that educational systems are doing a better job than ever at what they were designed to do but that society is increasingly calling on them to do things they were not designed to do. Therefore, educational systems must coevolve to meet the changing educational needs of society.

To identify how an educational system should coevolve, there are two issues to look at. One is how its environment has changed. This includes changes in the community's educational needs, in the tools it offers to educators, and in other community (and societal) conditions that impact education, such as drugs, violence, teen pregnancy, and latchkey children. However, an educational system is not just shaped by its community; it also helps shape its community. Thus, the second issue for identifying how an educational system should coevolve is the ways the community would like its educational system to change to better reflect the values of the community and thereby to help make the community more consistent with its values. Therefore, an educational system should coevolve based on the evolving values, beliefs, and visions of the community and on the evolving educational needs of the community. This raises the all-important question: How can coevolution be fostered in educational systems?

Disequilibrium and Positive Feedback

According to chaos theory and the sciences of complexity, coevolution is fostered by disequilibrium and positive feedback. Equilibrium is defined as "a condition in which all acting influences are canceled by others, resulting in a stable, balanced, or unchanged system" (American Heritage Dictionary, as quoted by Wheatley 1999, p. 76). Systems can be in a state of equilibrium, in which case, minor changes or adjustments to the system are all that is necessary; or systems can be in a state

of disequilibrium, in which case, they approach "the edge of chaos." This might lead one to believe that disequilibrium is a bad thing. However, Wheatley (1999) makes the following points:

> "I observed the search for organizational equilibrium as a sure path to institutional death." (p. 76)
>
> "In venerating equilibrium, we have blinded ourselves to the processes that foster life." (p. 77)
>
> "To stay viable, open systems maintain a state of non-equilibrium. . .. They participate in an open exchange with their world, using what is there for their own growth." (p. 78)
>
> "Prigogine's work demonstrated that disequilibrium is the necessary condition for a system's growth." (p. 79)

Hence, disequilibrium is one important condition for coevolution. The other is positive feedback, which has a particular meaning in systems theory.

Systems may receive both negative and positive feedback. Negative feedback provides information about deficiencies in attaining a system's goals, so that the system can adjust its processes to overcome those deficiencies. In contrast, *positive feedback* provides information about opportunities for a system to change the goals that it pursues. Thus, positive feedback is information from the environment that helps a system to coevolve with its environment. Often, it takes the form of *perturbations* (or disturbances) that cause disequilibrium in a system.

Perturbation

A perturbation is any change in a system's environment that causes disequilibrium in a system. For example, as society in the United States has evolved deeper into the information age, a new educational need that has arisen is the need for lifelong learning. Rapid change in the workplace and the new reality of multiple careers during one's life require people to be lifelong learners. To help people become lifelong learners, schools must cultivate both the desire to learn (a love of learning) and the skills to learn (self-directed learning). However, typical industrial-age school systems do the opposite on both counts, placing stress on the environment (coevolutionary imbalance) and causing the environment to put pressure (perturbation) on the educational system to undergo fundamental change or *transformation*.

Transformation

Disequilibrium creates a state in which the system is ripe for transformation, which is reorganization on a higher level of complexity. Transformation occurs through a process called *emergence*, by which new processes and structures emerge to replace

old ones in a system. Transformation is paradigm change and stands in contrast to piecemeal change, which leaves the structure of a system unchanged. Piecemeal change often involves finding better ways to meet the same needs, whereas transformation entails modifying the structure of a system, usually in response to new needs. Piecemeal change usually changes one part of a system (albeit perhaps a part that exists in all schools within a district) in a way that is still compatible with the rest of the system, whereas transformation (or paradigm change) entails such a fundamental change that it requires changes in other parts of the system because the other parts are not compatible with the change.

According to Duffy, Rogerson, and Blick (2000), transformation of an educational system requires simultaneous changes in the core work processes (teaching and learning), the social architecture of the system (culture and communications), and the system's relationships with its environment. So, what factors can help guide transformation?

Fractals and "Strange Attractors"

Transformation is strongly influenced by strange attractors, which are a kind of fractal (Wheatley 1999). Fractals are patterns that recur at all levels of a system, called *self-similarity*. In educational systems, they can be considered core ideas and values or beliefs (Banathy, 1991, 1996) that guide or characterize the design of the new (transformed) system. These recurring patterns can be structural or behavioral –that is, they can be patterns of form or function, and they strongly influence, and are influenced by, complex system dynamics (Senge 1990). One example of a fractal in education is **top-down, autocratic control**. On the district level of an educational system, the school board typically controls the superintendent, who controls the principals. On the building level, the principals control their teachers. And on the classroom level, the teachers control their students.

Another example of a fractal in education is **uniformity** or standardization. On the district level, all elementary schools are typically supposed to be the same (equal) in such key features as policies, curriculum, methods, and assessments. On the building level, all teachers at the same grade level are supposed to teach the same content at the same time with the same textbooks, again to provide equality. On the classroom level, all students in a classroom are typically supposed to learn the same thing at the same time in the same way. And even for professional development, all teachers typically engage in the same professional development activities at the same time.

Top-down control and uniformity are but two of many fractals that characterize the factory model of schools. Although changes are beginning to emerge in some of these patterns, few would argue that they were not typical of industrial-age educational systems and they are still the predominant paradigm in educational systems today.

A *strange attractor* is a kind of fractal that has a powerful influence over the processes and structures that emerge in a system undergoing transformation. Fractals are similar to what Dawkins called "memes," which are ideas or cultural beliefs that

are "the social counterpoints to genes in the physical organism" and have the power to organize a system in a specific way (Caine & Caine, 1997, p. 33). One example of a strange attractor, or meme, in education is stakeholder **empowerment** or ownership, which entails providing both the freedom to make decisions and support for making and acting on those decisions. On the district level, this takes the form of the school board and superintendent empowering each building principal to experiment with and adopt new approaches to better meet students' needs and to make other important decisions (hiring, budgeting, and so on). On the building level, the principal empowers each teacher to experiment with and adopt new approaches to better meet students' needs and to participate in school policymaking and decision-making. On the classroom level, the teacher empowers each student to make decisions about how to best meet her or his needs (self-regulated learning). This form of leadership at all levels entails providing guidance and support to cultivate the ability to make good decisions and act effectively on them. It is a distinct paradigm of leadership from the top-down, command-and-control paradigm.

A second example of a strange attractor is **customization** or differentiation (or diversity). On the district level, each school has the freedom to be different from other schools. On the school level, each teacher has the freedom to be different from other teachers. And on the classroom level, each student has the freedom to be different from other students (with respect to both what to learn and how to learn it). Note that this strange attractor is systemically interdependent with the previously described one, empowerment.

A third example is **shared decision-making** or collaboration. On the district level, the school board and superintendent involve community members, teachers, and staff in policymaking and decision-making. On the school level, the principal involves parents, teachers, and staff in policymaking and decision-making. And on the classroom level, the teacher involves the student and parents in decisions and activities to promote the student's learning and development.

To become an effective strange attractor for the transformation of a school system, the core ideas and values (or beliefs) must become fairly widespread to cultural norms among the stakeholders most involved with making the changes. Once that status is reached, little planning needs to be done for the transformation to take place. Appropriate behaviors and structures will emerge spontaneously through a process called *self-organization*.

Self-Organization

Self-organizing systems are adaptive; they evolve themselves; they are agile (McCarthy, 2003). They require two major characteristics: openness and self-reference (Wheatley 1999). To be *open* with its environment, a system must actively seek information from its environment and make it widely available within the system. The intent of this new information is to keep the system off balance, alert to how it might need to change. An open organization does not look for

information that makes it feel good or that verifies its past and validates its present. It is deliberately looking for information that might threaten its stability, knock it off balance, and open it to growth (Wheatley 1999, p. 83). But the system must go beyond seeking and circulating information from its environment; it must also partner with its environment. As Wheatley (1999) notes: "Because it partners with its environment, the system develops increasing autonomy from the environment and also develops new capacities that make it increasingly resourceful" (p. 84).

A second characteristic of self-organizing systems is the ability to *self-reference* on the core ideas, values, or beliefs that give the organization an identity. ln this way, "When the environment shifts and the system notices that it needs to change, it always changes in such a way that it remains consistent with itself. ... Change is never random; the system will not take off in bizarre new directions" (Wheatley 1999, p. 85).

A third characteristic is freedom for people to make their own decisions about changes. Jantsch (1980) has noted a paradoxical but profound systems dynamic: "The more freedom in self-organization, the more order" (p. 40, as cited by Wheatley 1999, p. 87). As long as the freedom is guided by sufficient self-reference, it will allow change to occur before a crisis point is reached in the system, thereby creating greater stability and order. Paradoxically, the system is "less controlling, but more orderly" by being self-organizing (Wheatley 1999, p. 87). Typically, coevolution occurs through self-organization, but complex system *dynamics* have a powerful influence on self-organization and any resulting systemic transformation.

Dynamic Complexity

According to Peter Senge, social systems have detail complexity (which is not very important in systems theory) and dynamic complexity (which is crucial).

> When the same action has dramatically different effects in the short run and the long, there is dynamic complexity. When an action has one set of consequences locally and a very different set of consequences in another part of the system, there is dynamic complexity. When obvious interventions produce nonobvious consequences, there is dynamic complexity (1990, p. 71).

System dynamics are the web of causal relationships that influence the behavior of a system at all its various levels. They help people understand how a change in one part of an educational system is likely to impact the other parts and the outputs of the system and to understand how a change in one part of an educational system is likely to be impacted by the other parts of the system. Dynamic complexity is captured to some extent by Senge's "11 laws of the fifth discipline" and his "system archetypes." The laws include such general dynamics as:

- The harder you push, the harder the system pushes back.
- The easy way out usually leads back in.
- The cure can be worse than the disease.

- Faster is slower.
- Cause and effect are not closely related in time and space.
- Small changes can produce big results, but the areas of highest leverage are often the least obvious.

Senge's (1990) system archetypes include:

- "Limits to growth," in which an amplifying process that is put in motion to create a certain result has a secondary effect (a balancing process) that counters the desired result.
- "Shifting the burden," in which the underlying problem is difficult to address, so people address the symptoms with easier "fixes," leaving the underlying problem to grow worse unnoticed until it is much more difficult, if not impossible, to fix.
- "Tragedy of the commons," in which a commonly available but limited resource is used to the extent that it becomes more difficult to obtain, which causes intensification of efforts until the resource is significantly or entirely depleted.
- "Growth and underinvestment," in which growth approaches a limit that can be raised with additional investment, but if the investment is not rapid nor aggressive enough, growth will be stalled and the investment will become unnecessary.
- "Fixes that fail," in which a fix that is effective in the short run has unforeseen long-term effects that reduce their effectiveness and require more of the same fix.

Senge's laws and archetypes identify high-level or general system dynamics, but it is also important to identify the complex system dynamics at play in a particular educational system. Those dynamics are complex causal relationships that govern patterns of behavior, explain why piecemeal solutions are failing, and predict what kinds of solutions may offer higher leverage in transforming a system to better meet students' needs.

How Can Chaos Theory and the Sciences of Complexity Inform the Transformation of Educational Systems?

The remainder of this chapter explores the ways that chaos theory and the sciences of complexity can inform the systemic transformation of educational systems. They can do so in two fundamental ways. First, they can help people understand the present system of education and how it is likely to respond to changes that are attempted. Second, they can help people understand and improve the transformation process, which is itself a complex system that educational systems can use to transform themselves.

Understanding the Present System

Chaos theory and the sciences of complexity can help people understand the present systems of education, including (a) when each is ready for transformation and (b) the system dynamics that are likely to influence individual changes attempted and the effects of those changes.

Readiness for Transformation

Chaos theory and the sciences of complexity indicate that readiness for transformation is influenced by several factors. First, there must be sufficient impetus for transformation, which is created by perturbations from outside the system that produce a state of disequilibrium in the system. That disequilibrium may be caused by either of two kinds of changes in the environment (a school system's community): (1) ones that create problems for the system, such as dysfunctional home environments and lack of discipline in the home, or (2) ones that present opportunities to the system, such as the Internet or other powerful technologies to support learning. Second, there must also be sufficient enablers of transformation, which are created by factors inside the system, such as "participatory" (Schlechty, 1990) or "transformational" leadership (Duffy et al., 2000), as opposed to the industrial-age command-and-control form of leadership – or more appropriately, management – and sufficient levels of trust within and among stakeholder groups, such as the teachers' association, administration, school board, and parents.

System Dynamics

System dynamics are complex sets of causes and effects that are largely probabilistic, meaning that a cause increases the chances that an effect will take place but does not guarantee that it will take place. The complex sets of causes and effects are also highly interactive, meaning that the extent of influence of a cause on an effect is strongly influenced by other factors, including other causes. Regarding causes, system dynamics provide an understanding of aspects of the current system that will likely influence the viability and durability of any given change. For example, there is evidence that high-stakes tests that focus on lower levels of learning in Bloom's taxonomy (Bloom, Krathwohl, & Masia, 1956) are likely to reduce the viability and durability of attempts by teachers to develop higher-order thinking skills because such efforts would necessarily reduce the amount of time the teachers spend on the lower-level content, causing a decline in the high-stakes test scores.

Regarding the effects of any given change, system dynamics help people predict the effects that a change is likely to have on the outcomes of the transformed educational system, such as levels of student learning. For example, as the Saturn School of Tomorrow found (Bennett & King, 1991), allowing students to be self-directed learners can cause a reduction in "time on task" to learn the designated skills

and understandings, resulting in a reduction in those kinds of learning. This indicates the importance of clarifying the goals that the new system values and being sure to measure attainment of all those goals, not just the ones that may be measured by the standardized tests.

Understanding the Transformation Process

Chaos theory and the sciences of complexity can also help people understand and improve the transformation process in which educational systems engage to transform themselves. The transformation process is itself a complex system composed of many subsystems, processes, and dynamics. With research and experience, people can expect to learn much about the dynamics that influence the subsystems and processes that are most likely to foster systemic transformation, but chaos theory and the sciences of complexity indicate that one cannot hope to control the transformation process (Caine & Caine, 1997; Wheatley 1999). Caine and Caine state that "the underlying belief is that we are in charge and can control the nature of change. All the reports on how difficult it has been to change education confirm the failure of this logic" (p. 12).

Chaos theory and the sciences of complexity also indicate that one can hope to influence the process through the use of such tools as strange attractors and leverage points and that one must constantly adjust and adapt the process to the emerging, ever-changing reality of a particular educational system and its environment (Caine & Caine, 1997; Wheatley 1999).

Strange Attractors

The most powerful strange attractors are core ideas and beliefs like those described previously: ownership (or empowerment), customization (or differentiation), and shared decision-making (or collaboration). These core ideas stand in stark contrast to those that characterize the industrial-age mindset about "the real school" (Tyack and Cuban 1995): centralization and bureaucracy, standardization (or uniformity), and autocratic (or command-and-control) management. However, to have a powerful influence on the features that emerge in the system undergoing transformation, the core ideas and beliefs must become integral parts of the *mindsets* or mental models held by a critical mass of participants in the transformation process, and, therefore, they must collectively compose the culture of the transformation process as a system. This means that the major focus of a systemic transformation process in a school district must be on helping all stakeholders to expand their mindsets about education and to develop a set of shared core ideas and beliefs about the ideal kind of educational system they would like to have (Banathy, 1991; Caine & Caine, 1997; Reigeluth, 1993; Reigeluth & Karnopp, 2013; Reigeluth & Karnopp, 2020). This entails helping people to uncover the mental models that often unwittingly control their views of education and then deciding whether or not that is the way they really want their educational system to be.

Leverage Points

Leverage points can greatly facilitate the systemic transformation of educational systems. An example of a leverage point is **student assessment**. The current industrial-age schools reflect the belief that the purpose of student assessment is to compare students with each other. Hence, they use norm-based tests, they grade on a curve, and students become labeled as winners and losers and successes and failures. In contrast, if one wants all children to succeed, then the purpose of assessment should be to compare students with a standard of attainment, so that they may continue to work on a standard until it has been met. The current report card, with its list of courses and comparative grades, could be replaced by a list or "inventory" of attainments that are checked off as they are reached by each student. This one change could exert powerful leverage on other parts of the system, most notably the way teaching and learning occur in the classroom – leverage that might be more powerful than the forces that the rest of the system would place on the inventory of attainments to change it back to a sorting-focused assessment system. Furthermore, if appropriate strange attractors have been developed (e.g., enough stakeholders have expanded their mental models to encompass the belief that student assessment should be designed to inform learning rather than to sort students), those strange attractors will create a powerful force in support of such a compatible leverage point and against those aspects of the current system that would otherwise be working to change the assessment system back to what it was.

Conclusion

Just as the industrial revolution made the one-room school house obsolete, the information revolution has made the current factory model of schools obsolete. Educational systems must transform themselves to better meet the dramatically changing needs of children and their communities (coevolution). An understanding of chaos theory and the sciences of complexity (two relatively recent developments in systems theory) is crucial to successfully navigate such systemic (or paradigmatic) transformation of educational systems. Helpful concepts include coevolution, disequilibrium, positive feedback, perturbation, transformation, fractals, strange attractors, self-organization, and dynamic complexity. These concepts can help people understand when a system is ready for transformation and the system dynamics that are likely to influence individual changes attempted and the effects of those changes.

Furthermore, chaos theory and the sciences of complexity can help people understand and improve the transformation process as a complex system that educators use to transform their educational systems. Strange attractors and leverage points are particularly important to help educational systems to correct the dangerous coevolutionary imbalance that currently exists.

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