Enhancing Engineering Education with Computational Thinking

"Seldom have so many independent studies been in such agreement: simulation is a key element for achieving progress in engineering and science… Formidable challenges stand in the way of progress in SBES research… Significantly, one of those challenges is education of the next generation of engineers and scientists in the theory and practices of SBES." — Simulation-Based Engineering Science: Revolutionizing Engineering Science through Simulation, Report of the NSF Blue Ribbon Panel on SBES, 2006

The Need

Infusing simulation-based engineering science into grassroot education

Simulation-based engineering science (SBES) is increasingly important in accelerating research and development in engineering because of the analytical power and cost effectiveness of computer simulation[1]. Advanced simulation tools based on solving basic equations in physics are routinely used to tackle complex engineering problems and to search for optimal solutions in many engineering practices, ranging from microelectromechanical devices to Mars rovers. Representing the application of computational thinking [1] in engineering, SBES is an interdisciplinary subject indispensable to the nation's continued leadership in science and technology [2].

SBES, however, has virtually no place in the current engineering or science curricula at the secondary level. Nor is there an agenda to introduce it, to the best of our knowledge. Despite the fact that modern simulation tools can run on an ordinary computer and be used without having to know how the computational engine actually works[2], it is still commonly thought that SBES mandates advanced mathematics and science, uses abstruse jargon, requires monster supercomputers, works only through the esoteric command line, and cannot be possibly taught or used at secondary level. As a result, most pre-college students are not exposed to this modern engineering methodology and are deprived of an opportunity to develop interest in it earlier in their education. The consequence of this deficiency may have contributed to the erosion of the nation's leadership in SBES and engineering science in general [2]. This proposal responds, in part, to the challenge posed by the NSF Blue Ribbon Panel by initiating a research-based agenda articulated below.

Adding simulation to support engineering design

There is a consensus among educators that design-based learning is essential for *all* students in STEM education and is especially important in engineering education [3-12]. Typical design challenges for high school students consist of designing, drawing, building, testing, and re-designing. However, the activity is

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[1] Throughout this proposal, simulation specifically refers to the application of computational models to the study and prediction of physical events or the behavior of engineered systems. Simulation of this type aims at solving a practical problem based on rigorous numeric solution of basic physics equations, such as the Navier–Stokes equations of fluid dynamics and Fourier's Law of heat conduction. This is very different from virtual world simulations that primarily simulate human characters and their interactions (e.g., SecondLife). Also, typical geometry designs using tools such as *AutoCAD* and *Google Sketchup* are *not* considered simulations in the context of this proposal.

[2] An example is the *Molecular Workbench* software (http://mw.concord.org), developed by the proposers. Its computational engine is based on research-grade molecular dynamics methods, which empower it to produce correctly many emergent behaviors at the molecular level. The tool helps students learn difficult concepts in the microscopic world without having to know that there are complex computations "under the hood."

traditionally carried out on an empirical, trial-and-error basis. When the design involves tasks more sophisticated than assembling structures, for example, when one needs to consider abstract concepts such as heat transfer and fluid dynamics as part of the design, students lack appropriate tools to help them predict and visualize how energy and matter flow in a complex system. Without visualization—in many cases only practical through a computer program—many abstract concepts may remain simple hunches to most students, preventing them from thinking more creatively and truly achieving the learning goals. In some cases, students are simply instructed to follow prescribed procedures, and are often left to wonder about what in essence they are supposed to learn. Many studies have revealed that this kind of laboratory experience does not result in a significant gain in learning science and engineering [13].

We hypothesize that this learning inefficacy can be partially remedied by making simulations an integral part of the design-based learning. Sophisticated general-purpose simulations contain profound scientific insights in a logical and generic form. They not only guide rational engineering design, but also infuse deeper science into the design process. Invisible or intangible field distributions, such as temperature gradient, stress, airflow, or electromagnetic waves, are often related to the most important learning goals. Visualization of these distributions and their time evolution calculated in simulations can be very expressive of the embodied scientific and engineering ideas. Furthermore, simulations can be made interactive to support in-depth inquiry of causality by allowing variation of different parameters over a wide range of values. Student activity can be electronically logged and monitored. Just-in-time instructions based on analyzing student data in real time can be embedded. Student results can be automatically sent to teachers and researchers for grading, tracking, and evaluation. All these advantages can be realized without adding extra burdens to students if the simulation tool is thoughtfully designed for education.

Engineering education in high schools can benefit from integrating science and engineering into a design-based framework [14, 15]. Incorporating simulations into this framework has the potential to enhance it, as they provide powerful problem-solving tools—in addition to the hands-on tools—that can compensate for time, material, safety and environmental constraints. When integrated with carefully designed curriculum units with clearly defined learning goals, and appropriately customized for teachers and students, simulations can serve as an accelerator of knowledge transfer from science to engineering, and, in turn, reinforce what students have learned from science courses.

Engineering design is a systematic, science-based process in which designers create, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or meet users' needs while satisfying a specified set of constraints [8]. In a simulation-guided design activity, students use a simulation tool to assist the design process: they experiment with and learn core scientific concepts through simulation-based inquiry, try different schemes through exploring many what-if scenarios, choose the optimal design, and build a physical system following the design. When encountering a problem, they use simulations to analyze it and find a solution. This is similar to "inquiry through design" [16], "learning by doing" [17], or "constructionism" [18], but has a strong emphasis on the cognitive resonance between simulations and hands-on activities. Students learn much more deeply when they see the results measured from their products agree with those predicted by their simulations.

Simulation-based cyberlearning: issues and challenges

Simulation is a cornerstone of the cyberlearning infrastructure envisioned by the NSF Task Force on Cyberlearning [19]. Virtual labs based on scientifically sound simulations promise to deliver rich learning experiences that supplement and strengthen learning from real experiments. The recent virtualization trend in science education, however, has prompted the American Chemical Society to issue a statement in 2008, which suggested that in academic transcripts simulations may not substitute lab work [20]. While most educators agree that cyberlearning should be tremendously fruitful in fostering learning for students who grow up with the cyber culture, extensive research needs to be carried out to substantiate the effectiveness of learning through simulations, to analyze the interplay between learning in the virtual world and learning in the physical world, and to learn how to take advantage of the strengths of both. The proposed research will shed light on these critically important questions.

The paramount question to study is whether the knowledge gained from simulations can be effectively translated into problem-solving skills required in hands-on activities. One possibility is that a student's understanding of a concept could bifurcate—meaning one thing in the simulation-based activity and another in the hands-on activity. In other words, the student could fail in synthesizing the knowledge obtained from the simulation and the knowledge obtained from the hands-on experiment. Another possibility is that learning in one activity overrides learning in another, resulting in the inability to correlate theory and practice. The Knowledge Integration Theory [21-24], which will be used in this project, provides an excellent framework to probe into these important questions.

Goals and Objectives

The overarching goal of this project is to investigate the educational value of scientific simulations for learning engineering through engaging high school students to do simulation-guided, hands-on design activities. Partnering with the Center for Engineering Education and Outreach (CEEO) at Tufts University, this research will concentrate on finding evidence of learning improvement contributed by simulations by comparing the learning outcomes of a control group, in which students use only a hands-on kit, and an experimental group, in which students use the complete set of engineering tools—a hands-on kit plus a simulation program. Specifically, we will work on the following objectives:

Develop the simulation tool. To support the research, we will develop an education-oriented, student-friendly simulation tool called *SimEng* (*Sim*ulated *Eng*ineering), which will be able to model the engineering problems students will encounter in this project. *SimEng* will have unique features needed to ensure the success of this research, which will be explained in the Project Rationale.

Develop the instructional units. To scaffold the design activities and facilitate the research, we will develop four instructional units that integrate basic science concepts, engineering principles, simulations, and hands-on projects. Each unit will require two to four class periods to complete. Professional development materials for the units will also be developed. Teacher workshops and online supporting materials will be used to prepare the teachers for the implementation and the field tests.

Research. We will implement a controlled study with 600 students using our materials. Data will be extensively collected through various research instruments and analyzed statistically.

Disseminate. We will publish our results in peer-reviewed journals in engineering education, present at related conferences, and disseminate our materials through teacher networks and through collaborators and coordinators at the Museum of Science in Boston, Tufts, Purdue, and Hofstra.

Project Rationale

Every field of science and engineering has been revolutionized by the ability to model complex systems. This advance has triggered a major paradigm shift of how people think, communicate, and design, which engendered the Cyberinfrastructure Initiative [25]. Engineering, like other STEM fields, is undergoing a transformative change driven by computational thinking [1]. This poses many intriguing challenges on how to integrate computational thinking with engineering design for K-12 engineering/technology education. In close collaboration with Michael Hacker, the PI of the NSF-funded Simulation and Modeling in Technology Education (SMTE) Project [26], who is on our Advisory Board, we will create a joint task force to address these fundamental issues (see Hacker's letter in the Supplementary Materials). There is a strong prospect of aligning our projects. The SMTE Project focuses on using a gaming environment to contextualize instruction and facilitate design for middle school students, whereas this project focuses on using advanced simulations to integrate science and engineering for high school students.

Massachusetts is one of the few states that has established K-12 engineering standards [27, 28]. The Massachusetts Science and Technology/Engineering Curriculum Framework [29] requires that "In high school, students develop their ability to solve problems in technology/engineering using mathematical and scientific concepts. High school students are able to relate concepts and principles they have learned in science with knowledge gained in the study of technology/engineering… students pursue engineering questions and technological solutions that emphasize research and problem solving. They achieve a more advanced level of skill in engineering design by learning how to conceptualize a problem, develop possible solutions, design and build prototypes or models, test the prototypes or models, and make modifications as necessary." Our project and research design is centered around these standards.

To narrow our research scope, we selected the topic of energy and power in thermal systems. Both Massachusetts standards and the Standards of Technological Literacy (STL) of the International Technology Education Association [30] require high school students to develop an understanding of power and energy technologies. Students should learn that thermal systems involve transfer of energy through conduction, convection, and radiation, and are used to control the environment. Students should demonstrate the ability to use the engineering design process to solve a problem or meet a challenge in a thermal system. Specifically, they should be able to 1) differentiate among conduction, convection, and radiation; 2) give examples of how conduction, convection, and radiation are considered in choosing materials for buildings and designing a heating system; 3) explain how environmental factors such as wind, solar angle, and temperature affect design; 4) identify and explain alternatives to nonrenewable energy.

Why develop *SimEng*

Modeling a thermal system with complex geometry (such as a house with windows or a Trombe wall) that involves all three heat transfer processes requires mathematical tools far beyond a simple calculator, especially when the field effect caused by convection becomes significant. Today's average engineering class is missing a substantial part of every engineer's toolbox—the simulation tools. There are many simulation tools for professionals. Commercial software such as *Simulink* [31], *MSC Nastran* [32], *Comsol Multiphysics* [33], *LS-DYNA* [34] and *ANSYS* [35] are excellent, but their costs are far beyond what a typical technology budget at a high school can afford. More importantly, none of them, free or commercial, were intentionally made for average high school students.

In general, a designing process using a professional tool is divided into three phases: 1) Pre-processing: the designer defines the model and the environmental factors to be applied to it; 2) Solving: the designer submits a computational job to a solver and waits for the calculation to complete; 3) Post-processing: the designer analyzes the results and evaluates the design. This cycle is repeated until the desired solution is found. The three modules—the pre-processor, the solver, and the post-processor—commonly have a complicated, general-purpose user interface (UI) that has numerous options and controls, sometimes driven by command lines. Some programs (such as *Comsol Multiphysics*) seamlessly integrate them in a single operating environment so well that the workflow switches from one module to another automatically. But none allow educators to design a learning-oriented, task-focused custom UI that can be used easily by students [36, 37]. The downside is that these tools become difficult to use in a classroom without time-consuming prior training and technical assistance from an on-site expert. This limits their use in the classroom and greatly complicates our research if they were to be used without modification.

Our research goal rests on the assumption that students be able to operate the simulation software proficiently to create meaningful designs without being distracted, confused, or frustrated by it. This requires that the learning curve be as smooth and short as possible and the simulation environment be as contextualized as possible, such that students will be confident with advanced simulations and can focus on engineering tasks. Additionally, a learning-oriented tool should also be able to convey effectively the underlying engineering science while students are working with it [38]. Optimizing a design involves adjusting different variables and observing how the system's performance changes accordingly. It provides a motivation to learn what these variables mean, whether they are correlated, and how they affect the system.

We propose to develop *SimEng* to meet these requirements. The development will be based on the lessons about computationally intensive educational simulations that we have learned through developing the *Molecular Workbench* [39], and follow the design principles of serious gaming [40] wherever applicable. The development will also draw upon open source programs (e.g., *Impact* [41] and *Code_Aster* [42]), as well as decades of research on visualization and modeling in science education [43-46]. With the advice of experts in computational methods (see Suo and Dolbow's letters) and engineering design (see Lovelace's letter), our team has the unique expertise needed to develop *SimEng* into a versatile, robust, and configurable tool that will run on ordinary school computers, which—like the widely used *Molecular Workbench*—will be a valuable asset to the nation's educational cyberinfrastructure.

Why engineer an energy-efficient house

Designing an energy-efficient house—an important topic due to the environmental concern—is an activity that covers most of the learning goals required by the available standards about energy and power in thermal systems. Reasoning about the relationship between the structure and function of a house provides students with many learning opportunities that connect the science and the design. Project 2.0 "*Design a Building of the Future*" of the "*Engineering the Future (ETF): Science, Technology and the Design Process*" curriculum [47], developed by the Boston Museum of Science, offers excellent content that will be the starting point of our instructional units. The curriculum is receiving widespread acceptance since its recent publication. In Massachusetts alone, at least 16 high schools have already adopted it. The coordination with the Museum of Science team, represented by Dr. Peter Wong on our Advisory Board, ensures that our materials will be well-received by these schools (see Wong's letter).

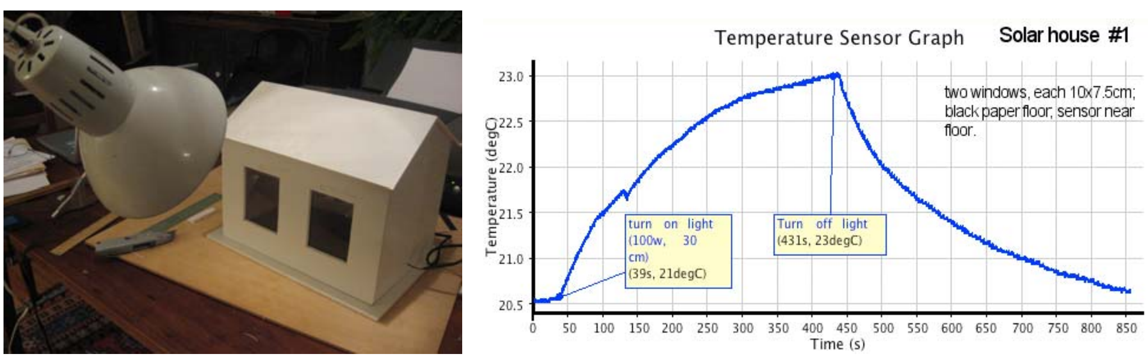

Figure 1. Left: A prototype scale model house made of foamcore. A desktop lamp (100w) placed at 30 cm away was used to simulate the sun. Right: This is a graph that shows the temperature inside the house recorded by a sensor. The lamp was turned on to simulate daylight and then off to simulate night. As you can see, as soon as the light was turned off, the temperature started to drop exponentially and finally returned to the original value (just as Newton's Law of Cooling predicts).

The "*Design a Building of the Future*" project ends after the scale model house is built and some preliminary data are measured. Our additions are as follows:

Measuring the thermal performance using our probeware. Students will evaluate the energy efficiency of the houses they have built. For example, students will measure the thermal property of the house by putting a jar filled with hot water or ice cubes inside it and recording the temperature change using a sensor with the windows open or closed, to check if the temperature changes as expected. Multiple sensors may be used to record a field distribution in order to establish a better picture of the overall performance, to find out where heat energy leaks the most, and to detect convection.

Creating devices to improve the house using renewable energy sources. Having measured the thermal performance of their houses, students will learn how to improve the energy efficiency. Since they have limited material supply, they cannot destroy their houses and start over. They will have to think hard about how to work under the constraints. We will guide them through possible passive heating and cooling solutions in the instructional units to help them achieve their goals, but they will have to make their own decisions of choosing a solution or a combination of solutions.

Using simulations to learn and design. While students in the control group will make design decisions based on information they learn from traditional curriculum, those in the experimental group will use *SimEng*. They will learn the science through simulations. For example, they can set up a simulation in which a heat source is placed inside their virtual house, observe how heat energy dissipates, calculate heat fluxes at different locations, and then compare the results with the data measured by sensors placed in their scale model house. They will learn the engineering through simulations, too. As their project goal is to maximize the energy efficiency of their houses, one design aspect will be to evaluate different solutions for reducing the heat loss, choose one they consider optimal, and then customize it to meet their goals. *SimEng* provides them with a powerful tool to analyze all the contributing factors at the system level. Through adjusting different design parameters and visualizing the heat flow change in the house, students will get a better mental picture of the entire process and use that to make the best design decision.

Our contribution to the widely adopted house design activity will be significant. The design of energy-saving buildings relies more and more on simulations, according to researchers [48, 49] from the Passive House Institute in Darmstadt, Germany, which recently was highlighted in the New York Times for their remarkably energy-efficient homes [50]. By bringing this advanced engineering design methodology to the classroom, this project will contribute profoundly to the education of future engineers who are set to solve the pressing energy and climate challenges.

Implementation strategy: the mini Solar Decathlon in a high school classroom

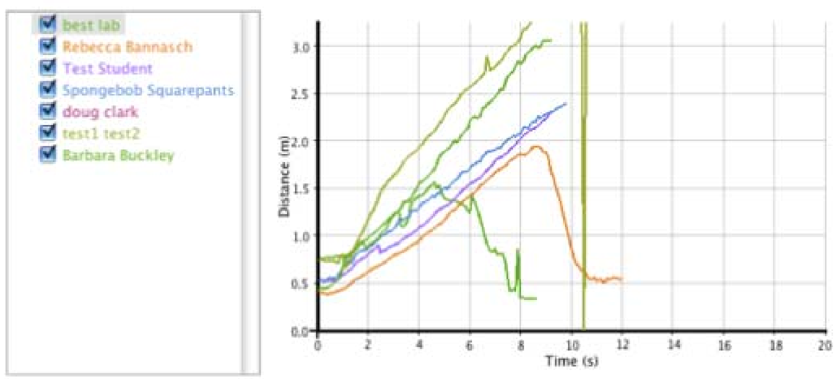

Figure 2. This screenshot shows how data collected by different users of our probeware can be shown in a single graph in a report automatically generated by SAIL/Otrunk. This functionality allows us to compare easily the thermal performances of the houses students designed. (Note: the data shown in this graph is not real temperature data from a scale model house. This image is used to illustrate the existing functionality.)

As the design activity lasts several days and students from different teams will have plenty of time to trade or share ideas, there is a tendency that all teams in a class would converge to a similar design, which could weaken our research. To encourage divergence and motivate creativity, we will introduce a competition modeled after the Solar Decathlon. Students will learn how to build energy-saving houses through our scaffolded instructional units. At the end of the project, the class will hold a competition in which every team will participate. The procedure of the competition is to run a sensor to collect the temperature inside their scale model houses for 15 minutes with a swivel lamp that shines from a fixed height and angle on the house. The sensor graphs will be collected using our probeware and overlaid for judging (see Fig. 2 for an explanation of the SAIL/Otrunk technology [51] that enables this). The winner will have the highest overall temperature in a situation that mimics the winter condition or the lowest overall temperature in a situation that mimics the summer condition—measured at one centimeter above the floor in the middle of the house. Each team will be asked to give a five-minute presentation to the whole class about their design choices. The first two places will be awarded with a certificate signed by CC's President and a small gift card. In the future, the competition could be generalized to the national level, following the successful example of the West Point Bridge Design Contest [52].

The research challenges in engineering education

A key issue of design-based or project-based learning is that there seems to be tension between understanding and performance goals [9]. Students may spend more time on optimizing a design and less time on understanding how it actually works. Conversely, they may spend more time on understanding why a design succeeds or fails and less time on improving it. Evaluation based solely on performance goals may not reflect the actual learning gains. A comprehensive assessment rubric that measures both performance and conceptual understanding is needed. A transfer study that evaluates conceptual understanding is also helpful. Our research plan includes these instruments.

The tension between understanding and performance can be eased by framing learning within a challenge-based environment [53]. Scaffolding guides student progress through reachable challenges, which provide motivations for students to achieve the learning goals, with significantly higher gains than traditional curriculum [54]. Scaffolding also leads to a controlled learning progression that gives students adequate time for inquiry at each step. This principle will guide our instructional materials design.

Another issue in the research of engineering education is that it is difficult to devise a test that can measure learning. Part of the problem is that it is hard to capture what students have learned in the design process quantitatively. A simulation tool can log a student's activity and record his/her work, which contains useful information about learning that researchers can score. However, this only works for the experimental group. The data collected from the sensors may be used as a source of learner data for both groups, but the association of these data to student activities is not always reliable. Our research will collect data from many sources to attempt to address these issues (see the Research Plan for more details).

Broader impacts

Although this project focuses on one engineering design example, the research methodology is broadly applicable and the results will have important implications for engineering education in general. Many states are considering establishing engineering standards. The National Academy of Engineering is also assessing the potential value and feasibility of developing and implementing national K-12 content standards for engineering education [55]. A major concern is how to make engineering content more rigorous than it is now and to fit better with science [27]. This project will make a major contribution to research on secondary engineering education, which will inform the educational policymakers and the curriculum developers involved in this movement [56].

The project will promote diversity and equity, as *SimEng* will be open source and free, and our instructional units will be freely available online for educational use. The materials will be tested with a socio-economically diverse student population to ensure that the results of this study apply to all students.

Results from Prior NSF Support

The project will be built on several NSF-funded programs, listed below:

> The **Molecular Workbench** project (REC-9980620. $1,364,944. 1/2000-8/2004. Berenfeld, PI) supported both the initial development of the *Molecular Workbench* software and the classroom research in middle schools and high schools using simulation-based instructional units covering topics in physical sciences and biology. Xie, the PI of this proposed project, was the developer of the software.

Team member Damelin was an activity developer, and Pallant was the educational researcher. See: http://workbench.concord.org.

TEEMSS II: Technology-enhanced Elementary and Middle School Science (DRL-0352522. $2,706,804. 4/2004-9/2007. Tinker, PI) developed 15 learning units supported through innovative use of models and probes. Bannasch, the Co-PI of this proposed project, was the chief technologist. Team member Hazzard was a senior curriculum developer. See: http://teemss.concord.org.

Tufts Engineering the Next Steps (DGE-0230840. $1,681,666. 6/2003-5/2007. Rogers, PI) placed Tufts engineering and computer science students in Malden, MA, public school classrooms to help teach these subjects to elementary, middle, and high school students. See: http://www.tens-gk12.org.

The team has a long-term history of success in building and applying simulation systems for K-12 education. The *Molecular Workbench* created by the team provides an interactive learning environment based on molecular dynamics simulations that allow users to investigate and understand more deeply the atomic-scale mechanisms of basic phenomena in science and engineering. The system consists of molecular dynamics simulation and visualization engines, an easy-to-use graphical user interface and activity authoring tool, and an embedded assessment tool for measuring student learning. It has been used to produce numerous learning activities, now widely used in classrooms (>300,000 downloads).

Senior educational researcher Pallant has led several studies on student learning using these interactive activities, covering a broad range of content and involving students from middle school to community college. The results demonstrated that students who used well-designed activities achieved a solid understanding of atomic-scale phenomena and were able to transfer the knowledge to new contexts [57-59]. In an independent study, Moher and collaborators used the *Molecular Workbench* to engage students to design self-assembling nanostructures. Their results showed that students demonstrated the ability to design nanoscale models using the tool [60] and highlighted the value of the construct-centered design methodology in learning nano-engineering [61]. These positive results of learning enhancement by simulations, though in a different content domain, suggest that a similar treatment applied to the engineering domain may work as well because the major learning obstacles are similar: the difficulty of molecular scale and nanoscale concepts arises from the invisibility of atoms and molecules and their strange thermal motion; similarly, the difficulty of thermal engineering concepts arises from the invisibility of air and heat flow.

The team also has extensive experience in creating and using probeware to promote students' hands-on investigative skills and understanding of science concepts through data acquisition [62], which will be very important in this project. Furthermore, CEEO's expertise and excellence in LEGO robotics and worldwide dissemination of tools and curriculum will be very helpful to the success of this project [63].

WORK PLAN

Software Development

The development of *SimEng* is a major technological undertaking of this project. *SimEng* will have a sophisticated architecture that seamlessly integrates a computational engine, a visualization engine, and a design studio. *SimEng* will have a simple yet powerful graphical UI for students to design with a variety of properties, such as the environmental temperature, the size and shape of the house, the number of windows and doors, the location and size of windows, wall insulation, air exchange with the environment, glazing, thermal mass, insolation, and light absorption of materials. Students will be able to extract rich data from simulations conveniently via virtual sensors for comparing with data collected by real sensors.

Part 1: Developing the computational and visualization engines. A multiphysics computational engine capable of modeling light absorption, heat transfer, air flow and their coupling (e.g., the stack effect) will be built. The generic engine will be based on the finite difference method [64] and/or the finite element method [65] for solving partial differential equations for complex systems[3]. Open source mesh generators [66] will be incorporated to divide the problem domain. A visualization engine will be developed to render the calculated results and deliver a vivid graphical representation that clearly shows how heat and matter flow in the system.

The computational engine will be able to simulate nonsteady states. This capacity has significant educational and scientific importance. A system is in a nonsteady state during a heating or cooling process—only when the thermal equilibrium is reached is it in a steady state. The ability to simulate nonsteady states allows students to do transient analysis of heating/cooling rate that can be experimentally verified using a sensor (see Fig. 1). The heating/cooling rate is important in actual passive house design [49], and can only be calculated using dynamic simulations [48]. Of more importance, the ability allows us to build salient educational software that enables students to learn rapidly and deeply through dynamically interacting with the system and seeing its response instantaneously (instead of waiting for the equilibrium to be reached and the steady state to be reported). For example, students can change the angle of the sun continuously in a simulation and observe the temperature fluctuations inside a house. They may experiment with hypothetical conditions such as what happens to the temperature if the earth spins five times more slowly (will the house be too hot in the day and too cold at night?). It is through this kind of inquiry that students learn most effectively. The important thing is that this learning advantage is only achievable by applying the core science itself directly to the educational tool, not by any other means.

Part 2: Developing the design studio. We will create an easy-to-use design studio for designing a house and setting up simulations. Existing open source, scene graph-based 3D application programming interfaces such as the high-performance jMonkeyEngine [67] will be used to simplify the development.

Part 3: Supporting multiple sensors in our probeware. Currently, our probeware does not allow using multiple sensors to generate time series of multiple simultaneous measurements. We will add this functionality, which is needed in our units to compare heat flow at different locations.

Instructional Materials Design

We will create four instructional units for designing energy-efficient homes, based on the ETF curriculum [47], the Massachusetts standards [29] and the STL [30]. In developing them, we will also learn from the "*Solar House*" curriculum in the "*Challenges of Physical Science*" series [68]. Since the units teach identical content based on the same curriculum (we will work with teachers who are using the ETF), our research will not conflict with the teachers' syllabi.

There will be two versions for each unit: one for the control group and one for the experimental group. The content that covers the hands-on part will be identical in the two versions. For the remaining part, the version for the control group will have traditional content similar to that of ETF, whereas the version for the experimental group will be largely based on simulations.

It is noteworthy that there are two distinct levels of using simulations to promote learning. Learning at the qualitative level means knowing approximately how an engineered system behaves without having to correlate results to real data. Learning at the quantitative level means knowing exactly how a system behaves with an expectation to use that knowledge to correlate results to real data and/or guide real design. For example, when studying the cooling of a system, the learning goal may be considered achieved at the qualitative level if students discover that the simulation data and the sensor data have an exponentially decaying behavior that resembles each other in shape. But at the quantitative level, students may be required to calculate and compare the heat transfer coefficient. The quantitative level sets a higher learning

[3] These generic methods make the engine very general. Additional physics (e.g., structural mechanics) can be incorporated to extend *SimEng*'s modeling capacity, making it broadly useful for engineering education.

goal that needs more investment of the student's time and a higher level of mathematical competency. *SimEng* will support both levels of learning. The units will be structured to help students acquire the quantitative skill, but not disable them from learning if they cannot achieve it.

The outlines of the four units are listed below:

Unit 1: Introduction. This unit will introduce basic concepts such as units, heating/cooling rates, energy conservation, conduction, convection, and radiation, and engineering elements such as insulation, glazing, thermal storage, and passive heating and cooling. This unit will ensure that every student receives some introduction to the science and the engineering, considering the fact that their prior knowledge may vary. The experimental group will learn these concepts with interactive simulations embedded in the unit, while the control group will learn in a traditional way (as illustrated in the ETF). At the end of this unit, students should have a basic understanding of the physical processes involved in the design challenge, such as how heat transfer occurs between the house and the environment under different weather conditions.

Unit 2: Designing and building an energy-efficient house. This unit will instruct students how to construct a scale model house using a hands-on kit supplied by the project[4]. They will learn to use the sensors to measure the heat gain or loss and evaluate insulation. They will explore different heating and cooling factors using the tools provided and other low-cost materials on hand. For instance, a swivel lamp models the sun at any angle, the effects of wind can be studied using an electric fan, and thermal mass can be added by plastic jars filled with water. Students will be required to follow some basic rules so that their next steps will not be undermined. Other than these restrictions, they can design freely. The experimental group will design the house using *SimEng* before building it. They will be able to experiment with various design factors (e.g., is a square house more efficient than a long one? Does the internal structure matter? How does window size affect day-night temperature fluctuations?). At the end of this unit, students will be more familiar with *SimEng* and be better prepared for further design tasks using the tool.

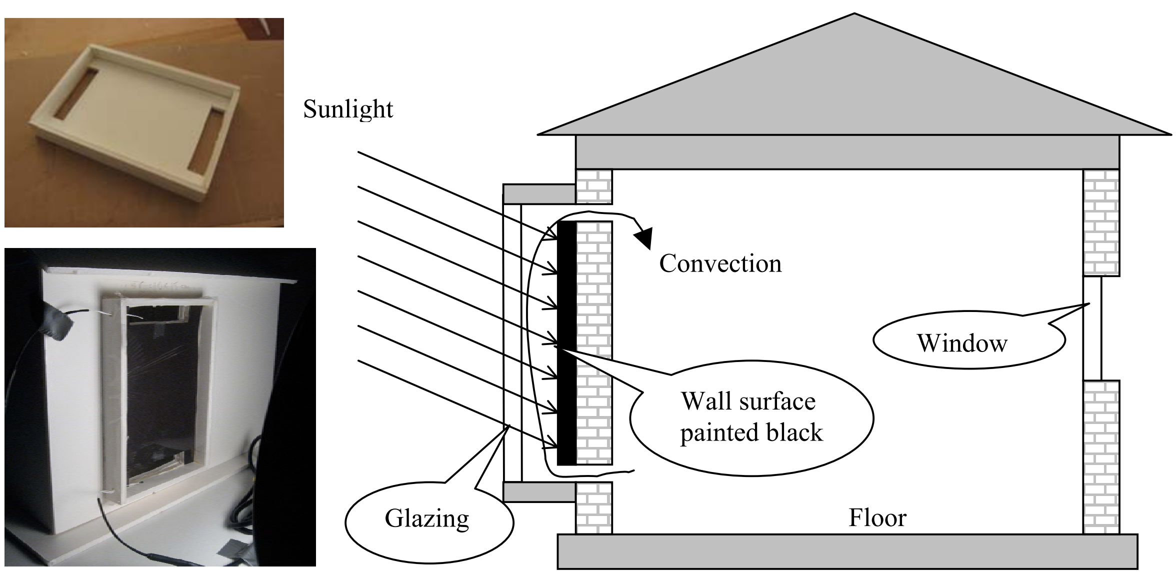

Figure 3. Students can create a Trombe wall and investigate its effect in heating the house. The photos on the left show a prototype (10x15 cm). When shining a 100w lamp on it at different distances, the upper part maintained a temperature 5-10°C higher than the lower part, suggesting strong convection. The schematic drawing on the right shows a possible design scenario using SimEng (a 2D cross section).

[4] The kit includes: 1) Materials: foamcore, glue, tape, clear plastic wrap, and black paper; 2) Tools: a utility knife, a steel ruler with a straight edge for cutting, a hot melt glue gun, a scissor, a swivel desk lamp, reusable ice packs, plastic water jars, an electric fan, an aquarium heater, and a set of Vernier sensors.

Unit 3: Exploring natural heating. Students will learn that a green design should harness renewable energy such as sunlight as much as possible. They will learn that there are many different ways to collect renewable energy: a Trombe wall (see Fig. 3), a water wall, a roof pond, a thermosiphon, an attached greenhouse, and an earth tube. Both the control and experimental groups will choose one design and use it with their houses. The experimental group will additionally use *SimEng* to evaluate and optimize the designs as they build their houses. For example, they will determine the size and shape of a Trombe wall based on computing the energy output before building it. They will calculate under what light condition the convection loop will stop adding energy into the house. (The data could help students invent a feedback mechanism that opens and shuts the air exchange holes automatically to maintain maximal efficiency based on the reading from a light sensor attached to the wall.) Through this unit, students will understand that a design may only work under certain circumstances, and engineering often needs trade-offs.

Unit 4: Inventing natural cooling devices. This unit presents a task that tests near transfer of knowledge from the heating context to the cooling context. Students will be challenged to invent designs for cooling the houses under a condition that simulates summer. The design goal is to keep the temperature in the scale model house lower than the room temperature when the light from the lamp shines on it. Ice packs or ice cubes can be placed under the insulated floor to simulate a cool ground. To get started, they will be introduced to the ideas of natural cooling, such as windcatchers, evaporative cooling, convective cooling through ventilation, and solar chimneys that draw cool air through a geothermal heat exchanger. They will use their prior knowledge to increase the cooling rate, and use sensors to check if the design works. The experimental group will be allowed to use *SimEng* to assist their designs. We will monitor closely how well they use the simulation tool to reason in the design process.

Unit 1 will take two class periods to complete. The other units are estimated to require two to four class periods each. The final length of each unit will depend on the feedback of students and teachers after the project unfolds. The solar house competition is not included in the units and will occur in an additional class period. For each unit, there will be a teacher guide and accompanying online supporting materials. Researchers from CEEO at Tufts will contribute actively to the development process.

Educational Research

This project will test the common assertion that simulations and hands-on projects can be mutually reinforcing. To assess the effectiveness of using simulations in design activities for improving students' learning, a quasi-experimental approach in which both process and outcome data will be collected and analyzed will be adopted. The following questions will guide the research: 1) Does the experimental group do better in meeting the design challenges, acquiring the content knowledge, and transferring it to a new context than the control group? 2) Does the experimental group explore a greater variety of designs in order to optimize the design? 3) Does the experimental group show an increased ability to integrate the science with the engineering design?

In collaboration with Prof. Purzer at Purdue (see Purzer's letter), pre/post content intervention measures will be devised and collected from all students. In addition, we will collaborate with Prof. Lee at Tufts (see Lee's letter) to design a Knowledge Integration (KI) scoring rubric schema [21] for capturing an understanding of student ability to integrate the science and engineering concepts in solving problems encountered in the design project and the transfer challenges. In all measures, at least two independent evaluators will review the samples and score them in order to increase inter-rater reliability. We will work with a number of selected schools that use the ETF curriculum (see teachers' letters) to conduct the controlled studies[5]. A pilot study with three classes in the experimental group and three classes in the control

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[5] We sent out an invitation letter to schools during the New Year holiday. In two days, we received enthusiastic responses from 12 teachers! This indicates there is a great interest in this project.

group will start in year two to test our materials. We will collect preliminary data and revise instructional units and assessment tools that will then be used in a larger study in year three, which will involve 20 classes. The classes will be randomly divided into control and experimental groups (if a teacher teaches multiple classes, we will divide them evenly into each group). Students from both groups will spend an approximately equal amount of time on the design activities. In each class, students will work in teams of two or three students.

The following research instruments for collecting data will be developed:

Student products: After students complete the projects, researchers who do not know which groups created which houses will assess the designs and score them according to a rubric that is based on the sophistication of the design, the performance of the house, and the level of integration of science concepts with engineering principles reflected in student final reports and presentations.

Pre/post measures: Pre/post tests will be administered to all students at the beginning and the end of the project. Items on pre/post tests will be aligned to science and engineering standards and unit learning goals. These tests will contain items from released test item sets. For any questions not found in released items, our Advisory Board will review test items to examine the extent to which they are representative of the domain. Using confirmatory factor analytic procedures, we will examine pilot data collected from year two to establish reliable measures.

Embedded assessment: Embedded assessment items and tasks will be included in each unit. These tasks will have students grappling with multiple ideas requiring the integration of science and engineering in a transfer situation. There are multiple types of embedded assessment that provide rich research data sources. We will collect data from the end-of-unit assessment, the design journals, and the transfer tasks from both the control and experimental groups. In addition, we will collect students' artifacts designed using *SimEng* from the experimental group. A designated staff will carefully remove any explicit association with simulations and demographic information in the data and provide the neutral content for third-party evaluation. Several types of analysis will be undertaken to address the research questions, including the calculations of learning gains, the KI analysis of design and transfer activities, and the comparisons of the control and experimental groups.

Student interviews: Interviews will be conducted with randomly selected teams from both the experimental and control groups shortly after they have completed the project. The interview will focus on student understanding of basic science and engineering concepts, and test their ability to apply the knowledge they have learned to a different design challenge (e.g., how a solar updraft tower generates electricity). The interviews will look for ways students describe how they might solve the challenge, and look at how they might optimize the design. A KI rubric will be used to determine the level of integration of the science and engineering concepts.

Fine-grained process data: For the experimental group, we will log student activity data with simulations: which tools they use, which parameters they vary, what their results are, and how they interpret them. The data records students' interactions with simulations and will be analyzed to determine if it is predictive of subsequent performance in designing the product or explaining the design.

Background survey: The survey will collect demographic information (e.g., age and gender), prior academic achievement, prior science and engineering knowledge, mathematical skill, and prior experience with simulations. The data will be used to describe the sample of students and use as covariates to conduct secondary analyses.

Several types of analysis of the data collected through the above instruments will be undertaken. These analyses will include the calculations of descriptive statistics, analysis of variance to examine the equivalence of the experimental and control groups, and an analysis of covariance to determine the treatment affect. To analyze the fine-grained process data generated by the experimental groups while using

SimEng, we will build on techniques developed by the Modeling Across the Curriculum project funded by the NSF [69]. We will prepare case studies to show the differences in knowledge integration for those who use simulations versus those who do not. In all interviews, presentations, and embedded assessments, we will look for evidence of how simulations change student reasoning and engineering skills.

Dissemination

SimEng and all the instructional units will be freely available on a project website for educators. Our results will also be published in our free newsletter *@Concord*, which is distributed on the web and mailed to over 10,000 educators, as well as in professional journals. The team will also disseminate materials and results through coordination with the CEEO and the Boston Museum of Science, which run various programs in teacher professional development.

PROJECT EVALUATION

The goal of the project evaluation is to determine the extent to which the project achieves its objectives and successfully executes an effective plan. The project will utilize the services of Sun Associates as its external evaluator (see Sun's letter). Sun Associates evaluates a wide range of educational projects in K-12 school districts, state departments of education, institutions of higher education, and other educational consortia. They will bring their strong expertise in quantitative data analysis, evaluation design methodology, and project management to this project. Evaluation for this project will focus on three essential questions: 1) To what extent has the project advanced engineering education through the development and classroom implementation of the proposed software, hardware, and instructional units? 2) To what extent has the project improved students' understanding of science and engineering and improved their design skills within the context of the available engineering educational standards? 3) What activities has the project taken to meet the objectives?

The evaluation will be based on a few sample groups, and an attempt will be made to provide some measure of insight into the project's potential impact on overall student population. As an initial step in the project's calendar of work, the evaluators will work with the project staff, the Advisory Board, and the participating teachers to develop a benchmarked set of project performance indicators based on the evaluation questions and the project goals and objectives. Arranged into a rubric, these indicators will provide clear criteria for project success as well as benchmarks that can be used throughout the project's three years to show how the project can qualitatively and quantitatively improve its performance. The evaluators will report summatively via an annual project performance report that will be developed in consultation with project staff and partners. The reports will include recommendations addressed to the project leadership team so that it can make modifications to the materials and address any significant issues. These annual reports will constitute one of the project's annual deliverables to the NSF. In addition, the Advisory Board will review all of our materials. They will focus on the following questions: Do the materials incorporate accurate content, good pedagogy, and relevant standards? Are appropriate review and assessment strategies used to ensure this?

PROJECT SCHEDULE

The project comprises the development cycle for the software, the probeware, and the instructional materials, as well as the classroom tests and the educational research.

October 1, 2009-September 30, 2010: The team will focus on developing *SimEng* and the hands-on kit after holding a launching meeting that will be attended by members of our Advisory Board and participating teachers. By the middle of this period, an alpha version of software and hardware will be ready for reviews and comments. In the second half of this period, development will continue. Calibration and parameterization will be carried out to make sure that simulation results can match probe measurement.

At the same time, quality assurance and usability tests involving students will be started. By the end of this period, we will release beta versions. The team will begin to develop the research instruments including the pre/post tests, surveys, and KI rubrics, as well as the instructional units and teacher materials.

October 1, 2010-September 30, 2011: The team will focus on completing the pilot draft of the instructional units, research instruments, teacher guides, and online materials, and conduct a pilot study involving six classes. A teacher workshop will be held before the pilot study. Software development will continue: more functionality will be added, the stability will increase, and the UI will be improved. At the end of the pilot tests, interviews with students will be conducted, data will be analyzed, and the materials will be revised. During the summer, we will arrange a second workshop for teachers involved in the field test. Integration our materials with the materials developed at Hofstra will be initiated. The second Advisory Board meeting will be held.

October 1, 2011-September 30, 2012: The team will focus on field tests involving 20 classes. A training workshop involving all participating teachers will be held before the field test. Development will be limited to feature requests, bug fixes, and integration with other technologies and materials. Data collection and analysis will involve most staff and will be intensive. Materials will be revised for dissemination. Definitive results are expected at the end of this period. Results will be summarized and presented through reports, papers, and conferences. The third meeting with the Advisory Board will occur.

PROJECT PERSONNEL

Advisory Board

The Advisory Board will oversee this project and determine if the objectives of the project have been met. They will help to ensure that the materials incorporate accurate content and good pedagogy. The advisors will meet with the staff and review the proposal, the materials developed, the research plan, and the research data. The advisors will prepare a report after each meeting that will include recommendations addressed to project staff and will be forwarded to the cognizant program officer. The Board members are:

Dr. Zhigang Suo is Professor of Mechanics and Materials at Harvard University and member of the National Academy of Engineering. He will ensure the scientific integrity of our software and content.

Dr. John Dolbow is Associate Professor in the Department of Civil and Environmental Engineering at Duke University. He will be our advisor on computational methods and numeric simulations.

Michael Hacker is Co-Director of the Center for Technological Literacy at Hofstra University and also a member of the STL Development Team. He will advise us on technology/engineering education in schools, ensure that our materials will be standards-based, and facilitate the collaboration between our team and the Hofstra team.

Dr. Peter Wong is Director of University Relations at the Museum of Science in Boston. He will advise us on integrating with the "*Engineering the Future*" curriculum.

Dr. Hee-Sun Lee is Assistant Professor in the Department of Education at Tufts University. She will advise and help our research on knowledge integration in science and engineering.

Dr. Senay Purzer is Assistant Professor at the School of Engineering Education at Purdue University. She will advise and help our instrument development and gender studies.

Dr. Edward Lovelace is Director of Research at Satcon Technology Corporation. He will be our industry advisor on the application of simulations to solving real engineering problems.

Larry Weathers is Director of Science at Belmont Public Schools, MA. He will advise us on field tests, educational research and practical school implementation.

Staff at the Concord Consortium

The nonprofit Concord Consortium is internationally recognized for innovative development of STEM educational initiatives that exploit the power of IT. CC combines research and development with expertise to stimulate change in diverse educational settings. The common thread of CC's work is the innovative use of technology to address an important social need: to make it possible for learners, regardless of socio-economic background, to attain fundamental understanding of important scientific concepts which will make it possible for them to enter STEM career fields.

Dr. Qian Xie will serve as the Principal Investigator and will take overall responsibility for the research and development of the project. He will be responsible for developing *SimEng* and analyzing data. He holds a Ph.D. in Materials Science and Engineering from the University of Science and Technology, Beijing. Qian has extensive experience in modeling physical, chemical, biological, and engineering systems. He is the creator of the NSF-funded *Molecular Workbench* that has turned research-grade molecular dynamics into an effective learning and teaching tool, which has had an impact in education worldwide. He is currently Co-PI of the NSF-funded Electron Technologies project that helps students decipher quantum mechanics concepts behind many problems in engineering and technology using simulations.

Stephen Bannasch, CC's Director of Technology, will serve as a Co-Principal Investigator. Stephen holds a B.A. from Hampshire College. His thesis project "*Monitoring and Analysis of an Experimental Passive Solar Envelope House*" highlights our team's expertise in solar house design. Stephen pioneered the technology used in educational applications of computer interfaces to laboratory experiments. He will contribute to the enhancement of the probeware system and the embedded assessment technology.

Amy Pallant will be the Project Manager, responsible for project management and coordination of the research and evaluation. She has been the Project Manager and senior science education researcher on several NSF-funded projects. Amy holds an M.A. in Science Education from Harvard.

Edmund Hazzard will develop the instructional materials for the hands-on part. Ed has worked on various projects at CC involving probes and models. Ed holds a Master's Degree in Architecture from the University of California Berkeley and is a registered architect in Massachusetts. His experience in architecture is a great asset to this project. He also holds a Master's Degree in Teaching from Tufts.

Dan Damelin will develop the instructional materials based on *SimEng*. Dan holds a B.S. in chemistry, computer science and environmental studies, and an M.A.T. from Tufts. He has developed numerous instructional materials based on simulations. He is the PI of the NSF-funded RI-ITEST project at CC.

Dr. Kimberle Koile will assist with software development and educational research. She holds a Ph.D. in computer science from Massachusetts Institute of Technology. She is also a research scientist at MIT's Center for Educational Computing Initiatives, and the PI of the NSF-funded INK-12 Project.

Chad Dorsey, President of CC, will ensure the cogency of the research and development, and oversee the coordination and dissemination efforts. He holds an M.A. in physics from the University of Oregon.

Staff at Tufts University

Dr. Chris Rogers, Professor, Department of Mechanical Engineering at Tufts, will serve as a Co-Principal Investigator. Chris has a strong commitment to engineering education, and at Tufts has started a number of new directions, including learning robotics with LEGO bricks and learning manufacturing by building musical instruments. He is currently the director of the CEEO.

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