SMARTCAD:
GUIDING ENGINEERING DESIGN WITH SCIENCE SIMULATIONS

Overview. This Full Design and Development proposal from the Concord Consortium, Purdue University, and the University of Virginia addresses the Learning Strand. It targets middle and high school physical science and engineering. This project will conduct design-based research on SmartCAD, a computer-aided design (CAD) system that supports secondary science and engineering with three embedded computational engines capable of simulating the mechanical, thermal, and solar performance of the built environment. These engines will allow SmartCAD to analyze student design artifacts on a scientific basis and provide automatic formative feedback in forms such as numbers, graphs, and visualizations to guide student design processes on an ongoing basis. The research hypothesis is that appropriate applications of SmartCAD in the classroom will result in three learning outcomes: 1) Science knowledge gains as indicated by a deeper understanding of the involved science concepts and their integration at the completion of a design project; 2) Design competency gains as indicated by the increase of iterations, informed design decisions, and systems thinking over time; and 3) Design performance improvements as indicated by a greater chance to succeed in designing a product that meets all the specifications within a given period of time. While measuring these learning outcomes, this project will also probe two research questions: 1) What types of feedback from simulations to students are effective in helping them attain the outcomes?; and 2) Under what conditions do these types of feedback help students attain the outcomes? To test the research hypothesis and answer the research questions, this project will develop three curriculum modules based on the Learning by Design (LBD) Framework to support three selected design challenges: Solar Farms, Green Homes, and Quake-Proof Bridges. This integration of SmartCAD and LBD will situate the research in the LBD context and shed light on how SmartCAD can be used to enhance established pedagogical models such as LBD. Research instruments include knowledge integration assessments, learning analytics, embedded assessments, classroom observations, participant interviews, and student questionnaires. This research will be carried out in Indiana, Massachusetts, and Virginia simultaneously, involving more than 2,000 secondary students at a number of socioeconomically diverse schools. Professional development workshops will be provided to familiarize teachers with SmartCAD materials and implementation strategies prior to the field tests. An external Critical Review Committee consisting of five engineering education researchers and practitioners will oversee and evaluate this project formatively and summatively. Project materials and results will be disseminated through publications, presentations, partnerships, and the Internet.

Intellectual merit. The incorporation of engineering into the Next Generation Science Standards mandates that precollege engineering activities designed for science courses must support an appropriate integration of engineering design and science learning. One way to inspire students to learn and apply science in a design process is to continuously provide formative feedback to illuminate how science concepts play out in their own designs. This project will investigate how this kind of formative feedback can be automatically composed from the results of computational analysis of student design artifacts supported in SmartCAD and used to guide student design in a scientific direction. The research will be conducted by a team of award-winning researchers and developers who have track records of successes in STEM innovations.

Broader impacts. Modern CAD software that computerize a significant part of engineering design have the potential to support K-12 engineering education at a level and scale comparable to modeling and simulation in science education. The proposed research will provide timely results that could motivate the development of an entire genre of CAD-based learning environments and materials to accelerate and scale up K-12 engineering education. To educational researchers, the envisioned SmartCAD will provide a versatile open-source platform for exploring new possibilities and testing new theories. To cash-strapped schools, SmartCAD will provide a zero-cost alternative to expensive commercial software or hardware.

SmartCAD:
Guiding Engineering Design with Science Simulations

The Vision

The incorporation of engineering into the new science standards (National Research Council, 2010, 2012; NGSS Lead States, 2013) mandates that precollege engineering activities designed for science courses must support an appropriate integration of engineering design and science learning. Although approached from different perspectives (e.g., Apedoe & Schunn, 2013; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Hmelo, Holton, & Kolodner, 2000; Kafai & Resnick, 1996; Kolodner et al., 2003; Mehalik, Doppelt, & Schunn, 2008; Sadler, Coyle, & Schwartz, 2000; Vattam & Kolodner, 2008), research in both science and engineering education suggests that this integration is still rife with challenges (e.g., Berland, 2013; National Academy of Engineering & National Research Council, 2014).

A cognitive barrier for students to learn and apply science in engineering design arises from the fact that science concepts are often far more obscure than other design variables such as price, shape, or aesthetics. Many science concepts are invisible and alien to students and difficult to recollect when students are overwhelmed by the complexity of design. Furthermore, the ability to apply a science concept to improve a design rests not only on the understanding of the concept alone, but also on the understanding of its interplay with all the other science or non-science concepts that may affect the system function. The latter understanding is a prerequisite to core engineering practices such as satisfying multiple criteria and making trade-offs. These difficulties can impede students' development of "engineering habits of mind" (National Academy of Engineering & National Research Council, 2009) through design activities.

Apart from "creating the demand" for science (Kanter, 2010) in the curriculum, another way to inspire students to learn and apply science in a design process is to continuously provide formative feedback to illuminate how science concepts play out in their *own* designs. Specific feedback can help students learn the effect of a science concept and then make an actionable design choice. In typical engineering projects, students are challenged to construct an artifact that performs specified functions under constraints. To determine whether a change of form can result in a desired function, students have to build and test a physical prototype or rely on the opinions of an instructor. This creates a delay in getting feedback at the most critical stage of the learning process, slowing down the iterative cycle of design and cutting short the exploration in the design space. When students' time for a design project is limited—as is typical in secondary education settings—a significant delay in the feedback loop will be detrimental to learning. Even if there is enough instructional time, not all teachers are expert at evaluating complex student designs and not all students have access to resources for meaningful prototyping and testing.

All these problems can be addressed by supporting engineering design with a computer-aided design (CAD) platform that embeds powerful science simulations to provide formative feedback to students in a timely manner. Simulations based on solving fundamental equations in science such as Newton's Laws model the real world accurately and connect many science concepts coherently. Such simulations can computationally generate objective feedback about a design, allowing students to rapidly test a design idea on a scientific basis. Despite these advantages, there are very few developmentally appropriate CAD software available to K-12 students—most CAD software used in industry not only are science "black boxes" to students, but also require a cumbersome tool chaining of pre-processors, solvers, and post-processors, making them extremely challenging to use in secondary education (see the letter from Mr. Miranda who routinely teaches engineering with CAD software in his physics classes). The proposed SmartCAD will fill in this gap with two key educational features centered on guiding student design with feedback from simulations:

- **Visual feedback**. Cognitive research has suggested the importance of visual contexts for processing complex information (Chun & Jiang, 1998). Simulations can visualize invisible scientific processes on top of design artifacts to render individual or joint effects of science concepts in an engineering context. For example, a view of an otherwise unseen heat flux distribution around a building generated by a simulation can be overlaid onto a 3D view of the building to show how the heat transfer depends on its design. Details such as the shorter heat flux vectors through a roof surface facing the Sun on a winter day, compared with those through a surface not facing the Sun, can bring students' attention to the interplay between heat transfer and solar radiation. Visual feedback like this can create numerous opportunities for students to see science concepts in action together in their own designs, thereby fostering the integration of different science concepts and the connection between science and design.

- **Analytic feedback**. Science simulations can be used to analyze student design artifacts and compute their distances to specific goals to detect whether students are zeroing in towards those goals or going astray. For example, the energy cost of a building or the output of a solar farm under design can be calculated and compared with a given goal. Students can run these simulations at any time to request such feedback to guide their design. This type of feedback facilitates an intimate coupling between scientific inquiry and engineering design: Searching for a design solution becomes an active process of inquiry as students ask what-if questions about their own designs and are quickly informed by the feedback from simulations (see also Figure 1 in the next section). This coupling can thus spur design iteration along the direction of science learning. In addition, this type of feedback is personalized and adaptive by nature as it is based on analyzing each individual student's work step by step.

With these features, SmartCAD will be able to provide fine-grained, science-based feedback to guide *every student* in the classroom, creating a new driving force for engineering design that supplements curricular scaffolding, teacher instruction, and student discussion. The box to the right describes a scenario of this.

How feedback in SmartCAD may help students and teachers. Students may simply cover the roof of a house with solar panels without considering their orientation to the Sun in four seasons—a mistake that may stem from their partial knowledge in everyday life that solar panels are installed on the roof. The typical intervention by a teacher is to keep reminding students to pay attention to orientation, but to provide specific feedback to each student, the teacher must know the exact orientation of the house and the shape of the roof under design. This instructional function can be offloaded to SmartCAD. By analyzing the outputs of all the solar panels based on simulations, SmartCAD will provide visual feedback (e.g., graph or coloring) to highlight that some of the solar panels do not produce as much as others (due to incorrect orientation or shade). This allows the teacher to steer student learning to a more inquiry-based direction: She can advise students to run a simulation, make their own judgments based on the feedback, revise their designs by moving the solar panels or the house, and then run a simulation again to check if their designs have been improved. Looping between design and inquiry, students come to an understanding of the importance of solar orientation—not only for a single solar panel, but also for the entire house.

Goal and Objectives

The goal of this project is to explore the educational value of science simulations for guiding secondary students through complex, authentic engineering design assisted by the envisioned SmartCAD in classrooms. The **research hypothesis** is that appropriate applications of science simulations to guide student design will result in three learning outcomes: 1) **Science knowledge gains** as indicated by a deeper understanding of the involved science concepts and their integration at the completion of a design project; 2) **Design competency gains** as indicated by the increase of iterations, informed design decisions, and systems thinking over time; and 3) **Design performance improvements** as indicated by a greater chance to succeed in designing a product that meets all the criteria and constraints within a given period of time. While measuring these outcomes, we will also probe two **research questions**: 1) **Feedback types**: What types of feedback from simulations to students are effective in helping them attain the outcomes?; and 2) **Feedback conditions**: Under what conditions do these types of feedback help students attain the outcomes?

As any learning technology must integrate with good pedagogy to be effective, we will situate this research in the **Learning by Design** (LBD) Framework (Kolodner et al., 2003) by extensively applying SmartCAD to the LBD cycle as illustrated in Figure 1. Research will test the hypothesis and answer the questions in the LBD context. Although LBD has a focus on science learning, it has all the elements essential to helping students develop engineering design thinking (Dym, Agogino, Eris, Frey, & Leifer, 2005). These elements will be further enhanced by SmartCAD.

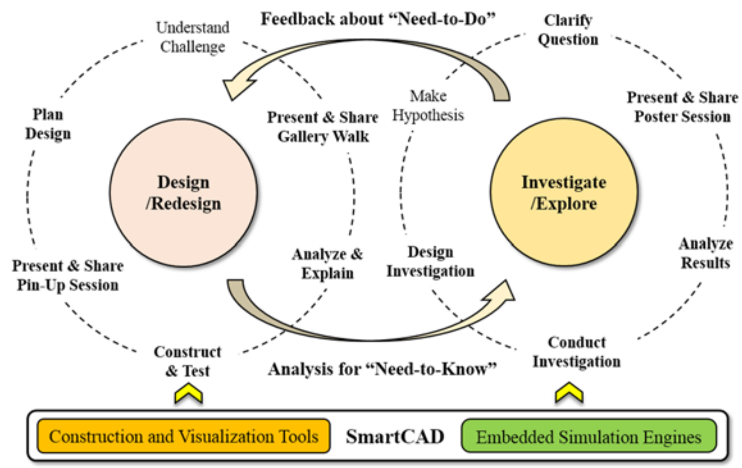
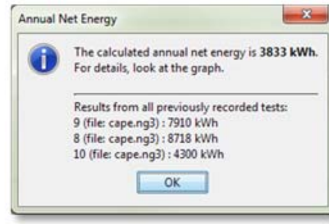


Figure 1. An illustration of using SmartCAD to couple the design (left) and inquiry (right) loops of the LBD cycle with rapid feedback from science simulations capable of analyzing student design artifacts.

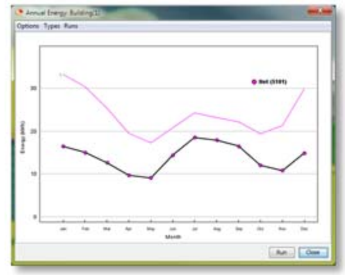
A partnership of researchers and developers from the Concord Consortium (CC) (Charles Xie, Saeid Nourian, and Jie Chao), Purdue University (Alejandra Magana and Brenda Capobianco), and the University of Virginia (UVA) (Jennifer Chiu and Larry Richards), in collaboration with Clive Dym and Janet Kolodner as consultants and Stephanie Adams of Virginia Tech, Chris Rogers of Tufts, Valerie Shute of Florida State University, Cary Sneider of Portland State University, and Larry Weathers of Arlington High School as members of an external Critical Review Committee, will carry out this project. The CC team has created successful STEM software that have benefited over a million learners and is developing data mining tools for engineering assessment. The Purdue team has developed Indiana's first design-based approach to increasing grade 3-6 student learning of science. The UVA team has created K-12 design activities with technology-enhanced scaffolding and digital fabrication. Dym and Kolodner will bring their combined expertise in structural analysis, artificial intelligence, engineering design, and engineering education to this project. As the success of SmartCAD will depend on the synergy of research and development, all the partners will collaborate closely to ensure that the development will support the research and the research will inform the development. The objectives of this project are:

- **Develop and integrate simulation engines to bridge the gap between design and science**. We will create a set of powerful, yet efficient, simulation engines for performing **mechanical**, **thermal**, and **solar** analyses of the built environment to support secondary school science and engineering. These engines will be seamlessly integrated into a CAD tool that has been designed for K-12 students. They will empower students to analyze any design that they create with the CAD tool. They will deliver *visual* simulations of a variety of topics in civil and energy engineering. These topics will be connected to disciplinary core ideas and crosscutting concepts required by the Next Generation Science Standards (NGSS), such as those related to seasons (ESS1), energy (PS3), forces and interactions (PS2), and renewable energy sources (ESS3). Details are provided in the Technology Development Plan.
- **Develop three design challenges and their supporting curriculum materials**. Although SmartCAD will be a generic tool for solving a broad range of engineering problems, this project will select three authentic design challenges, **Solar Farms**, **Green Homes**, and **Quake-Proof Bridges**, as the research testbeds. A curriculum module will be developed to support each challenge following the LBD principles. Details are provided in the Curriculum Development Plan.
- **Develop formative feedback based on simulation analysis**. In general, feedback for guiding open-ended design is difficult to prescribe because of the unpredictability of students' design paths. To avoid this uncertainty, SmartCAD will focus on the feedback that can be generated by analyzing student artifacts using science simulations. We will explore the **type**, **format**, **detail**, and **condition** of feedback about student designs that can be constructed from simulations to orient the design process towards a

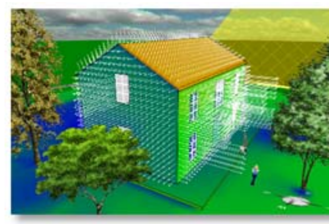
more scientific end. Feedback will be communicated to students in forms such as numbers, graphs, and visualizations (Figure 2), supplemented by hyperlinks to a related glossary or simplified simulations that explain science or engineering concepts (not shown in Figure 2). An advantage of graphic feedback is that it can deliver complex messages more effectively than raw data or words (i.e., a picture is worth a thousand words). Feedback in these forms will require that students interpret them correctly—a basic STEM skill that the supporting curriculum will cover. This requirement will likely reduce the chance of students creating a design that meets the specs through "gaming the system" (Baker et al., 2008) without learning. To further individualize these feedback, SmartCAD will "stealthily" (Shute & Ventura, 2013) keep track of student actions, artifacts, and trajectories and use all this information to contextualize feedback. For example, in a design project with the goal to minimize the annual energy usage of a house, feedback that reports the energy cost can be presented along with the previous results to show the trend (Figure 2a). If seasonal details are needed, the current and previous results of the monthly energy costs can be juxtaposed in a line graph to provide comparative feedback (Figure 2b). The scientific origins of these differences, i.e., solar radiation and heat transfer, can be visualized on the surface of the house using representations such as heat maps or vectors (Figure 2c). Note that, although we emphasize feedback related to science, SmartCAD will also provide feedback on non-science criteria included in the specs, such as budget, for full support of design.



(a) Feedback as numbers



(b) Feedback as graphs



(c) Feedback as visualizations.

Figure 2: Three types and levels of feedback using the thermal analysis of a house as an example. (a) Feedback of the annual energy cost as a number (like a game score); (b) Feedback of the monthly breakdown of the energy cost as a 2D graph; (c) Feedback of heat flux and heat map for a selected day, revealing the details of heat transfer and solar radiation on the building envelope, as a 3D visualization.

- **Provide professional development**. In Years 1-2, we will work with six pilot teachers in Indiana, Massachusetts, and Virginia to iteratively design and test the SmartCAD materials. In Years 3-4, we will offer a three-day workshop to 10-15 additional teachers in the summer of each year. At these workshops, we will introduce the project, explain the goal, demonstrate the technologies, discuss the pedagogies, and share earlier results and experiences from the pilot teachers. Teachers will learn about the curriculum modules, the SmartCAD software, the LBD pedagogy, and the assessments. In addition, technical supports will be provided during their initial classroom implementations.
- **Conduct design-based research**. We will adopt the Design-Based Research Framework (The Design-Based Research Collective, 2003) to develop the SmartCAD software and materials. The six pilot teachers will serve as the co-designers who will participate in this process. The research will use the following instruments to measure the effectiveness of SmartCAD: 1) Students' gains of science knowledge and design competency will be measured using pre/post-tests created using the Knowledge Integration Framework (e.g., Lee, Liu, & Linn, 2011; Liu, Lee, & Linn, 2011) extended to engineering assessment, currently being developed at UVA; 2) Students' design behaviors—for example, how they switch back and forth between the LBD design and inquiry loops (Figure 1)—will be characterized by analyzing the fine-grained process data of their actions, artifacts, and notes logged by SmartCAD behind the scenes using the process analytics being developed at CC (more on this in the next paragraph); and 3) students' performance improvements over time will be measured by computing the distances of their designs to all the specified goals as a function of time.
- **Support design-based research with process analytics**. Process analytics is a type of learning analytics that focuses on finding patterns and relationships from the fine-grained learner data logged by a learning technology, with the goal of understanding what learner-technology interaction is responsible

for a learning outcome (Xie, Zhang, Nourian, Pallant, & Bailey, 2014; Xie, Zhang, Nourian, Pallant, & Hazzard, 2014). Process analytics in this research will be used to 1) provide a "high-resolution lens" for viewing into the details of a learning process and 2) investigate the two research questions on feedback using data mining techniques such as association rule mining (e.g., Romero, Ventura, Pechenizkiy, & Baker, 2010) to identify the correlation between formative feedback and summative outcomes. For example, to what extent can a gain in understanding the concept of heat capacity measured by pre/post-tests be attributed to the student's decision process of choosing a floor that has a higher heat capacity for storing solar energy to release at night? Details are provided in the Research Plan.

- **Disseminate results**. All SmartCAD software and materials will be freely available online. SmartCAD will be integrated into UVA's **Engineering Teaching Kits** developed by Co-PI Richards to support some of the design challenges. We will partner with Purdue's **Discovery Learning Research Center**, directed by Co-PI Capobianco, to provide SmartCAD workshops to hundreds of teachers supported by the center. Research findings will be disseminated through journal publications and conference presentations. Design principles distilled in this project will inform the field of how design and simulation can be coupled to simultaneously promote science and engineering learning.
- **Evaluate the project**. A Critical Review Committee consisting of researchers and practitioners introduced earlier will oversee and evaluate this project, as described in the Project Evaluation Plan.

Although SmartCAD aims to address many issues in secondary engineering education, it is **not intended** to replace the teachers' role, but rather will help them successfully integrate engineering design into science classrooms and exploit the pedagogical advantages of design-based learning.

RATIONALE

The importance of CAD software to engineering education is equivalent to that of modeling and simulation to science education. In science education, simulations of science phenomena have been widely used to support inquiry learning (e.g., Honey & Hilton, 2011; Landriscina, 2013; Wieman, Adams, & Perkins, 2008; Wilensky & Reisman, 2006; Xie et al., 2011). In engineering education, modern CAD software that computerize a large part of engineering design have the potential to support design learning at a comparable level and scale. Such CAD tools allow students to take on a design challenge without regard to the expense, hazard, and scale of the challenge. They provide viable platforms for teaching and learning engineering design, because a significant part of design thinking is abstract and generic, can be learned through designing computer models that work in cyberspace, and is transferable to real-world situations. Modern CAD tools also offer many affordances that facilitate design. For example, CAD tools present a clear view of design and support easy modification and versioning that are critical to iteration. Analogous to spell check in word processors, intelligent CAD tools can automatically inspect designers' work, detect problems, and suggest solutions in real time. With 3D printers, students can easily translate their CAD designs into physical models. Current research on artificial intelligence and computational design will even empower CAD tools to spur creativity (Cheok & Nee, 1997; Hayes, Goel, Tumer, Agogino, & Regli, 2011; Jin & Li, 2007; Menges & Ahlquist, 2011; Woodbury & Burrow, 2006). Engineering education should leverage these enormous advantages and opportunities.

Figure 3: Sample original architectural designs by high school students from scratch using Energy3D (upper); Assembled model buildings from Energy3D print-outs (lower).

The majority of CAD tools currently used in schools were not designed to accomplish K-12 education goals. Software such as AutoCAD, SketchUp, and SolidWorks are design tools, *not* design learning tools. Their focus on product design may even impact design learning in such negative ways as premature fixation (Brown, 2009; Robertson & Radcliffe, 2009). As most of those tools are proprietary, it is difficult to embed educational supports such as logging and feedback in them. With prior NSF support, we have created a CAD program, Energy3D (Figure 3), to provide researchers an open-source platform to rethink how computer-based design can foster STEM learning in ways unimaginable before. A remarkable feature of Energy3D is its short learning curve for sketching up a complex building. In our pilot tests with more than 200 high school students, everyone mastered the basics of the tool within 15 minutes and teachers reported an exceptionally high degree of student engagement (not surprising given that, to the students, the CAD tool was similar to a design game like Minecraft). Based on this initial success, we will use Energy3D as an example to demonstrate how a CAD tool can be transformed into a powerful learning platform.

Instructional scaffolding is necessary for guiding students through complex engineering design. While various scaffolding strategies such as distributed scaffolding (Puntambekar & Kolodner, 2005) and Web-based WISEngineering (Chiu et al., 2013; Chiu & Linn, 2011) have been developed, scaffolding design with formative feedback is underexplored. Compared with static scaffolding that gives students instruction before they take a design action, formative feedback attempts to modify students' design and learning courses by providing corrective suggestions based on analyzing the design actions that they have taken. As such, **formative feedback provides a powerful mechanism that supports students to learn from mistakes and failures**. The envisaged SmartCAD resonates with the formative feedback guidelines synthesized by Critical Review Committee member Dr. Shute from about 180 publications, as outlined in Table 1 (while not tailor-made for engineering design, these guidelines nonetheless provide an excellent baseline).

Table 1. Formative feedback guidelines to enhance learning through engineering design.

Prescriptions (Shute, 2008)	SmartCAD design principles
"Focus feedback on the task, not the learner."	The change of the performance of an artifact due to a task in SmartCAD can be computed by analyzing the artifact before and after the task. SmartCAD can then create feedback based on this change.
"Present elaborated feedback in manageable units."	Engineering design consists of many design steps. Science simulations involve multiple layers of knowledge. In SmartCAD, these steps and layers can provide natural units based on which "bite-sized" feedback can be created to divide and conquer a cognitive barrier.
"Keep feedback as simple as possible but no simpler."	Feedback can use graphs and visualizations constructed from simulations to convey complex messages.
"Reduce uncertainty between performance and goals."	Feedback in SmartCAD can reduce the uncertainty between understanding and performance as they require students to truly understand their scientific meanings in order to advance towards the design goals.
"Give unbiased, objective feedback."	Feedback in SmartCAD is computed using science simulations, which are based on unbiased, objective scientific laws (e.g., F=ma).
"Promote a learning goal orientation via feedback."	Feedback can be linked to goals in the design specifications or target specific science concepts and engineering principles.
"Provide feedback after learners have attempted a solution."	In SmartCAD, the solution to each problem cannot be exactly known without analyzing the specific situation with a simulation. This nature of design in SmartCAD requires students to attempt a solution first and then use the feedback to evaluate it quantitatively.

BROADER IMPACTS

Considering the ubiquity of CAD software in the workplace and their diffusion into precollege classrooms, this research will provide timely results that could motivate the development of an entire genre of CAD-based learning environments and materials to accelerate and scale up K-12 engineering education. This genre can also introduce students to the concept and practice of virtual prototyping—a cost-effective engineering method based on CAD and analysis that engineers use to develop products entirely on the computer before making physical prototypes. Importantly, this genre can increase the participation of underrepresented populations in engineering as a recent study has suggested that authentic engineering design supported by a simulation game can "increase women's motivation to persist in engineering" (Arastoopour, Chesler, & Shaffer, 2014). To cash-strapped schools, the open-source SmartCAD will provide a zero-cost alternative to expensive commercial software or hardware that only benefit a small fraction of privileged students (see also Adams' letter). To ensure that all schools can run SmartCAD on their increasingly diverse computers, a cross-platform JavaScript version of SmartCAD will also be developed simultaneously.

TECHNOLOGY DEVELOPMENT PLAN

The technology development in SmartCAD consists of two main parts: 1) developing its simulation capability of analyzing student artifacts and 2) developing its feedback capability of informing students with the simulation results to guide their design and learning. Simply put, the first part aims at "getting the science right" whereas the second part aims at "getting the instruction right."

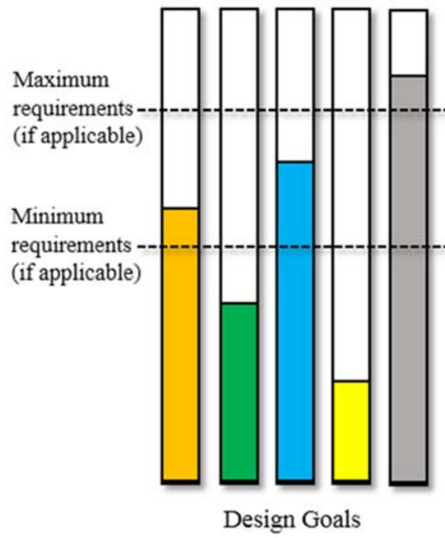
Building the Scientific Simulation Capability of SmartCAD

The vision of SmartCAD rests on the ability of the embedded simulation engines to visualize science concepts and provide rapid feedback. Although many engineering analysis tools such as finite element analysis may be too computationally expensive for SmartCAD, there are approximations that run fast enough to provide satisfactory results for educational purposes (especially when parallelized to run on GPUs). For this research to have broad implications, we will develop three such engines for SmartCAD that will empower students to solve a wide range of engineering problems. These engines are described as follows:

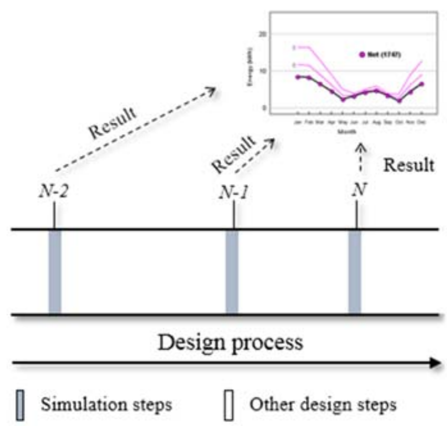
- **The Solar Simulation Engine**. This engine will compute the energy received by any surface at any location of the Earth from the Sun at any time of the year. Engineering applications will include solar ovens, solar photovoltaics, solar thermal power, and solar architecture. This engine will divide a surface of a shape into a grid of small cells. To calculate the light energy that shines on each cell, the engine will rotate the simulated Sun in a 24-hour cycle along its path relative to the location. A ray from the Sun to the center of each cell will be emitted every few minutes of the simulated time. If the ray hits any object before reaching the cell, its energy will not be absorbed by the cell. Otherwise, a certain part of its energy will be absorbed, transmitted, or reflected by the cell, depending on its optical properties. For the engine to accurately model the reality, effects such as the scattering and absorption of sunlight in the atmosphere and the diffuse reflection from the ground objects will be incorporated (Wong & Chow, 2001). Climate data from the National Oceanic and Atmospheric Administration will provide inputs of weather parameters such as sky clearness and precipitation. We will ensure that the predicted results of monthly insolation on surfaces with different tilt angles at locations across the country agree with sensor data collected by the U.S. Department of Energy. Accuracy with this geographic diversity is essential as it will support students anywhere in the country to design for a location near them.
- **The Building Simulation Engine**. This engine will model the energy production, flow, usage, and control of a building. Engineering applications include passive solar technologies, wind power, geothermal power, HVAC systems, energy-efficient buildings, and smart homes. This engine views the entire building under design as a network of interconnected nodes, each representing a building element such as a wall, a window, an air conditioner, and a solar panel or an external input such as air temperature, ground temperature, and wind speed (Clarke, 2001; Malkawi & Augenbroe, 2004). These nodes interact with one another through the exchange of energy and fluid, the rate of which is determined by thermostats, fans, ducts, relative humidity, dew point, outdoor climate, infiltration, and other mechanisms that can cause temperature, concentration, or pressure gradients. The dynamics of the building is then simulated by solving the group of differential equations that link all these variables together, subject to the conservation of energy and mass and the requirements to maintain indoor conditions. The total energy consumption is computed by summing up the inputs. Like the Solar Simulation Engine, this engine will also provide local climate data to support students' designs for their regions.

- **The Mechanical Simulation Engine**. This engine will model the effects of static and dynamic loads on the strength, stiffness, and stability of structures such as buildings and bridges. Engineering applications will include space frames, architectural structures, and quake- or hurricane-proof structures. A solid structure in SmartCAD will be approximated as a simplified nodal framework with interconnected nodes representing key interaction points of elements such as studs, posts, struts, trusses, beams, and columns. SmartCAD will ensure that these elements can be easily added, removed, displaced, or modified by students and any revision will automatically update the underlying nodal network. Virtual work principles (e.g., the Dummy Load method) or energy methods (e.g., the Castigliano Theorems) (Dym, 2005) will be used to calculate the forces and displacements at each node. Based on these results, students will evaluate whether a design meets the safety requirements under the specified test conditions.

The development of these engines is essential because, as a general design principle, SmartCAD must **be able to analyze the change of system performance due to the manipulation of a single design element in order to generate feedback to address learning at such a granular level**, at which foundational science and engineering design ultimately meet. However, this is *not* to say that SmartCAD will require students to learn the sophisticated science involved in creating these engines. As in a real-world experiment, a SmartCAD simulation will allow students to learn the underlying science through interaction. For example, the basic ideas of conduction and insulation can be elucidated using an interactive thermal simulation of a house without invoking the differential form of Fourier's Law of Thermal Conduction (Xie, 2012).



(a) Goal-directed feedback



(b) Stepwise feedback

Figure 4: (a) A dashboard that provides goal-directed feedback based on multiple criteria. For example, the budget, size, and total energy usage of a house can be shown on a dashboard so that students can see how well their designs meet the specs right away. (b) A graph that displays the differences in students' simulation results from step to step as feedback. For example, the monthly energy usages calculated in the last three simulations can be shown in a graph so that students can see from the trend that their design choices only affect the energy usages in the winter, triggering them to think about why.

Designing Automatic Feedback in SmartCAD

Feedback types for directing or facilitating design learning. Research shows that elaborated feedback is more effective than verification feedback (Lipnevich & Smith, 2009; Shute, 2008), suggesting that a summative assessment to rate a design would be insufficient to support learning. To create elaborated feedback, SmartCAD will automatically log all student design actions and simulation results. The types of feedback that can be constructed from these data include, but are not limited to, **goal-directed feedback** and **stepwise feedback**. Goal-directed feedback tells students the "distance" to a design goal. Stepwise feedback, on the other hand, provides information at each simulation step, utilizing data across multiple steps to compute changes and provide results for students to self-assess their improvements. In terms of **timing** and **frequency**, goal-directed feedback will be provided through a dashboard that students can access any time, whereas stepwise feedback will be provided only when students run a simulation. These two types are schematically illustrated in Figure 4.

Feedback forms for delivering different types of information. Student data produced in simulations and logged by SmartCAD can be organized and presented in basic forms such as numbers, graphs, and visualizations. Similar to game scores, numbers can be aligned with design goals to inform students how much has been accomplished. When the description of the current design requires many numbers, the message can be better conveyed through a graph. When the feedback involves even more data specific to the components of the system under design, a complex visualization may need to be constructed to render the details on top of the components to explicitly reveal the linkages between science ideas and design artifacts. Feedback in these forms can thus support the learning of different levels of knowledge (see Figure 2 for examples).

Feedback elaboration. To further help students connect science and design, basic feedback can be augmented with hyperlinks to related science and engineering concepts explained by: 1) Simplified simulations provided by **a repository of configurable exploratory simulations**—similar to those inserted into the LBD cycle to bridge the design-science gap (Vattam & Kolodner, 2008)—that illustrate how the concepts work under the current design condition and 2) text provided by **a built-in glossary** when no related simulation is available or a gentle reminder is needed. For example, a graph of 12-month heat flux through a wall can contain links to the glossary of related concepts such as temperature gradient, heat flux, thermal conductivity, and Fourier's Law. Or it can contain a link to a visual simulation that shows how the heat transferred through a wall depends on the temperature gradient, the thermal conductivity, and the wall thickness. This configurable simulation can use the parameters from the current design situation, such as the current indoor and outdoor temperatures, as inputs to further foster the contextual linkage. Hyperlinks can lead to an expanded view within the feedback display or a pop-up window.

CURRICULUM DEVELOPMENT PLAN

We will iteratively develop three curriculum modules targeting physical science or engineering classes in middle or high school (these materials may also be applicable to Earth science and technology classes). Each module will explain the design challenge, the science and engineering principles involved, and how SmartCAD can be used to solve typical problems students will encounter (with examples). It will contain a clear specification of design criteria and constraints. Each module will scaffold a design challenge with the LBD cycle shown in Figure 1 and will also: 1) require each student (or each group) to design at least three different solutions and summarize their pros and cons; 2) align the design challenge with the "three-dimensional learning" defined in NGSS, especially the engineering standards ETS1; 3) suggest strategies for combining SmartCAD with social interactions such as teacher-led brainstorming, student discussion, and classroom presentation to enhance learning (e.g., students demonstrate in front of the whole class with real-time simulations on a projector about how their designs meet the specs); 4) include assessment items for measuring the targeted outcomes; and 5) provide an implementation guide for teachers. Each module will take 6-8 hours to complete. The three design challenges are outlined below:

- **Solar Farm Design**. Students will design a solar farm consisting of an array of photovoltaic panels or reflection mirrors within a specified land area at a location near their schools. The goal is to maximize the annual electricity output so that it can power a certain number of households. To meet the goal, students can even design a solar tracker for each photovoltaic panel or reflection mirror. An optional challenge is that the solar farm must be able to provide electricity at night. Design elements include tilt angles, Fresnel reflectors, terrain quality, site layout, power tower, and energy storage. Science concepts include the Sun path, solar radiation, seasons, geometric optics, projection effect, and Beer's Law.
- **Green Home Design**. Students will design a house of specified square footage, height, and style that can be constructed under a budget at a location near their schools. The goal is to minimize the annual energy usage. Students will evaluate if their designs meet two levels of energy independence: 1) the house harvests more energy than it consumes throughout the year; and 2) the house harvests and stores sufficient energy to power itself all the time so that it can be taken off the grid. Design elements include walls, roofs, windows, insulation, solar panels, geothermal heat pumps, wind turbines, batteries, and HVAC systems. Science concepts include the Sun path, seasons, solar radiation, heat capacity, heat transfer, renewable energy sources, and energy conversion.

- **Quake-Proof Bridge Design**. Students will design a bridge that spans a given length and path over a given type of riverbed or seafloor. The goal is to allow the safe passage of a vehicle that weighs up to 100 tons (static load) and to withstand an earthquake of up to 8.0 magnitude (dynamic load). An optional challenge is that it must be safe for a 100-ton vehicle to pass even when an 8.0 earthquake strikes (combined load). These criteria can be evaluated by examining whether the stresses at the joints and pilings are within the safety limits of the selected types of safety reinforcements such as bearings, shock absorbers, or shear links. Students can choose, configure, and test a number of structure types such as a beam bridge, a truss bridge, an arch bridge, a suspension bridge, or a cable-stayed bridge. Design elements include various bridge parts, the geological conditions of the foundation, the static load from self-weight, and the dynamic load from traffic, wind, or an earthquake. Science concepts include seismic waves, gravity, force, balance, impact, elasticity, and plasticity.

RESEARCH PLAN

Our design-based research will study not only student learning outcomes from SmartCAD with regard to science learning, design competency, and design performance, but also the types and conditions of feedback that can lead to those outcomes. Research will also shed light on how SmartCAD can be integrated with established pedagogical models such as LBD to enhance science and engineering learning.

Research Design and Timeline

Over the four project years, more than 2,000 students from socioeconomically diverse schools in Indiana, Massachusetts, and Virginia, listed below, will participate in this project (see the attached teacher letters).

Table 2. At least 2,000 students from the following schools or districts will participate in this project.

School	Contact Teacher	# Students/year	Minority	Lunch Aid
Arlington MS+HS (MA)	Larry Weathers	100	16%	10%
Southwestern MS (IN)	Karen Shuman	300	20%	36%
Charlottesville MS+HS (VA)	Matt Shields	200	58%	53%
Lowell HS (MA)	Roger Morneau	100	59%	58%
Revere HS (MA)	Joshua Miranda	100	56%	71%

Depending on the classroom settings and the availability of computers, students will work either individually or collaboratively. The research data under these two different conditions will be analyzed separately.

This research is planned as follows:

- **Years 1-2:** To serve as a baseline, in Year 1 we will develop a version of each module with only feedback to verify a design (e.g., whether the designed bridge will support a weight). **This baseline is comparable to feedback from a typical physical test**. In collaboration with the pilot teachers, we will test these baseline versions with a small number of students to understand the kinds of feedback needed to be implemented within SmartCAD through analyzing the data collected from classrooms (described in the next section). Findings from these data will guide us to develop feedback in SmartCAD appropriate for students. For example, if we find that teachers need to frequently explain a science concept to help students understand the purpose of a design task, we will ensure that SmartCAD can capture that need and then design feedback to address it. In this way, **each upgrade of SmartCAD will incorporate a set of new instructional functions learned from the previous iteration**. As we integrate more instructional support into SmartCAD, we will investigate how new feedback may change teacher guidance and student interactions. We will then analyze these newly emerged interactions and develop new feedback mechanisms to support them in later versions of SmartCAD.
- **Years 2-4**: We will explore **under what conditions and for what students each type of feedback will be effective**. For example, feedback about a science concept may be critically important at the beginning of a design project because students either do not fully understand the concept or do not

understand its engineering implication. As students learn more about it and become more expert at designing with it, the expertise reversal effect (Homer & Plass, 2010; Kalyuga, 2007) may occur. We will develop strategies for curbing this kind of effect. For instance, SmartCAD will allow students to choose which feedback should be collapsed or expanded on the feedback display.

- **Years 3-4:** Student learning with the more powerful versions of SmartCAD in these years will be compared with the data from the baseline versions in Years 1-2 to provide a summative evaluation. To scale up the research, 10-15 new teachers will be recruited to join the six pilot teachers. We will compare both within and across teachers to understand the effects of new features added to SmartCAD as well as effects of teacher familiarity with SmartCAD materials. Hypotheses generated for successful feedback conditions will also be tested in these new classrooms. Considering that teachers may use SmartCAD twice a year to teach different topics and each teacher may use the materials at a different time, we will be specific about versioning, time, and teacher when processing student data.

Data Sources and Instruments

This research will collect the following types of data using instruments that will be iteratively calibrated through the planned design-based research:

- **Pre/post-tests.** We will take advantage of integrated science and engineering assessments under development at UVA based on the Evidence-Centered Design model (Mislevy & Haertel, 2006) and the NGSS standards, as well as previous research at secondary and college levels (e.g., Asunda & Hill, 2007; Kelley & Wicklein, 2009). The open-ended items extend knowledge integration (KI) items (Lee et al., 2011; Linn, Lee, Tinker, Husic, & Chiu, 2006; Liu et al., 2011) to capture individual ideas as well as their connections. KI aligns well with engineering design as design can be considered as a process of knowledge integration in which multiple items in the specifications must be accommodated within a scientific framework and guided by engineering principles to develop an optimal solution. KI assessments capture just the kind of systems thinking (Kali, Orion, & Eylon, 2003) and interdisciplinary thinking (Shen, Liu, & Sung, 2014) that SmartCAD will promote. To strike a balance between instructional sensitivity and transfer of learning, these items will represent an appropriate range of proximity to the original learning context. Item validation will consist of backward translation and construct and content validity review. Piloting and interviews will provide evidence of alignment between constructs and actual performance. Item analysis will ensure basic effectiveness and generalizability theory will determine variability and interactions associated with items and raters.
- **Process data.** Intermediate and final design artifacts, student actions, simulation results, time on tasks, and other process data will be automatically collected by SmartCAD (Figure 5). These process

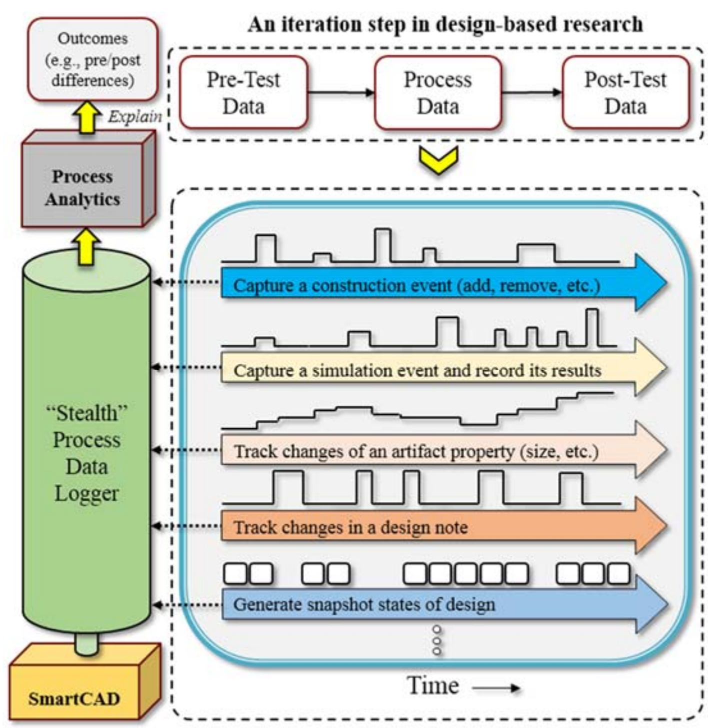


Figure 5. This illustration shows how SmartCAD will capture and track a complete design process and how process analytics based on mining these process data can be integrated in design-based research to help researchers identify and improve key interactions responsible for a learning outcome.

data, combined with other data such as pre/post-tests, will be used to answer the research questions about feedback types and conditions (more on this in the next section). Student design performance will be gauged from the logged simulation results of final artifacts, contextualized with those for intermediate artifacts to construct a trajectory of how students reach the design goals.

- **Embedded assessments**. SmartCAD will embed widgets for students to take notes, record simulation results, and write reports at different stages of the LBD cycle (Figure 1). Students will be required to document their rationales and explain their design choices at each major step. Students will write final reports to describe how their designs meet the specifications and how their designs are influenced by the feedback from simulations. In the final report, they will be asked to conceive a plan to accomplish a better design if they were to redo the project. These data will complement pre/post-tests to provide evidence of how students construct science and design knowledge and develop systems thinking throughout design processes. Coding and rubrics for embedded items will mirror pre/post-test items.
- **Classroom observations, participant interviews, and case studies**. Classroom observations will be used to capture usability issues, student engagement, distribution of teaching resources, and instructional needs reflected in student-teacher and student-student interactions. Student/teacher interviews will be used to 1) reconstruct learning and teaching processes through participants' retrospective self-reporting and 2) explore participants' subjective experiences learning or teaching with SmartCAD.
- **Participant information**. We will use NAEP's student questionnaire for science (NAEP, n.d.) to gather demographic and domain-specific academic information of students. A few additional questions will be added to inquire about students' experiences in engineering, simulation, and CAD. A similar questionnaire will be used to collect teachers' information as well.

Data Analysis

Comparison of learning outcomes across different versions of SmartCAD. To address the research hypothesis about the three learning outcomes, we will compare student data in Years 3-4 to the baseline data in Year 1. For science knowledge gains, we will use regression models to compare students' gain scores between baseline and subsequent student cohorts, accounting for students' background knowledge, prior experiences, and teacher effects. For design competency gains, we will use similar techniques to process the related pre/post-test items as well as the performance indicators derived from process data and embedded assessments to capture iterative cycles, informed design decisions, and systems thinking. For design performance improvements characterized by how students accomplish multiple dependent or independent design goals defined in the specs, we will use multiple logistic regression, multivariate multiple linear regression, and ANCOVA to probe the data under different assumptions.

Process analytics to track feedback effects. Process analytics, being developed at CC, allow researchers to look into what happens in every student's learning process to 1) **identify key factors that may lead to certain learning outcomes** and 2) **characterize students' responses to different types of feedback under different conditions**. Figure 6 illustrates how process analytics may track the effects of feedback. Student activities in SmartCAD involve complex interactions among feedback, science ideas,

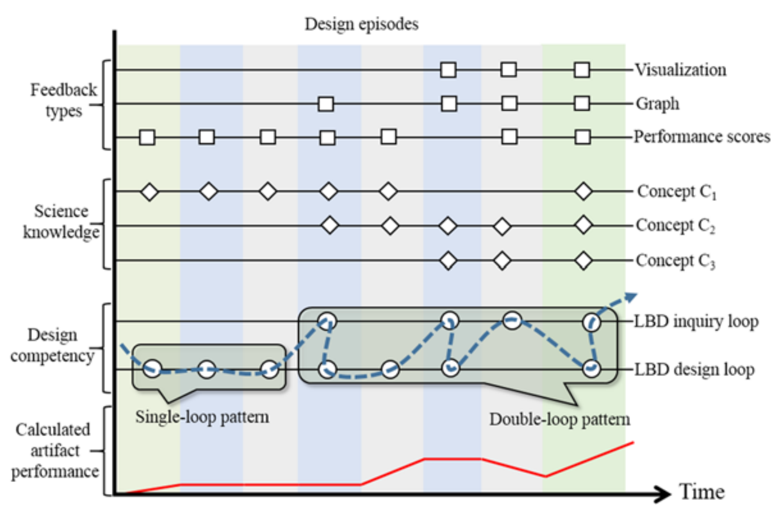


Figure 6. A view of process data for analyzing the correlations between feedback types and indicators that link to three learning outcomes in terms of science knowledge, design competency, and performance.

design tasks, and artifacts. All these interactions can be captured by SmartCAD: 1) Students' interaction with a science concept can be represented by a change of parameter related to that concept; 2) The degree of informed design can be represented by the frequency of students moving between the LBD loops of inquiry and design; 3) Students' design performance can be represented by the performance of their design artifacts computed using science simulations; and 4) The effect of feedback on students can be represented by the relevance of their subsequent actions. Using these data, we will explore questions such as 1) Will students be more likely to stay only in the LBD design loop (Figure 6) if just given simple feedback based on performance scores?; 2) Which types of feedback will foster informed design indicated by the double-loop pattern in Figure 6?; and 3) How does student prior or current knowledge (captured by pre-tests and embedded asssements or logged by SmartCAD) influence the effectiveness of feedback? To triangulate and validate the findings to these questions, we will analyze students' design notes, classroom observations, and follow-up interviews to provide complementary views.

Project Evaluation Plan

The Critical Review Committee will evaluate this project. Each year, the committee members will attend a two-day annual on-site meeting with project staff and spend another three additional days working with staff remotely on formative evaluation and feedback throughout each project year. The evaluation will focus on five questions: 1) To what extent has the project accomplished the SmartCAD research and development goals?; 2) To what extent has the project found evidence of learning improvements due to SmartCAD?; 3) How effectively does the project support teachers?; 4) How is the scientific integrity and technical quality of the SmartCAD materials?; and 5) How has the project created broader impacts? At the beginning of the project, the committee will work with project staff to develop a benchmarked set of project performance indicators based on these questions and a data protocol that specifies what data should be collected and how. Arranged into a rubric, the performance indicators will provide clear criteria for project success (summative evaluation) and benchmarks used throughout the four project years to show how the project qualitatively and quantitatively improves its performance (formative evaluation). As the majority of the evaluation data will be a subset of the research data, project staff will prepare and analyze these data for the committee to review based on the performance benchmark and the data protocol. The committee and project staff will resolve any issue in data interpretation and analysis methods. Based on the analysis results, the committee will compile an annual evaluation report, to be included in the project's annual report submitted to NSF. The report will also include recommendations for improvements.

Prior Support

This proposal is based on many prior or current projects of the PIs, Co-PIs, and consultants. Due to limitations of space, we can only select the most relevant ones to report here:

Enhancing Engineering Education with Computational Thinking (DRL-0918449, $2,191,552, 10/2009-9/2013, PIs: Xie & Chiesa). **Summary of results**: This project developed two engineering software tools, Energy2D and Energy3D, and the Engineering Energy Efficiency Curriculum that they support. **Intellectual merit and broader impacts**: This project demonstrated how computer models and simulations can be used to infuse science into hands-on engineering activities. The software products have been used by nearly 100,000 learners. **Publications**: Seven peer-reviewed journal papers (including a cover and a featured paper), one book chapter, and five conference presentations (including a keynote).

Large-Scale Research on Engineering Design Based on Big Learner Data Logged by a CAD Tool (DUE-1348530, $999,921, 10/2013-9/2018, PIs: Xie & Nourian). **Summary of results**: This project is developing cutting-edge process analytics for tracking and assessing learning in engineering design supported by Energy3D. **Intellectual merit and broader impacts**: This project spearheads a highly scalable "big data" approach that aims to reveal temporal and statistical patterns about how secondary students learn through engineering design. **Publications**: Four peer-reviewed journal papers (one under review).

SLED: Science Learning through Engineering Design (SLED) Targeted Math Science Partnership (DRL-0962840, $6,793,800, 9/2011-8/2017; PIs: Panitch & Capobianco). **Summary of results**: SLED has involved over 20 STEM faculty with over 100 teachers and 2,000 students in Indiana. It has developed a new teacher induction program and an interactive repository of best practices with over 20 classroom-tested curricular resources and assessments. Gains in student learning range from 37% to 53% measured in science and engineering assessments. **Intellectual merit and broader impacts**: SLED has successfully extended research to test hypotheses of whether authentic engineering learning tasks are more likely to hold the attention and interest of students, lead to deeper levels of science achievement, and advance teacher understanding of engineering practice. **Publications**: Nine peer-reviewed journal publications, six manuscripts under review, two book chapters, and 13 conference paper presentations/proceedings.

RIGEE: Integrating Computation into the Materials Science and Engineering Core (EEC-1137006, $150,000, 10/01/2011-09/30/2014, PI: Falk, Co-PI: Magana). This project developed computational learning modules that were permanently adopted into six materials science and engineering courses at Johns Hopkins University. **Intellectual merit and broader impacts**: This project increased understanding of the ways in which integrating computation into core engineering curricula can lead to improved acquisition, application, and retention of disciplinary concepts. **Publications**: Three peer-reviewed journal papers.

CAREER: Scaffolding Engineering Design to Develop Integrated STEM Understanding with WISEngineering (DRL-1253523, $513,283, 6/2013-5/2018, PI: Chiu) and **WISEngineering: Revolutionizing Education through Engineering Design** (EDUCAUSE, $249,453, 2011-2012, PIs: Burghardt & Chiu). **Summary of results**: These projects have developed and refined WISEngineering, an online learning environment that scaffolds engineering design for secondary students. Middle school students have used WISEngineering projects that incorporate simulations and CAD tools separately to learn science and math concepts. **Intellectual merit and broader impacts**: These projects study how cyberlearning technologies can help students learn science and math subjects through engineering as well as research how students develop design thinking. **Publications**: One peer-reviewed journal paper, three book chapters, six published conference proceedings, and seven conference presentations.

PERSONNEL

Senior Staff at the Concord Consortium

Dr. Charles Xie, senior scientist, will serve as the PI at CC. He has 15 years of research and development experience in STEM education. He has authored more than ten refereed journal papers related to educational research and created several science and engineering simulation tools that have helped more than a million students. Charles holds a Ph.D. in materials science and engineering from the University of Science and Technology, Beijing. **Dr. Saeid Nourian**, senior research scientist, will serve as the Co-PI at CC. A main developer of Energy3D, he has conducted cutting-edge research in 3D graphics, haptic interface, and other virtual reality technologies. Saeid holds a Ph.D. in computer science from the University of Ottawa. **Dr. Jie Chao** will serve as a senior educational researcher. She has led multiple research projects on how innovative learning technologies can enhance conceptual understanding in science and engineering. Jie holds a Ph.D. in Instructional Technology in STEM education from UVA.

Senior Staff at Purdue University

Dr. Alejandra Magana, Assistant Professor in the Department of Computer and Information Technology and Engineering Education, will serve as the PI at Purdue. She conducts research on computation for problem solving and design. She holds a Ph.D. in Engineering Education from Purdue. **Dr. Brenda Capobianco**, the Interim Director of Purdue's Discovery Learning Research Center and an Associate Professor of Science Education and Engineering Education, will serve as a Co-PI. Her research focuses on K-12 science teachers' attempts at integrating engineering design and how this impacts students' science learning. She holds an Ed. D. from University of Massachusetts Amherst.

Senior Staff at the University of Virginia:

Dr. Jennifer Chiu, Assistant Professor in the Curry School of Education, will serve as the PI at UVA. Jennifer's research examines how to scaffold engineering design to help students learn STEM concepts in K-12 settings as well as how to help teachers implement engineering projects in science classrooms. Jennifer holds a Ph.D. in science education from the University of California, Berkeley. **Dr. Larry Richards**, Professor in the Department of Mechanical and Aerospace Engineering, will serve as Co-PI at UVA. He is an ASEE fellow and has brought Engineering Teaching Kits (ETKs) into middle school science and math classes for over ten years. These ETKs introduce an engineering design approach to problem solving.

Senior Consultants

Dr. Clive Dym is Professor Emeritus of Engineering at Harvey Mudd College. His primary interests are in engineering design and applied mechanics. He received a Ph.D. from Stanford. He has authored 19 books and 96 refereed journal articles. A Fellow of ASCE, ASEE, and ASME, he received many awards including the prestigious Gordon Prize from the National Academy of Engineering in 2012. **Dr. Janet Kolodner** is Professor Emeritus of Computing and Cognitive Science at Georgia Tech. She pioneered research on case-based reasoning and design-based learning. She is the founding Editor of Journal of the Learning Sciences, a founder and first Executive Officer of the International Society for the Learning Sciences, and a fellow of the Association for the Advancement of Artificial Intelligence.

The External Critical Review Committee

Dr. Stephanie Adams is Professor and Head of the Department of Engineering Education at Virginia Tech. Her research includes effective teamwork, active learning, and diversity in engineering education. She will infuse her perspectives and insights of engineering education to this project. **Dr. Chris Rogers** is Professor in the Department of Mechanical Engineering at Tufts University. His research involves engineering design through robotic approaches to learning science and mathematics. His extensive experience in K-12 engineering education will be a great asset to this project. **Dr. Valerie Shute** is Professor of Education at Florida State University. She has conducted research related to assessment, cognitive diagnosis, and learning from advanced instructional systems. Her expertise and leadership in formative feedback will be extremely valuable to the success of this project. **Dr. Cary Sneider** is Associate Research Professor at Portland State University. He led the development of the NGSS engineering standards and has been involved in numerous efforts on K-12 engineering. He will ensure that the goal and implementation of this project will be aligned with the NGSS. **Larry Weathers** is Science Director at Arlington District. He has taught K-16 STEM subjects for over 40 years. A renowned educator, he has received a Presidential Citation from the White House for Excellence in Science Teaching and has been inducted into the Massachusetts Teaching Hall of Fame. He will ensure that the SmartCAD materials are pedagogically sound and applicable in classrooms.

Collaboration Plan

The CC team will lead the development whereas the Purdue and UVA teams will co-lead the research. All three teams will conduct design-based research in their states throughout the project. Dr. Kolodner will provide inputs to the overall research and development and ensure an appropriate integration of SmartCAD and LBD. Dr. Dym will provide expertise in structural engineering and ensure that SmartCAD will meet the important need to help secondary students develop engineering design thinking while learning science. The three teams and consultants will have regular teleconferences throughout the project. To manage and share the complex research data among the partners, CC will provide a powerful data server based on a software version control system to support collaborative processing, archiving, and analysis of student data produced in the planned iterations of design-based research.

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