Science and Engineering Education for Infrastructure Transformation (SEEIT)

Importance

The Report Card for America's Infrastructure (American Society of Civil Engineers, 2013) gives it an overall rating of D+ and estimates that $3.6 trillion of investment would be needed to revamp it by 2020. Building a sustainable and resilient infrastructure, however, requires a STEM-proficient workforce. As the workplace becomes increasingly reliant on technology, new workers need different skills than their predecessors. The current education pipeline is viewed by many as inadequate to meet workforce demands (e.g., National Research Council, 2013, p. 6), resulting in an unemployment rate among youth that is three times the average of all age groups (Wyman, 2015). To mitigate this problem, the inspiration and preparation of future workforce must begin in K-12 (The President's Council of Advisors on Science and Technology, 2010).

As Forbes reported (Wyman, 2015), there is a new movement to redesign American high schools so students graduate with both job-ready technical skills and strong academic skills. Authentic learning that involves developing and using both sets of skills to solve real-world problems and create impacts outside the classroom is a key to this reform. As students often perceive the learning topics that are more closely related to their lives and future as important, authentic learning can be more engaging (Lombardi, 2007; Strobel, Wang, Weber, & Dyehouse, 2013). Furthermore, there is also evidence that authenticity can increase girls' participation in STEM activities (e.g., Arastoopour, Chesler, & Shaffer, 2014; Riedinger & Taylor, 2016).

Infrastructure affects every student, irrespective of gender, race, or address. The need to improve infrastructure provides meaningful contexts, personal relevance, and other triggers of interest for *all* students to learn STEM. By situating learning at solving infrastructure problems in an authentic way, STEM education in high school—the final phase of formal education for many underprivileged students—can simultaneously accomplish its two major missions: developing a STEM-literate citizenry and developing a STEM-proficient workforce (National Research Council, 2012). Engineering education, an increasingly important part of K-12 education (National Research Council, 2009, 2012; NGSS Lead States, 2013), represents a viable pathway to deliver this promise. The demand for STEM-proficient workers to rebuild America's infrastructure, expected to rise in the foreseeable future, provides a strong rationale and opportunity to strengthen engineering education in high school—an area that has been relatively underdeveloped compared to its counterparts in elementary and middle schools (Householder & Hailey, 2012, p. 2). This project will demonstrate how problems in infrastructure engineering can be turned into opportunities for authentic learning, contributing thereby to forging a school-to-work transition model (Krumboltz & Worthington, 1999; Rogers & Creed, 2000) that serves both the citizenry and workforce goals of STEM education.

Goals

Future sustainable and resilient infrastructure is expected to be powered by renewable energy, be able to respond intelligently to changes in the environment, and support smart and connected communities (Ebsworth-Goold, 2016; Moreno & Stern, 2016; National Science Foundation, n.d.; Royal Academy of Engineering, 2012). In accordance with this vision, the Concord Consortium (CC) and Purdue University will collaborate in this project to conduct research and development on engineering education with the overarching goal to inspire and prepare high school students for meeting the challenge of building tomorrow's infrastructure through working on authentic problems in today's infrastructure around them.

The **goal of development** is to create innovative educational technologies and curriculum materials to support project-based constructionist learning (Papert, 1991) of science, engineering, and computation concepts and skills underlying the strategically important "smart" and "green" aspects of the infrastructure through design-based research (The Design-Based Research Collective, 2003). The technologies will include two innovations: 1) The **Smart High School** is an engineering platform for designing Internet of Things (IoT)[1] systems for managing the resources, space, and processes of a school based on real-time analysis of data collected by various sensors deployed by students on campus; and 2) the **Virtual Solar World** is a computational modeling platform for students to design, deploy, and connect virtual solar power solutions for their homes, schools, and regions (Figure 1). These technologies are transformative in that they have the potential to turn the entire campus of a school or a geographical information system such as Google Earth into an engineering laboratory with virtually unlimited opportunities for learning and exploration. The challenges to solve authentic problems in the infrastructure with these technologies will engender the need and provide pathways to learn and practice science, engineering, and computation in an integrated way, rather than in isolation (National Research Council, 2014).

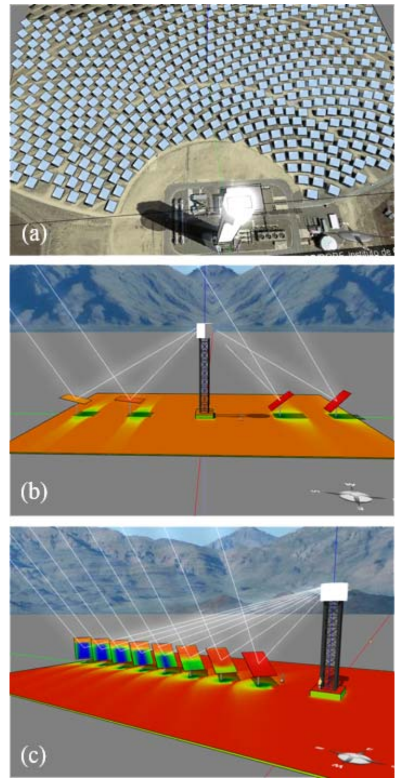

Figure 1. Solar power plants represent an increasingly important part of the electric grid. A 2 GW, $5 billion concentrated solar power (CSP) plant currently under construction in Nevada will produce electricity roughly equal to the output of the Hoover Dam and create thousands of jobs (Kraemer, 2016). The dynamic visualization of the related science concepts can lead to the understanding of engineering principles for designing CSP plants. (a) A CAD model of a CSP plant such as the PS20 that consists of 1,255 mirrored heliostats can be deployed to the Virtual Solar World. (b) A color visualization of the cosine efficiency explains why heliostats are installed only to the north of the power tower in PS20. (c) A color visualization of shadowing and blocking illustrates how they affect the output of each heliostat in an array.

The **goal of research** is to identify technology-enhanced instructional strategies that can simultaneously foster the growth of skills and self-efficacy in scientific reasoning (Zimmerman, 2000), design thinking (Dym et al., 2005), and computational thinking (Wing, 2006), *all* of which are needed to build a smart and green infrastructure. Mechanisms for integrating these skills already exist partially in current education practices. For example, IoT systems use sensors to collect data from the real world and analyze them in real time to provide inputs for making intelligent decisions. The widespread use of sensors in science education to support inquiry (Tinker, 2000) makes it logical to extend learning from science to engineering or computation using IoT as a compelling context. Throughout this project, approximately **2,000 high school students** with diverse socioeconomic backgrounds from rural, suburban, and urban schools in Indiana, Massachusetts, New Hampshire, and Ohio will participate in the research. A rich set of formative and summative data will be collected from these students for probing into the following **three research questions**: 1) To what extent does the integrated learning model help students develop and connect scientific reasoning, design thinking, and computational thinking skills?; 2) To what extent is students' interest in cognate careers affected by the authenticity of engineering design challenges?; and 3) How do the variations in the solutions to overcome the cognitive and practical difficulties of real-world problems impact learning outcomes and career interest?

EXPERTISE

Our team is uniquely qualified to develop the envisioned innovations and conduct the proposed research. **CC is a leading innovator in educational technology** that has produced numerous free digital resources

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1 The Internet of Things (IoT) is the worldwide network of interconnected cyber-physical objects that can collect and communicate data. Each thing is uniquely identifiable through its embedded computing system but is able to interoperate within the existing Internet backbone. IoT technologies promise to bring unprecedented safety, efficiency, reliability, and economic benefits to the infrastructure in the 21st century (Lohr, 2009; Stephenson, 2016).

in STEM for millions of students. PI Xie has a track record of developing and researching cutting-edge technologies that successfully support K-16 science and engineering education. These technologies include, but are not limited to: 1) an augmented reality technology that situates virtual simulations with perceptual anchors through sensors so that abstract science concepts can be visually and audibly enacted in the real world (Xie, 2012a, 2013); 2) infrared thermography for physical and chemical applications recognized by DOE (U.S. Department of Energy, 2016), InfraMation (Xie, 2012c), and *Journal of Chemical Education* (Jacobsen & Slocum, 2011); and 3) physics-based energy simulation software (Xie, 2012b) that have over 50,000 users. A hallmark of our technologies is their applicability to solving real-world problems. For example, *eight* research papers that used our Energy2D software to simulate natural phenomena and engineering problems have been published by scientists worldwide in the past two years, indicating high acceptance of our work by the science community and our capacity to create authentic engineering software. Meanwhile, we have also been spearheading data-intensive research on engineering education (Chao et al., 2016; Xie, Zhang, Nourian, Pallant, & Bailey, 2014; Xie, Zhang, Nourian, Pallant, & Hazzard, 2014). The Visual Process Analytics, a cloud-based process mining platform for visualizing and analyzing complex design dynamics, has been in ongoing development (Xie, 2014, 2015). The Results from Prior NSF Support section provides further details. The CC team will lead the research and development of this project.

The School of Engineering Education and **the Energy Center** at **Purdue University** provide resources and incentives to promote continuous engagement of K-12 teachers and students in STEM-related energy topics of power generation, transmission, energy efficiency, and research frontiers. Purdue has launched the Duke Energy Academy, managed by Co-PI Sharma, to inspire students and teachers in energy sciences and engineering. Co-PI Purzer has a track record in research on engineering education (Purzer, 2011; Purzer & Fila, 2013; Purzer et al., 2015; Purzer, Myers, & Duncan-Wiles, 2012). The Purdue team will lead the teacher professional development efforts and contribute also to the research and assessment on engineering design in this project.

The CC-Purdue collaborative will be **reinforced by a partnership with industry**. Borrego Solar is the third largest company in the U.S. commercial solar market, focusing on large-scale solar solutions. CLEAResult is the largest provider of energy efficiency programs and services in North America, covering smart and connected building technologies. They will provide technical assistance and consultation to ensure that this project produces technologies and materials that conform to industry standards and teach employability skills. In addition, a six-member Advisory Board consisting of engineers, educators, and researchers will oversee and evaluate the project.

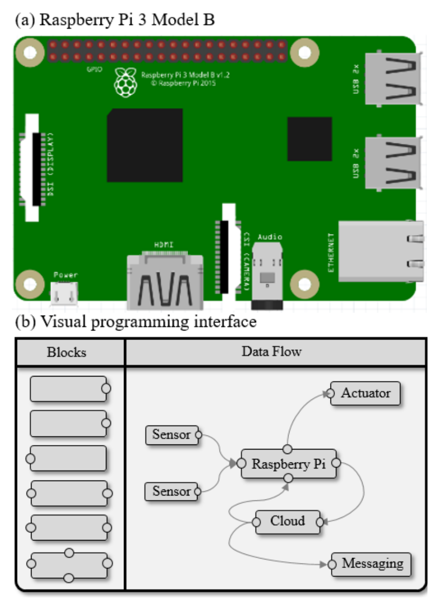


Figure 2. (a) The $35 Raspberry Pi 3 Model B released in 2016 is an incredible credit card-sized computer powered by a 1.2GHz 64-bit quad-core CPU. With built-in Wi-Fi and Bluetooth capabilities, it provides a versatile platform to support the design and implementation of IoT applications. (b) The Smart High School IoT platform will provide a visual drag-and-drop programming interface for system design and integration based on sensors and actuators connected to the Raspberry Pi and cloud services for data persistence, analysis, and exchange.

WORK PLANS

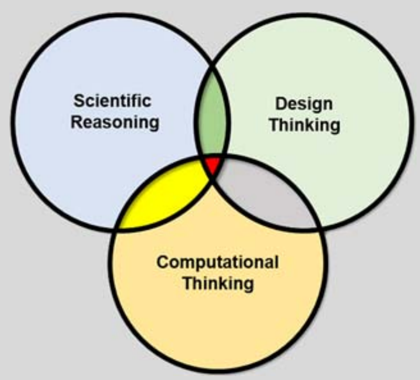
This project will accomplish its research and development goals through the following plans:

- **Develop the Smart High School IoT platform to turn a campus into an engineering laboratory**. Based on the low-cost Raspberry Pi ecosystem, this platform (Figure 2) will empower students to design IoT applications that can manage the resources, space, and processes in their schools with functional modules such as sensors, actuators, data stores, data analyzers, and Web services, similar to what IoT technologies can accomplish for other types of infrastructure (Lohr, 2009). This cyber-physical platform will comprise an IoT hardware kit and a visual programming environment. Abstracting away the functions, variables, and idiosyncratic syntax rules of the underlying code, the programming environment will present an intuitive drag-and-drop interface for designing IoT systems out of building blocks that represent the constituent functional modules and the logic that connects them in order to perform specific system functions. This environment will allow students to prototype concepts rapidly, encouraging iteration, experimentation, and systems thinking that are essential to practicing engineering design. Students will deploy their IoT systems on campus to test how their designs can improve their own infrastructure, such as saving energy for their schools or showing the availability of their parking space in real time. Designing IoT systems provides a unique opportunity of engineering education because IoT is not only a crucial part of electrical engineering and information technology, but it is also one of the few ways through which computer programming can be directly linked to scientific inquiry and engineering design in the material world (Box 1). The vision of IoT-enabled smart infrastructure (Stephenson, 2016) perfectly illustrates the combined power of science, engineering, and computation. The Research and Development Design section provides a roadmap to attain this objective.

- **Develop the Virtual Solar World simulation platform to turn Google Earth into an engineering laboratory**. Based on physics principles (e.g., solar radiation, optics, and heat transfer), geographical information (from Google Earth), and meteorological data (National Renewable Energy Laboratory, n.d.), this platform will empower students to design and simulate various solar energy solutions for their homes, schools, and regions. As is in the case of the Smart High School, the Virtual Solar World will also support integrated STEM learning (Box 2), but in a cyberworld powered by Google Maps and computational modeling. Students will deploy their completed designs to a virtual electric grid, overlaid onto Google Maps, that generates virtual electricity, connects student work, and simulates power distribution on an ongoing, autonomous basis. Allowing students to store and publish their virtual solar power designs online and displaying the generated virtual electricity on an Internet scoreboard, which shows the results from others, may spur them to revisit their designs later for further improvement and deeper learning. This online collection and network of student projects, which will provide experiences similar to a gallery walk, is important as constructionism suggests that sharing creation processes and produced artifacts can motivate students to learn (Papert, 1991). The Research and Development Design section provides a roadmap to achieve this objective.
- **Develop six curriculum units to support project-based learning with technologies**. Based on the two innovations

Box 1: Integrated STEM learning on the Smart High School IoT platform

Designing an IoT system provides plenty of opportunities to learn science, engineering, and computation practices in an integrated fashion. Working with sensors allows students to learn the science behind them through inquiry. For example, to calibrate an IoT system, students must understand what specific variables the sensor data represent scientifically. They must analyze the data to explore in what ranges the variables are supposed to vary in different scenarios in order to determine which type of response should be triggered, to what, and when. The acquired knowledge is then applied to the design of an IoT system, which requires engineering design thinking to make trade-off decisions, optimize system performance, and achieve cost effectiveness. Finally, the control, response, and integration of the entire system are realized through computer programming that deals with all foreseeable complexities.



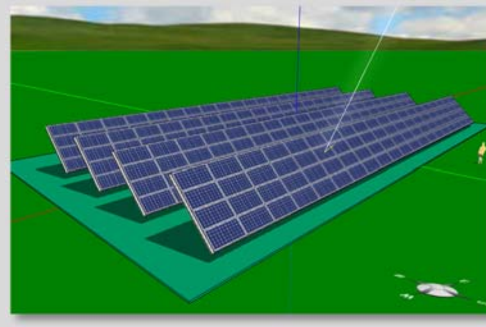
The overlaps among three basic skills—scientific reasoning, design thinking, and computational thinking—supported by the IoT platform provide researchers an opportunity to study their integration.

described above, we will develop a set of standards-aligned curriculum units to guide student learning through designing engineering solutions for improving infrastructure. Each unit will require 4-8 hours to complete, covering the disciplinary core ideas, crosscutting concepts, and science/engineering/computation practices needed to solve the design challenges (NGSS Lead States, 2013). Three of these units, *Save Energy for Your School*, *Manage Space Utilization*, and *Track the Crowd*, will be based on the Smart High School platform. The other three, *Solarize Your Home*, *Solarize Your School*, and *Solarize Your Town*, will be based on the Virtual Solar World platform. The development of these units will be guided by existing instructional design principles such as four-component instructional design (4C/ID) for teaching complex skills (van Merriënboer, 1997) and concreteness fading for reducing complexity (Fyfe, McNeil, Son, & Goldstone, 2014). Considering that some of these existing instructional models may not have been applied extensively to scaffold authentic engineering design challenges, the adoption will be adjusted considering the distinctive nature of engineering design. Concreteness fading in the context of engineering design, for example, represents a possible simplification method that gradually reduces a concrete engineering problem into representations of abstract concepts. A practical example is that, while designing an IoT system, a sensor module packed with electronic components can be represented by a building block in a visual programming environment with its other hardware details irrelevant to the functionality of transmitting data to a controller temporarily omitted ("faded away"). By allowing students to see the connection between the sensor and the controller through such a simplification, the abstract concepts of data link and data flow become clear.

- **Support socioeconomically and geographically diverse schools in four states**. To ensure that our final products and research findings will benefit all students in the long run, this project will work with a diverse student population from rural, suburban, and urban areas in Indiana, Massachusetts, New Hampshire, and Ohio. Box 3 describes a possible scenario in which this project can help under-resourced schools reduce their energy costs and therefore motivate their participation. We also recognize that rural areas represent one of the greatest, yet underexplored, opportunities for STEM education to impact workforce development (e.g., Boynton, Carrico, Paretti, & Matusovich, 2013; Carnegie Science Center, 2014). The rural perspective is crucial because rural areas have not yet been a major focus of STEM education but they nonetheless need support to succeed in STEM education and infrastructure transformation. Preparing students in rural schools with strong leading-edge STEM skills is as important as preparing those in suburban and urban schools with the same skill sets. By partnering with organizations such as the Indiana Small and Rural Schools Association and the Duke Energy Academy, this project will reach out to many rural students and teachers.

Box 2: Integrated STEM learning on the Virtual Solar World simulation platform

The Virtual Solar World will support integrated learning of science, engineering, and computation in the cyberspace.



For instance, when designing a photovoltaic solar farm, students must first learn solar science in order to understand the design constraints. For example, the rows of solar panels cannot be too close to one another as the inter-row shadowing reduces the total output, but they cannot be too far away from one another, either, as a longer distance between rows decreases the efficiency of land use. Determining the optimal inter-row spacing for the solar farm under design requires some computational thinking, as the question depends on a number of confounding factors such as the location, time of year, and shape of the site that complicate the problem to the point that it can only be solved through computation. In fact, this is related to the research frontier of *computational design* that is dedicated to solving complex design problems with computational thinking and methods (Menges & Ahlquist, 2011).

By setting the stage of engineering activities on campus and computer—rather than in advanced laboratories, this project will promote equity. To ensure fair access to resources for all participants, regardless of where they live, we will provide free IoT kits, software tools, curriculum materials, and technical support.

- **Collaborate with teachers to implement curriculum units and collect research data**. Many high school science teachers have enthusiastically responded to our request for collaboration (see a list of them in Table 1). Some teachers also welcome the unique opportunities provided by this project to integrate computational thinking into their teaching. Recognizing that science teachers are often inadequately prepared for teaching engineering, especially with authentic engineering design challenges, we will provide free professional development workshops and webinars before each round of classroom implementation. These workshops and webinars will familiarize teachers with the technologies and materials, as well as the data collection protocols and procedures needed to conduct the research. Teachers' feedback before and after classroom implementations will also be used to guide iterative design of technologies and materials. The goal of professional development and teacher collaboration is to help teachers build expertise and confidence in adopting the project technologies and materials in their classrooms.
- **Conduct research and evaluation**. This study will be based on analyzing formative and summative data collected from approximately 2,000 high school students in diverse settings using a variety of instruments and techniques. The formative data will come from students' process data logged by the software, their design journals, and other embedded assessments. The summative data will come from students' final reports and design artifacts. Researchers at CC and Purdue will collaborate to develop analytics and rubrics to glean student performance and learning from these data. Additional data will be collected using surveys, observations, and interviews for cross validation and contextualization. Subjects for observations and interviews will be selected from diverse settings to ensure broad applicability of results. A six-member Advisory Board will oversee and evaluate this project, as described in "Mechanisms to Assess Success of the Project."

Box 3: How can this project potentially benefit cash-strapped schools?

Energy costs are second only to salaries in K-12 school budgets, totaling $8 billion annually (U.S. Environmental Protection Agency, 2011). An estimated $2 billion could be saved by improving energy efficiency in K-12 schools. For schools in underserved communities, this saving may be a significant relief to their financial stress. This project will empower students to design IoT solutions to monitor the energy usage of their schools and use data to promote energy efficiency awareness and encourage energy saving behaviors. Students can also explore how to take advantage of solar power options to offset the energy costs as well. For small rural schools, ground-mounted solar farms may be a viable option. Although these activities may not yield immediate results, they will inform and inspire a large body of students who may become changemakers over time.

The dissemination plan is discussed in a separate section later. The approximate **timeline** of this four-year project is as follows: From 2017 to 2019, we will focus on developing technologies, curriculum materials, and assessments; from 2019 to 2021, we will focus on research and dissemination.

Broader Impacts

The authentic learning opportunities to be created by this project can contribute to workforce development in the strategically important areas of IoT technology and renewable energy. The focus on infrastructure transformation is aligned with NSF's vision of smart and connected communities. Although this project will use the context of smart and green infrastructure to engage students to solve real-world problems, the scientific reasoning, design thinking, and computational thinking skills that they will acquire through meeting the challenges of this project can be transferrable to other topics and fields. The inclusion of a large student population from rural, suburban, and urban schools in four states in the research will shed light on how educational innovations can foster science and engineering learning to meet diverse needs.

Research and Development Design

The HS-ETS1 performance expectations of the Next Generation Science Standards (NGSS) require every high school student to learn how to design engineering solutions to complex real-world problems. Effective engineering education should not only help students acquire a deeper understanding of science concepts and processes, but it must also empower students to demonstrate their understanding by designing developmentally appropriate engineering systems that work in the real world.[2] This is a great challenge to students. From a cognitive point of view, the complexity of real-world problems can sometimes impede the development of conceptual understanding with overshadowing perceptual information and excessive cognitive loads (e.g., Goldstone & Son, 2005; Sloutsky, Kaminski, & Heckler, 2005), which in turn undercuts the development of transferrable problem solving skills. Hence, part of the difficulty for developing effective and meaningful engineering design challenges is to know where to strike a balance between what is feasible in the classroom and what engineers do in the workplace. This project hypothesizes that the difficulty can be overcome by using technologies and curricula that reduce the complexity of real-world engineering problems. These technological and curricular supports include, but are not limited to: 1) **Visualization of science concepts** to allow students to see science at work in real-world scenarios through techniques such as concreteness fading (Fyfe et al., 2014), 2) **decomposition of complex systems** to enable students to carry out simplified tasks at various modular levels (which conforms to NGSS HS-ETS1-2) through scaffolding (Puntambekar & Kolodner, 2005; van Merriënboer, 1997), and 3) **facilitation of task transition** to help students connect science, engineering, and computation with integrated software environments that minimize tool-switching and data-sharing efforts.

By situating engineering design challenges in the context of building a smart and green infrastructure and empowering students to solve them with authentic technologies, this project will increase students' interest in cognate STEM careers as the technology experiences allow them to learn how to design valuable engineering systems to improve their own infrastructures and thereby truly appreciate the real-world value of STEM skills. This hypothesis is well grounded in literature. According to the Social Cognitive Career Theory (Lent, Brown, & Hackett, 1994; Lent, Lopez, Lopez, & Sheu, 2008), career interest is influenced by self-efficacy, outcome expectations, and personal goals. For students to become interested in STEM careers, learning experiences should be designed to promote their self-efficacy and outcome expectations in the related STEM practices. For instance, to increase their self-efficacy, an authentic task in a complex design challenge should be broken down to flexible subtasks that are within their zones of proximal development at each step (without compromising the open-ended, creative nature of engineering).

Research Participants

Over the course of the project, a total of 2,000 students from socioeconomically diverse schools in Indiana, Massachusetts, New Hampshire, and Ohio, listed below, will participate in this study.

Table 1. The following high schools in four states will participate in this project (data from high-schools.com).

School	State	Type	Teacher	Minority	Lunch Aid
Arlington HS	MA	Urban	Larry Weathers	21%	12%
Athens HS	OH	Rural	Eric Miller	14%	41%
Blackford HS	IN	Rural	Brigham French	3%	46%

[2] This is reflected by the subtle difference between "learning through design" and "learning to design." The former is often billed as a pedagogy for teaching science using design as a strategy (the focus is on science education). Examples include design-based science learning (Fortus et al., 2005) and learning by design (Kolodner et al., 2003). The latter often refers to engineering design in which science is treated as an important driving force or constraint in the quest of designing a functioning product or process (the focus is on engineering education). As design is based on science and should be informed by science, the two learning models have significant overlaps.

Boston Latin School	MA	Urban	Cate Arnold	52%	30%
Everett HS	MA	Urban	Anna Seiders	59%	69%
Farmington HS	NH	Rural	Stephen Pascucci	2%	42%
Haverhill HS	MA	Suburban	Edward Roberts	33%	51%
Kennett HS	NH	Rural	Scott Lajoie	3%	37%
Medford HS	MA	Urban	Curtis Tuden	41%	28%
Pembroke Academy	NH	Rural	Dan Morris	5%	22%
Providence HS	IN	Rural	Laura Swessel	6%	-
Riverside HS	OH	Rural	Kirsten Haury	8%	11%
South Vermillion HS	IN	Rural	Kim Terry	3%	42%
Stevens HS	NH	Rural	Mellany Harrington	8%	38%

In addition, the Duke Energy Academy at Purdue has been collaborating with the Academy of Science & Entrepreneurship (Bloomington), Maconaquah High School (Bunker Hill), Mississinewa High School (Gas City), and South Adams Schools (Berne) in Indiana. These schools will also be included in this project. A total of $75,000 has been budgeted to allow the project to support teachers' participation of professional development workshops and webinars at CC and Purdue and to provide stipends for them to prepare for classroom implementations, facilitate data collection, and give formative feedback.

Data Sources and Instruments

The design-based research of this project will be guided, in part, by three research questions (RQs), repeated as follows: RQ1: To what extent does the integrated learning model help students develop and connect scientific reasoning, design thinking, and computational thinking skills? RQ2: To what extent is students' interest in cognate careers affected by the authenticity of engineering design challenges? RQ3: How do the variations in the solutions to overcome the cognitive and practical difficulties of real-world problems impact learning outcomes and career interest? The third question will drive this design-based research as the project will evolve with improved solutions over the project years and accumulate research data from different versions to address the question. To probe into RQ1 and RQ2, we will collect the following types of data using instruments that will be iteratively calibrated through the planned design-based research:

- **Pre/post-tests for knowledge, skills, and abilities.** To gauge the integrated learning of scientific reasoning, design thinking, and computational thinking (RQ1), we will use the Evidence-Centered Design (ECD) framework (Mislevy & Haertel, 2006) to design pre/post-test items that can capture individual knowledge, skill, and ability (KSA) in the three domains as well as their correlations. Scientific reasoning items will be based on existing frameworks such as multifaceted assessments (Liu, Lee, & Linn, 2010). Design thinking items will be based on Crismond and Adams's Informed Design Teaching and Learning Matrix (2012). Computational thinking items will be based on the frameworks of Brennan and Resnick (2012) and others (Grover & Pea, 2013). The Knowledge Integration (KI) framework (Chiu & Linn, 2011; Lee, Liu, & Linn, 2011; Linn et al., 2006; Liu, Lee, & Linn, 2011) will be used to guide the creation of the student model, the evidence model, and the task model of the ECD-based assessment of KSA integration across the three domains as the KI framework aligns well with the six curriculum units, in which multiple knowledge items must be accommodated within a conceptual framework and multiple skills must be used in a concerted way to design an optimal solution. For example, an assessment task that challenges students to devise a hypothetical IoT system to notify staff when a trash receptacle is full can measure students' ability to integrate science, engineering, and computation KSAs to solve the problem. In this scenario, they have to use science knowledge to determine what scientific effects may be used to measure the filling level of the receptacle, use engineering principles to design prototypes, and then use computational thinking to create a management system. KI assessments capture just the kind of systems thinking (Kali, Orion, & Eylon, 2003) and interdisciplinary thinking (Shen, Liu, & Sung, 2014) that this task reveals. 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 set in the curriculum units. Item validation will consist of backward translation as well as construct and content validity review. Piloting and interviews will also provide evidence of alignment between constructs and actual performance. Generalizability theory (Shavelson, Webb, & Rowley, 1989) will be used to determine variability and interactions associated with items and raters.

- **Pre/post-measures for self-efficacy**. As a single all-purpose scale for perceived efficacy does not exist (Bandura, 2006), multifaceted measures will be devised to gauge students' beliefs in their capabilities of succeeding in science, engineering, and computation tasks based on earlier work (e.g., Carberry, Lee, & Ohland, 2010; Ketelhut, 2007; Ramalingam & Wiedenbeck, 1998). These measures will also draw from Co-PI Purzer's work with undergraduate engineering students (Purzer, 2011). Analyzing the correlation among items in these measures will shed light on the extent to which the self-efficacy developed in one area affects the self-efficacy development in another. Analyzing the correlation between these inter-domain self-efficacy interaction results and the inter-domain KSA integration results will establish the degree to which the integration of domain practices supported by an intervention facilitates the crossover. The correlation between self-efficacy and authenticity is a key to study RQ2. To measure this correlation, we will provide an operationalizable definition of authenticity and describe a method for measuring authenticity variations in the "Data Analysis" subsection.
- **Process data.** The process data is defined as the collection of intermediate artifacts, student actions, sensor data, and other types of data automatically logged by the supporting software. The process data will also include embedded assessment items, which come from widgets embedded in the curriculum units for students to report progress, record results, and write reflective design journals (students will be required to document their rationales and explain their design choices at each major step). These process data will provide an in-depth, dynamic view about student learning. For instance, the intermediate artifacts can be used to reconstruct the trajectory through which students reach the final designs as a tool for performance assessment. Process data can also show the transition among the three core tasks of scientific reasoning, design thinking, and computational thinking, which will be useful to understand how these tasks can mutually drive or enhance one another (RQ1).

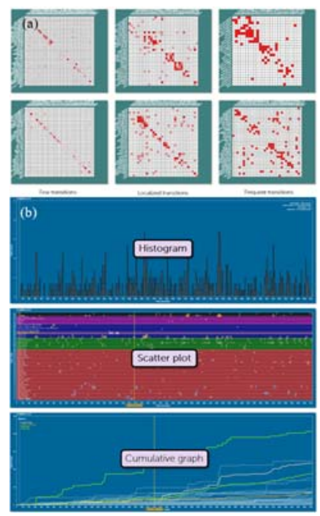


Figure 3. (a) A heat map analysis of task transitions in a design process (data collected from high school students). The left maps show few transitions, the middle ones show localized transitions, and the right ones show frequent transitions.(b) Three tools for analyzing the time series data. Histogram shows the total number of actions within each time bin. Scatter plot shows the number of actions of different types within each time bin. Cumulative graph shows the growth of the total number of actions of different types.

- **Final self-reports**. Students will write final reports to describe how their solutions meet the specifications of the design challenges. These data will complement pre/post-tests and process data to provide evidence of how students construct science and engineering knowledge and develop systems thinking and computational thinking skills through the design processes. Coding and rubrics for these student reports will use the same theoretical frameworks as the pre/post-test items.
- **Classroom observations and participant interviews**. Classroom observations will 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 of learning or teaching with project materials and technologies.
- **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' prior experiences in engineering, programming,

and computer science. A similar questionnaire will be used to collect teachers' information as well.

Data Analysis

KSA and self-efficacy measures will be examined to identify how individual pre/post results vary, how the results from different measures correlate, and how the authenticity of the project tools and materials contributes to self-efficacy changes. We will also take several steps to keep results statistically rigorous. KSA and self-efficacy changes as reflected in the measures will be analyzed through repeated measure ANOVA and ANCOVA. The interconnections and dynamics in students' learning and self-efficacy as reflected in the measures will be examined through multiple regression with and without lagged variables, as well as structural equation modeling for uncovering a map of construct interrelationships. For example, to test whether gains in computation KSAs are more attributable to a linkage in engineering gains or students' prior ability, we can use multiple regression with lagged variables to compare the explanatory power and significant relationships of a series of models. To analyze the effect of authenticity, we conceptualize that **authenticity arises from three levels**: 1) a real-world design problem that has realistic criteria and constraints, 2) a tool that enables students to solve the problem like a professional, and 3) a solution that is similar to a professional version to some extent. Through the planned design-based research, we will improve our technologies and materials iteratively across project years, resulting in several versions with different levels of tool and task authenticity. From these versions, the effects of authenticity variations on students' design solutions and self-efficacy changes will be examined through repeated measure ANOVA and ANCOVA, as well as multiple regression, to address RQ2. In terms of accountability, we will: 1) collect students' demographics, prior experiences, and teacher effects as control measures, 2) compute effect-size coefficients, such as Cohen's d (Sawilowsky, 2009), as a comparison metric for changes across measures, and 3) employ significance testing corrections, such as Bonferroni correction (Dunn, 1961), to reduce the risk of statistical inference errors from conducting multiple tests with the same data. Furthermore, the results from rural, suburban, and urban student cohorts will be compared to check whether the intervention has resulted in similar outcomes based on the measures across the three settings.

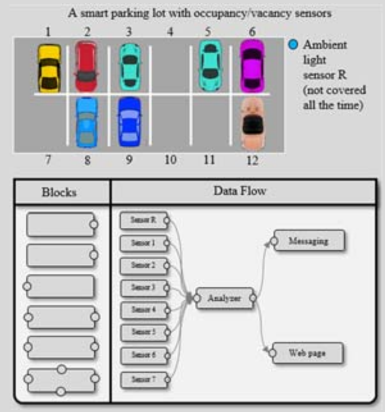
The Visual Process Analytics (VPA), being developed at CC (Xie, 2014, 2015), allows researchers to look into what happens in every student's learning process to characterize their behavior patterns over time. VPA will be used in this project to mine the process data. For example, the heat map analysis of VPA will be used to measure and visualize the transitions among science, engineering, and computation tasks (Figure 3a). Three descriptive tools in VPA, histogram, scatter plot, and cumulative graph (Figure 3b), will be used to characterize student design processes similar to Atman, Deibel, and Borgford-Parnell's work (2009) but with flexible controls of process granularity from fine-grained actions to domain-level tasks. Each type of visualization represents a different view of the data and a different aspect of the process. The results of VPA will be used to complement or explain the findings from the pre/post measures. Process analytics is also important to implement design-based research as it can be used to track the use of individual software or curricular features over time and examine the details of student interactions with those features.

The Smart High School IoT Platform and the Supported Curriculum Units

In a broad sense, the Smart High School IoT platform will allow students to design a "computational nervous system" for their own schools. **The hardware of the platform will be a low-cost IoT kit** that includes, but is not limited to, a Raspberry Pi 3 Model B as the hub (we prefer the Raspberry Pi over Arduino as the former provides more horsepower for on-board computing and data processing than the latter), a variety of sensors (e.g., photodetectors and thermometers) and actuators (e.g., buzzers and LED lights) supported by the Raspberry Pi, and other components such as batteries, breadboards, resistors, and wires. The wireless LAN of the Raspberry Pi 3 allows data collected by sensors to be posted to a HTTP server and actuators to be remotely controlled via the Internet. To support different levels of learning, the IoT kit will come with two configurations: Preassembled modules and customizable modules. The preassembled modules, which eliminate the need for students to design their own circuits and write their own Python code to connect sensors and actuators to the Raspberry Pi, can be used right out of the box. The customizable modules, on the other hand, will give students certain flexibilities in choosing sensors and actuators and in designing circuits to link them. In both cases, the goal is to provide students with an easy-to-use IoT interface to interact with the material world.

The software of the platform will be a cloud-based visual programming environment in which sensors, actuators, databases, analyzers, services, and other components, along with the code logic and flow controls, are represented by blocks and arrows that can be dragged, dropped, and snapped (Figure 2b). This software environment will be similar to MIT's Scratch in some ways, but will focus on IoT engineering rather than game programming. It will be written in JavaScript/HTML5 in order to run within a modern Web browser on a regular computer (*not* on the Raspberry Pi). When a request for connection from a Raspberry Pi device is received and authenticated by the environment, it will initiate the procedure to import the data links from all the sensors and actuators connected to the Raspberry Pi. Once the link is imported, a sensor will appear in the visual environment as an identifiable block with an output port, an actuator as an identifiable block with an input port, and a controller or analyzer as an identifiable block with both input and output ports. Such a visual diagram will be dynamically compiled into JavaScript code behind the scenes in order for it to run on the browser in which it is constructed.

Box 4: Engineering an IoT system through team working



Designing a smart parking lot provides opportunities for students to learn and collaborate. Each team can devise and deploy an occupancy sensor to a designated parking spot. All the sensors can then be made available to any participant when she designs her own IoT app using the visual interface. In this way, students can co-build a hardware infrastructure but still be independent in designing the software. For example, they can decide how to respond differently (e.g., tweet a message when a spot becomes available or update a Web page that displays current vacancies).

A smart school relies on many sensors and actuators placed at different locations inside and outside a building to continuously monitor various parameters and control various facilities. The "collaborative" nature of sensors and actuators in IoT networks lends itself to collaborative learning and team working (Box 4). Three units are planned for the Smart High School curriculum: **1) Save Energy for Your School**. Students use temperature sensors to monitor the temperature distribution in their school buildings and fluctuation over a period of time to detect any thermal anomalies or to find room for saving energy. They use light sensors to monitor lighting in classrooms. To discern human presence, they can use passive infrared sensors to detect thermal radiation from human bodies or motion sensors to track human activities. Data from these sensors can be used to design IoT systems that react to situations identified as energy waste conditions (e.g., the light is on for a long period of time while no one is in the room). The responses to energy waste can vary from triggering a buzzer to reporting the total amount of wasted energy on a dashboard and to sending a message to the custodian's phone (for safety and practical reasons, we do not expect students to control the lighting or HVAC systems of their schools—most responses will be limited to increasing awareness). **2) Manage Space Utilization**. Students use a light sensor on the ground to determine whether an outdoor parking spot is occupied based on the signal it reads relative to the ambient light. They use a passive infrared sensor mounted on the underside of a table to detect human thermal radiation in order to tell whether a seat in the library or computer lab is available. Vacancy information based on analyzing these sensor data can be displayed and updated on a Web page to help anyone find a spot. **3) Track the Crowd**. The combination of a digital camera and computer vision software can turn the Raspberry Pi into a versatile sensor for tracking objects and crowds (Jacques, Musse, & Jung, 2010; Zhao & Nevatia, 2004). Images from the camera can be processed within the Raspberry Pi and only the computed results will be transmitted to the cloud. The elimination of image upload reduces the use of bandwidth and removes the concern of privacy. Students can use this technology provided by the project to analyze the length of the waiting lines in a cafeteria or at a bus station. As IoT systems are engineering products, they should be developed through the complete process of engineering design including problem scoping, investigation, iteration, optimization, trade-off, test, evaluation, and troubleshooting (including debugging) to meet the specified criteria within constraints—as required by NGSS HS-ETS1-3. Note that, when designing an IoT system, students are subjected to the constraint of not only system costs, but also battery power of standalone sensors or actuators—a factor that will compel them to design efficient solutions. We will use the informed design framework (Burghardt & Hacker, 2004; Crismond & Adams, 2012) to guide our curriculum development.

The Virtual Solar World Simulation Platform and the Supported Curriculum Units

The Virtual Solar World simulation platform targets NGSS HS-ETS1-4 that requires high school students to "use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem." It will consist of two parts: a CAD program that empowers students to design solar power solutions and a cloud-based simulation program that virtually houses, connects, and operates their solutions. The relationship between these two programs is similar to that between SketchUp and Google Earth. Considering that CAD programs for solar engineering typically cost $1,000 per annual subscription and most do not support student learning, we have been developing a free alternative for students called Energy3D, which will be used and further developed in this project. Energy3D integrates geometric, physical, and financial modeling in a single program to provide an agile design environment in which users can rapidly test ideas. To model the real world, Energy3D allows users to import site images via the Google Maps APIs, upon which they can draw their designs (Figure 4). With a simulation accuracy that rivals its pricey counterparts, this versatile tool can be used to design rooftop solar systems for residential and commercial buildings, solar canopies for parking lots, ground-mounted photovoltaic solar farms with or without trackers (Box 2), and concentrated solar power stations (Figure 1). Furthermore, Energy3D is full of visual effects and graphing tools that are essential to teaching and learning solar science, as demonstrated in Figure 1. As an innovation of this project, a basic functionality of computational design (e.g., automatic parametric design through control flow) will be added to Energy3D to allow students to apply computational strategies to the design process (e.g., Kilkelly, 2016), thereby providing opportunities for students to integrate computational thinking and design thinking.

Figure 4: Energy3D is a powerful CAD program for designing various solar power solutions. This project will allow an Energy3D model to run in the cloud to create a virtual electric grid.

Once completed, an Energy3D design can be submitted to an online database and become "connected" to a virtual electric grid. Each submission will be displayed on the Google Map view of the grid and seen by other students. A cloud-based simulation program will run in the background to continuously generate virtual electricity for each submission based on its design parameters and the typical meteorological year (TMY) weather data for its location (i.e., TMY3, National Renewable Energy Laboratory, n.d.). If multiple designs are submitted for the same site (e.g., the same school, parking lot, or landfill), the amount of virtual electricity generated by each design in the same period will be shown on a scoreboard for comparison. This will create a mechanism for students to learn from one another's design.

Three units are planned for the Virtual Solar World curriculum: **1) Solarize Your Home**. Students design solar panel arrays for the roofs of their own home buildings. They sketch up Energy3D models of the buildings, add solar panels, and use simulations to decide whether their families or communities should "go solar." **2) Solarize Your School**. Students design solar solutions that turn the roofs and parking areas of their schools into small power plants. If their schools have already installed solar panels, students can model the existing designs as a baseline and investigate whether they can be revised to produce more electricity. **3) Solarize Your Town**. Students search appropriate sites in their towns on Google Maps and explore all sorts of solar solutions. Students have flexibility in selecting different types of solar technology, sites, and scales. In all three projects, students must perform feasibility analyses to evaluate the costs and benefits of their designs. They should also leverage governmental incentives and policies available in their areas, such as net metering. Importantly, the Virtual Solar World has the potential to extend learning beyond the classroom. One of the problems with implementing authentic engineering projects in schools is that students' work on their designs often ends prematurely due to the limitation of time, causing their budding interest to be abruptly extinguished and their creations quickly forgotten. This is detrimental to the development of self-efficacy and career interest. Part of the reason that students do not revisit their designs after the school projects end is the lack of incentive. The Virtual Solar World will provide a mechanism for students' work to continue to "live" online. The virtual electricity that a design generates can roughly represent the target site's solar potential that may have been overlooked by solar companies and may become a valuable lead for their business. This creates a possibility for students' work to be acknowledged and even rewarded by the industry. Such a recognition may provide the needed incentive and boost students' interest in engineering careers. In partnership with Borrego Solar, we will test this hypothesis in this project.

DISSEMINATION

This project will involve approximately 2,000 students from more than a dozen high schools in four states, constituting a broad base for dissemination. The technologies and materials developed in this project will be disseminated through a project website, the Indiana Small and Rural Schools Association, and Purdue's Energy Center. In collaboration with industry partners, we will also explore the possibility of working with companies serving schools' needs for smart campus and solar energy technologies to disseminate our products as added value to their school customers who can then utilize their IoT networks, green buildings, or solar systems to engage their students in STEM learning. Research findings of this project will be disseminated to scholars and teachers interested in engineering education and workforce development through conference presentations and journal publications. All the project information will also be disseminated through CC's biannual newsletter *@Concord*, which reaches more than 25,000 educators.

MECHANISMS TO ASSESS SUCCESS OF THE PROJECT

This project will rely on the expertise of the Advisory Board to assess its success. Each year, the members will attend an on-site meeting with project staff and also work with staff remotely on formative evaluation and feedback throughout the year. Each member is expected to spend a total of four days on these efforts. The evaluation will focus on six questions: 1) To what extent has the project accomplished the research and development goals?; 2) To what extent has the project found evidence of learning improvements?; 3) To what extent has the project found evidence of increased student interest in STEM careers?; 4) How effectively does the project support teachers?; 5) How is the scientific integrity and technical quality of the technologies and materials?; and 6) How has the project created broader impacts? At the beginning of the project, the board 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 (e.g., Google Analytics can be used to collect data that shed light on some of these questions such as the scope of impacts). 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 board to review based on the performance benchmark and the data protocol. The board and staff will resolve any issue in data interpretation and analysis methods. Based on the analysis results, the board 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.

Results from Prior NSF Support

This project is based on the following prior work:

1) **Next Step Learning: Bridging Science Education and Cleantech Careers with Innovative Technologies** (NSF 1512868, $1,187,365, 2015-2018, PIs: Xie, Massicotte, & Spangenberg). **Summary of results**: This project created a learning pathway from school to home and then to cognate careers. The project has developed the Building Science Investigation curriculum, which was pilot-tested with approximately 100 students in classrooms. It is now being scaled up to more than 10 schools in New England. **Intellectual merit**: This project is designed to meet the goals of workforce development and science education simultaneously by providing students a technology-enabled pathway from classroom science to workforce readiness. **Broader impacts**: This project promotes the energy literacy and technical competency of students from diverse socioeconomic backgrounds and inspires an even greater population as their families are also involved. **Publications**: Three conference papers and one magazine article.

2) Large-Scale Research on Engineering Design Based on Big Learner Data Logged by a CAD Tool (NSF 1348530, $999,921, 2014-2018, PIs: Xie & Nourian). **Summary of results**: This project has advanced the data mining capability of Energy3D, a CAD tool for building energy simulation and solar power design. It has also developed VPA (Figure 3), a cloud-based platform for visualizing student performance and learning through complex projects such as engineering design using CAD. **Intellectual merit**: This project probes how students learn and apply science concepts in engineering design processes, an important topic in research on K-12 engineering education. **Broader impacts**: Data mining is emerging as a promising method for assessing student learning. This project contributed to this frontier from the perspective of engineering education. **Publications**: Four journal papers, six conference papers, and two magazine articles.

3) SmartCAD: Guiding Engineering Design with Science Simulations (NSF 1503196, $2,192,610, 2015-2019, PIs: Xie & Nourian). **Summary of results**: This project has greatly expanded Energy3D's engineering capacities in the direction of solar power simulation. Capable of modeling both photovoltaics and concentrated solar power, Energy3D has been featured on the Facebook page of SolarPACES, a technology collaboration program of the International Energy Agency. **Intellectual merit**: This project is developing intelligent CAD software that can automatically generate formative feedback to guide students' design and learning based on computationally analyzing their process data in real time. **Broader impacts**: This project demonstrates that modern CAD programs capable of virtual prototyping can support engineering education at a level and scale comparable to the role of modeling and simulation in science education. **Publications**: One journal paper and three conference papers.

4) CAREER: A Study of How Engineering Students Approach Innovation (NSF 1150874, $466,681, 2012-2017, PI: Purzer). **Summary of results**: This project focuses on the education of creative and innovative engineers. The **intellectual merit** is highlighted in its approach to investigating engineering students' view of innovation and using these data to inform ways to assess and support the development of innovation skills. The **broader impacts** lie in its potential influence on workforce development. The results have widely been disseminated to education scholars and decision makers. **Publications**: Four journal articles, 15 conference papers, one book chapter, and one magazine article.

Personnel

Senior Staff at the Concord Consortium

Dr. Charles Xie will serve as the PI. A physicist by training, he has 17 years of research and development experience in STEM education. As a developer, he has created several scientific simulation tools used by over a million students and numerous professionals. As a researcher, he has authored over 40 papers and is leading research on data mining for assessing project-based learning. He is the recipient of a 2011 SPORE Prize from *Science Magazine*, the winner of the 2016 DOE JUMP Smartphone Innovation Challenge, and a fellow of the International Society of Design and Development in Education. **Joyce Massicotte** will serve as the Project Manager. She has eight years of experience in energy education and program management in industry. She directed the award-winning Sustainable Energy Education Drive that mobilized environmental science clubs at 18 schools. She holds an M.S. in Resource and Administration from the University of New Hampshire and is a Building Performance Institute (BPI) certified analyst. **Dr. Saeid Nourian** will serve as a senior developer for the proposed technologies. He has done extensive research in virtual reality and computer graphics. He has created Graphing Calculator 3D, which has been used by more than 200,000 people. He holds a Ph.D. in computer science from the University of Ottawa. **Dr. Jie Chao** will serve as a learning scientist responsible for leading the research of this project. She works on statistical analysis and learning analytics for assessing learning in student-centered and open-ended environments for engineering education and computer science education. She holds a Ph.D. in STEM education from the University of Virginia. **Dr. Corey Schimpf** will serve as a postdoctoral researcher. He has experience studying how innovative learning technologies affect students' conceptual understanding as well as science and engineering practices. His dissertation investigated how learning technology influenced student-centered inquiry practices. He holds a Ph.D. in engineering education from Purdue University.

Senior Staff at Purdue University

Dr. Şenay Purzer will serve as a Co-PI. She is an Associate Professor in the School of Engineering Education and the Director of INSPIRE Assessment Research. She conducts research on assessing student learning in engineering design and integrated STEM. She will support the research associated with student abilities in scientific reasoning, design thinking, and computational thinking and the assessment of student self-efficacy contextualized within the specific project activities. **Dr. Pankaj Sharma** will serve as a Co-PI to coordinate the efforts of teacher professional development and dissemination. He holds appointments of courtesy Associate Professor at Purdue Polytechnic Institute and National Cheng Kung University. He is also the Managing Director of the Energy Center and the Duke Energy Academy. He holds a Ph.D. in physics, a master's degree in solid-state physics, and an MBA.

The Advisory Board

Michael Arquin is Director of KidWind, a successful educational project that teaches K-12 students the science and engineering about wind energy with hands-on design and experimentation, which will serve as a great model of development and dissemination for this project. **Dr. Michael Barnett** is a Professor at Boston College. His research focuses on promoting urban high school students' interest in STEM. One of his projects is a hydroponic farming project that uses solar panels and windmills to help power the indoor gardens. **Michael Hacker** is co-director of the Hofstra Center for Technology Education who has been instrumental in K-12 technical education. At the New York State Education Department, he conceptualized, managed, and implemented the process of technology education reform and led the development of the state-mandated middle school Introduction to Technology program and the high school Principles of Engineering project. **Emily Kemper** is Senior Engineering Manager at CLEAResult with 14 years of experience in building science, including smart and connected home technologies and integrated sustainable design. **Dr. Gary Stager** is a recognized pioneer in 1:1 computing, online learning, and computer science for all students. He has taught learners from preschool through the doctoral level and spent 35 years helping teachers around the world embrace technology as way of amplifying the potential of each student. **Larry Weathers** is Science Director of the Arlington School 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.

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