HOW TO ENGINEER ENGINEERING EDUCATION

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Abstract: The new national science education standards will encourage science teachers to include engineering in their classrooms. This article suggests five strategies for developing effective engineering projects for secondary schools. The *Engineering Energy Efficiency* project is used as an example to explain each strategy.

INTRODUCTION

Precollege engineering education is increasingly recognized as an indispensable part of STEM education [1]. The National Research Council's conceptual framework for new science education standards (referred to as the Framework throughout this article) has recommended incorporation of engineering into American science education [2]. For years to come, thousands of science teachers will be charged with teaching engineering —a topic that could be new to many. Innovative materials and projects closely linked to core ideas and crosscutting concepts of the Framework will be needed more than ever. For example, energy as both a core idea and a crosscutting concept deserves to be supported through engineering projects that science teachers can use to improve the teaching of this often elusive topic in a practical way.

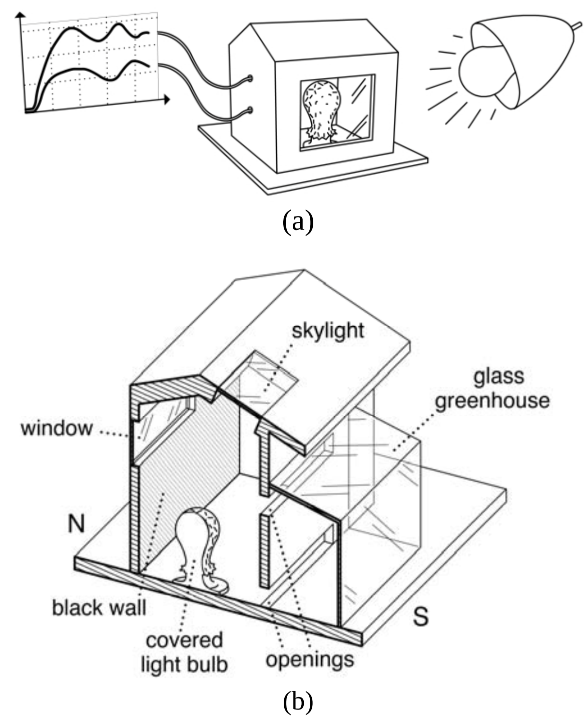


Figure 1. (a) A very simple model house that can be heated by a light bulb inside and an adjustable table lamp outside, simulating a furnace and the sun, respectively. Multiple temperature sensors can be used to monitor and investigate the temperature distribution inside the house and heat flow across the building envelope. This model house could be used as a science laboratory for learning the three mechanisms of heat transfer. (b) A more complex model house with some energy efficiency measures—a skylight window, a greenhouse attachment, and a convective air loop for exchanging heat between the main room and the greenhouse. These architectural elements demonstrate the richness of design supported in the EEE project.

The Concord Consortium's *Engineering Energy Efficiency* (EEE) project (http://energy.concord.org) adds a new choice of engineering project for high school students and teachers. The EEE curriculum bridges science and engineering by combining scientific inquiry and engineering design in a hands-on, project-based, and technology-enhanced learning process with the concept of energy at the center. Through laboratory experiments and computer simulations lasting 10-16 class periods, students will be guided to learn the science behind energy flow and usage in houses. Prepared with the basic knowledge and skills necessary to undertake more sophisticated tasks, they then team up to design, construct, test, and improve a model house step by step, with the goal of maximizing its energy efficiency (Figure 1). The project uses free or inexpensive materials and tools, making it widely implementable.

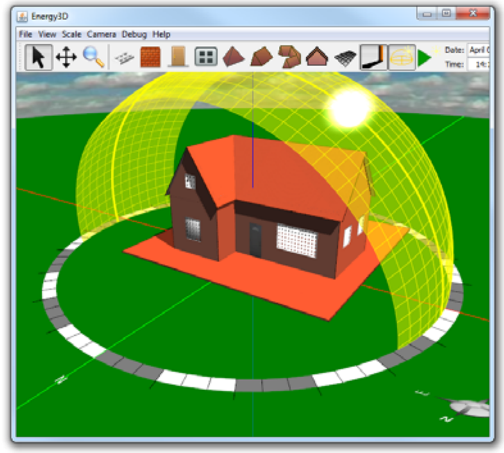
The EEE project has been designed, tested, and improved through several rounds of field tests involving more than 300 high school students. In a sense, they themselves are the results of engineering. Five key strategies to be presented below emerged from our efforts to “engineer” this project. They also summarize the main features that constitute a good engineering project, especially from the perspective of science teachers. They could be broadly useful to practitioners of engineering education.

STRATEGY #1: SITUATE ENGINEERING IN A SOCIETAL CONTEXT

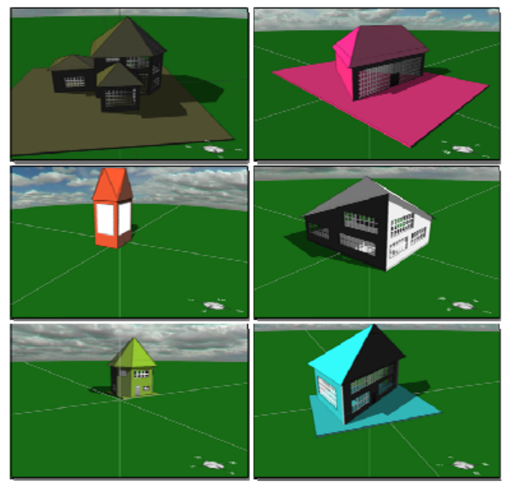
How to attract students to engineering is a pressing question. A project that simulates solving a real-world problem with societal significances may be more motivating. Critical challenges, such as clean energy, electric vehicles, seawater desalination, or cures for diseases, could offer exciting learning opportunities—not only for engineering itself, but also for the related science. Science teachers can take advantage of these engineering challenges to stimulate student interest.

One of the two core ideas of engineering education suggested by the Framework is the influence of engineering on society and environment. An engineering project placed in a societal context would provide students with hands-on experiences about this idea.

The EEE project is focused on the energy efficiency of our houses and the sustainability of our society. The engineering field of green buildings covers architecture, construction, green retrofits, renewable energy, electricity, control, and more. Designing an energy-efficient model house can support experiential learning of these topics. The knowledge students will learn can help raise their energy literacy. For instance, an experience of measuring how much more energy would have to be spent on keeping their own model houses at higher temperatures could prompt them to think about a strategy for conserving energy used to heat their real houses. Furthermore, the skills students will acquire could be translated into technical competency needed for green jobs.



(a)



(b)

(c)

Figure 2. (a) A virtual house designed using Energy3D is examined under a virtual heliodon to study the solar heating at different times and latitudes in different seasons. (b) Computer models of six houses designed by students in the EEE Summer School 2011. (c) Two sample houses assembled by students from print-out paper pieces (the smaller color ones in the front row) and from scale-up foam board pieces (the larger white ones in the back row).

Strategy #2: Enhance Learning with Technology

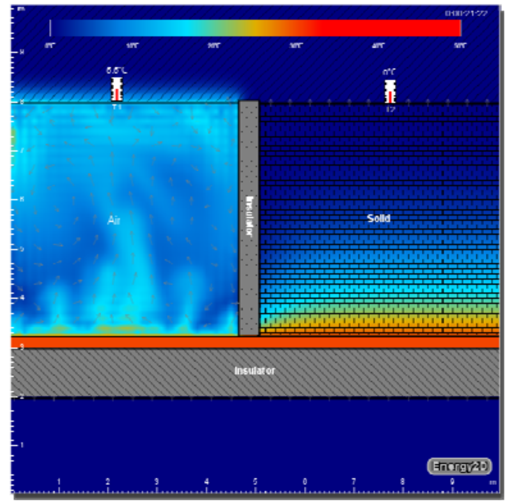
New technologies have caused paradigm shifts of engineering principles and practices that frequently redefine the frontiers of engineering. Educators need to catch up with technology and bring their teaching practices up to date.

Technology can be used both as an application tool and a cognitive tool to enhance engineering education.

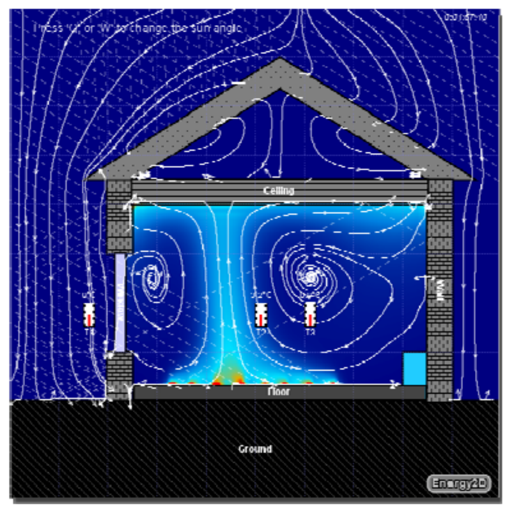
In the catalog of *application tools*, computer-aided design (CAD) is one of the most fundamental changes brought by computer technology to engineering. CAD tools empower engineers to conceptualize products before making prototypes. We have developed an educational CAD tool called *Energy3D* (http://energy.concord.org/energy3d) that enables novices to design buildings and evaluate their energy performances (Figure 2a). Two innovative features of *Energy3D* make it broadly useful.

a) **Simplicity**. *Energy3D* can add, combine, and modify standard elements to make a wide variety of designs. Due to the complexity of 3D geometry, the design of roofs often turns out to be hard when students use a general-purpose CAD tool. *Energy3D* greatly simplifies roof design. Students can add different types of roof to a house, reshape them, or transform one type into another. Our pilot study showed students were capable of using *Energy3D* to rapidly sketch up complex houses (Figure 2b).

b) **Fabrication**. The hands-on nature of engineering projects mandates that students finish up with products in hand. To bridge the gap between the virtual and real worlds, *Energy3D* can deconstruct a 3D structure into 2D pieces and generate a layout of them for printing. Every piece is numbered and annotated to guide students to scale up to constructional materials such as cardstock or foam board (Figure 2c). The entire deconstruction process is animated so that the user has an intuitive understanding of the relationship between the 3D representation of a house and its 2D pieces.



(a)



(b)

Figure 3. (a) An online computational fluid dynamics simulation using Energy2D shows the difference between conductive and convective heat transfer. (b) A streamline analysis of thermal convection in a house heated by solar radiation through a window.

Technology offers not only application tools for solving problems, but also *cognitive tools* for learning concepts. A design challenge, regardless of its level of sophistication, can only teach based on what students see, hear, and touch during the design activity. Many learning goals, however, rest on the application of abstract concepts such as heat transfer, stress, airflow, reaction rates, or electromagnetic signals that are often invisible, inaudible, and intangible. An engineering project must "open the black box" for students to see how science concepts and engineering principles are put to work in a design. For the EEE project, we have developed a tool called *Energy2D* (http://energy.concord.org/energy2d) that can be used to simulate conduction, convection, and radiation

(Figure 3). Students can observe and interact with an *Energy2D* simulation, analyze the results, and experiment with various energy-related problems.

In addition to the above two computer-based tools, the EEE project also uses other technologies extensively. For example, we have devised hands-on experiments using temperature sensors to "capture" invisible energy flow. All these technologies support, guide, and extend learning in a way similar to their use by scientists and engineers.

STRATEGY #3: GUIDE ENGINEERING DESIGN

It is important that students learn and use science in an engineering project. A typical problem is that, when making an engineering system, students tend to "forget about" the science part as if they had not been taught about it previously. This is partly because they were too immersed in the task and partly because its engineering nature is too distinct from their mental pictures about science. As a result, the connection between science and engineering is marginalized or missed. For engineering systems involving familiar subjects such as houses, students may already have their own ideas about how they should look. This increases their inclination to just "use their gut." In many cases, superficial learning could be concealed by the illusion of a product "success." For example, students could be satisfied with the looks of their model houses, even though hardly any science has been applied to make them.

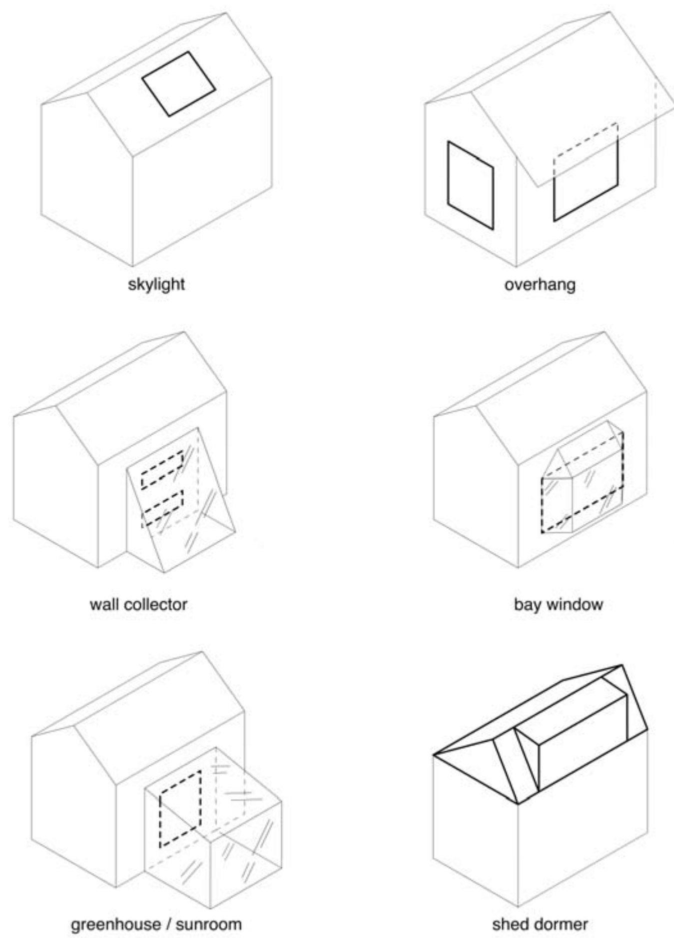


Figure 4. Like experts, students learn fast through examples. The EEE project guides students to design their own model houses by providing them a comprehensive set of design choices, which they can try, test, adopt, modify, and optimize.

This tension between student autonomy and their need for guidance is fundamental in education. Research has shown that guided inquiry is usually more effective than open inquiry [3]. Guided Inquiry uses clear goals, careful scaffolding, ongoing assessment, and teacher intervention to lead students to independent learning. These kinds of guidance are essential to engineering design, too. A complex design process should be divided into accomplishable and assessable individual tasks to aid students gradually. In particular, the linkage between science and engineering should be thoughtfully forged to encourage the application of science.

The need of guidance is not to suggest engineering design should be reduced to "cookbook" instructions, however. Guided design seeks an appropriate balance between complete open-endedness and complete determinateness. As much as the overall direction of an engineering project should be confined to ensure students progress on the right track, each task that represents a milestone of the project should be as flexible as possible.

The principle of guided design was implemented throughout the EEE curriculum. To get students started with designing their houses, a set of architectural design choices that have energy-efficient implications (positive or negative) is provided (Figure 4). The goal of this is to constrain design within an acceptable range while still allowing for creative tinkering with design options (e.g., the model house shown in Figure 1b combines multiple features shown in Figure 4). To some extent, this treatment resembles replacing an open-response question with a multiple-choice question. But unlike a multiple-choice question that needs only a pick, students will have to work hard to realize their designs and justify their choices.

Having constructed the "baseline" versions of their model houses following the guidance, students are then challenged to modify them to improve their energy efficiency. These "green retrofit" tasks require the application of science and are scaffolded using a set of explicit science-engineering links. Each task focuses on exploring how a heat transfer mechanism can affect the energy performance of a model house and how different countermeasures can be taken to prevent heat loss through that mechanism. These tasks keep prompting students to think about science during a complex engineering project.

Strategy #4: Integrate Inquiry and Design Practices

Inquiry and design are at the hearts of science and engineering practices. In an engineering project, both types of practices are needed to solve a problem or to design a system. All engineering systems are tested during the development phase. A substantial part of engineering is to find problems through tests in order to build robust products. The diagnosis of a problem is, in fact, a process of scientific inquiry into an engineered system. The results of this inquiry process provide explanations of the problem, as well as feedback to revise the design and improve the system. The modified system with new designs is then put through further tests. Testing a new design can lead to more questions worth investigating, starting a new cycle of inquiry. This process of interwoven inquiry and design repeats itself until the system is determined to be a mature product (Figure 5).

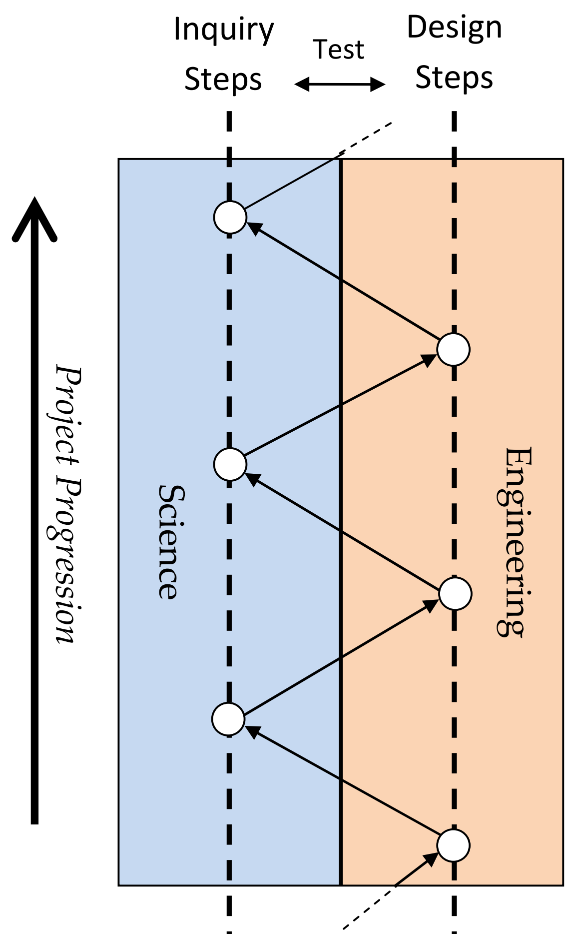


Figure 5. Design and inquiry can be interwoven in a project-based learning environment to inform, guide, and enhance each other. This integration of the two types of practice creates an intimate linkage that "stitches" science and engineering.

The EEE curriculum shows how the coupling of inquiry and design can guide students to apply science to engineering. Using a temperature sensor as a data logger, we have developed a test for estimating the energy cost for keeping a model house warm. During the process of house improvement, students run this test repeatedly to evaluate the effects of their modifications. Any claim of energy savings must be backed by test data. The result of each inquiry may affect students' next design choices.

For instance, there are several steps in designing a passive solar collector (Figure 6). In an ideal learning situation, students would investigate why or why not a new feature works. It is through these inquiry tasks that the engineering designs are connected to science concepts such as natural convection and solar radiation. Skipping the inquiry part for the "why" questions, the design challenge would be downgraded to a "cookbook" operation. Furthermore, students would miss the opportunity to learn that a design decision is always made by calculating the trade-off among options and constraints based on scientific data from tests.

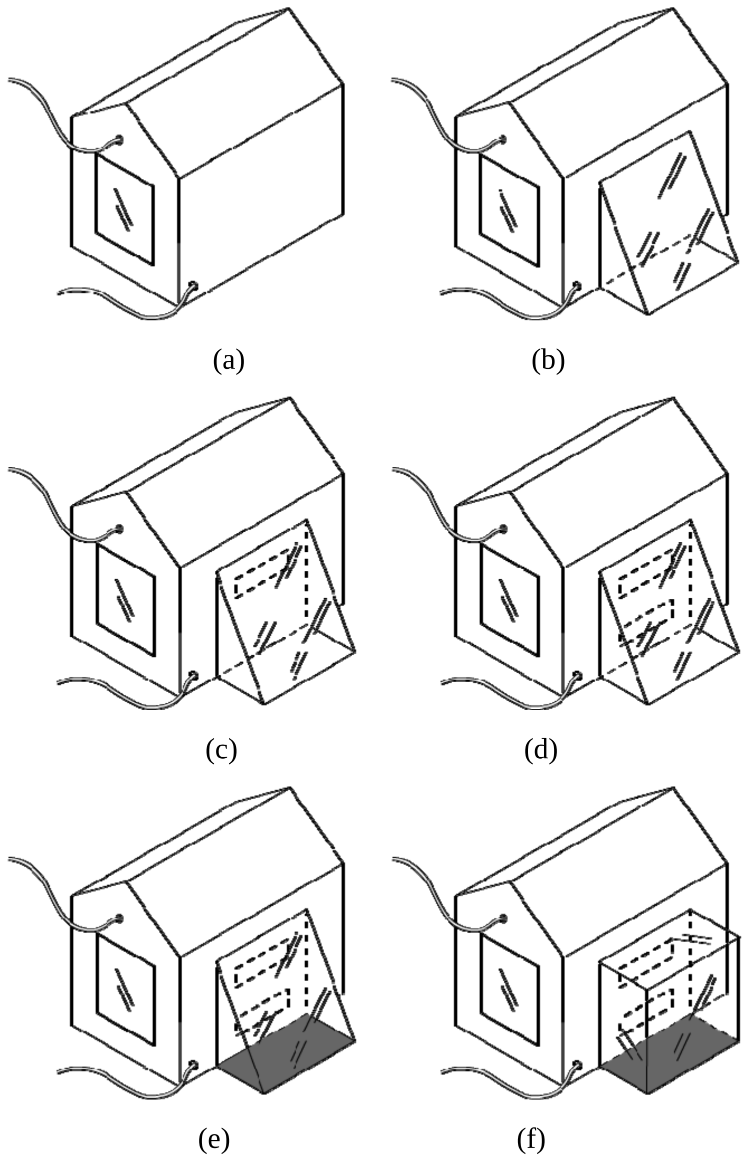


Figure 6. This example of adding a solar collector to a model house (a) shows how inquiry can be coupled to design to provide scientific guidance. At each of the design steps, a new feature is added to the model house and its effect evaluated using temperature sensors as inquiry tools: (b) Add a triangular sunspace; (c) Cut a slit at the top to let the hot air diffuse into the house; (d) Cut a slit at the bottom to let the cool air diffuse out of the house; (e) Place a black paper on the floor inside the sunspace to increase light absorption. The shape of the sunspace can also be modified and the energy performance can be compared (f). In the experiments, the "sun," which is not shown in the above images, always faces the solar collector.

STRATEGY #5: ASSESS STUDENT ENGINEERING PERFORMANCE

Evaluating student learning in an engineering project that involves many variables, processes, and artifacts is non-trivial. Traditional assessments that measure knowledge gains, such as pre/post tests, fall short in measuring students' engineering skills.

Inspired by the virtual performance assessments (VPA) for measuring inquiry skills in virtual worlds [4], we are developing engineering performance assessments (EPA) for measuring engineering skills. Unlike traditional assessments that rely on student responses to individual test items, EPA uses three criteria: (a) Do students claim engineering success of their designs? (b) How do students collect data as evidence to support their claims? (c) How do students present reasoning that links claims with evidence? EPA centers on student interactions with engineering subjects they have designed and built. The rich data resulted from these interactions can reveal students' understanding about their designs.

Table 1: An example of EPA for a design task: how much insulation does a house need?

Claim	Evidence	Reasoning	Score
Insulation did not save energy for our house. So there was no need to add insulation.	No data or wrong data.	No reasoning or wrong reasoning.	0
Insulation saved energy for our house. We added one layer of insulation and it should work.	No data.	No reasoning.	1
Insulation saved energy for our house. We added some insulation and collected some data.	Sensor data.	No reasoning or wrong interpretation of data.	2
Insulation saved energy for our house. We tested our house with and without insulation and compared the data.	Sensor data.	Correct reasoning and interpretation of data.	3
Insulation saved energy for our house and we determined that applying two layers of insulation is the most cost-effective energy efficiency measure.	Sensor data for multiple tests with different thicknesses of insulation.	Correct reasoning for each case. Consideration of constraints such as space limitation, material cost, and labor cost.	4

The development of EPA will result in rubrics for measuring student learning with the EEE project (Table 1). This may remove concerns from some teachers that engineering projects are not useful in the classroom because they cannot be reliably scored.

FINAL NOTE

The above five strategies emphasize primarily on the axis of science and engineering integration. They do not mean, however, that other education factors are considered less important. Nor do they suggest that the EEE project is limited to them. For example, mathematical analysis, classroom discussions, team working, and teacher professional development are all incorporated in the EEE project. In a nutshell, the project provides technologies, materials, assessments, and inspirations for educators in a time when pre-college engineering education could not be more needed.

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