Complex Systems and Educational Change: Towards a New Research Agenda

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I. Studying the Complexity of Educational Change

How might we usefully apply concepts and procedures derived from the study of other complex and emergent dynamical systems to analyzing systemic change in education?

This seemed a natural question to the diverse group of about 40 leading natural science and education researchers who met first in 1999 at MIT's Endicott House under the sponsorship of the National Science Foundation and the New England Complex Systems Institute (NECSI, 1999) to consider the future role of complex systems science in the K-16 curriculum. It was clear that whatever recommendations for curriculum development might eventually emerge, the curriculum change process itself would pose challenges to making this important new area of the sciences accessible to large numbers of students. The Endicott conference participants were hopeful that complex systems theory could offer insights into the processes of curriculum change and, more generally, of systemic reform in education. A working group was formed to examine this question, and it produced an initial report (Lemke et al., 1999).

A key recommendation from the Endicott House conference was to bring these issues to wider attention in the education community, and at a smaller second meeting sponsored by NECSI, plans were developed for a symposium at the American Educational Research Association annual meeting in 2002 (Jacobson et al., 2001). At the same time a number of the participants also convened in 2001at the Balcones Springs conference sponsored by NSF and the University of Texas to discuss issues of urban systemic reform with leaders of four major NSF-sponsored projects and about 16 other experts in the science and mathematics education community (Confrey et al., 2001). This article describes a number of the important concepts and research issues that have developed out of this continuing line of thought.

New conceptual approaches to the study of complex systems have been developed in the last two decades by mathematicians, physicists, chemists, biologists, and computer scientists. They are being applied and extended by economists, psychologists, organizational scientists, and researchers in many disciplines whose insights are being scaffolded not only by new quantitative techniques, but by new qualitative conceptions of phenomena common to many different complex systems. Concepts such as multi-scale hierarchical organization, emergent patterning, agent-based modeling, dynamical attractors and repellors, information flows and constraints, system-environment interaction, developmental trajectories, selectional ratchets, fitness landscapes, interaction across timescales, and varieties of self-organization are becoming key tools for qualitative reasoning about complex systems as well as for quantitative modeling and simulation.

Can the new tools of complex system analysis help us understand the potential impact on the educational system of new technologies and help us predict the paths that different efforts at systemic reform follow? Can they help us design new educational systems to meet the needs of all citizens in the new century? Can they help us identify critical relationships within the educational system that resist systemic change or afford opportunities for new alternatives? Can we realistically hope for an educational system that will teach large numbers of students to use the new tools for thinking that complexity theory has developed? Can we find ways to make the value of these tools sufficiently evident and attractive to large numbers of students and teachers so that they will seek them out?

If the answers to any of these questions are to be 'yes', we will require collaboration within a diverse new community of researchers seeking a common framework for sharing ideas from different disciplines and approaches to both complex system analysis and to education. There is an urgency to the formation of such a community. If the response of the educational system to the new demands of the public for reform and to the new opportunities technology affords is not guided by the best ideas of the research community, and by research- and data-driven decision-making, it will be guided by other forces.

The concepts and tools we consider in this article have been put to use in practice and tested in managing complex and ill-defined ecological systems. We use what has been called the “active adaptive management” technique as a case study of handling the complexity inherent in a multifaceted system to merge scientific knowledge and public-interest goals (see Farr 2000 for definitions and references and Gunderson & Holling 2002 for a related approach). Active adaptive management is a "process of testing alternative hypotheses through management action, learning from experience, and making appropriate change to policy and management practice". Active adaptive management differs from learning-by-doing by the conscious use of experimentation. We will return to this point later in the paper.

II. Developing a Conceptual Framework

It is not our aim here to present a complete conceptual framework for the analysis of education as a complex system. Our purpose is to begin to define possible agendas for further research toward such a framework. Towards this end, we will present below an example of the plausibility of defining such a framework, and the relation between frameworks and the crucial aggregation of data across “systemic experiments.” Even within what we might eventually agree on as a common framework and terminology for describing such a complex system, there will continue to be room for many existing alternative models and, over an extended period of research, for the emergence of new data-driven models and syntheses appropriate to various specific tasks. We will describe the core issues for a framework under the following headings: Defining the System, Structural Analysis, Relationships Among Subsystems and Levels, Drivers for Change, and Modeling Methods

Defining the System

The U.S. K-16 educational system is conventionally defined as the system of public and private schools and colleges that offer students formal education from kindergarten to college graduation. For research purposes, however, the system must ultimately be defined by our analysis of its constituent elements and the environmental dynamics, such as which institutions and social practices and which sources and users of information and material and human resources are tightly enough coupled and interdependent in their behavior that they must be included within the system? Likewise, what are the range of timescales characteristic of the critical processes that enable the system to maintain itself? What are its significant levels of organization, not simply or primarily in terms of lines of authority (control hierarchies), but in terms of characteristic structures and characteristic emergent processes and patterns at each level? What kinds of material resource and information flows connect adjacent and non-adjacent levels? How is information transformed, filtered, re-organized, and added to from level to level? How is information-overload avoided by emergent systems through pattern-recognition that extracts from large data-flows only what matters for the dynamics of the next higher level?

If we consider the longest timescales experienced by students within the system, we will need to extend its definition to consider pre-school education, post-graduate study, and continuing adult education. If we examine all the source institutions that contribute to students' understanding of particular topics within the formal curriculum, we must include informal educational institutions such as science museums and information sources and learning sites afforded by mass media, print publishing, and interactive communication technologies. If we look at resource constraints and decision-making bodies, we will add school boards and trustees and state education authorities. If we include ourselves within the system, we will consider our roles as teachers and researchers, and the relationship between research institutions and sponsors and the communities which make use of research results.

Structural Analysis

Formal organizational hierarchies propose one starting point for identifying levels within the core educational system: individual learners and teachers, small groups, classrooms, departments, schools, districts (LEAs), states (SEAs), federal agencies, the total system. What would a dynamical analysis propose—one that takes into account the differing timescales at which different levels of the system function? If we analyze the system in terms of dynamical processes and emergent phenomena on different timescales, what would the units of analysis be? How do brief actions by teachers and students add up to coherent activities over periods of minutes and hours, days and months? How do curriculum change processes that occur over periods of years exchange information with classroom activities that occur over periods of minutes? How do learning events in a laboratory or at a computer workstation and those in classrooms and hallways and cafeterias add up to a coherent longer-term process of educational development, or perhaps the development of facility with a particular concept? How do networks of social interaction with peers in the classroom, in the wider neighborhood community, and in virtual online communities contribute to long-term processes of identity development and formation of lasting attitudes and values, which affect decisions and actions on very short timescales? How do the changing priorities, populations and problems of a local community influence the larger educational system's agendas and programs?

Having focused on some of the characteristic educational processes that involve the student, we could raise similar questions about those in which teachers participate but which may not always involve students, and similar questions about supervisors and administrators, teacher educators, curriculum developers, educational materials publishers, and ourselves as researchers.

Relationships Among Subsystems and Levels

Whatever level of organization or subsystem is the focus of our concerns at a particular point, we can always ask a series of key questions motivated by the perspectives of complex system theory:

- What next higher level of organization determines constraints on the dynamics at the focal level?
    - How do all subsystems subject to those constraints interact to constitute the dynamics of the higher level?
    - What degrees of freedom remain at the focal level after the constraints are allowed for?
- What units of analysis at the next level below interact to constitute units (or processes or patterns) at the focal level?
    - What characteristics of those lower level units determine the range of dynamical possibilities at the focal level?
- What are the typical attractors of the focal level dynamics?
    - Under what conditions is each attractor dominant for the (sub-) system?
    - How do new attractors emerge over the history of the system's development and the evolution of this kind of system?
- Which features of system behavior are determinate and which are not?
    - Which regions of the space of possibilities are accessible and which are not?
    - What manifolds describe the conditions on the range of values of all other

parameters that must be met to achieve some value of the parameter of interest?

- At a given level of organization, how are the different units and processes coupled with one another?
  - What kinds of matter, information, and energy do they exchange?
  - How tightly coupled are they and what is the topology of the coupling network?
  - What are the significant branchings, closed loops, and connectivity decompositions?
- What is system and what is 'environment'?
  - How do system and environment form a supersystem from the viewpoint of some still larger-scale unit or process?

As an example, we will see that any focal pedagogical "innovation" introduced into a tightly bound [constrained?] school system is in fact a series of embedded innovations at levels *above and below* the focal intervention, and strategies for all levels have to be considered coherently.

Drivers for Change

How is the educational system as a whole driven by external events and pressures such as advances in scientific understanding, the increasing complexity of problems addressed by communities and societies, changing technologies, and public demands for reform? How is educational change constrained by resource limitations, standardized curricula and testing, or deeply held cultural beliefs? How is educational change enabled or made possible by bringing new kinds of people into contact with one another or utilizing new technologies (e.g. cross-age tutoring, or tele-mentoring)? How would educational processes be affected by creating new feedback loops, such as research data that systematically describes outcomes back to teachers, students, and parents? How might new educational institutions (e.g. charter schools, online courses) create niches for themselves in the educational ecology? How might new spontaneous networks, such as online communication groups of teachers within a school or across the country, affect the rate of educational change?

We will emphasize later in this paper the importance in our view of the concept of ‘drivers for change” with respect to three other ideas: the use of hypothesis-testing; the need for computational experimentation (modeling) to predict patterns of change, and the inescapable fact that all education is local, and thus the championing of change, and its drivers, must be localized.

Modeling Methods

How would we model and analyze issues like these using the concepts and techniques of ecosystem theory and adaptive management, developmental biology, reaction-diffusion chemistry, non-equilibrium statistical mechanics, nonlinear dynamical systems analysis, cellular automata models, artificial life systems, neural networks, parallel distributed computation, agent-based modeling theory, informatics and infodynamics? Given access to data and expertise about the educational system, how would you yourself approach one of these issues? Given the collaboration of others, who could offer different insights about complex system behavior, how would you and other educators and researchers begin to formulate any one of these problems for actual study?

How well could we design today a 'SimSchool' or 'SimDistrict' school- or school district- simulation program? Not just to model an existing system, but to enable us to create alternative systems and study their evolution over time, their needs and problems, their probable outcomes? What kinds of schools would students design if given access to an appropriate version of this software? And how would they evaluate various designs proposed by others? Who would we enlist in the team to create such a software package? What research literatures would we want to consult? What is not yet known that would be needed to complete the project?

What kinds of data would be needed to realistically attempt such a project? Insofar as we are only interested in easily quantifiable parameters of the system, such as school budgets, teacher qualifications, and student test-scores, we need to know how much value added there might be from a complex system model compared to more static statistical analyses. Good use has been made of static and isolated case analyses, particularly when the dynamics of the relation with the environment or with environmental variables are taken into account, usually by statistical methods, and more recently, by the dynamical inclusion of environmental variables (Jost, 2003.) Agent-based dynamical and simulation models hold the promise of enabling us to explore potential effects of changes in quantitative parameters and assumptions about how variables interact to produce observable statistical relationships. Complex systems models are designed to model change and dynamics, especially qualitative change: the emergence of new social networks, changes in daily routines or actor preferences. In a human social system, these kinds of changes are mediated by the meanings and values assigned by actors, individually and collectively, to the objectively definable affordances of their environments. To build effective dynamical models of educational institutions we will need to know not just what people do, but why they do it, how they might imagine things being different, and what they would really want to do.

Even if such systems models are not predictive in any detailed way, they can still be useful in identifying possible alternatives, potential problems, and overall qualitative features of the change process which may not be intuitively evident to a linear logic of cause and effect. In complex systems every causal chain is mediated, and many chains branch and loop back on themselves in complicated webs of mutual interdependent, self-regulation, and amplification of effects. This conceptualization is consistent with Michael Fullan's "systems at the edge of chaos" view of education (Fullan, 1999).

No mention of the data needed for analysis and the development of theoretical models can leave out considerations of sharing information across projects (i.e. across localized case studies). This sharing and aggregation is a major problem for a topic so dependent on localized conditions as education reform is. We will develop the importance of understanding local environments as 'data" in section IV below.

III. Modeling Lessons from Real Cases

The important report from the Balcones Springs conference (Confrey et al., 2001) summarizes the lessons learned from four major educational reform projects (see Table 1). Such lessons represent hard-won long-term information about the specificity and diversity of implementations of various closely-related curriculum and system-wide reform models. The projects were related in being implemented in urban schools and districts with highly diverse students, using different models of how to achieve sustainable enhancement to teaching and learning. Any research effort to develop a complex system model of educational change would do well to take into account this data about what matters to the success of existing systemic reform initiatives.

<Insert Table 1 about here.>

Perhaps the most important of these lessons is that adaptation of models for system reform to local conditions matters more than efforts to replicate successes elsewhere, without extensive knowledge of how the systemic variables differ between environments. This "localization effect" points to the importance of determining whether any single complex system model can be both general and specific enough that it can include design templates to identify key local parameters that need to be set. Alternatively, more heuristic guidance needs to be developed to aid in the design of quite different models for each educational system (i.e. differing structurally and not just parametrically from one another). Here are some of the more detailed lessons learned from these research projects that seem especially relevant to the design of realistic system models:

Timescales and Stepwise Structure

It was found that in most cases it takes a long time, of the order of 5 – 10 years, to establish effective collaborations between researchers and school systems, and that during this period there may be a need to re-negotiate and re-commit to goals and strategies developed together whenever there are major changes in leadership or personnel on either side of the partnership. The development of effective partnerships takes 5-10 years, and the fruits of reform efforts tend to become visible only after at least 3-5 years. Any evaluation and tests of scalability require at least a second or third cycle of enlargement or replication, implying a minimum of 10 years' scope for models of effective change.

For reform efforts to be maximally adaptive to changing environmental conditions, an iterative process is needed in which plans are continuously modified in response to issues that only come to light once implementation has begun, or to the mere change of individuals in either the research or implementation personnel. Successful multi-year reform processes include periods of consolidation of gains; these periods provide a respite to plan for needed changes and for people to become comfortable with one set of changes before contemplating others. In this sense, reform should be viewed as a 'stepwise' process, in which advances alternate with such periods of reflection and consolidation. This stepwise strategy promotes buy-in from skeptics, allows for non-disruptive change and establishes a culture of continuous improvement. Under these conditions, modeling of different "scheduling paths to innovation" may lead to a more integrated and sustainable organization that is resilient with respect to changing future conditions.

Sustainability and Scaling

Reforms often begin locally and then face the problem of "scaling out", i.e. including more units at the same level of organization (e.g. from a few teachers, or one grade level, to all teachers in a school or all grades), and also of "scaling up", i.e. from small-scale systems (e.g. a small suburban district) to much larger scale systems (e.g. a large urban system or an entire state). As reform scales, there is no guarantee that it will maintain validity with respect to its fundamental principles or goals. For this to happen, some self-regulatory feedback must exist within the system to assess whether such validity has been maintained and to provide an incentive for maintaining it.

Agents of Scaling

There were found to be a number of agents of scaling. For example, student cohorts can motivate scaling up as they move through a system, carrying the reform "upward" with them. This type of spread appears to require a critical mass of students and an initial phase that includes a plan for such "vertical" growth. Another model of spread is to systematically plan for horizontal growth, or scaling out. In doing so, pressures on the reform implementation can create situations that indicate problems with the model, or its limits of applicability (e.g., whole school models in contexts where there are not sufficient resources to support that model). Scaling is a useful strategy for testing the robustness of the process, making it more sustainable, and finding its weakest spots. This points to the *interdependence of scaling and sustainability* as a key issue for any model.

Role of Sustainability in Considerations of Models

Sustainability, it was found, has two key aspects. The first is the need for a match between stakeholders' expectations regarding the nature and pace of results and the ability to provide persuasive demonstrations of timely effects. Early successes, as judged by stakeholders, appear to be crucial for sustaining the reform process. The second aspect depends on relationships among the timescales of change processes in different elements of the system and between the system and larger social-political-economic systems in which it is embedded and on which its functioning depends.

Sustainability is threatened by normal process of change in larger-scale systems within which the educational system operates (e.g. changes in political administrations, new superintendents with new policies, changes in state regulations or funding formulas, etc.) Widespread commitment and a critical mass of practitioners can ensure that maintaining gains in achievement will move the community to the continuous updating of policies and practices needed to sustain reforms while responding to other inevitable social changes.

Many of these lessons point to the importance of multi-scale modeling techniques for educational change, and particularly to multiple timescale models (Lemke 2000a, 2000b). When we consider that many key structural features of educational practice (e.g. student-teacher ratios, use of textbooks, age-grading, local-taxation funding, curriculum areas, teacher training institutions) have been stable on timescales of a century or longer, we can infer that there are powerful system-regulatory relationships maintaining this stability. Reform mandates and implementations, on the other hand, are formulated and expect results on timescales of the order of a decade or less. Complex system models need to help us understand why so many features of the educational system do not change, as well as under what conditions they will change. Many current reform policies assume that no major structural changes are necessary to achieve reform goals. Realistic models, based on detailed case studies of reform efforts, as well as on general system modeling principles, may help us understand if such assumptions are realistic or not. We need to know whether or not current modest reforms have any realistic chance of producing major gains at the large-scale in realistic timeframes. If it should appear that more radical re-engineering of the educational system is needed, we will need to understand very well the functional roles and interdependencies of current structural features.

IV. Organizing for Research

If we judge that it is worthwhile and feasible to try to develop dynamic models of educational change based on the principles of complex system science, how should such a research effort be organized? In this section we will attempt to show how thinking about the education system as a complex system, together with complexity ideas introduced earlier, can help advance our scientific knowledge about systemic change, and help define promising experiments and areas where more knowledge will be useful.

The local success of any intervention – reform, pedagogies, or materials – is dependent upon the fidelity to the original with which its application is enacted. Studies of a reform strategy or intervention in venues where local conditions (financial and human capacity included) differ and comparisons among many interventions in terms of their resilience are not common. This chapter will suggest one way in which independent research that considers the complexities of practice can be conducted so as to contribute to the aggregation of results across studies into more robust, comprehensive and generalizable frameworks that could in time address the "awful reputation of education research" (Kaestle 1993, 1997).

Rather than start from an intervention and discuss the fidelity of its enactments, we purposely focus our analysis on the environment in which the intervention is carried out, with the purpose of characterizing environments for enactment and comparing their outcomes. Many of the existing studies of educational change are conducted as case studies of a particular innovation, as a logical consequence of the fundamental importance of local conditions to the practice of education. But collections of case studies are difficult to abstract and generalize from, and they have contributed only peripherally to the identification of clusters of environmental conditions that support or prevent the success of particular sets of changes.

One barrier to converting the broad generalizations that are the outcomes of case studies into a more grounded and actionable set of ideas is the lack of a small number of commonly accepted, reusable, and succinct means of describing the many system variables that define practice environments and whose analysis can help identify correlations. We have as yet no language for describing and annotating either good practice, for example, or the types of support provided by successful schools and districts for such practice. We know little about critical correlations, such as the timescales at which the impact of changes in different variables will be felt. Much like symptoms in individual medical histories, noted by their absence as much as their presence, knowing what conditions are present or absent is crucial for making informed decisions in educational systems.

We propose an approach in which we (a) look at the problem from the standpoint of the system itself and not of a particular innovation, (b) use the crucial role of local environments as an opportunity rather than as a limiting constraint, and (c) highlight the processes by which the variables influence each other. Stronger links between theory-building research and large-scale practice have fundamental implications for the accumulation and validation of research results.

Our view of the term “theory building” has been influenced by the concepts of ecological “active adaptive management” discussed before, and by their use to integrate scientific knowledge, local environments, and public interests—a situation which in many respects resembles the problems of education. Using complexity science ideas, we propose that independent research which considers the full environment of practice, and studies of practice-initiated reform, can be seen as experimental "probes" into the education system. By carefully designing interventions to explore variations in the environment between two mostly similar environments, it is possible to choose 'case studies" that contribute directly to building and modeling testable theories (see the discussion of critical cases in Flyvjerg, 2001.) Even if each case has no control over the conditions under which it operates, the actual conditions can be documented to support the aggregation of results across cases. This aggregation will allow more robust and generalizable frameworks useful for program design in ways that unsystematic knowledge cannot. Aggregation and cumulativity are tasks for the field, rather than a task for each individual researcher.

Exploring how systematically annotating the environmental, contextual conditions under which reforms take place can allow for the selection of subsets of that are sufficiently coherent projects to be productively compared. In time, sufficient information may be generated to frame testable hypotheses about the critical design characteristics of successful efforts, given a set of contextual conditions.

As in most of science, a productive conversation can start by designing protocols for data gathering and research that respond to the needs of many if not most experimental case studies, and which can be tested against practice. Frameworks to analyze reform have been proposed at multiple levels of analysis: the district level (NSF 2001; Gomez & Marx, 1999; Blumenfeld et al., 2000; Knapp, 1997), the classroom level

(Cohen & Ball 2000; Confrey et al. 2000), and the school level (Confrey, Sabelli, & Sheingold, 2002). We show below how these frameworks could be integrated to provide a more accurate view of how the education system responds to changes.

Crafting a Shared Framework

We develop as an example one possible framework for the systematic annotation of interactions between critical elements of education reform implementation activities. We describe an exemplar to open the discussion and provide a basis for such frameworks to evolve assuming this approach proves useful.

Our discussion of how to annotate and document the conditions under which implementation and systemic research take place is based on the need to develop more robust and validated insights across studies. This need in turn requires a common set of language markers that identify the external systemic conditions under which individual research studies take place—the given variables outside the researchers' control. We take as a starting point the scheme shown in Figure 1, and consider that:

- Classroom interactions between teachers and students constitute the arena where learning takes place (shown in red);
- The policy (Federal, State and local) system exerts strong pressures on all levels of the system, including classrooms and community views of education that cannot be ignored by any other level (shown in black);
- The linkages between goals within and across levels of granularity in the school system are crucial to systemic implementation.

The structure uses as variables (vertexes): ***Cognition*** (how people learn), ***Content*** (what people learn), ***Context*** (where people learn or learning environment), ***Equity*** (which people learn and why). These labels are critical at many levels of the system; content, cognition, context, and equity are valid considerations for schools, districts, states, as well as for classrooms.

<Insert Figure 1 about here.>

Furthermore, the higher administrative levels of the local system constrain the classroom level and act as a driver for policy as shown in blue in Figure. 2. We have chosen to use “accountability” as a recognizable term as the “system attractor”; others could be chosen. Represented in the figure are considerations that:

- Linkages within and across levels of granularity are crucial to systemic implementation, and
- The meaning of cognition, content, context, and equity variables are often expressed differently at different system levels,
- The policy (Federal, State, local) system exerts strong pressures (some mediated, some not) on all levels of the system.

We can draw for the school level a structure similar to the one at the classroom level (Figure 2). The activities that link and are defined by the vertices differ between levels, where administrative tasks both constrain and are constrained by the work in classrooms. In practice, one would start by drawing a figure that shows the level of focus, and both one level up from it and one level down from it, as sites of the strongest operating drivers. Although not shown in the Figure, the links between levels should indicate a time delay between action and reaction: the focal level interactions are immediate, and react to constraining and constitutive levels with some, as yet undefined, time delay.

<Insert Figure 2 about here.>

Figure 3 presents a more complex view of the education system, and how three distinct studies, conducted at three different levels of system granularity, can be correlated. The three sets of system change drivers abstracted here are those proposed by the NSF Systemic Reform Program (2001), by Cohen and Ball (2000), and by Confrey and collaborators (2000).

<Insert Figure 3 about here.>

Figure 4 sketches a still more general view of the description of an education system and the interaction across levels. The importance of a three-dimensional scheme, whether tetrahedral or tabular, lies in the ability to represent simultaneously different levels of aggregation while still focusing on the enacted linkages operating at any level. This allows the correlating concepts prevalent at a given level to be reinterpreted and renamed, as needed, at other levels, where they may be subject to different time constraints, as well as to different operational pressures. The activities represented by a model such as that in Figure 4 are shown in Table I.

<Insert Figure 4 about here.>

In this limited framework design, row and column headings correspond to the vertices as in Figure 4. The content of each cell is a pointer to the activities that tie variables to each other, across levels or within levels. If we concentrate on studying work in classrooms, the contextual information underlying the study can be organized as shown in Table I. Each level is enabled and/or constrained by actions or expectations expressed one level above and one level below. It is possible to add the vertices and sides of Figure 3 (school level, blue) to Table I, and to include a community or parental level that documents public resources and expectations. One would then have, *for each implementation study*, a table of cells that represent the system actual constraints, such as:

- The district's direct and indirect influence on classrooms
- The school's coherence of policies, ways of dealing with demographics and with standard-based instruction, and the constraints on how it solves its instructional workforce needs, as in part determined by district actions
- The school's authority over internal alignment, assignment of the teachers in its pool, allocation and distribution of resources; these decisions in turn impact teachers' work
- Teachers deployment their pedagogical content knowledge and expertise to do their work, using the data they have available from assessment and other resources made available by the school
- Parental expectations which help determine how successful teacher work is, and even how teachers feel about their jobs – the operational constructs here include the career expectations of parents, their potential agency, their level of education, expectations for homework, etc.
- Parent and teacher views of each other and other socio-cultural expectations
- In time, comparisons across studies would lead to a set of tables that can be searched for similarities among the environmental variables of independent studies. This would enable to select studies for detailed comparisons, while still keeping the environmental variables as crucial to any interpretation. Table cells themselves could be extracted from, and help guide, detailed case studies.

Conclusions

The conceptual basis of complex systems ideas reflects a change in perspective about our world. This perspective emphasizes both the limits of predictability as well as the possibility of understanding indirect consequences of actions taken, both positive and negative, through modeling interdependence. The study of complex systems involves experimental, computational, and theoretical approaches for observation, analysis, modeling, and dynamical simulation.

Complex systems concepts are used in science to provide organization for the otherwise bewildering properties of diverse and often unpredictable systems in a common framework and language. These systems are often unpredictable because small changes in a variable may result in major changes in outcomes while other, large, changes might not disrupt the system.

The application of these concepts in conjunction with computational models and visually compelling data-driven simulations yields unprecedented means for understanding complex phenomena and revealing new, sometimes counter-intuitive patterns and relationships. Such understandings lead to new and essential questions and viewing systems in new perspectives. This understanding of complex systems also appears to be critical to our ability to apply knowledge and techniques across very different individual contexts. It is the hope of the authors that our contribution can spark conceptual and principled discussions and testable hypotheses about simulating reform strategies, along the lines of ecologically inspired “active adaptive management” constructs (Farr, 2000).

The education system is one of the most complex and challenging systems for research. Much as we know about cognitive aspects of learning, pedagogical strategies, and reform implementation, we currently lack the modeling capability needed to help practitioners and policy makers explore the potential impact of proposed interventions, although efforts in this area are currently at a very preliminary stage of development. Indeed, in this perspective there are no independent interventions: each proposed change to a classroom has direct implications at school and district levels (e.g. in teacher development, parental expectations, school resources, accountability, and so on) and calls for related interventions across multiple levels. The ability to explore such dynamic linkages (already incorporated in scenario-based corporate planning) could be a significant tool for educators and policy makers.

The authors hope that these reflection may spur a sustained discussion within the education research and education reform communities, one that could lead to the evolution of a methodology for modeling systemic change, and to a better understanding of how to compare, evaluate and aggregate outcomes, hypotheses and theories of educational practice.

References

Blumenfeld, P., Fishman, B., Krajcik, J., Marx, R., & Soloway E. (2000). *Creating usable innovations in systemic reform: Scaling up technology-embedded project-based science in urban schools*. Educational Psychologist, 35(3), pp. 149-164.

Cohen, D.K., & Ball, D.L. (2000). *Instruction and innovation: Reconsidering the story*. Working paper, Consortium for Policy Research in Education, Study of Instructional Improvement. Ann Arbor: University of Michigan.

Confrey, J., Castro-Filho, J. & Wilhelm, J. (2000). Implementation research as a means to link systemic reform and applied psychology in mathematics education. *Education Psychologist*, 35 (3): 179-191.

Confrey, J., Lemke, J. L., Marshall, J., & Sabelli, N. (2001). *Conference on Models of Implementation Research in Science and Mathematics Instruction in Urban* Schools. Austin, TX: University of Texas.

Confrey, J., Sabelli N., and Sheingold, K. A Framework for Quality in Educational Technology Programs, *Educational Technology*, Vol.42, 7-20, 2002.

Farr, D. (2000). Defining Active Adaptive Management. [Online] http://www.ameteam.ca/About%20Flame/AAMdefinition.PDF,

Flyvbjerg, B. (2001). *Making Social Science Matter*. Cambridge: Cambridge University Press

Fullan, M. (1999). *Change Forces: The Sequel.* New York: Routledge/Falmer .

Gomez, L., & Marx, R.W. (1999). At the nexus of challenging curriculum design, learning technologies, and school transformation: The first year of the Center for Learning Technologies in Urban Schools. Symposium presented at the annual meetings of the American Educational Research Association, Montreal, Canada.

Gunderson, L. & Holling, C.S. (2002). Panarchy: Understanding Transformations in Human and Natural Systems. Washington: Island Press.

Jacobson, M., Kaput, J., Wilensky, U., & Lemke, J. L. (2001). Complex systems in education: integrative conceptual tools and techniques for understanding the education system itself. [Online] http://edtech.connect.msu.edu/Searchaera2002/viewproposaltext.asp?propID=6203

Kaestle, C. (1993). The awful reputation of educational research, *Educational Researcher*, 22 (1), 23-31.

Jost, J. (2003) External and Internal Complexity of Complex Adaptive Systems, SFI Working Paper Abstract 2003. Available at www.santafe.edu/sfi/publications/wpabstract/200312070 -

Kaestle, C. (1997). Improving the awful reputation of educational research, *Educational Researcher,* 26(7), 26-28.

Knapp, M. S. (1997). Between systemic reforms and the mathematics and science classroom: The dynamics of innovation, implementation, and professional learning. *Reviews of Education Research*, 67 (2): 227-266. [See also Madison, WI: National Institute for Science Education, University of Wisconsin.]

Lemke, J.L., et al. (1999). Toward systemic educational change: Questions from a complex systems perspective. Working Group 3, Systemic Educational Change. Report of an NSF-funded Workshop, Endicott House, MA. [Online] http://necsi.org/events/cxedk16/cxedk16_3.html

Lemke, J. L. (2000a). Across the Scales of Time: Artifacts, Activities, and Meanings in Ecosocial Systems. *Mind, Culture, and Activity*, 7(4), 273-290.

Lemke, J. L. (2000b). Opening Up Closure: Semiotics Across Scales. In J. Chandler & G. van de Vijver (Eds.), *Closure: Emergent Organizations and their Dynamics* (pp. 100-111). New York: New York Academy of Sciences.

National Science Foundation [NSF], Educational System Reform. (2001). Six Critical Drivers. [Online]. http://www.ehr.nsf.gov/esr/drivers/

New England Complex Systems Institute [NECSI]. (1999). Planning documents for a national initiative on complex systems in K-16 education. [Online] http://necsi.org/events/cxedk16/cxedk16.html

Table 1

Four Major Educational Reform Projects

Project	Research Organization	Urban Sites	Participants	Years in Operation
LeTUS (Learning Technology in Urban Schools)	NWU U Michigan	Chicago IL Detroit MI	62 schools	9
http://www.letus.org				
SYRCE (Systemic Research Collaborative for Education)	U Texas	Austin TX	6 schools	4
http://syrce.org				
(SFT) School For Thought	Vanderbilt	Nashville TN	1251	6
http://peabody.vanderbilt.edu/projects/funded/sft/general/sfthome.html				
Union City Online	EDC	Union City NJ School District	11 schools	6
http://www2.edc.org/CCT/cctweb/project/descrip.asp?2				

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1 The number is approximate because the configuration of Nashville schools and teachers was in a continuous state of flux throughout the project. Accordingly, many teachers changed schools throughout the project. This makes it difficult to provide an exact number of schools because many of the teachers take the reform with them but the project has no access to data on what they do after leaving, how the reform survives, or the impact on student learning.

Table 2

Activity Links between School and Classroom Levels

		District	*School Level*	*School Level*	*Classroom Level*	*Classroom Level*	*Parental Level*
		Accountability	Context	Cognition	Content	Equity	Expectations
District	Accountability	**Use and analysis of data**	Coherence of policies	Demographic Needs	*Indirect*		Political constituents
School Level	Content	Standards-based Instruction	Alignment	Teacher Pool			Community human resources
School Level	Equity	Instructional Workforce	Distribution of Resources	Incentives and resources			Career expectations
Classroom Level	Context	*Indirect*			Availability data from assessment	Available Resources	Socio-cultural expectations
Classroom Level	Cognition				Pedagogical knowledge	Teacher Expectations	Homework expectations
Parental Level	Expectations	Political constituents	Career expectations	Parental agency	Parental level of education	Parent & teacher views of each other	**Strength of community groups**

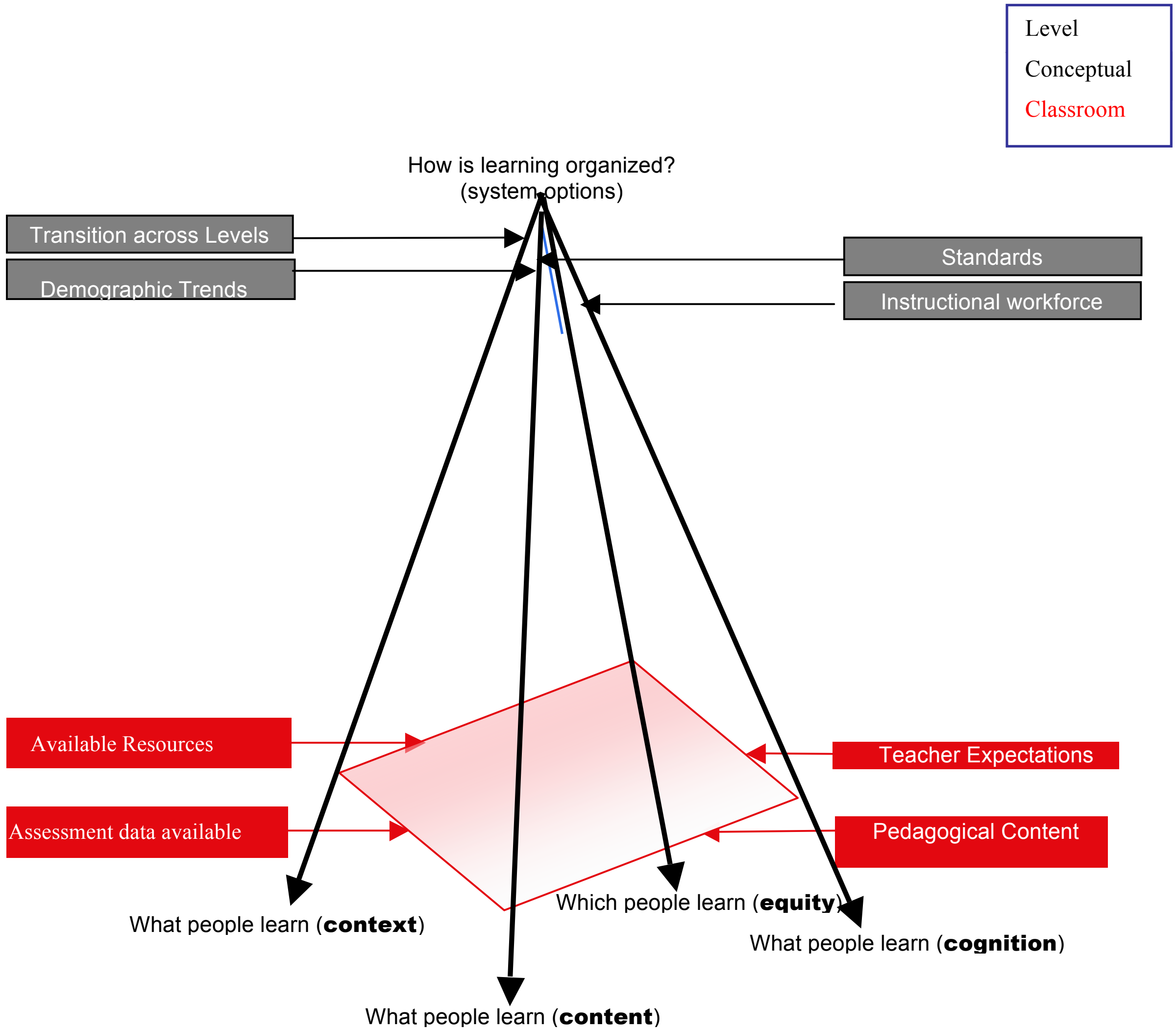

Figure 1. A schematic representation of four critical components of education (context, content, cognition, the learner) and their instantiation in the classroom and in the policy level of the system as a whole.

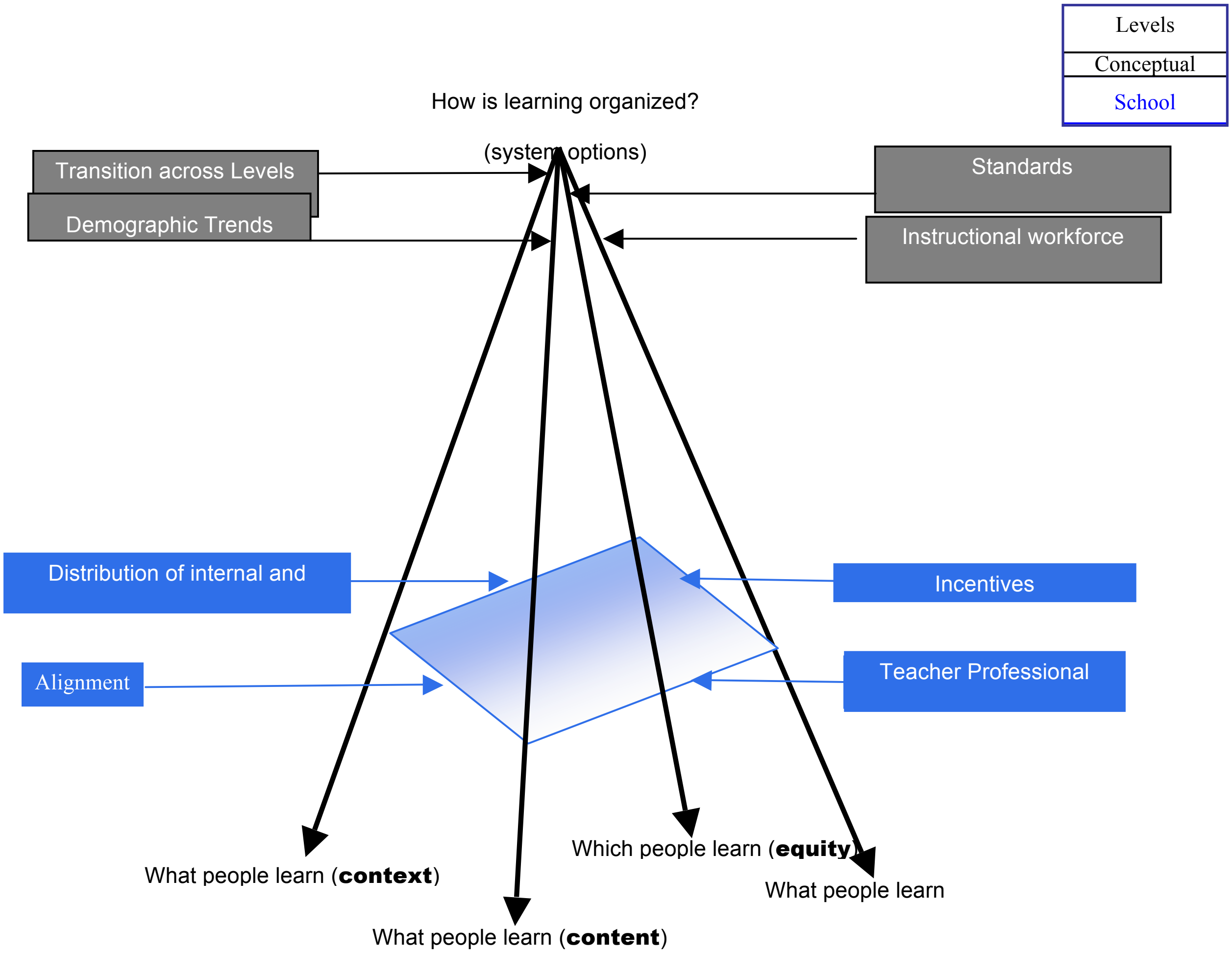

Figure 2. Same as Fig. 1, but highlighting the instantiation at the school level.

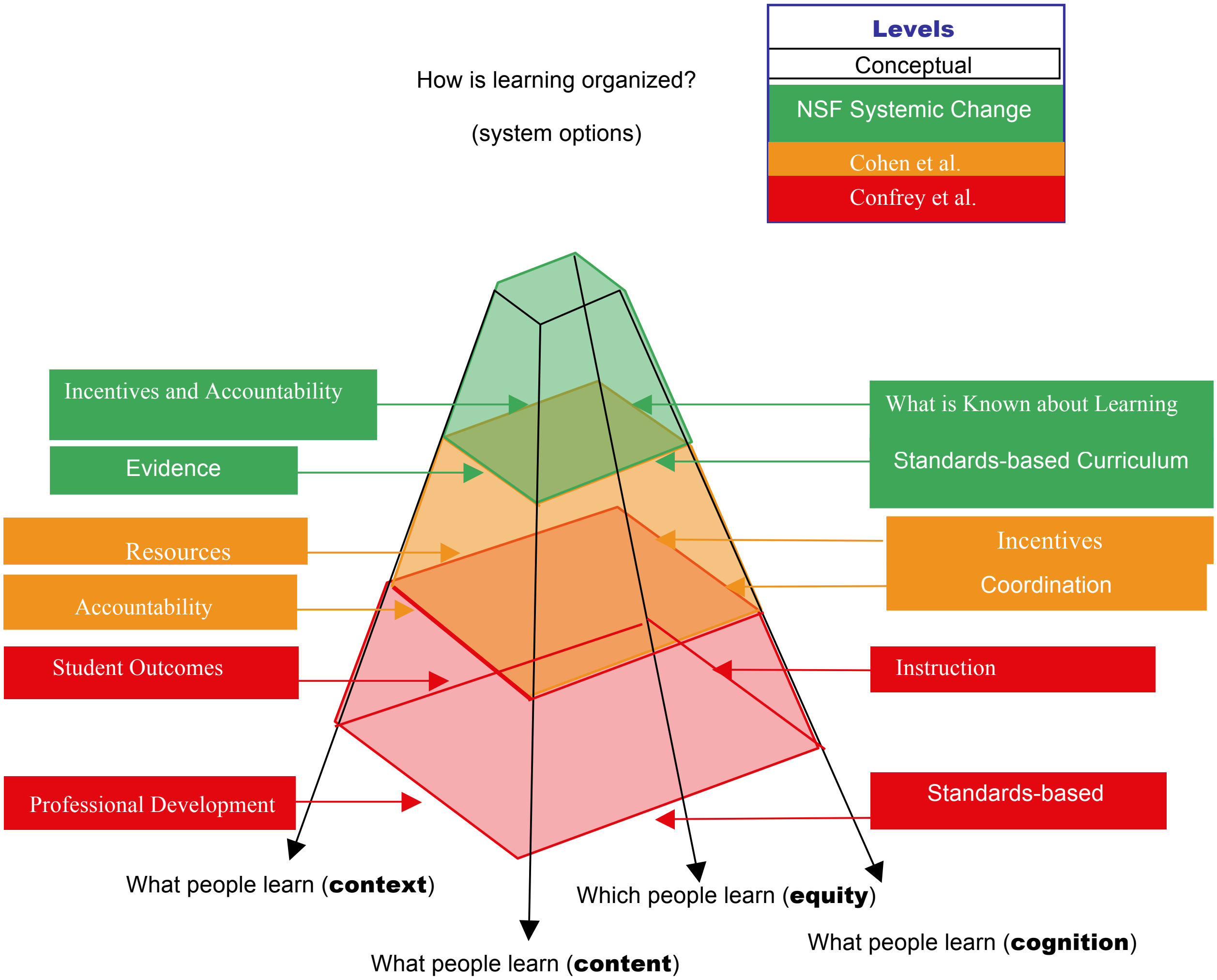

Figure 3. Several levels of the education system and the nature of the core variables at each level.

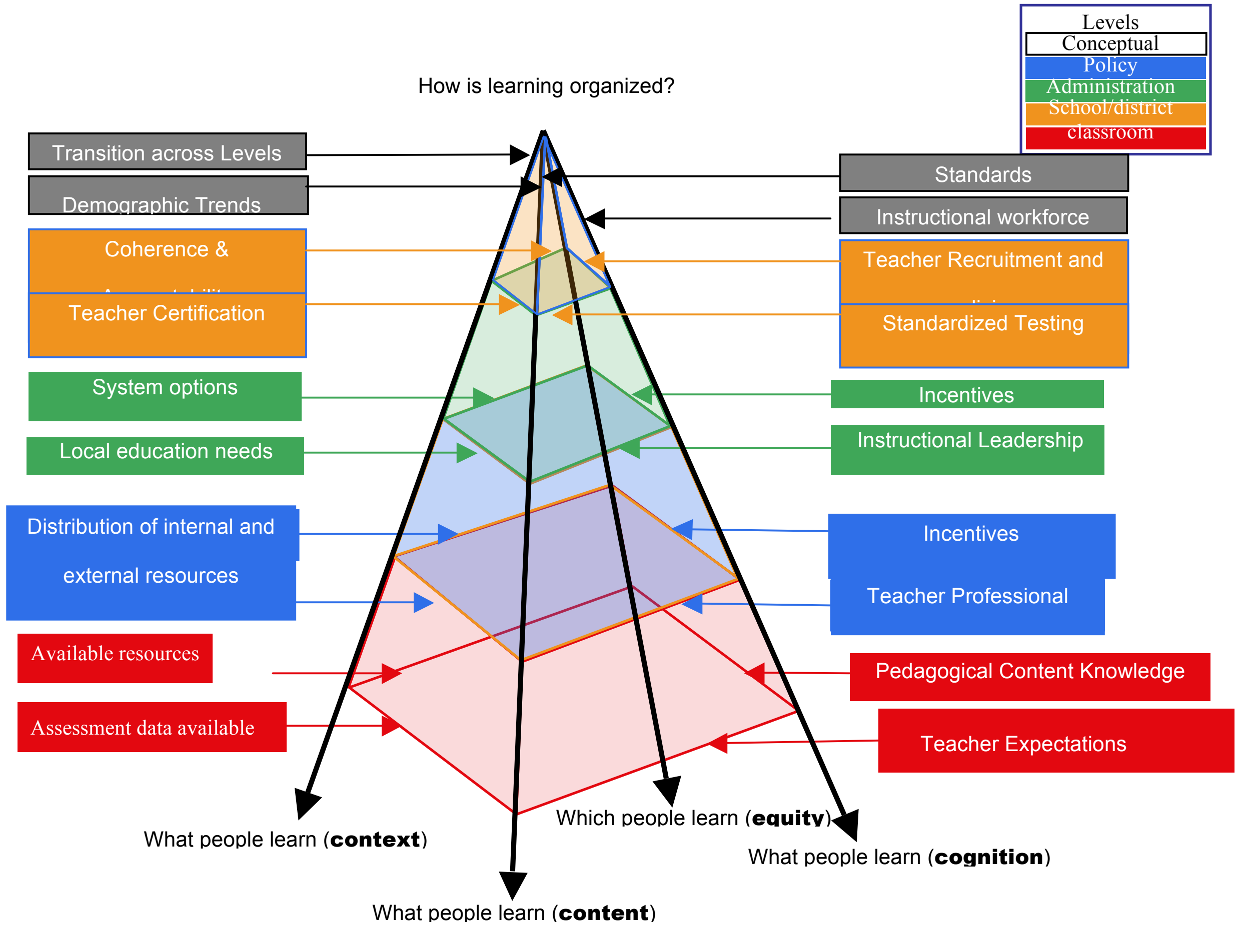

Figure 4. A View of the Education system