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Combining Systems Thinking, Model-based Reasoning, and Project-based Learning to Advance Student Agency, Increase Student Engagement and Understanding, and Provide an Authentic and Accurate Method of Assessing Student Competencies in a High School Aquatic Science Course

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by

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Dedication

This work is dedicated to my great departed friend and mentor, Glenn Crisman, who taught me to lust after knowledge, to see and appreciate the glorious intricacy of nature, to relish every discovery of truth, regardless of its source, and to be a decent human being while living a truthful life. And to teachers everywhere.

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Abstract

Combining Systems Thinking, Model-based Reasoning, and Project-based Learning to Advance Student Agency, Increase Student Engagement and Understanding, and Provide an Authentic and Accurate Method of Assessing Student Competencies in a High School Aquatic Science Course

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Science elective courses for high school seniors provide an opportunity to engage students in rigorous, relevant instruction that requires students to employ a broad range of science knowledge and skills from previous courses toward real world problems with relevance to students' current and future life experiences. The goal of this work is to provide teachers of high school science courses with a methodology for the introduction of strong STEM components into traditional science courses, particularly model eliciting activities, system dynamics, and engineering based design challenges. Employing these instructional methods in an aquatic science course produced an effective, engaging curriculum that increased students understanding of science content and provided students with the tools to analyze, evaluate and design solutions to real world problems. Teaching the concept of system dynamics early in the course gave students tools, including causal loop diagrams, to create useful models for analyzing interactions in

complex systems. Student creation of such models proved an effective instructional method for teaching science content and the nature of scientific processes. Students displayed the ability to apply these techniques, once taught, to a diverse set of problems and expressed an intention to continue to use these skills both personally and professionally in the future. Having students create, analyze, and discuss their own models of complex systems provided the teacher with an effective method for both formative and summative assessment of student knowledge and comprehension. The models provided a more authentic and accurate evaluation of student knowledge and understanding than a written test or multiple choice response exam alone. Student use of software modeling tools, such as STELLA, can be added to these methods, providing students with the ability to add the concepts of rate and flow to their models.

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Chapter 1: Introduction

Much has been made of the need, perceived by many as urgent, to increase the number of college graduates in science and engineering fields. Sentiments of this nature go back at least as far as 1957 when the Soviet Union successfully launched Sputnik, the first artificial satellite, leaping ahead of the United States in the "space race." In an atmosphere of near hysteria, the United States poured unmatched money into science, engineering, and mathematics at all levels of education. (Peoples, C. 2008) Hysteria again erupted in 1983 when President Reagan's National Commission on Excellence in Education published the report, *A Nation at Risk: The Imperative for Educational Reform*. The report sighted an erosion of America's educational foundations by a "rising tide of mediocrity that threatens our very future as a nation and a people…"[1] The report fueled numerous educational reform movements, the likes of which continue in various forms to this day.

We may have survived the Soviet nuclear threat, but many of the issues facing society today are at least equally threatening. The two major drivers of the world economy and modern society, petroleum and water, are both in depletion models. Climate change and human activity will continue to affect the health and availability of food, water, and energy resources. Crumbling infrastructures are in urgent need of innovative redesign and repair. Regardless of one's opinion on the effectiveness of educational reform or the motives behind it, it is obviously in every nation's best interest to produce a skilled workforce that can provide the innovation, creativity, and problem solving skills needed to face current and future challenges. Many professional educators share a deep conviction that it is their responsibility to contribute to this outcome in a

[1] Full Report of A Nation At Risk. Language attributed to T. H. Bell.

positive way by teaching students critical problem solving skills alongside content and by influencing a greater number of high school graduates to pursue science, engineering, mathematics, and other technical fields. Even students who seek other career paths need to have the skills to analyze problems and proposed solutions to problems in order to make essential life decisions and to function effectively as part of an informed electorate. As Thomas Jefferson stated, “Every government degenerates when trusted to the rulers of the people alone. The people themselves therefore are its only safe depositories. And to render even them safe, their minds must be improved to a certain degree.” (Jefferson, 1784).

Due to advances in public education made largely by educators themselves, the degree to which the people’s minds are improved has been raised dramatically since Jefferson’s time. Long division, once considered high mathematics even at the college level, is now relegated to primary grades. With enormous advances in science, engineering and information technology, the content students learn is now broader and deeper than at any time in history. In science classrooms in particular, the amount of content has increased dramatically as has the number of students that must be educated. With ever growing information and limited time and resources, science teachers are forced to constantly innovate their curriculum and instructional methods to produce students with not only content knowledge, but also with the problem solving, data analysis, communication, and collaboration skills needed for applying content knowledge in the context of the modern world.

To that end, the author has experimented in the classroom extensively with pedagogical approaches and instructional methods designed to teach science content while also engaging students in the practice of so-called “soft skills” or, as the author prefers, 21st Century Skills, of collaborative problem solving, ideation, solution design, result evaluation, technological literacy and effective communication skills.

The purpose of this design experiment was not the creation of a single lesson or content unit, but to combine specific factors in the curriculum which would work synergistically to produce desired student outcomes. It was hypothesized that the combination of system dynamics, student modeling of complex systems, and engineering-design based PBL units would result in deeper student understanding of the content, an increased interest in science and engineering fields and ultimately greater student agency, defined as the capacity to act responsibly in the real world based on their own reasoning and understanding. It was also hypothesized that these methods would generate higher student engagement and a means of assessing student knowledge and understanding that is more accurate and insightful than multiple choice response tests.

The methods described in this report were implemented in a yearlong aquatic science course consisting mostly of seniors in their last year of high school. However, these methods could be adapted to many different courses and to different age groups. This report details the first iteration of a design experiment that lays the groundwork for further investigation. Although quantitative analysis of the efficacy of the methods described in this report has not yet been carried out, this preliminary work provides qualitative results and insights to guide educators who choose to incorporate these techniques to the betterment of their students. Those educators are the primary audience of this report.

Chapter 2: Literature Review

This review of relevant literature is divided into four sections. The first three sections will review current research on the instructional methods and pedagogical approaches examined in the design experiment. The final section will review literature pertinent to the design experiment as a definable and valid method of education research.

2.1 Model-based reasoning

Models are at the heart of the very nature of scientific endeavor. Models have been defined as "conceptual systems that generally tend to be expressed using a variety of interacting representational media, which may involve written symbols, spoken language, computer-based graphics, paper-based diagrams or graphs, or experience-based metaphors." (Lesh and Harel, 2008). In both the laboratory and the classroom, models have a sense-making function. "A person interprets a situation by mapping it into his or her own internal model, which helps him or her make sense of the situation. Once the situation has been mapped into the internal model, transformations, modifications, extensions, or revisions within the model can occur, which in turn provide the means by which the person can make predictions, descriptions, or explanations for use in the problem situation."(Schorr and Clark-Koellner, 2003). This process of making sense of phenomena using models is referred to as model-based reasoning, a foundational component of the methodology described in this report.

The importance of models in both science and engineering cannot be overstated. One can argue that most of a scientist's time is spent designing some model of a complex system that represents part of the natural world. A model must then be constructed in such as way as to be able to control specific variables germane to the inquiry being conducted. The scientist then intervenes by changing a variable and observing the effect of that intervention on the system. Philosopher Ian Hacking referred to this process as *Representing and Intervening*. (Hacking, 1983). This key method of inquiry is a fundamental process of what Thomas Kuhn called *Normal Science*. (Kuhn, 1996).

In the engineering design process, numerous types of models are used to achieve a variety of goals. Mathematical models help define the constraints of potential designs by approximating the forces that will act within the system. Functional models are used to analyze inputs and outputs that must be designed into a system. Physical models, such as prototypes, are constructed and used to analyze and evaluate design decisions and feasibility.

Students arrive in the classroom with pre-constructed models already in place. Classrooms are subsystems of the community at large from which students flow. What teachers can most affect in the classroom system is the learning experience of individual students. Students are part of the classroom system, but they are also a part of many other systems, some of which intrude on the classroom in the form of the values, misconceptions and biases of the student's world view. In short, students come to us with a mental model of the world. If they are to attain new knowledge, they must modify or reconstruct that model to a closer representation of truth. It is the goal of teaching to facilitate this reconstruction.

The goal of teaching can also be thought of as facilitating the development of student expertise from novice to expert. The development of expertise has been framed as requiring: (a) a deep foundation of factual knowledge, (b) a conceptual framework, and (c) organization to support retrieval and use (Bransford, Brown, & Cocking, 2000). Instructional methods that involve model-based reasoning can have a larger impact on moving students toward expertise than traditional, fact-based instruction. "Model-based reasoning can be thought of as a continuum in which the teacher begins with students' basic representational capacities and tries to end up near the practices of mathematicians and scientists" (Petrosino, et al. 2003).

Three types of model-based reasoning have been defined in literature. First is analogical modeling, in which the model represents what is common among the members of a system in a specific context or problem. Second is visual modeling, in which external visual representations provide support for the processes of constructing and reasoning with a mental model. "These representations can model phenomena in several ways, including providing idealized representations of aspects of phenomena and embodying aspects of theoretical models. Finally, thought experimenting is a specific form of model-based reasoning, which makes the intention clear that the situation is one that is to represent a potential real-world situation" (Nersessian, 1999).

There is research to support that having students build their own models is a successful context for developing student understanding of the natural world. David E. Penner, Richard Lehrer, and Leona Schauble of the University of Wisconsin, Madison, conducted a study in which students designed, built, tested and evaluated models of the human elbow. Student models were then used as a basis for the exploration of the mechanics of the human arm. By building on the student-made models, they were able to engage students in an investigation of the relationships between force and the location of the attachment position on the biceps. This provided students with an opportunity to develop their understanding of the relations between mathematics and science by creating tables and graphs. (Penner, et al. 1996).

The above experiment is representative of an instructional method called Model-Eliciting Activities (MEAs). MEA design focuses on eliciting from students conceptual models that they iteratively revise in problem solving. This is a powerful method of instruction because it requires the student to be interactive. Students may find themselves using skills and understandings they would not have demonstrated in a traditional classroom and may not have been cognitively aware they possessed. "…MEAs in middle school and high school settings leverage sizable mathematical understandings, intuitions, and tacit knowledge that students possess but that are not invoked in formal instruction". (Hamilton, et al. 2008).

MEAs are typically thought of as short-term projects lasting for only one or a few 45 - 90 minute class periods and focus on models more than on solutions. Model-based reasoning and MEAs can be incorporated into longer and more complex units of learning for senior level courses and courses for advanced learners, many of which require knowledge integration from previous courses.[2] Shuman has coined the term "model-integrating activities" to refer to MEAs that are formulated for upper level students in such a way as to force connections between content from prior courses. (Shuman, et al. 2007). In this circumstance, MEAs are typically incorporated into longer project-based or design-based instructional units.

2.2 Project-based learning

There is extensive literature regarding how people learn that has developed significantly over the past several decades. (For an overview, see Bransford, et al. 2000). Problem-based Learning (PBL) has been at the forefront of much research because it offers significant instructional advantages over traditional lecture-based instruction. Problem-based learning (PBL) is regarded by many as an effective instructional methodology. (Hung, Jonassen, & Liu, 2008). PBL is considered a learner-centered instruction method because it changes the focus of instruction from the teacher to the

[2] For example, the aquatic science course used in this study was a capstone science elective for 12th graders which incorporated biology, chemistry, physics, and 8th grade earth science along with new concepts in marine science and oceanography.

students. In PBL, the role of the teacher shifts to facilitating instruction rather than directing instruction. (Liu, et al. 2012). In a comprehensive overview of PBL, Savery (2006) defines it as "an instructional (and curricular) learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (p. 12).

There are several characteristics of PBL that make it a powerful instructional method. Students work as part of small, collaborative groups. Extensive research supports the idea that students can develop their knowledge and skills much more effectively in well-structured group-learning environments than they can individually (Johnson, Johnson, and Smith,1991). This collaboration provides students with an opportunity to practice responsibility, provide useful feedback, ask good questions, manage work flow, communicate with peers in the appropriate register, and hold others accountable. These are all valuable skills that employers have increasingly complained are lacking in the current work force.

In PBL, the problem is often ill-structured so that students must define the problem, plan a process to generate several possible solutions, evaluate these solutions, and finally, select the optimal solution (Barrows, 2002). The focus of learning is not only the knowledge outcome, but also the process by which students become self-reliant and independent and learn to be collaborators and problem solvers (Barrows, 1996). Numerous studies corroborate that PBL is an effective approach to cultivate critical thinking and problem-solving skills (Brush & Saye, 2000). Studies show that PBL is effective for improving content learning when compared to traditional teaching approaches (Druckman and Ebner, 2008, among others).

Although the terms *Problem-based Learning* and *Project-based Learning* are sometimes used interchangeably, most educators and researchers distinguish between them on the basis of length, complexity and integration. Problem-based learning tends to be composed of short units over narrow content in which the process (or model) being explored is as important as the outcome (solution). Project-based learning consists of longer units requiring the integration of multiple disciplines and having more solution-based outcomes, although process is still emphasized. *Design-based Instruction* is different from Project-based instruction only in that the problem is an engineering design problem (such as reverse-engineering a hair dryer for better ergonomics or building a robot that can complete underwater tasks) and students work through the engineering design process in order to construct a solution. The problems in this methodology are referred to as "design-based challenges."[3] Design-based challenges have been used outside of a strict engineering context, such as challenging students to construct a model that can be used to measure the forces placed on human joints in a sports context. This application can be referred to as *Challenge-based Instruction* (as in Mandy, et. al. 2004).

Several PBL structuring platforms have been devised, each to provide a roadmap for implementing successful project-based learning in the classroom. A prominent example is that provided by the Buck Institute for Technology in Novato, California.[4] Students are introduced to a content-related problem via an "entry document" which places students into groups, presents them with a challenge, and gives them preliminary information needed to begin asking questions and brainstorming a solution.[5] Students conduct a Know/Need to Know analysis from which the intended learning goals of the unit should precipitate, although this does require a skilled instructor and much up-front

[3] The author wishes to emphasize his belief that design-based instruction need not, and should not, be restricted to engineering classrooms. Any course can benefit from students using the engineering design process to solve problems and create models.

[4] The author has been extensively trained in this PBL platform and has worked within two schools that use this PBL platform strictly for all courses.

[5] The "entry document" need not be an actual document. It often takes the form of a video, audio recording, or live- action skit.

planning. The Need to Know list then guides classroom activity, as students decide how to acquire the necessary information to complete the challenge. The teacher provides support and advice, providing "workshops" at student request to relay underlying content knowledge. A "workshop" could be an optional lecture attended by some or a required laboratory experience in which all students participate. Content knowledge gained from these workshops is considered "scaffolding" that students will use to construct a solution to the challenge. They then present their solution in a formal report, preferably in front of experts from the community (Markham, et al. 2003).

Strict use of this procedure can result in a highly student-centered classroom environment. 21st Century skills are emphasized and regularly practiced by students. In the best managed classrooms, instruction is highly student driven but far more structured than it appears to observers. It requires extensive training of instructors and considerable administrative support. Project development can place a significant up-front burden on the instructor, although many pre-designed PBL units are widely available. There is also a significant technology component necessary to run this program with a high degree of efficiency, so technology support and instructors well trained in the use of technology are often required. [6]

Another framework for implementing successful PBL in the classroom is the STAR Legacy Cycle, developed by Vanderbilt-Northwestern-Texas-Harvard-MIT (VaNTH) Engineering Research Center for Bioengineering Educational Technologies. Their instructional design, based on the How People Learn (HPL) framework, suggests that student achievement can be significantly enhanced by the integration of four types of learning environments: (a) learner-centeredness, (b) knowledge-centeredness, (c)

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[6] This assessment is derived less from literature than from the author's extensive experience of working within this learning environment both as a teacher and as an administrator, and from having visited and observed many model schools using this method.

assessment-centeredness, and (d) community-centeredness. (Bransford, et al. 2000). "The STAR-Legacy Cycle is a software shell designed to promote research on the design of challenge-based instruction. It intends to help scaffold students' learning from case-, problem-, and project-based learning. The model has seven parts: 1) Look Ahead and Reflect Back, 2) The Challenge, 3) Generate Ideas, 4) Multiple Perspectives, 5) Research & Revise, 6) Test Your Mettle, and 7) Go Public. Students repeat the cycle if their initial proposal for answering the challenge was unsatisfactory or incomplete or if there is more than one challenge. Instructors use the STAR-Legacy Cycle to develop and deliver course materials consistent with the four types of environments of the HPL framework." (Pandy, et al. 2004).

The group performed an experiment in which a STAR-Legacy Cycle unit on biomechanics was implemented. The challenge-based approach to learning was developed to teach a deep understanding of disciplines (biomechanics) while at the same time scaffold the development of the skills of problem solving, collaboration, and communication via the utilization of problem-based learning followed by more open-ended project-based learning. "The results showed that the HPL approach increased students' conceptual knowledge as well as their ability to transfer knowledge to new situations. These findings indicate that challenge-based instruction, when combined with an intellectually engaging curriculum and principled instructional design, can accelerate the trajectory of novice to expert development in bioengineering education." (Pandy, et al. 2004).

2.3 Systems Dynamics

Modeling is an essential function of project-based learning. The author suggests that students could not successfully complete PBL challenges without constructing and utilizing a variety of models, such as theoretical, mental, experimental, graphical and mathematical. Indeed, it can be said that project-based learning turns the classroom into a model of problem solving in the real world. Many PBL units place students in the role of researchers, engineers, medical professionals, scientists, astronauts and corporate executives. Research has shown that this method has substantial advantages over more traditional methods. However, problems in the real world are rarely as static as even PBL models can lead students to believe they are.

> "Missing from most education is direct treatment of the time dimension. What causes change from the past to the present and the present into the future? How do present decisions determine the future toward which we are moving? How are lessons of history to be interpreted to the present? Why are so many corporate, national, and personal decisions ineffective in achieving intended objectives? Conventional educational programs seldom reveal the answers. Answers to such questions about how things change through time lie in the dynamic behavior of social, personal, and physical systems. Dynamic behavior, common to all systems, can be taught as such. It can be understood." (Forester, 1992).

The kind of understanding Jay Forester was referring to can be accomplished by the introduction of system dynamics to a curriculum. When analyzed closely, even seemingly simple systems display a complex nonlinearity. System dynamics is a way of analyzing this behavior of systems by looking at the feedback loops and time delays that affect the system as a whole.

Perhaps the most important assertion of this paper is that student understanding and agency can be advanced by embedding the study of system dynamics into science curriculum. The rationale behind this assertion is that students gain more agency in making science-based decision making when they can synthesize models for accurate analysis of a problem from interacting fields of knowledge. The most frequently used curriculum sequences do not frequently provide a context for this kind of integration.

> "Education is compartmentalized into separate subjects that, in the real world, interact with one another. Social studies, physical science, biology, and other subjects are taught as if they were inherently different from one another, even though behavior in each rests on the same underlying concepts. For example, the dynamic structure that causes a pendulum to swing is the same as the core structure that causes employment and inventories to fluctuate in a product distribution system and in economic business cycles. Humanities are taught without relating the dynamic sweep of history to similar behaviors on a shorter time scale that a student can experience in a week or a year. High schools teach a curriculum from which students are expected to synthesize a perspective and framework for understanding their social and physical environments. But that framework is never explicitly taught." (Forester, 1992).

Unifying science education is not just an attractive goal. It addresses a primary reason students do not leave the public education system with a higher degree of agency and the ability to make critical decisions related to scientific and technological issues. David Chen and Walter Stroup (1993) articulated five reasons why General System Theory (GST) provides a mechanism for unifying science education: 1) the multidisciplinary nature of systems theory, 2) the ability to engage complexity, 3) the capacity to describe system dynamics and change, 4) the ability to represent the relationship between the micro-level and macro-level of analysis, and 5) the ability to bring together the natural and human worlds.

Chen and Stroup are not alone in their assertion. Advocates of systems-based teaching say that traditional, lecture-format teaching results in students passively receiving and memorizing large quantities of fragmented information (Richmond, 1990). "They believe the systems approach is integrative, promotes active learning, and helps students develop critical thinking and problem solving skills." (Hooper and Stave, 2008).

Grant (1998: 70) argues that the systems approach presents a "common conceptual framework and vocabulary" that is necessary to "develop an integrated educational program." Research has shown that active learning creates a longer lasting understanding of scientific concepts, skills, and the nature of science (Leonard, Speziale, and Penick, 2001).

Stuntz, Lyneis, and Richardson (2002: 4) argue that a systems perspective helps students better understand interdependencies, long- and short-term decisions, and the consequences of their own actions within a system. This line of reasoning certainly advocates for the use of providing a systems perspective to students if the intention in to increase student agency.

Although system science itself is only decades old, the idea that it can be a powerful instructional tool is not recent. For more than two decades, studies have been conducted on various aspects of system science learning. Of particular interest in relation to this experiment is the study conducted by Nancy Roberts (1978) who studied how fifth and sixth graders learned to read dynamic feedback system causal-loop diagrams. The use of feedback concepts and causal-loop diagrams constitutes an important part of system thinking. They are also a fundamental part of the pedagogy used in this design experiment. Roberts' results show that 5^{th} and 6^{th} graders can learn the "underlying problems usually taught at the college level and beyond." (Roberts, 1978).

Despite the fact that K-12 students can learn to use systems theory, it differs from PBL in that there are not yet widely accepted and used curriculum structures for teaching system dynamics.

"Systems thinking interventions, that is, teaching methods that promote systems thinking skills or abilities have been implemented in schools for at least 20 years. Researchers have also tested the effect of systems thinking teaching on students' critical thinking and decision-making skills. Still, there is no clear definition of systems thinking or identification of the best methods for teaching or testing the effectiveness of systems thinking (ST) interventions." (Hooper and Stave, 2008).

However, there is literature to guide us in the implementation of a systems approach to content. Roberts' work showed the advantage of reversing the traditional educational sequence that normally progresses through five steps: 1) learning facts, 2) comprehending meaning, 3) applying facts to generalizations, 4) analyzing to break material into constituent parts, and 5) synthesizing to assemble parts into a whole. (Roberts, 1975). Forester suggested that synthesis be practiced first. "Most students never reach that fifth step of synthesis. But, synthesis—putting it all together—should be placed at the beginning of the educational sequence. By the time students are in school they already possess a wealth of observations about family, interpersonal relations, community, and school. They are ready for a framework into which the facts can be fitted. Unless that framework exists, teaching still more facts loses significance." (Forester, 2003).

"Mintz (1987) studied ninth-graders learning about ecological systems in a computer simulation environment. A major focus of this work was how student comprehension of the components of a system and the interaction between variables could be advanced by working in a computer program that had 'pictures, graphs and numerical tables.' The effectiveness of this kind of learning environment for having students come to an understanding of complexity was addressed. The researcher's conclusions in this area were significant. 'While passive viewing of the system dynamics is sufficient for the learning of simple principles,' to achieve the understanding of the 'high level principles,' the active manipulation of 'at least two variables is needed.'" (Chen and Stroup, 1993).

"Hopkins, et al. (1987) studied how veterinary students and cardiovascular research experts made judgments of the relationship among properties and variables of complex systems…The authors found 'that using the simplest form of representation, a digraph, has several advantages over other representations.' This study arrived at the conclusion that 'the distinction between properties and variables is fundamental to the understanding of dynamic systems.'" (Chen and Stroup, 1993).

"Mettes (1987) has incorporated system thinking in an elaborate model called a systematic approach to problem solving (SAPS). At a certain stage in his analysis of problem solving, the ideas of system boundaries, system content, and system state are needed. Using this model, Mettes has developed and studied academic courses at Twente University of Technology in the Netherlands. Courses of mathematics, physics, and chemistry were developed whereby the learning process was divided into two phases. In the first phase, the learner receives instruction and information in the skill to be acquired. This is the declarative phase. In the second phase, this knowledge is gradually converted into procedural form by practicing problem solving. Evaluation studies have shown that in a course on thermodynamics and a course on magnetism, the effect was significant." (Chen and Stroup, 1993).

The rise of the personal computer and the invention of powerful systems modeling software allowed researchers, Forester primary among them, to make enormous leaps forward in the understanding of systems. The invention of user-friendly graphic user interfaces (GUIs) finally made complex computer simulations of systems feasible in the classroom. Virtually all current research in systems education involves the use of modeling software. The software supports not only an understanding of graphical and mathematical models that underlie systems thinking, but also the 21st Century skill of technological literacy. It can allow students to build and evaluate models far more complex and nonlinear than the mathematics backgrounds of most high school students (and their teachers) would normally permit.

Several prominent systems modeling software platforms are available. Many are commercial platforms, such as DYNAMO, VisSim, and Powersim Studio. More pertinent to use in school settings is STELLA, a powerful computer modeling environment developed at the Media Lab at MIT with a GUI that makes it feasible for students to learn to use in the classroom. Students can build models and control input and outputs of the systems being modeled. Prepackaged STELLA simulations are also widely available. Another language, *LOGO (pronounced *star LOGO*), also developed at MIT, is used in the NetLOGO program, an open source platform. It can be used to model complex systems and has great potential for classroom use, including elementary grade levels. Open source platforms suitable to classroom use have become more available since the beginning of the author's research. These include Insight Maker and Simantics Systems Dynamics Tool. Each of these platforms may appeal to different educators for different uses.[7]

There are examples of system thinking approaches to instruction resulting in highly learner-centered classroom environments. Among the earliest occurred when Gordon Brown of MIT loaned the STELLA program to Frank Draper, an 8th grade

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[7] A table of system dynamics modeling software platforms, both commercial and open source, may be viewed at http://en.wikipedia.org/wiki/List_of_system_dynamics_software.

biology teacher. Draper's results are demonstrative of the many positive aspects of introducing systems thinking into the classroom.

> "At first, Draper expected to use system dynamics and computer simulation in one or two classes during a term. Then he found they were becoming a part of every class. With so much time devoted to system dynamics and simulation, he feared he would not have time to cover all the required biology. But, two thirds of the way through the term, Draper found he had completed all the usual biology content. He had a third of the term left for new material. The more rapid pace had resulted from the way biology had become more integrated and from the greater student involvement resulting from the systems viewpoint." (Forester, 1993).

Also, much credit goes to the "learner-centered learning" organization of student cooperative study teams within the classroom. Draper wrote of his classroom experience:

> "There is a free lunch. Since October 1988 our classrooms have undergone an amazing transformation. Not only are we covering more material than just the required curriculum, but we are covering it faster (we will be through with the year's curriculum this week and will have to add more material to our curriculum for the remaining 5 weeks) and the students are learning more useful material than ever before. 'Facts' are now anchored to meaning through the dynamic relationships they have with each other. In our classroom students shift from being passive receptacles to being active learners. They are not taught about science per se, but learn how to acquire and use knowledge (scientific and otherwise). Our jobs have shifted from dispensers of information to producers of environments that allow students to learn as much as possible. "We now see students come early to class (even early to school), stay after the bell rings, work through lunch and work at home voluntarily (with no assignment given). When

> we work on a systems project—even when the students are working on the book research leading up to system work—there are essentially no motivation/discipline problems in our classrooms." (Draper, 1989).

Of Draper's procedures, Brown wrote, "Before doing a simulation the students spend several class periods gathering information about the topic; they take notes during lectures, learn about a library and read references, and, working as a group, plan the simulation. By working this way Draper's students do not merely try to remember the material for a test but actually have to use it in a project simulating real life situations. This has led us to identify a new teaching paradigm which we define as SYSTEM THINKING with LEARNER-CENTERED LEARNING." (Brown, 1990).

The STELLA framework was also used to organize a study of literature by Pamela Lee Hopkins (1992). Several weeks after the experiment, Jay Forrester received a letter from Louise Hayden, the director of Ideas Associated[8], who had been an observer. She wrote: "Pam and I are so pleased and surprised at the ongoing involvement and depth of interest the high school students in her workshop of last June are showing. They are meeting with her weekly after school, eager to learn more about system dynamics and to use their advances to help younger students learn. They are arousing considerable teacher interest as they try to use causal loops in all their class rooms. Information is flowing upward—and from students who varied in achievement from high to very low.

> "We attribute the enthusiasm and commitment to their sense of the potential of systems thinking, and to the feelings of self-worth from being regarded as educational consultants. It is their first experience in learner-centered learning.

[8] Ideas Associated, 2570 Avenida de Maria, Tucson, AZ 85718, USA, is a small foundation that has fostered an approach to learning that enlists students themselves in an active participation that contributes to the momentum of the educational process.

> This may well be the first time they have considered themselves a responsible part of the social system." (Hayden, 1990).

The author is unaware of any instructional method that works equally well in all communities across student ability levels. That having been said, there is evidence that systems thinking can serve many different kinds of students. Of the early attempts at using systems thinking in the classroom Forester wrote,

> "Many people assume that only the 'best' students can adapt to the style of education here suggested. But who are the best students? Results so far indicate no correlation between students who do well in this program and how they had been previously labeled as fast or slow learners. Some of the so-called slow learners find traditional education lacks relevance. They are not challenged. In a different setting they come into their own and become leaders. Some of the students previously identified as best are strong on repeating facts in quizzes but lack an ability to synthesize and to see the meaning of their facts. Past academic record seems not to predict how students respond to this new program." (Forester, 1993).

Other research endeavors have reached similar conclusions. The Educational Testing Service has established the Systems Thinking and Curriculum Innovation Network Project (STACI) involving about a dozen schools to explore the use of system dynamics in classrooms.

> "The approach consists of three separate but interdependent components: system dynamics, the theoretical perspective; STELLA, a simulation modeling software package; and the Macintosh computer.… The STACI Project is an implementation and research effort that examines the cognitive and curricular impact of using the systems thinking approach in pre-college instruction…the

> project focuses on the examination of cognitive and learning outcomes… the systems approach is being used in courses that reach a range of students. Contrary to initial beliefs, the perspective can be used to facilitate instruction of low- as well as high-ability students… from initial results, the use of the systems approach for less able learners seems to be yielding promising outcomes." (Mandinach and Cline, 1989).

Some other countries have moved ahead rapidly with the integration of systems dynamics in the classroom. For example, Scandinavian countries have worked together to implement the philosophy below the college level.

> "System dynamics is a method used in the study of complex, dynamic systems. Its pedagogical qualities are under investigation in several countries.…our final goal is to provide our students with an effective way of thinking about complex, dynamic systems. Thus we want to change their cognitive style. Far beyond establishing a basis of values, attitudes, and factual knowledge, our schools significantly influence the way each one of our students will be thinking.… we encourage our students to become critical users of models and to question assumptions underlying models, used for professional and political purposes. They should gain respect for real life complexity and variety and question simple solutions to complex problems.… In Norwegian and Nordic schools, we have chosen to utilize the conceptual framework offered by system dynamics for our educational purposes… When we have established an understanding of the basic dynamic processes, we are ready to address ourselves to reality. Then we will have to tackle systems of far greater complexity, typically characterized by feedback, delays, nonlinearities, and noise.… (pursuing) causal chains until they close upon each other, leads us to a multi-disciplinary approach.… Academic

> boundaries no longer constitute the boundaries of our imagination or our investigation. Historic and economic considerations are merged with physics and chemistry in our study of ecological issues." (Davidsen, 1990).

Not all experiments with these methods have been equally successful. Riley (1990) focused more explicitly on student use of computer simulations to make models. As is related by Chen and Stroup (1993), Riley addressed a number of issues including,

> "whether the time involved in using the STELLA environment is 'worth the effort,' 'what-if' kinds of experimentation, and seeing 'structure as cause' of behavior… Unfortunately, none of the assertions made by Steed are supported by empirical research or extended theoretical analysis. In the end, the author is only left with the following: 'It is concluded that model construction software might prove to be a useful way of making explicit our assumptions about dynamic systems and bring us to a better understanding of a system's behavior.' The operative word in the conclusion is 'might.' The potential continues to be underanalyzed and underrealized." (Chen and Stroup, 1993).

In studies by Mandinach and Thorpe, (1987, 1988), classroom time restrictions and software complexity complicated results. The results were inconclusive using the STELLA platform. The researchers articulated a concern that the actual classroom time committed to system work probably was insufficient to produce significant results. In general, the students were not able to construct their own models.

While research still does not describe a universal system for teaching systems thinking, Hopper and Stave (2007) proposed a taxonomy for systems thinking to be used in developing classroom methodologies. The proposed taxonomy suggests the following key levels:

1. Recognizing Interconnections

The base level of thinking systemically is recognizing that systems exist and are composed of interconnected parts. This includes the ability to identify parts, wholes and the emergent properties of a whole system. A number of authors used the analogy of being able to see both the forest and the trees. Recognizing interconnections requires seeing the whole system and understanding how the parts of the system relate to the whole.

2. Identifying Feedback

This characteristic includes the ability to identify cause-effect relationships between parts of a system, describe chains of causal relationships, recognize that closed causal chains create feedback, and identify polarity of individual relationships and feedback loops.

3. Understanding Dynamic Behavior

A key component is understanding that feedback is responsible for generating the patterns of behavior exhibited by a system. This includes defining system problems in terms of dynamic behavior, seeing system behavior as a function of internal structure rather than external perturbations, understanding the types of behavior patterns associated with different types of feedback structures, and recognizing the effect of delays on behavior.

4. Differentiating types of flows and variables

Simply recognizing and being able to describe causal relationships is not sufficient for a systems thinker. Being able to identify rates and levels and material and information flow, and understanding the way different variables work in a system is critical.

5. Using Conceptual Models

Being able to explain system behavior requires the ability to synthesize and apply the concepts of causality, feedback, and types of variables.

6. Creating Simulation Models

The ability to create simulation models by describing system connections in mathematical terms is an advanced component of systems thinking according to some authors. Others see simulation modeling as beyond the definition of systems thinking. This category includes the use of qualitative as well as quantitative data in models, and validating the model against some standard. It does not specify which type of simulation model must be used.

7. Testing Policies

Most people see the use of simulation models to identify leverage points and test hypotheses for decision making as the full expression of systems thinking. This includes the use of simulation models to understand system behavior and test systemic effects of changes in parameter values or structure. (Hopper and Stave, 2007).

This taxonomy, or modifications thereof, could be used to develop systems thinking interventions. It should be noted that not every study involving system dynamics in the classroom has stressed the creating of simulation models such as those implied in this taxonomy. “The system dynamics community believes that creating simulation models is at the top of the abilities for systems thinkers; however, this may not be true for the entire systems thinking community. According to Anderson and Krathwohl (2001) students at the evaluation level should be able to: argue, critique, defend, interpret, judge, measure, test, and verify. Displaying these abilities does not require the creation of a system dynamics model. Students can use other means to display these qualities, so the top level of the systems thinking taxonomy can be achieved through different means according to a specific field. Students need to demonstrate that they can propose and evaluate hypotheses based on a framework." (Hopper and Stave, 2008).

Most of the literature with regard to implementing systems thinking activities in the classroom is qualitative and involves observations by teachers. The author asserts that, although qualitative studies of the efficacy of these methods are needed and should continue, the contributions from experienced teachers who understand the problems and opportunities in class rooms and can translate ideas into effective teaching materials are essential to the continued advancement of systems thinking in the classroom.

2.4 Discussion of the Design Experiment as research methodology

As was previously discussed in this paper, the model testing environment of the laboratory is at the heart of scientific inquiry. Not all inquiry investigations can be encapsulated in the pristine, variable controlled climate of a laboratory. Classrooms are not laboratories. They are complex and dynamic interacting systems that adapt and evolve in real time. It is impossible to control for the multidimensional variables present in educational practice. And yet, most of the research into classroom interventions is being done in the classroom. Most of it is informal and never published, although it does inform practice in at least one classroom for one teacher, and that alone can affect thousands of students over time.

This situation has resulted in two areas of tension among educational researchers. The first contentious struggle is between theoretical goals and practical goals. Researchers may be dedicated to the ideal of establishing a theoretical model of learning that is firmly based in empirical study, but may also recognize the need for intervention work designed to impact practice and create innovation (Brown,1992). Clearly, education requires a research methodology in addition to the laboratory without expanding the “credibility gap” that hovers over education research. (Levin & O’Donnell, 1999, as cited in *The Design Based Research Collective*, 2003). “It has become increasingly clear that we need a new type of learning theory to inform the design of learning environments, including those that are situated in settings of formal schooling.” (Brown and Campione, 1996, p. 290).

The methodology suggested is referred to as a Design Experiment (DE), a name it was given by Brown (1992) and Collins (1992) in separate writings with many similarities, although they do approach the subject from somewhat different philosophical underpinnings; Collins as a laboratory empiricist wanting to bridge the gap with practice, and Collins as the laboratory scientist looking to free valuable interventions and innovations from the most stringent empirical restraints that would not permit them to happen. Although design experiments are probably quite old, most sources represent Brown and Collins as the earliest to formally treat the subject in literature.

The work of Cobb, Confrey, diSessa, Lehrer, & Schauble (2003) provides an example of good design experiment methodology.

> “Prototypically, design experiments entail both ‘engineering’ particular forms of learning and systematically studying those forms of learning within the context of the means of supporting them…This designed context is subject to test and revision, and the successive iterations that result play a role similar to that of systematic variation. … Design experiments ideally result in greater understanding of a *learning ecology*—a complex, interacting system involving multiple elements of different types and levels—by designing its elements and by

anticipating how these elements function together to support learning." (Cobb, et al, 2003, p. 9).

They outlined five "cross-cutting features" of a design experiment:

A) Develop a class of theories about both the process of learning and the means that are designed to support it

B) DEs are highly interventionist methodologies

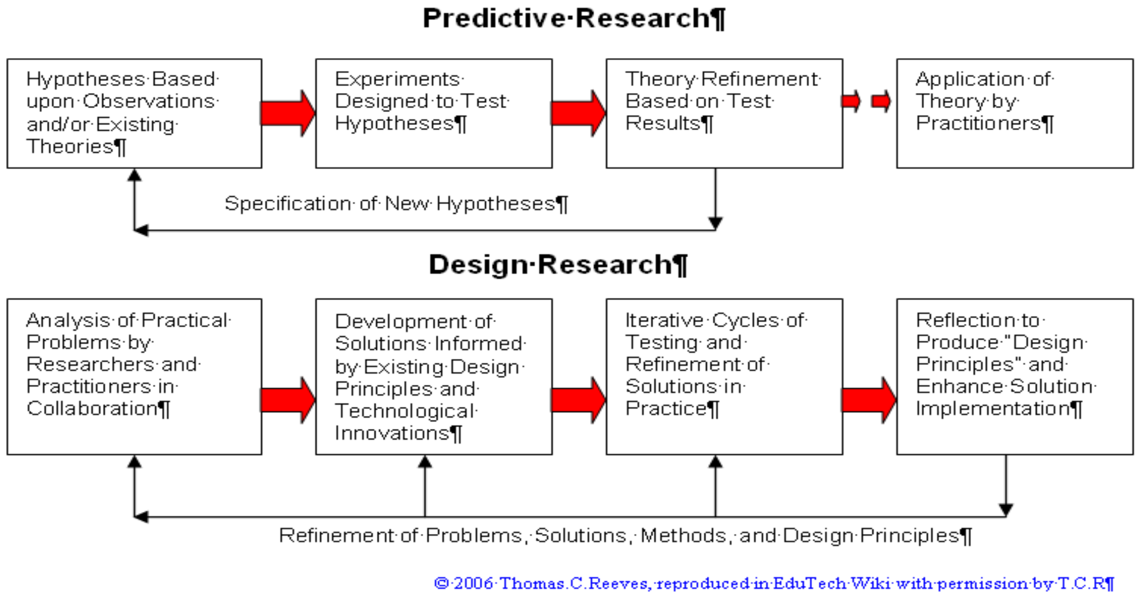
C) They create the conditions for developing theories, yet must place these theories in harm's way

E) DEs are an iterative design process featuring cycles of invention and revision

F) They have pragmatic roots—they're concerned with domain-specific learning processes and are at the same time accountable to the activity of design—they must do "real work." (adapted from Cobb, et al., 2003, pp. 9-11).

Several researchers investigating Instructional Technology in the classroom have written about the use, validity, and importance of design experiments. Reeves (2000) created a flow chart (Figure 1, below) that demonstrates the difference between design experiments and traditional empiricism. Reeves wrote, "…despite its primary focus on considerations of use for local practitioners, it can be regarded as a legitimate form of research provided reports of it are shared with wider audiences who may themselves choose to draw inferences from these reports in a sense similar to reports of interpretivist research."

Figure 1: The Difference between predictive research and design research. (from Reeves, 2000).



Van den Akker (1999) identifies a significant characteristic of development research as focusing on "complex, innovative tasks for which only very few validated principles are available to structure and support design and development activities" (p 7). Van den Akker clarifies the differences illustrated in Figure 1:

> "More than most other research approaches, development research aims at making both practical and scientific contributions. In the search for innovative 'solutions' for educational problems, interaction with practitioners…. is essential. The ultimate aim is not to test whether theory, when applied to practice, is a good predictor of events. The interrelation between theory and practice is more complex and dynamic: is it possible to create a practical and effective intervention for an existing problem or intended change in the real world? The innovative challenge is usually

> quite substantial, otherwise the research would not be initiated at all. Interaction with practitioners is needed to gradually clarify both the problem at stake and the characteristics of its potential solution. An iterative process of 'successive approximation' or 'evolutionary prototyping' of the 'ideal' intervention is desirable. Direct application of theory is not sufficient to solve those complicated problems." (pp. 8-9).

Over the past few decades, design experiments have gradually advanced toward being an accepted and necessary methodology. "Much like any good design experiment, the fundamental underpinnings of design research, such as the situated nature of DEs and their emphasis on inclusion of multiple perspectives and collaboration, were well founded and have remained central in modern DEs. Also remaining constant are the twin goals of extending theories of learning and the goal of designing real classroom activities with positive educative value." (Hurfurd, 2004). Pervasive in later literature is the iterative nature of design experiments. "Design experiments… start with planned procedures and materials… that are revised according to their success in practice. … The goal is to start with teaching methods that are most likely to succeed but to monitor how they are working and to modify them when appropriate." (Collins, 1999, pp. 291-292).

The Design Based Research Collective, a group of privately sponsored researchers who participate in design research, outlined the benefits of design research in a special issue of *Education Researcher*. The Collective argued that "design-based research methods can compose a coherent methodology that bridges theoretical research and educational practice. Design experiment methods focus on designing and exploring the whole range of designed innovations: artifacts as well as less concrete aspects such as activity structures, institutions, scaffolds, and curricula. Importantly, design-based research goes beyond merely designing and testing particular interventions. Interventions embody specific theoretical claims about teaching and learning, and reflect a commitment to understanding the relationships among theory, designed artifacts, and practice. At the same time, research on specific interventions can contribute to theories of learning and teaching." (The Design Based Research Collective, 2003).

The author intends that the design experiment that is the basis of this paper makes exactly the kinds of contributions outlined above.

Chapter 3: The Design Experiment – Methods and Observations

3.1 THE LEARNING ENVIRONMENT

Classrooms are dynamic environments in which many factors (systems and subsystems) interact synergistically to produce outcomes. Ann Brown (1992) wrote, "Aspects of it that are often treated independently, such as teacher training, curriculum selection, testing, and so forth actually form part of a systemic whole. Just as it is impossible to change one aspect of the system without creating perturbations in others, so, too, it is difficult to study any one aspect independently from the whole operating system." That being true, it is helpful to examine the learning environment in which the design experiment was conducted when considering the feasibility of transferring these methods to other environments.

The experiment was conducted in the 2012-2013 school year during a yearlong Aquatic Science course at Round Rock High School (RRHS), a suburban high school in Round Rock, Texas, with a student enrollment of 2,732 and a professional staff of about 200.[9] Relevant student ethnicity statistics are given in Table 1. Table 2 provides student enrollment by program. Table 3 provides student performance data. These indicators[10] combined provide an overview of the student population.

Table 1: Student Ethnic Distribution at Round Rock High School

AFRICAN AMERICAN	HISPANIC	WHITE	NATIVE AMERICAN	ASIAN	PACIFIC ISLANDER	TWO OR MORE RACES
6.5%	26.5%	57.5%	0.7%	5.3%	0%	3.5%

[9] Enrollment and staff numbers as of September 4, 2012, as reported by www.roundrockisd.org.
[10] Information compiled from 2011-2012 AEIS Report.

Table 2: Student Enrollment by Program, RRHS

BILINGUAL/ESL	CAREER & TECHNICAL	GIFTED & TALENTED	SPECIAL EDUCATION
2.4%	63.5%	8.8%	6.3%

Table 3: Student Performance Data, RRHS

Attendance Rate	94.6%
Annual Dropout Rate (Grades 9-12)	0.1%
Completion Rate/Retention Rate	97%
Advanced Course/Dual Enrollment Completion	37.5%
AP/IB Results (% of examinees who met criteria)	40.8%
Percentage of college-ready graduates (English Language Arts, Math)	78%, 70%
Percentage of economically disadvantaged students	20.7%
Percentage of at-risk students	24.4%

In the State of Texas, Aquatic Science is a two-semester course ideally taught in the senior year of high school. Successful students are granted the fourth science credit required for graduation in Texas, having already received credit for Biology, Chemistry and Physics. In an average class of twenty-five, it is common to have one or two juniors who are on advanced graduation plans that require five science credits. Aquatic Science is one of a number of fourth-year science electives, such as Environmental Science, Astronomy, and Research and Design. Alternatively, students may choose to attempt college credit by taking the Advanced Placement versions of the science courses they have already completed for credit, such as AP Biology and AP Chemistry.

Students choose to take Aquatic Science for a variety of reasons. Some are truly interested in marine biology and zoology as future college majors and careers, or as extensions of their general interest beyond the classroom. Intrinsic motivation varies widely among students. On student exit surveys at RRHS, the most common reasons given for choosing the course were A) I thought it would be the easiest and B) I thought it would have less math than other available courses. Others cited good word of mouth concerning specific instructors or the course in general. A reasonable estimate, made by examining two years of enrollment at RRHS, suggests the course has typically attracted approximately 80% of general education students on the recommended plan, 10% advanced twelfth grade students, 2% advanced eleventh grade students, 6% special education students and 2% students on the minimal graduation plan.

Exit surveys also show that students are surprised by the high rigor of the course. At Round Rock High School, the course is taught as a science capstone course, where students must engage previously mastered content from biology, chemistry, and physics in addition to new content specific to the study of aquatic environments. A significant amount of earth and space science is also used, although students are likely to have had little exposure to this content since eighth grade due to the fragmented nature of science curriculum in traditional public school curricula.

The vast majority of students who take aquatic science at RRHS have already completed the required high stakes tests, and Aquatic Science is not a state or district measured content area. As a result, curriculum design for the course is rarely a priority of district curriculum specialists. Each campus is left to create an Aquatic Science curriculum from the state standards for the course. (Texas State Standards for Aquatic Science are located in Appendix 1). This reason alone makes Aquatic Science an ideal course for intervention work. Potential innovations are not mired in the constraints placed on courses measured with high stakes tests. Instructors are therefore free and obliged to create their own interventions and assessments.

Instructors play a pivotal role in the student experience. The observations for this design experiment were made in two classrooms: my own and that of the second Aquatic Science teacher, Jonathan Hallmark. Both of us had biology-related degrees and professional laboratory and field experience in our content areas. Both had extensive experience with and training in aquatic science generally, although Hallmark's expertise is heavily weighted in freshwater environments while the author's is in marine environments. Both of us held identical teaching license certified to teach all science courses from eighth grade to twelfth grade. At the beginning of the 2012-2013 school year, Hallmark had five years of experience as a classroom teacher and three years experience teaching Aquatic Science. I had ten years as a classroom teacher and two years as a district science curriculum specialist, but only half a year's experience teaching Aquatic Science.

The interpersonal relationships of teachers and staff also affect the learning environment. Hallmark and I enjoyed a superior professional relationship, both functional and amiable. We worked together closely as the only two members of a Professional Learning Community (PLC)[11]. This association facilitated the standardization of classroom norms, grading policies, expectations, and generally similar classroom environments. Interventions were, for the most part, identical in both courses. All students participated in common laboratory experiences and field work, and all took the same assessments. Grading policies were identical in all sections regardless of instructor. We met informally on a daily basis to discuss student and pedagogical issues, and formally at least twice weekly for more in-depth planning, assessment writing, assessment data analysis, evaluation of previous instruction, and to compare notes from

[11] All teachers at RRHS are required to function as members of one or more PLCs, and strict adherence to grading and classroom policies within a PLC is monitored by administration. Because I also taught freshman biology, I was a member of the Biology PLC as well.

our instructor journals. We were committed to a reflective practice aimed at making each lesson more learner centered.

There is no way to completely control for the differing effects of each instructor's personality and life experiences on the student experience. However, both Hallmark and I have been observed to be proficient in classroom management and skilled at creating a safe and nurturing classroom environment with clear and purposeful expectations and procedures. Our teaching styles, including the way we built relationships with students, were not identical but were certainly compatible and complimentary. We each made an effort to know the other's students and treat them as our own.

3.2 Experimental Rationale

It is the nature of good design research that any design experiment begins with planned interventions and materials to be tested. The researcher must then "place in harm's way" (from Hurford, 2004) the instructional design to determine if the hypothesized effects occur, to what degree, and in what situations. The curriculum used during the design experiment was fully designed by Hallmark and me with this in mind.

We began our curriculum design with what might seem a simple question about outputs: As a result of this instruction, what impact do we desire to see in students? Arriving at an answer to that question turned out not to be a trivial undertaking. After much discussion and some compromise, we arrived at the following statement:

> Upon completing the aquatic science course, students will have built a deeper understanding of their place in and connection to the Cosmos. They will better understand how their short- and long-term decisions affect the systems they are a part of and realize that the solution lies within the system. They will understand the interconnectedness of all living

> things and recognize the importance of aquatic resources to all living systems. They will be able to apply scientific reasoning in making personal, political, and professional judgments. They will feel prepared and able to take responsibility for their own decisions and actions to effect positive change in their own lives and the global community.

From this "purpose statement," it became clear that our focus was to create student agency. We wanted to produce students who were scientifically literate enough to analyze problems and evaluate solutions so that, through their actions, choices, and informed voting practices, they can be good citizens. A necessary step toward agency is teaching students to see the interconnectedness of themselves and the world. Systems thinking was incorporated into the curriculum for this purpose and because we felt its transferability to many types of problems beyond aquatic science would benefit students.

Also necessary for agency are the skills for acting effectively in the modern world. For this reason, it was important to us that students acquire and practice 21st Century Skills. Based on significant research in this area, we agreed to heavily incorporate computer- assisted, project-based learning as another primary intervention. Collaborative problem solving would be ubiquitous, and challenge-based instruction would be employed where appropriate. It was important to me (although less so for Hallmark) that the engineering design process also be incorporated, as many students are never otherwise exposed to this valuable tool and have never considered engineering as a career path.

A final suggestion arising from our purpose statement was that scientific literacy and the ability to use scientific reasoning were desired student outcomes. Aquatic Science is, after all, a science course. As has been discussed previously, the ability to design, construct, test, evaluate, and improve models is at the heart of scientific endeavor.

The first two interventions, systems thinking and project-based research, are activities requiring a rich understanding of modeling concepts. For this reason, it seemed essential that teaching students to construct and analyze models be another primary intervention.

Each of us had separately used each of these three interventions before to some degree. Our hypothesis became that combining the three interventions as unifying components of the course, the synergistic effect would lead to outputs of deeper understanding of content and higher student agency. On the pedagogy side, we hypothesized that student models would allow for more accurate assessment of student understanding than the multiple choice assessments which had been previously used in the course.

I decided that the first iteration of this research would focus on collecting qualitative data of the efficacy of the interventions, to include student artifacts, surveys, student interviews, and professional journals kept by the instructors. As multiple researchers and multiple perspectives are hallmarks of good design research, observations were made in all nine sections of the on-level course, four taught by the author and five taught by Hallmark.[12] Essentially, all students received treatment so that larger sample sizes could provide clear feedback on the interventions and reveal needed improvements and efficiencies in their delivery. In later iterations, richer quantitative studies will be used which will require control groups and designated treatment groups not taught by the observing researcher.

3.3 CURRICULUM DESIGN

The purpose statement proved to be a powerful guide in making curriculum decisions. Although it was a given that the curriculum would have to address all of the

[12] An applied aquatic science, offered only to certain special education students and taught by a special education specialist, did not receive treatment, although that possibility should be considered in the future.

state standards for Aquatic Science[13], we used our purpose statement to decide where to place emphasis, depth, and time. Table 4 provides the scope and sequence we created. Instructional blocks were normally 90 minutes long.

Much of the first three six weeks was devoted to freshwater systems. This decision was made largely to capitalize on the local watershed, where students do long-term monitoring of water conditions, which is more productive in the months of September to December. The two semesters could easily be flipped for schools using a marine environment as the watershed model. However, the author suggests that Chemical and Physical Properties of Water remain the first unit in either case. Not only is this content (a review and expansion of content from Biology, Chemistry, and Physics) necessary scaffolding for later content and field work, but it also provides an excellent opportunity to introduce model-based reasoning to the course.

[13] Referred to as the Texas Essential Knowledge and Skills. See Appendix 1.

Table 4: Scope and Sequence for Aquatic Science at RRHS, 2012-2013

Six Weeks (14 blocks on average)	Content Unit	Time Allocated (90 minute blocks)
1	Physical and Chemical Properties of Water	3
	Aquatic Field Study Methods	8
	Watersheds	3
2	Systems Thinking	6
	Geochemical Cycles	5
	Energy Flow in Aquatic Systems	3
3	Freshwater Ecosystems	3
	Freshwater Organisms and Populations	7
	History of Oceanography	2
4	Cosmology and the Origin of Oceans	3
	Plate Tectonics and Ocean Basins	3
	Air-Sea Interactions: Climate and Weather	4
	Air-Sea Interactions: Waves and Current	4
5	Land-Sea Interactions	2
	Marine Ecosystems	3

	Life in the Sea	8
6	Life in the Sea (continued)	4
	Ocean Resources	3
	Human Impacts on Marine Environments	4
	Capstone Project Prep and Presentation	3

3.4 Model-based Reasoning – Methods and Observations

Early and often is as good a strategy for teaching model-based reasoning as it is for voting. Our strategy was to introduce it on day one while establishing classroom procedures and establishing expectations. The classroom was described as a “model of human interaction” with norms and goals different from other such models. Students were placed in collaborative groups and asked to model both “novice” and “expert” examples of classroom interactions, such as having an academic discussion, using digital devices, getting permission to leave the room, and using safety equipment.

In the second half of class, students are given an overview of types of models, including graphic, mathematical, physical, theoretical, and experimental models with examples of each. The flat earth vs. the global earth and the earth-centered solar system vs. the sun-centered solar system were discussed as examples. Students were reminded that there are mental and behavioral models that each of us uses to structure our interactions with the world. For many students, this was a new way of thinking about human behavior. Considerable student-initiated discussion arose in all sections. There are key concepts that were uncovered in these discussions:

- People behave differently (and think differently) because they structure their behavior on different models of the world.
- Many of these models are created unconsciously as a result of experience and must be modified as inconsistencies are uncovered in order for growth to take place.
- Designing, constructing, testing and evaluating models is a powerful way of gaining new insight into the nature of the world and yourself.

Key to getting students to create their own models is reducing the “fear of failure” often associated with modeling tasks, even among high-performing students. Students must feel safe enough to take risks and make mistakes without the fear of being ridiculed or disappointing the teacher. This trust may take time to establish in many students. However, a key piece of our modeling instruction helps dramatically. Students are provided with an abstract of a lecture given by John D. Sterman, Director of the System Dynamics Group at the MIT Sloan School of Management. The full text of the abstract is given in Appendix 2. Students are asked to discuss the abstract in small groups and then share what they feel are the most important or interesting aspects of it. For instructional purposes at this point, the important statements are in the last sentences:

> Most important, and most difficult to learn, systems thinking requires understanding that all models are wrong and humility about the limitations of our knowledge. Such humility is essential in creating an environment in which we can learn about the complex systems in which we are embedded and work effectively to create the world we truly desire. (Sterman, 2002).

This statement is used to reassure students that they need not be afraid of making mistakes when dealing with models in the classroom. All models are wrong. The value in models occurs in the construction and evaluation of them. This provides a structure for evaluating our perceptions and understandings of the world. From that point forward, “All Models are Wrong” became a constant and persistent slogan, writ large on the message board and invoked by teachers and students alike as a way of reducing barriers to learning and side-stepping simple, closed-ended solutions to complex problems.

The last statement also implies the importance of model-based reasoning in developing agency by allowing us to “work effectively to create the world we truly desire.” We found this notion to be appealing to many students. One student told me after class, “That first lesson was the most useful thing I’ve ever learned in a science class. Why don’t they teach that in elementary school?” It has, of course, been taught in elementary school (see Garigliano, 1975 and Hill and Redden, 1985) and, to some degree, in science courses throughout the students’ school careers. The reason both instructors received the degree of positive feedback that we did was perhaps the deliberate manner in which it was presented. Model-based reasoning is used throughout school, but rarely is it taught as a key concept for scientific literacy and the advancement of human understanding across disciplines, let alone on the first day of instruction.

The second block of instruction began with our first Model Eliciting Activity (MEA). Students were immediately paired and given the challenge of working together to create a model of water. They were allowed to use any materials in the room but were not allowed to access digital or printed information. By limiting information to prior student understanding, the model becomes a pre-assessment of student knowledge. Based on the previous lesson in which an overview of types of models had been given, students immediately asked “what kind of model” we wanted. We replied that any kind of model the student chose would be fine. Much to my delight, a student contributed, “It doesn’t matter what kind since all of them are wrong.”

As students shared their knowledge and constructed a model, we were able to make critical observations about the level of retention students have from previous courses. Although the structure and properties of water are fundamental principles in both chemistry and biology, surprisingly few students are confident in the validity of their models. The results of the MEA included a variety of molecular models drawn on paper and some crafted from wads of paper taped together. None of these in any section included any indication that students understood that polarity, resulting from the electronegativity of oxygen and uneven distribution of electrons, was an important property of water. Only four student pairs in the nine sections were able to add the polarity concept to their model when prompted. This lack of understanding would likely not have been easy to ascertain from a multiple choice assessment item.

A common response of students to this challenge was the drawing of bodies of water of various size and, in one case, an ice crystal. Graphical models of this nature may have been chosen by students as an easy way out, an attempt to hide what they perceived as a lack of understanding of water at a deeper level. But even here, I was able to demonstrate the usefulness and limitations of such models depending on their intended use. We asked questions such as, "Why did you choose to draw a river instead of the ocean? Are rivers more important to you or just more familiar? Does this model represent a particular river or rivers in general? Why did you choose to model the mouth of the river and not the headwaters? How could your model be modified to represent the property of cohesion?" We were able to ascertain information about students' background experiences, biases, and content knowledge from this kind of guided model analysis.

In a few cases, students retrieved water from the faucet and placed it on a lab table. This led to a discussion of the difference between a model and a sample. There was considerable disagreement in one of my sections as to whether a sample was, in fact, a kind of model. One student commented, “It is only in the sense that a fish in an aquarium is a model for all fish of its kind in the world.” Another student replied,” That’s not a model. It’s an example.” The discussion became somewhat cyclical, and so I asked if the proposed model allowed us to make any predictions and test them. The answer we ultimately arrived at was that a sample might serve as a model under some circumstances. If you include the table as part of the experiment, you could make predictions about certain behaviors of water with regard to cohesion, adhesion, and viscosity. I had to facilitate this discussion only by providing content-specific vocabulary already familiar to the students and by asking a few questions.

The next step was to provide the students with pre-fabricated molecular models of a water molecule, purchased from a vendor, which were equipped with magnets to demonstrate molecular bonds and dipole movements, making each molecule of water interact with other models only in specific ways. From testing and evaluating the behavior and structure of these models, students were able to deepen their understanding of how the structure of water relates to its properties, such as polarity, adhesion, and cohesion. Students were then asked to refine their own models based on this experience, serving as a measure of how their understanding had changed.

Students were challenged to make another model as we began our study of watersheds. This MEA was prefaced by a PowerPoint presentation on the subject. This was not delivered by the teacher as a lecture, but was provided via our online learning environment (MOODLE) and assigned as homework the block before. On the day of instruction, students were first asked to take a brief “practice test,” with no impact on student grades, concerning the components of watershed. The test was given via the assessment function of our online learning environment so that results could be instantly viewed and evaluated.

Results were dismal, with an average score of only 11 out of 20, or 55%. This speaks either to a low percentage of students having done the preparatory homework or an unreasonable assessment. The author suspects the former. To be fair, the assessments used in the course include open ended, short answer questions and non-dichotomous multiple choice questions with more than four answer choices and more than one possible answer. Many students are not accustomed to this level of rigor, having been drilled using four-choice multiple test questions with only one correct answer for most of their school careers in preparation for high stakes tests. This was undoubtedly a contributing factor to the low score here, and on many such assessments in the first semester of the course. It took students several six weeks to learn to prepare for these more stringent testing methods in which strategic guessing is less effective.

Following the pre-assessment, students were placed in groups of two or three and provided with a list of features common to watersheds. They were also given a container holding a variety of items. The exact number and nature of items was not identical to each container, but all contained an assortment of office supplies (rubber bands, paperclips, tape), lab equipment (pipettes, beakers, a test tube holder, a bowl), and craft supplies (straws, toothpicks, small beads, yarn, pipe cleaners, a piece of cloth, and assorted toy animals and plants) purchased from a dollar store. Figure 2 is representative of the kinds and number of items each team received. Students were given twenty minutes to create a model of a watershed representing all of the features on the list. The vocabulary list may be found in Appendix 3.

Figure 2: Watershed Modeling Materials

Unfortunately, pictures of student watershed models were lost as the result of a corrupted hard drive. Most teams were able to make models perfectly adequate to discuss how components in a watershed are related to each other, and to reveal misunderstandings. For example, one team had represented a stream as flowing uphill from a spring toward the mountains. By questioning their modeling choices, I was able to assess that none of the three students in the team clearly understood the nature of a spring or the roll gravity plays in water distribution. On a multiple choice test, they could have simply guessed and I might never have known.

Once models were built, students took turns sharing their models with other groups in a round robin fashion. They were instructed to ask questions about model choices and suggest modifications. (It should be noted that I modeled the interview and analysis procedure for them ahead of time with a volunteer group.) Seeing different models of the same concepts provided students multiple perspectives into the nature of watersheds. Whether or not they had viewed the preparatory presentation, students were able to learn the components of a watershed from this MEA. Scores on the summative assessment averaged 16 out of 20, or 80%.

These two MEAs are discussed to demonstrate how such activities were used to teach content, demonstrate model-based reasoning, and practice 21st Century Skills simultaneously. They are by no means the only MEAs we used, nor are such MEAs the only kind of modeling activities employed. Round Rock High School and most of our students' houses are in the Brushy Creek Watershed. We have access to a large section of the watershed that can be easily visited in a single class period. The watershed serves as a model of watersheds generally. Students do long-term monitoring of the system on frequent field laboratories and are able to make predictions about how the model will change as a result of weather, seasonal change, and human activity. The fact that it is "their water" they are monitoring creates relevance and demonstrates to students how they are functioning as part of a larger system, even though most had been unaware of their interactions with it.

One final modeling activity is important to mention explicitly here as it provides us with much of the artifacts and feedback used to evaluate this first iteration of our design experiment. I speak of the capstone project, which serves as a final exam grade[14] for the students and is an ultimate assessment for us as to how our curriculum has impacted students. The activity (referred to as Tag-It-and-Bag-It by my mentor, Ruben Garza of Texas State University, who taught it to me) is actually a way of eliciting from students a model of their own growth throughout the year as a result of instruction.

[14] It is the policy of the Aquatic Science PLC that students are not permitted to exempt this project which serves as a final exam grade. We feel it is simply too valuable an experience to both the students and the instructors.

Complete instructions for the project may be found in Appendix 4. Unlike most other MEAs, students each create their own model individually. Students are asked to acquire a bag or box with four distinct sides and an open top. They are given explicit instructions on what they must represent on each of four sides of the bag. These instructions are designed to elicit from students some representation of the content that they learned, how and why the content affected them, and how they have revised their model of interacting with the world. They must also put five items into the bag, each of which represents to them the most important concepts of the course. Each item must represent a different concept. On presentation day, students were placed in groups of five or six and presented their model to the group, including each side of the bag and the items in it. As students shared out in groups, the instructors circulated to get an overview. We would look at these artifacts more closely later.

Students peer grade each other using a rubric designed by the instructor. The rubric may be found in Appendix 5. Although this may seem like a mere craft project, the rubric is actually quite rigorous as appearance and effort only account for a small portion of rubric points. Presentation skills, modeling choices, academic vocabulary, and 21st Century Skills are all addressed by the rubric. It was our experience that students were surprisingly committed to grading fairly according to a rubric. Numerous students did receive failing scores, obliging them to revise their models for a second evaluation by the instructor.

It is important to note that the presentation of the capstone models was done a class period ahead of final exam day. This was important in providing students with a chance to improve their models for a higher grade and in providing the instructors with time to closely examine the artifacts in order to evaluate the outputs of our design experiment. On the last day of class, students participated (voluntarily) in the deconstructing of their capstone projects so that each panel could be incorporated to an even larger model of the aquatic science community at RRHS. Two enormous mixed media boards were created to hang in the hallway around the entrances to the aquatic science classrooms at the beginning of the following school year. This would be the graduating students' legacy for the next group of aquatic science students behind them. One of these "legacy boards" is shown in Figure 3.

Figure 3: A legacy board, designed to hang in the hallway around the classroom door.

Presentation day was surprisingly emotional for many students as well as the instructors. Most students, we estimated 85%, were sincere in their efforts to effectively model their own growth and understanding. It was clear from looking at the artifacts, listening to presentations, and interviewing students afterwards which students had grown the most, what interventions had been most useful to them, and the range of knowledge and skills they had acquired. Specific student outcomes from this capstone experience as it relates to the design experiment will be discussed in more detail in Chapter 4.

3.5 Systems Thinking

Justification for Inclusion

A study of systems is explicitly written into the state standards for the Aquatic Science Course. The word system(s) is used no less than nine times in the standards. Systems as a general theme of the course are described in the introduction to the standards:

> (5) Scientific systems. A system is a collection of cycles, structures, and processes that interact. All systems have basic properties that can be described in terms of space, time, energy, and matter. Change and constancy occur in systems as patterns and can be observed, measured, and modeled. These patterns help to make predictions that can be scientifically tested. Students should analyze a system in terms of its components and how these components relate to each other, to the whole, and to the external environment.

Systems thinking is directly applied to content in TEKS 4.A.B.

> (4) Science concepts. Students know that aquatic environments are the product of Earth systems interactions. The student is expected to:
>
> (A) identify key features and characteristics of atmospheric, geological, hydrological, and biological systems as they relate to aquatic environments;
>
> (B) apply systems thinking to the examination of aquatic environments, including positive and negative feedback cycles;

If students are expected to apply systems thinking, they must certainly be taught what systems thinking is and how to distinguish between positive and negative feedback. The author cannot claim to know to what extent systems thinking is actually taught, or even discussed, in most aquatic science classrooms. For the purpose of this experiment, we chose to teach it directly, refer to it constantly, and incorporate it as a central lens through which the course was taught. From the first day of class, the phrase "Be a Systems Thinker" was displayed on a large marquee above the whiteboards.[15]

In the several years before this experiment, systems thinking was not incorporated into the scope and sequence until the second semester. It was taught directly before teaching air-sea interactions to support the understanding of ocean systems. As systems thinking was to become a lens for the course, we chose to teach it near the beginning of the course. This seemed logical given the transferability of systems thinking to many different kinds of problems as the course would unfold. Reviewing our instructional journals at the end of the year, we would conclude that was a wise decision.

Defining Systems, Boundaries, and Feedback

Our approach to teaching systems dynamics was carefully planned to incorporate MEAs and collaborative problem solving. At the beginning of the lesson, students were provided with an article on systems thinking (included as Appendix 6) which they first read individually and then discussed in groups of four. Groups then created a quick poster on chart paper illustrating what they felt were the salient points in the article and what they wished to learn more about. Each group shared their poster with the class.

Having introduced students to the concept and vocabulary of systems dynamics, we then challenged the students with an MEA. Students were provide with a kit containing a sewing needle, a magnet, a small square of styrofoam, a petri dish, and a small beaker containing 50 mL of water. The basic materials for this MEA are shown in Figure 4.

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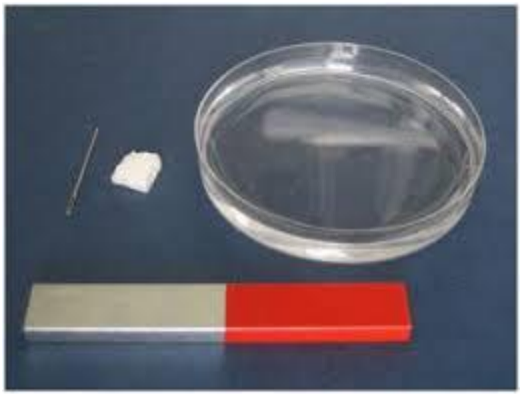
[15] This prompted some intrinsically motivated students to do advance research on systems thinking even before it was introduced as part of content.

Figure 4: Materials for Compass Model Construction



Each team of two students was challenged to be the first to create a functional compass using this assortment of items. Although this activity is well known and widely distributed, surprisingly few students had done it before or remembered how, which made the challenge interesting to watch. As they tried different ideas, the instructors walked around the room holding a manufactured compass so that the accuracy of student created compasses could be verified. At any rate, the point is not to teach the students about electromagnetism or compasses (although compasses are discussed later in the unit on History of Oceanography).

The point, of course, is to demonstrate properties of systems. Once all groups had created a working compass, the instructors engaged the class with questions deigned to assess student understanding of system parts, system boundaries, and system interactions. This began by having groups list the parts of the system they had built and comparing the lists. Some groups included the desk the Petri dish was sitting on as part of the system while others did not. Surprisingly few groups included the earth itself or the electromagnetic force as parts of the system. Although these are certainly essential parts, the fact that they are not visible components in the room causes students to overlook them. This provided an opportunity for discussion on how causal relationships in systems are often hidden and overlooked in hastily constructed models.

From this simple MEA and the associated discussion, students gain an understanding of how to define systems and system boundaries based on what is being studied. At this point, the instructors presented a short PowerPoint presentation on system dynamics designed to reinforce lessons learned in the MEA and expand on student understanding of positive and negative feedback loops. To assess student understanding of the content presented, teams were then asked to each provide an example of both positive and negative feedback in any system they choose. Some examples of student responses for positive feedback were drug addiction, stress and overeating, and exercise and weight loss. One group offered that orgasms were an example of positive feedback in biological systems, which generated considerable discussion.

Examples of negative feedback included appetite and feeding, temperature and sweating, and earning and spending. As in any class discussion, some student examples were more accurate and inventive than others. All responses allowed for quick assessment of student understanding and the opportunity to reinforce the mantra that all models are wrong. The value is in creating models so that analysis and discussion can deepen understanding.

CAUSAL LOOP DIAGRAMS

Causal loop diagrams provide a mechanism for understanding the dynamic nature of our world and the interconnections within it. In causal loop diagramming, variables are linked together to show the causal relationship between them. By connecting multiple causal loops together, we can model a particular system and get a coherent story about a problem or issue.[16] Causal loop diagrams are frequently used tools in system dynamics, and researchers have found this kind of model to be useful in teaching students system thinking. (see Roberts,1975, 1978).

Causal loop diagrams were introduced in the second block of our systems thinking unit. We chose to direct teach the concept with a PowerPoint presentation. Students wrote down step- by-step instructions in their journals. Several simple examples of causal loop diagrams were examined and students were asked how to modify or expand each model.

Via PowerPoint, we introduced students to the concept of *albedo*, the reflection coefficient that describes how much sunlight a given surface reflects back into space. For example, snow has an albedo of 85% - 90%, but black asphalt has an albedo of only 5% - 10%. This was new content for virtually all students, although it does build on concepts studied in physics. Once the basics were taught, students were put in teams of two and given a premade model of the relationship between albedo and global warming to analyze. This diagram and the accompanying information on albedo are given in Appendix 7. Students then structured their analyses around a series of guiding questions:

1. This system diagram contains five reinforcing loops and two balancing loops. Identify each loop.
2. What is the most important effect of decreased albedo?
3. What effect would decreased net radiation have on shrub growth?
4. How does low latitude warming affect net radiation?

Students had fifteen minutes to analyze the diagram as instructors walked around listening and answering fact-based questions when asked. This interaction allowed the

[16] A useful description and how-to guide for making causal loop diagrams can be found at http://www.thesystemsthinker.com/tstgdlines.html

instructors to assess students' prior knowledge of issues relating to climate change as well as what students had or had not learned about albedo. More important, instructors could assess and quickly address any misunderstandings students had about reading causal loop diagrams.

For homework, students were assigned the task of creating a causal loop diagram of their own that modeled some problem or issue in their own life. On the following class day, students were asked to share their causal loop diagrams at their tables. Before they began, they were reminded that all models are wrong and there was no reason to be shy about sharing. After most students had shared at their table, the instructors asked for student volunteers to come to the whiteboard to demonstrate their models while the class as a whole analyzed, modified and expanded them.

We would stress that this application of causal loop diagrams to students' personal lives was a powerful instructional technique with above 90% active student engagement in all sections.[17] The sense of relevance it brought to our study of system dynamics would be extended later into content. Hallmark in particular found this to be an exceptional tool for teaching system dynamics and creating bonds with students that would pay dividends for the rest of the school year. For those teachers or administrators who might lament about the time spent teaching system dynamics without embedded content, I offer Hallmark's words to me as we later evaluated this trade-off:

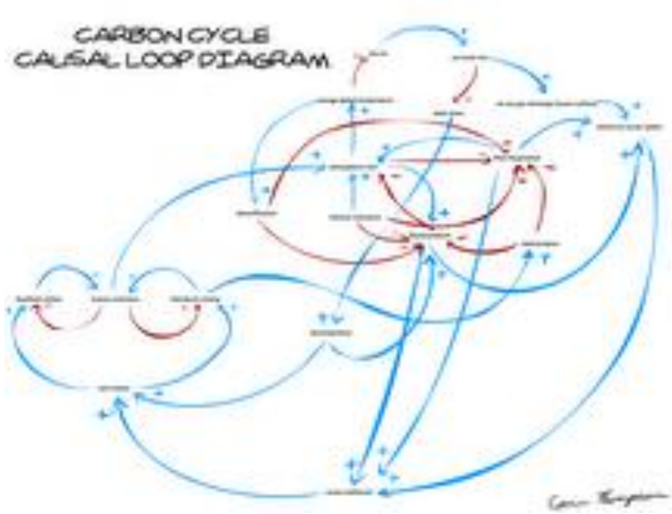
> My chief regret as an educator is not diving into the idea sooner that being a slave to my content is not what makes students better people. Students don't respond with 'I'm so glad you taught me about the ocean.' Students respond because their general understanding of the world around them,

[17] Hallmark and I regularly wrote down student engagement estimates in learning journals. Estimates were made simply by counting the number of students actively on task at any given time.

and of themselves as relating to the world around them, has fundamentally changed. Students express system dynamics as being influential in accommodating such a fundamental shift. (Hallmark, 2013).

The next step in teaching systems thinking was to assign students the challenge of modeling the carbon cycle using causal loop diagrams. The full assignment is given in Appendix 8. The carbon cycle should not have been new material for students as it is repetitive throughout science courses from elementary grades through high school biology. However, this assignment turned out to be difficult for students, more so than we had expected. Hallmark said, “The causal loop model that students were asked to complete themselves was one of the most incomplete assignments because students had not mastered the fundamental concepts and knowledge. With other kinds of assessment, students would turn in something to get points. With causal loops, it was much more difficult for students to fake their way through.” (Hallmark, 2013). This speaks volumes to the power of causal loop diagrams as assessment tools in addition to teaching tools. A highly proficient example of a student artifact from this assignment is shown in Figure 4.

Figure 4: A student-created causal loop diagram.



One noteworthy point this assessment showed us was that there are some students who have significantly higher difficulty mastering causal loops than others. It was not only low-performing students who had issues. Some normally high-performing students struggled for reasons that they themselves could not verbalize with precision. Some normally low-performing students performed better than the average on causal loop assessments. The reason remains unclear, but future research should include the creation of interventions to probe this question.

Perhaps the most common misunderstanding to overcome in teaching causal loop diagrams is the difference between positive and negative feedback. On written assessments, students across the spectrum had trouble correctly identifying whether a given feedback loop was positive or negative. We were able to ascertain that part of the problem was rooted in language. We found that it is critical to emphasize that "positive" does not mean "good or desirable." Likewise, "negative" does not mean "bad or undesirable." Positive feedback frequently leads to dynamic change in a system, while negative feedback tends to lead toward stability. Once we were able to clarify this point, students who retook the assessment were much more successful. As the year progressed and causal loops were used more frequently to test student understanding, most students (we estimate 80%) had moved from novice to intermediate in this skill.

Throughout the year, students were asked to use their knowledge of system dynamics to analyze a great many interactions, including geochemical cycles in their own watershed, their interrelationship with the watershed they live in, how dwindling water resources affect geopolitical stability, and how ocean acidification affects coral reefs, reef fish stocks, and poverty in third world countries. This is not light fare. What system dynamics reveals to us about water in the world is not entirely an optimistic picture. We struggled against allowing aquatic science to become the pessimistic course of doom. Our goal was to create agency, and helplessness is agency's enemy. John Sterman said:

> One of the main challenges in teaching system dynamics is helping people to see themselves as part of a larger system, one in which their actions <u>feed back</u> to shape the world in ways large and small, desired and undesired. The greater challenge is to do so in a way that <u>empowers people</u> rather than <u>reinforcing the belief</u> that we are helpless, mere leaves tossed uncontrollably by storm systems of inscrutable complexity and scope. (Sterman, 2002)

This negativity may pose less of an issue when teaching system dynamics in other courses, but in aquatic science, the problem is pronounced and instructors must strive to emphasize solutions over despair. As will be discussed in Chapter 4, our observations suggest that the majority of students felt more powerful after their studies in system science.

COMPUTER SIMULATIONS OF SYSTEM DYNAMICS MODELS

As was mentioned in Chapter 2, virtually all research on teaching system dynamics involves computer simulations or models, and with good reason. Powerful modeling software allows students to "intervene" and test models repeatedly. The outputs of these simulations and the process of building models teach students to differentiate between key systems thinking concepts of stocks and flows. It allows even students with low math skills to graph complex, non-linear relationships and examine causal relationships.

Originally, we intended that students would be taught to build and analyze models using the STELLA platform with which the author was already familiar. This was to be taught immediately after teaching causal loop diagrams. Unfortunately, STELLA was by that time no longer a free license, and the science and technology budgets simply were not sufficient to purchase licenses. An open source platform with a graphic user interface feasible for classroom use was not known to the author at that time. However, at the time of this writing, freely available and adequately powerful system dynamics software is available.[18] Computer simulations will be part of future iterations of this design research.

3.6 Project-based learning

There is a large body of research validating the use of Project-based Learning (PBL) as a powerful instructional tool for a variety of desired outcomes. It has been shown that PBL can have significant positive effects in advancing student expertise, particularly in terms of increasing transferability of knowledge to novel environments. (see Pandy, et al., 2004). It should be noted that in literature, and in the author's experience, PBL does not necessarily have a significant impact on student mastery of fact-based knowledge. This paper already contains numerous examples of the use of project-based instruction during the experiment, but for some distribution of facts and fundamentals, other instructional methods were used. The PowerPoint lectures on system dynamics and causal loop diagrams are examples.

We did, however, employ project-based learning as often as was feasible and appropriate. With regard to the field work carried out along the Brushy Creek Watershed over the entirety of the course, students worked in permanent teams of four or five, each team responsible for monitoring a specific section of the watershed with the goal of arriving at a statement about the health in that part of the system. Students worked in groups to create models analyzing the flow of energy through their part of the watershed

[18] For example, see Insight Maker at http://insightmaker.com/

as well. Groups competed using mathematical models of fluid dynamics and water stocks and flows to get as close as possible to the actual flow rate of Brushy Creek.

The author's students participated in a Legacy Cycle (Pandy, et al, 2004) project in which they were cast as members of a marine engineering team. They were challenged to design a device that could measure wave height over time along a coastline. Built into the stages of the Legacy Cycle were the processes of the engineering design cycle. Scaffolding lessons included an introduction to engineering, the interrelation between engineering and science, and the engineering design process from ideation to concept selection. Other embedded content included an entire Aquatic Science unit on waves. The entry document for this project is given in Appendix 9.

It is outside the scope of this paper to detail the various project-based methods used during the experiment. The author mentions this particular Legacy Cycle for two reasons. First, it allowed the introduction of the engineering design process, a powerful problem solving tool that most students would never have learned otherwise. An anonymous survey of student knowledge and attitudes toward engineering was given before and after the project. A number of students remarked that they had never really understood what engineering was or what engineers did before the project. Second, the project resulted in increased student agency. Some 40% of the students who participated expressed an intention to use the engineering design process to solve personal problems. Four students said that they were now considering careers in engineering that they had not considered before. More than 85% of post-test respondents said that they believed they had the skills to function as part of an engineering team, an increase of 42% over the pre-test responses. Only 36% said that the engineering content did not belong in the Aquatic Science curriculum.

Prepackaged PBL units are now widely available for virtually all subjects and most content. They are also fun to create, although the upfront work can be considerable. One constraint that many point to is the time required for the processes of PBL to play out in the classroom. In most cases, these processes must be taught upfront in the first project and reviewed frequently. In many cases, PBL units are highly efficient in terms of instructional time, but not always. In the author's experience, it can take more time to teach content inside a PBL unit than with other instructional methods, sometimes considerably more. We encountered this constraint during the design experiment. Our conclusion was that not all content can be deeply covered inside of PBL environments if we are to teach all of the standards, but we should choose some content to teach deeply, particularly where deep transfer of knowledge may positively impact student agency. The watershed monitoring project previously mentioned is an example.

A primary benefit of PBL is that it provides a model of instruction closer to real world problem solving, anchoring the instruction and giving it relevance. Relevance leads to higher engagement. In addition, students are obliged to practice 21st Century Skills on a regular basis. We estimated that students who completed our course had each participated in an average of 24 formal presentations of solutions to problems in which content was embedded. We absolutely concurred that student collaboration skills and presentation skills were advanced for most students enrolled. These skills are prerequisites for developing agency in the modern world.

Chapter 4: Student and Instructional Outputs

In this first iteration of an ongoing design research, we collected and examined a wide array of qualitative evidence including pre and post unit surveys, student exit surveys, pre and post unit assessments, student artifacts, and detailed instructor reflection journals. We used the similar data collected the previous year when students did not receive the treatment as a baseline for evaluating effectiveness.

Eliciting students to create their own models proved to be powerful in terms of advancing student instruction and providing a means of accurate formative assessment. When students built and analyzed models as part of collaborative teams, they gained new perspectives into content resulting in increased assessment scores over students the previous year. As students discussed models, misconceptions and gaps in knowledge became clearer to the instructors than would be possible on a multiple choice test where test taking ability and guessing strategies may be cloud the data. This allowed instructors to give faster, more targeted feedback, resulting in higher assessment scores than on pre-assessments before the modeling activity (but after traditional methods of delivery over the same content).

Collaborative problem-based instruction, which was often incorporated into challenge-based units, was clearly more engaging than traditional lecture-based methods. We estimate that discipline problems were reduced by at least 30% from the previous year based on parent contact logs and referrals numbers. Instructor notes on student engagement, collected by counting the number of students clearly engaged at random points during instruction, showed an average 15% increase in student engagement over the previous year. Engagement ranged from a high of 90% during collaborative model making to a low of 10% during independent student research.[19]

Interestingly, we observed that most of the gain in engagement occurred among students who we would classify as “at least somewhat intrinsically motivated to participate in the learning process.” This kind of student, representing about 70% of the total student sample, was noticeably more engaged than similarly motivated students in previous years. We did not see large gains in engagement or assessment performance from the minority, perhaps 15%, which we would call “not intrinsically motivated to actively participate in learning.” Hallmark concluded, “Our hypothesis seems to be supported in intrinsically motivated students.” (Hallmark, 2013). To what extent these methods are effective with lower-motivated students is an area that could benefit from further research.

Senior capstone projects and anonymous exit surveys were particularly useful in evaluating student growth toward agency. We examined student reflections and representations for evidence of increased student awareness of their own interconnectedness to the world and a willingness to act based on this new awareness. The majority of student reflections expressed a deepened concern for issues relating to aquatic science. Perhaps this is to be expected given the nature of the content and the assignment. More illuminating for us was that more than 60% of students expressed an intention or strong desire to contribute meaningfully. The following are representative student reflections taken from capstone projects:

- “…Aquatic Science showed me a world that is much bigger than me but something that I still impact daily, whether it be positively or negatively.

[19] We found that students doing computer-based research individual were far more likely to be off-task than students doing similar collaboratively. There are many distractions on the web, but we taught students that holding each other accountable was a critical collaborative skill.

This made think of the negative impacts people have on the ocean environment…and also that I have the capability of saving the ocean which is the body and heart of the earth."

- "Prior to this course, I had not given extensive thought to the impact humans have on water resources. Our study of biomagnification…and its impact were astonishing. It became clear to me how everything humans do influences the water and is *interconnected*."[20]
- "I was one of these people who did not think much beyond the fact that I when I turned on the faucet, clean water came out. I am not that person anymore. I try hard to control my water usage on a daily basis and absolutely place more value on water. I make an effort to take shorter showers and not waste water whenever possible."
- Hopefully when I have the ability to travel, I can go volunteer and help families (displaced by dam construction) and advocate for not using people's homelands."
- "I believe, *and will fight for*[21] when I'm older, that the United Nations should have stricter policies and regulations to protect the (other) animals that also share this planet and more restrictions on fishing to protect future fish populations."
- "I really appreciated this year and the understanding I got of system dynamics. The understanding I got of systems dynamics changed the way I look at the world around me and how I think about myself."

[20] Emphasis added by the author.
[21] Emphasis added by the author.

- "I took this course thinking it would be easy and that I would mostly learn about marine animals. That was not the case. We learned so much more about things I never expected. I'm now thinking of changing my major to engineering because this course showed me I can learn how."

References to systems thinking commonly appeared on capstone projects and in exit surveys as being valued by students. Hallmark and I agreed that placing systems thinking and the modeling of system dynamics early in the sequence and eliciting student use of these tools across content should be continued moving forward. This was our most powerful instructional tool for teaching students to see themselves as part of a system. If you are part of the system, you can change it, and this is the path to agency. Hallmark's general conclusion was, "With regard to positive and negative feedback and modeling, our approach of 'this is you in your world' was far more effective and engaging for students, as opposed to students in the previous year when system dynamics was not stressed as an essential tool for life." (Hallmark, 2013).

Although most student responses with regard to systems thinking were positive, not all student experiences were equivocal:

- "I really didn't quite get causal loops. I still don't feel like I'm very good at it."
- Sometimes system dynamics seems too complex for me. I have trouble keeping track of all the variables and I always miss something that's connected."
- "This class was too hard for a senior elective. Students shouldn't to have to be afraid of (not) graduating because of this class."
- "I didn't like modeling sometimes because I felt I didn't have enough information to do it correctly. I always thought of myself as a good student

who made good grades but I wasn't as good at this class. I guess I'm not used to thinking the way this class thinks."

- "I don't see why engineering and system dynamics has to be a part of aquatic science. I thought we were going to learn mostly about fish and hurricanes."

As is likely true of any course regardless of the instructional methods used, student outputs are heavily influenced by the amount of student by-in and effort. It was clear to us from the qualitative evidence that more students were more engaged more of the time with these methods than was the case in the previous year without them. As a result, students gained deeper understanding and a tendency to act on what they have learned. There is still room for improving this synergistic affect so that it impacts more students at different levels of motivation and performance.

Chapter 5: Conclusions

There is significant research to support that systems thinking, model-based reasoning, and project-based learning, used individually, have significant advantages over traditional lecture based instruction. Over a year long course in Aquatic Science at Round Rock High School, we conducted a design experiment examining the effectiveness of incorporating all three strategies as foundational lenses through which all course content was examined. We hypothesized that combining these proven instructional methods together in a deliberate manner would produce student outputs of deeper understanding of content and increased student agency. We hypothesized that instructional outputs would be higher student engagement and more accurate and authentic assessment than multiple choice tests.

With regard to instructional outputs, we conclude that these methods produced higher student engagement, although not necessarily among the least motivated students. Project-based instruction and eliciting student models were particularly effective engagement strategies. Student models provided not only an effective tool for teaching students course content, but also an accurate and effective means of assessment. This allowed for faster and better feedback to students, improving student performance.

With regard to student outputs, we observed increases in the proficiency of most students in the 21st Century Skills of collaboration, communication, asking good questions, creative problem solving, and in science and technology literacy. Project-based learning, as is noted in numerous studies, supported the teaching and practice of these skills in an effective manner and was a favored instructional method amongst most students, perhaps more so in lower performing students than in more advanced learners. We concluded that expanding the use of project-based construction to include more challenge-based units is desirable and should be a component of future experiments in this line of design research.

Model-based reasoning and systems thinking were exceptional lenses through which to view the content of the aquatic science course. We feel that inclusion of systems thinking and causal loop modeling should continue to be introduced early in the curriculum and remain a guiding concept. Evidence suggests that most students learned to use the tools of system dynamics to more deeply understand science content. Perhaps more importantly, students were able to transfer these tools to novel problems.

Many students expressed a change in their awareness of how they are connected to the larger systems around them. In many cases, students expressed a willingness or intent to act on what they learned to produce a positive result beyond the classroom. This type of agency, which students can carry forward into their adult lives, is a powerful outcome and a primary outcome of our curriculum design.

Future research should look at refining these three methods to determine if it can more effectively engage students with lower intrinsic motivation. Now that positive results have been seen using qualitative evidence, quantitative research methodologies should be incorporated to search for statistically significant improvement in student assessment scores as a result of model eliciting activities embedded in a project-based instructional environment, versus a control group that does not receive treatment.

Research on the effect of these methods to advance student agency should be carried beyond high school. The creation of an online interface where student attitudes and behaviors with regard to course content can be followed over several years to see if agency increases or diminishes with time. A significant effort to involve students in long-term data collecting and the maintaining of a “legacy” of student and graduate participation in aquatic science related action research and public involvement is planned for the next iteration of this design research.

Once these methods have been examined by multiple researchers over several iterations in the Aquatic Science Program at Round Rock High School, the deign research should be expanded to other courses. On-level Biology, Chemistry, and Physics courses are all obvious and ideal choices for this line of research. The degree to which learning systems thinking in earlier courses, such as Biology, might effect student performance in later courses, such as Chemistry and Physics, is also an interesting question for future research. Perhaps the reduction of high stakes testing in these classes can provide additional degrees of freedom for more teachers to expand their pedagogy to include these methods.

Once these methods have been researched across science courses, it is a logical progression to expand them to other disciplines. It has already been shown that project-based learning and systems thinking are each individually effective in achieving some instructional goals in most disciplines. The synergistic effect of all three methods together could prove powerful in courses such as literature, history, and mathematics, among many others. Once the research has been examined in many disciplines, design experiment should be transferred to other populations. The degree to which learning system dynamics in a PBL environment could create agency in students in low socio-economic groups and students in low income urban communities deserves consideration.

Although the author does not assert that any one combination of methods will be equally successful for all types of students and teachers, this design experiment has shown early promise that the combination of model-based reasoning, systems thinking, and project-based learning as course foundations seems to create a synergistic effect that is positive to desirable student and instructional outputs.

Chapter 6: The Application of the MASEE Program to Personal Practice

My participation in the Masters of Arts in Science and Engineering Education (MASEE) program has changed my personal perspective, my outlook on the world, and has accommodated a fundamental shift in my approach to pedagogy and curriculum design. Access to current research and the professors who are doing that research revealed that many of the beliefs I had adopted about how students learn were wrong. This knowledge allowed me to grow as an instructor. As a professional educator, my practice is now more informed, more focused, more reflective, and more likely to create student agency as a direct result of my MASEE experience.

6.1 Developing Engineering Awareness

I applied to participate in the ESIT (Engineering Summer Institute for Teachers), which would become the first course of the MASEE program, because I was teaching science at a technology themed high school that required all students to take an engineering course. My experience of engineering up to that time consisted of having friends who were structural, electrical or chemical engineers and noting that they seemed to have a lot more disposable income than I on my teacher's salary. I felt that I needed to know more than this depressing tidbit if I were to teach in an engineering-geared school.

I was nervous about taking that first engineering course because I feared I would be less skilled at mathematics and other engineering skills than necessary to be successful. I was challenged during that first course on numerous occasions, but I found that the course was ideal for science educators like me. Within a few days, I had learned the kinds of things engineers do. Keeping an invention log taught me to look at the world in a new way. Instead of seeing problems and annoyances, I began to see opportunities for innovation. I find that the world I live in is now a far more positive and beautiful place as a result of that paradigm shift, and I try to influence that same kind of mind change in my students.

6.2 DEVELOPING ENGINEERING HABITS OF MIND

Perhaps the single most important thing I learned in the MASEE program is that engineering is a design process that anyone can learn. That realization allowed me to become an engineering educator in addition to being a science educator. The first habit of mind that engineering students must develop is understanding that they have contributions to make to the design process. The specific performance tasks and tools used by engineers can each be learned and improved through practice, but students must first accept that they can be successful.

MASEE also taught me that careful documentation is as important to the engineering process as it is to science. Maintaining an engineering notebook taught me to carefully document more of my daily activities in a useful manner, and this practice has caused me to be a more reflective educator. I now teach my students that documentation is an essential engineering habit of mind, and I hope it effects a positive change in their lives as it has in mine.

A focus of the MASEE program is that the engineering field is improved when different cultural, ethnic, sexual, and academic backgrounds are involved. It is an important engineering habit of mind to seek diverse points of view when designing solutions to complex problems. Women and men would likely not design exactly the same automobile. A biologist will place different emphasis on the design of a shopping cart than will a physicist. An Asian engineer may bring a different approach to the design of a windmill than would a Hispanic engineer. The same is true of groups of engineering students. It is important to teach students that a diversity of input to the process is welcomed and that everyone has something to contribute.

It follows that collaboration is an essential habit of mind for engineers and engineering students. I direct teach my students when and how to provide constructive criticism and how to hold each other accountable for their input. Students are encouraged to first give positive feedback using the statement, "I like that…" They can then give critical feedback using the statement, "I wonder if…" I have had a number of students comment later that applying this simple technique in their private lives has yielded positive results in their relationships. Students are also taught how to ask questions and request help using canned phrases on display in the classroom. These phrases serve as a starting point for helping students develop agency, which leads to higher engagement and deeper understanding.

Iteration is a key engineering habit of mind. In the current milieu of high stakes testing, there is little time in required science courses for students to practice iteration. Senior science electives, because they are not tested, are among the few courses outside of a dedicated engineering course where the instructor can take the time to teach students to evaluate their results and take a systematic approach to improving them. Not only is iteration a foundational part of the design process, it is also a great habit of mind for students to take out into the world. The idea that all models are flawed and most outcomes can improve through effort is widely applicable in students' lives.

6.3 Developing an Understanding of the Design Process

The engineering professors of the MASEE program demonstrated excellent instructional methods for teaching students the design process. These methods, imbedded in challenge-based units, were so effective at teaching me the techniques used by engineers during the design process that I have used these challenges and the instructional materials provided by UTeach to go along with them in my classroom. I have also used the UTeach Engineering instructional materials to augment original challenges I developed for the aquatic science course.

In the engineering-based design challenges incorporated into my courses, students are guided through the design process including identifying customer needs, defining constraints, market research, concept generation, ideation, concept selection, functional modeling, testing and iteration. I am able to guide students through this process only because I was so expertly guided through it myself as part of the MASEE program engineering courses. I find that this practice provides students with a general understanding of how engineers work and, in many cases, allows students who had never considered engineering as a career to realize that they can understand and participate in the design process.

6.4 Developing knowledge for and of engineering teaching

One of the great attributes of the MASEE program is that it places professional teachers and engineering professors into a classroom together. The resulting synergy between professionals highly trained in instructional design and professionals who are experts in engineering improves the practice of both. This association provided me with the tools and understanding that I needed to teach engineering effectively and with confidence.

Students expressed gratitude at having been exposed to the engineering design process. Four students from a cohort of 86 students who participated in an engineering design challenge unit expressed an interest in pursuing engineering education in college.

Many said that they understood for the first time what engineers actually do and would have taken an engineering course if they had known this earlier in their academic careers. Many students also expressed that they intended to use engineering techniques, such as the Pugh Method of concept selection, when making decisions on personal issues later in life. For any teacher, this kind of qualitative feedback, however anecdotal, is a major triumph. For me, it validates the methods taught in the MASEE program and provides me with hope that we as educators can catalyze the kind of change in our students that contributes to a stronger nation of problem solvers and, ultimately, to a more verdant and peaceful global society.

Appendices

Appendix 1: Texas State Standards for Aquatic Science

§112.32. Aquatic Science, Beginning with School Year 2010-2011 (One Credit).

(a) General requirements. Students shall be awarded one credit for successful completion of this course. Required prerequisite: one unit of high school Biology. Suggested prerequisite: Chemistry or concurrent enrollment in Chemistry. This course is recommended for students in Grades 10, 11, or 12.

(b) Introduction.

(1) Aquatic Science. In Aquatic Science, students study the interactions of biotic and abiotic components in aquatic environments, including impacts on aquatic systems. Investigations and field work in this course may emphasize fresh water or marine aspects of aquatic science depending primarily upon the natural resources available for study near the school. Students who successfully complete Aquatic Science will acquire knowledge about a variety of aquatic systems, conduct investigations and observations of aquatic environments, work collaboratively with peers, and develop critical-thinking and problem-solving skills.

(2) Nature of science. Science, as defined by the National Academy of Sciences, is the "use of evidence to construct testable explanations and predictions of natural phenomena, as well as the knowledge generated through this process." This vast body of changing and increasing knowledge is described by physical, mathematical, and conceptual models. Students should know that some questions are outside the realm of science because they deal with phenomena that are not scientifically testable.

(3) Scientific inquiry. Scientific inquiry is the planned and deliberate investigation of the natural world. Scientific methods of investigation can be experimental, descriptive, or comparative. The method chosen should be appropriate to the question being asked.

(4) Science and social ethics. Scientific decision making is a way of answering questions about the natural world. Students should be able to distinguish between scientific decision-making methods and ethical and social decisions that involve the application of scientific information.

(5) Scientific systems. A system is a collection of cycles, structures, and processes that interact. All systems have basic properties that can be described in terms of space, time, energy, and matter. Change and constancy occur in systems as patterns and can be observed, measured, and modeled. These patterns help to make predictions that can be scientifically tested. Students should analyze a system in terms of its components and how these components relate to each other, to the whole, and to the external environment.

(c) Knowledge and skills.

(1) Scientific processes. The student, for at least 40% of instructional time, conducts laboratory and field investigations using safe, environmentally appropriate, and ethical practices. The student is expected to:

(A) demonstrate safe practices during laboratory and field investigations, including chemical, electrical, and fire safety, and safe handling of live and preserved organisms; and
(B) demonstrate an understanding of the use and conservation of resources and the proper disposal or recycling of materials.

(2) Scientific processes. The student uses scientific methods during laboratory and field investigations. The student is expected to:
(A) know the definition of science and understand that it has limitations, as specified in subsection (b)(2) of this section;
(B) know that scientific hypotheses are tentative and testable statements that must be capable of being supported or not supported by observational evidence. Hypotheses of durable explanatory power which have been tested over a wide variety of conditions are incorporated into theories;
(C) know that scientific theories are based on natural and physical phenomena and are capable of being tested by multiple independent researchers. Unlike hypotheses, scientific theories are well-established and highly-reliable explanations, but they may be subject to change as new areas of science and new technologies are developed;
(D) distinguish between scientific hypotheses and scientific theories;
(E) plan and implement investigative procedures, including asking questions, formulating testable hypotheses, and selecting, handling, and maintaining appropriate equipment and technology;
(F) collect data individually or collaboratively, make measurements with precision and accuracy, record values using appropriate units, and calculate statistically relevant quantities to describe data, including mean, median, and range;
(G) demonstrate the use of course apparatuses, equipment, techniques, and procedures;
(H) organize, analyze, evaluate, build models, make inferences, and predict trends from data;
(I) perform calculations using dimensional analysis, significant digits, and scientific notation; and
(J) communicate valid conclusions using essential vocabulary and multiple modes of expression such as lab reports, labeled drawings, graphic organizers, journals, summaries, oral reports, and technology-based reports.

(3) Scientific processes. The student uses critical thinking, scientific reasoning, and problem solving to make informed decisions within and outside the classroom. The student is expected to:
(A) in all fields of science, analyze, evaluate, and critique scientific explanations by using empirical evidence, logical reasoning, and experimental and observational testing, including examining all sides of scientific evidence of those scientific explanations, so as to encourage critical thinking by the student;
(B) communicate and apply scientific information extracted from various sources such as current events, news reports, published journal articles, and marketing materials;

(C) draw inferences based on data related to promotional materials for products and services;
(D) evaluate the impact of research and technology on scientific thought, society, and the environment;
(E) describe the connection between aquatic science and future careers; and
(F) research and describe the history of aquatic science and contributions of scientists.

(4) Science concepts. Students know that aquatic environments are the product of Earth systems interactions. The student is expected to:
(A) identify key features and characteristics of atmospheric, geological, hydrological, and biological systems as they relate to aquatic environments;
(B) apply systems thinking to the examination of aquatic environments, including positive and negative feedback cycles; and
(C) collect and evaluate global environmental data using technology such as maps, visualizations, satellite data, Global Positioning System (GPS), Geographic Information System (GIS), weather balloons, buoys, etc.

(5) Science concepts. The student conducts long-term studies on local aquatic environments. Local natural environments are to be preferred over artificial or virtual environments. The student is expected to:
(A) evaluate data over a period of time from an established aquatic environment documenting seasonal changes and the behavior of organisms;
(B) collect baseline quantitative data, including pH, salinity, temperature, mineral content, nitrogen compounds, and turbidity from an aquatic environment;
(C) analyze interrelationships among producers, consumers, and decomposers in a local aquatic ecosystem; and
(D) identify the interdependence of organisms in an aquatic environment such as in a pond, river, lake, ocean, or aquifer and the biosphere.

(6) Science concepts. The student knows the role of cycles in an aquatic environment. The student is expected to:
(A) identify the role of carbon, nitrogen, water, and nutrient cycles in an aquatic environment, including upwellings and turnovers; and
(B) examine the interrelationships between aquatic systems and climate and weather, including El Niño and La Niña, currents, and hurricanes.

(7) Science concepts. The student knows the origin and use of water in a watershed. The student is expected to:
(A) identify sources and determine the amounts of water in a watershed, including rainfall, groundwater, and surface water;
(B) identify factors that contribute to how water flows through a watershed; and
(C) identify water quantity and quality in a local watershed.

(8) Science concepts. The student knows that geological phenomena and fluid dynamics affect aquatic systems. The student is expected to:
(A) demonstrate basic principles of fluid dynamics, including hydrostatic pressure, density, salinity, and buoyancy;
(B) identify interrelationships between ocean currents, climates, and geologic features; and
(C) describe and explain fluid dynamics in an upwelling and lake turnover.

(9) Science concepts. The student knows the types and components of aquatic ecosystems. The student is expected to:
(A) differentiate among freshwater, brackish, and saltwater ecosystems;
(B) identify the major properties and components of different marine and freshwater life zones; and
(C) identify biological, chemical, geological, and physical components of an aquatic life zone as they relate to the organisms in it.

(10) Science concepts. The student knows environmental adaptations of aquatic organisms. The student is expected to:
(A) classify different aquatic organisms using tools such as dichotomous keys;
(B) compare and describe how adaptations allow an organism to exist within an aquatic environment; and
(C) compare differences in adaptations of aquatic organisms to fresh water and marine environments.

(11) Science concepts. The student knows about the interdependence and interactions that occur in aquatic environments. The student is expected to:
(A) identify how energy flows and matter cycles through both fresh water and salt water aquatic systems, including food webs, chains, and pyramids; and
(B) evaluate the factors affecting aquatic population cycles.

(12) Science concepts. The student understands how human activities impact aquatic environments. The student is expected to:
(A) predict effects of chemical, organic, physical, and thermal changes from humans on the living and nonliving components of an aquatic ecosystem;
(B) analyze the cumulative impact of human population growth on an aquatic system;
(C) investigate the role of humans in unbalanced systems such as invasive species, fish farming, cultural eutrophication, or red tides;
(D) analyze and discuss how human activities such as fishing, transportation, dams, and recreation influence aquatic environments; and
(E) understand the impact of various laws and policies such as The Endangered Species Act, right of capture laws, or Clean Water Act on aquatic systems.
Source: The provisions of this §112.32 adopted to be effective August 4, 2009, 34 TexReg 5063.

APPENDIX 2: ABSTRACT FOR STERMAN, ALL MODELS ARE WRONG

Thoughtful leaders increasingly recognize that we are not only failing to solve the persistent problems we face, but are in fact causing them. System dynamics is designed to help avoid such policy resistance and identify high-leverage policies for sustained improvement. What does it take to be an effective systems thinker, and to teach system dynamics fruitfully? Understanding complex systems requires mastery of concepts such as feedback, stocks and flows, time delays, and nonlinearity. Research shows that these concepts are highly counterintuitive and poorly understood. It also shows how they can be taught and learned. Doing so requires the use of formal models and simulations to test our mental models and develop our intuition about complex systems. Yet, though essential, these concepts and tools are not sufficient. Becoming an effective systems thinker also requires the rigorous and disciplined use of scientific inquiry skills so that we can uncover our hidden assumptions and biases. It requires respect and empathy for others and other viewpoints. Most important, and most difficult to learn, systems thinking requires understanding that all models are wrong and humility about the limitations of our knowledge. Such humility is essential in creating an environment in which we can learn about the complex systems in which we are embedded and work effectively to create the world we truly desire. The paper is based on the talk the author delivered at the 2002 International System Dynamics Conference upon presentation of the Jay W. Forrester Award. Copyright! 2002 John Wiley & Sons,Ltd. Syst. Dyn. Rev. 18, 501–531, (2002)

Appendix 3: Watershed vocabulary For MEA

watershed

basin

tributary

groundwater

Confluence

Floodplain

Watercourse

Head waters

aquifer

spring

Precipitation

Catchment area

Point and non-point source pollution

Appendix 4: Capstone Project Instructions

You will be decorating the four side panels of a bag. Your bag must have 4 side panels and a bottom panel. Your bag can be as big as you like and can be made of any material, so long as it is at least 30cm wide X 30cm tall X 15cm deep. You may, if you wish, use a box instead of a bag

.

How to decorate your bag:

Your bag will likely have two wide panels and two narrow panels. (If your bag (or box) has four equal sides, then it doesn't matter which side you designate for each theme.

Wide panel 1: Decorate this wide panel to illustrate and communicate the OVERALL themes of this Course. (Please include content from both semesters.) Think of this panel as the DVD cover or Title Poster for the whole course. Be creative. You don't have to limit yourself to 2 dimensions.

Wide Panel 2: This panel is all about expressing your own ideas and feelings about the content. Decorate this panel to illustrate and communicate the concept or idea that you found to be the most interesting, thought-provoking, or influential on your thinking. Consider this as a guiding question: How did this course change the way you view water, lakes, rivers and oceans and your relationship to them?

Narrow Panel 1: Throughout the year, we have seen a large number of unique and diverse organisms. On this panel, illustrate and describe your favorite organism and an organism with which it interrelates in a meaningful way. (examples of interactions: predation, symbiotic, mutualistic)

Narrow Panel 2: As you finish up high school and head on to the rest of your life, we want you to think a bit about the future. We have looked at a number of issues facing your generation and the generations to come. What issue do you feel is the most pressing? Explain and illustrate the issue and include what you feel will be the most likely outcome and what you might do to help create that outcome.

Put it in the Bag!

Choose five major topics of the course you wish to discuss. Place five items in your bag, one item to represent each topic. You will do a "show and tell" with your five items. You must explain clearly and sincerely how each item you chose represents a major topic of this course (one item per topic). Refer to the scope and sequence for help with topic selection. Please refer to the rubric when planning your presentation, as points are awarded for content as well as communication skills. The presentation of your items and your bag should be no longer than 10 minutes.

Please do not bring live or dead animals, weapons, or contraband in your bag. School norms do apply.

APPENDIX 5: CAPSTONE PROJECT RUBRIC

Round Rock High School

Hallmark/Ryan Student: ____________________

Class: ____________________ Grade: _________

Rubric: Aquatic Science Capstone Tag-It-And-Bag-It

This rubric assesses the capstone project for seniors taking aquatic science. Students decorate four sides of a bag according to insgtractions and then place five items in the being relating to content.

Capstone Tag-It-and-Bag-It	Not assessable/unacceptable 0 pts	Underachieved 1 pts	Developing 2 pts	Achieving 3 pts	Exceptional 4 pts
Promtness	Not assessable/unacceptable The project is presented more than 2 days late.	Underachieved The project is presented 2 days late.	Developing The project is presented one day late.	Achieving The student presents the project on the due date.	Exceptional The student's project is completely finished and ready to present at the beginning of class. Student attitude demonstrates readiness to share.
Artful Expression and Effort	Not assessable/unacceptable The student's project has no art or art that is unrelated to course content. No meaningful effort was used.	Underachieved The project has relevant art but - it is so poorly executed that it distracts from the project as a whole AND/OR - minimal effort and thought was required.	Developing The student's project is adequately decorated. Some effort and thought was employed to express the content artfully, but could be more engaging.	Achieving The student's project is attractive. The art expresses the content in a meaningful way and adds to the viewers understanding.	Exceptional The students project represents an extraordinary effort to represent the content in a meaningful way. The art is well crafted, exhibiting pride in craftsmanship. It is exceptionally engaging.
Wide Panel 1: Overall Theme	Not assessable/unacceptable Panel is not completed or does not illustrate or express the required content.	Underachieved The panel does illustrate some of the required content, but little engaged thinking was required.	Developing The panel illustrates the required content. The student can explain how the art and prose relate to overall themes of the course.	Achieving The overall themes of the course are immediately obvious in the panel's design. Art and prose are clear and student can confidently explain how they relate to the course.	Exceptional The student went to extraordinary effort to capture most of the courses major themes in art and prose. Both the panel and the student's explanation of it are highly engaging.
Wide Panel 2: Your Growth	Not assessable/unacceptable Panel is not completed or does not illustrate or express the required content.	Underachieved The panel does illustrate some of the required content, but little engaged	Developing The panel illustrates the required content. The student can explain their feelings	Achieving The panel illustrates the required content. The student can explain how their	Exceptional The panel clearly expresses the student's growth and understanding as a

		thinking was required.	or describe their experience engaging with the content of the course.	understanding of and relationship with water and the sea have changed because of the content of the course.	result of engaging with course content. The student's explanation demonstrates careful reflection.
Narrow Panel 1:Related Organisms	Not assessable/unacceptable Panel is not completed or does not illustrate or express the required content.	Underachieved The panel does illustrate some of the required content, but little engaged thinking was required.	Developing The panel illustrates the required content. The student can explain how the two organisms are related to each other.	Achieving The panel illustrates the required content. The student describes both organisms and clearly explains their relationship to each other.	Exceptional The panel clearly attempts to fully describe two organisms in terms of their biology and importance in their ecosystems. The organisms are related in a meaningful way and this relationship is clearly explained.
Narrow Panel 2:Important Issue	Not assessable/unacceptable Panel is not completed or does not illustrate or express the required content.	Underachieved The panel does illustrate some of the required content, but little engaged thinking was required.	Developing The panel illustrates the required content. The student can explain the issue accurately.	Achieving The panel illustrates the required content. The issue is accurately illustrated. The student gives a full explanation of the issue and possible solutions.	Exceptional The student uses the panel to fully illunminate an important issue in aquatic science. The student uses concrete examples from the course material and scientific vocabulary in explaining the content. The explanation includes possible solutions and how they personally intend to participate.
Object 1:	Not assessable/unacceptable Object is absent or student cannot give a meaningful explanation of how it relates to course content.	Underachieved The object relates to the one unit of the content, but only in a vague or tangential manner.	Developing The object relates to one unit of the content in a meaningful way. The student gives an explanation that is adequate.	Achieving The object relates to one unit of the content in a meaningful way. The student gives a complete explanation of how the object represents key content.	Exceptional The object relates to one unit of the content in a meaningful way. The student explains how the object represents content in way that demonstrates imaginative or deeply reflective thinking.
Object 2	Not assessable/unacceptable Object is absent or student cannot give a meaningful explanation of how it relates to course content.	Underachieved The object relates to the one unit of the content, but only in a vague or tangential manner.	Developing The object relates to one unit of the content in a meaningful way. The student gives an explanation that is adequate.	Achieving The object relates to one unit of the content in a meaningful way. The student gives a complete explanation of how the object	Exceptional The object relates to one unit of the content in a meaningful way. The student explains how the object represents content in way that

				represents key content.	demonstrates imaginative or deeply reflective thinking.
Object 3	Not assessable/unacceptable Object is absent or student cannot give a meaningful explanation of how it relates to course content.	Underachieved The object relates to the one unit of the content, but only in a vague or tangential manner.	Developing The object relates to one unit of the content in a meaningful way. The student gives an explanation that is adequate.	Achieving The object relates to one unit of the content in a meaningful way. The student gives a complete explanation of how the object represents key content.	Exceptional The object relates to one unit of the content in a meaningful way. The student explains how the object represents content in way that demonstrates imaginative or deeply reflective thinking.
Object 4	Not assessable/unacceptable Object is absent or student cannot give a meaningful explanation of how it relates to course content.	Underachieved The object relates to the one unit of the content, but only in a vague or tangential manner.	Developing The object relates to one unit of the content in a meaningful way. The student gives an explanation that is adequate.	Achieving The object relates to one unit of the content in a meaningful way. The student gives a complete explanation of how the object represents key content.	Exceptional The object relates to one unit of the content in a meaningful way. The student explains how the object represents content in way that demonstrates imaginative or deeply reflective thinking.
Object 5	Not assessable/unacceptable Object is absent or student cannot give a meaningful explanation of how it relates to course content.	Underachieved The object relates to the one unit of the content, but only in a vague or tangential manner.	Developing The object relates to one unit of the content in a meaningful way. The student gives an explanation that is adequate.	Achieving The object relates to one unit of the content in a meaningful way. The student gives a complete explanation of how the object represents key content.	Exceptional The object relates to one unit of the content in a meaningful way. The student explains how the object represents content in way that demonstrates imaginative or deeply reflective thinking.

APPENDIX 6: SYSTEMS THINKING INTRODUCTION ARTICLE

What is systems thinking?

Systems thinking offers you a powerful new perspective, a specialized language, and a set of tools that you can use to address the most stubborn problems in your everyday life and work. Systems thinking is a way of understanding reality that emphasizes the relationships among a system's parts, rather than the parts themselves. Based on a field of study known as system dynamics, systems thinking has a practical value that rests on a solid theoretical foundation.

Why Is Systems Thinking Important?

Why is systems thinking valuable? Because it can help you design smart, enduring solutions to problems. In its simplest sense, systems thinking gives you a more accurate picture of reality, so that you can work with a system's natural forces in order to achieve the results you desire. It also encourages you to think about problems and solutions with an eye toward the long view—for example, how might a particular solution you're considering play out over the long run? And what unintended consequences might it have? Finally, systems thinking is founded on some basic, universal principles that you will begin to detect in all arenas of life once you learn to recognize them.

What Are Systems?

What exactly is a system? A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole. Systems are everywhere—for example, the R&D department in your organization, the circulatory system in your body, the predator/prey relationships in nature, the ignition system in your car, and so on. Ecological systems and human social systems are living systems; human-made systems such as cars and washing machines are nonliving systems. Most systems thinkers focus their attention on living systems, especially human social systems. However, many systems thinkers are also interested in how human social systems affect the larger ecological systems in our planet.

Systems have several defining characteristics:

- Every system has a purpose within a larger system. Example: The purpose of the R&D department in your organization is to generate new product ideas and features for the organization.
- All of a system's parts must be present for the system to carry out its purpose optimally. Example: The R&D system in your organization consists of people, equipment, and processes. If you removed any one of these components, this system could no longer function.
- A system's parts must be arranged in a specific way for the system to carry out its purpose. Example: If you rearranged the reporting relationships in your R&D department so that the head of new-product development reported to the entry-level lab technician, the department would likely have trouble carrying out its purpose.
- Systems change in response to feedback. The word feedback plays a central role in systems thinking. Feedback is information that returns to its original transmitter such that it influences that transmitter's subsequent actions. Example: Suppose you turn too sharply while driving your car around a curve. Visual cues (you see a mailbox rushing toward

you) would tell you that you were turning too sharply. These cues constitute feedback that prompts you to change what you're doing (jerk the steering wheel in the other direction somewhat) so you can put your car back on course.

• Systems maintain their stability by making adjustments based on feedback. Example: Your body temperature generally hovers around 98.6 degrees Fahrenheit. If you get too hot, your body produces sweat, which cools you back down.

Systems Thinking as a Perspective: Events, Patterns, or System?

Systems thinking is a perspective because it helps us see the events and patterns in our lives in a new light—and respond to them in higher leverage ways. For example, suppose a fire breaks out in your town. This is an event. If you respond to it simply by putting the fire out, you're reacting. (That is, you have done nothing to prevent new fires.) If you respond by putting out the fire and studying where fires tend to break out in your town, you'd be paying attention to patterns. For example, you might notice that certain neighborhoods seem to suffer more fires than others. If you locate more fire stations in those areas, you're adapting. (You still haven't done anything to prevent new fires.) Now suppose you look for the systems—such as smoke-detector distribution and building materials used—that influence the patterns of neighborhood-fire outbreaks. If you build new fire-alarm systems and establish fire and safety codes, you're creating change. Finally, you're doing something to prevent new fires!

This is why looking at the world through a systems thinking "lens" is so powerful: It lets you actually make the world a better place.

Systems Thinking as a Special Language

As a language, systems thinking has unique qualities that help you communicate with others about the many systems around and within us:

• It emphasizes wholes rather than parts, and stresses the role of interconnections—including the role we each play in the systems at work in our lives.

• It emphasizes circular feedback (for example, A leads to B, which leads to C, which leads back to A) rather than linear cause and effect (A leads to B, which leads to C, which leads to D, . . . and so on).

• It contains special terminology that describes system behavior, such as reinforcing process (a feedback flow that generates exponential growth or collapse) and balancing process (a feedback flow that controls change and helps a system maintain stability).

Systems Thinking as a Set of Tools

The field of systems thinking has generated a broad array of tools that let you (1) graphically depict your understanding of a particular system's structure and behavior, (2) communicate with others about your understandings, and (3) design high-leverage interventions for problematic system behavior.

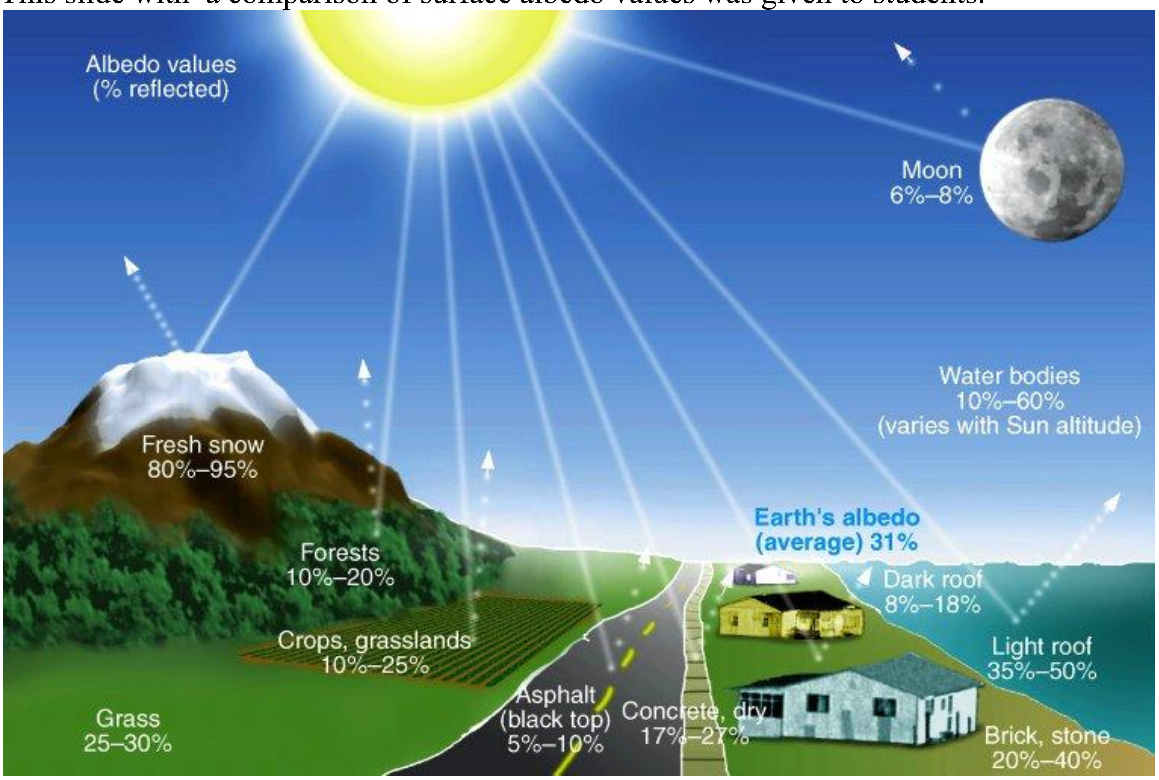
These tools include causal loops, behavior over time graphs, stock and flow diagrams, and systems archetypes—all of which let you depict your understanding of a system—to computer simulation models and management "flight simulators," which help you to test the potential impact of your interventions.

• • •

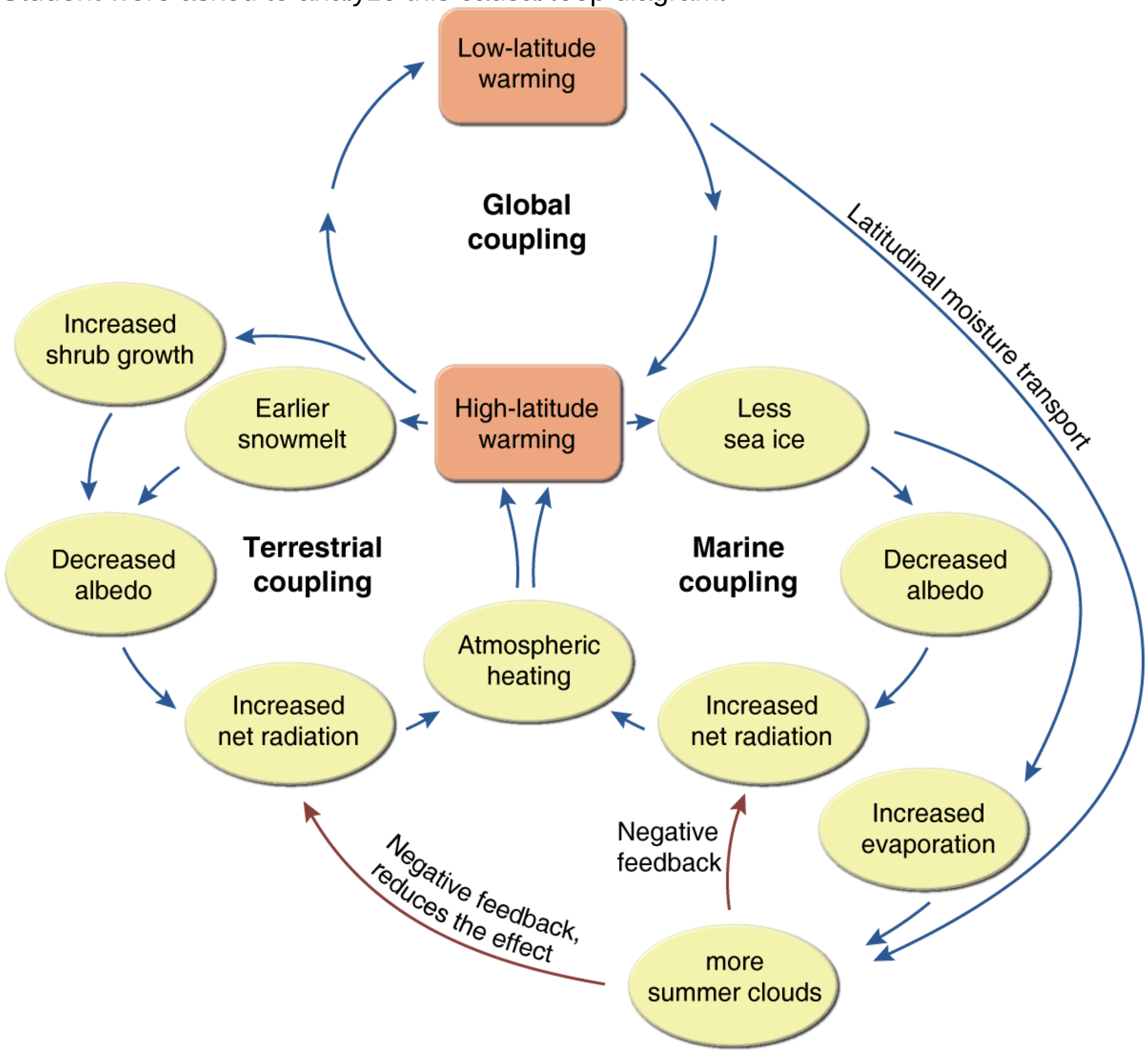
Whether you consider systems thinking mostly a new perspective, a special language, or a set of tools, it has a power and a potential that, once you've been introduced, are hard to resist. The more you learn about this intriguing field, the more you'll want to know!

APPENDIX 7: ALBEDO CAUSAL LOOP DIAGRAM AND INFORMATIONAL SLIDE.

This slide with a comparison of surface albedo values was given to students.



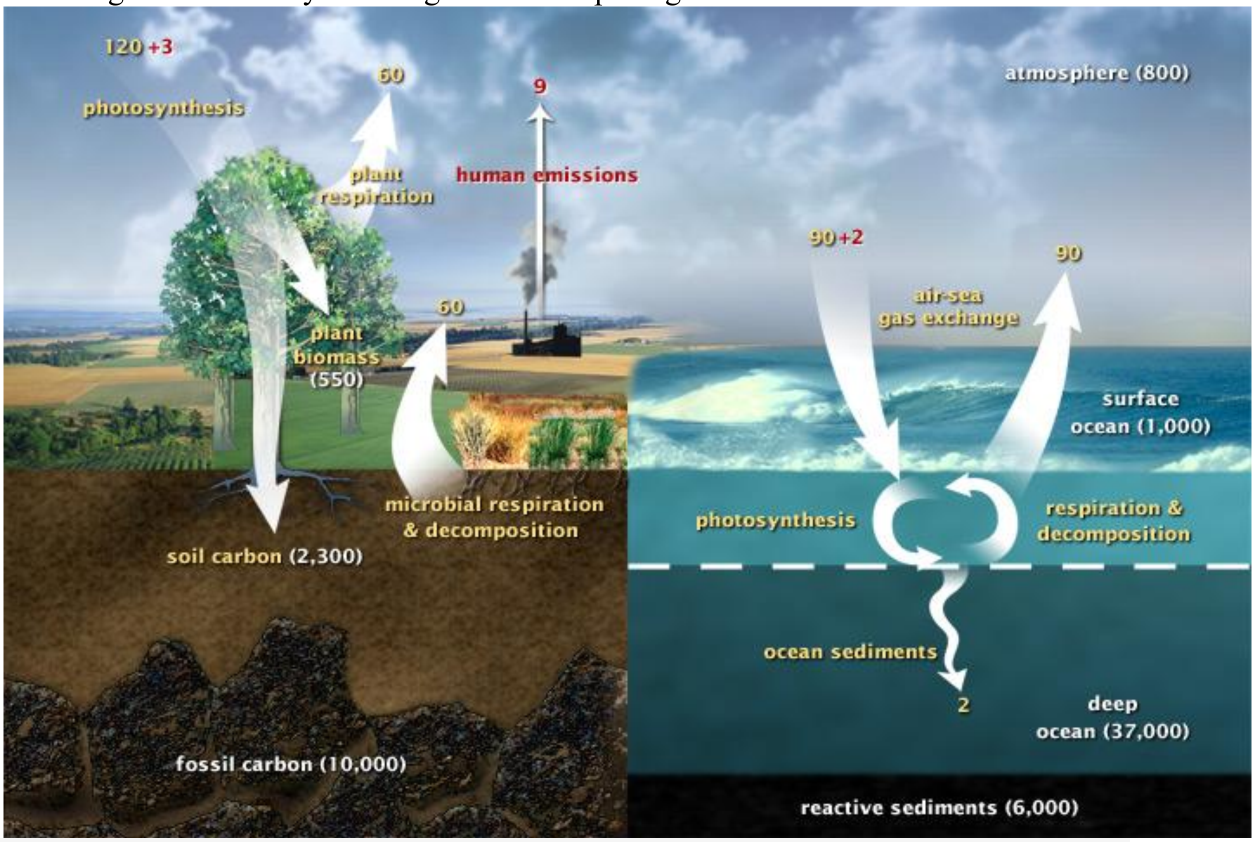
Student were asked to analyze this causal loop diagram.



From:
http://www.siswebs.org/water/story.php?title=Causal_Loop_Diagram_CLD_of_Climate

APPENDIX 8: CARBON CAUSAL LOOP ASSIGNMENT

Modeling the Carbon Cycle Using Causal Loop Diagrams



This diagram of the fast carbon cycle shows the movement of carbon between land, atmosphere, and oceans. Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored carbon. (Diagram adapted from U.S. DOE, Biological and Environmental Research Information System. Courtesy of NASA)

Instructions

Use this diagram to help you build a qualitative causal loop diagram of the fast carbon cycle. (You will be using lines, arrows, +, -, and words only. You will not be drawing pictures.

Your causal loop of the carbon cycle must include the following variables:

Photosynthesis	**Plant Respiration**	**atmospheric CO_2**	**Soil Carbon**
Volcanic emissions	**decomposition**	**human emissions**	**fossilized carbon**
Petroleum mining	**ocean sediments**	**air-sea gas exchange (ocean surface)**	**H_2CO_3 (in ocean water)**

In addition to the required variables above, choose one or more of the following variables to include in your causal loop. (You may have to add additional variables of your own to connect these to the required variables): **average global temperature, sea level rise, coral reefs, sea ice, deforestation, polar bears, desertification, albedo**

APPRNDIX 9: ENTRY DOCUMENT FOR THE LEGACY CYCLE WITH EMBEDDED CONTENT OF ENGINEERING DESIGN AND WAVES

Oceanfront Development Inc.
42069 Ekman Lane   Gulf Stream, Texas 78666

Hydrologic Solutions, Inc
Executive Team
Round Rock, TX 78664

Dear Colleagues,
Our company has long been known for its quality developments along many of the finest coasts of the state. We have recently acquired a number of waterfront properties along the undeveloped Brushy Creek Bay. It is our intention to develop this property for mixed use retail. Before we can begin to apply for permits, we must insure that the area is safe to build on.

We are seeking your services to determine the potential risk to this property from wave action. As you are the primary hydrological testing company in the state, we are asking for you help in determining if the Bay Front Properties are susceptible to high waves from wind, tsunamis, storm surge, or landslides. You will need to measure the maximum height of various forms of waves that can come into the bay so that we can direct our architects to create piers and boardwalks that are unlikely to be damaged in these events.

We would also like you to submit a design for a wave barrier that will reduce wave impact on the bay without stopping normal tidal and shore wave action.
This will be a lucrative contract for you, but we are under time constraints due to annual permit restrictions on land development. Please have data for us to use by no later than 4:15 PM on Friday, April 6, 2012.

Most Sincerely,
Phinneas Sunfish, COO

Bibliography

A Nation at Risk: The Imperative for Educational Reform, A Report to the Nation and the Secretary of Education United States Department of Education by The National Commission on Excellence in Education. April, 1983. Full Report.

Anderson, L.W. and D.R. Krathwohl. 2001. A taxonomy for learning, teaching, and assessing. Longman: New York

Assaraf, O. B., N. Orion. 2005. Development of system thinking skills in the context of earth system education*. Journal of Research in Science Teaching 42(5):518-560.*

Barrows, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. *New Directions for Teaching and Learning, 68*, 3-12. Accessed at http://dx.doi.org/10.1002/tl.37219966804

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). How People Learn: Brain, Mind, Experience, and School. Expanded Edition.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. The Journal of the Learning Sciences, 2(2), 141-178.

Brown, Gordon S., 1990. The Genisis of the System Thinking Program at the Orange Grove Middle School, Tucson, Arizona . Personal report. 6301 N. Calle de Adelita, Tucson, AZ 85718: March 1. 8 pp.

Brown, Gordon S., 1992. “Improving Education in Public Schools: Innovative Teachers to the Rescue.” *System Dynamics Review, Vol. 8, No. 1, pp. 83-89.*

Brush, T., & Saye, J. (2000). Implementation and evaluation of a student-centered learning unit: A case study. *Educational Technology Research and Development, 48(3), 79-100.* http://dx.doi.org/10.1007/BF02319859

Carlson, M., Larsen, S. & Lesh, R. (2002). Integrating a model and modeling perspective with existing research and practice: In R. Lesh & H. Doerr (Eds.), Beyond Constructivism in Mathematics Teaching and Learning: A Models & Modeling Perspective. Hillsdale, NJ: Lawrence Erlbaum.

Chen, David and Stroup, Walter (1993). " General System Theory: Toward a Conceptual Framework for Science and Technology Education for All.*" Journal of Science Education and Technology, Volume 2, Number 3, page 2.*

Creswell, J.W. 2002. Educational research : planning, conducting, and evaluating quantitative and qualitative research. Upper Saddle River, NJ: Merrill.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in education research. *Educational Researcher, 32*(1), pp. 9-13.

Collins, A. (1992). Towards a design science of education. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology (pp. 15-22).* Berlin: Springer.

Collins, A. (1999). The changing infrastructure of education research. In E. C. Condiff & L. S. Shulman, (Eds.), Issues in education research: Problems and possibilities (pp. 289-298). San Francisco: Jossey-Bass.

Davidsen, Pål I., 1990. "System Dynamics, a Pedagogical Approach to the Teaching of Complex, Dynamic Systems by Means of Simulation." In for EURIT 90, The European Conference on Technology and Education, pp. 12.

DBRC. Design Based Research Collective, The. (2003). DBRC, (2003). Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher, 32*(1), 5-8.

Draper, Frank, 1989. *Letter to Jay Forrester*. Personal communication, Orange Grove Junior High School, 1911 E. Orange Grove Rd., Tucson, AZ 85718. May 2.

Draper, Frank. 1993. A proposed sequence for developing systems thinking in a grades 4-12 curriculum. *System Dynamics Review 9(2)207-214.*

Druckman, D., & Ebner, N. (2008). Onstage or behind the scenes? Relative learning benefits of simulation role-play and design. *Simulation & Gaming, 39(4), 465-497*. http://dx.doi.org/10.1177/1046878107311377

Forrester, Jay. 1992. System Dynamics and Learner-Centered-Learning in Kindergarten through 12th Grade Education. Accessed via The Creative Learning Exchange, http://www.clexchange.org/gettingstarted/intropacket.asp, on August 28, 2013.

Forrester, J.W. 1994. System dynamics, systems thinking, and soft OR. *System Dynamics Review 10(2/3)245-256.*

Grant, W.E. 1998. Ecology and natural resource management: reflections from a systems perspective. *Ecological Modeling* 108(1) 67-76.

Hacking, Ian. Representing and Intervening: Introductory Topics in the Philosophy of Natural Science. Cambridge University Press, 1983.

Eric Hamilton, Richard Lesh, Frank Lester, and Michael Brilleslyper. 2008. Model-Eliciting Activities (MEAs) as a Bridge Between Engineering Education Research and Mathematics Education Research. *Advances in Engineering Education, Volume 1, Issue 2, Page 6.*

Hallmark, Jonathon. Recorded in an interview with Douglas Ryan on the outcomes of a design experiment. July 13, 2013. Personal communication, pp 1.

Hayden, Louise, 1990. Letter of October 2, 1990 to Jay Forrester. Personal communication, 1 pp.

High Performance Systems, 1990. STELLA II Users Guide. PC. 45 Lyme Road, Hanover, NH: High Performance Systems.

Hopkins, Pamela Lee, 1992. "Simulating *Hamlet* in the Classroom." *System Dynamics Review*, Vol. 8, No. 1, pp. 91-98.

Hopkins, R. H., Campbell, K. B., and Peterson, N. S. (1987). Representations of perceived relations among the properties and variables of a complex system. IEEE Transactions on Systems, Man, and Cybernetics smc-17(1) 52-60.

Hopper, M. and K.A. Stave. 2008. Assessing the Effectiveness of Systems Thinking Interventions in the Classroom. *Proceedings of the 26th International Conference of the System Dynamics Society.* Athens, Greece, July 20-24, 2008. Available at: http://www.systemdynamics.org/conferences/2008/proceed/index.htm.

Hurfurd, Andy. 2004. Response to Qualifying Examination, Question 3, Department of Mathematics Education, University of Texas at Austin.

Hung, W., Jonassen, D. H., & Liu, R. (2007). Problem-based learning. In M. Spector, M. D. Merrill,J. V. Merrienboer, & M. P. Driscoll (Eds.), Handbook of Research for Educational Communications and Technology (3rd Ed.) (pp. 485-506). New York, NY: Routledge/Taylor &Francis Group.

Jefferson, Thomas. (1784) Notes on the State of Virginia, Queries 14 AND 19, 146--49, 164—65

Johnson, D. W., R. T. Johnson, and K. A. Smith. 1991. *Cooperative learning: Increasing college faculty instructional productivity.* ASHE-ERIC Higher Education Report 1991–4. Washington, DC: The George Washington University, School of Education and Human Development.

Kuhn, Thomas S. The Structure of Scientific Revolutions. 3rd ed. Chicago, IL: University of Chicago Press, 1996. Pages 37, 144.

Leonard, W.H., B.J. Speziale, and J.E. Penick. 2001. Performance assessment of a standards-based high school biology curriculum. *The American Biology Teacher* 63:310-316.

Lesh, R. and G. Harel, Problem Solving, Modeling, and Local Conceptual Development. *Mathematical Thinking & Learning, 2003. 5(2/3): p. 157–189*

Liu, M. , Wivagg, J. , Geurtz, R. , Lee, S. , & Chang, H. M. (2012). Examining How Middle School Science Teachers Implement a Multimedia-enriched Problem-based Learning Environment. *Interdisciplinary Journal of Problem-based Learning, 6(2).*

Available at: http://dx.doi.org/10.7771/1541-5015.1348

Mandinach, Ellen B., and Hugh F. Cline, 1989. “Applications of Simulation and Modeling in Precollege Instruction.” *Machine-Mediated Learning*, Vol. 3, pp. 189-205.

Mandinach, E. B., and Thorpe, E. T. (1987). *The Systems Thinking and Curriculum Innovation Project: Technical Report. Part 1* (TR-87), Educational Technology Center, Harvard Graduate School of Education, Nichols House, Appian Way, Cambridge, Massachusetts 02138.

Mandinach, E. B., and Thorpe, M. E. (1988). *The Systems Thinking and Curriculum Innovation Project: Technical Report. Part 2 (TR88-12)*, Educational Technology Center, Harvard Graduate School of Education, Nichols House, Appian Way, Cambridge, Massachusetts 02138.

Markham, Thom, John Larmer, and Jason Ravitz. Project Based Learning Handbook. Second Edition. Copyright by the Buck Institute for Education. Novato, California, 2003.

Miller, D. W. (1999, August 6). The black hole of educational research: Why do academic studies play such a minimal role in efforts to improve the schools? *The*

Chronicle of Higher Education, pp. A17-A18.

Mintz, R. (1987). Computer simulation as an instructional tool for the teaching of ecological system. Doctoral thesis, Tel Aviv University.

Nersessian, N. J. & Patton, C. (2009). "Model-based reasoning in interdisciplinary engineering," The Handbook of the Philosophy of Technology & Engineering Sciences, A. W. M. Meijers, ed., Springer, pp. 678-718.

Pandy, Marcus G., Petrosino, Anthony J., Austin, Barbara A., and Barr, Ronald E. (2004). "Assessing Adaptive Expertise in Undergraduate Biomechanics," *Journal of Engineering Education, July 2004, pp 211-223.*

Penner David E., Richard Lehrer and Leona Schauble, "From Physical Models to Biomechanics: A Design-Based Modeling Approach," *The Journal of the Learning Sciences, 7(3&4), 429-449.*

Peoples, C. (2008). "Sputnik and 'skill thinking' revisited: technological determinism in American responses to the Soviet missile threat". *Cold War History 8(1): 55–75.*

Petrosino, A. J., Lehrer, R. & Schauble, L. (2003). Structuring error and experimental variation as distribution in the fourth grade. *Mathematical Thinking and Learning, 5(2&3), 131-156.*

Reeves, Thomas C. (2000). Enhancing the Worth of Instructional Technology Research through "Design Experiments" and Other Development Research Strategies. Paper presented on April 27, 2000 at Session 41.29, "International Perspectives on Instructional Technology Research for the 21st Century," a Symposium sponsored by SIG/Instructional Technology at the Annual Meeting of the American Educational Research Association, New Orleans, LA, USA.

Riley, D. (1990). Learning about systems by making models. Computers in Education 15(1-3): 255-263.

Roberts, Nancy. (1975). *A Dynamic Feedback Approach to Elementary Social Studies: A Prototype Gaming Unit*. Ph.D. thesis, available from University Microfilms, Ann Arbor, Michigan: Boston University.

Roberts, Nancy. (1978). Teaching dynamic feedback systems thinking: An elementary view. *Management Science 24(8): 836-843.*

Savery, J. S. (2006). Overview of PBL: Definitions and distinctions. *Interdisciplinary Journal of Problem-based Learning, 1(1), 9-20.*

Schorr, R.Y. and K. Koellner-Clark, Using a modeling approach to consider the ways in which teachers consider new ways to teach mathematics. *Mathematical Thinking and Learning: An International Journal, 2003. 5(2): p. 191–210.*

Shuman, L., M. Besterfield-Sacre, and R. Clark, Improving Engineering Students' Learning Strategies Through Models and Modeling, in Thirteenth International Conference on Teaching Mathematical Modeling and Applications (ITCMA13). 2007: Bloomington IN

Sterman, John D. 2002. All Models Are Wrong: Reflections on Becoming a Systems Scientist, *System Dynamics Review Vol. 18, No. 4, (Winter 2002): 501–531*

Stuntz, L. N., D. A. Lyneis, and G. P. Richardson. 2002. The future of system dynamics and learner-centered learning in K-12 education: A report from the planning meeting. Essex, Massachusetts. The 20th International Conference of the System Dynamics Society. Palermo, Italy.

Sweeney, L.B. and J.D. Sterman. 2000. Bathtub dynamics: initial results of a systems thinking inventory. *System Dynamics Review 16(4)249-286.*

Van den Akker, J. (1999). Principles and methods of development research. In J. van den Akker, N. Nieveen, R. M. Branch, K. L. Gustafson, & T. Plomp, (Eds.), Design methodology and developmental research in education and training (pp. 1-14). The Netherlands: Kluwer Academic Publishers.

Vita

Douglas Ryan is a STEM educator with an extensive background in science and special knowledge in combining curriculum alignment, research-based pedagogy, and cutting-edge assessment practices to yield immediate improvement and continuous growth in student achievement. He is an accomplished writer, nature photographer, and underwater explorer. He was featured in a film by Discovery Channel Australia for Animal Planet regarding his work on identifying manta rays by their markings to track their movements and familial relationships in the Pacific Ocean. He has been featured in a national magazine for his success as an underwater photographer and travel writer. He has published many articles for pay.

CAREER & ACHIEVEMENTS

Round Rock Independent School District, Round Rock, Texas July, 2010 –
Senior Capstone Science Teacher at Round Rock High School,
Incorporating project-based pedagogy with integrated STEM components.

Austin Independent School District, Austin, Texas June 2009-July, 2010
Science Team Lead and Project-based Physics Teacher – I served as the science team lead in opening this new campus under the New Technology High School method of project-based learning. I also taught physics to 9th grade students in an inner-city, urban neighborhood.

Manor Independent School District, Manor, Texas February, 2007 – June 2009
Science Curriculum and Instruction Specialist – I reported directly to the Superintendent and Deputy Superintendent on all matters pertaining to science instruction at all grade levels in the district. I created comprehensive TAKS preparation strategies for science courses at all grade levels. I facilitate the writing and revision of all curriculums of science courses at all grade levels, pre-k thru 12, at 11 different schools. I created, implemented and continuously monitor an integrated assessment system for science used district wide. I created, implemented, and continuously monitor a system of reflective instructional improvement for all science teachers in the district. I continuously monitor classroom instruction at all levels and provide professional development and interventions where needed to improve instruction and student achievement.

Round Rock Independent School District, Round Rock, Texas October, 2002 – January, 2007
Classroom Teacher/Collaborative Teacher Leader – I taught Pre-AP Biology and Integrated Physics and Chemistry to a diverse population of students at the Stony Point Ninth Grade Center. I also held several district leadership stipends and served as science department chairman. I was awarded the 2006 Teacher of the Year Award. I consistently lead the department in developing instructional practices that resulted in continuous improvement in student achievement and retention of tested standards. I created a fully functional, content-rich web portal for all campus science courses that linked students and parents to the teachers, the standards, and the assessment system developed for each course. I provided district level professional development during new teacher orientation and the summer learning institutes on classroom management, science pedagogy, and professional ethics.

Cornerstone Business Development Group April, 1997 – March, 2001
Founding Partner/Education Consultant – I consulted with school districts and nonprofit organizations to create effective, research-based curriculum for schools and other educational programs. I wrote four successful petitions for open enrolment charter schools in the State of Texas. I argued successfully before the Texas State Board of Education for the granting of a waiver allowing the opening of El Sendero Academy, an open enrolment charter school in San Antonio, Texas. I created a web portal to advertise and sell the products of the firm I started, including consulting services, various publications, and TEA approved education related accounting software developed in-house.

University of Texas at Austin, Division of Biological Sciences May, 1992 – April, 1997
Instructional Laboratory Biologist – I provided laboratory support and instruction for all of the undergraduate biology teaching labs and some graduate biology labs at the University of Texas at Austin. I developed and continuously improved laboratory techniques used to teach undergraduate biology students in molecular, organismal, and ecological techniques. I provided full laboratory support for students and instructors before, during and after laboratory classes. I supervised and managed the work-study students and teaching assistants who served as the laboratory staff. I maintained and managed all laboratory resources including equipment, microorganisms, plants, fungi, animals, and chemicals.

EDUCATION, QUALIFICATIONS & PROFESSIONAL MEMBERSHIPS

• University of Texas At Austin, Austin, Texas 2010-2013
Master of Arts in Science and Engineering Education
• University of Texas At Austin, Austin, Texas 1991 – 1995
BA in Biology, Minor in Chemistry
• Classroom Teacher Certification: Science 8-12
• Active member of the National Staff Development Council(NSDC) and the Texas Association of Supervision and Curriculum Development (TASCD)
• Active member of the Texas Science Education Leadership Association (TSELA) and the Science Teachers Association of Texas (STAT)

FURTHER PROFESSIONAL ACTIVITY
• Trained in curriculum audit management by Curriculum Management Systems, Incorporated (CMSI), Levels I and II.
• Trained in enhanced context, problem-based learning, and design-based learning by the NewTech Foundation.
• I have attended more than 60 hours of professional development on best practices for teaching English language learners and am a certified trainer of trainers in sheltered instruction.
• I have received special instruction and certification in teaching high-end learning including training in pre-AP and AP Biology from the College Board and GTAL techniques from a variety of certified providers including Joe Renzulli at Confratute at the University of Connecticut.

PERSONAL

Douglas Ryan was born on March 7, 1967 in Tyler, Texas. Before he became completely submerged in education, underwater photography was the driving passion of his life. His first gallery photo show opening was attended by over 400 people from eight states and three countries. In addition to diving, Mr. Ryan also pursues other hobbies related to his lust for outdoor adventures and his love of science. His is an amateur vulcanologist and has climbed and photographed many volcanic craters. He loves to backpack and hike his camera deep into wilderness to capture what remains of the truly wild. Mr. Ryan's hobbies include gardening, gourmet cooking, birding, skiing, cosmology, comparative mythology, film, television, and raising his dogs.

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This thesis report was typed by Douglas Wayne Ryan.