Simulating and Stimulating Systemic Change in Education:
SimEd Technologies

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The Need for an Educational Systems Theory

As the 'No Child Left Behind' (NCLB) legislation is being implemented, K-12 schools in America face increasing pressure to meet state standards. Successful change is imperative for schools classified as failing, since the consequences of repeated failure can result in school closure. How, then, should changes in school systems be planned to obtain better results? What principles could be used to predict possible consequences of change strategies?

Changes in educational policies have the potential to impact a large number of students within an educational system across extended time periods. The stakes for such changes are high, since it is difficult for students to relive their educational experiences, and much more difficult to reverse negative consequences of policy decisions. Even with the best intentions of wanting to improve education, attempts to change will be based mostly on trial and error. At a time in American education where our education systems face very real and pressing problems, it may appear to be the wrong time to claim that we need good educational systems theory. But, in fact, we do.

In the decades following the publication of *A Nation at Risk* in 1983 (National Commission on Excellence in Education), considerable effort has been undertaken to improve public schooling. Reform efforts have been typically referred to as site-based management, school restructuring, and educational systems design. Researchers such as Banathy (1991), Reigeluth (1992), Frick (1991), Jenlink, Reigeluth, Carr & Nelson (1996), Caine & Caine (1997), Duffy, Rogerson and Blick (2000) and Senge, Cambrom-McCabe, Lucas, Smith and Kleiner (2000) have argued for systemic change in education. Systemic change contrasts with numerous piecemeal reform efforts that have largely failed in twentieth century schooling. However, the rhetoric of systemic change is not likely in itself to make any real difference in schooling, since such rhetoric has been around for some time.

For intelligent action, a scientifically based theory that could explain and predict the behavior of educational systems is needed. By this, we do not refer to a learning theory, a pedagogical theory, an instructional method, a leadership theory, classroom management theory nor a curriculum theory – but an educational systems theory, a theory to describe, explain and predict whole educational systems and their transactions with societies in which they are embedded. Educational systems theory should precisely define the concepts and relationships of system elements and provide operational ways in which these can be observed and measured. Education does not have the equivalent of a Newtonian theory of physics. Educators seldom agree on definitions of terminology. We do not have well established and clearly defined terms such as mass, force, acceleration, velocity, time, gravity, etc. as in physics. In short, we lack a scientific educational systems theory.

Development of General Systems Theory (GST)

The concept of general systems theory (GST) was first introduced by Ludwig von Bertalanffy in 1949. Bertalanffy (1968) argued that there exists a general theory that could characterize the behavior of systems, regardless of whether these are scientific, natural or social; and he proposed GST as an interdisciplinary theory that could contribute to the unity of science. System behavior results from the relationships between its components, and is not just a simple summation of its parts. The characteristics of each system component therefore cannot adequately explain how the system itself behaves.

Since then, there have been extensive contributions by others in the development of GST as a logical and mathematical theory to provide an "exact language permitting rigorous deductions and confirmation (or refusal) of theory" (Bertalanffy, 1972, p.30). Others have also contributed well-developed descriptive theories (e.g., Wymore, 1967; Cornacchio, 1972; Mesarovic & Takahara, 1975; Lin, 1987; Lin, 1999; Bar-Yam, 2003). In education, GST has been used by researchers to discuss educational systems design and systemic change, but these approaches have not been grounded in scientific theory about educational systems (Banathy, 1991; Caine & Caine, 1997; Duffy, Rogerson & Blick, 2000; Senge, Cambron-McCabe, Lucas, Smith, Dutton & Kleiner, 2000). Rather these approaches largely describe processes through which organizations can change, not whether those changes are likely to result in desired outcomes.

The SIGGS theory model provided the first extensive formalization of a GST model for educational theorizing (Maccia & Maccia, 1966; Steiner, 1988). Through the synthesis of four theories: Set, Information, di-Graph, and General Systems, SIGGS provided a logical description of general system properties, which enabled retroduction of 201 hypotheses in a theory of school systems. Frick, Hood, Kirsch, Reigeluth, Walcott and Farris (1994) extended Maccia and Maccia's work by classifying the system properties into basic, structural, and dynamic properties. This classification recognized that some SIGGS properties were structural as they described the connectedness between system components (SIGGS Website, 1996a). Yet, others were dynamic and described how patterns of relationships between system components are altered due to changes within the system or between the system and its environment (SIGGS Website, 1996b). Thompson (2005) recognized that the structural properties essentially defined the system topology.

To provide a theory that is logically and mathematically sound, a system-descriptive axiom set is needed. Although SIGGS was fairly comprehensive, there was no attempt to analyze the 201 hypotheses for consistency nor to finalize an axiom set that would be the underlying axioms for a GST. Thompson has since been developing Axiomatic Theories of Intentional Systems (ATIS), which is a logico-mathematical theory model for analyzing and predicting behavior of systems that are goal-directed or intentional. Using the original SIGGS hypotheses, Thompson developed a nomenclature to define system properties, which improved the precision with which SIGGS properties could be used (Thompson, 2005). Thompson also identified an initial list of approximately 100 axioms (subject to change, as this work is on-going), and extended the 73 SIGGS general system properties to 136 in ATIS (APT&C Website, 2005). Development is on-going and theorems are now being derived from the ATIS axioms for validation.

SimEd is a software program designed to model educational systems. It is a model of an education system and is designed so that selected parameters can be evaluated to determine projected outcomes in view of these parameters. Any behavior-predictive software must be founded on a logical base of some kind. The axioms of ATIS are being used as the rule-base for *SimEd* in the development of educational systems theory.

Using General System Properties to Describe an Educational System

Following are a few examples of how general system properties formulated in ATIS can be applied to educational systems. For greater detail, the reader is referred to extensive reports by Thompson (APT&C Website, 2005): http://www.indiana.edu/~aptfrick/reports/ .

Basic Properties

Basic properties define the initial attributes required to identify and analyze a system. In ATIS, there are only three Basic properties—complexness, general system state, and size. For example, a system consists of at least two components that are connected by an affect relation. Understood in the context of an education system, one example would be teachers and students, who are components that are connected together by an 'guidance of learning' affect relationship. These affect relations determine the complexness of the system. The formal definition and logico-mathematical typology of 'complexness' is:

Complexness, $\mathcal{X}(\mathbb{S})$, $=_{df}$ the connectedness of an affect relation.

$$\mathcal{X}(\mathbb{S}) =_{df} (\mathcal{A}_m \in \mathcal{A}) \mid (x,y) \in \mathcal{A}_m \supset x \in {}_C\mathcal{O}$$

Complexness is measured by the number of connections.

Structural Properties

'Strongness' is an example of a structural property that describes relationships between system components. 'Strongness' is defined formally:

Strong system (strongness), ${}_{S}\mathfrak{S}$, $=_{df}$ a system with affect relation sets characterized by strongly connected components.

$$ {}_{S}\mathfrak{S} =_{df} \mathfrak{S} \mid \exists \mathcal{A}_{i}({}_{S}\mathcal{C}) $$

'Strongly connected components' means that all components in the affect relation set are connected to each other, but at least one of the connections is unilateral (one or more is not bi-directional; otherwise the components would be completely connected).

Assume that we examining the affect relation of 'guidance of learning' in a classroom. If classroom instruction is solely from the teacher (e.g., demonstrating, explaining, questioning, prompting, and evaluating student responses), then such 'guidance of learning' is unilateral connectedness from the teacher to students. Strongness can be increased if there were more connections between system components. For example, when students work in project groups, 'guidance of learning' connections can be created among students as they share what they know with each other. Such affect relations become 'comp letely connected' when all of them have bi-directional connections with each other. 'Completely connected' components are defined formally:

Completely connected components set, ${}_{CC}\mathcal{C}$, $=_{df}$ a set of system components that are pair-wise path-connected in both directions.

$$ {}_{CC}\mathcal{C} =_{df} \mathfrak{X} = \{x \mid x \in \mathfrak{R} \subset \mathfrak{S}_0 \wedge \exists y \in \mathfrak{R}[x \neq y \wedge (x,y) \in {}_{cc}E]\} $$

Dynamic Properties

'Adaptableness' is an example of a dynamic property that describes how the relationship between system components changes over time. It is defined formally:

Adaptable system (adaptableness), ${}_{A}\mathfrak{S}$, $=_{df}$ a system compatibility change within certain limits to maintain stability under system environmental change.

$$ {}_{A}\mathfrak{S} =_{df} \Delta\mathfrak{S}'_{t(1),t(2)} \Vdash \Delta \mathscr{E}_{t(1),t(2)} < \alpha \Vdash {}_{SB}\mathfrak{S}_{t(1),t(2)} $$

For example, a school system has high adaptability if its graduation rates do not vary significantly when the standards for passing state examinations are raised.

'Filtration' is another example of a dynamic property. It describes the criteria a system uses to determine which toput qualifies as input to the system. The criteria for selecting its applicants act as a filter for entry to the school (e.g. students who are less than 5 years old are typically not allowed to enter K-12 schools). 'Filtration' is defined formally:

Filtration, $\mathscr{F}(\mathfrak{S})$, $=_{df}$ the set of *toput system-control qualifiers* that control *feedin* of *toput*.

$$ \mathscr{F}(\mathfrak{S}) =_{df} \{P(x) \mid P(x) \in {}_{T_{\mathcal{P}}}\mathscr{L}_{C} \wedge A^{\mathcal{F}iltration}\sigma_{x}\ (\sigma_{x}\colon T_{\mathcal{P}} \times {}_{T_{\mathcal{P}}}\mathscr{L}_{C} \to (T_{\mathcal{P}}, I_{\mathcal{P}}))\} $$

Simulating Change in Education: An Application of Logic-based Simulation in *SimEd*

Logic-Based vs. Scenario-Based Simulation

Scenario-Based programs are defined as programs that provide "scripts" to determine outcomes. The scripts can be narrative or quantitative. Narrative scripts characterize the qualitative parameters of a system; that is, the social, philosophical, and individual descriptions and the uncertainty of future outcomes. Quantitative scripts define the scientific facts, known or credible data, and quantitative models that are used to determine future outcomes. However, regardless of the type of script, their content is closed; that is, there are a limited number of possible outcomes, and the scripts predetermine the outcomes.

Friedman (1999) recognizes this closed characteristic of Scenario-Based Models in his report on SimCity, "The Semiotics of SimCity," when he states:

> Of course, however much "freedom" computer game designers grant players, any simulation will be rooted in a set of baseline assumptions. SimCity has been criticized from both the left and right for its economic model. It assumes that low taxes will encourage growth while high taxes will hasten recessions. It discourages nuclear power, while rewarding investment in mass transit. And most fundamentally, it rests on the empiricist, technophilic fantasy that the complex dynamics of city development can be abstracted, quantified, simulated, and micromanaged.

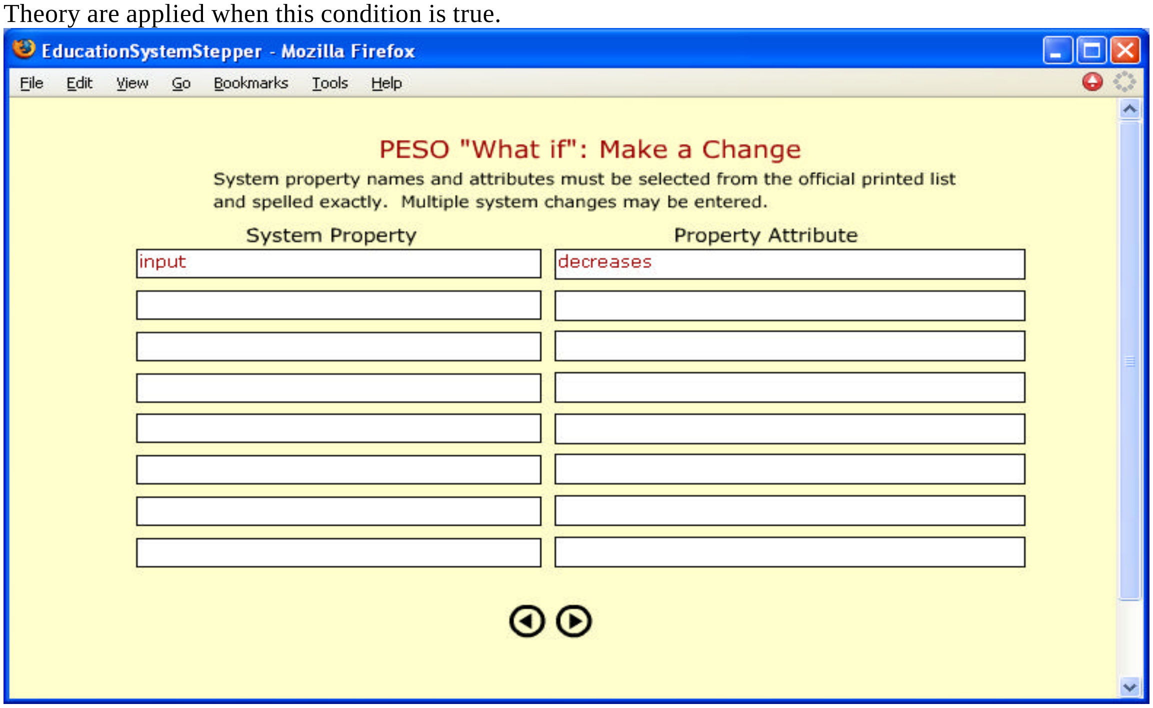
On the other hand, Logic-Based Models are not dependent on analyses of predetermined values, but on the logic of a theory that has been shown to be valid for the targeted empirical system; for example, an education system. The theory describes the empirical system in terms of its affect relations, properties, and axioms. The theory is then used to project outcomes founded on the theory with respect to input parameters. The instantiated axioms would generate a set of outcomes, which become input parameters that instantiate yet more axioms. Unlike Scenario-Based Models that are closed due to the limited number of scripts, Logic-Based Models potentially have an infinite number of outcomes. This is the model that *SimEd* is based upon.

Example of *SimEd PESO* Predictions

Suppose a school called Smithtown is labeled as failing by NCLB criteria, and consequently student enrollments begin to drop (input decreases), as parents send their children to other schools. What would happen as a result of falling enrollments? How might *SimEd* help administrators of Smithtown school predict and plan their required change of strategies?

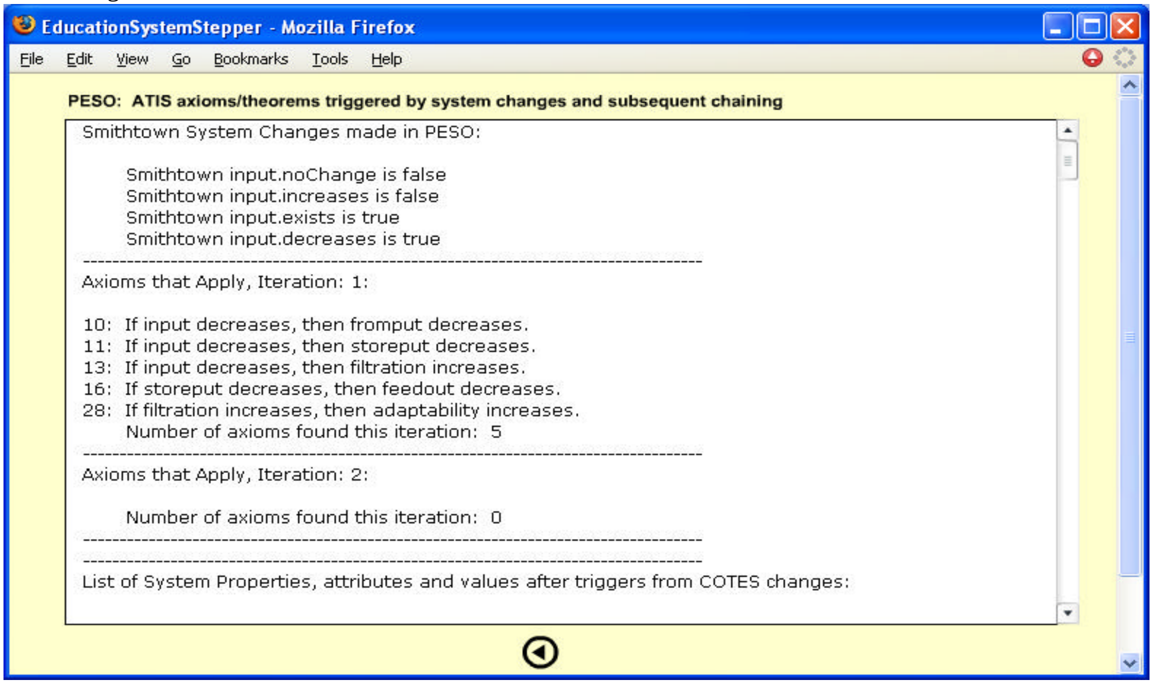
Using system properties defined by ATIS, if the student enrollments in the Smithtown School System are decreasing, this means that the educational systems property, input, is decreasing. One enters the current system conditions into the *SimEd PESO* prototype as illustrated in Figure 1. *PESO* refers to Predicting Education System Outcomes. *PESO* is one of the *SimEd Technologies*.

Figure 1: If input is decreasing in the educational system, the options set from the Educational System Theory are applied when this condition is true.



Next, *SimEd PESO* applies the relevant axioms and theorems from ATIS to make predictions, as illustrated in Figure 2.

Figure 2: Predictions made by *SimEd PESO* when it is the case that educational systems input is decreasing.



It can be seen from Figure 2 that the following axioms have been triggered:

10: If input decreases, then fromput decreases.
11: If input decreases, then storeput decreases.
13: If input decreases, then filtration increases.
16: If storeput decreases, then feedout decreases.
28: If filtration increases, then adaptability increases.

How *SimEd PESO* Makes Logic-based Predictions

Even though there are approximately 100 axioms in ATIS at the current moment (APT&C Website, 2005), only 5 axioms apply under this condition (input decreases). Axioms 10, 11 and 13 predict thee outcomes of decreasing input. However, Axiom 11 predicts a decrease in storeput, which triggers Axiom 16. Similarly, Axiom 13 triggers Axiom 38. This kind of chaining illustrates how the inference engine that is built into *SimEd PESO* works. *SimEd PESO* actualizes the logical implication of transitivity – e.g., if A implies B, and if B implies C, then A implies C.

Interpreting the Predictions

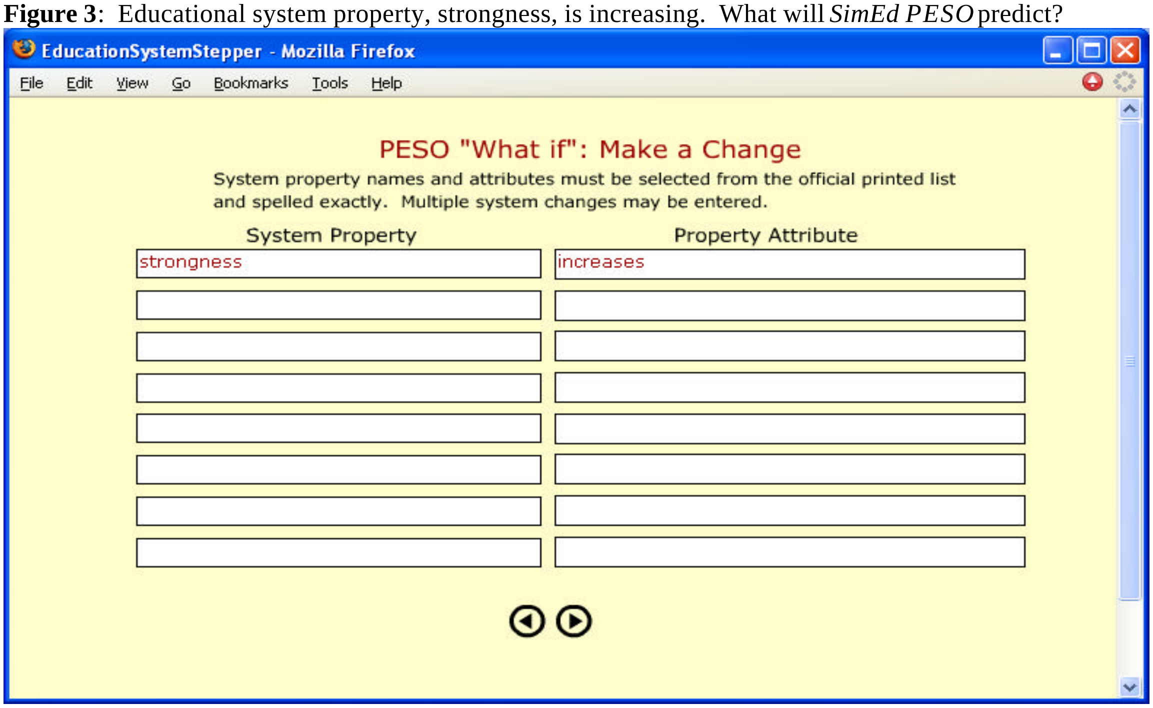
It can be seen that when enrollments decrease in Smithtown school, there will be fewer students attending classes (storeput decreases) and fewer students who will fulfill exit requirements (e.g., qualify for graduation). Thus, fromput decreases also. When there are fewer students attending classes (storeput decreases), there will be fewer students who eventually leave the system as feedout (e.g., through graduation or as dropouts). Another prediction is that filtration, or criteria for entry into Smithtown, increases. Inadvertently, the NCLB rating has acted as a filter by deterring parents from sending children to Smithtown. While the axioms discussed may seem logically obvious, Axiom 28 also predicts that Smithtown would change to maintain system stability. If filtration increases, adaptability is also predicted to increase. For example, Smithtown school may try to change instructional practices so that student performance will be improved, so that the school can be removed from the NCLB "failing" list. It could also adapt by firing incompetent teachers, and hiring competent ones – though this kind of adaptation would be typically resisted by teacher's unions and tenure stipulations. It could adapt by purchasing and using computer software to tutor students who are not meeting expected annual yearly progress.

Using *SimEd* to Stimulate Change

One way that Smithtown school could better its enrollment rate is to improve student achievement. Suppose Smithtown wants to improve its learning guidance by changing its predominantly teacher-guided system to use of more instructional technology and bringing in parent or senior citizen volunteers as teacher aides. Essentially, Smithtown is attempting to increase system strongness with respect to instructional affect relations (i.e., increase the number of 'guidance of learning' connections to students).

Suppose that an education system wants to increase the system property 'strongness'. What does *SimEd PESO* predict?

Figure 3: Educational system property, strongness, is increasing. What will *SimEd PESO* predict?



It can be seen in Figure 4 that increasing system strongness has an impact on the hierarchical order and flexibility of instructional relationships in classrooms. It will also affect other aspects of the system such as the enrollment (input) and criteria for entering the system (filtration). Correspondingly, these in turn impact other aspects of the system such as isomorphism (how the system replicates the same strategy to other parts of the system) and regulation (which fromput qualifies to become output).

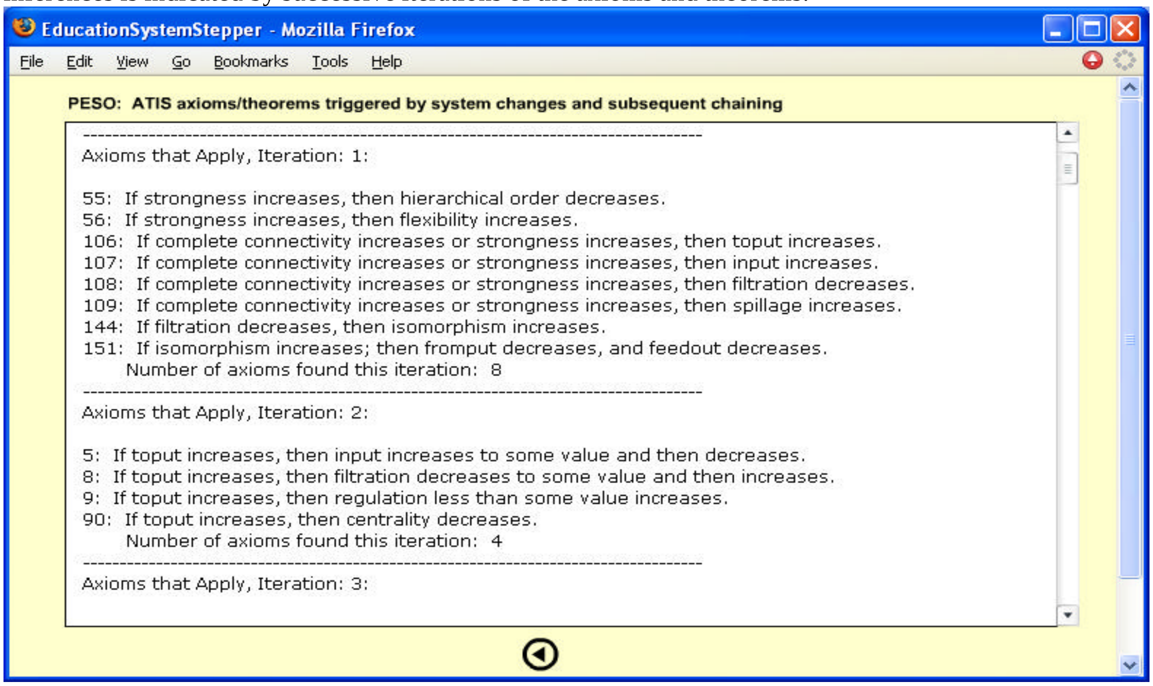
These are but two examples of what the *SimEd PESO* software is currently capable of doing. Through the *SimEd PESO* interface, users will be able to predict behavior of complex systems via Axiomatic Theories of Intentional Systems (ATIS) without needing to be experts in mathematics or logic.

***SimEd Technologies* Will also Include *APT&C* Software**

Education system administrators and researchers will also need to be able to measure system properties such as strongness, flexibility, filtration, centrality, etc. We have recently obtained funding for developing software to measure system dynamics and structure: Analysis of Patterns in Time and Configuration. *APT&C* is a different kind of measure paradigm that bridges traditional quantitative and qualitative research methods. *APT&C* builds on work done by Frick (1990) on *APT* and by Thompson

(2005). Further information on *APT&C* and additional references are found in: http://education.indiana.edu/~frick/proposals/apt&c.pdf.

Figure 4: *SimEd PESO* makes a number of predictions when system strongness increases. The cascade of inferences is indicated by successive iterations of the axioms and theorems.



Conclusion

SimEd Technologies are theories, methodologies and software tools to help people understand complexity in educational systems. As the validity of the Education Systems Theory is established, educators can use *SimEd Technologies* to better understand how education systems can be improved. A valid educational systems theory will show educators all the consequences – even the unintended consequences – of changing one part of the complex educational systems they direct. These consequences could then be pre-empted and managed before the impact of changes is realized.

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