Complex Systems in Engineering and Technology Education: A Mixed Methods Study Investigating the Role Computer Simulations Serve in Student Learning

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COMPLEX SYSTEMS IN ENGINEERING AND TECHNOLOGY EDUCATION: A MIXED METHODS STUDY INVESTIGATING THE ROLE COMPUTER SIMULATIONS SERVE IN STUDENT LEARNING

by

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ABSTRACT

Complex Systems in Engineering and Technology Education: The Role Software Simulations Serve in Student Learning

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This research was conducted to determine if students receiving complex systems instruction in the form of software simulations recognize patterns and underlying elements of complex systems more effectively than students receiving traditional instruction. Complex systems were investigated with an analytic (reductive) approach in a control group and with a synthesis approach in the treatment group. Exploration of this top-down approach to learning complex systems counters traditional bottom-up methodologies, investigating systems and subsystems at the component level. The hypothesis was that students experiencing complex systems scenarios in a computer-based learning environment would outperform their counterparts by constructing a greater number of explanations with emergent-like responses.

A mixed method experimental, pretest posttest, control group triangulation design research study was designed for high school students enrolled in an *Introduction to*

Technology and Engineering course. A pretest consisting of one open-ended near transfer problem and one far transfer problem was administered, investigating the generation of reductive (clockwork) and complex (emergent-like) mental models. A stratified sampling procedure was used to assign students to control or treatment groups. Following treatment, an analysis of covariance failed to reveal statistically significant evidence supporting the hypothesis. However, qualitative data in the form of student transcriptions, daily lab reports, and data entry worksheets revealed evidence of emergent-like response and behaviors.

(214 pages)

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CHAPTER I

INTRODUCTION

Problem Statement

It is important for high school students to be able to synthesize information from disparate courses (Frank, 2005; Jacobson & Wilensky, 2006). The American education system tends to teach core concepts classes such as science and math in separate rooms and seldom explains how concepts from both disciplines can be used to solve real problems (Thode & Thode, 2002). "For nearly a century, Western society in general and American society in particular, has been dominated by a form of thinking and an approach to life that is narrowly reductive and deeply analytical" (Pink, 2006, p. 2). Frank explained this analytical focus as, "the traditional approach in engineering and technology teaching [which] is bottom-up, i.e., component to system" (p. 20). However, Pink stated, "What's in greatest demand today isn't analysis but synthesis – seeing the big picture, crossing boundaries, and being able to combine disparate pieces into an arresting new whole" (p. 66).

Students in U.S. high schools are well versed in the recall of facts and procedures from reductive teaching approaches but are often unable to apply this knowledge to more complex situations (Lemke et al., 2004). Factual information, merely recalled for standardized tests, is of little value if it cannot be transferred to applications outside the school walls (Bransford, Brown, & Cocking, 1999; Garmire & Pearson, 2006; Programme for International Student Assessment [PISA], 2006). Reductive approaches lead to school situations in which science is a focal point for 45 minutes separate from math, language arts, and other subjects.

An alternative approach capitalizing upon interdisciplinary connections, which may be effective in engineering and technology education, is that of complex systems teachings (Charles, 2003; Jacobson & Wilensky, 2006). Exploration of a top-down approach to learning complex systems counters traditional bottom-up methodologies that investigate systems and subsystems at the component level. This approach provides students with a holistic perspective exploring scenarios with cultural, environmental, economic, political and societal interactions. Actively engaging students in complex systems teaching aligns with *Standards for technological literacy: Content for the study of technology* (International Technology Education Association [ITEA], 2000/2002) standards four through seven, focusing on technology and society relations.

Complex systems approaches have not been researched in Engineering and Technology Education (ETE) programs. Complex systems thinking has its roots anchored in scientific domains which, due to their compulsory nature, make them well suited for complex inquiry. However, ETE is particularly well suited to investigate complex systems since “technology education teachers are in a unique position in that their curriculum is often more flexible, and they have the opportunity to present the ‘big picture’ to their students by tying the other areas together in realistic activities” (Thode & Thode, 2002, p. 15).

An experimental study was conducted with high school students enrolled in a technology education class utilizing a stratified sampling method for the control and treatment groups. The study addressed the research question: Can high school students' exposure to complex systems scenarios within a software simulation increase the generation of emergent framework mental models (EFMM), as demonstrated by the ability to create emergent-like explanations as they are applied to near and far transfer problems? This research may demonstrate whether students have the ability to transfer information more effectively to new settings.

Engineering and Technology Education

This research was funded by the National Center for Engineering and Technology Education (NCETE). The research agenda of NCETE investigates student learning and teaching of engineering design infused into technology education. Technology education as a discipline has undergone multiple name changes since the late 19^{th} century reflective of technological advances. Discipline names from the past include industrial arts and manual arts. ETE as a discipline title reflects the latest evolution within a domain typified by hands-on, practical learning approaches. The ETE designation does not infer "hard" engineering. Additionally it should be noted that in various locales ETE is referred to strictly as Technology Education. However the ETE designation is used throughout this research as it supports the NCETE mission and subsequently aligns with a current shift in the field.

Worldview

Pragmatism represents the worldview in which this research is grounded.

Meaning or truths are a result of practical consequences within a pragmatic worldview, defined by five primary elements. Creswell and Plano Clark (2007, p. 23) identified these worldview elements as the ontology (nature of reality), epistemology (how we gain knowledge of what we know), axiology (the role values play in research), methodology (the process of research), and rhetoric (the language of research).

Within this research, the ontological perspective is one of singular realities, substantiated with quantitative results and multiple realities, demonstrated through qualitative evidence in the form of multiple perspectives from student participants. Epistemology pertains to the practicality of using what works to address the research question. This research relied upon qualitative data complementing quantitative results which, otherwise, would have been limited in interpretation. Multiple stances address axiological matters related to biased and unbiased perspectives. The researcher is a former technology education teacher who brings an inherent bias to the research setting from a decade of teaching experience in public schools. A mixed methods design balances biased/unbiased perspectives with valid and purposefully analyzed quantitative and qualitative data. Finally, rhetoric style relies upon both formal approaches, used primarily throughout this document, and informal approaches, used with examples of student's work within complex systems.

Complex Systems

Complex systems defining characteristics include adaptation, emergence, and self-organization (Ottino, 2004). Richardson, Cillers, and Lissack (2001) stated that "a complex (adaptive) system can be simply described as a system comprised of a large number of entities that display a high level of interactivity. The nature of this interactivity is mostly nonlinear, containing manifest feedback loops" (p. 7). Such systems surround us and appear in any number of forms to include pure science examples such as large schools of fish or great flocks of birds seemingly moving as one, or the dynamics of complete ecosystems. Additionally, complex systems may appear in a purely technological form, such as lasers, the internet, or robotic machines operating by artificial intelligence.

There is an important distinction to be made between the complex systems described above and the perception of complex systems within an ETE environment. ETE teachers are likely to think of a complex system in the form of complex technologies such as automated robots or in a number of subsystems interacting with one another (e.g., chemical, electrical, fluid, and mechanical subsystems found in an automobile in the form of steering, braking, and suspensions systems).

In this study, complex systems were investigated with an analytic (reductive) approach in the control group through a robotic design and construction process. A synthesis approach to complex systems was used in the treatment group as they experienced embedded complexity elements in a global warming simulation. Group differences were measured to determine whether the treatment group would better be able to recognize the underlying elements and patterns representative of complex systems characteristics. Pink (2006) stated that "the future belongs to a very different kind of person with a very different kind of mind–creators and empathizers, pattern recognizers, and meaning makers" (p. 1). This research serves as an initial probe into student learning, utilizing complex systems approaches in ETE to determine whether such approaches lead to recognition of underlying complexity elements, transferable to other settings.

Student Learning

The dependent variable for this research was student learning as it pertains to the generation of mental models. In order for learning to occur, the cognitivist perception is that new information is mapped and connected to a learner's existing information. This is referred to as a schema (Shuell, 1986). An individual's schema is comprised of smaller units of knowledge, or schemata. These smaller units exist as mental representations of given characteristics in the form of structures or system functions and behaviors (Ball, Ormerod, & Morely, 2004; Shuell).

Unlike the cognitive science view that learning occurs when a schema is mapped to information in different settings [transfer], an ecological perspective embraces a differing philosophy. Barab and colleagues (1999) stated:

> Systems dynamics of this kind suggest an alternative to the traditional view of transfer of learning, according to which the learner abstracts (constructs) a more generalized (idealized, symbolic) view. Instead, "transfer" might be thought of as a more responsive enterprise in which the learner has come to recognize invariant properties across a range of instantiations. (p. 75)

As the independent variable in this research, complex systems instruction was used to facilitate student recognition of underlying patterns and relationships with the goal of transferring this knowledge to other settings. Pink (2006) referred to this as "big picture" thinking that "demands the ability to grasp the *relationship between relationships*. This meta-ability goes by many names–systems thinking, gestalt thinking, holistic thinking" (p. 141).

A web-based interactive simulation represented by a dynamic model of global climate change served as the complex systems treatment. Students in the treatment condition received an introduction to a simulation developed on a NSF grant based on Fiddaman's (1997) dissertation on feedback complexity in integrated climate-economy models. Treatment students participated in this simulation, CO2FX, a total of six times during 3 separate weeks in November and December, 2007. Students experienced cultural, economic, social, and political effects of technology as they attempted to mitigate CO_2 emissions and rising average global temperatures.

Qualitative evidence of student learning in complex systems scenarios was gleaned from transcriptions collected during three sessions of student work within the CO2FX intervention. Within each session, the conversations of three teammates were captured on digital audio as they made decisions controlling the environment over a 100-year timeframe. Throughout the recorded sessions, "learning is not viewed as an isolated activity that is externally arranged and context independent; instead, learning (participation) is (re)contextualized practice and meaning, as part of an ecological system" (Barab et al., 1999, p. 353).

Purpose Statement and Objectives

The purpose of this mixed methods experimental study was to determine if students receiving complex systems instruction, in the form of software simulations, recognize underlying elements of complex systems more effectively than students receiving traditional instruction. A triangulation mixed methods design was used in which different, but complementary, data were collected on the same topics (Creswell & Plano Clark, 2007). In this study, an analysis of covariance (ANCOVA) was used to test systems theory. The hypothesis was that students experiencing complex systems scenarios in a computer-based learning environment would outperform their counterparts by constructing a greater number of explanations with emergent-like responses. Concurrently, qualitative data was gathered in the form of student transcriptions, daily lab reports, and data entry worksheets. This provided evidence of student learning within a global warming simulation for freshman students in the *Introduction to Technology and Engineering* class at Mid-Western High School. Quantitative and qualitative data were collected to strengthen the research. Qualitative data supports quantitative results and, ultimately, provides a rich description of the student experience participating in a complex systems simulation.

To achieve the purpose of the study, the following objectives guided the research:

1. Determine mean differences between control and treatment group pertaining to the generation of EFMM on near and far transfer problems.

2. Determine mean differences between control and treatment group pertaining to the generation of clockwork mental models (CWMM) on near and far transfer problems.

3. Identify differences over time (pretest to posttest) with treatment group's generation of EFMM of near and far transfer problems.

Procedures

A mixed method experimental, pretest posttest, control group triangulation design research study was designed for high school students enrolled in an *Introduction to Technology and Engineering* course. A pretest consisting of one open-ended, near transfer problem and one far transfer problem was administered, investigating the generation of reductive (clockwork) and complex (emergent-like) mental models. A stratified sampling procedure was used to assign students to control or treatment groups. The purpose of stratification was to minimize internal validity conflicts with group differences and “helps ensure that each segment of the population is proportionally represented” (Cohen, 2001, p. 165).

Gall, Gall, and Borg’s (1999) three-step experimental research procedure guided this research. Students were, first, randomly assigned using the aforementioned random stratification procedure. During the second step, Gall and colleagues stated, “The experimental group is exposed to an intervention (also called the treatment or the independent variable), while the control group either is exposed to an alternate treatment or receives no treatment” (p. 233). The third step was a measure between groups on the dependent variable. With regard to the intervention, the control group received no alternate instruction in this study. Their systems-based instruction proceeded in the form of a course capstone robotic project. Students in the treatment condition participated in a global warming simulation with embedded complex systems elements.

The intervention period was a total of seven classroom sessions. Treatment consisted of an introductory session followed by six interventions with CO2FX Global

Warming Interactive simulation. Each session occurred over a 45-minute class period. Students in the treatment condition were recorded during three of the sessions. Qualitative evidence was gathered in a digital format of student spoken statements while working in the intervention. Additionally, a series of video primers (FRONTLINE/ NOVA, 2007) served as a supplement to prepare students for complex systems jargon in the CO2FX intervention. Three teams, of three students each, worked as economic, policy and science/technology advisors in a simulation whereby the students allocated resources over a 100-year span. Advisor decisions in this complex environment impacted climatic change. Participants experienced complexity concepts in their attempts to reduce CO_2 emissions and minimize global warming.

The aforementioned video supplement and regular, project-based curriculum served as the independent variable for the control group. Complex systems were investigated with analytic approaches emphasizing electrical, mechanical, hydraulic and pneumatic subsystems in the construction of a robot. The approach to delivering systems-related content differed between groups. The control group received direct instruction on complex systems focused upon inputs, processes, outputs and feedback in robotic subsystems. Treatment group members also worked to design and build the robots serving as a capstone to the *Introduction to Technology and Engineering* course. However, in addition, they participated in a computer simulation requiring synthesis of embedded complex systems elements in a global warming simulation with cultural, economic, political, and social-interrelated events.

Following the month-long intervention, all participants completed a posttest with one open-ended, near transfer and one far transfer question. Using a clockwork mental model (CWMM) and emergent framework mental model (EFMM) analysis framework, the quantity of clockwork (reductive) and complex (emergent-like) responses were determined in relation to an ontological mental model taxonomy (OMMT). Qualitative measures in the form of transcriptions from digital audio and videotape recordings and data entry worksheets captured the treatment group's actions within the CO2FX simulation intervention.

ANCOVA was used to determine group differences with the generation of complex (emergent-like) and clockwork (reductive) mental models. An ANCOVA was selected because it is a more sensitive test accounting for group differences existing on pretest, which existed from stratification and assignment (Cohen, 2001). Selection of the ANCOVA was deemed appropriate as the following assumptions of Cohen's were met:

1. The relation between the covariate and the dependent variable in the population was linear.
2. Homogeneity of regression.
3. The covariate was measured without error. (pp. 590-591)

This research utilized the mental model framework analysis of Charles (2003) and Jacobson (2000), who relied upon similar frameworks with CWMM and EFMM. The CWMM and EFMM were used to code systematically participant pretest and posttest responses to near and far transfer questions (as cited in Bar-Yam, 1997; Casti, 1994a, 1994b; Gell-Mann, 1994; Holland, 1995; Kauffman, 1995; Resnick, 1994). Open-ended questions with a technological orientation were employed to gather student responses fulfilling the CWMM and EFMM frameworks.

Principal Research Question

Can high school students' exposure to complex systems scenarios within a simulation increase the generation of EFMM, as demonstrated by the ability to create emergent-like explanations as they are applied to near and far transfer problems?

Null Hypothesis 1: There is no significant difference between control and treatment groups in the generation of EFMM and CWMM when solving the posttest near transfer problem.

Null Hypothesis 2: There is no significant difference between control and treatment groups in the generation of EFMM and CWMM when solving the posttest far transfer problem.

Null Hypothesis 3: There is no significant difference from pretest to posttest in the generation of EFMM and CWMM for the treatment group.

Definitions of Terms

ANCOVA: Analysis of co-variance; a statistical procedure for testing mean differences.

Clockwork mental model (CWMM): "Theories which are reductive and influenced by a Newtonian view of science" (Charles & Apollonia, 2003, p. 9). Reduces elements to the component level, often searching for causal relationships.

Complex systems dynamics: Term used to describe research that utilizes computational modeling software investigating feedback loops and time delays, dates to Dr. Jay Forrester's work at MIT in 1950s.

Complex systems mental model (CSMM): "A framework which consists of eight component beliefs that are hypothesized to be associated with complex systems concepts" (Jacobson, 2000, p. 16; e.g., randomness, decentralized control, nonlinearity, emergence).

Complex systems thinking: Attempts to illustrate that, in complex systems, events

are separated by distance and time; hence, small catalytic events can cause large changes in a system…the sum is greater than the parts.

Complexity: "The label given to the existence of many interdependent variables in a given system; the more variables and the greater their interdependence, the greater that system's complexity" (Dörner, 1996, p. 38).

Complexity theory: "Critically interacting components self-organize to form potentially evolving structures exhibiting a hierarchy of emergent system properties" (Charles, 2003, p. 297).

CO2FX: A web-based program representing a dynamic model of global climate change in which a team of three students act as economic, policy, and science/technology advisors mitigating CO_2 emissions and rising average global temperatures over a century-long simulation.

Decentralized control: A lack of central control predicated upon cause and effect.

Emergence: "How local interactions of elements in a complex system at a micro level can contribute to higher order macro level patterns that may have qualitatively different characteristics than the individual elements at the micro level" (Jacobson & Wilensky, 2006, p. 15).

Emergent framework mental model (EFMM): mental representations that exhibit complex qualities.

ETE: Engineering and Technology Education. An evolution of Technology Education, primarily at grade levels 6-12.

Far transfer: Application of skills or knowledge in situations that differ in structure or function (e.g., information learned in school within a knowledge context applied to situations in everyday environments with different features).

Feedback loops: A cyclical process whereby the change in one variable brings about change in one or more others (e.g., "in predator-prey relationships we observe population growth of one species and as that growth matures, a balancing feedback dynamic is engaged which tends to stabilize both the predator and prey populations at some level") (Sweeney, 2004, p. 10).

Mental model: "Internal mental representations that allow human beings to comprehend the world" (Charles, 2003, p. 49).

Near transfer: Applying knowledge or skills to a similar task, oftentimes, related to procedural events (e.g., having learned how to drive a car, one transfers these skills to driving a truck or bus).

Nonlinearity: Within complex systems, this term is used to refer to: (a) a situation in which change is disproportionate (e.g., exponential growth) or (b) circular causality (i.e., there is not a causal relationship).

Programmable modeling environment: Software designed as the most efficient means of exposing students to a variety of complex situations, and the resulting outcomes, based upon decisions made by the user (e.g., StarLogo, STELLA).

Randomness: Actions or events which occur without predictability.

Schema: An active knowledge structure for representing generic concepts stored in memory.

Stochastic: "Probabilistic, not goal-directed rather affected by principles of self-organization" (Charles, 2003, p. 65).

Technological literacy: "One's ability to use, manage, assess, and understand technology" (ITEA, 2000/2002, p. 9).

Limitations of the Study

This research served as a starting point, investigating complex systems which have a history in science domains, and bringing it into ETE. The advantage in doing so is that ETE courses are, typically, electives. By their nature, elective courses are not tied as rigidly to a mandated curriculum connected to end of year standardized testing. As such, they present ideal multidisciplinary opportunities to conduct "big picture" complex systems inquiry (Thode & Thode, 2002). However, the limitation in doing so is that ETE teachers possess a different skill set when it comes to addressing complex systems. ETE teachers addressing complex systems often do so from a technician's point of view versus that of a scientist. Troubleshooting a fuel-injected engine with various computer controls and sensors would be viewed as more complex than troubleshooting an older engine with a carburetor-style intake manifold.

This limitation then becomes one of either preparing the teacher for complexity inquiry from a scientist's point of view or modifying the intervention to provide an opportunity for student learning within complex systems. Previous literature indicates, "it can take several years (most research indicates 3 to 5) for teachers to become routine in their use of a new practice or program; therefore, expecting student achievement to change in a short period is unrealistic" (Loucks-Horsley, Hewson, Love, & Stiles, 1998, p. 40). Realizing the limitation of transforming a practicing teacher's approach in a short timeframe, a decision was made to implement a simulation, programmed with computational modeling software, of a climate control model with embedded complexity elements (Fiddaman, 1997).

Addressing two of four power standards for the *Introduction to Technology and Engineering* course, the intervention was selected as it addressed: (a) students' understanding that technology affects society and the environment in ways that are both planned and unplanned and desirable and undesirable, and (b) students' recognition that systems are made up of individual components and that each component affects the operation of the system and its relationship to other systems. While addressing course standards, a subsequent limitation is one of the computational model of the global warming scenario.

One final limitation would be the research site itself at Mid-Western High School (MWHS). With an enrollment of 1,767 students (2007-08), MWHS is located in a suburban community of a city of 200,000 in the Midwest. Ethnic composition reported by the school district for the 2007-08 school year consisted of 4.9% Asian, 11.7% Black, 5.0% Hispanic Origin, 0.6% American Indian, and 77.8% White students.

Assumptions of the Study

The following assumptions are made regarding this study.

1. Mental models are incomplete and evolving, therefore, the possibility exists that a student's change in representation could occur through computational modeling simulation interaction and exposure.

2. Participating students share similar characteristics and understandings of engineering and technology.

3. The intervention (CO2FX) was developed with necessary and appropriate complex systems elements embedded within the software simulation.

4. Students would be able to generate responses with emergent-like characteristics without a classroom teacher providing complex systems instruction.

5. The instrument used in this study accurately measures the generation of mental models pertaining to reductive (clockwork) and complex (emergent-like) thinking.

CHAPTER II

REVIEW OF LITERATURE

This research investigates student learning. Of particular importance in engineering and technology education is the ability to transfer information learned in school and apply it to real world contexts. Wulf (2002) stated a current limitation in engineering is that, “many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems” (p. 1). ETE address interdisciplinary learning at different levels with engineering undoubtedly addressing advanced levels of mathematics and science. Both rely upon math and science as core cognitive concepts with technology as the building blocks to hands-on, practical problem solving and engineering to design in a systematic manner, developing solutions to a wide array of issues.

The delivery of applicable content is a problem as it relates to student learning, interest, and motivation. McMurtray (2004) stated:

> Our present system of teaching science to our citizens does not work for everybody because it is not designed to. The system reserves advanced science and mathematics for a small subset of the population…. Advanced science and mathematics are for the chosen few. For the rest, it may be a painful and sterile exercise of meaningless and unrelated activities presented in a linear progression for an unknown purpose. (p. 2)

As students become acclimated to a linear progression of isolated course offerings, taught as separate “chunks” of knowledge, they struggle to organize decontextualized facts and procedures into a cognitive structure which transfers to applicability in the real world. Barab and colleagues (1999) referred to this as an artifactual view of education, stating:

> Implications of the artifactual view for education are that the “order” to be created is imposed on the learner who is expected rotely to memorize “facts,” which, purportedly, can later be matched up in a meaningful way with some real-world phenomena. (p. 352)

Research into expert-novice differences found that “novice learners tend to build their explanations (mental models) based on surface features, and their intuitive naïve interpretations, therefore, lead to incorrect conclusions and misconceptions” (Charles, 2003, pp. 1-2). Structure-Behavior-Function theory investigated by Hmelo-Silver and Pfeffer (2004) and Jacobson (2000, 2001) similarly indicated novice learners’ tendency to focus upon physical, structural characteristics while expert learners rely upon explanations across structures, behaviors, and functions, specifically, upon the latter two. Novice learners’ tendency to focus upon physical characteristics lead to difficulties gaining an understanding of certain concepts, primarily because other concepts have become habituated, leading to difficulties categorizing new information (Charles).

The fact that students demonstrate a tendency to focus on physical characteristics and structural properties can be seen as a result of content as it is delivered in the current educational system. Beyond the elementary level, in which teachers are trained as generalists, students are educated for the most part by content area specialists from junior high school years through college. Too often, the content is prescribed in a linear fashion in the preparation for end of year standardized tests. This lends itself to de-contextualized teaching practices with teachers feeling pressure to “get through” required content for tests. Barab and colleagues (1999) stated, “As long as educators continue to separate content from context, information from application, learning from participation, knowledge from experience, they will sever the essential connection that facilitates the learner in developing meaningful relations in the world" (p. 354).

If a different approach were taken with students participating in simulations with embedded complexity elements, could novice learners recognize the underlying patterns and relationships? If so, would it lead to greater conceptual understanding transferable to other contexts? That is the focus of this research. Unlike the time-honored tradition of teaching separate subjects, subsequently reduced to specialized content teachings (e.g., algebra, geometry, and calculus), this study explored a complex interdisciplinary approach. Simulations built around complex computational models are used in an attempt to discover common underlying patterns and relationships, attempting to enhance student comprehension of complexity elements.

Theoretical Foundation

This study relied upon an ecological paradigmatic orientation that is a significant and fundamental change in empirically driven ETE practices. An ecological discourse tends to be oriented toward questions of meaning, ethical action, spiritual entanglement, and mindful participation (Davis, 2004). This is in opposition to current ETE practices, emphasizing analytical thinking, evolved from the "metaphysical" in which "the universe is viewed as complete and unchanging" (Davis, p. 185). Davis states that given truths exist, delivered to the student as "acquisitions and accumulations of absolute facts" (p. 185). Such approaches hold meaning as an internalized process. Barab and colleagues (1999) contended that the goal of such instruction is

> …for the all-knowing teacher to transfer abstract and potentially generalizable content to the passive learner. It is simply assumed, and central to the

> representational/symbolic view of mind, that learners can and will apply these abstracted facts, concepts, principles, and skills when the relevant situations present themselves. (p. 356)

Traditional behaviorism and cognitive science approaches embrace this internalized process to learning, through mental representation for cognitivists and influence of stimuli for behaviorists (Reed, 1996).

Ecological psychology takes an entirely different theoretical tack because it starts from different assumptions. Meanings and values are *external*, not internal (Davis, 2004). Within an ecological discourse, “learning is not simply the acquisition of a set of preprocessed facts” (Barab et al., 1999, p. 382). Davis stated that “teaching and learning are not about convergence onto a preexistent truth, but about divergence–about broadening what is knowable, doable, and beable. The emphasis is not on what *is*, but on what might be brought forth” (p. 184). Barab and colleagues further elaborated in that “meaning arises within (as part of) context (as meaningful relations), and it is the responsibility of the educator to support (scaffold) the learner in developing relations with the learning situation in particular and society in general” (p. 382).

Diverging from traditionally relied upon ETE empirical and rationally oriented approaches, frequently employing instructing and training conceptions of teaching, this research relies on participatory and conversing teaching conceptions (Davis, 2004). As practiced, students derive meaning through their interactions with team members, as well as with the complex systems simulation. While the primary focus of this research lies within a post-modern ecological discourse, by no means was traditional, analytic practice abandoned. Analytic focus at the component level served a complementary role in this research to the "bigger picture" synthesis skills needed to understand multifactor interrelationships.

Ecological and complexity science discourses share many of the same features. Realizing they share much in common is important as a transition from an ecological perspective as the language spoken in this theoretical foundation section will transition into a language of complexity and complex systems in the following chapters. However, a distinguishing trait between an ecological perspective and complexity science occurs within the conceptions of "meanings" and "working." ETE tends to focus on the "working" of systems with rationalized reasoning and empirical measures. Complexity science similarly emphasizes working. Davis (2004) illustrated it as follows:

> Complexity science, for the most part, describes itself in the detached rhetoric of modern science and concerns itself more with the workings than with the meanings of things. Ecological discourses, by contrast, are more oriented to questions of meaning, ethical action, spiritual entanglement, and mindful participation in the evolution of the cosmos. (p. 161)

The distinguishing feature in this research lies within an ecological perspective for the treatment group engaged in a complex systems environment with a CO2FX simulation of a global warming scenario. Participating in this environment, the treatment group was exposed to cultural, economic, political, and social effects of technology. In contrast, the control group investigated the "workings" of complex systems with a more traditional, project-based, engineering and technology education approach, whereby, investigation of a complex system came in the form of subsystems analysis within a functioning robot (i.e., electrical, mechanical, hydraulic and pneumatic systems).

Complex Systems

According to Dörner (1996), "*complexity* is the label given to the existence of many interdependent variables in a given system; the more variables and the greater their interdependence, the greater that system's complexity" (p. 38). Defining characteristics of complex systems include emergence, self-organization, and adaptation (Ottino, 2004). Jacobson and Wilensky (2006) defined emergence as, "how local interactions of elements in a complex system at a micro level can contribute to higher order macro level patterns that may have qualitatively different characteristics than the individual elements at the micro level" (p. 15). An example of emergence is the property of wetness that emerges as two hydrogen molecules are combined with one oxygen molecule.

In sporting arenas across the U.S., the property of self-organization can be observed and experienced in the form of a "human wave." The actions of thousands of individuals: rapidly standing, waving their hands overhead while making noise, and sitting just as quickly results in a "wave" circling the stadium. Self-organization is defined by Davis (2004) in the following manner:

> A complex phenomena is self-organizing, meaning that it is composed of and arises in the co-implicated activities of individual agents. It is not the sum of its parts – an object; it is the product of its parts and their interactions – an interobject. (p. 151)

Richardson and colleagues (2001) stated, "A complex (adaptive) system can be simply described as a system comprised of a large number of entities that display a high level of interactivity. The nature of this interactivity is mostly nonlinear, containing manifest feedback loops" (p. 7). Nonlinearity in complex systems is acknowledged in one of two forms. As opposed to singular causality tested by the scientific method, nonlinearity consists of feedback loops resulting in circular causality. Disproportionate change (e.g., exponential growth) would be a secondary case used to describe nonlinearity. Along with nonlinearity, feedback loops represent the other variable defined by Richardson and colleagues in an adaptive system. Feedback loops are cyclical processes whereby the change in one variable brings about change in others. An example would be predator-prey relationships. As cottontail rabbit numbers rise and fall within an ecosystem, red fox populations tend to follow in a cyclical fashion. Feedback loops are well suited for ETE, which speaks a language of "inputs" and "outputs."

Complex systems characteristics such as nonlinearity, emergence and self-organization represent a number of small-scale properties of which the sum is greater than the parts in defining complexity. Of particular interest to this research was the lack of identifiable physical traits with each of the complexity characteristics, which novice learners generally rely upon. As ETE courses, typically, revolve around projects, discovering how students learn about non-physical complexity properties is noteworthy. Speaking to this point, Jacobson and Wilensky (2006) noted, "research is needed to explore if the use of appropriate pedagogies, curricular materials, and learning tools helps students understand that complex systems conceptual perspectives have relevance across what have traditionally been taught as separate subject areas" (p. 24).

Systems in Engineering and Technology Education

Systems serve as the building blocks of technology. "The core concepts of technology highlighted by *Technology Content Standards* are systems, resources, requirements, optimization and trade-offs, processes, and controls” (2000/2002, p. 32). Forty specific references to systems and subsystems are made in the *Standards for technological literacy: Content for the study of technology* (*STL*) in the form of benchmarks stating what students should know and be able to do.

ETE’s approach to systems is somewhat similar to that found within science domains. Gomez, Oakes, and Leone (2007) defined it as “a system is a mechanism for achieving a desired result; it involves Input, Process, Output, and Feedback” (p. 75). The ITEA (2000/2002) defined a system as “a group of interrelated components designed collectively to achieve a desired goal” (p. 32). While both definitions share similar characteristics pertaining to relationships between parts, engineering and technology education tends to differ in its technological focus.

As technological systems are investigated at the subsystem level the tendency is to incorporate concrete examples of physical items. One such example from Gomez and colleagues (2007) illustrated the point, “an automobile has systems and subsystems: mechanical systems (gears and pulleys), electrical systems (battery, wiring, and computers), and fluid systems” (p. 75). This automobile illustration is representative of a wide variety of examples found in technology textbooks and in the STL. This focus on physical properties can be identified with prototypical systematic inquiry examples introduced in an age-appropriate sequence at grades K-2, 3-5, 6-8, and 9-12.

> *K-2: Systems have parts or components that work together to accomplish a goal* [italics added]. For example, a bicycle can be thought of as a system. It has many parts – wheels, handlebars, pedals, brakes, gears, and chains – and each is important for the bike to function properly.

> *3-5: A subsystem is a system that operates as a part of another system* [italics added]. An example of a subsystem is the collection of water pipes in a house, which is part of a larger fresh-water distribution system in a town.
>
> *6-8: Technological systems include input, processes, output, and, at times, feedback* [italics added].. For example, the fuel level indicator of a car is a feedback system that lets the user know when the system needs additional fuel.
>
> *6-8: Systems thinking involves considering how every part relates to others* [italics added]. For example, discussing a computer system may involve the particular parts of a single computer, or it may include the entire computer network.
>
> *9-12: Systems, which are the building blocks of technology, are embedded within larger technological, social, and environmental systems* [italics added]. For example, a food processor is a system made up of components and subsystems. At the same time, a food processor is only one component in a larger food preparation system that, in turn, is a component in a larger home system. (ITEA, 2000/2002, pp. 34-42)

These examples provide a reductive method of analyzing sub-systems at the component level. ETE educators rely upon such methods while illustrating core concepts.

Reductionist practices are important for the technician repairing a fuel level indicator, computer system or bicycle. However, such practices run counter to traditional thinking in more complex situations. Dörner (1996) stated, “In complex situations it is almost always essential to avoid focusing on just one element and pursuing only one goal and instead to pursue several goals at once” (p. 64). Richardson and colleagues (2001) echoed the sentiment:

> Where we once focused on the parts of a system and how they functioned, we must now focus on the interactions between these parts, and how these relationships determine the identity not only of the parts but of the whole system. (p. 7)

An ecological perspective to complex systems provides a participatory experience for students to find meaning in cultural, economic, political and social interactions and interrelationships, with the realization that, “in complex situations we cannot do only one thing. Similarly, we cannot pursue only one goal. If we try, we may unintentionally create new problems” (Dörner, 1996, p. 52).

Understanding linkages between interrelated systems and subsystems is akin to the ability to synthesize isolated school subjects. Students who recognize such connections have an increased capacity for applying understandings to new settings. Gee (2003) contended this is an inherent human strength, “The human mind is a powerful *pattern recognizer*. In fact, humans are quite adept at finding complex patterns where none actually exist (witness astrology)” (p. 91). Student ability to recognize patterns and synthesize complexity elements is an important step dictating appropriate strategies to incorporate in classroom teachings.

Complex Systems and Student Learning

Current educational practice is in need of alternative options to enhance student learning. King and Frick (1999) stated, “As the amount of information increases exponentially, our educational system can no longer focus primarily on memorizing a core body of knowledge. There is no way any single individual can master all of the information available” (p. 2). In *How People Learn,* Bransford and colleagues (2000) stated that “traditional education has tended to emphasize memorization and mastery of text” (p. 239). These statements speak to a need moving beyond reductive practice and analytic thought processes to one entailing synthesis capabilities. Frank (2005) described analysis and synthesis as applied to the educational system:

> According to Bloom's taxonomy, analysis is the disassembly of a unit of content into its component elements while retaining the components' interconnections. The purpose of analysis is to arrive at an understanding of the content components…. Synthesis is the combination, arrangement, organization, and assembly of elements and parts with the purpose of creating a system that did not previously exist. Synthesis is the connection of components or sub-systems into a whole system. (p. 26)

Comparing U.S. high school student scores to those of international peers demonstrates issues with the current focus upon reductive practices in U.S. schools (Lemke et al., 2001, 2004).

Complex systems approaches are designed to provide a top-down approach to learning, rather than the traditional bottom-up approaches used in education. Bottom-up, reductive approaches are most often illustrated at the component level whereby smaller elements give way to larger components in a systematic manner. Engineering is renowned for such approaches as identified in Figure 1. This logic dictates that students need to understand specific factual content prior to comprehending the "bigger picture."

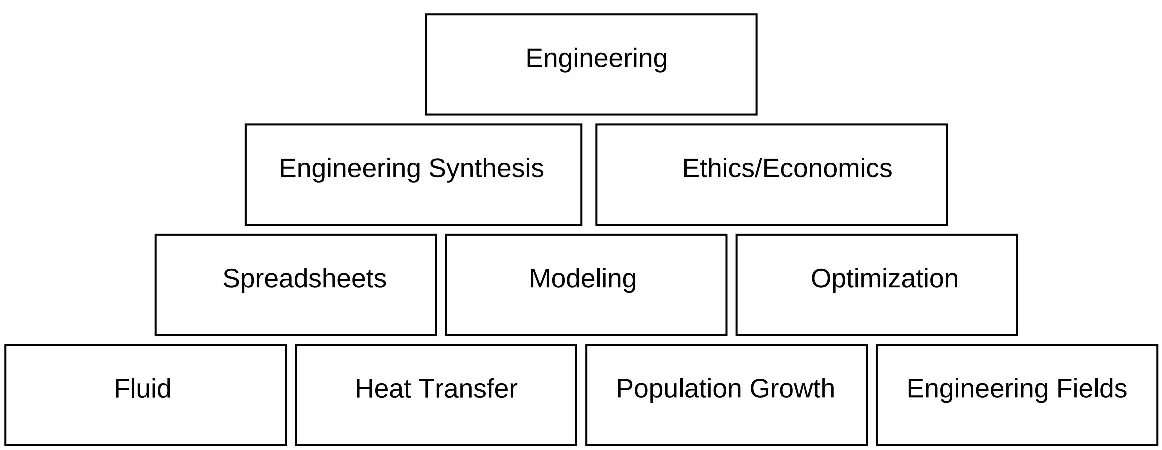

Figure 1. Bottom-up content organizer leading to an engineering degree.

T. Taylor (personal communication, February 14, 2007)

According to Frank (2005), the central premise in a systems thinking approach, "is that complete systems can be handled, conceptually and functionally, without needing to know the details…in other words, the focus must be on the characteristics and functionality of whole systems and the interdependence of the subsystems" (p. 20). Working within complexity simulations provides students an opportunity to identify connections between interrelated social, economic and political systems. Dörner (1996) stated, "A planning and decision making scenario simulated on a computer may be less complex than one in the real world, but it has the great advantage of letting us run our experiments on fast-forward and of bringing us face to face with our mistakes" (p. 197). Goldstone (2006) concurred:

> Students who interact with the simulations actively interpret the resulting patterns**,** particularly if guided by goals abetted by knowledge of the principle. Their interactions are grounded in the particular simulation, but once a student has practiced building an interpretation, it is more likely used for future situations. (p. 40)

In these environments, "learning is not viewed as an isolated activity that is externally arranged and context independent; instead, learning (participation) is (re)contextualized practice and meaning, as part of an ecological system" (Barab et al., 1999, p. 353). Meaning arises from the student's participation in the simulation. "Unlike departmentalized knowledge that has been abstracted and taught to the student by the teacher, a systems approach acknowledges that meaningful relations emerge through the situated activity" (Barab et al., p. 380).

Complex systems thinking research, investigating the role of complexity in student learning, has its roots in scientific domains. Complexity approaches are an alternative to well established practices in science, such as the scientific method.

> In the minds of many, the study of complexity is not just a new science, but a new way of thinking about all science, a fundamental shift from the paradigms that have dominated scientific thinking for the past 300 years. (Resnick & Wilensky, 1997, p. 4)

Considering complex systems frequently interwoven cultural, social, economic and political interrelationships, a complexity approach to teaching lends itself well to engineering and technology education as the ITEA (2000/2002) addressed such effects of technology in the technology and society standards.

Complex Systems Meta-Analysis

Tangible connections with technology were a main point of interest with complex systems studies selected for this review. If not a physically identifiable complex technology such as lasers, superconductivity, the Internet, U.S. power grids and highways (Ottino, 2004), tradeoffs and impacts of technology were the key characteristics in study selection. For example, the proliferation of transportation technologies powered by fossil fuels has a negative impact on the environment due to carbon dioxide emissions. Studies such as this were selected for this review, as opposed to an extensive array of science-oriented studies currently existing in the literature.

Charles (2003), Dörner (1996), and Resnick and Wilensky (1997) have all cited the need for complexity research outside of science. Investigating the current literature reveals a predominance of articles and studies from science, with some leaning towards multidisciplinary investigation into technology and engineering education. Studies for this literature review were selected under the five following criteria:

1. Timeliness;
2. Identifiable technology/engineering connection;
3. Definitive focus on complex systems and student learning;
4. Alignment with the ITEA standards, primarily standard #4 [impacts]; and
5. Professionally worthy; meet peer review or similarly identified as credible.

ITEA standard #4 stated, “Students will develop an understanding of the cultural, social, economic, and political effects of technology” (ITEA, 2000/2002, p. 210). This is an important standard addressing complexity issues across a wide range of topics.

An electronic review of the literature was conducted using electronic resources. ERIC, EBSCO HOST, Google Scholar, and Utah State University’s digital dissertations and education full text archives were searched with a combination of terms beginning with “Complex Systems AND Simulations OR Gaming AND Student Learning.” Interest was focused on student learning and comprehension through computer simulations and gaming pertaining to complex systems. Subsequent searches were made for “computer uses in education,” “computer assisted instruction,” “computer simulation,” “simulation and gaming,” “academic achievement,” “student learning,” and “gaming and student learning,” “complex systems thinking/dynamics,” with “technology education” or “engineering education,” “computational modeling” and “cognition.” An initial search of complex systems thinking resulted in 385 resources, which were eventually reduced to 15 studies meeting the 5-point criteria.

Study Findings

Studies ranged from elementary school level to graduate school. Elementary studies in this review were qualitative studies, focused upon hands-on investigation of complex systems. Middle school studies shared some hands-on complexity investigation such as Thinking Tags (Yoon, 2005), but also used programmable modeling environment with StarLogo (Klopfer, Yoon, & Um, 2005). Mixed method designs and quantitative designs at the high school and university level particularly relied upon computational modeling software, most often with STELLA (Systems Thinking for Education and Research).

Software packages are designed to present a variety of complexity scenarios whereby a participant is in control of a number of variables (i.e., complex systems elements), which outputs the results of micro level changes made of the macro level complex system. Dörner (1996) stated that with computational software:

> We can learn to deal with different situations that place different demands on us. And we can teach this skill, too – by putting people into one situation, then into another, and discussing with them their behavior and, most important, their mistakes. (p. 199)

Using computational modeling software packages is an efficient means of exposing students to a variety of complex situations. Complex systems educational resources used for this review include the Creative Learning Exchange and the Waters Foundation.

Reviews of 15 complex systems studies investigated student learning and comprehension of complexity elements predominantly by mixed and qualitative measures (refer to Table 1). The latitude in research across studies suggests that students at many

Table 1

Summary of Complex Systems Study Characteristics

		Grade level				Research design			Course content				Assignment		Overall quality ranking		
Study ID	# Subjects	Elem	M.S.	H.S.	Univ.	Mixed	Qual.	Quan.	Science	Tech/Eng	Math	Other	Random	Nonrandom	High	Medium	Low
2	10	X			X		X					X		X		X	
9	15	X					X					X		X		X	
10	7	X					X					X		X		X	
11	32	X	X				X					X		X		X	
3	4		X				X		X					X	X		
4	30		X		X	X			X					X	X		
5	80		X				X		X	X	X			X	X		
8	42		X				X		X				X		X		
16	40		X			X			X				X		X		
17	11		X			X			X					X	X		
13	9			X		X			X					X	X		
14	45			X			X		X				X		X		
1	16				X	X			X					X	X		
6	98				X			X	X	X			X		X		
12	212				X	X						X	X				X
TOTALS		4	7	2	5	6	8	1	10	2	1	5	5	10	10	4	1

levels are capable of learning with this top-down approach, as suggested by Jacobson and Wilensky (2006):

> Though we are still at an early stage of research into learning about complex systems, overall, the studies … suggest that students at pre-graduate school levels, from approximately middle school through college, can learn and benefit from important concepts and perspectives related to the scientific study of complex systems. (p. 19)

Table 1 identifies a summary of the previous reviews, including characteristics for the proposed study: number of subjects, grade level, type of research design, course content, type of assignment, and an overall quality ranking.

Overall quality rankings were based on the 5-point criteria stated earlier with an emphasis on the degree to which the study focused on student learning, as all investigated complexity issues to some degree. A subjective ranking of low, medium or high quality was determined based on effect size (*ES*) and differences between groups. It should be noted that this rating was not intended to assess the quality of research. The intent was to identify, based on rank, studies with attributes contributing cognition, complex systems and research design elements to the current research.

Sterman and Sweeney's (2006) study (#12) was ranked low because the learning focus was related to current misconceptions, rather than on how learning changes over time. While ranked low in this regard, the study had excellent content with climatic change complexity inquiry. This study investigated graduate students misconceptions about greenhouse gases, focusing on stock-flow reasoning and mass balance versus pattern matching. Education's role with policy making was of interest due to the misconceptions of the highly educated adults participating in this study.

Qualitative studies at the elementary level were deemed as medium quality. Although differences were noted in these studies, results tended to lack quantifiable support. Zuckerman and Resnick (2005) and Zuckerman's (2004) research (studies #2 and #9) were designed to investigate stock and flow structures with a hands-on modeling manipulative (system blocks). This research investigated the difficulties people have understanding dynamic behavior. Net-flow dynamics and the role of feedback were emphasized as core concepts of systems.

Additionally, qualitative research at the elementary level investigated SIGGS (studies #10 and 11), a combination of four theories: Set, Information, di-Graph, and General Systems (King & Frick, 1999). This highly complex mathematical model, created by Maccia and Maccia (1975), analyzed SIGGS concepts related to student learning and teacher approaches as currently practiced. SIGGS was modified into an everyday common language for age-appropriateness for the elementary students at the Montessori school and museum sites of study. King and Frick's study complemented students' learning via complexity approaches investigating the educational system (i.e., school, teacher, and student interrelationships).

The remainder of the studies received a high-quality ranking based upon differences noted, large *ES* (e.g., 0.8 or greater, and/or significant contributions in a technological context). Davidovitch, Parush, and Shtub's (2006) research (study #6) investigated the role of transfer utilizing simulations in engineering education. A project management trainer was used to teach in dynamic, stochastic, and multi-project environments. Student decision making skills were assessed in single-project and multi-project scenarios. Findings indicated that a history mechanism enhanced learning as participants reflected upon past experience to guide future decisions. Based upon this finding, a history mechanism was developed for the current student. Data entry worksheets were developed so that students could reflect upon prior results to inform current and future decision making.

Penner's (2000) qualitative study (#3) investigated middle school student understanding of emergent phenomena. Incorporating an analytic approach, students explored emergence patterns on grid paper related to four scenarios: talus slope formation, v-shaped pattern of geese in flight, traffic jam formation, and mature forest formation. The traffic jam and geese in flight scenarios were subsequently incorporated into the current research. The conclusions of the study were that students relied upon singular cause-and-effect and centralized control explanations at the macro-level rather than potential influences at the micro-level.

Klopfer and colleagues (2005) qualitative research (study #5) explored differences between fifth- and seventh-grade students' learning about the scientific methodology and complex systems in StarLogo. Students explored two StarLogo projects: Mystery Shapes and Mystery Epidemic. Embracing abstract challenges in StarLogo was more evident in grade five students, perhaps, due to an elementary level playfulness. The authors concluded that complex systems principles are not too complicated to be integrated at the elementary level.

Hmelo, Holton and Kolodner (2000) research (study #8) investigated knowledge as design approach relying on structure-behavior-function models. The human respiratory system was explored as a complex system for sixth-grade students. During the 2-week respiratory system unit, students designed and built an artificial lung. Students demonstrated a tendency to focus on structure (physical properties) rather than behavior or function. Limited classroom discussion, as well as student-designed static artificial lung models, contributed to structural foci. As a component of the qualitative study, students contributed pretest and posttest sketches of the respiratory system to demonstrate conceptual change over the two week unit. The underlying behavior-function elements were of interest in the current research with regards to student transferring knowledge to different settings or contexts.

Mixed methods design had high overall rankings for quality in five out of six studies in Table 1. Each of these studies investigated the role of student learning, as well as highlighting complex systems principles. Goldstone (2006, as cited in Bransford & Schwartz, 1999 and the National Research Council, 1999) stated:

> If students can learn to learn these principles and recognize when they are applicable, then they not only develop an appreciation of the integrated web of science, but they also can transfer what they have learned to widely dissimilar domains, one of the greatest unsolved challenges for education. (p. 36)

The five mixed-method design studies ranked high by the 5-point selection criteria also displayed the greatest connection between complexity elements and measures of student learning. With qualitative, mixed methods, and quantitative studies reviewed, a common qualitative measured was needed. Table 2 demonstrates a common metric by which all studies were compared. The metric selected across the diverse studies was a measure within studies between control and treatment groups consisting of differences noted, no difference, or regressed. Additionally mixed design and quantitative

Table 2

Summary of Research Designs

	Independent							Dependent				Descriptive			
Study ID	Emergence	Decentralized	Nonlinearity	Randomness	Stochastic	Dynamic	Other	Mental models	Analogies	Homologies	Other	Mean/ *SD*	*ES*	Differences	No differences
2							X				X			X	
9						X	X	X						X	
10															X
11															X
3	X										X				X
4		X	X								X	X	3.04	X	
5				X			X				X			X	
8								X						X	
16			X				X			X		X	.11		X
17		X	X	X	X	X			X			X	4.67	X	
13	X	X	X	X	X	X		X				X	1.37	X	
14	X	X	X	X	X	X	X	X						X	
1	X	X	X	X	X	X	X	X				X	2.31	X	
6					X						X	X	.76	X	
12							X	X							X
TOTALS	4	5	6	5	5	5	7	6	1	1	5	6	NA	10	5

designs include an *ES*, which was noted as a common metric for comparison. *ES* interpretation was based upon Cohen (as cited in Cohen, 1998), "in which .2, .5, and .8 represent small, medium and large gains, respectively" (Cohen, 2001, p. 222). Statistically significant differences regarding student ability to learn complexity elements was identified in four of the five mixed design studies.

Hmelo-Silver and Pfeffer (2004) and Jacobson (2000), studies #4 and #1, respectively, investigated differences between expert and novice learners' understanding of complex systems. Hmelo-Silver and Pfeffer's study resulted in an effect size of 3.04 as they investigated the structure-behavior-function theory as a framework for analysis. Seventh-grade students and preservice teachers served as novices, along with experts in aquatic systems, all identified requisite ecosystem elements for aquariums. Novice learners tended to focus on physical characteristics (i.e., structures); whereas, significant differences were noted in the quantity of underlying complexity principles (i.e., behaviors and functions) that experts generated.

Similarly, Jacobson's research in this area identified significant differences between novice and experts with an effect size of 2.31. In this study, a CSMM framework was used to analyze the quantity of complexity elements identified in nine problem questions designed to test near and far transfer ability. Novice learners generated more CWMM, which tend to focus on physical characteristics similar to the structures in Hmelo-Silver and Pfeffer's (2004) research, whereas experts tended to generate more CSMM equally comparable to the behaviors and functions component. As one example, novice learner's CWMM focus upon a single cause (e.g., a cause-and-effect relationship between variables) and an expert's CSMM look at multiple causes between complexity elements. Table 3 identifies and contrasts each of the complex elements as clockwork set mental models (simple/reductive) and complex systems set mental models (complex).

Paralleling the focus on mental models in Jacobson's study, Charles (2003) (studies #13-14) used a comparable analysis framework investigating CWMM's and EFMM. This research utilized the same open-ended problems from Jacobson's study deriving from earlier work (as cited in Bar-Yam, 1997; Casti, 1994a, 1994b; Gell-Mann, 1994; Holland, 1995; Kauffman, 1995; Resnick, 1994). Subject responses were coded as clockwork and EFMM to the following questions: How do

Table 3

Comparison of Clockwork Set Mental Model and Complex Systems Mental Models

	Types of component beliefs	
Categories of component beliefs	Clockwork set	complex systems set
1. Understanding Phenomena	Reductive (e.g., step-wise sequences, isolated parts)	Nonreductive: whole-is-greater-than-the-parts
2. Control	Centralized (within system) external agent (external to system)	Decentralized (system interactions)
3. Causes	Single	Multiple
4. Actions effects	Small actions → small effects	Small action → big effect
5. Agents actions	Completely predictable	Not completely predictable/ stochastic/random
6. Complex actions	From complex rules	From simple rules
7. Final causes or purposefulness of natural phenomena	Teleological	Nonteleological or stochastic
8. Ontology	Static structures; Events	Equilibration processes

Note. Adapted from Jacobson (2000), p. 17.

ants find and collect their food? Is it possible for a butterfly in Brazil to cause a snowstorm in Alaska? What causes the formation of traffic jams? (Charles, 2003). Differences were noted in both of these studies, including an effect size of 1.37 in study #13.

Charles (2003) and Jacobson's (2000) research identified important elements of systems at the component level. Reductive-like and complex attributes in Table 3 defined characteristics and provided examples beneficial to the current research. Using Jacobson's component beliefs as a starting point, Charles' research modifies this taxonomy with the addition of an ontological perspective. Along with the fine grain component belief analysis from Jacobson's work, an additional ontology component provides a large grain analysis characteristic for items that would otherwise go unused.

Of particular interest in Table 2 was the listing of independent variables investigated in relation to student learning. The work of Jacobson (2000), Charles (2003), and Yoon (2005) (study #17) identified the greatest quantity of complex systems elements investigated. Statistically significant differences were noted in the form of effect sizes or differences noted with each of the studies with five or more independent variables. Mental models were the dependent variable of choice in three of the four studies generated by these researchers.

Yoon's complexity research investigating memetic [*sic*] processes (i.e., analogies) generated the most significant *ES* at 4.67 in her study of genetic engineering. The content focus of this study was genetic engineering for eighth-grade students preparing for a freshman-level biology course. This was the only study found that included a technology component addressed directly in the ITEA standards. Standard #14 is medical technologies, including a specific grade 6-8 benchmark on genetic engineering (ITEA, 2000/2002). Considering the focus upon preparation for biology, it does appear in this case the focus was a science and technology connection in the standards.

One final study of importance was that of Sweeney [study #16] that investigated the role of homological reasoning (i.e., pattern recognition or structural similarity) in complex elements. Nonlinearity, feedback loops, and stock and flow structures similar to Zuckerman (2004) were investigated in this mixed methods design study. Although statistical significance was not generated in students (N = 29) with an *ES* of 0.11 (Table 2), differences were noted in the teacher population (N = 11).

Summary of Literature Reviews

Investigating student learning through mental model, analogical and homological reasoning have proven to be effective frameworks of analysis with complex systems. Mental model frameworks of Jacobson (2000) and Charles (2003) relied on similar frameworks with clockwork set mental models, complex set mental models and EFMM, respectively. Mixed methods designed studies ranked of high quality in Table 1, those based upon a 5-point criterion, subsequently identified noticeable differences within at least one population of inquiry (study #16 with teacher population).

Findings from studies in this literature review predominantly show studies originating from scientific disciplines. With the exception of elementary studies in Table 1 with a general content area of study, typically deriving from science, 10 of the 11 remaining studies are scientific in origin. Resnick and Wilensky (1997) and Dörner (1996) suggested the need for research in disciplines outside of science and across multiple disciplines, echoing the sentiments of Charles (2003), who stated in her educational implications:

> There is a need to develop easily accessible curricula topics that demonstrate complex systems behaviors…this alternative explanatory framework may be beneficial for all disciplines, not just science. If students are better able to explain the social, political, and economic interactions they encounter with more than a linear perspective they may in fact do a better job of understanding the unpredictable and probabilistic nature of many of these phenomena. (p. 5)

Charles' educational implications statement, investigating complex systems outside of science, segued into ETE's contextualized teaching approaches, specifically with ITEA standard #4, which stated that "students will develop an understanding of the cultural, social, economic, and political effects of technology" (ITEA, 2000/2002, p. 210).

Research Lacking in Engineering and Technology Education

The review of the literature into "complex systems" and "technology education" revealed just two resources: Yoon's dissertation (2005) and a dissertation from Patrick Foster (1997). Yoon's work was the closest to the purpose of the proposed research as it focused on genetic engineering, albeit through a science approach for eighth grade students preparing for high school biology. Foster's research with technology education at the elementary level, while not directly connected to complex systems thinking or dynamics, may prove valuable for future research on designing learning environments conducive to complex systems inquiry.

Although a vast amount of literature exists on complex systems thinking and dynamics in science and engineering, particularly biology and ecology, no research has been found within engineering and technology education. *Standards for technological literacy: Content for the study of technology* (ITEA, 2000/2002) addressed what complexity researchers have identified as an area rich in potential for complexity investigation. Technology and Society standards four through seven possess important societal, environmental, and political complexity interrelationships. Student-centered, contextualized teaching approaches in ETE present ideal complexity inquiry opportunities.

CHAPTER III

METHODOLOGY

A mixed methods triangulation design-convergence model provides quantitative and qualitative data with results converging during interpretation and subsequently used to draw valid conclusions about the research problem (Creswell & Plano Clark, 2007). In the mixed methods triangulation design the researcher first gathers quantitative and qualitative data concurrently. The quantitative and qualitative data are then analyzed independently. An equal weighting of the data sets results during the merging and interpretation phase. The rationale for this approach is that the qualitative data will provide a rich description of students actively participating in the learning environment to support the quantitative results while addressing the research question. This section describes the mixed design experimental study including: research hypothesis, research question, design of the study, data analysis, and procedures.

Research Hypotheses

Previous research in science (Dörner, 1996; Goldstone, 2006; Jacobson & Wilensky, 2006) demonstrated that students from middle school through pregraduate levels are able to recognize elements of complex systems as a result of interactions with computational modeling software. The hypothesis of this study is that ETE students who experience complex systems scenarios in a computer-based learning environment will outperform a control group by constructing a greater number of explanations with complex systems elements (e.g., randomness, decentralized control, nonlinearity, and dynamic nature).

Research Question

Can high school students' exposure to complex systems scenarios within a simulation increase the generation of EFMM, as demonstrated by the ability to create emergent-like explanations, applied to near and far transfer problems?

Null Hypothesis 1: There is no significant difference between control and treatment groups in the generation of EFMM and CWMM when solving the posttest near transfer problem.

Null Hypothesis 2: There is no significant difference between control and treatment groups in the generation of EFMM and CWMM when solving the posttest far transfer problem.

Null Hypothesis 3: There is no significant difference from pretest to posttest in the generation of EFMM and CWMM for the treatment group.

Design of the Study

Research Design

A mixed method experimental, pretest posttest, control group triangulation design research study was designed for high school students enrolled in an *Introduction to Technology and Engineering* course. Pretests and posttests consisting of one open-ended near transfer problem and one far transfer problem investigated the generation of reductive (clockwork) and complex (emergent-like) mental models.

Gall and colleagues' (1999) three-step experimental research procedure guided this research. Students were first randomly assigned using a random stratification procedure. During the second step, Gall and colleagues stated, "The experimental group is exposed to an intervention (also called the treatment or the independent variable), while the control group either is exposed to an alternate treatment or receives no treatment" (p. 233). The third step is a measure between groups on the dependent variable. With regard to the intervention, the control group received no alternate instruction in this study. Their systems-based instruction proceeded in the form of a course capstone robotic project. Students in the treatment condition participated in a global warming simulation with embedded complex systems elements.

Setting and Subject Description

Instructional Setting

The site for this study was a MWHS. With an enrollment of 1,767 students (2007-08), MWHS is located in a suburban community of a city of 200,000. Students enrolled in the freshman-level *Introduction to Technology and Engineering* class were the subjects in this study. Throughout this research pseudonyms were used for the research site and pilot study schools, as well as to protect the identity of the classroom teacher and students.

Instructor Description

Mr. Fenn is the teacher for the Engineering track of the MWHS Technology and Engineering department. Mr. Fenn, a teacher for 4 years, has a B.S. in Technology Education and was completing a master's degree during this research. Mr. Fenn taught the *Introduction to Technology and Engineering* class using a project-based approach. He used case studies from the *Engineering Your Future* (Gomez, Oakes, & Leone, 2006) book that serves as the primary text for his class. The course syllabus can be found in Appendix A.

Student Description

Eighteen of 20 students enrolled in the freshman-level *Introduction to Technology and Engineering* course served as the study participants. Due to the qualitative component of this research, consisting of time consuming tasks related to verbal protocol analysis of pretest and posttest answers and subsequent coding, the sample class size was limited to twenty. The sample size for the study aligns with comparable samples identified within mixed methods and qualitative studies identified in Table 1 and were subsequently determined based on an a priori sample size analysis.

Course Description

During the first 6 weeks of the *Introduction to Technology and Engineering* course, foundational knowledge and skills were the focal point. Students received instruction on: data collection, measurement, orthographic sketching, computer-aided design, scheduling and flowcharting (Appendix A). During this process, students were also introduced to systems design. Systems design is aligned with one of four school district power standards that dictate expected student results at the completion of the course. The school district's standards for Technology and Engineering Education align with the International Technology Education Association and state that students will recognize that systems are made up of individual components and that each component affects the operation of the system and its relationship to other systems.

In the middle 6 weeks of the semester students completed assignments with respect to the aforementioned school district power standard. These include power and transmission, alternative energy, hydraulics and pneumatics, and electrical circuits. Such systems-based delivery in ETE typically focuses on inputs, processes, outputs, and some form of feedback (ITEA, 2000/2002). Concepts related to power, electrical circuits, hydraulics, and pneumatics were ultimately integrated into a long-term project over the remaining 6 weeks of the semester. Students designed and built a robotic arm as a capstone project for a semester-ending student competition. All students received the same instruction during 83 of the 90 class periods throughout the semester. The remaining 7 periods served as the intervention period in which the delivery of systems-based instruction differed for control and treatment groups.

The approach to delivering systems-related content differed in that the control group received instruction with a systems focus pertaining to inputs, processes, outputs and feedback in the design and construction of a robotic arm. An investigation of subsystems at the component level of electrical, mechanical, pneumatic and hydraulic systems was completed throughout the intervention. Students in the treatment group received lecture content pertaining to the same technical concepts. However, their exposure to systems during the intervention period was embedded within a computer simulation of a complex system. Students participated in a complex system simulation of a global warming scenario designed with random generators and embedded complexity characteristics such as feedback loops and nonlinearity.

Student Informed Consent

Utah State University's institutional review board (IRB) granted permission contingent on written school district approval (Appendix B). The MWHS district administration, subsequently, provided written approval supporting this research.

Variables

Independent Variable

The use of a simulation of a complex environment served as the intervention in this study. The method of complex systems instruction as the independent variable differed between groups. Control students received complexity instruction in a project-based environment related to the construction of a robotic arm. An analytic approach from the bottom-up explored electrical and fluid power systems (i.e., hydraulics and pneumatics) at the component level. Treatment students were exposed to a top-down synthesis of cultural, economic, political, and societal effects of technology in the form of a global warming simulation.

Dependent Variable

Three possible outcomes exist for the generation of mental models in response to pre-test and post-test questions related to near and far transfer. The dependent variable measures for this study were complex responses in the form of EFMM and reductive responses in the form of CWMM. An alternative for EFMM and CWMM was a lack of understanding, identified as no model (NM).

Instrumentation

A pretest and posttest was administered with one open-ended near transfer problem and one open-ended far transfer problem coded and analyzed with Charles' (2003) OMMT. The problems used in this research derive from articles and books on complex systems used previously in complexity research (Bar-Yam, 1997; Casti, 1994a, 1994b; Charles, 2003; Gell-Mann, 1994; Holland, 1995; Jacobson, 2000; Kaufman, 1995; Resnick, 1994). Problems with a technological orientation were selected over problems with a purely scientific orientation for the pretest and posttest to alleviate content validity concerns. Jacobson stated, "the problems were written so that they could be answered in a qualitative manner appropriate for both complex systems experts and for individuals who had not received formal or informal (i.e., self-educated) training in areas dealing with complex systems" (p. 43).

Reliability

The taxonomy used to determine clockwork or complex categorization emerged from Jacobson's (2000) CSMM taxonomy and was tested with a Cronbach alpha statistical test. Gall and colleagues (1999) stated, "The alpha statistic is a means of testing whether the items comprising a measure consistently measure the same attitude, ability, or other construct" (p. 196). A widely accepted reliability coefficient of 0.7, the minimum level of acceptability in social sciences, was used in this research (Schloss & Smith, 1999).

This research utilized Charles' OMMT, which expanded upon Jacobson's CSMM taxonomy. Jacobson (2000) reported a reliability alpha of .76 with the clockwork category and .72 with the complex systems. The complex systems overall reliability was eventually improved to .85 with the removal of several items following an examination of the correlation matrix and inter-item statistics for each scale (clockwork and complex). The clockwork category's reliability alpha was improved to .81 as the scale was revised to include: reductive, centralized, small actions-small effects, and predictable as variables.

Validity

Pre and posttest questions for this research were derived from past complexity research of (Bar-Yam, 1997; Casti, 1994a, 1994b; Charles, 2003; Gell-Mann, 1994; Holland, 1995; Jacobson, 2000; Kauffman, 1995; Resnick, 1994). Of the initial nine near and far transfer questions used in prior research pertaining to reductive and complex responses, five were eliminated due to content validity concerns. Schloss and Smith (1999) stated, "an instrument with high content validity includes a representative sample of the skills or concepts being assessed, stimulus features comparable to those found in real situations, and response features comparable to the expected real situations" (p. 112). Since the original questions were exclusively biological or science related (e.g., ants, amoebae cells, cheetahs, butterflies, salamanders, and birds), they were eliminated because of the content or concept lacked an engineering or technological context aligning with the *Introduction to Technology and Engineering* course.

The validity of the four remaining open-ended questions (Appendices D and I) selected from the previous bank of nine were deemed appropriate in that the engineering or technological context matched the construct being evaluated (Schloss & Smith, 1999). Additionally, each technologically orientated question aligns with the ITEA's STL's (2000/2002). The far transfer questions both investigate robots and robotic programming associated with ITEA standards #1, 2, 11, 12, and 18. The near transfer questions include transportation, housing, and design, thereby, lending themselves to numerous technological elements identified in standards #2-6, 8, 10-12, 18, and 20.

Data Analysis

A concurrent form of analysis was selected for this mixed methods triangulation design research study. This method of analysis consists of four primary steps conducted independently for qualitative and quantitative data. Those steps include: preparing the data for analysis, exploring the data, analyzing the data and validating the data (Creswell & Plano Clark, 2007). Following the analysis of both, a merger of qualitative and quantitative datasets provided a more comprehensive picture of all data. As the analysis methods differ for qualitative and quantitative data, a descriptive analysis of each follows separately.

Quantitative Data

An ANCOVA was used to determine group differences with the generation of complex (emergent) and reductive (clockwork) mental models. The ANCOVA was selected because it is a more sensitive test accounting for the group differences existing on the pretest (Cohen, 2001). Selection of the ANCOVA was deemed appropriate as the following assumptions of Cohen's were met:

1. The relation between the covariate and the dependent variable in the population was linear.
2. Homogeneity of regression.
3. The covariate was measured without error. (2001, pp. 590-591)

After carefully balancing the potential impact of Type I or Type II errors, the level of significance determined appropriate for this study was 0.05. This follows convention as stated by Cohen (2001) that "a probability corresponding to .05 is generally considered the largest amount of risk worth taking" (p. 129) but deemed appropriate based upon the selected intervention. As there would be little harm in implementing a software simulation intervention at no cost, the decision was made not to set alpha at .01. Data were carefully analyzed to determine if there were any unusual values, and descriptive statistics were run on the sample using Statistical Package for the Social Sciences (SPSS Version 16 for Windows). Agreement with coding (discussed in next section) was calculated with a two-way mixed interclass correlation coefficient for single measures.

Qualitative Data

A qualitative analysis was completed on three primary forms of data collected for the mixed methods triangulation design research. Data forms consisted of: (a) worksheets from the software simulation intervention, (b) student daily lab reports, and (c) 11 sets of transcriptions from three teams of three students each working within the intervention.

Data entry worksheets provided a numerical output of student decisions working within the simulation. An intraocular analysis quickly revealed trends. Student decisions were investigated to reveal patterns during 10 separate data entry periods, representing 10 decades in the century-long global warming simulation. Trends were investigated based upon two primary elements of interest in complex systems: (a) oftentimes it is better to make no changes to better gauge what is happening over a long time frame (Dörner, 1996), and (b) small changes can have big effects (Charles, 2003; Jacobson, 2000). With that in mind, data were analyzed to reveal student patterns holding factors consistent, over a minimum of 3 decades, or the opposite pattern revealing continuous change on a decade-by-decade basis. A mean of the responses was then generated over three trials. Each trial represented two sessions of the students working in the CO2FX intervention, comprised of a practice session and recorded session.

Student daily logs were analyzed using Glaser and Strauss's (1967) method of constant comparison, and Miles and Huberman's (1994) suggestions for coding qualitative data. All student responses were first read for overall flavor. Next to each line, initial codes were generated. The next step was a sorting of the initial codes to reveal emerging themes. This required several iterations of rereading, analyzing at a finer grain, which provided items with comparable characteristics. Finally, all themes were reviewed to determine whether the coded expressions could be sufficiently reduced and categorized to ensure an appropriate fit.

A challenge to overcome with the recordings of students working in the CO2FX simulation was presented with student pointing to onscreen actions while speaking. On-screen actions were videotaped, including student's pointing and hand gestures, while simultaneously capturing student audio. Transcriptions alone did not capture the essence of all student gestures while participating in the simulation. Determining what a learner knows includes, pointing and gesturing, is addressed by Chi's (1997) verbal analysis selected to systematically "capture the representation of knowledge that a learner has and how that representation changes with acquisition" (p. 274). Chi's eight-step method was used for coding and analyzing data.

1. Reducing or sampling the protocols.
2. Segmenting the reduced or sampled protocols.
3. Developing or choosing a coding scheme or formalism.
4. Operationalizing evidence in the coded protocols that constitutes a mapping to some chosen formalism.
5. Depicting the mapped formalism.
6. Seeking pattern(s) in the mapped formalism.
7. Interpreting the pattern(s).
8. Repeating the whole process, perhaps coding at a different grain size. (p. 283)

Initially, nine sessions of students' working in the simulation were intended to be sampled. However, after reviewing the recorded sessions, it was noted the length of recorded sessions decreased as students became more accustomed to working in the simulation. Therefore, rather than reduce the sample, the opposite decision was made to expand the sample to 11 segments as the earlier recordings provided more data. The extra segments represent the first practice attempt working in CO2FX.

Segmenting occurred during the transcription process at the phrase level for each student. Grain size was based on topics addressing the research question with either emergent-like or reductive characteristics. Developing a coding scheme was the most difficult step due to the open-ended nature of verbal utterances. During the coding scheme selection process, emphasis was placed upon the first half of each decade's data decision and entry periods. Codes were developed which tended to emphasize problem-solving attempts, student inquiries/hypotheses, and indicators of causality. The latter portion of each decade's data entry period, typically, focused upon students stating budgetary decisions, transcribed in mostly numerical form. This provided evidence primarily hidden within the transcripts. Therefore, the data entry worksheets were used to highlight numerical output decisions within the triangulation design.

Operationalizing evidence for coding placed emphasis on determining what utterances provided ample evidence to be coded similarly. As one example, "trial-and-error" approaches to problem solving often led to frequent and dramatic data inputs within CO2FX on a decade-by-decade basis. The output most often was harmful to the global environment of interest. Student comments such as, "let's try this," "I have an idea," "let's see what happens if we…" all fit into the theme coded as trial and error.

Depicting the mapped formalism consisted of a taxonomy of categories represented in a table across the three trial periods. Each trial consisted of two sessions working within the CO2FX simulation due to extraneous factors disallowing the recording of all teams on the same day. For example, a student from one team inadvertently unplugged the computer during one session when they were nearly half completed. This session was then recorded during the next practice session.

Patterns and coherence in the depicted data were next investigated across the three trials. Emergent-like evidence supporting the research question was the focal point. However, disconfirming evidence in the form of reductive answers were sought as well to support quantitative results. The patterns were then interpreted to reveal proportionality amongst themes. A frequency count revealed a disproportionate percentage of responses fitting a singular causality theme, leading to the need to further analyze at a finer grain.

Sample Size Analysis

An a priori sample size analysis revealed the smallest number of subjects needed for a reasonable chance of obtaining significant results with a meaningful effect size was $N = 15$ (Cohen, 2001). This was based upon an effect size of 0.4 and a power of 0.8. Therefore a class with 20 students was sought as it exceeded the minimum N thereby providing room to err on the side of caution.

Procedures

Pilot study

In the month prior to the anticipated research start date, a pilot study was conducted at Rural High School (RHS) in Utah. Students enrolled in the technology education program at RHS were selected because their ETE coursework was comparable to that at MWHS. The purpose of the pilot study was to: (a) conduct student training within the CO2FX intervention, (b) develop a procedure for data entry working within teams, and (c) determine researcher's clarifying questions for verbal protocol methodology on pretest and posttest questions.

Emphasis was first placed upon teaching students to use the CO2FX simulation intervention. Although this software has been designed in a user-friendly gaming environment, there could potentially be issues navigating within a shared learning environment (Gee, 2003). Procedures for navigating the CO2FX intervention were tested during the pilot study. Written instructions were developed for enhanced student performance during the study's data collection phase. Appendix C illustrates the procedures for working within the CO2FX intervention.

A second purpose of the pilot was to determine a procedure for working in teams of three within the CO2FX intervention with a single means of data input. Computer control was investigated since it pertains to teaming concerns when assigning students to roles as economic, policy, and science and technology advisors. A procedure for working within the roles was developed based upon observations and input from students whereby computer control rotated through team members as they shifted from policy to economic to science/technology advisors throughout working sessions in CO2FX.

The final purpose of the pilot was to test clarifying questions within the verbal protocol methodology following the written pretest questions. This lent valuable insights to the student ability to answer open-ended problems, generating CWMM and EFMM responses. Following the written test, participants responded verbally in greater detail to the researchers' clarifying questions and comments. General, clarifying questions and comments to encourage student participation were tested to determine their effectiveness in generating a student response. Clarifying questions to be used included: “tell me more about that”; “what do you think would be required to make this work?”; “discuss how this could happen in the future.” The purpose of these questions was to encourage a student response that may, for some other reason, be limited in written form. Jacobson’s (2001) research with novice and expert differences in complex systems suggests that novice learners may necessitate a cognitive verbal protocol methodology. Answers from the pretest were also used in the training session for the two coding analysts.

Acclimation Period and Pretest

Six weeks into the school year, at the research site, a pretest was administered at the end of the first week of observation. Creswell (1998) stated the need for the researcher to establish a rapport with research subjects. During this researcher’s first week on site, the classroom teacher introduced the researcher and the purpose of the forthcoming research. Parent permission was secured for each participant, and the researcher then spent the first week observing the classroom dynamics and classroom interactions from an outsider’s perspective (Creswell). As part of Creswell’s seven recommended steps for observation, an acclimatization period was incorporated to subtly bring the researcher into the research site. The purpose of this acclimatization period was to reduce the observer effect which “refers to the impact of the observer’s participation on the setting or participants being studied” (Gay & Airasian, 2000, p. 224).

On the fifth day in the research setting, a pretest was administered in written form.

In discussion with the classroom teacher, a determination was made that it would be best to limit the time of response on each question to maintain student focus and assure initial ideas were captured for the follow-up interview sessions. Seven minutes were allotted for each question. The following directions were read aloud to students for each question. “You are not expected to know the ‘real’ scientific/technical explanations; however, you may have some personal ‘theories’ or understanding about the following phenomena. Therefore, please answer these questions using your intuition (best guess) or knowledge from informal learning experiences” (Charles, 2003, p. 302). Students answered in written form one near transfer question and one far transfer question, both of which were read aloud. The pretest questions appear in Appendix D and were presented as follows:

1. (Near transfer). How would you design a large city to provide food, housing, goods, services and so on to your citizens so that there would be minimal shortages and surpluses?

2. (Far transfer). You have probably observed the migration of birds in the spring and fall. Using your intuition, what programming would be required to have robotic birds display a similar behavior resulting in the V-shaped formation that is created by a flock of birds?

It should be noted there was no desired “correct” answer. These questions were ambiguous by design, providing great latitude in student response. A range of student responses was important to determine whether answers indicate reductive or complex (emergent) thought processes. Written responses to pretest questions were analyzed to determine whether a sufficient level of evidence existed pertaining to identifiable complex and reductive responses.

A number of issues may initially hinder student ability to answer pretest questions (e.g., low-level reading ability or difficulty with written response—ability or possibly desire). Relying upon Jacobson's (2000) research, a follow-up data collection in a digitally recorded medium was implemented to gather sufficient pretest data. During this one-on-one session, the students first read their prior response aloud, transcribed and viewable on a computer screen, to assure the essence of their intent was captured. Each participant was asked to elaborate upon his or her answer and, finally, a series of clarifying questions were asked of each participant to encourage them to respond verbally in greater detail to the near and far transfer problems.

A weakness of the verbal protocol methodology, as identified by Jacobson, is that novices may struggle to organize thoughts and respond while speaking aloud. Accounting for this limitation, as well as the fact some students may struggle to generate written responses alone, a combination of Charles' and Jacobson's methods were employed. The initial written portion served as a primer for all students during the follow-up interviews conducted within five to eight days of the written pretest administration.

Coding Analysts Training

Pretest and posttest responses were coded by two analysts. The first coding analyst was a former technology teacher and current Curriculum and Instruction doctoral student at Utah State University. The second analyst was a former science teacher and current Curriculum and Instruction doctoral student at Utah State University. These two individuals were purposefully selected, as their expertise extends across several domains of interest. The majority of previous complex systems research lies within science domains. Along with the technology/engineering domain of interest for this research, both disciplines were represented.

The researcher led a 1-day training session for the coding analysts so they could familiarize themselves with the six component beliefs of interest: ontological perspective, control of system, actions effects, agents' effects, underlying causes, and systems' nature (Charles, 2003). This training consisted of three main components. First, priority was given to understanding complex systems and the two taxonomies used to guide the coding analysts throughout their work. These taxonomies appear in the form of a CWMM for reductive elements (Table 4), and an EFMM for complex elements.

The second training element provided coding analysts an opportunity to explore past student responses (Charles, 2003). A coding example for EFMM follows in Figure 2.

Table 4

Taxonomy for Coding Clockwork Mental Models

Clockwork mental model (CWMM)	Components of coding
Ontological perspective - Reductive	1. Agents act in isolation. 2. Simple stepwise description.
Control of system – Centralized	1. Orders/controls come from outside. Or is within the system but not attributed to the individual agents within (e.g., different agents have different rules: mention of hierarchy).
Action effects – Linear	1. One thing leads to another (e.g., direct link between controller and controlee [i.e., action/reaction]).
Agents' effects – Deterministic (i.e., Predictable)	1. Agents' actions are predictable (e.g., they (it) will perform the action). There is no mention of randomness or chance in their actions.
Underlying causes – Teleological	1. The system knows the end point (e.g., it knows it has to survive).
Systems' nature – Static	1. Explicit descriptions of non-changing system.

Note. Adapted from Charles, 2003.

Example of Coding EFMMs Only

Pretest

Sam: I believe ants must find their food through random
random behavior
wanderings and communication with other ants who have had luck.
chance happenings
They all wander, one finds food, returns with information on its
independent behavior of the individual
location and a number of ants collect it.

Delayed Posttest

Sam: How do Ants find their food? I think that ants go about
finding their food by sending out "scouts", ants that wander
randomly, maybe following paths or general directions in which
Random behavior
they previously found food, maybe not. As these ants walk, I
role of history probabilistic behavior
think they leave a trail of pheromones that they can follow back
to the ant hill. If per chance they find food, they can go back
probabilistic behavior
to the ant hill by following their trail and "stimulate" other
ants to follow it back to the trail of food, all the while
positive feedback – flows
following the pheromone. As for rules and a complex system, I
would think that the simple rule the ants follow involves nothing
much than finding the said food. In other words going out and
Simple rules – algorithmic behavior
perhaps wandering aimlessly until they find the food or run into
an obstacle which would break the randomness, for they would have
to act in response to this new stimulus.
variability
So it's probability I guess, once again. Yeah. Cause the chance
Probabilistic behavior
that they'd wander in one direction might be because of the
weather. Like if it's wet on one side and dry on the other they'd
most likely take the dry side. So the probability that they'd
take one path might lead them to the food.
Probabilistic behavior
S: When looking at the entire system, we would look at the ants,
their goal (food), stimuli (obstacles and weather), which are all
directed by a sense of "chaos" for it is impossible to figure out
where or when the ants will encounter any of these. The ants are
Probabilistic behavior
the components that interact

with their environment and follow general rules, even if those
rules are to wander randomly. The environment, food and stimuli,
only follows the basic rule that it must be present at some place
or another. The system comes together and is organized by the
goal,
Self-organization – goal seeking driven by internal forces
that of finding the food, which is the basic rule to the entire
system. If the ants, don't have a goal the system is unorganized
and the components cannot come together.
Self-organization

Figure 2. Coding example of an emergent framework mental model. Used for coding analysts training session demonstrating emergent-like (complex) responses. (Adapted from Charles, 2003)

The third and final element of the training consisted of coding the pilot study data (see Appendix E). The coding analysts' results were compared to reach a widely accepted inter-rater reliability coefficient of 0.7 as the minimum level of acceptability in social sciences (Schloss & Smith, 1999). Several rounds of coding were necessary to establish consistent interrater reliability results. This work extended outside the one-day session and continued over the following week.

The CWMM and EFMM taxonomies were the primary instruments used by the coding analysts to complete their work. Table 4 identifies the CWMM taxonomy used to distinguish characteristics of each reductive element. The left-hand column comprises the six systems elements of interest. In the right-hand column, descriptions of each element are provided as examples that may be found in student answers.

Along with the CWMM taxonomy, both coders used the EFMM taxonomy for explanations of complex characteristics. Table 5 identifies the complex elements taxonomy. The purpose of Tables 4 and 5 was to provide both coding analysts with tools to distinguish all reductive and complex elements of interest. The taxonomies were used throughout the training session and were retained by the coders throughout pretest and posttest coding.

In addition, a data collection instrument in the form of an OMMT was used to record each student's near and far transfer answers (Table 6). The data-analyzing instrument identifies all six elements, along with a side-by-side comparison of CWMM and EFMM characteristics. Within the right-hand column of Table 6 the coding analysts used a binary system (1 or 0) to indicate presence of attribute (1), or lack of presence (0)

Table 5

Taxonomy for Coding Emergent Framework Mental Models (EFMM's)

Emergent framework mental models (EFMM)	Components of coding
Ontological perspective – Emergent self-organization ontology Question: 1. Does a pattern emerge? 2. Is there a difference between agents and system? 3. What draws the system together?	1. Local interactions among agents; 2. Leads to the creation of something that exhibits a differential behavior than those of the component agents; 3. This interaction is made possible due to some type of identification (tagging device/organizing agent); and 4. Communication (flows of information and/or resources).
Control of system – Decentralized control Question: Who or what initiates the formation of the system?	1. The individual agents are independent of each other, yet they all operate under the same rules.
Action effects – Nonlinear effects Question: Are there feedback loops within the system? Do they amplify or control the outcome?	1. Positive feedback is a feature of these systems therefore small actions can exhibit exponential results.
Agents' effects – Random action (indeterminacy) Question: How do the agents behave before they are part of the system?	1. Agents appear to act in random independent fashion, 2. Also possibly present in answer: 3. Randomness allows for variability and variety within the system.
Underlying causes – Probabilistic causes (Stochastic) Question: Is the same outcome guaranteed each time the system forms?	1. The system organizes itself based on the interactions of the agents as described above, therefore the resulting structure is never certain, rather it is stochastic which implies that there is a probability based emergent pattern. 2. Also possibly present in the answer: 3. Like other probabilistic processes, larger numbers over longer time periods are more likely to result in the formation of normal distributions.
Systems' nature – Dynamic homeostatic nature Question: Is there movement of the agents within the system?	1. Agents may move through, and in and out, of the system. However the system persists in a self-organizing fashion. 2. Once the system, the recurring structure, emerges it exhibits a more stable quality; yet all the component agents have the potential to be replaced by other similar independently operation agents.

Note. Adapted from Charles (2003).

Table 6

Ontological Mental Model Taxonomy

Student Identifier: ________________

Component Beliefs explaining the behavior of phenomena	Response Types	Coded Response
1. Ontological perspective (understanding phenomena)	a. Reductive: step-wise sequences – isolated parts, no mention of interaction.	
Emergent self-organization	b. Nonreductive/emergent: interaction of parts (agents) resulting in patterns or recurring structures at a higher level (system).	
2. Control of system	a. Centralized control (within system) – Each player is given specific and potentially unique rules.	
Decentralized control	b. Decentralized control (within system): Rules are invariant – All players are given same rules but the interactions change the results.	
3. Actions effects	a. Linear explanations: small actions ⟶ small effects.	
Nonlinear effects	b. Nonlinear explanations: small action ⟶ big effect. Inputs and outputs are not proportional and results cannot be assumed to be repeatable.	
4. Agents' effects	a. Completely predictable	
Random actions	b. Not completely predictable / random / chance. Noise within the system may affect the agent's actions.	
5. Underlying causes	a. Teleological – purposeful, goal-directed. The end point is determined a priori.	
Probabilistic causes	b. Stochastic – probabilistic, not goal-directed rather affected by principles of self-organization. The end point is in deterministic.	
6. Systems' nature	a. Static structures or event processes: Not dynamic – elements are discreet in time and space.	
Dynamic homeostatic nature	b. Ongoing dynamic process that self organize thru flows of information & feedback resulting in a state of equilibrium.	

Note. Shaded rows represent Clock-Work Mental Models. Adapted from Charles (2003).

for component beliefs in accordance with the OMMT created by Charles (2003).

Coding

The following analysis procedure was used for each student's response to near and far transfer questions and coded in the following manner. A parsed sentence approach, adapted from Mosenthal and Kirsch (1992a, 1992b), was first used to identify the verb (action), the noun (agent), and the object (agent effect) on student pretest and posttest responses. With the sentence parsing completed, Charles' (2003) OMMT was used to code each parsed statement into one of three possibilities: EFMM, CWMM, or NM. This coding reflected a fine grain analysis of items 2-6 based on attributes unique to each category:

1. A large grain analysis of student conceptions of reality–"Ontological Perspective"
2. Who or what is controlling the system–"Control of System"
3. How do the agents behave at the start of the process–"Action Effect"
4. What are the effects of the agent actions–"Agents' Actions"
5. What is the underlying cause of the system's behavior–"Underlying Cause" and
6. How does the system behave–"Systems' Nature." (p. 48)

Three possible answers existed for each of the six OMMT component beliefs. Complex (emergent-like) responses were coded as EFMM, reductive type responses were coded as CWMM, and a third option existed for answers lacking sufficient evidence of either EFMM or CWMM were coded as NM. Item number one was coded last with a large grain analysis indicative of an overall response that potentially included aspects of items two through six, and additionally represented portions of answers not fitting other categories.

In previous research, Charles determined that the greatest consistency between coding analysts, one which subsequently reduced "order effects," was the coding of each question twice (e.g., first with the CWMM for all responses and then again with the EFMM). Order effects were reduced with one analyst beginning coding with the CWMM taxonomy and the other analyst beginning with the EFMM taxonomy.

Stratification/Assignment

Based upon pretest results, students were stratified and assigned to control and treatment groups. The purpose of stratification was to minimize internal validity conflicts with group differences and "helps ensure that each segment of the population is proportionally represented" (Cohen, 2001, p. 165). Each student was assigned a pseudonym to provide anonymity. Student pretest scores were generated in a list form with highest scores at one end of a continuum and lowest at the other end based upon mean responses generated. An average was first taken of the EFMM responses from the near and far transfer questions. A secondary stratification for students generating no EFMM responses was employed with CWMM in an identical manner since eight students failed to record emergent-type responses to either question. A stratified sampling procedure was used to assign every other student on the continuum to control or treatment groups, thereby, assuring equal group representation of low, middle and high level respondents.

Computational Modeling Intervention

The treatment group received seven complex system simulation interventions. This intervention was a STELLA software simulation modeling a complex global warming scenario that evolved from Fiddaman's feedback complexity in integrated climate-economy models research. "This research builds on earlier system dynamics models of energy economy interactions, creating a model that tests the implications of a number of feedback processes that have not been explored in the climate change context" (Fiddaman, 1997, p. 3). The intervention treatment students received was "CO2FX" which evolved out of a National Science Foundation grant [NSF award number 044133].

> CO2FX is a web based multi-user educational game which explores the relationship of global warming to economic, political and science policy decisions. The game is driven by a systems dynamics model and is presented in a user friendly interface intended for the high school user. (Global Warming Interactive, 2007)

This intervention was selected because it is a multi-player environment that encourages collaboration, replicating the tradeoffs necessary in the "real world" to identify and overcome complex problems with economic, environmental, political and societal underpinnings, all connected in subtle and, oftentimes, unrecognizable manners. Figure 3 displays the interface students worked in while making decisions controlling CO_2 output and minimizing global temperature fluctuations. Students collaborated in teams of three, assuming the roles of economic, policy, or science and technology advisors. Nine decisions were made each decade within the simulation. The simulation began in the year 1960 in the country of Brazil. Each decade, students decided how to allocate finances with budgetary decisions in the following areas: (a) developmental

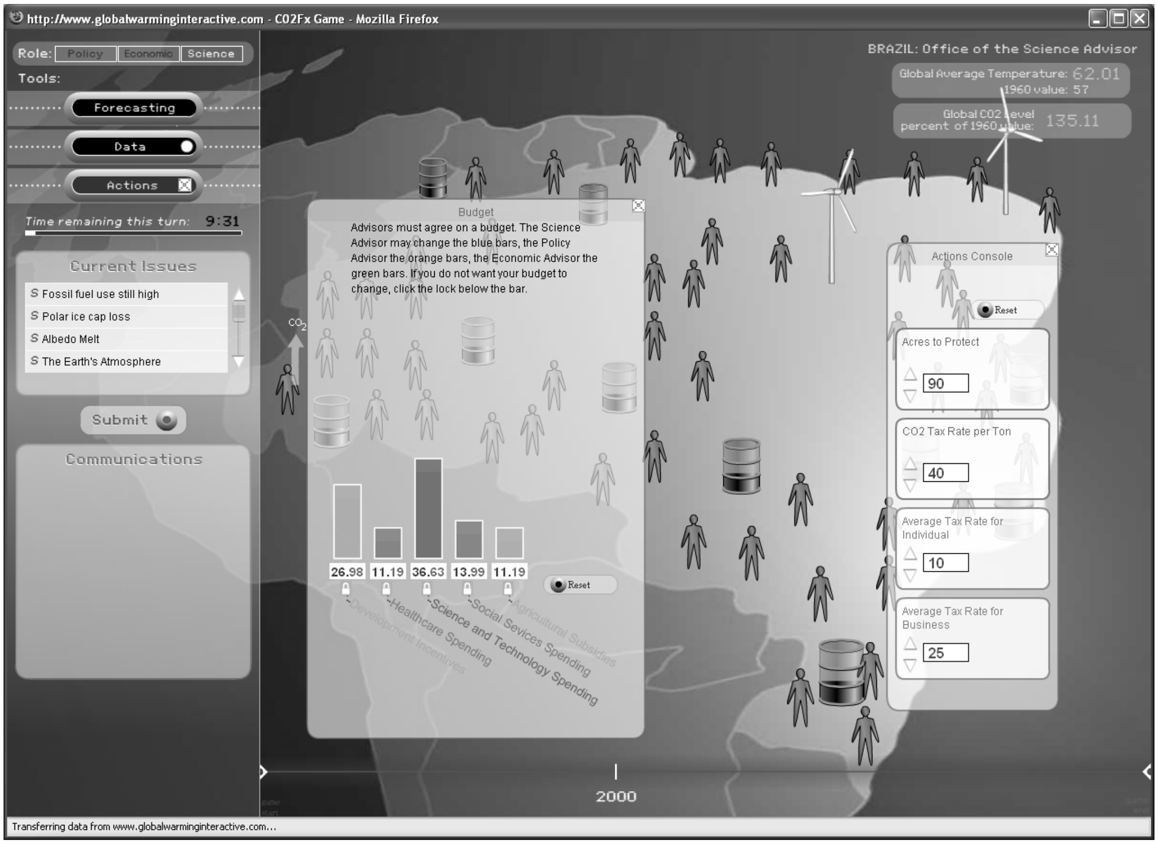

Figure 3. CO2FX simulation screen capture. Economic, policy, and science advisor determine budget allocation and other actions to make over ten decades within the game.

Note. Full page image appears in Appendix F.

incentives, (b) healthcare spending, (c) science and technology, (d) social services spending, (e) agricultural subsidies. See Appendix L for further CO2FX description.

Four additional decisions were made each decade, ending in the year 2050. Within the geographic setting, several important conservation decisions were made each decade. Brazilian rainforests serve an important role within the ecosystem absorbing CO_2 with expansive acreage. The following science decisions regarding the fate of rainforests, as well as policy decisions affecting the Brazilian populace were made decade-by-decade: (a) acres to protect, (b) CO_2 tax rate per ton, (c) average tax rate for individuals, and (d) average tax rate for businesses.

While working within the CO2FX simulation, students recorded each of their decisions into a data entry matrix on paper (Appendix H). Along with decisions made, the simulation provides immediate feedback with policy, economic, and science/technology matters (Figure 4). Students recorded these additional items into their CO2FX data entry matrix:

1. CO_2 output
2. Average life expectancy
3. Popular opinion
4. Unemployment rate
5. Population in millions
6. Fossil fuel remaining
7. Global average temperature

Each team of three students maintained a portfolio with separate data entry worksheets for each simulation attempt. Students frequently referred to past attempts to determine effective approaches to reduce CO_2 emissions, minimize global temperature increases, promote economic growth, and meet the daily needs of the Brazilian populace. The team decisions of the three advisors were ultimately responsible for changes to the environment. One class session simulated 100 years of environmental impact based upon the collective decisions of economic, policy, and science/technology advisors.

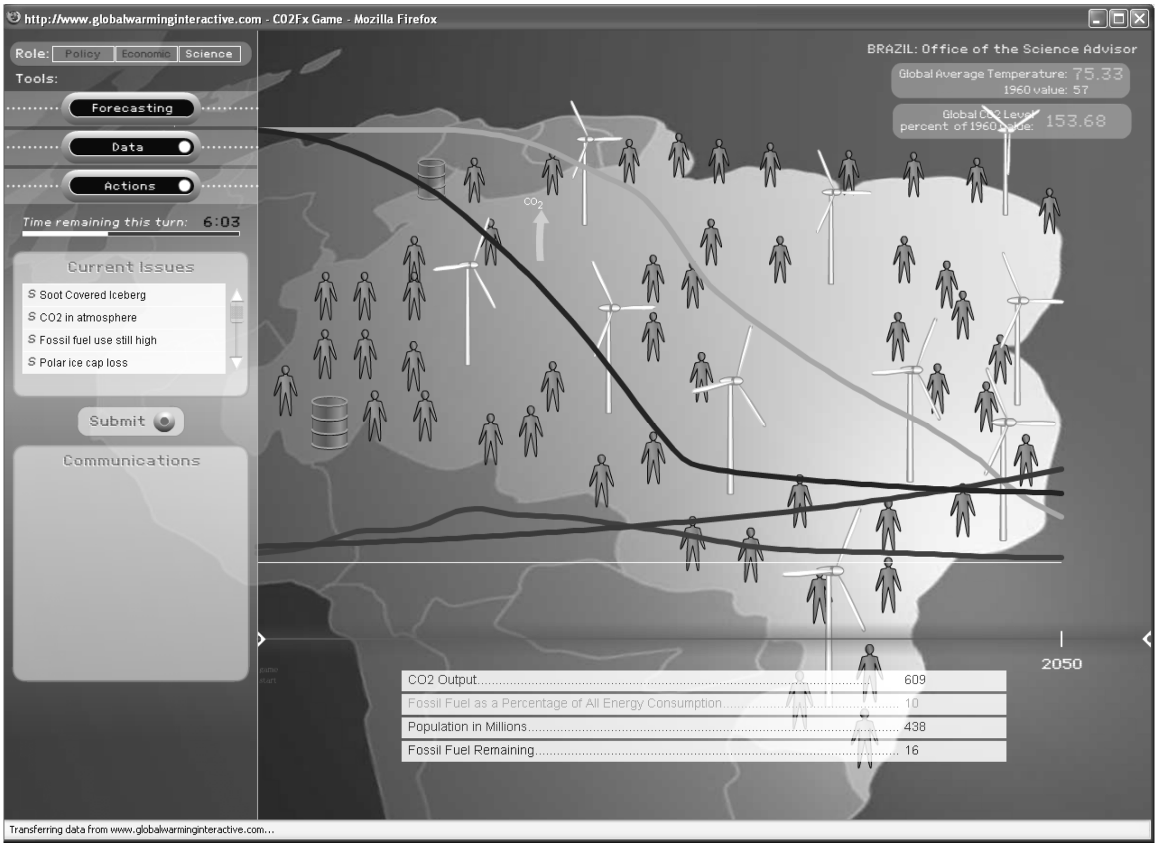

Figure 4. CO2FX forecasting window. Feedback is provided following decisions made within each decade. The line graph provides a visual representation regarding CO_2 output, fossil fuel as a percentage of energy consumed, population in millions, and fossil fuel remaining over the first nine decades within the simulation.

Note. Full page images appears in Appendix G

Video Segments Supplement

All students viewed seven video segments about the complexity of global warming in a DVD format with a video titled *Global Warming: What's Up With the Weather*? (FRONTLINE/NOVA, 2007). This video was selected because it aligned with the school district's power standard for Technology and Engineering Education stating that students will understand that technology affects society and environment in ways that are both planned and unplanned and desirable and undesirable. Within this video, the complexity of global warming issues was presented in a point/counterpoint format with scientists presenting current data and skeptics countering scientist claims of data supporting global warming. Complex interactions in the form of the interrelationship between cultural, economic, environmental, political, and societal happenings were evident throughout the video. Video clips were played at the beginning of class throughout intervention administration. The order of video clips is listed below.

Day 1: Introduction and What Does Science Know?

Day 2: Forensic Climatology

Day 3: How the Greenhouse Effect Works

Day 4: The Role of CO_2

Day 5: Forecasting a Century of Change

Day 6: America's Relationship with Energy

Day 7: Energy Alternatives

After each video clip was played, students in the control group accompanied Mr. Fenn into an attached laboratory for daily assignments. Treatment group participants remained in the classroom completing their assignments within the computer simulation environment

Intervention

Intervention Day #1

All students watched the first two video segments (12:08 elapsed time) of the global warming video that would be incorporated throughout the intervention. Students were placed into control and treatment groups based upon stratified random assignment from pretest questions. Control group: Worked in teams with electronics module for HyPPO (Hydraulic and Pneumatic Power-Operated) robots learning about amps, ohms, and volts as electrical measuring units. Treatment group: CO2FX intervention was introduced by examining data entry of 3 decades and with students becoming familiar with the data entry worksheet. Students investigated data entry within the simulation and operation through multiple windows.

Intervention Day #2

All students watched the forensic climatology segment of the video (9:16 elapsed time). Control group: Investigated why ohms are important relative to voltage and resistance in the development of an electromagnet for their HyPPO robot. Treatment group: Worked within CO2FX simulation for the first time. The practice session was recorded for all three groups. A test was conducted to determine the feasibility of gathering sufficient audio from three groups, simultaneously, factoring in group placement and technical issues with microphones. Students were encouraged to explore selections within the game that would provide further information. For example, the *Current Issues* window has over a dozen ever-changing selections pertaining to economic, policy, and science/technology issues throughout the game.

Intervention Day #3

All students watched how the greenhouse effect works segment of the video

(10:07 elapsed time). Control group: Investigated the relationship between voltage and resistance in order to reduce amperage as it pertained to HyPPO robot needs. Intervention group: Completed first recorded session of CO2FX global warming simulation. Students were encouraged to complete the 100-year-long simulation. Teams of students had 35 minutes to work within the simulation, similar to the control group, working in the laboratory with robots.

Intervention Day #4

All students watched a video segment on the role of CO_2 (10:36 elapsed time). Control group: Worked in teams to discuss and investigate the purpose of the robotic arm as it relates to the end of semester HyPPO robotic competition. Investigation of the movement and capabilities of the arm to maximize its ability to collect balls with an electromagnet was emphasized. Treatment group: This day was described as a practice day leading up to the following day's recorded session. Students were encouraged to explore new options and possibilities as they attempted to minimize the global average temperature while completing the century-long simulation.

Intervention Day #5

All students watched forecasting a century of change video segment (15:34 elapsed time). Control group: Investigated limitations of robotic arms based upon syringes that would be used to supply either pneumatic or hydraulic power for HyPPO robots. Treatment group: Teams of students were recorded completing a century-long session in CO2FX. One team of students experienced computer malfunction at 1960 data entry period throughout class period and was recorded during following intervention session.

Intervention Day #6

All students watched video segment on America's relationship with energy (12:54 elapsed time). Control group: Investigated pneumatics with 6 milliliter (ml), 12 ml, 20 ml, 35 ml, and 60 ml syringes and tubing of different sizes exploring power and pressure relationships. Treatment group: This day was introduced as a final practice session to explore new possibilities to minimize the global average temperature in CO2FX simulation. Students were encouraged to investigate different options prior to the upcoming final recorded session. Team that struggled with computer issues on prior attempt was recorded.

Intervention Day #7

All students watched the final video segment of the intervention period on energy alternatives (14:45 elapsed time). Control group: Investigated differences between hydraulic and pneumatic power for the appropriate selection with HyPPO robots. Most students noted they would select hydraulic power for their HYPPO robots since air molecules are compressible, while water molecules are not. Treatment Group: Final recorded session of team work in CO2FX was completed with same goal of controlling the overall global average temperature.

Posttest

The posttest format followed the same procedure as the administration of the pretest. Students were once again read the directions and questions aloud. They were provided with one open-ended near transfer problem and one open-ended far transfer problem and allotted seven minutes to write answers for each question. The posttest (Appendix F) consisted of the following questions.

1. (Near transfer). How would you explain the formation of traffic jams? Are there rules that would direct this type of activity?

2. (Far transfer). Suppose large deposits of gold are discovered on a distant planet. It is too dangerous and costly to send human astronauts to this planet, so we decide to send a spaceship with several thousand small robots. Each robot has a sensor to detect when it gets near gold and a scoop to dig for and carry the gold. Once the spaceship lands on the planet, we want the robots to explore for gold and bring the gold back to the spaceship. How should we program each of the robots? In other words, what type of rules and strategies should the robots follow?

The same administrative procedure implemented with the pretest was utilized with the posttest. Students, initially, responded in written form and a follow-up with a cognitive verbal protocol methodology was used to complete their responses. By doing so, students of all ability levels were provided an opportunity to demonstrate their understanding of mental model generation as thoroughly as possible.

Research Timeline

Table 7 provides a synopsis of the research tasks completed on a week-by-week basis. The coding analysts work occurred at a location away from the research site, but is noted as it was a prerequisite for random stratification assignment. A break occurs following Trial #1 of the CO2FX intervention prior to Trials #2-3 accounting for a period of time in which students were off limits to the researcher per instructor's request.

Summary

The purpose of this mixed method, experimental research study was to determine whether exposure to, and subsequently working within, software simulations increases the likelihood of high school student recognition of underlying patterns and elements of

Table 7

Research Timeline at Mid-Western High School

Week #	Dates	Task
1	10/01-10/04	Classroom observation and written pretest administration
2-3	10/08-10/19	Student interviews and transcription of digital audio
4-5	10/22-11/02	Analysts code pretest written/verbal responses
6	11/05-11/09	Random stratification assignment & CO2FX troubleshoot
7	11/12-11/16	CO2FX demo and Intervention Trial #1: Sessions 1/2
8	11/19-11/23	Thanksgiving break: no in-school research
9	11/26-11/30	Teacher's only full week w/ students in Nov: no research
10	12/03-12/07	CO2FX intervention trial #2: Sessions 3/4
11	12/10-12/14	CO2FX intervention trial #3: Sessions 5/6
12	12/17-12/21	Administer written posttest & begin student interviews
13	01/07-01/11	Student interviews and transcription of digital audio
14-15	01/13-01/25	Final observations and analysts posttest coding

complex systems. The research investigates the generation of mental model responses to near and far transfer questions with complex and reductive characteristics. Previous research has indicated the likelihood that recognition of complex systems elements leads to the ability to transfer more effectively information to new settings.

CHAPTER IV

RESULTS

Description of the Sample

Table 8 contains the demographic data for the study sample from the *Introduction to Technology and Engineering* course. The sample (*N* = 18) consists of freshmen from a suburban, Midwestern high school. Seventeen students were male (94.2%), and one was female (5.8%). Ethnic diversity in the study consisted of one Asian student (5.8%), two Black students (11.1%), two Hispanic students (11.1%), and 13 White students (72.2%). This constitutes a representative sample of the larger school population. Demographics reported by the school district for the 2007-08 school year consist of 4.9% Asian, 11.7% Black, 5.0% Hispanic Origin, 0.6% American Indian, and 77.8% White students within

Table 8

Demographic Data for Freshman Level Introduction to Technology and Engineering Class

Categories	Sample (*N* = 18)	Control (*n* = 9)	Treatment (*n* = 9)
Gender			
Female	1 (5.8%)	0	1
Male	17 (94.2%)	9	8
Age			
14	10 (66.7%)	5	5
15	8 (33.3%)	4	4
Race/Ethnicity			
Hispanic	2 (11.1%)	0	2
Asian	1 (5.8%)	1	0
Black	2 (11.1%)	1	1
White	13 (72.2%)	7	6

the school district. Comparing control and treatment groups in Table 8 identifies samples with similar characteristics following a stratified random sampling procedure for assignment. Each group had an equal percentage of 14-year-old students (44.4%) and 15-year-old students (55.6%). Additionally, the composition of each team relative to ethnicity demonstrated a similar pattern of representation. Composition of the control group was 11.1% Asian, 11.1% Black, and 77.8% White students. The treatment group was comprised of 22.2% Hispanic origin, 11.1% Black, and 66.7% White Students.

Throughout the intervention, students worked in teams of two or three students. Following random assignment, it was noted that students of minority populations were dispersed in such a manner that not more than one was on any given team. The same does not hold true for majority population students. With 72.2% of students fitting this demographic, multiple teams consisted of two or more White students. Additional information collected in the demographic survey related to student time spent computer gaming outside of school. Students were asked to report how much time per week was spent gaming. Options to select included zero hours for students who did not play computer games up to 25+ hours. Increments of five hours comprised the remainder of the choices. Figure 5 reveals student reported hours per week spent computer gaming.

Only two students (11.1%) reported they did not use computer games outside of school. Both students, one each male and female, were in the control group. The largest percentage of students (72.2%) spent between one and 5 hours per week gaming, seven control group and six treatment group students. Almost 17% (16.7%) of students reported 6-10 hours per week gaming, two control group and one treatment group student. Finally

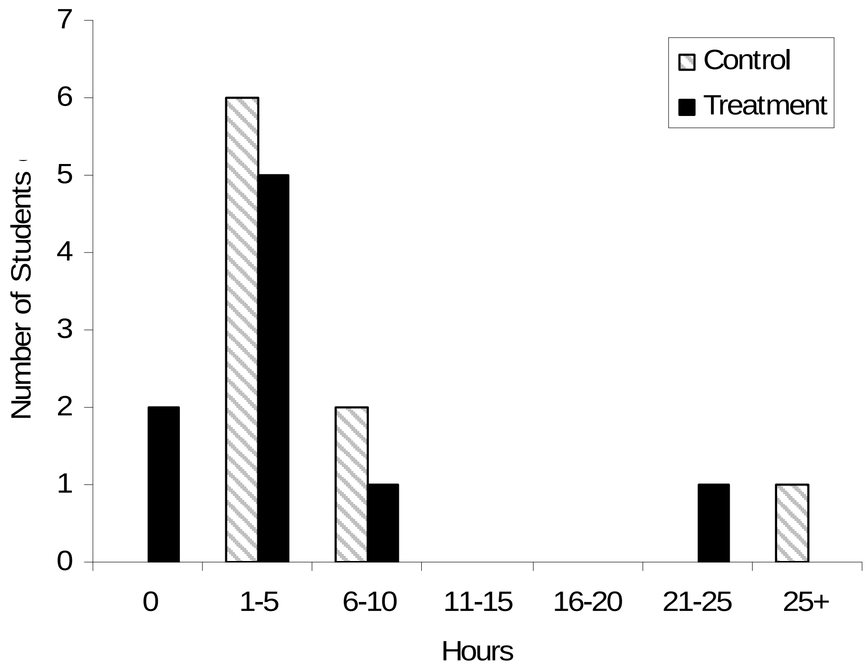

Figure 5. Reported hours per week students spend computer gaming.

one student each (5.5%) reported spending 21 to 25 hours gaming (treatment group) and over 25 hours per week (control group).

One last item reported on the survey pertained to the use of the CO2FX computer simulation outside of school. This game was available online, and any student could access it if they desired. Due to external validity issues related to the generalizing to a larger population, students were asked to report on this item. Only one student reported accessing the CO2FX simulation outside of school. This was a treatment group student who reported spending two hours playing the game. Based upon student reports, it appears any potential external validity threats due to diffusion are negligible.

Results Relevant to Research Question

Interrater Reliability

An item analysis was completed for each of the OMMT component beliefs following the analysts' pretest and posttest coding. The analysts compared their individual coded segments for each student's pretest questions in October and followed the same procedure in February with posttests. A procedure was established whereby the analysts compared coded responses, student-by-student, to gauge each analyst's understanding of the twelve items. Where differences of opinion existed, the analysts negotiated for agreement. A percent agreement of 90% was established as the baseline to meet. On the pretest, the coding analysts agreed on 369 of 408 items (90.4%), and on the posttest, agreement reached 384 of 432, (88.9%).

A reliability coefficient was then calculated with Cohen's Kappa. Table 9 displays the results with a pretest Kappa of 0.77 and a posttest of 0.69. The overall Kappa calculated (pretest and posttest) was 0.73, thereby exceeding a widely accepted reliability coefficient of 0.7 as the minimum level of acceptability in social sciences (Schloss & Smith, 1999).

Near Transfer Question

A one way analysis of covariance (ANCOVA) was conducted for each of the three dependent variables: EFMM, CWMM, and NM. The independent variable was complex systems instruction. A preliminary analysis evaluating the homogeneity-of-slopes assumption indicated that the relationship between the covariate (pretest) and the

Table 9

Cohen's Kappa Reliability Coefficients for OMMT Component Beliefs

	Pretest		Posttest	
Item	Q1	Q2	Q1	Q2
Reductive	1.00	.76	.56	.78
Nonreductive	1.00	1.00	1.00	.68
Centralized	.76	.75	1.00	.75
Decentralized	1.00	.77	.51	1.00
Linear	1.00	.64	.56	.48
Nonlinear	1.00	1.00	.61	.73
Predictable	.07	.64	.37	.87
Nonpredictable	1.00	1.00	1.00	.62
Teleological	.46	.23	-.06	.77
Stochastic	1.00	.30	.75	.87
Static	.43	1.00	.46	1.00
Dynamic	1.00	.67	.31	1.00
Ave. Kappa/Question	.81	.73	.59	.80
Total Kappa	Pretest	.77	Posttest	.69

dependent variables did not differ significantly as a function of the independent variable, CWMM: F (1, 13) = 0.63, p = .43, partial η2 = .05; NM: F (1, 13) = .01, p = .92, partial η2 < .01; EFMM: F (0, 15) = N/A, p = .N/A, partial η2 < .01. It should be noted that no students in either group provided EFMM responses on the pretest, thus, no *F* or *p* data were generated.

The ANCOVA (Table 10) was not significant for EFMM: F (1, 15) = .29, *p* = .60. However, group significance was found in CWMM: *F* (1, 14) = 7.37, *p* = .02 and NM: *F* (1, 14) = 7.36, *p* = .02. The strength of relationship between the complex systems instruction and CWMM or NM was very strong, as assessed by a partial η2, with the

Table 10

ANCOVA for Near Transfer Question

Source (Q1)	Type III sum of squares	*df*	*F*	Sig.	Partial η2
Emergent-like (EFMM)					
Intercept	21.57	1			
Pre-EFMM	0.00	0	-	-	0.00
Group	.57	1	.29	.60	.02
Error	30.19	15			
Clockwork (CWMM)					
Intercept	1.12	1			
Pre-EFMM	2.77	1	2.90	.11	.17
Group	7.02	2	7.37	.02	.35
Error	13.34	14			
No model (NM)					
Intercept	1.11	1			
Pre-EFMM	9.98	1	4.99	.04	.26
Group	14.72	1	7.36	.02	.35
Error	27.99	14			

method of instruction accounting for 35% of the variance of the dependent variables. With the control group producing twice as many clockwork responses as the treatment group, it is possible the method of instruction could lead to causal relationship thinking lending itself to group differences. However, the treatment group produced twice as many NM responses and fewer CWMM and EFMM responses. As this research is primarily interested in emergent-type thinking, the empirical evidence does not indicate notable significant differences.

The means for the EFMM generated adjusted for initial differences did not differ significantly between groups (Table 11). The EFMM adjusted means for the control (*M* = 1.31) and treatment (*M* = 0.94) provide no evidence regarding outcomes based upon method of complex systems instruction. Group differences were noted with CWMM and NM categories. The NM category had the largest adjusted mean in the treatment group (*M* = 4.01). With six component belief categories, this result demonstrates group responses lacking evidence in four of the six measurable component beliefs. The control group generated the most responses with CWMM reporting an adjusted mean (*M* = 2.37). Of the six OMMT component beliefs, there is a tendency in the control group to rely upon reductive thought processes.

Figure 6 provides a visual depiction of the mental model adjusted means by group. Included is the standard error which provides an estimate of the difference between the measured and true means. Mean responses are provided on a 4-point scale,

Table 11

Near Transfer Question Estimated Marginal Means

			95% confidence interval	
Dependent variable/group	Mean	Std. error	Lower bound	Upper bound
EFMM				
Control	1.31	.50	.24	2.38
Treatment	.94	.47	-.06	1.95
CWMM				
Control	2.73	.39	1.89	3.58
Treatment	1.29	.36	.52	2.06
NM				
Control	1.97	.58	.72	3.22
Treatment	4.01	.53	2.87	5.15

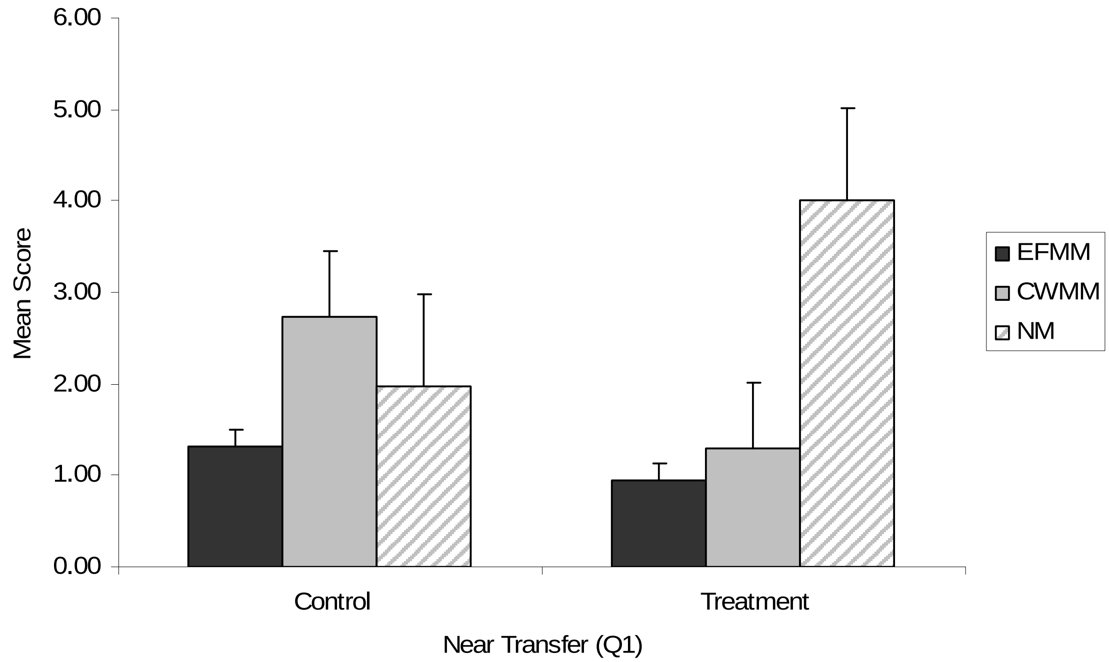

Figure 6. Comparison of posttest, near transfer mental models generated.

representative of the six possible component beliefs. This figure displays student responses demonstrating more reductive thinking instead of the emergent-like behavior of interest in this research. Perhaps, most noteworthy is the disproportionate response rate within the treatment condition with NMs generated.

Qualitative Results

Quantitative results from the ANCOVAs were supported by three forms of qualitative data. Patterns of reductive-type actions and thoughts were evident within transcriptions of students working in CO2FX, in data entry worksheets capturing budgetary decisions, and in the student daily lab reports. A pattern emerged displaying a focus upon individual elements within the simulations. Frank (2005) explained this analytical focus as, “the traditional approach in engineering and technology teaching [which] is bottom-up, i.e., component to system” (p. 20). An analytic or reductive approach addressing the global warming scenario by the treatment group is not all that surprising as it represents the primary approach to schooling.

Transcriptions from students working in the simulation captured actions, gestures, and verbal utterances in eleven recorded sessions. Information from these sessions was subdivided into three trials. Each trial consisted of two sessions working within the CO2FX simulation. The first session was a practice attempt in which students were encouraged to attempt new strategies, attempting to minimize global warming. The second session was designed to capture all gestures (e.g., finger pointing towards the computer screen and verbalizations with digital videotape). Triangulated data sources from each trial consisted of CO2FX data entry worksheets from both sessions, student daily lab reports for both days, and a transcription from the recorded session.

Coding and theme development in the transcriptions and daily reports revealed evidence of reductive-type behavior across all three trials. Table 12 presents a comparison of the three forms of qualitative data. Emerging themes within the transcripts and daily lab reports provide reductive and emergent-like evidence. Across the three trials, an initially surprising trend revealed a decrease of emergent-like themes. The opposite was expected. This, however, can be largely explained with a significant reduction in the spoken statements by students within subsequent simulation attempts. It appears that as students gained a comfort level with the simulation, they settled into an established pattern with unspoken roles. The third and final form of data, CO2FX worksheets, was used to quantify and represent the decisions of teams with a fine grain analysis, decade-by-decade. No change, or very small change, within any budgetary decision (e.g., social services or healthcare spending) represents characteristics displaying emergent-like qualities. Larger data input decisions (i.e., 5% or greater change is indicative of reductive-type behavior).

Triangulating the data sources revealed a predominance of reductive-type behavior early in the trials, giving way to patterns of emergent-like behavior following the final attempt. Although the transcripts themes do not initially tend to support this statement in Table 11, an analysis of CO2FX worksheets demonstrated that the actions of

Table 12

Qualitative Triangulated Data Sources: Coded Themes Across Three Trials

Data forms	Trial 1	Trial 2	Trial 3
CO2FX student transcripts (themes)	Singular causality trial and error tradeoffs Big change = Big effect **Change Over Time** **Additive Effects**	Singular causality trial and error tradeoffs	Singular causality trial and error (or) experimentation
CO2FX student worksheets (mean responses)	Large input = 17.67 **Small input = 15.67** **No change = 5**	Large input = 12 **Small input = 18.33** **No change = 8**	Large input = 12.33 **Small input = 26.33** **No change = 10.33**
Daily lab reports (themes)	Singular causality trial and error rational **Small change = Big effect** **No change**	Singular causality emphasis upon controllable events **Averages/small input** **Circular causality**	Singular causality tradeoffs applied knowledge **Balance variables**

Note. Words identified in bold letters represent emergent-like characteristics. Regular text represents reductive traits.

students speak louder than their transcribed words. Evidence of this claim will be supported in the following far transfer question section with support from Trial #3 as the nature of reductive behavior exhibited in Trials #1-#2 reinforce the ANCOVA's pertaining to the near transfer question.

Trial #1

A majority of the comments made during the first trial were cause-and-effect statements focusing upon singular elements. Dörner (1996) stated:

> In complex situations it is almost always essential to avoid focusing on just one element and pursuing only one goal and instead to pursue several goals at once. In a system complicated by interrelationships, however, partial goals often stand in contradictory relation to one another. (p. 64)

Reductive-type behaviors coded from the transcripts tended to substantiate Dörner's claim. Qualitative themes of singular causality, trial and error, tradeoffs, big change = big effects emerging from the data all exhibited cause-and-effect characteristics at the component level.

Singular causality. Evidence of cause and effect relationships was evident from individual student's claims and from interchanges between teammates. As Jamie and Wyatt completed their first attempts in the CO2FX simulation, they demonstrated an emphasis upon singular causality with these statements.

Jamie: There are too many people, so we need less healthcare.

Wyatt: You want to keep the science and technology, because that's how we got the windmill

Causality claims in the first trial were evident from individual student's statements such as Jamie and Wyatt and during team's dialogue exchanges as follows.

Guillermo: Alright let me do this. Science … [drags budget lower on screen]

Jamie: Wait what was so high that we got so many more windmills? Do you think its development incentives or agricultural subsidies?

Wyatt: No, it's social services spending.

Jamie and Wyatt's initial statements provide classic examples controlling one variable with another. An interchange between all three teammates further illustrates how the teammates attempt to gain more windmills with a strict focus upon a budgetary allocation to one area, albeit with the mention of three different areas of interest. A team comprised of Nathan, Blake, and Ramon disagreed on how to increase the popular opinion of the Brazilian citizenry with an exchange about an average tax rate to assess. However, this, too, focuses upon one component to bring about the desired change.

Nathan: That's not going to raise our popular opinion you know.

Ramon: Yes it will, yes it will. Just do it [value begins to be reduced].

Nathan: Average tax rate per individual is not going to do that.

Although not emphasized, decisions regarding budgetary allocations with agricultural subsidies or social services and healthcare spending could just as likely complement Ramon's singular focus upon lowering the individual tax rate to increase popular opinion. However, even this focus upon a single entity is counterproductive when addressing issues in a complex system. Finally, the team of Jackson, Matt, and Nadine displayed singular causality traits with their emphasis on reducing the use of fossil fuels.

Jackson: So we just got to do something about unemployment. Holy cow we are using a lot of fossil fuel.

Nadine: That's why we should do more science and technology, shouldn't we?

Daily lab reports lend further evidence regarding student reliance upon causal relationships. Reflections from the first practice attempt (11/15/07) emphasize societal troubles and problems Jamie and Blake encountered. Additionally, Jamie references his concerns with oil usage. Jackson more clearly emphasized a cause-and-effect relationship between fossil fuel usage and its relationship to global average temperature.

> Jamie: We played the Brazil game and had trouble with unemployment and with the population increasing. Oil was being used a lot.
>
> Blake: My group and I did the entire simulation with a little bit of creativity for the last two decades. Some of our main problems were popular opinion and unemployment.
>
> Jackson: Although we tried very hard to make sensible decisions our temperature kept increasing and fossil fuels decreased.

Trial and error. Singular causality was additionally represented with thematically coded samples as: trial and error, tradeoffs, and big changes = big effects. Students most often relied upon trial-and-error methods of inquiry, especially during early attempts in the simulation. This method is not surprising since technology education tends to emphasize problem solving in an iterative manner. Thode and Thode (2002) suggested the following steps in a typical problem solving loop:

1. Identify the problem,
2. Explore possible solution ideas,
3. Select an idea,
4. Test the idea,
5. Evaluate the results, and
6. Retry (if necessary).

Using an approach comparable to this would lead students working in a simulation to move quickly through these steps. Trial-and-error approaches within the first trial were typified by “let’s see what happens” statements, as demonstrated by the teams of Jamie, Guillermo, and Wyatt, as well as by Nadine, Matt, and Jackson.

Jamie: Dude, let’s see what happens. I want to put science at like 50 [percent of budget allocation] let’s see what happens

Guillermo: Tax everybody dude, put businesses all the way up (to a maximum tax rate of 100%)

Wyatt: Yeah, let’s see what happens.

Nadine: Holy crap, look at our CO_2 output.

Jackson: Oh my gosh, how much did it go up?

Nadine: We went from 5000 to 11000.

Jackson: Ohhh, we went up 6000. How the heck did we do that?

Matt: (sarcastically) We’re geniuses.

Jackson: Okay, agricultural subsidies. I’m boosting … let’s see what happens when I boost this.

“Let’s see what happens” approaches tended to result in rather dramatic changes in Trial #1 attempts. As small changes can bring about large effects in complex systems, such gut-feel approaches tend to bring about undesired results. Trial-and-error approaches are guided by one’s intuition. Dörner (1996) stated that this intuition is based upon a “reality model” of which the student may or may not be consciously aware. “A reality model can be explicit, always available to the individual in conscious form, or it can be implicit, with the individual himself unaware that he is operating on a certain set of assumptions” (p. 41). Implicit reality models bring about situations whereby students cannot articulate their assumptions, yet guide their approach. Ramon illustrates this "operating by intuition" approach, much to the displeasure of his teammates.

Blake: Okay, next one. Our unemployment is still up though, so, maybe if we dropped social services that will make it…

Nathan: No, dude.

Ramon: Maybe if we make science 99 [percent], I have a feeling.

Blake: Stop doing that

Ramon: No, dude, I have a feeling.

As the conversation within this group continued, a distinction between trial-and-error approaches for Trial #1 and later sessions became apparent. During this trial, students assumed ownership of their given roles. In this capacity, there is limited give and take between advisors. This leads to contentious debate, which hinders progress mitigating global temperature fluctuations.

Nathan: Alright, what do you want to do? What do you want to do? [Pointing at science/technology budget allocation bar]

Ramon: As high as it can go.

Nathan: Dude, it can go to 100 alright, but it's NOT gonna happen [as bar is dragged to maximum value]

Blake: I don't think that's a very good idea.

Ramon: 99 [percent budget allocation], it's my choice.

Nathan: No, dude, we gotta [begins dragging bar back down]

Ramon: Fine, 56 [percent budget allocation].

Nathan: 55 [percent budget allocation].

Blake: Yeah, I don't think we need to lock that.

Ramon: FINE, then put it on 99 [percent budget allocation], and don't lock it.

Nathan: [begins to move pointer to actions console decisions]

Ramon: Hold on, hold on.

Nathan: NO, dude.

Ramon: I'm not going to put it at 100 [percent], I'm just … [drags budget bar up] and then… [Begins to increase acres to protect] 28… [Begins to lower CO_2 tax rate per ton]

Nathan: Why are you doing that?

Ramon: I don't know. Something different. Maybe it will save the world. You never know.

Blake: No, it's going to kill us all

Just as Ramon argued for control of his advisor role decisions, Jamie demonstrated the same strong-willed intention as he debated budgetary decisions with Guillermo. Disregarding input from peer advisors indicates that students failed to recognize the economic, social, and political complex interrelationships. A focus at the component level in the following exchange illustrates traditional reductive approaches.

Guillermo: Do 30 [percent tax rate], dude put it down for businesses.

Jamie: No this is for you. Individuals have to pay 25 [percent]. Business's is like a whole business, have to pay 30 [percent tax rate]

Guillermo: But that's going to drop down.... That's going to drop down the employment.

Jamie: Okay, fine I will put this to 20 [individual tax rate] and let me put this one at 10 [business tax rate].

Guillermo: Put that at 30 [individual tax rate] that's going to get less people.

Jamie: No, I'll put it at [clicks down to 15].

Guillermo: That will, that will…. (Reaches for control of mouse to raise rate).

Jamie: No, this is good.

Guillermo: NO, no it's like more people.

Jamie: [turning to Guillermo-forcefully] NO, IT'S MY SECTION. I can do what I want.

Guillermo: More people.

Jamie: I CAN DO WHAT I WANT!

Guillermo: It's your fault if our population keeps going up.

Jamie: No, it ain't my fault. I'm the policy person, not the economic.

Guillermo: Yea but…

Jamie: Fine, I'll put it to 20 [individual tax rate].

Guillermo: [pointing to screen] 25, 25.

Jamie: No 20, I'm putting 20.

Guillermo: PLEASE.

Jamie: I'm putting 20. 20 is as high as I'm going.

Wyatt: We arguing?

Guillermo: It's called debating, okay? We're trying to save Brazil up in here and this kid is trying to ruin it by increasing our population. It's not good, not good.

Tradeoffs. As students struggled to control CO_2 emissions, they began to place a greater emphasis upon individual elements. Oftentimes, this tended to focus upon popular opinion, population, and employment matters. All of these issues are important to promote economic growth while balancing societal concerns. However, as teams focused on such matters, it was often to the detriment of the environment, as gauged by CO_2

output and the average global temperature. When teams recognized this, often they became quite animated while addressing the initial goal placed upon them by the researcher. Meeting this goal of minimal global temperature fluctuations resulted in tradeoffs sacrificing societal and economic concerns over those of the environment. Statements by members of two teams illustrate as follows.

Guillermo: Let's make our people happy [reduces individual taxes to zero].

Jamie: (Sarcastically) Yeah, forget the Earth.

Guillermo: Look at our popular opinion though, it's…

Jamie: WHO CARES dude? You just screwed the Earth over.

Blake: Our CO_2 output dropped by like 1700, which is good. Our people are living two years less though.

Nathan: Who cares?

Ramon: Who cares about the people (laughs)?

Nathan: We just want to save the world here.

Balancing tradeoffs to address student concerns as economic, policy, and science/ technology advisors within the simulation frequently resulted in the use of either sarcasm or humor, as noted in the examples. Students seemed to rely upon such approaches during early attempts in the simulation as they took ownership of their individual roles. However, a strict focus upon factors associated with their roles was often detrimental to the bigger picture environmental concern. As teams proceeded through the series of simulation attempts, their verbal interchanges became less frequent. Individual roles began to evolve into a "team" dialogue, resulting in fewer spoken statements.

Big change = big effect. One characteristic of complex systems is that small changes can have big effects. If small changes have big effects, big changes made during Trial #1 would potentially have even larger effects. Singular causality was displayed in numerous forms during early attempts, oftentimes, through trial-and-error, problem solving approaches. Attempting to “see what happens” if a certain variable is adjusted led to students’ making dramatic changes, presumably to bring about a noticeable change more rapidly. Each of the three teams provides an example of large changes.

Jamie: We’re totally putting 100 down [business tax rate percentage].

Guillermo: Put it down to zero then everybody can be…

Wyatt: Put both of them at fifty [individual and business tax rates].

Guillermo: Everybody can be working.

Blake This time [begins to reduce science budget allocation]…

Ramon: Put it on zero. Do something extreme or something.

Blake: Yes, bring sciences down to nothing because I think we have…

Ramon: Yeah bring it down like a lot.

Matt: CO_2 [tax rate per ton] we should jack that up. I’m talking like 50 (begins clicking to raise rapidly, meeting maximum allocation at 40%).

Jackson: 40, you can’t go any higher.

Matt: Dang it.

Jamie, Guillermo, and Wyatt discussed how to reduce a runaway unemployment rate by adjusting an unheard of business tax rate of 100% down to either 50% or 0%.

Knowing that small changes can bring about large effects, their approach certainly would cause dramatic change within a complex system. All teams explored options to raise values to their extreme during Trial #1 attempts. When they failed, alternative approaches frequently included the opposite extreme resulting in budgetary decisions reduced to 0.

Transcripts coded from Trial #1 revealed 78% (95 of 116) thematically coded statements demonstrating reductive-type characteristics. The remaining coded statements (22%) exhibited emergent-like characteristics of some form. During Trial #1, attempts reductive in nature causality traits existed simultaneously with complexity elements. Emergent-like themes were coded as change over time and additive effects.

Causality claims fitting thematic coded segments as trial-and-error, tradeoffs and big change = big effects were supported within student daily lab reports during their first recorded session on 11/16/07. Jamie reflected upon his team's trial-and-error approach emphasizing increased budgets to determine outcomes with the challenge, then upon predicting a singular category to focus upon. Ramon was quite proud of his team's successes in most areas of the CO2FX simulation as an important tradeoff is mentioned with high unemployment. Blake addressed the need to reflect upon prior experience in the simulation to address dramatic changes.

> Jamie: We found adding higher % to different categories new results came out. The hardest part was finding out which one should we give a higher %.
>
> Ramon: My partners and I accomplished to make everything good except for our country 71% of our people didn't have jobs.
>
> Blake: My group and I completed the simulation again, this time looking back for possible solutions and dramatic changes in actions to explore the resulting consequences.

Change over time. Through trial-and-error attempts, teams began to stumble onto the idea that changes made at certain points in the simulation may result in a patterned behavior with positive outcomes. Each team addressed this with a focus on different factors throughout the three trials. However, during Trial #1, all teams focused on the science/technology budgetary decision as the primary method to reduce global warming. Perhaps, it's not surprising that students in an *Introduction to Technology and Engineering* class would gravitate towards technology as a panacea. Yet the mindset of the two following teams differed in approach and strategy.

Jamie: Dude, we got no windmills. What's up with that?

Guillermo: It's the 1970s.

Wyatt: It's the 1980s.

Jamie: I told you…hold off on science for awhile. That's why we're all messed up and stuff.

Guillermo: Nobody wants to make them [windmills], you know?

Jamie: We'll make them in 1990. Hopefully people are smart enough then. Hopefully people are smart enough they know how to make them.

Blake: I'm starting to think it's not science that keeps everything from crapping out on us.

Nathan: What else could it be?

Blake: Maybe if we had more science near the beginning instead of towards the middle. Okay we will keep that in mind for next time.

Jamie, Guillermo, and Wyatt determined that the role of science and technology was not of importance early in the game. Quite interesting is their hypothesis that people are "not smart enough" early on to make windmills. However, allocating resources near the middle decades of the simulation will hopefully prove beneficial, if only people are smart enough. Ramon's teammates, Blake and Nathan, capitalized upon a similar idea. However, their intuition guided them toward allocating larger resources to science and technology early in the game. Although both teams were still focusing at the component level (i.e., science and technology), they were beginning to exhibit an understanding of the role of feedback in complex systems. Richardson and colleagues (2001) defined complex systems as, "a system comprised of a large number of entities that display a high level of interactivity. The nature of this interactivity is mostly nonlinear, containing manifest feedback loops" (p. 7). Recognition of complexity elements and underlying interrelationship patterns is an important cognitive step for novice learners.

Additive effects. This coded theme refers to the interrelationship between multiple factors or components. As previously defined by Richardson and colleagues (2001), additive effects addressed a high level of interactivity between several entities. Trial #1 attempts resulted in students on only a few occasions verbalizing initial hypotheses pertaining to the interaction of more than two variables. In particular, the team of Jackson, Nadine and Matt shared two lengthy exchanges about the role of CO_2 in the ecosystem.

Matt: I think we should put that up [acres to protect].

Jackson: Up?

Matt: Yeah, cause that means there's like trees and stuff.

Nadine: Yeah, the trees take in CO_2.

Matt: 40 [percent of acres to protect].

BREAK

Matt: Look how low our fossil fuel is.

Jackson: Fossil fuel remaining…

Matt: 44 [percent remaining].

Nadine: So we should tax them per ton a lot more. Shouldn't we? Because then they wouldn't use as much.

Matt: Okay, so I guess that movie was saying CO_2 is kind of like good (referring to in-class video supplement).

Nadine: Yeah, that's what I got from it too, but we can't have large amounts of it.

Jackson: It was saying we can't have too much or too little. Like we have to have the perfect balance of CO_2 levels and plants in order for it to be stable.

BREAK

Nadine: Acres to protect. We should protect a lot of acres because that would mean there are a lot of trees.

Matt: Yeah and that takes in our CO_2.

This session provided an example of students drawing from prior knowledge gained in the form of a video supplement to the intervention, as well as prior skills and knowledge gained working in the CO2FX simulation. Their lengthy exchange and hypothesis shared similar characteristics of a comment by Jamie. Both statements tend to support the theory that more acres protected will result in more trees growing, which will absorb more CO_2 emissions, giving off more oxygen, thereby, protecting the environment.

Jamie: Well the more acres we have the more oxygen we have and the less temperature…CO_2 output.

Trial #2

Trial #2 resulted in the second recording of the student's work. Data gathered from this trial represents the third and fourth attempts in the CO2FX simulation. During Trial #1, students assumed ownership of their individual advisor roles, resulting in lengthy dialogue exchanges, while defending their decisions. As the students grew accustomed to the simulation in Trial #2, they collaborated more as teammates. Verbal exchanges became less frequent and lengthy as teams settled into a more repetitive behavior within each simulation cycle.

During the second trial, teams started focusing on additional primary components to address global warming. Blake, Ramon, and Nathan exhibited a singular causality approach, emphasizing science/technology budgetary allocations. Wyatt, Guillermo, and Jamie also focused upon science and technology, combined with developmental incentives as a second factor, to minimize temperature fluctuations. The team of Nadine, Matt, and Jackson displayed a consistent pattern emphasizing three main factors. Their repeated efforts conserving acreage, maintaining a high CO_2 tax rate and a heavy reliance upon agricultural subsidies demonstrates a level of understanding, or an intuitive approach, addressing the high level of interactivity between multiple entities.

An emphasis upon cause and effect relationships during the second trial shifted to a repair service behavior. Teams made a transition from their initial hypotheses searching for singular categories controlling global temperature to causality behaviors "fixing" perceived broken or dysfunctional components. Dörner (1996) stated:

> By not breaking their complex goal down into partial goals, they almost inevitably condemn themselves to what I call "repair service" behavior…. They

> go out in search of things that are malfunctioning, and once they find them, their immediate goal becomes fixing whatever is broken. (p. 59)

Repair service behavior. This behavior is demonstrated in the following singular causality and tradeoff themes. Jamie, Guillermo, and Wyatt illustrated how failing to break a complex goal down into partial goals lead to behavior resulting in fixing whatever is broken.

> Jamie: Huh, looks as if people have gone unemployed. We should fix that probably, yes?
>
> Guillermo: Yeah.
>
> Jamie: 2827 for CO_2 output. We've gone up another 500. We should fix that in science in the next ten years.
>
> Guillermo: Unemployment…
>
> Jamie: Is 57 [percent], we can fix that too.

This team was still relying upon strict causal relationships to address perceived broken components as identified with science "fixing" CO_2 output. While not verbalizing "fix it" terminology, the team of Jackson, Nadine, and Matt abandoned an approach with emergent-like characteristics (i.e., holding factors consistent over time) to "fix" the unemployment rate.

> Jackson: Holy cow, the unemployment rate is like sky high.
>
> Nadine: So are we leaving it all the same again?
>
> Matt: Sure.
>
> Jackson: No, no, no I don't think we should keep it the same again. The unemployment rate is like super, super high.
>
> Matt: Yeah, so take down this…average tax rate. Yeah right there [adjusts individual tax rate]…that will take our unemployment down.

Jackson, Nadine, and Matt fell into a pattern of chasing the broken factor. Dörner (1996) stated, "In complex situations we cannot do only one thing. Similarly, we cannot pursue only one goal. If we try, we may unintentionally create new problems" (p. 52). Jamie, Guillermo, and Wyatt considered a tradeoff between lowering CO_2 emissions and the popular opinion of Brazil's citizens, calling for an unemployment rate "fix."

Jamie: So our life expectancy is 49 [percent]. Popular opinion is 34 [percent].

Guillermo: That's good. That's bad isn't it?

Wyatt: Yeah.

Jamie: Well we dropped our CO_2 output which is really more important. Unemployment is 79 [percent]. We can fix that. We can fix that.

Trial and error. In the 2 weeks between Trial #1 and Trial #2 while singular causality claims tended to shift toward repair service behavior, trial-and-error approaches remained relatively consistent. Intuition and "let's see what happens" approaches were used, respectively, by Ramon and Jackson. However, a gradual shift was noted in that teammates collaborated with more subtle tones guiding the conversation. Exchanges between Jackson and Nadine, as well as Nathan and Blake, illustrate the point.

Jackson: I'm going to put acres to protect, just for one round, down to 50 [percent protected] and see what happens. But then I'm going to put this up to like [CO_2 tax rate per ton].

Nadine: That's as high as it can go [40%].

…

Nadine: And then 10 and 15 [for individual and business tax rates].

Jackson: Actually no, this is going to go up to 20 [business tax rate].

Nadine: Okay I got it.

Jackson: Actually this I’m going to change to 12 [individual tax rate].

Ramon: Should I do all of them for the actions? [Set all five budget values] Hey I have an idea okay, let’s bring this down to 30 [science/technology budget].

Nathan: 30.

Ramon: And then economics, we’ll have that at 15 [lowers developmental incentives].

Nathan: No, we want to have that at 20.

Ramon: Yeah, actually… [Re-raises value].

Although teammates in the exchanges above have begun collaborating in decision making, their tendency to employ trial-and-error problem-solving strategies guided by a “gut-feel” approach is counterproductive. Dörner (1996) stated, “In achieving one goal, we may move far from another. By solving one problem, we may make another worse” (p. 57). While a shift was noted in the reductive approaches employed by all teams between the first two trials, the overall analytic approach chosen to operate in a complex system remained counterproductive.

Emergent-like traits. As noted previously, dialogue exchanges decreased significantly from Trial #1 to Trials #2 and #3. With shorter and fewer verbal exchanges providing emergent-like evidence, decisions made within the simulation were investigated for patterns revealing emergent-like or reductive characteristics. CO2FX data entry worksheets revealed a significant decrease with decision making patterns exhibiting reductive behaviors between the first two trials. Between the first two trials teams reductive decisions decreased from an average of 17.67 in Trial #1 to 12.00 during

Trial #2. At the same time, the average number of emergent-like decisions increased from 15.67 to 18.33 over the two trials.

Patterns of emergent-like and reductive decision making tend to indicate students' intuition guides them in the right direction with repeated simulation attempts. Jacobson and Wilensky (2006) stated, "Students need opportunities to experience complex systems phenomena in ways that will let them enhance their ontological and conceptual understandings" (p. 20). Triangulated data sources revealed student behaviors, as well as statements, indicating underlying pattern recognition at some level for members of all teams. Daily lab reports from 12/10/07 provided evidence. Jackson alluded to the interaction of multiple variables. Blake's intuition seemed to guide him to recognizing the role of feedback allocating finances early in the game for desired results later on. Jamie recognized his team's improvement was due to multiple factors.

> Jackson: So far we have made great improvement. Our final temperature this time was much better than last time due to our high taxes on CO_2 and plant conservation [acres protected].

> Blake: My group and I make our best attempt at the simulation yet. We discovered that high funding in science and technology in the beginning will stay throughout the entire game for long-lasting positive effects.

> Jamie: We did way better than we ever have done before. The temperature was only 73° and unemployment was only 20 [%] we ended with 11 windmills.

Two days later, during his group's recorded session, Jackson's team encounters technical difficulties accessing the CO2FX simulation. Maximizing the limited time available, his team decided to hold their initial settings constant across all decades. The outcome was their best, to date. Jackson's brief reflection provided an example demonstrating a positive behavior while working within a complex system.

> Jackson: We didn't get a whole lot done because our computers weren't working, but at the end I did the same setting every decade and it came to 71.1° F.

While working within the simulation on the second trial, Jackson, Matt, and Nadine discussed a strategy incorporating multiple factors. Apparently, prior attempts had led them to the conclusion a conservation of acres, along with high CO_2 tax rates and an emphasis upon agricultural subsidies, would prove most beneficial.

> Jackson: Do you think we should do the quick three things all the way up that were helping?
>
> Matt: What were the high, what were the high ones, what were the good ones?
>
> Jackson: This [points to acres to protect] this [points to CO_2 tax rate] and agricultural subsidies.
>
> BREAK
>
> Nadine: There, now it works. Okay so we are leaving it the same?
>
> Jackson: Okay. It should have the same effect.
>
> Nadine: Should I leave it at the same numbers [budgetary decisions].
>
> Jackson: Well, what happened? Sure, let's do it again. We can see the results more clearly.

Guillermo and Jamie provide an example on Trial #2 consistent with statements and actions their team made during the first trial. This team recognizes the need to address budgetary allocations at the proper time, as the role of feedback [not stated by students as such] in complex systems, will bring about positive outcomes.

> Guillermo: No windmills yet.

Jamie: What year is it? 1980?

Guillermo: 1980.

Jamie: Okay next year we'll probably put some more money towards science maybe.

Guillermo: About the 1990s.

A preponderance of evidence from the triangulated qualitative data sources supports the quantitative findings for the near transfer question. Quantitative results do not provide statistically significant evidence of emergent-like representation of thought. Qualitative evidence displays strong evidence of cause and effect problem solving approaches. Such approaches are reductive in nature. From Trial #1 to Trial #2, students' verbalizations leading to emergent-like characteristics decreases as their verbal exchanges become more abbreviated. However, their actions within the simulation display a change in action with decision making displaying reductive traits decreasing, while patterns of emergent-like characteristics increases.

Far Transfer Question

A one-way analysis of covariance (Table 13) was conducted for each of the three dependent variables: EFMM, CWMM, and NM. The independent variable was complex systems instruction. A preliminary analysis evaluating the homogeneity-of-slopes assumption indicated that the relationship between the covariate (pretest) and the dependent variables did not differ significantly as a function of the independent variable, EFMM: F (1, 13) = 0.02, p = .91, partial $\eta 2 < .01$; CWMM: F (1, 13) = 0.32, p = .59, partial $\eta 2 = .02$; NM: F (1, 13) = 1.74, p = .21, partial $\eta 2 = .19$. The ANCOVA was not

Table 13

ANCOVA for Far Transfer Question

Source (Q2)	Type III sum of squares	*df*	*F*	Sig.	Partial η2
Emergent-like (EFMM)					
Intercept	7.133	1			
Pre-EFMM	8.92	1	2.26	.16	.14
Group	.18	1	.05	.83	.00
Error	55.30	14			
Clockwork (CWMM)					
Intercept	23.27	1			
Pre-EFMM	2.34	1	.49	.50	.03
Group	1.08	1	.22	.64	.02
Error	67.27	14			
No model (NM)					
Intercept	7.21	1			
Pre-EFMM	5.23	1	2.06	.17	.13
Group	.88	1	.35	.57	.02
Error	35.64	14			

significant, EFMM: F (1, 14) = 0.05, p = .83; CWMM: F (1, 14) = 0.22, p = .64; NM: F (1, 14) = .35, p = .57. The strength of relationship between the complex systems instruction and mental models generated was weak, as assessed by a partial η2, with the method of instruction accounting for only 1% of the variance with EFMM and 2% with CWMM. With NM existing as an alternative to either EFMM or CWMM in the form of lack of sufficient evidence, the NM partial η2 is of no importance.

The means for mental models generated adjusted for initial differences did not differ significantly between groups (Table 14). The CWMM had the largest adjusted mean in control (M = 3.47) and treatment (M = 2.93). This demonstrates that of the six

Table 14

Far Transfer Question Estimated Marginal Means

			95% confidence interval	
Dependent variable/group	Mean	Std. error	Lower bound	Upper bound
EFMM				
Control	1.37	.73	-.22	2.95
Treatment	1.58	.69	.08	3.07
CWMM				
Control	3.47	.82	1.71	5.24
Treatment	2.93	.78	1.24	4.61
NM				
Control	1.34	.56	.14	2.54
Treatment	1.85	.53	.71	2.98

OMMT component beliefs, there is a strong tendency in both groups to rely upon reductive thought processes. Evidence of emergent-like responses similarly does not differ between groups. The EFMM adjusted means for the control (*M* = 1.37) and treatment (*M* = 1.58) provide no evidence regarding outcomes based upon method of complex systems instruction. Of the six OMMT component beliefs, evidence of no mental models (NM) existed at an adjusted mean for the control (*M* = 1.34) and treatment (*M* = 1.85) groups.

Figure 7 provides a visual depiction of the mental model adjusted means, by group. Included is the standard error which provides an estimate of the difference between the measured and true means. Mean responses are provided on a four-point scale which is representative of the six possible component beliefs. This figure conveys student responses more likely to display reductive thinking than an emergent-like pattern of interest in this research.

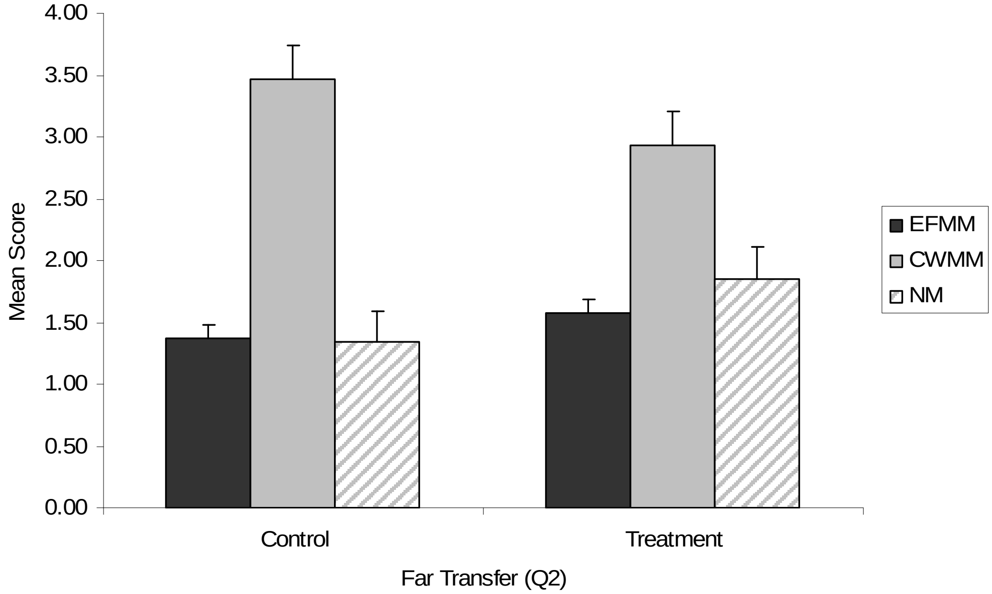

Figure 7. Comparison of posttest, far transfer mental models generated.

Qualitative Results

Figure 8 displays the clearest trend within the qualitative evidence gathered that students working within the CO2FX simulation begin to exhibit emergent-like decision making over time. Each trial represents an average from the student activity within a practice session and actual recorded session within CO2FX. During a simulation cycle, a total of ten decades' of data input decisions were made in each class period. Nine decisions were made per decade. Five budgetary decisions were made for: developmental incentives, healthcare spending, science and technology spending, social services spending, and agricultural subsidies. Additionally, four actions decisions were made, including: acres to protect, CO_2 tax rate per ton, an average tax rate for individuals, and average tax rate for businesses. Figure 8 displays patterns in which teams made decisions exhibiting either reductive or emergent-like characteristics over a minimum of three consecutive decades.

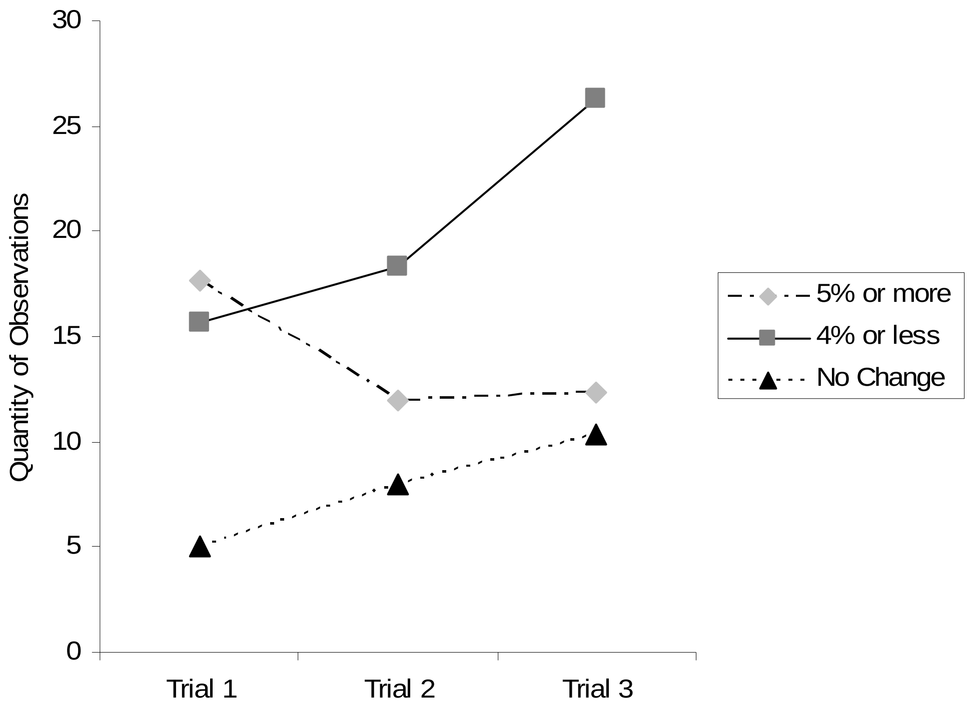

Figure 8. CO2FX data decisions over three or more decades. No change line displays an emergent-like pattern with values held consistent across a minimum of 3 decades. The 4% or less line displays emergent-like characteristics with minor changes of 0% to 4% input between three or more consecutive decades. The 5% or more line represents attributes of reductive-type behavior with data input decisions varying decade-to-decade between 5% and 99%.

CO2FX Data Entry Budgetary Decisions

Within Figure 8 each trial displays a point in time over the administration of the intervention. Figures 9 thru 14 (shown and described separately below) more accurately depict a given team's budgetary decision making patterns over the course of the intervention. Initially students made relatively large budget decisions in earlier attempts. As teams preceded through multiple iterations of CO2FX they, generally, refined their decisions with smaller incremental changes. That change over time can be seen in the following figures which represent six sequential CO2FX interventions.

Figures 9 and 10 display the results of Jackson, Matt, and Nadine's budgetary decision made during Trial #1. Small changes were identified as a budgetary "tweaking" between 1% and 4%. This value was selected following the viewing and transcribing of all CO2FX simulation attempts. Larger budgetary allocations frequently occurred in multiples of five or ten percentage. Small changes were noted in cases where students discussed subtle refinements of past budgetary decisions. Therefore decisions that revealed small change (i.e., 1% to 4%) were identified as such.

Figures 11 and 12 display the budgetary results for Trial #2 attempts. Trial #2 represents the third and fourth CO2FX intervention sessions. Jackson, Matt, and Nadine

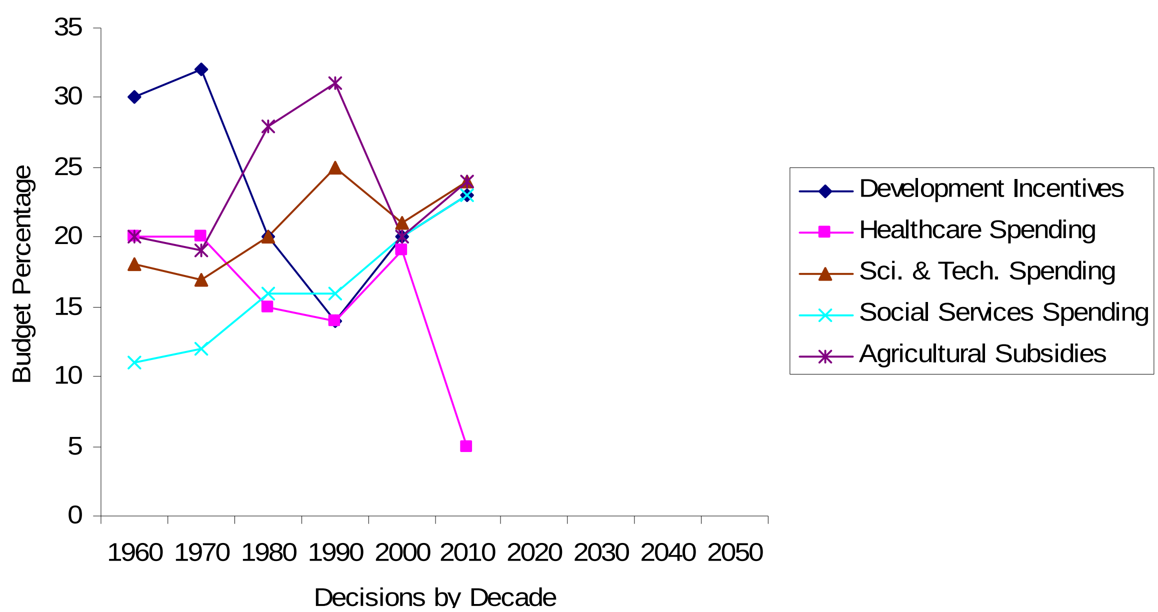

Figure 9. JMN CO2FX session #1. The first practice session reveals initially small budgetary decisions in the first two decades giving way to more noticeable allocation differences. Class ended before the simulation could be completed.

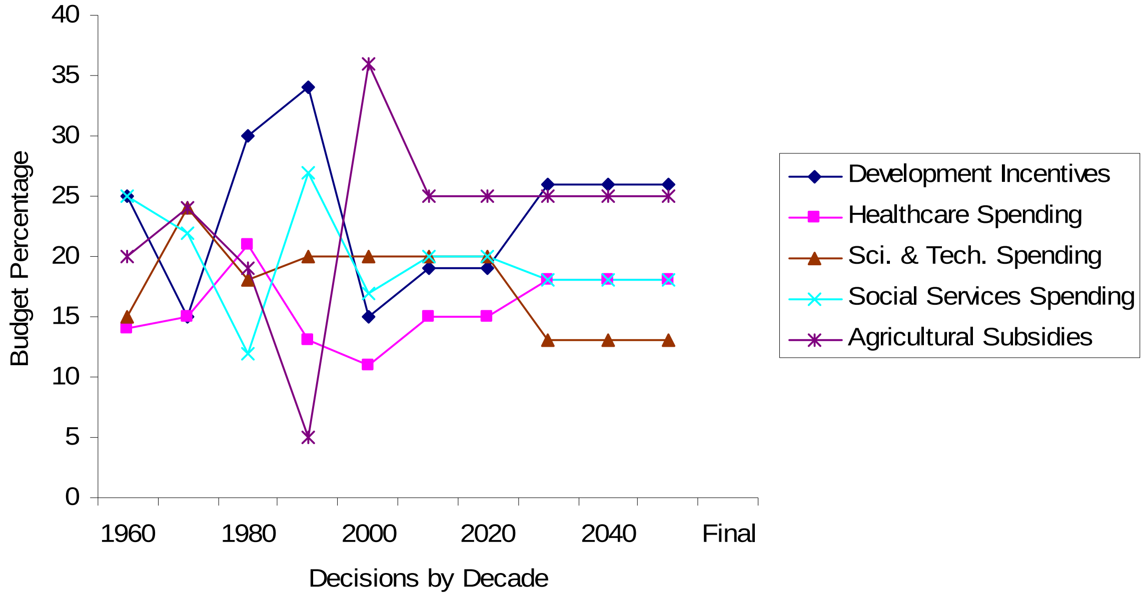

Figure 10. JMN CO2FX session #2. Large budgetary decisions in the first half of the simulation transition into smaller changes in the middle of the game. The final three decades display a pattern in which all budget decisions are held constant. It should be noted these decisions were based on time as the class period was ending.

experience technical difficulties with the computer during their fourth session. However by this time they have identified the shared contributions of protecting a large percentage of acres, administering a high CO_2 tax rate per ton, and allocating more funds towards agricultural subsidies as important factors to reduce CO_2 emissions.

Figure 12 provides a glimpse into Jackson, Matt, and Nadine's initial decision to allocate a disproportionate percentage of their budget to agricultural subsidies. This team experienced difficulties logging into the session initially. As the game began one team member had his feet tangled in the power cord and accidentally unplugged the computer. With computer restart and logging in hindering their progress the team discussed choices they would make during the upcoming simulation attempt.

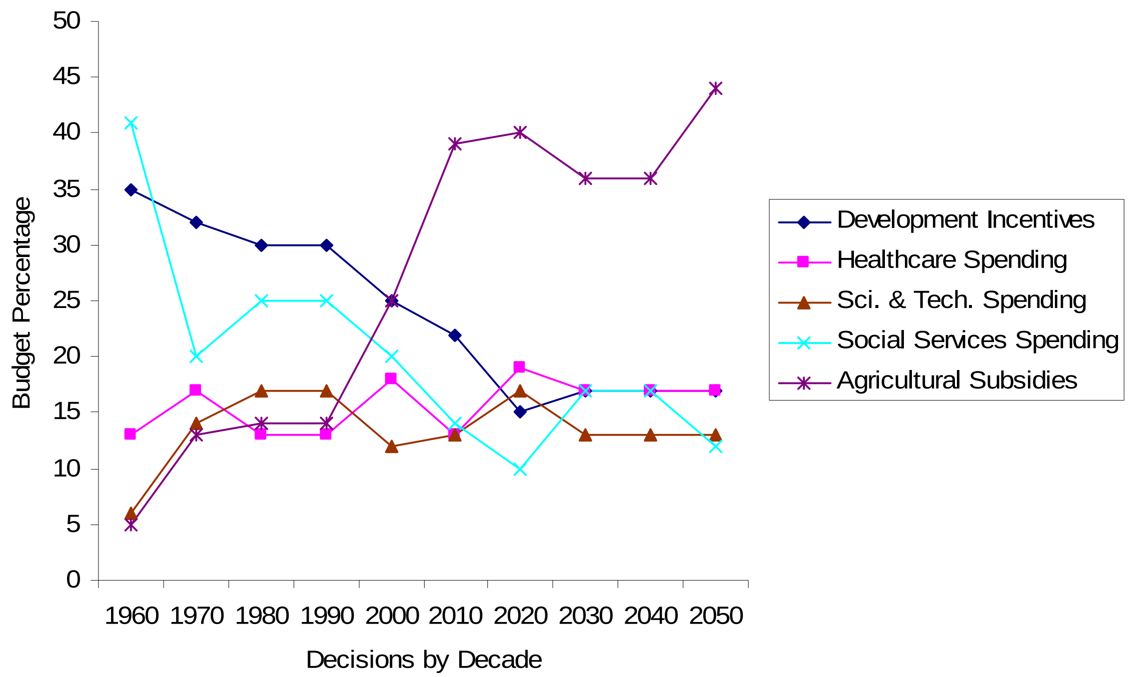

Figure 11. JMN CO2FX session #3. During this attempt the team focuses on Agricultural Subsidies as a primary element of concern, allocating a larger percentage of the budget. Overall 4 of the 5 budgets undergo smaller changes in the latter half of the game.

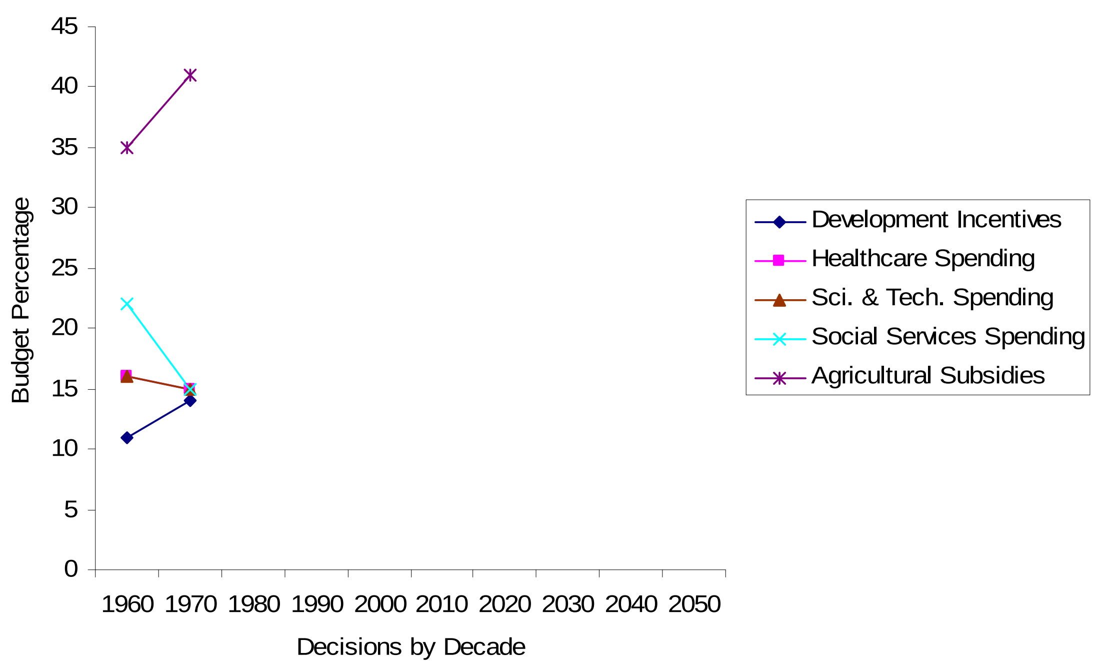

Figure 12. JMN CO2FX session #4. Team experiences technical difficulties attempting to login to CO2FX. As the session is running one team member inadvertently unplugs the computer. Disproportionate budget allocation to Agricultural Subsidies.

Figures 13 and 14 represent Trial #3 attempts in the fifth and sixth intervention sessions. As Jackson, Matt, and Nadine progress through the series of simulation attempts their overall decision making reveals subtler changes over time. Holding more variables constant over a longer time frame provides evidence of intuition, or feedback from repeated attempts, guiding this team in the right direction. Change over time from repeated simulation attempts reveals how this team refines larger budget allocations in Figures 9 thru 11 to more subtle changes in Figures 13 and 14. Budgetary decision making results for the remaining two teams can be found in Appendices J and K.

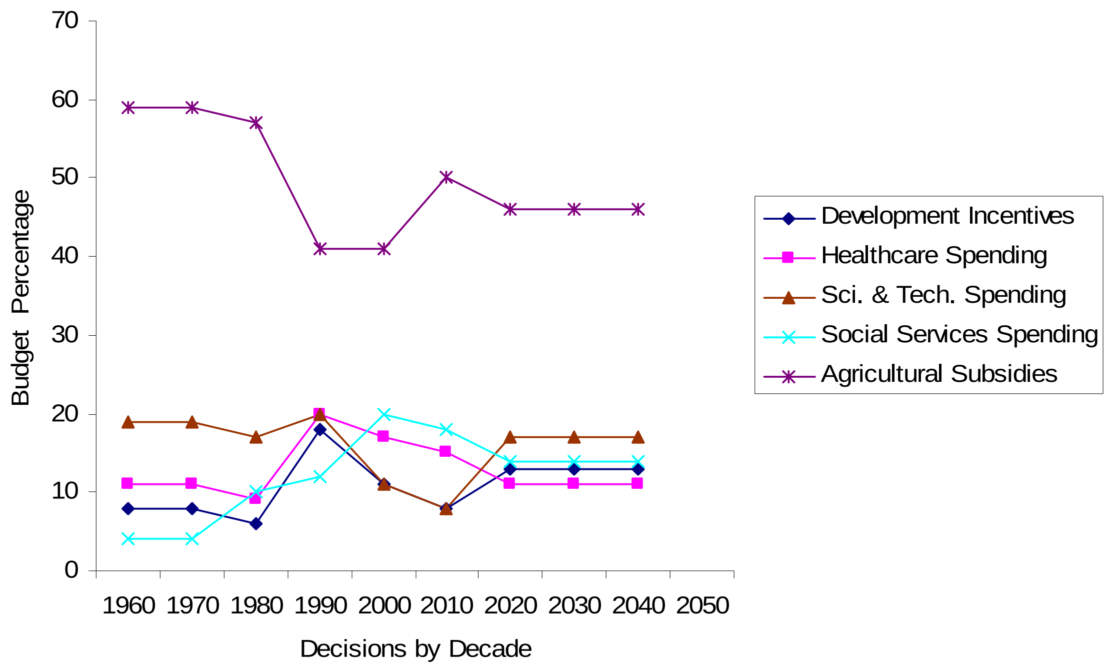

Figure 13. JMN CO2FX session #5. Budgetary decisions are held constant or very small change is made early on. Based on results, changes are made during middle portion of game and then values are held constant over final three decades.

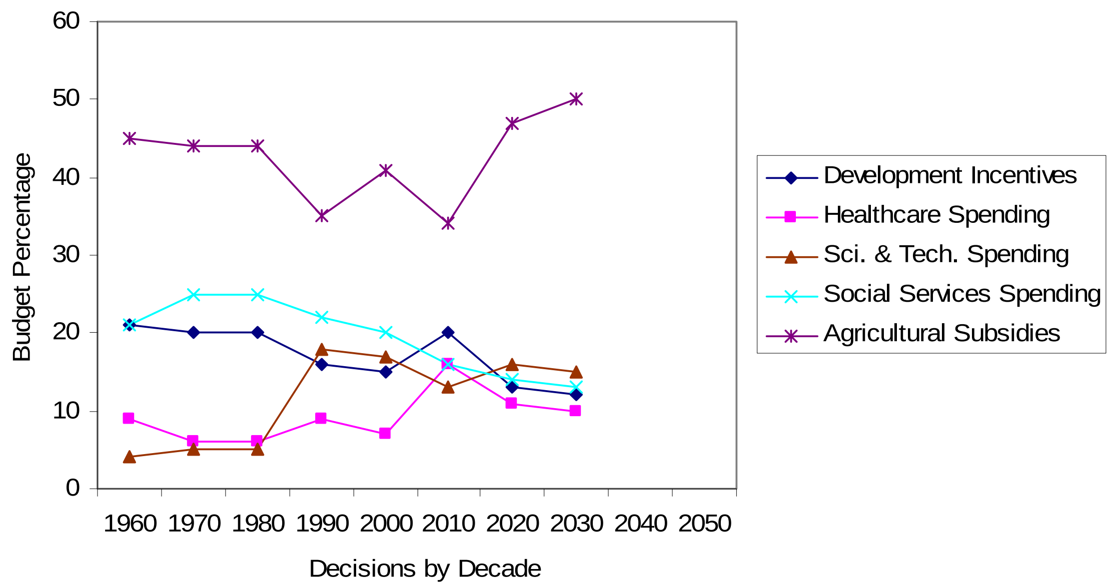

Figure 14. JMN CO2FX session #6. Although slightly more variation is displayed between sessions #5 and #6, a noticeable difference is observed in budgetary allocation variability over time.

Trial #3

Transcription data of students working in the simulation during Trial #3 was limited due to computer difficulties accessing the CO2FX simulation for two of the three teams. Additionally, the remaining team was missing a student who seemed to initiate the vast majority of conversations during the first two trials. Therefore, recording sessions were noticeably abbreviated for two teams and marked with lengthy audio silence in the third. Of the transcript data collected, only two reductive themes were noted.

Singular causality. Throughout the intervention, verbalizations were predominantly of reductive nature. Nathan, Blake, and Ramon provide an example with disagreement related to healthcare and popular opinion. Jackson and Nadine were members of the team who, early on, determined there was interaction between at least three significant factors. However, by their final attempt, their team joins the other two teams, as they focus upon science/technology allocations as the means to increase windmills.

Nathan: Umm, policy … what was popular opinion, 45 [percent]?

Blake: Um huh.

Nathan: So raise social services up to 20 [percent] and lower the other one down to 13 [healthcare spending percentage].

Blake: [lowers and locks budget] I don't know how less healthcare is going to make people happy, but…

Ramon: Yeah, I think we should raise the healthcare just a little bit. Yeah, it's gonna make people happy.

Jackson: What do you think this should be? [Pointing to science budget].

Nadine: I think it should be higher, because it will give us windmills and stuff. Won't it?

Trial and error. Although intermittent patterns displaying emergent-like characteristics increased in magnitude over the course of the intervention, overall, the qualitative evidence substantiates quantitative findings. Perhaps this is best illustrated by the team that seemed intuitively guided toward more emergent-like behavior over the month-long intervention. During their final data decision of the last decade, Jackson and Matt provided an example of the engrained trial-and-error problem-solving approach.

Jackson: The last one let's put this at 50 [agricultural subsidies allocation] and this at 95 [percent of acres to protect] and see what happens.

Matt: That's a good idea.

Jackson: Just as an experiment.

Final lab reports. Student reflections gathered from the final week of the intervention support reductive foci. Jackson's final reflection addressed a tradeoff between employment and global temperature. Blake referred to singular causality with science/technology as the focus. However, he brought up an important point in that balance is the key, thereby, displaying some emergent-like comprehension. Ramon's final statement was reductive in nature, just as his approach was guided by intuition throughout the intervention revealing comparable findings.

> Jackson: I think we have successfully controlled our world temperature by learning from our mistakes but our unemployment was horrendous.
>
> Blake: We did much worse this attempt. We've come to the understanding that science + technology is good for the game, but too much will ruin the people. We couldn't test this for the fact we accidentally clicked something wrongly.
>
> Ramon: I learned that if you have science all the way up it will get people to start liking you and if you put everything equal then Brazil will not do good and no windmills.

Summary

Quantitative and qualitative evidence tended to support one another in this research. ANCOVA results did not provide statistically significant evidence of emergent-like understanding following the intervention. Qualitative data revealed a predominance of student statements, actions, and behaviors within the simulation displaying reductive characteristics. Not surprisingly, students relied upon a trial-and-error problem-solving approach typifying strategies used within engineering and technology education settings. However, over the course of the intervention, students provided examples displaying emergent-like characteristics across all three qualitative data forms. Verbal exchanges between students working in teams of three tended to indicate that through repetitive trial-and-error approaches, students exhibited a novice level, complex systems understanding. Revelation of underlying complexity elements was demonstrated in spoken and written form but most often through a pattern of decisions revealed on CO2FX data entry worksheets. Speaking of complex systems, Goldstone (2006) stated:

> Students who interact with the simulations actively interpret the resulting patterns, particularly if guided by goals abetted by knowledge of the principle. Their interactions are grounded in the particular simulation, but once a student has practiced building an interpretation, it is more likely used for future situations. (p. 40)

Within an ecological approach to participating within complex systems, students derive meaning through their interactions in the simulation, as well as through conversations and actions with teammates. Each student brings to the setting a unique set of skills and experiences based upon their prior life experiences. Gauging a change in behavior and comprehension for each student across the month-long decade would be difficult, since two of the three data forms reveal interwoven decisions from all three teammates. For that reason, an exemplar from one student's daily lab report was selected to investigate change over time. Nadine's reflections provided an illustration of student learning, exhibiting emergent-like qualities, within the complex systems simulation.

> 11/13/07: I learned that the years over a long period of time can be affected by little things we do. I learned also about how to work the program (CO2FX) we did and how it changes our world on things we do also.
>
> 11/15/07: We learned that doing all these changes to our country's decisions. We tried many different ideas to try to change the temperature but it didn't work out.

11/16/07: I learned that after we made a big mistake on what numbers to change and adjusted them, then kept them the same, we did better than if it would or did before.

12/03/07: I learned by previous experiences for being in this group to make certain things go up and down according to the temperature to keep it at an average.

12/04/07: I learned that by having different jobs in our groups have and gives us more opportunities to change our minds and compare and contrast why things should go the way they are, also by making averages.

12/10/07: In class we watched a movie about global warming and said ways we could limit emmisions [sic]. We then used what we learned by the movie to adjust CO_2 and fossil fuels in our simulation group.

12/12/07: In class we watched a movie and worked in our groups today. We used ideas we found last time so that this time we did better than previous times we did it. We also worked well together.

Barab and colleagues (1999) stated, “Meaning arises within (as part of) context (as meaningful relations), and it is the responsibility of the educator to support (scaffold) the learner in developing relations with the learning situation in particular and society in general” (p. 382). Perhaps, the most significant element to note is the need for the educator supporting the learner. Reflections from Nadine indicated that through her actions in the CO2FX simulation and an accompanying supplemental video, she had comprehension of important elements of complex systems. Her mention of small actions having large effects, as well as the need for balance, would be enhanced with teacher support of such beliefs. The findings of this study provided reason to believe that, with additional complex systems instruction from classroom teachers, student recognition of underlying complexity patterns and elements would be further enhanced.

CHAPTER V

SUMMARY, DISCUSSION, IMPLICATIONS, AND RECOMMENDATIONS

Global warming, ethnic violence, military conflict, and border control issues are only a sampling of complex systems (Bar-Yam, 2004). Interwoven cultural, economic, social and political elements comprise parts of these complex systems which give rise to their collective behaviors. If people better understood multifactor interrelationships within complex systems, they would be better prepared to move beyond reductive approaches in solving complex issues. As engineering and technology education tend to incorporate such reductive approaches, there exists a need for complex systems research utilizing an alternative approach. Therefore, this research was conducted.

The purpose of this study was to investigate how complex systems approaches differ between a synthesis (top-down) focus in a treatment group and an analysis (bottom-up) focus in a control group. This mixed method, triangulation design, experimental research study utilized a pretest posttest, control group design to determine if students receiving complex systems instruction differ in their recognition of complexity elements and underlying patterns. The hypothesis was that students experiencing complex systems scenarios in a computer based learning environment would outperform their counterparts by constructing a greater number of explanations to near and far transfer questions with emergent-like responses.

A STELLA-based software simulation, modeling a complex global warming scenario which evolved from Fiddaman's (1997) research in feedback complexity in integrated climate-economy models, served as the intervention. Students in the treatment group worked in teams of three during six sessions as economic, policy, and science/ technology advisors facing global warming issues in the country of Brazil. A cyclical rotation through advisor roles resulted in students' experiencing each advisor position twice. Within their advisor position, students made several economic and policy decisions over ten separate points in time throughout each century-long simulation. The overall goal was to minimize CO_2 emissions and hold constant the average global temperature. Additionally, students monitored issues related to an increasing population, public opinion, unemployment, fossil fuel consumption, and the Brazilian citizenry's average life expectancy.

This research was conducted under the premise that, through multiple iterations within complex systems simulations, students may experience conceptual change in understanding complex systems. As an initial probe into complexity research within engineering and technology education, this would provide quantitative data supporting the research question. Additionally, and, perhaps more importantly, qualitative data would provide evidence of how students think and act on a moment-by-moment basis within complex systems environments.

Quantitative and qualitative evidence supporting the research question is discussed in this chapter. The following topics are addressed: (a) summary of research question; (b) discussion of findings, reliability, internal validity and external validity; (c) implications; and (d) recommendations for further research.

Summary of Research Question

Borrowing from Charles' work (2003), the research question was: Can high school students' exposure to complex systems scenarios within a software simulation increase the generation of EFMM, as demonstrated by the ability to create emergent-like explanations as they are applied to near and far transfer problems? EFMM were the primary element of interest in this research. An analysis of covariance did not reveal statistically significant evidence supporting the research question with regard to the generation of emergent-like responses. Mean differences were, additionally, measured for reductive responses for CWMM and for NM as a comprehensive alternative option to CWMM and EFMM.

Far transfer findings were not statistically significant for EFMM, CWMM, or NM. The ANCOVA results were: EFMM: F (1, 14) = 0.05, p = .83; CWMM: F (1, 14) = 0.22, p = .64; NM: F (1, 14) = .35, p = .57. Additionally, near transfer findings did not provide statistically significant evidence with emergent-like responses. The ANCOVA was not significant for EFMM: F (1, 15) = .29, p = .60.

Group differences on the near transfer question were significant in CWMM: F (1, 14) = 7.37, p = .02. Of the six component beliefs measured, the control group generated an estimated marginal mean response of 2.73 versus the treatment group's 1.29. A significant group difference provided some indication of how reductive approaches delivering content in the control group potentially contributed to more posttest clockwork responses. Additionally, the NM category provided statistically significant group differences: NM: F (1, 14) = 7.36, p = .02. Discussion of significant findings addressing the control group's NM estimated marginal mean response of 1.97 versus the treatment group's 4.01 will follow.

Qualitative data gathered from students working in the CO2FX simulation in the form of student transcripts, CO2FX data entry worksheets, and student daily lab reports supported quantitative findings. Most of the qualitative data provided evidence of thought process and actions that displayed reductive attributes. Across three trial periods within the intervention, references to singular cause and effect relationships and trial-and-error approaches were evident. Students demonstrated a tendency to make large data input decisions in earlier attempts, apparently to determine effectively change based upon immediate short-term impacts. As their attempts within the simulation proceeded, students demonstrated "fix it" behaviors. These attempts resulted in chasing the "broken" factor, a band-aid approach based upon short-term fixes.

However, evidence of emergent-like thought and action was identifiable across the triangulated qualitative data. Over time, students generally refined and minimized substantial changes made during early simulation attempts. Teams began to make decisions based upon balancing variables. Budgetary decisions demonstrated tendencies allocating averages more representative of economic, policy, and science/technology needs. Decision making included more behaviors that were guided by intuitive approaches and demonstrated emergent-like action. Teams began to hold multiple factors consistent across consecutive decades to determine the cumulative effect of budgetary allocations over time.

Verbalizations within the simulations decreased in quantity over time. This may be due in part to procedural knowledge gained while working through multiple trials. Earlier trial attempts provided examples of "let's see what happens" approaches as students explored new and unknown features within the CO2FX global warming game. As dialogue exchanges decreased over repeated trials, the CO2FX data entry worksheets provided examples of emergent-like and reductive behaviors.

Discussion of Findings

Statistically significant results were found for the near transfer question in CWMM and NMs. This finding is interesting in that, initially, all 18 participants failed to generate a single response coded as an emergent framework mental model on the pretest near transfer question. Therefore, all initial responses were classified as either CWMM or NM. On the posttest, no group difference was found in the generation of EFMM. However, the control group generated a statistically significant estimated marginal mean response of 2.73 CWMM versus the treatment group's 1.29. Considering the random assignment to group based on stratification, both groups should have shared common characteristics.

During the intervention phase, control group participants received laboratory instruction pertaining to complex systems delivered in a traditional manner. Relying upon a project-based learning environment, robots were investigated as complex systems. An analytic method investigated electrical, mechanical, and fluid power at the subsystem and component level. It is conjectured that learning and, subsequently, investigating at the component level could have contributed to a reductive mentality leading to the identified group differences. Accompanying this result is the statistically significant NM group differences. An estimated marginal mean response of 1.97 NM versus the treatment group's 4.01 was found.

For all practical purposes, there were no differences between groups in the generation of EFMM. The control group generated .35 more mental models on the near transfer question, while the treatment group generated .21 more on the far transfer question. This finding aside, students would then generate either more CWMM or NM responses. With statistical significance leading to more CWMM for the control group, the only alternative for the treatment group were NM responses.

Based on input from coding analysts who reviewed pretest and posttest answers, there was a sense that the posttest near transfer question did not lend itself to the six component beliefs of interest as well as the pretest question. The question then becomes one of accounting for what factor(s) contributed to the differences. If method of instruction, indeed, led to the generation of more CWMM for the control group, it would make sense the treatment group generated more NM responses, considering no differences were found relative to EFMM generated. Additionally, the coding analysts mentioned student answers "hinting" of either emergent-like or reductive responses without sufficient evidence to code as either.

Penner's research (2000) into emergent phenomena found that students lack the cognitive capacity to represent accurately emergent-like concepts: "that is, even though students might possess considerable domain knowledge, they do not necessarily possess the ways of thinking that can help them analyze phenomena appropriately" (p. 804).

During this research it is possible treatment condition participant's intuition led them to believe certain emergent-like happenings were occurring in the CO2FX simulation. However, failing to possess the cognitive tools to analyze independently, their answers, subsequently, lacked sufficient evidence to be coded as EFMM.

An alternative explanation could be that experience during multiple trials within the intervention was, in itself, an inadequate treatment. Jacobson and Wilensky (2006) cite the importance of experience in complex systems. However, Hmelo-Silver and Azevedo (2006) stated, "Discovery alone is not sufficient. Students need scaffolding to guide their exploration and experience" (pp. 55-56). This research relied upon a video supplement to complement the complex systems intervention. Interwoven cultural, economic, social, and political effects of technology were highlighted since they connected to complex systems elements. Instruction and participation in the CO2FX simulation delivered these concepts in a covert manner, in that they were not, specifically, called out by name. This leads to another important issue with complex systems instruction: the teacher's role.

ETE instructors typically possess a wide variety of analytic knowledge and skills sets in areas, such as electronics, engineering, design, communication, construction, manufacturing, or transportation (ITEA, 2000/2002). Mr. Fenn delivered complex systems instruction related to robotic design and construction to the control group in his *Introduction to Technology and Engineering* class. While control group participants had the advantage of his direct instruction with analytic complex systems instruction, the treatment group participated in a complex system designed to provide a synthesis experience. Additional resources for the treatment group came, exclusively, from the supplementary video.

It could be argued that without a teacher calling out complexity concepts by name, students would miss one of the most important tools for their success. However, considering research into complex systems concepts and principles is still in its infancy, further research is required related to appropriate teacher pedagogical content knowledge (Jacobson & Wilensky, 2006). Hmelo-Silver and Azevedo (2006) identified learning tools, curricular materials, and pedagogical content needs as research areas to address teaching effective approaches in the delivery of complexity concepts.

Evidence of change in emergent-like thinking from pretest to posttest was the primary dependent variable of interest in this research. Quantitative evidence did not support initial hypotheses to either near or far transfer questions. This finding is partially substantiated by prior transfer research, indicating great difficulty in far transfer with student and adult populations alike, necessitating explicit reminders with situational relevance (Bransford & Schwartz, 1999; Goldstone, 2006). Regarding transfer, Goldstone stated, “To generalize across originally dissimilar domains, one needs training that allows the domains to be spontaneously seen as reflecting the same principle” (p. 40). In this research, the embedded complexity elements did not reflect common surface feature principles generally identifiable by novice learners.

As the treatment group teams began working together with shared decision making, they demonstrated a tendency to focus upon singular causality hypotheses. These hypotheses most often revolved around science/technology budget allocations as the global warming panacea. Student efforts were designed to bring in more windmills, thereby reducing fossil fuel consumption. These efforts most often failed to connect underlying policy, economic, and science/technology interrelationships. Hmelo-Silver and Pfeffer's (2004) research indicated "that structures are the most cognitively available level of a complex system for novices" (p. 136). Throughout six trials, the treatment group relied upon surface level happenings (structure) to inform their decision making. Occasional references and short exchanges between teammates infrequently connected the interwoven nature of economic, policy, and science/technology advisor decisions.

Hmelo-Silver and Pfeffer's (2004) research into structure-behavior-function theory identified the importance of understanding behaviors and functions in complex systems. Breaking systems down beyond structure features to underlying behaviors and functions interwoven in the CO2FX global warming game would encourage transfer opportunities. Hmelo and colleagues (2000) found that, in order to understand complex systems, students need to be able to "break problems down into functional systems" (p. 291). Furthermore, they emphasize the need to design and build working models focusing upon interactions at the subsystem and component level. This was the approach incorporated by the control group. This seems to be the point where complex systems instruction in science and technology diverge.

Whereas complexity in science pertains to concepts such as emergence, adaptation and self-organization, complex systems in ETE tend to focus upon the level of complexity within a technical device or machine. Considering standards address important cultural, economic, social, and political effects of technology (ITEA, 2000/2002), this discipline seems ideally suited for complexity inquiry. Referencing Hmelo and colleagues (2000) notion of complex systems analysis at the subsystem level with working models, it appeared this, too, suited ETE quite well. Identifying what concepts to address becomes the key. In this research, focus at the element level highlighted concepts such as: ohms, voltage, amperage, compression, force, and power in the control group's robotic design and construction phase. However, presenting feedback, nonlinearity, and randomness as complexity concepts is an entirely different challenge.

Beyond presenting complexity terms, the challenge is one of demonstrating complex systems understanding over time. Transferring information to a new domain with emergent-like component beliefs would serve as a practical demonstration. However, that did not occur in this study. This could be partially due to the treatment group's repeated exposure in a single complexity scenario. Gick and Holyoak (1983) found that a single analogous event failed to provide adequate abstract representation transferring to new settings. However, transfer increased when two or more analogs sharing similar characteristics were used. Utilizing several simulations embracing similar complexity concepts could provide complementary abstract representations facilitating transfer, whereas the use of a single complexity simulation failed to demonstrate statistical significance in this research.

Tracking emergent-like thoughts and behaviors in this study was a challenge since complex systems concepts were not overtly identified with direct instruction. As noted by Penner (2000), statements by students did not provide a deep understanding of emergent-like concepts. Students frequently rely upon "seeing what happens" as they manipulate variables in a quasi-scientific method experimental approach. Penner (2000) concluded, “their statements do suggest some understanding that ‘seeing what happens’ may be the only currently available means of studying the effects of micro-level changes on a system” (p. 800). In this research, students hinted at understanding complexity concepts in their daily logs and transcriptions. However, their CO2FX data entry log sheets provided a pattern of actions providing more evidence of change over time. Group patterns reflected fewer dramatic changes [reductive decision] over time, and an increase of multiple factors held consistent (emergent-like representation) over time.

Between the first two trials, the treatment group team’s reductive-like decisions decreased from an average of 17.67 in Trial #1 to 12.00 during Trial #2 (see Figure 8). At the same time the average number of emergent-like decisions increased from 15.67 to 18.33 over the two trials. Subsequently, Trial #3 results demonstrate reductive decision making held constant (12.33 decisions) and emergent-like still increasing (26.33 decisions).

Emergent-like and reductive-like decision making patterns tend to indicate student intuition guided them in the right direction with repeated simulation attempts. Jacobson and Wilensky (2006) stated, “Students need opportunities to experience complex systems phenomena in ways that will let them enhance their ontological and conceptual understandings” (p. 20). Triangulated data sources reveal student behaviors, as well as statements, indicating underlying pattern recognition at some level for members of all teams. From Trial #1 to Trial #2, student verbalizations leading to emergent-like characteristics decreased as their verbal exchanges became more abbreviated. However, their actions within the simulation displayed a change in action. Decision making that displayed reductive traits decreased, while patterns of emergent-like characteristics increased.

Discussion on Reliability

The taxonomy used to determine clockwork or complex categorization emerged from Jacobson's (2000) CSMM taxonomy and was tested with a Cronbach alpha statistical test. Gall and colleagues (1999) stated, "The alpha statistic is a means of testing whether the items comprising a measure consistently measure the same attitude, ability, or other construct" (p. 196). A widely accepted reliability coefficient of 0.7, the minimum level of acceptability in social sciences, was used in this research (Schloss & Smith, 1999).

This research utilized Charles' OMMT which expanded upon Jacobson's CSMM taxonomy. Jacobson (2000) reported a reliability alpha of .76 with the clockwork category and .72 with the complex systems. Following an examination of the correlation matrix and inter-item statistics for each scale (clockwork and emergent), the complex systems overall reliability was eventually improved to .85 with the removal of several items. The clockwork category's reliability alpha was improved to .81 as the scale was revised to include reductive, centralized, small actions-small effects, and predictable as variables.

Discussion of Validity

The triangulation design used in this research necessitated addressing potential validity threats unique to the concurrent data collection and analysis within the mixed methods design. Potentially biasing results was a concern of the researcher while conducting 36 pretest and posttest interviews. A series of follow up questions, very general and open-ended, were developed to minimize the potential of directed or leading questions differing between individual students. The answers to these questions provided the quantitative results and followed an analysis using Mosenthal and Kirsch's (1992a, 1992b) sentence parsing and Charles's OMMT classification.

Validity issues were addressed with what Creswell and Plano Clark (2007) term "triangulation validity" (p. 146). Quantitative results were triangulated with three main qualitative forms of data: transcriptions from students working in the intervention, data entry worksheets, and daily student lab reports. Qualitative evidence was used to confirm ANCOVA results. The quantitative results in this research did not provide statistical significance of the research question. Therefore, disconfirming evidence was used, in addition to triangulation, to establish validity. Evidence across the qualitative data are used to support student learning. This demonstrated, not only the emergent-like characteristics of interest in this research, but also reductive thinking substantiated with the aforementioned triangulated data sources.

Internal Validity

Gay and Airasian (2000) stated, "Internal validity is concerned with threats or factors other than the independent variable that affect the dependent variable" (p. 371). Research validity is dependent upon differences in the dependent variable. In this case, student learning in the form of mental models generated was attributed to the intervention itself and not to any extraneous variables. Such variables, outside of the treatment variable, can contribute to observed effects in the experiment and can limit the researcher's ability to determine whether group differences can be attributed to the treatment itself or other extraneous factors (Gall et al., 1999).

Gall and colleagues (1999) identified the following extraneous variables requiring control in experiment and quasi-experiment research studies: (a) history, (b) differential selection, (c) maturation, (d) attrition/mortality, (e) instrumentation, (f) statistical regression, (g) testing, (h) selection-maturation interaction. A description of how each of these internal validity threats was addressed follows.

History

History refers to events occurring outside of the treatment during the study that may impact the dependent variable (Gay & Airasian, 2000). The length of treatment was designed to occur within a timeframe of one month to minimize the likelihood of potential events outside the treatment impacting student learning. Student work in the treatment occurred during three separate weeks, beginning on November 13th and concluding on December 12th. All treatment condition students completed two CO2FX sessions per week on consecutive days throughout the intervention.

Differential

Differential selection occurs when already intact groups are used, increasing the likelihood that a difference between groups accounts for posttest differences (Gay & Airasian, 2000). The design of this study utilized a stratified random assignment to ensure equal representation among low, middle, and higher level achievers of emergent-type responses to pretest questions.

Maturation

Gay and Airasian (2000) stated, “Maturation refers to natural physical, intellectual, and emotional changes that occur in the participants over a period of time” (p. 373). Additionally, Gay and Airasian mentioned that, especially in lengthy studies, students may become “unmotivated, anxious, or just plain bored” (p. 373). The overall duration of the entire study, from pretest to posttest, lasted two and a half months to account for maturation differences. The timeframe for this research should not necessarily be long enough for maturation changes to occur. However, two students in the treatment group mentioned boredom while working in the simulation during the final two of seven intervention sessions and, at times, were noticeably disengaged. The comments of these students do not necessarily differ from what may be found in other students working in a project-based laboratory environment as students have different learning styles and preferences.

Mortality

Mortality refers to participants dropping out of the study (Schloss & Smith, 1999).

The research study did not begin until one full month of the school year had passed to account for students adding and dropping classes. No students were dropped from the class during this research study. During the first week of October, the researcher discussed the purpose of the research with students and spent the remainder of the week observing the class and securing written parent permission. In discussions with the classroom teacher, 2 of the 20 enrolled students were identified as potential attrition risks due to extensive absenteeism. Both students were contacted individually and declined participation in the study.

Instrumentation

Instrumentation refers to a lack of consistency in the measuring instrument, which in this case was the pretest and posttest (Gay & Airasian, 2000). Pretest and posttest questions for this research were derived from earlier complexity research of Bar-Yam, 1997; Casti, 1994a, 1994b; Charles, 2003; Gell-Mann, 1994; Holland, 1995; Jacobson, 2000; Kauffman, 1995; Resnick, 1994. Of the initial nine near and far transfer questions used in prior research pertaining to reductive and complex responses, five were eliminated due to content validity concerns. Schloss and Smith (1999) stated, “An instrument with high content validity includes a representative sample of the skills or concepts being assessed, stimulus features comparable to those found in real situations, and response features comparable to the expected real situations” (p. 112). The validity of the four remaining open-ended questions selected from the previous bank of nine were deemed appropriate in that the engineering or technological context matched the construct being evaluated (Schloss & Smith). Additionally, each technologically orientated question aligned with the ITEA's STL's (2000/2002).

Testing

Pretest sensitization results in improved posttests scores, typically as a result of a short timeframe between testing periods and frequently is identified within studies assessing factual recall (Gay & Airasian, 2000). The tests themselves consisted of two open-ended questions, one near transfer question and one far transfer question. While both pretest and posttest questions were designed to measure six component beliefs of students' ontological views, the open-ended nature did not lend itself to predisposed answers based upon pretest questions.

Statistical Regression

Statistical regression refers to extremely high or extremely low scores' likelihood of regressing to the mean with subsequent test administrations (Gay & Airasian, 2000). Therefore, higher pretest scores have increased odds of being lower (closer to the mean) on the posttest, as well as with odds of lower pretest scores increasing on the posttest. This research study utilized a stratified random assignment procedure for control and treatment groups, resulting in similar distributions of high, middle and low ranging scores on the pretest into both groups. Thus, a regression to the mean occurring in one group would be compensated for with comparable group dynamics.

Selection-Maturation Interaction

If established groups are used, one group may benefit more than another from the treatment due to maturation, history or testing factors (Gay & Airasian, 2000). In this study intact groups was not an issue due to the stratified random assignment of students prior to treatment.

External Validity

While internal validity is concerned with factors other than the independent variable that can be attributed to outcomes with the dependent variable, external validity is an equally important threat to an experiment's validity. Gay and Airasian (2000) described external validity as a "focus on threats or rival explanations that would permit the results of a study to be generalized to other settings or groups" (p. 372). This research is limited in its generalizability to a population comprised of suburban, freshman-level students enrolled in introductory ETE courses.

Gay and Airasian (2000) identified the following threats to external validity that limit generalizability to other populations: pretest-treatment interaction, selection-treatment interaction, multiple treatment interference, specificity of variables, treatment diffusion, experimenter effects, and reactive effects. The first four threats to external validity are not applicable to this research. However, the remaining three threats are worthy of inclusion as their relationship to the generalizabilty of this research is evident.

Diffusion

Diffusion refers to members of the control or treatment group sharing information with members of the opposite group, resulting in a contamination of the treatment. During this research, the opportunity for diffusion clearly existed as the treatment was a complex systems simulation available online at www.globalwarminginteractive.com.

Accounting for this limitation in controlling the availability of the treatment, a survey was administered following the posttest. All students reported the number of hours per week they spent playing video games outside of school, as well as how many hours were spent playing the CO2FX simulation. Only one student in the treatment group reported accessing the simulation outside of class, in this case for 2 hours. As the control group did not report use of the CO2FX, it appears the threat of diffusion can be dismissed.

Experimenter Effects

Gay and Airasian (2000) stated, "There is evidence that researchers themselves may present potential threats to the external validity of studies" either passively or actively (p. 381). During this study the researcher interviewed each student as a component of the pretest and posttest procedure. Sharing similar characteristics such as race or gender between researcher and research subject could present a passive potential threat opportunity (Gay & Airasian). Little could be done to account for this short of having a third party conduct the interviews, which in this case did not occur. Probably more noteworthy would be an active case in which the researcher was familiar with student membership in control and treatment groups as follow up questions were asked during the posttest interview session. Accounting for this potential threat, an effort was made to ask follow up questions that were not leading or designed to summarize student reflections. It should be noted that as the number of interviews increases, in this case a total of 36, the likelihood of error increases.

Reactive Arrangements

Reactive arrangements address potential validity threats that occur when research subjects' influence the outcome based upon perceptions that special attention is focused upon them during the study (Gay & Airasian, 2000). Two such examples are the Hawthorne effect and the John Henry effect. Within these examples, the research subjects performed to a higher level based upon their knowledge that they were being observed or felt part of a competition. During this research, all subjects were informed that they would participate eventually as members of their respective groups (control and treatment) receiving instruction within the treatment condition. This was done to minimize the perception of competition between groups or any related novelty effect.

Research Implications

This initial complex systems research in ETE provided qualitative evidence that freshman high school students recognized complex systems concepts, albeit through trial-and-error "see what happens" approaches. In written form and in transcribed statements, student complexity explanations tend to lack thorough descriptors. Penner's (2000) research found that "their statements do suggest some understanding that 'seeing what happens' may be the only currently available means of studying the effects of micro-level changes on a system" (p. 800). With additional research needed to substantiate this claim, ETE could provide a rich environment for multidisciplinary, "bigger picture" complex systems inquiry.

Each of the three treatment groups developed decision making patterns focused on variables unique to their team while addressing a global warming scenario. In addition to "see what happens approaches" teams were consistent in the refinement of initial dramatic budgetary decisions to subtler adjustments in later simulation attempts. Their problem solving attempts reflect similar strategies in CO2FX as would be found working in a hands-on, project based discipline. Gee (2003), speaking of characteristics of good video games, stated, "There are nearly always multiple solutions to any given problem. Players can choose strategies that fit their style of learning, thinking, and acting…this is highly motivating both for learning and playing the game" (p. 81). It appears an intrinsic trial-and-error problem-solving approach in ETE lends itself to a variety of learning approaches. Developing age appropriate complexity inquiry challenges with multiple avenues for success is equally important for gaming environments as it is in a project based environment.

For ETE as a discipline, complex systems approaches provide an alternative to the current perception within the discipline, that being one of complexity pertaining to machines or mechanical systems. *Standards for technological literacy: Content for the study of technology* (ITEA, 2000/2002) provide four technology and society standards that would serve as ideal starting points to address complex economic, social, political, and cultural effects of technology. Utilizing a technology and society framework, complex issues such as global warming, military conflict, and border control could be addressed. Approaches for doing so could be in a gaming environment as in this research or as part of a larger integrated interdisciplinary curriculum.

Hmelo and colleagues (2000) suggested that, in order to understand complex systems, students “need to build working models of subsystems, put some of those subsystems together, and focus on the interactions between the functional subparts” (p. 291). This is a domain complementary to ETE’s historical strength. Designed world standards addressing power and energy, communication, construction, manufacturing and transportation have been emphasized for nearly 30 years. This emphasis, however, has not addressed complex systems concepts in the same manner as science.

Identified in an appropriate framework with real world examples could make complexity concepts investigation and use “doable.” As one example, feedback is a term most technology teachers rely upon as a systems element. An input, process, output, feedback model is typically introduced at the middle school level. Communication teachers site examples of positive feedback in audio recording with an open microphone next to a speaker system. The role of feedback is addressed with thermostats in home heating control systems. Setting the cruise control on an automobile is another example from transportation domains.

Developing physical models to these examples highlighting complexity concepts could provide the structure novices learners need (Hmelo-Silver & Pfeffer, 2004). Along with physical models, animations and simulations could be used to provide deeper level behavior and function understanding required for transfer to dissimilar domains. Beyond learning terminology and gaining conceptual understanding, research into rich, complex systems learning environments could highlight a multidisciplinary approach utilizing ETE as an organizer. Actively engaging students with age-appropriate activities and technologies, such as Zuckerman’s (2004) approach with systems blocks at the elementary level, would be fruitful at middle and high school levels as well.

Student learning in complex systems in science provides concrete examples of how computational modeling technologies such as StarLogo and STELLA provide experiential learning via participatory engagement. Unlike the current research which used a single model repeated times, StarLogo research (Klopfer et al., 2005) provided multiple experiences across several simulations. Gick and Holyoak's (1983) research suggested that learning transfer was enhanced when multiple analogs were presented. Merging the strengths of current computational modeling capabilities demonstrated in science domains with "real world" approaches in technology education could provide an alternative method delivering concurrent analogous examples. These approaches could demonstrate structure [physical properties] from technologies developed, converging with complementary behaviors and functions through accompanying simulations.

Complex systems and events with cultural, economic, social and political effects of technology have become part of our everyday lives. During the year in which this research was conducted, the price of oil rose from $72 to $145 a barrel. Projections were estimated that the price would climb beyond $200 within 2 years. Transportation demands, plastics manufacturing, and home heating are just several consumers of fossil fuels. As the price increases, the demand grows for alternative energy options. *STL* (ITEA, 2000/2002) standards address effects of technology on the environment, the role of tradeoffs, and intricate cultural, economic, social and political effects of technology. Alternative or sustainable energy fit quite well here, lending themselves to contextualized and relevant complexity lines of inquiry.

Just as tradeoffs to the complex fossil fuel/alternative energy debate were highlighted in this class, students participating in the CO2FX simulation made similar tradeoffs serving as collaborating economic, policy, and science/technology advisors. Gick and Holyoak's (1983) research would lead us to believe that students' potential transfer skills will be enhanced when presented with multiple analogous examples. If student exposure to a framework of complex systems concepts does, indeed, enhance transfer, the transition from a "conceptual" learning mode to a "practical" working mode could address current education limitations. A past president of the National Academy of Engineering, Wulf (2002) stated, "Many of the students who make it to graduation enter the workforce ill-equipped for the complex interactions, across many disciplines, of real-world engineered systems" (p. 1).

Research is needed to determine if complex systems strengths from computational modeling approaches from science domains can be leveraged with ETE's levels of technical complexity of systems approaches. As ETE teacher preparation holds a different view of complex systems, alternative methods of computer simulation environments are desirable. The time taken to learn the content in order to understand programming within computational modeling programs such as STELLA could prevent teachers from taking the initial step needed to advance this area of inquiry. However, if more simulations similar to CO2FX were developed with the appropriate complex systems concepts, teachers could gain confidence working in these settings alongside their students.

Gee (2003) identified 36 principles related to learning in video games that can be applied to future development of complex systems simulations. Utilizing these principles, learning tools for complexity inquiry could facilitate abstract representation and cognition promoting transfer to dissimilar domains. Gee's 36 principles have been reduced to the five most representative of student learning issues in complex systems:

> *Semiotic Principle* [italics added]: Learning about and coming to appreciate interrelations within and across multiple sign systems as a complex system is core to the learning experience.
>
> *"Regime of competence"* Principle [italics added]: The learner gets ample opportunity to operate within, but at the outer edge of, his or her resources, so that at those points things are felt as challenging but not "undoable."
>
> *Transfer Principle* [italics added]: Learners are given ample opportunity to practice, and support for, transferring what they have learned earlier to later problems, including problems that require adapting and transforming that earlier learning.
>
> *Distributed Principle* [italics added]: Meaning/knowledge is distributed across the learner, objects, tools, symbols, technologies, and the environment.
>
> *Incremental Principle* [italics added]: Learning situations are ordered in the early stages so that earlier cases lead to generalizations that are fruitful for later cases. When learners face more complex cases later, the learning space is constrained by the sorts of fruitful patterns or generalizations the learner has found earlier. (pp. 207-211)

Simulations, whether developed by students or outside entities, following these principles could provide a multitude of opportunities to enhance student learning. While StarLogo or STELLA computational modeling software put the programmer in position to learn complexity concepts within their programs, other alternatives exist. The CO2FX simulation used in this research relied upon embedded complexity concepts, but also provided information on demand. Students come with a wide variety of learning preferences. Therefore, flexibility and alternatives within simulations are important. Perhaps, stop action animation could provide an alternative medium used in conjunction with simulations to provide more detailed behavior and function levels of analysis.

Recommendations

Jacobson and Wilensky (2006) stated that research into complex systems and student learning could "help address the unfortunate situation whereby many students view science as rote memorization of isolated and decontextualized facts for which they see little use in their daily lives" (p. 24). Further research is needed to identify effective pedagogy, curricular content, and student practice in complex systems. This research used a participatory experience relying upon student computer simulation and gaming experience to "defeat" global warming and, in the process, recognize embedded complexity elements. Identifying similar approaches necessitating student synthesis of economic, political, and science/technology elements or perhaps analytic methods requires additional research, as well.

The role of the teacher within the current research was limited to instruction as traditionally delivered with the control group. This was due, in part, to concerns related to professional development change over a short timeframe (Loucks-Horsley et al., 1998). As such, statistically significant quantitative results were not found as the intervention was delivered. However, expanding the role of the teacher including the reinforcement of complexity attributes such as "small changes have big effects," as was noted by a treatment student, would be noteworthy for future research. With the classroom teacher assuming a more significant capacity identifying complexity elements from the video supplement, or based on student's daily lab report reflections, different results could emerge. In this manner the teacher would serve to scaffold student comprehension or conjectures. Using this as an initial adjustment of the current research would be interesting to note CWMM and EFMM group differences or changes from the current study.

Further recommendations are provided in two distinct categories for teachers and future research. Teacher recommendations are directed at an audience comprised of engineering and technology educators. Ottino (2004) stated, "complexity and engineering seem at odds–complex systems are about adaptation, whereas engineering is about purpose" (p. 399). As current teaching approaches typically rely upon an analytic focus at the component level in engineering and technology domains, suggestions for a synthesis focus complementary of complex systems are provided. Recommendations for future research provide a suggested framework of potential studies investigating student learning, role of teacher professional development, and complexity pedagogy.

Recommendations for Teachers

Engineering and Technology Education teacher's undergraduate preparation typically consists of reductive-oriented approaches focusing upon systems at the component level. This leads to the study of "complex" problems, as was investigated in this research, whereby, the control group explored electrical, mechanical, and fluid power systems in the design of a robot. In order to recognize emergence, adaptation, and self-organization as defining concepts of complex systems, teachers will need professional development. Understanding the role of feedback loops, randomness, nonlinear action, and interrelationships is crucial in transitioning to complex systems top-down synthesis approaches.

Engaging with likeminded individuals in workshops presented by knowledgeable professionals would be the ideal starting point for teachers. Professional development opportunities can be found with the New England Complex Systems Institute. This non-profit research and education institute provides a wide range of opportunities for novice and experts alike. In order to better represent complex systems, teachers will need to understand terminology and convey how parts of a system give rise to its collective behaviors. This research identified an approach for doing so while focusing on technology standards (ITEA, 2000/2002) pertaining to the cultural, social, political, and economic effects of technology. Additionally, complexity readings addressing student learning such as Dörner's (1996) *The Logic of Failure: Recognizing and Avoiding Error in Complex Situations* provided the researcher an ideal starting point from which other novices would benefit as well.

Recommendations for Further Study

Just as exploring complexity concepts and principles at primary grades rather than waiting until students become acclimated to analytical education practices makes sense, so does a focus on pre-service teachers. Training future teachers with a method conducive to "bigger picture" learning would rely upon approaches fostering complexity principles. Initial research into technology teachers' employing nonlinear approaches from Foster (1997) and Berrett (2003) are starting points that require additional detail and extension.

Preparing learning environments for pre-service teachers to experience complexity concepts while structuring learning would assist in breaking a cyclical process, whereby, teachers repeat the practices of their teachers. Berrett's (2003) research into a nonlinear teaching pedagogy could be used to structure classroom settings and content delivery approaches incorporating thematic approaches complementary to complexity inquiry. His investigation of an exemplar veteran teacher's approaching integrating traditionally standalone ETE clusters (i.e., communication, construction, manufacturing, transportation, and power and energy into a contextualized aerospace framework) is worthy of further research. As just one example within a communication course, the use of modulated HeNe lasers used to transmit messages over fiber optics provide an ideal opportunity to investigate emergence as a complexity concept. Research into individual technologies as a component of a larger technology and society framework provides a wide variety of complexity research opportunities. Such research could train a new generation of teachers to enter with a complexity-rich, pedagogical content knowledge base. In closing, the following recommendations for further research conclude this section.

1. Repeat this study with senior level students who possess more domain knowledge and experience to determine if older students are more likely to recognize underlying complexity patterns.

2. Conduct the same study and invert pretest and posttest questions. One of the coding analysts commented during posttest analysis that the near transfer, posttest question did not seem as conducive to the range of responses across the six component

beliefs of interest. Reversing the order of questions may reveal differences that could be followed up with additional research.

3. Beyond student exploration within simulations representing complex scenarios, the next evolution would be a study investigating teacher roles delivering complexity instruction. This necessitates teacher professional development to illustrate to students how parts of a system give rise to its collective behaviors. Using the CO2FX simulation as an example, classroom teachers could better represent the interwoven nature of economic, policy, and science/technology matters. Doing so would reinforce student intuitive approaches which touched upon emergent-like elements and may have been enhanced if key complexity characteristics were so defined by a classroom teacher.

4. Following the investigation of current events with cultural, economic, social, and political elements, have students develop their own computational modeling simulations. Developing models with packages such as StarLogo or STELLA provides an opportunity for students to further understand complex systems principles. As student programmers creating complex scenarios with random generators and feedback loops, a scaffolding of learning occurs. Assess student answers to pretest and posttest questions with the same OMMT as part of a study in which they incorporate nonlinearity, randomness, and feedback loops into their complex systems simulation designs.

5. Replicate the study to isolate learning within individual students. Perhaps a single subject methodology with think aloud protocols could further elucidate learning progressions within a complexity framework. This could initially occur within a complexity simulation such as the CO2FX used in this research. Following up a student

over time, perhaps multiple semesters, as they continue on to program their own computational modeling could pinpoint cognitive growth within an individual.

6. A common complex systems principles and terminology framework to science and technology would prove beneficial. Emergence, adaptation, self-organization, feedback, nonlinearity, randomness and stochastic are terms a vast majority of technology teachers may find frightening. Relevant real world examples modeling concepts are needed for discipline renowned for hands-on learning approaches.

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APPENDICES

Appendix A

Course Syllabus

Course Syllabus

Course Title: Introduction to Technology and Engineering

Curriculum Area: Technology Education **Course Length:** Year <u>Semester</u>

Credit Status: Required <u>Elective</u> **Date Submitted:** 08/30/07

<u>Expected Student Results/Power Standards</u>

At the end of the course the student will be expected to:

1. **Students will understand that technology is an extension of human capability.**
2. **Students will recognize that systems are made up of individual components and that each component affects the operation of the system and its relationship to other systems.**
3. **Students will be able to define problems, gather information, explore options, devise a solution, evaluate the outcome, and communicate the results.**
4. **Students will understand that technology affects society and the environment in ways that are both planned and unplanned and desirable and undesirable.**

<u>Course Outline and Instructional Strategies:</u>

Aligned with the identified course standards

I. Data Collection

- a. Excel Spreadsheet Rubric
- b. PowerPoint Rubric

II. Measurement

- a. Metric System Assessment
- b. Imperial System Assessment
- c. Conversion Assessment

III. Orthographic Sketching

- a. Missing Views Assignment
- b. Orthographic from Isometric Views Assignment
- c. Sketching an Object Assignment

IV. Computer Aided Drafting

- a. SolidWorks Rubric

V. System's Design

- a. System Design Assignment

Course Syllabus (continued)

VI. Scheduling and Flowcharting

a. Flowcharting Assignment

b. Scheduling Assignment

c. Assembly Line Rubric

VII. Power & Transmission

a. Gear Assignment

b. Pulley Assignment

c. Transportation Design Rubric

VIII. Alternative Energy

a. Solar Energy Assignment

b. Solar Racer Rubric

IX. Mid-Term Exam

a. Object-Referenced Evaluation

X. Hydraulics & Pneumatics

a. Pneumatics Assignment

b. Hydraulics Assignment

XI. Electrical Circuits

a. Series Circuit Assignment

b. Parallel Circuit Assignment

XII. Safety Procedures

a. Safety Assessment

XIII. Engineering Design & Problem Solving

a. Performance-Based Evaluation Rubric

XIV. Final Exam

a. Subjective-Referenced Evaluation

Appendix B

Parental Consent Form

Utah State University

Date Created: August 31, 2007; Page 1 of 3
USU IRB Approved 08/31/2007
Approval terminates 08/30/2008
Protocol Number 1887
IRB Password Protected per IRB Administrator

COLLEGE OF ENGINEERING
Department of Engineering and Technology Education
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Telephone: (435) 797-1795
Fax: (435) 797-2567

PARENT PERMISSION
Complex Systems Dynamics in Engineering and Technology Education:
The Role Software Simulations Serve in Student Learning

Introduction/ Purpose

Dr. Kurt Becker in the Department of Engineering and Technology Education at Utah State University, and Student researcher, Doug Walrath are conducting a research study to find out how students learn engineering content with the use of computer simulations. This research is a unique opportunity to participate in a study on behalf of the National Center for Engineering and Technology Education; a Center for Learning and Teaching recognized for research into student learning in engineering environment. We are asking for your permission to have your son or daughter participate in this research. There will be approximately 20 student participants involved with this research.

Procedures

If you give permission for your child to participate in this research study, your child will be expected to do the following: answer two written engineering-related questions in October and two more in December; participate in two interviews designed to further understand the written questions and allow the researcher to observe your child's daily work within the *Introduction to Engineering* course, including the recording of a computer screen while working within a computer simulation. The computer screen will be recorded without visually recording students. However voice recordings will capture students' thoughts as they speak aloud while working in the simulation. The interviews will take about 15 minutes each and the observations will take place during 5 weeks in October 2007 through January 2008. Total time in the study will be approximately 10 hours of in-class time. Work related to this research is designed to replace other assignments and will not place extra coursework burden on students.

Risks

Students may feel a sense of uneasiness with an observer in the classroom environment and during interviews. To minimize potential discomfort, interviews will be conducted in isolation of other students. Daily observations will be in the confines of the students' classroom working environment. There is minimal risk in participating in this study.

Benefits

Students participating in this research will become part of a network of nine universities conducting research into how students learn engineering and technology education content. Their involvement will expose them to the latest engineering-related career pathways information and programs of these universities. Additionally student participants, as well as the classroom

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PARENT PERMISSION
Complex Systems Dynamics in Engineering and Technology Education:
The Role Software Simulations Serve in Student Learning

teacher, may gain insights into styles of learning, which could be highlighted through the computer simulation gaming environment.

Explanation & offer to answer questions
Doug Walrath has explained this research study to your son or daughter and answered their questions. If you have other questions or research-related problems, you may reach Professor Kurt Becker at (435) 797-2076, kbecker@cc.usu.edu; or Doug Walrath at (208) 720-9937, walrathd@comcast.net

Voluntary nature of participation and right to withdraw without consequence
Participation in this research is entirely voluntary. Your student may refuse to participate or withdraw at any time without consequence.

Confidentiality
Research records will be kept confidential, consistent with federal and state regulations. Only the researchers will have access to the data which will be kept in a locked file cabinet in a locked room. Your students name will be replaced with a code to protect his/her privacy. Personal, identifiable information will be kept for six months and then destroyed. Voice recording data will also be destroyed after six months.

IRB Approval Statement
The Institutional Review Board for the protection of human participants at USU has reviewed and approved this research study. If you have any questions or concerns about your rights, you may contact the IRB at (435) 797-1821

Copy of consent
You have been given two copies of this Informed Consent. Please sign both copies and retain one copy for your files.

Researcher's Statement
"I certify that the research study has been explained to the individual, by me or my research staff, and that the individual understands the nature and purpose, the possible risks and benefits associated with taking part in this research study. Any questions that have been raised have been answered."

Utah State University

COLLEGE OF ENGINEERING
Department of Engineering and Technology Education
Logan UT 84322-6000
Telephone: (435) 797-1795
Fax: (435) 797-2567

Date Created: August 31, 2007; Page 3 of 3
USU IRB Approved 08/31/2007
Approval terminates 08/30/2008
Protocol Number 1887
IRB Password Protected per IRB Administrator

PARENT PERMISSION
Complex Systems Dynamics in Engineering and Technology Education:
The Role Software Simulations Serve in Student Learning

______________________________ ______________________________

Kurt Becker, Ph.D.	Doug Walrath
Principle Investigator	Student Researcher
(435) 797-2076	(208) 720-9937

Signature of Parent/Guardian: By signing below I give my permission for my son/daughter to participate in this study.

______________________________ ______________________________

Parent or guardian's signature Date

Youth Assent: I understand that my parent(s)/guardian is/are aware of this research study and that permission has been given for me to participate. I understand that it is up to me to participate even if my parents say yes. If I do not want to be in this study, I do not have to and no one will be upset if I don't want to participate or if I change my mind later and want to stop. I can ask any questions that I have about this study now or later. By signing below, I agree to participate.

______________________________ ______________________________

Student Signature Date

Appendix C

Pilot Study Intervention Procedures CO2FX – Global Warming Simulation

Pilot Study Intervention Procedures CO2FX – Global Warming Simulation

1) Assign advisor roles to participants
- Economic
- Policy
- Science and Technology

2) Launch CO2FX computational modeling simulation

3) Record starting data values:
- Global Average Temperature: 57
  1960 Value: 57
- Global CO_2 level, percent of
  1960 value: 100

4) Read introduction, "You are starting SimuNation and entering the segment for the Country of Brazil. The time is 1960 and the world and Brazil are as yet unaware of the impacts development will have on the global environment. For the next 100 years you will be responsible for managing some of the decisions made by the Brazilian Government. If you choose wisely you can guide Brazil to a path of sustainable development and insure that the world 100 years from now is a place we would want to live."

5) Click "Continue"

6) Click on "Actions" button to open Budget Allocation box.
- Actions consoles includes:
  1. Acres to protect
  2. CO_2 tax rate per ton
  3. Average tax rate for individual
  4. Average tax rate for business

7) Click on "Data" button to determine current values
- CO_2 output = 1298
- Average life expectancy = 51
- Popular opinion = 59

8) Click “Policy” orange button
- Determine and set values in actions box
- Determine whether to lock settings or leave adjustable

9) Click “Economic” green button
- Determine and set values in actions box
- Determine whether to lock settings or leave adjustable

10) Click “Science” blue button
- Determine and set values in actions box
- Determine whether to lock settings or leave adjustable

11) Record any actions made within actions console and percentage of budget allocated:
    1. Science and Technology Spending
    2. Development Incentives
    3. Healthcare Spending
    4. Social Services Spending
    5. Agricultural Subsidies

12) Click “Submit” when all decisions have been made

13) Click “Continue” to jump forward ten years and initiate next turn.

14) Repeat steps #6 thru 13 for each decade throughout the century-long simulation.

Appendix D

Pretest Data Collection Instrument

Pretest

DATA COLLECTION INSTRUMENT

(Brain Teaser Questions)

Name: ___________________________ Date: ________________

DIRECTIONS: You are not expected to know the "real" scientific/technical explanations; however, you may have some personal "theories" or understanding about the following phenomena. Therefore, please answer these questions using your intuition (best guess) or knowledge from informal learning experiences.

1. How would you design a large city to provide food, housing, goods, services and so on to your citizens so that there would be minimal shortages and surpluses?

2. You have probably observed the migration of birds in the spring and fall. Using your intuition what programming would be required to have robotic birds display a similar behavior resulting in the V-shaped formation that is created by a flock of birds?

Appendix E

Coding Analyst's Procedures

Coding Analyst's Procedures

1. Use Mosenthal and Hirsch procedure to parse sentences into the: agent (noun), action (verb), and object (agent effect) by highlighting each element of student answer as follows:
    - Agent (noun) will be highlighted in yellow
    - Action (verb) will be highlighted in pink
    - Object (agent effect) will be highlighted in orange

2. As identified by trainer, one analyst will begin coding the six elements of interest to the pretest questions on the Ontological Mental Model Taxonomy beginning with the Clockwork Mental Model (CWMM) Taxonomy (use RED pen) and the other analyst will begin with the Emergent Framework Mental Model (EFMM) Taxonomy (use PURPLE pen).
   You have been selected to begin your subsequent analyses with the __________.

3. Using the CWMM or EFMM taxonomy you have been selected to begin training with, code each of the related elements on the OMMT. Be sure to use appropriate pen color from step #2.
    - NOTE: The CWMM elements are shaded on the OMMT form, whereas the EFMM appear as traditional text over paper.
    - Each element will be coded as 1 if supporting evidence exists
    - Each element will be coded as 0 if no supporting evidence exists

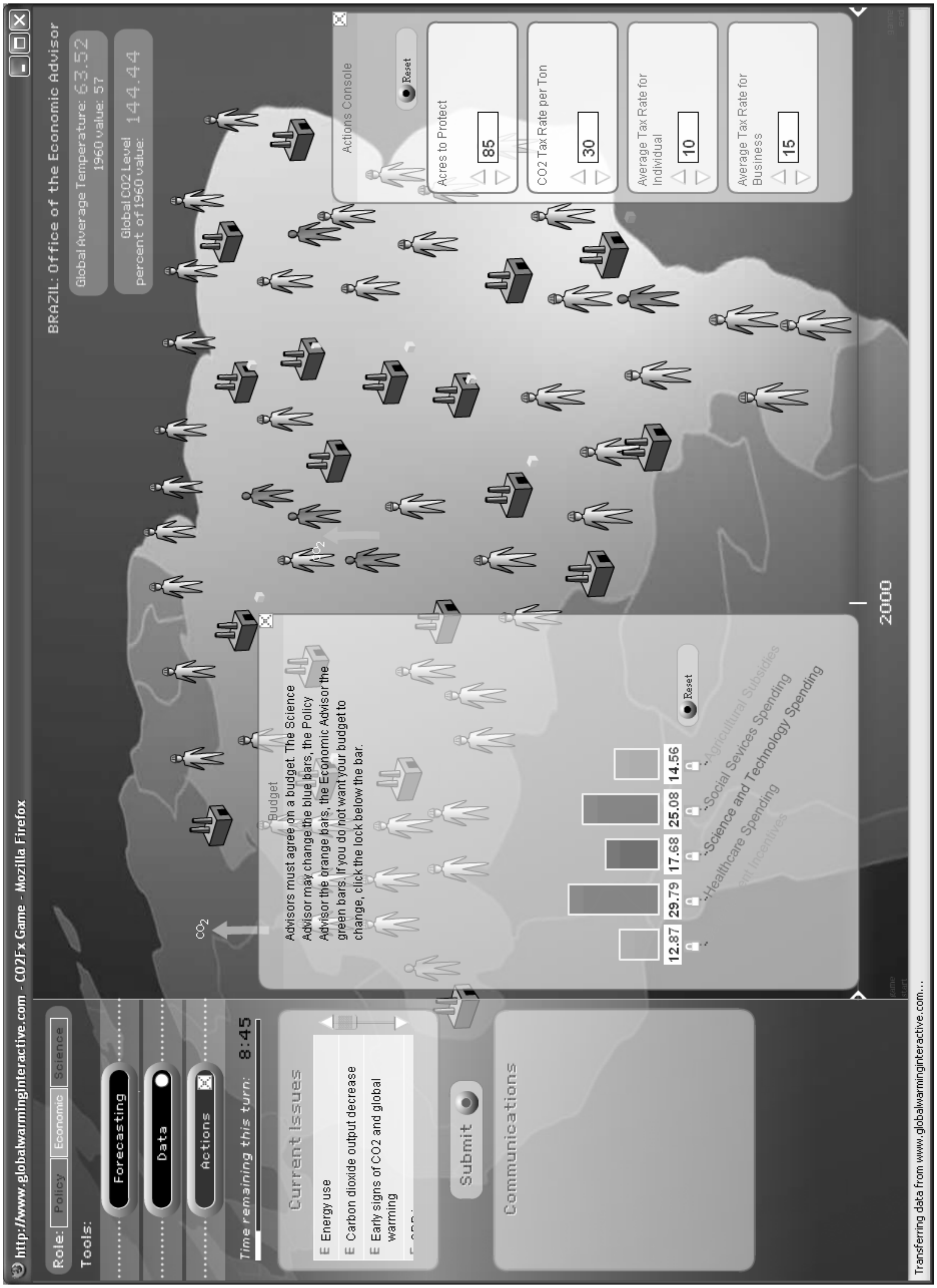
4. Using the 2nd of the Clockwork (CWMM) or Emergent Framework (EFMM) taxonomies code the pretest answers with the same procedure as step #3 above. Be sure to use appropriate pen color from step #2.
    - NOTE: examples of coding to prior student examples can be found behind the orange divider in your binder.

5. Helpful hints in coding:
    - Code the ontological perspective (large grain) last as the other five elements are to be coded at a fine grain level lending evidence to support the ontological perspective.
    - Control of system- can often be identified from yellow highlighted segments of answers (not exclusively however)
    - Actions effects- sometimes found within pink highlighted segments
    - Agents effects- a focus on the orange highlighted answer tend to support this element of interest.

6. Looking at your coded sheet, which should now be highlighted in accordance to step #1 and coded in red and purple writing to support the CWMM and EFMM taxonomies, fill out an OMMT form for pretest question #1 **AND a second** OMMT form for question #2. NOTE: (2 OMMT forms for each student).

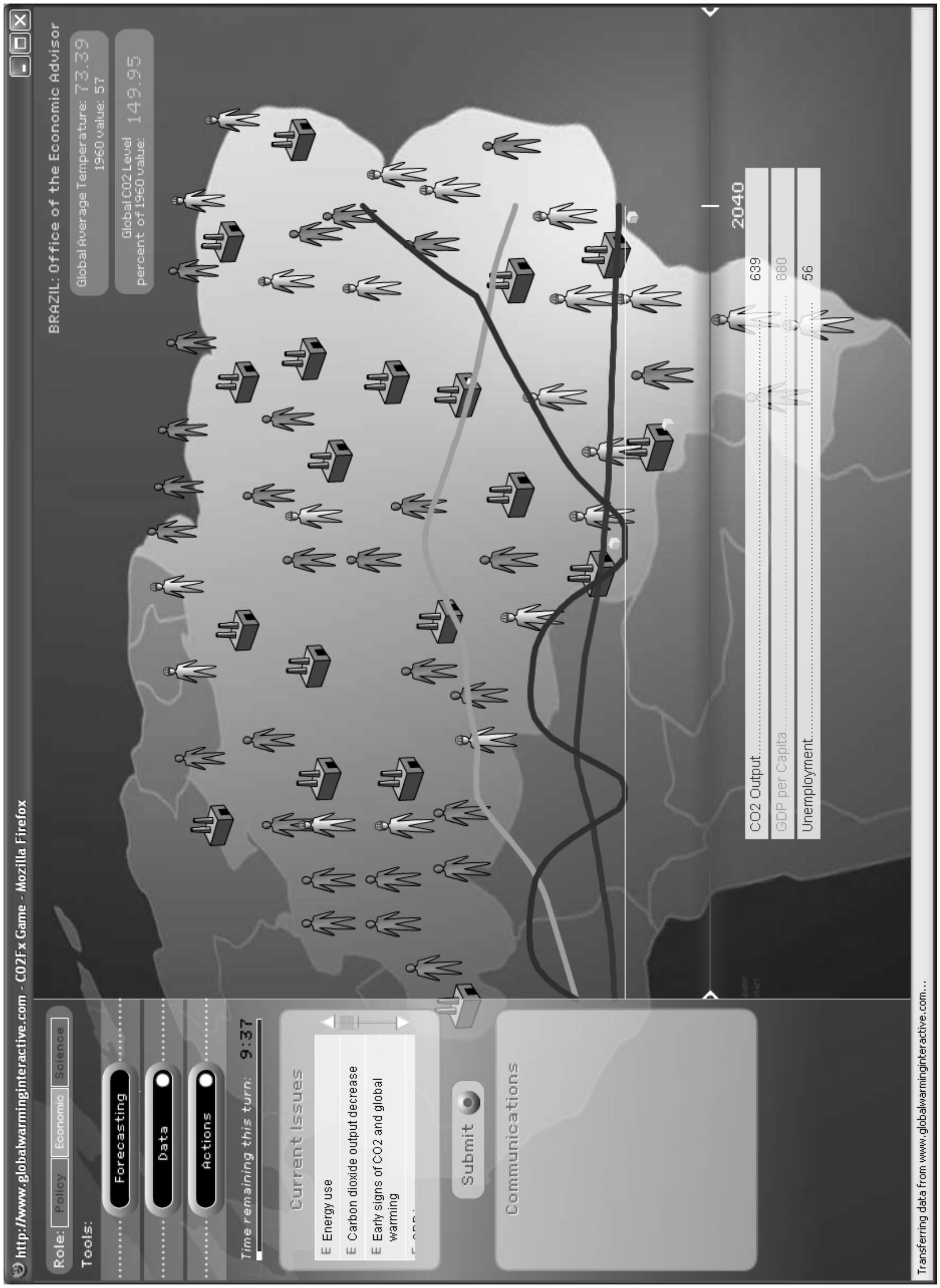
Appendix F

CO2FX Simulation Data Entry Main Screen


http://www.globalwarminginteractive.com - CO2Fx Game - Mozilla Firefox
BRAZIL: Office of the Economic Advisor
Global Average Temperature: 63.52
1960 value: 57
Global C02 Level percent of 1960 value: 144.44
Role: Policy Economic Science
Tools:
Forecasting
Data
Actions
Time remaining this turn: 8:45
Current Issues
E Energy use
E Carbon dioxide output decrease
E Early signs of CO2 and global warming
Submit
Communications
Budget
Advisors must agree on a budget. The Science Advisor may change the blue bars, the Policy Advisor the orange bars, the Economic Advisor the green bars. If you do not want your budget to change, click the lock below the bar.
12.87
29.79
17.68
25.08
14.56
Healthcare Spending
Science and Technology Spending
Social Sevices Spending
Agricultural Subsidies
Reset
Actions Console
Reset
Acres to Protect
85
CO2 Tax Rate per Ton
30
Average Tax Rate for Individual
10
Average Tax Rate for Business
15
2000
Transferring data from www.globalwarminginteractive.com...

Appendix G

CO2FX Simulation Forecasting Screen


http://www.globalwarminginteractive.com - CO2Fx Game - Mozilla Firefox
BRAZIL: Office of the Economic Advisor
Global Average Temperature: 73.39
1960 value: 57
Global CO2 Level
percent of 1960 value: 149.95
Role: Policy Economic Science
Tools:
Forecasting
Data
Actions
Time remaining this turn: 9:37
Current Issues
E Energy use
E Carbon dioxide output decrease
E Early signs of CO2 and global warming
Submit
Communications
2040
CO2 Output 639
GDP per Capita 880
Unemployment 56
Transferring data from www.globalwarminginteractive.com...

Appendix H

CO2FX Data Entry Worksheet

Team Members (1st name): ____________ ____________ ______________ Date: ________ Attempt #: 1 2 3 4 5 6 (circle one)

Advisor: Economic Policy Science/Technology

Data Entry Categories	1960	1970	1980	1990	2000	2010	2020	2030	2040	2050
Budget Decisions										
Development Incentives										
Healthcare Spending										
Sci. & Tech. Spending										
Social Services Spending										
Agricultural Subsidies										
Actions Console:										
Acres to Protect										
CO2 Tax Rate per Ton										
Ave. Tax Rate/Individual										
Ave. Tax Rate/Business										
Data Dialogue Box:										
CO2 Output										
Fossil Fuel % Energy Cons										
Population in Millions										
Fossil Fuel Remaining										
Global Average Temp:										
1960 Value:										
Global CO2 level % of 1960										

Appendix I

Posttest Data Collection Instrument

Posttest Data Collection Instrument

(Brain Teaser Questions)

Name: ___________________________ Date: _________________

DIRECTIONS: You are not expected to know the "real" scientific/technical explanations; however, you may have some personal "theories" or understanding about the following phenomena. Therefore, please answer these questions using your intuition (best guess) or knowledge from informal learning experiences.

1. How would you explain the formation of traffic jams? Are there rules that would direct this type of activity?

____

____

____

____

____

2. Suppose large deposits of gold are discovered on a distant planet. It is too dangerous and costly to send human astronauts to this planet, so we decide to send a spaceship with several thousand small robots. Each robot has a sensor to detect when it gets near gold, and a scoop to dig for and carry the gold. Once the spaceship lands on the planet, we want the robots to explore for gold and bring the gold back to the spaceship. How should we program each of the robots? In other words, what type of rules and strategies should the robots follow?

____

____

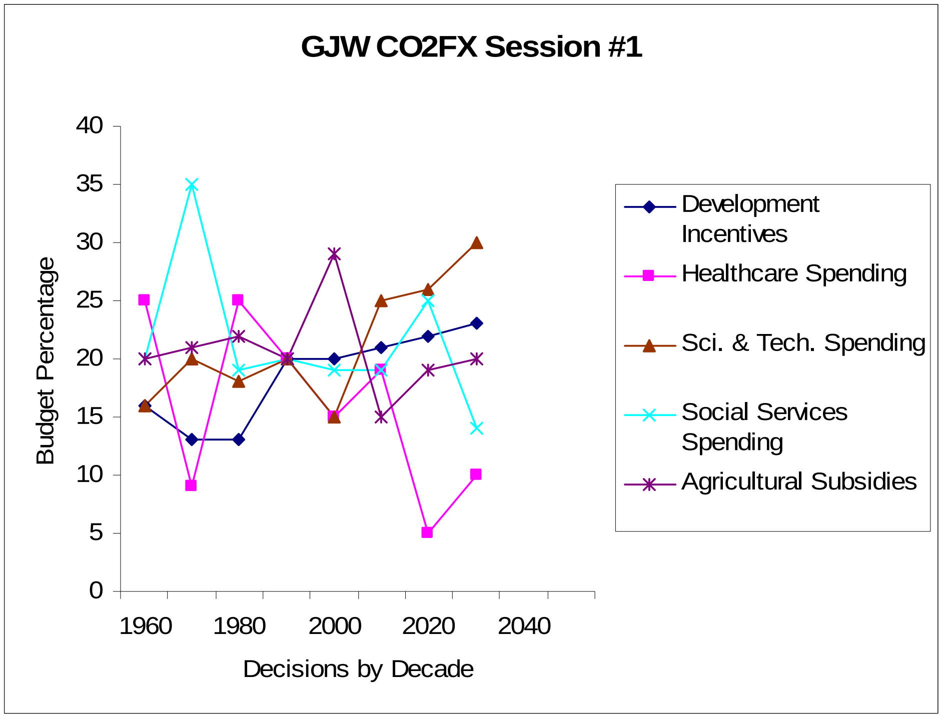
____

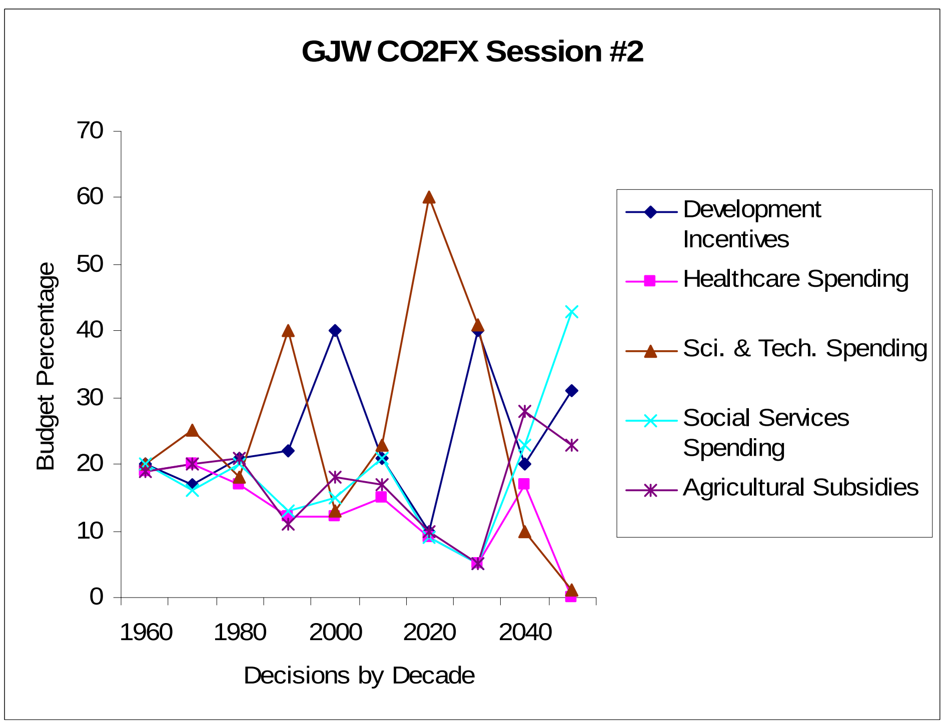
____

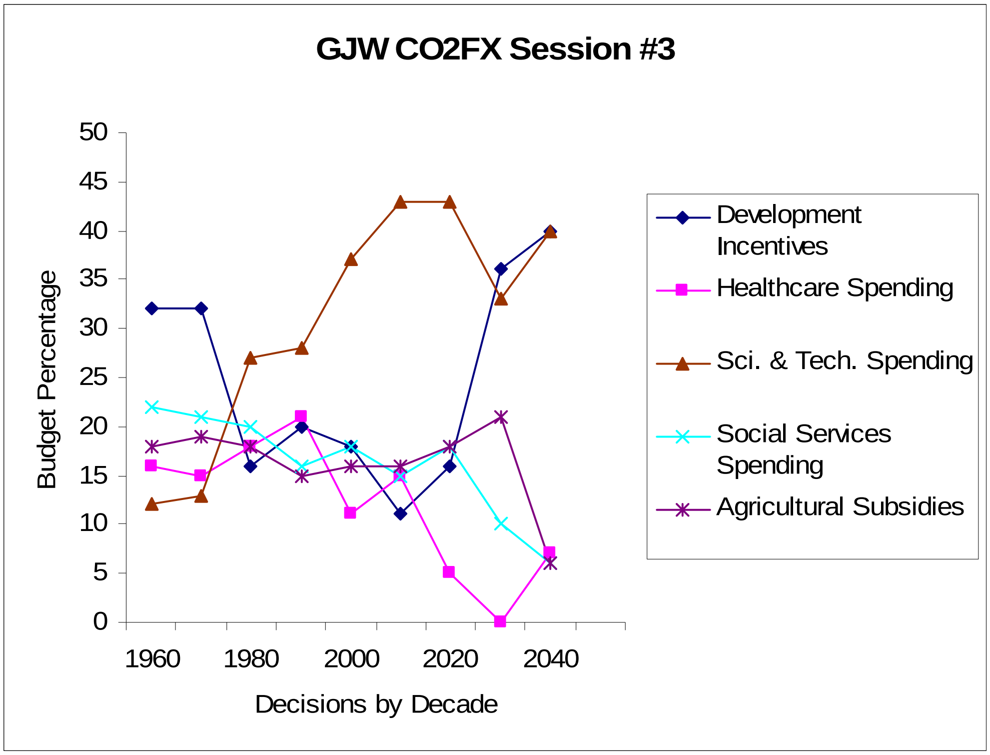
____

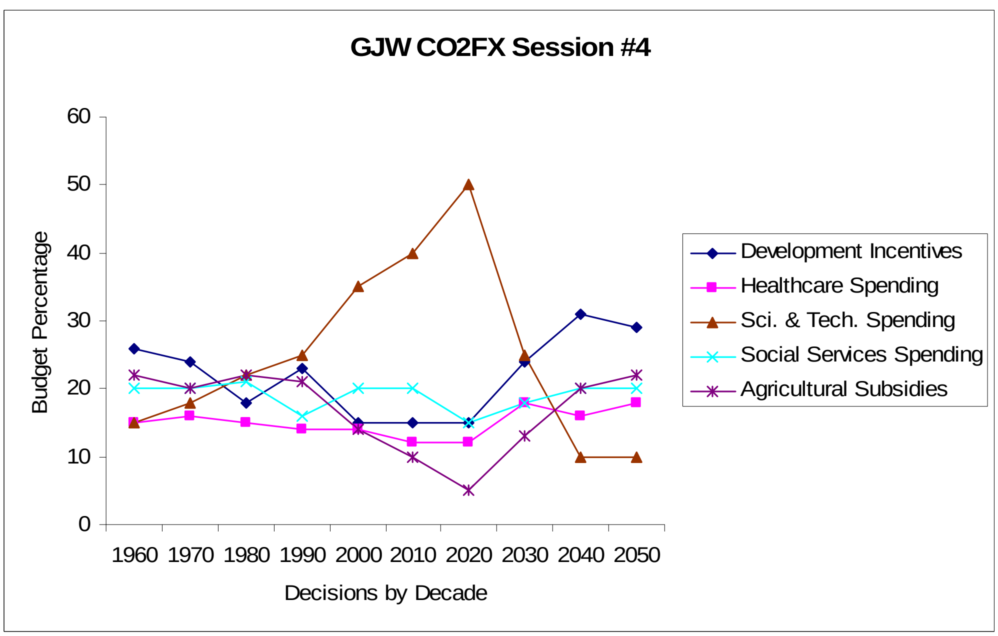
Appendix J

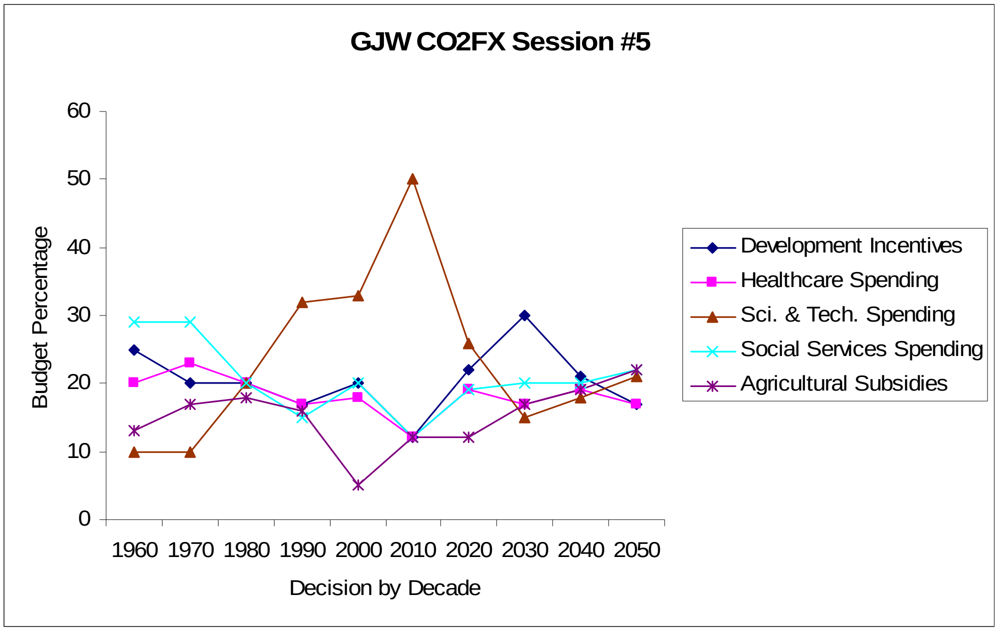
GJW CO2FX Budgetary Decisions

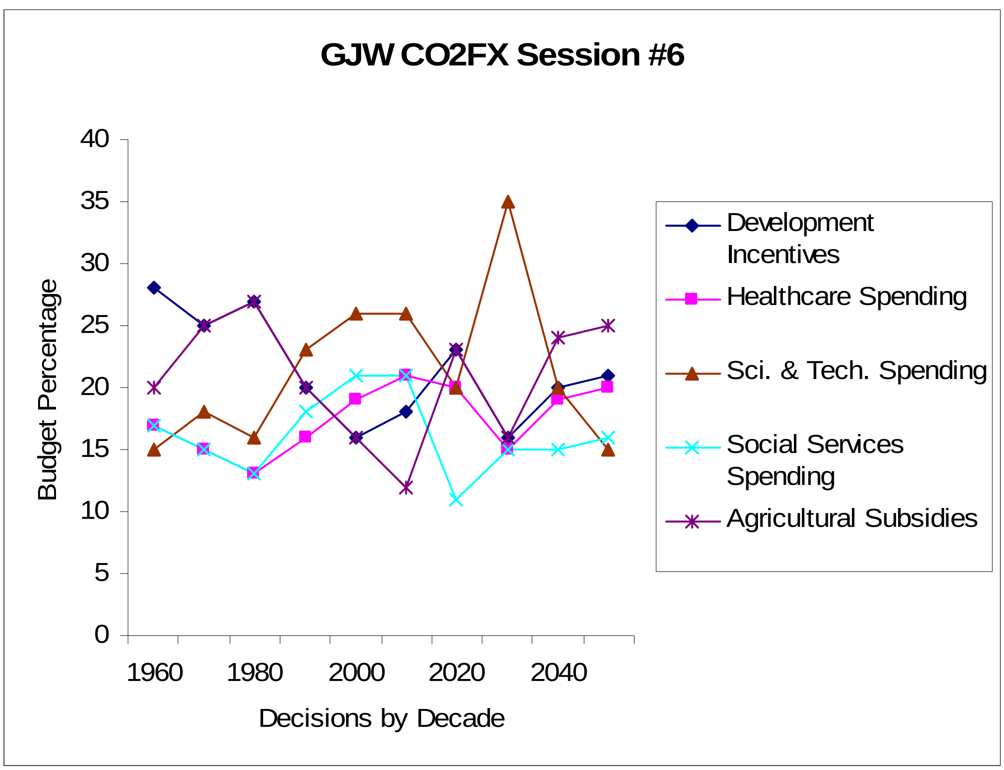

GJW CO2FX Session #1
Budget Percentage
40
35
30
25
20
15
10
5
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


GJW CO2FX Session #2
Budget Percentage
70
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


GJW CO2FX Session #3
Budget Percentage
0
5
10
15
20
25
30
35
40
45
50
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies

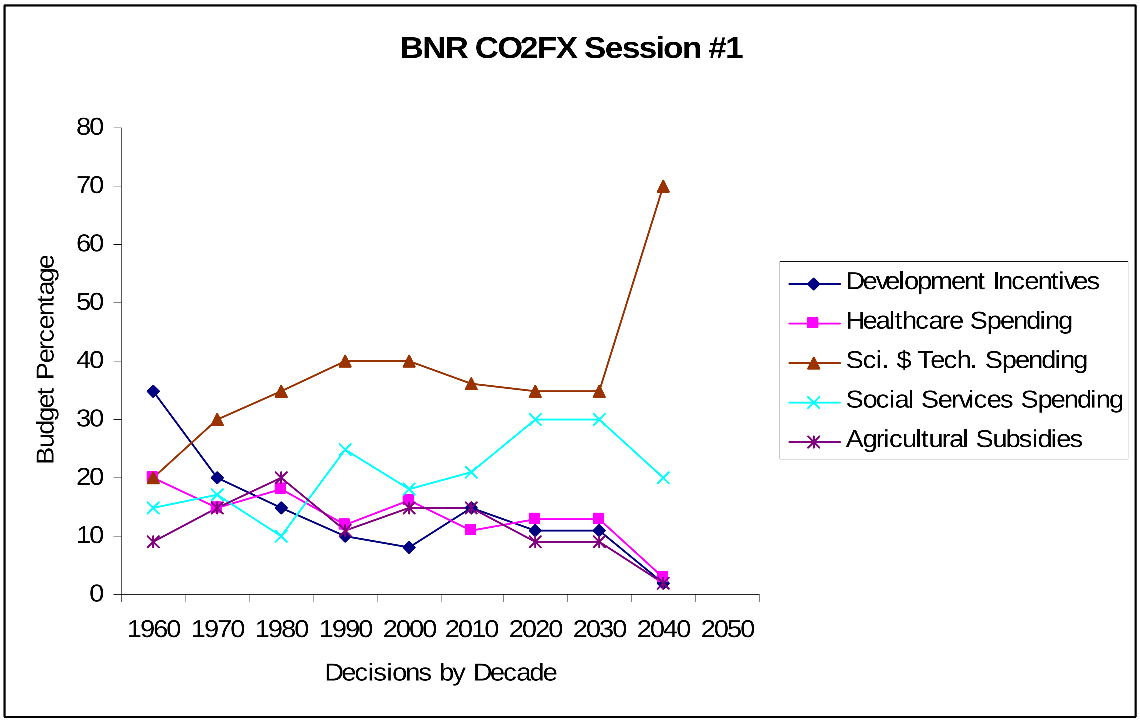

GJW CO2FX Session #4
Budget Percentage
0
10
20
30
40
50
60
1960 1970 1980 1990 2000 2010 2020 2030 2040 2050
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies

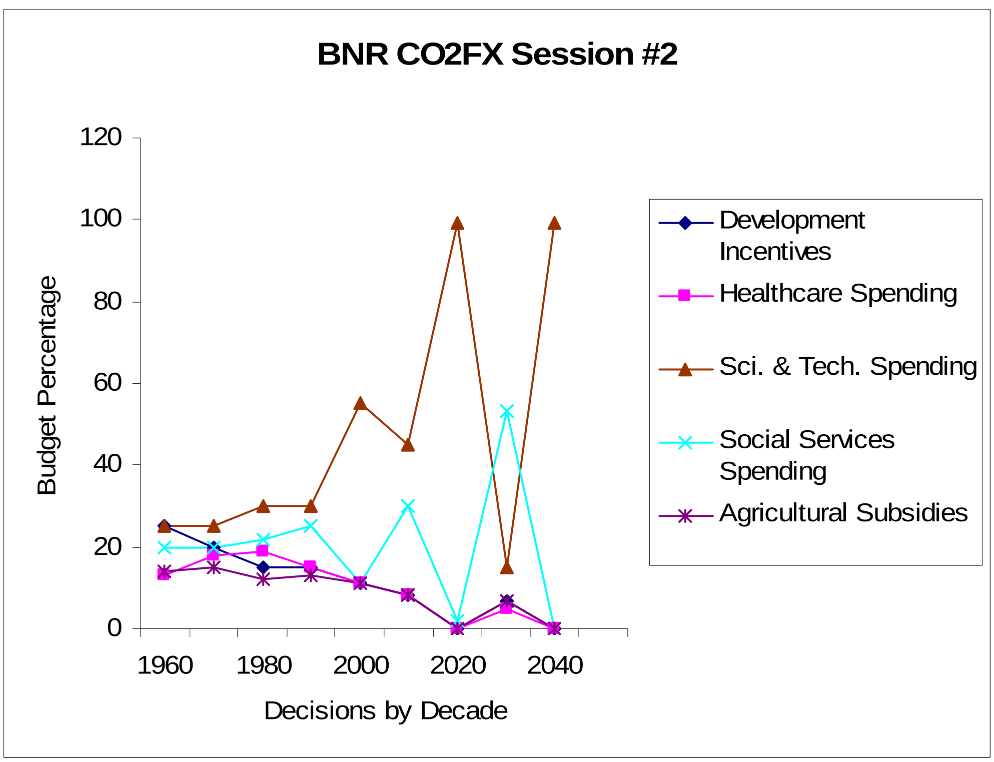

GJW CO2FX Session #5
Budget Percentage
60
50
40
30
20
10
0
1960 1970 1980 1990 2000 2010 2020 2030 2040 2050
Decision by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies

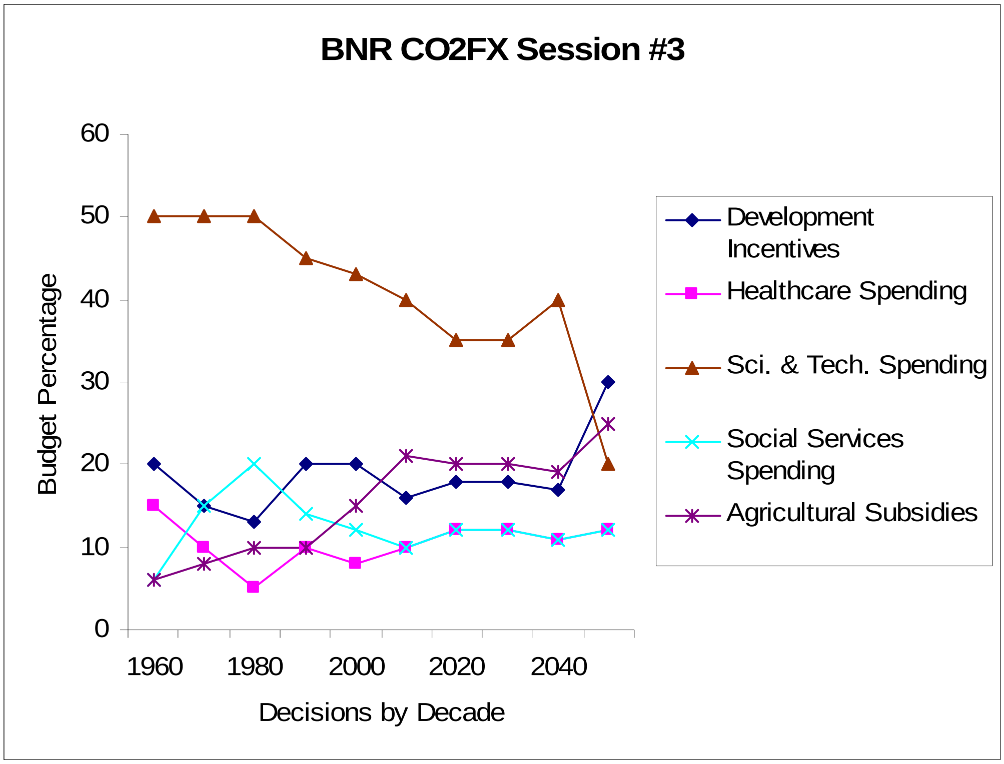

GJW CO2FX Session #6
Budget Percentage
40
35
30
25
20
15
10
5
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies

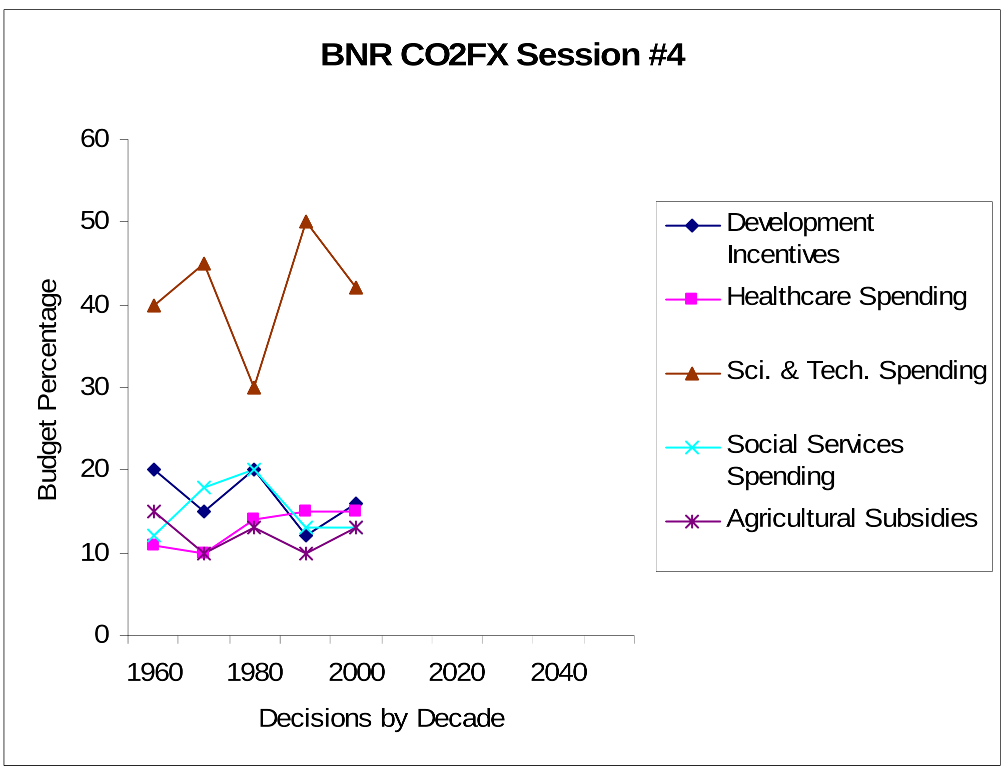
Appendix K

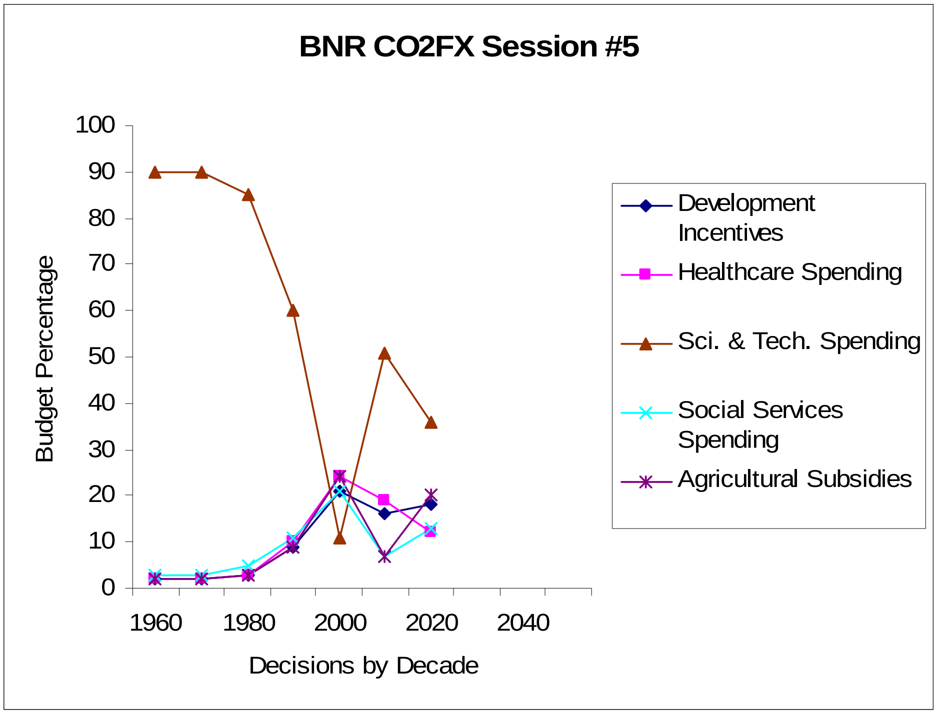
BNR CO2FX Budgetary Decisions

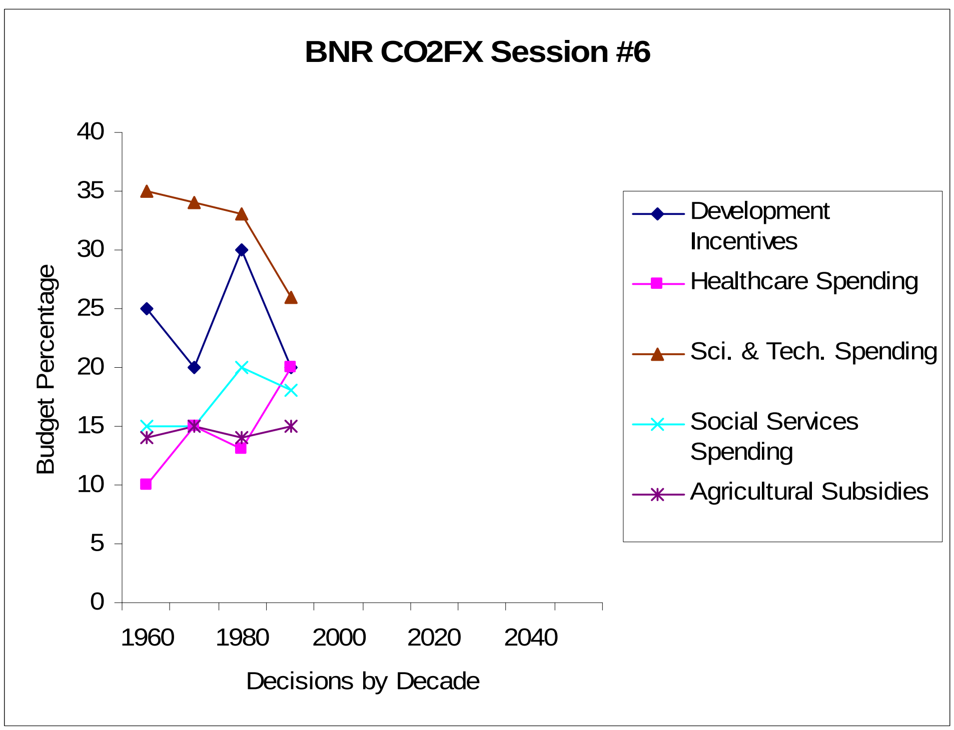

BNR CO2FX Session #1
Budget Percentage
80
70
60
50
40
30
20
10
0
1960 1970 1980 1990 2000 2010 2020 2030 2040 2050
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. $ Tech. Spending
Social Services Spending
Agricultural Subsidies


BNR CO2FX Session #2
Budget Percentage
120
100
80
60
40
20
0
1960 1980 2000 2020 2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


BNR CO2FX Session #3
Budget Percentage
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


BNR CO2FX Session #4
Budget Percentage
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


BNR CO2FX Session #5
Budget Percentage
100
90
80
70
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies


BNR CO2FX Session #6
Budget Percentage
40
35
30
25
20
15
10
5
0
1960
1980
2000
2020
2040
Decisions by Decade
Development Incentives
Healthcare Spending
Sci. & Tech. Spending
Social Services Spending
Agricultural Subsidies

Appendix L

CO2FX Descriptor

CO2FX Descriptor

CO2FX was selected as the intervention for this research as it fit several constraints. The CO2FX simulation needed to: (a) engage high school students for a minimum of six intervention sessions, (b) address cultural, economic, social, and political effects of technology, i.e., ITEA standard #4, (c) be developed with embedded characteristics of a complex system, and (d) be low-cost/no-cost. Addressing the final constraint, “CO2FX is a multiuser game. The model is hosted using a multiuser server (provided by Forio Inc)” (Global Warming Interactive, 2007). CO2FX is available for no cost at www.globalwarminginteractive.com. Considering that websites appear and disappear rather quickly, this descriptor is provided to leave the reader with an understanding of what attributes were desired during the selection of this treatment.

A pilot study with CO2FX in a Utah high school demonstrated students were engaged with the simulation over a week-long trial period. Questioning of the students while engaged with CO2FX and afterwards revealed the applicability of the simulation for the purposes of a six-session treatment period. A computer gaming/simulation format was desired as most high school aged students have prior experience in this realm. The game is based on the STELLA™ modeling system. “Students experience the model through the Flash-based game/scenario….Changes in model values trigger multimedia events such as video newscasts about the state of the country” (Global Warming Interactive, 2007). These triggers provide continually changing pieces of information students can select throughout the game to learn more about what events are occurring or expected based upon their decisions. This information on-demand appeared desirable to students.

Addressing the elements of ITEA standard #4 CO2FX is set within the cultural context of Brazil. With large rainforests this serves an important role in the balance of CO_2 levels. From a social and economic perspective, “the model also takes into account social and economic variables such as development of alternative energy sources, taxes on carbon production, unemployment levels, and even public opinion” (Global Warming Interactive, 2007). The political aspect is addressed with policy related matters the policy advisor must address in the game while collaborating with two teammates who serve as economic and science/technology advisors.

Feedback loops, nonlinearity and randomness as characteristics of complex systems were desired elements for students to experience within the CO2FX simulation. Randomness is addressed within the STELLA modeling system with random generators. The purpose of such generators is to provide a variation to outcomes so that players do not memorize a series of steps providing the means to “defeat” global warming. During this research students often relied upon a series of selections from previous attempts. A portfolio with values collected for each attempt was at their disposal daily. Teams relying upon such approaches were often confounded that the outcome was not the same during subsequent attempts relying upon values from earlier attempts.

Nonlinearity to some degree addresses feedback loops as well. Within a complex system nonlinearity can appear as exponential growth or as circular causality. This research explored the latter of the two options. It was hypothesized and later demonstrated that students would bring to the game a singular causality approach. As such students would, for example, reduce individual taxes and expect immediate feedback with an increase in the popular opinion of the people. However circular causality or feedback loops may take into account the variability of time, as well as the interrelationship of multiple factors. The CO2FX game was developed based upon the dissertation research of Tom Fiddaman in *Feedback Complexity in Integrated Climate-Economy Models*. Exploring the role of feedback Fiddaman (1997) stated:

> This research builds on earlier system dynamics models of energy economy interactions, creating a model that tests the implications of a number of feedback processes that have not been explored in the climate change context. Among these are endogenous technological change and bounded by rational decision making, with perception delays and biases. (p. 3)

The assumption is made that the STELLA model encompasses characteristics of complex systems students may begin to recognize through repeated attempts. Thus initial singular causality hypotheses may change as students explore trial-and-error methods or other applicable strategies, thereby beginning to develop a novice-level understanding that something such as circular causality is occurring.

The CO2FX simulation contained important elements meeting the constraints for this research. As models appear and disappear over time due to the nature of websites and the timeliness of world happenings other choices may be more desirable serving as treatments for future research. Forio Business Solutions, currently hosting CO2FX, has a number of other simulations addressing oil and energy dependence needs that are topics of contention as this research concludes. These would serve as viable alternatives based on factors unique to future research.

VITA

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Doctor of Philosophy Degree--Curriculum and Instruction: Specialization in Engineering and Technology Education, College of Education, August 2008, Utah State University.

Master of Science Degree--Industrial Technology and Education, College of Engineering, August 2002, Utah State University.

Bachelor of Science Degree (Magna Cum Laude)--Technology Education, College of Education, December 1996, University of Wisconsin-Stout.

Associate's Degree Coursework--General Education, University of Wisconsin Center-Fox Valley, (1992-1993) Menasha, WI.

WORK EXPERIENCE

2005-08 Utah State University, Engineering and Technology Education, Research Assistant, Logan, UT.

1996-2005 Blaine County School District #61, Wood River Middle School, Technology Education Instructor, Hailey, ID.

1996 Summit Performance Systems - Division of Oshkosh Truck, Manufacturing Systems Analyst, Weyauwega, WI.

1994-95 University of Wisconsin-Stout, Lab Assistant, Menomonie, WI.

1987-1991 U.S. Army, Combat Engineer – Veteran: Persian Gulf War; Stationed: Bamberg, West Germany; Deployed: Saudi Arabia, Iraq, Kuwait.

LICENSES AND CERTIFICATIONS

2004-2014 National Board of Professional Teaching Standards Certification: Career and Technical Education/Early Adolescence through Young Adulthood.

1997-2006 Idaho Education Credential, Industrial Technology 6-12.

PUBLICATIONS

Walrath, D. (2007, May). Technology in the home. *Technology and Children: Home*, 11(4) 8-9.

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Walrath, D. (2005, June). *Non-linear Teaching Approaches Utilizing Space Exploration Technologies.* Network of Educator Astronaut Teachers Conference; Kennedy Space Center, Orlando, FL.

Walrath, D., & Regan, J. (2005, February). *To Infinity and Beyond: An Out of this World Space-based Learning Environment.* Space Educators Exploration Conference; Johnson Space Center, Houston, TX.

Walrath, D. (2004, June). *Teaching Technology Education via Aerospace Activities.* Network of Educator Astronaut Teachers Conference; Johnson Space Center, Houston, TX.

Thode, B. & Walrath, D. (2004, February). *Status of Technology Education in Idaho.* Idaho Science, Mathematics, and Technology Coalition inaugural meeting, Boise, ID.

INTERNATIONAL/COLLOQUIA

Walrath, D. (2007, May). *Engineering and Technology Education as Practiced in the U.S.* Griffith University and Utah State University: An Australian and U.S. Engineering and Technology Education Partnership Planning Workshop, Griffith University, Brisbane, Australia.

Walrath, D., Daugherty, J., Denson, C., Zeng, Y., & International Graduate Students. (2006, October). *Global Colloquium on Engineering Education: A Student Forum.* 5th Annual American Society for Engineering Education Global Colloquium, Pontifícia Universidade Católica, Rio de Janerio, Brazil.

POSTER SESSIONS

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Zuga, K., Walrath, D., & NCETE Doctoral Fellows. (2007, March). *Microgravity Environments: A Comparative Analysis of Expert and Novice Cognitive Reasoning Abilities.* NCETE Research Symposium: International Technology Education Association Conference; San Antonio, TX.

ROUNDTABLES

Walrath, D., Mentzer, N., Daugherty, J., Denson, C., & Stricker, D. (2007, August). *NCETE PhD Cohort #2 Fellows Orientation Roundtable*. Utah State University, Logan, UT.

Mentzer, N., Walrath, D., Daugherty, J., Kelley, T., Denson, C., & Zeng, Y. (May, 2007). Necessary Tensions: Moving the Field (ETE) Forward. National Center for Engineering and Technology Education Summer Workshop. University of Illinois at Urbana-Champaign.

Walrath, D. & Zeng, Y. (2007, March). *Global Insights on Engineering Design as Content.* International Technology Education Association Conference; San Antonio, TX.

WORKSHOPS

Brusic, S. & Walrath, D. (2008, February). *TECC Technology, Innovation, Design, & Engineering (TIDE) Workshop for Elementary School Teachers* (Co-coordinator). International Technology Education Association Annual Conference; Salt Lake City, UT.

Walrath, D. (2007, May). *NCETE Graduate Workshop* - Coordinator. National Center for Engineering and Technology Education Summer Workshop; University of Illinois at Urbana-Champaign.

Johnson, S., & Walrath, D. (2006, May). *NCETE Core Course I: An overview*. National Center for Engineering and Technology Education Summer Workshop; University of Georgia, Athens, GA.

Thode, B., Thode, T., & Walrath, D. (1999, July). *TECH It Out: Technology Workshop-K-12 Technology Teachers and Administrators.* Wood River Middle School, Hailey, ID.

Thode, B., Thode, T., & Walrath, D. (1998, July). *TECH It Out: Technology Workshop-NASA Educational Outreach Specialists.* Wood River Middle School, Hailey, ID.

GRANTS/FUNDING

2007-08 Agency: National Center for Engineering and Technology Education
Title: Complex Systems in Engineering and Technology Education - The Role Software Simulations Serve in Student Learning
Role: Principal Investigator
Funding: $10,361

Purpose: Dissertation Research at Sun Prairie High School, WI

2007 Agency: National Science Foundation
Title: Griffith University and Utah State University: An Australian and United States Engineering and Technology Education Partnership Planning Workshop
Principal Investigator: Dr. Ed Reeve, Utah State University
Role: Graduate Student Participant
Funding: $25,000 (total); $4,167 (individual)
Purpose: Establish contacts and develop international partnerships for engineering and technology education research.

2006 Agency: National Science Foundation -Travel Grant
Title: American Society for Engineering Education 5th Annual Global Colloquium; Rio de Janeiro, Brazil
Principal Investigator: Dr. Scott Johnson, University of Illinois at Urbana-Champaign
Role: Graduate Student Participant
Funding: $3,700 (individual)
Purpose: Attend ASEE 5th Annual Global Colloquium and participate in graduate student roundtable sessions.

2005 Agency: Wood River Middle School Parent Teacher Association
Title: Sally Ride Toy Challenge
Role: Advisor to Western Region Finalist Team
Funding: $500
Purpose: Mentored three students who competed in Western states finals in San Diego, winning the technical competence award with educational toy developed for Idaho School for the Deaf and Blind.

2002 Agency: NASA Idaho Space Grant Consortium
Title: Texas Space Grant Consortium Lift-off 2002: Have Space Suit Will Travel Workshop
Role: Presenter/Participant
Funding: $200 Mini-grant
Purpose: Attend and present at summer workshop for math, science, and technology teachers.

1998-2003 Agency: Blaine County School District
Title: ITEA annual conference
Role: Presenter/Participant
Funding: Average $1,000/year
Purpose: Attend and present at International Technology Education Association's annual conference.

1997-2005 Partner Agencies: Idaho National Engineering Laboratory, Micron, Hewlett-Packard, Power Engineers, Lucent Technologies, Papoose Club, and Blaine County Education Association.
Role: Business and Industry Liaison
Funding: Average $30,000/year (equipment and monetary)
Purpose: Equip a 4000 sq/ft multi-purpose technology education laboratory with state-of-the-art equipment. Built television and radio broadcasting facilities, clean room and robotics/manufacturing laboratory.

PROFESSIONAL EXPERIENCES

UNDERGRADUATE RECRUITMENT for Utah State University (2005-08)

High School Program:	*Teacher:*
Northern UT Academy of Math, Engineering & Science High School, Roy/Kaysville, UT	Mr. Roger Snow
San Juan High School, Blanding, UT	Mr. Jared Berrett
Snow Canyon High School, St George, UT	Mr. Scott Day
Hurricane High School, Hurricane, UT	Ms. Tera Houston
Beaver High School, Beaver, UT	Mr. Brian Cook
Milford High School, Milford, UT	Mr. Andy Swapp
Uintah High School, Vernal, UT	Mr. Keith McMullin
Altamont High School, Altamont, UT	Mr. Cory Allred
Murray High School, Murray, UT	Mr. Quinn Drury
Two Rivers High School, Ogden, UT	Mr. Kurt Jensen
Northridge High School, Layton, UT	Mrs. Heather Hill
Copper Hills High School, West Jordan, UT	Mr. Ken McLaughlin
Jordan Applied Technical Center, Jordan, UT	Mr. Mike Smoot

STUDENT TEACHING Co-SUPERVISOR: Wood River Middle School, Hailey, ID

	University Supervised for:	*Student-teacher:*
2004	University of Wisconsin-Stout	Mr. Joe Regan
2002	University of Wisconsin-Stout	Mr. Travis Goecks
2001	University of Wisconsin-Stout	Mr. Alex Gray
2000	University of Wisconsin-Stout	Mr. David Brokopp
1999	Montana State University	Mr. Nathan Mentzer
1998	Utah State University	Mr. Roger Allen
1998	Eastern Michigan University	Ms. Gina Sartor
1998	Montana State University	Mr. Curt Thompson
1997	Montana State University	Mr. Scott Larsen

GRADUATE WORKSHOP COORDINATOR- National Center for Engineering and Technology Education (2007, May). *Doctoral Student Transitioning: A 1st Year Professor's Roundtable;* University of Illinois at Urbana-Champaign

University Represented:	Participant:
California State University-Los Angeles	Dr. Maricio Castillo
Central Connecticut State University	Dr. Michele Dischino
University of Georgia	Dr. Nadia Kellam
University of Minnesota	Dr. Tamara Moore
North Carolina State University	Dr. Terri Varnado

PROFESSIONAL MEMBERSHIPS

2006-present	American Society for Engineering Education
2004-present	NASA Network of Educator Astronaut Teachers
1997-2005	National Education Association
1997-2005	Idaho Education Association
1993-present	International Technology Education Association
Lifetime Member	Technology Education Association of Idaho

PROFESSIONAL DEVELOPMENT

2007 National Center for Engineering and Technology Education Graduate Student Workshop: Dr. Karen Zuga & NSF Program Officers; Ms. Patti Curtis & Boston Museum of Science.

2007 *Surveying the landscape: The nature and status of K-12 Engineering Education in the United States.* Reviewer of *Engineering is Elementary* curriculum for Dr. Ken Welty and NCETE national landscape study for the National Academy of Engineering.

2004 Robo-Educators Curriculum Development Workshop. National Robotics Engineering Center, Carnegie Mellon University, Pittsburgh, PA

2003 Idaho Reaches into Space Workshop. Twin Falls, ID

2003 Semiconductor Equipment and Materials International - SEMI Workforce Development Institute, Tempe, AZ

2002 Texas Space Grant Consortium Lift-off 2002 - Have Space Suit Will Travel Workshop, Johnson Space Center

2001 NASA Educational Workshop (NEW 5-8), Johnson Space Center

HONORS/AWARDS

2008	Donald Maley Spirit of Excellence, Outstanding Graduate Student
2005-08	National Center for Engineering and Technology Education, PhD Fellowship, Utah State University
2004-05	ITEA Teacher Excellence Award
2004	Technology Education Association of Idaho Program of the Year
2004	National Board of Professional Teaching Standards Certification
2003	National Aeronautics and Space Administration (NASA) Educator Astronaut Finalist
2003	Idaho Governor's Industry Award for Notable Teaching in Science
2002-03	Technology Education Association of Idaho Teacher of the Year
2002	ITEA Program Excellence Award
2000-01	Technology Education Association of Idaho Program of the Year
1999	Idaho Industrial Technology Education Association Teacher of the Year

PROFESSIONAL SERVICE

2008-10	Technology Education Children's Council (TECC), Secretary
2006-09	ITEA Membership Committee (Co-chair)
2006	NASA/ITEA Liaison: Educator Astronaut Ricky Arnold, Baltimore, MD
2005	ITEA Liaison: Society of Women's Engineers Conference, Los Angeles, CA
2005	ITEA Strategic Planning Committee; developed 5-year plan, Salt Lake City, UT
2005	ITEA Technology Festival Coordinator, Kansas City, MO
2004-06	ITEA Board of Directors: Region IV Director (13 Western States)

2003-06	ITEA Special Events Committee (Member)
2002-05	ITEA Affiliate Representative: Idaho
2002-03	President: Technology Education Association of Idaho
2001-02	President-Elect: Technology Education Association of Idaho
2000-01	Vice-President: Technology Education Association of Idaho
1995-96	Vice-President: Technology Education Collegiate Association, University of Wisconsin-Stout
1994-96	Coordinator: High Mileage Vehicle Competition, University of Wisconsin-Stout