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Translating systems engineering for high school teachers and students: an exploratory study of implementing some initial SE concepts

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Abstract: Systems engineering is a life cycle approach to engineering design: the integration of numerous technical and non-technical disciplines toward the development of new products, systems and services. This paper describes the experiences of the authors in designing and implementing a three-year project to engage high school classes in a geographically-distributed systems engineering design project that addresses relevant, social challenges of interest to students worldwide. Collaborating with others around the world to develop a solution to an engineering problem, students are introduced to systems-thinking, team work, effective communication and other 21st century workforce skills. This innovative project aims to increase the number of students interested in pursuing engineering as a career and to increase the pool of teachers familiar with engineering design and systems thinking.

Keywords: systems design; systems thinking; innovation; engineering education; systems concepts; systems engineering.

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Mercedes McKay has led several national and statewide K-12 teacher professional development programmes and curriculum development efforts in science and engineering including the Systems and Global Engineering project. Prior to joining Stevens, she was a practicing Mechanical Engineer and also taught high school science and mathematics.

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Debra Brockway performs program evaluations and develops assessments of student and teacher learning in a variety of K-12 engineering and science programs. Before joining Stevens, she taught high school science and worked for an educational testing organisation developing large scale assessments.

1 Introduction

The practice of engineering is increasingly conducted in a complex, globally-distributed environment. Multiple entities must work together on a range of project components and systems that must, themselves, work together in order for the entire system to operate effectively. The characteristics that are expected of engineers today are that they should understand the functional core of the engineering process as well as think across disciplines (laterally) and in disciplinary depth (vertically). They also need to communicate ideas effectively to influence diverse groups, including non-engineers, while acting both independently and as a team member. To do so, an understanding of the relationship of the engineering enterprise to the social/economic/political context of engineering practice and the key role of this context in engineering decisions are required (Bordogna, 1996). These characteristics and the demands of global economy require a holistic approach to addressing the engineering challenges.

A systems approach to design means designing from a holistic perspective. It is an approach focused on understanding the functionality for which the system is designed by keeping the focus on its need, context, and its intended lifecycle. In other words, this type of holistic design with a 360° view and a zoom lens is called total design (Pugh, 1991). Engineering education is, by necessity, mostly concerned with the acquisition of knowledge (in the humanities, management, the sciences …) and analytical techniques and skills in engineering, usually within a specific discipline or domain (e.g., mechanical, electrical, etc …). The rigorous application of such skills and knowledge to engineering elements is usually called partial design, and is often exemplified in some senior capstone design projects. But in today's world, industry is concerned with a systems approach to design or designing for the total system (total design): the integration of numerous technical and non-technical disciplines toward the development of new products, systems and services.

There is a pressing need to excite and attract students to engineering since it is estimated that 160,000 new engineering jobs, an 11% increase in the US engineering workforce, will be created by 2016 (NSB, 2008). Also of critical importance in the contemporary workforce are such technological literacy skills as designing, developing, and utilising technological systems; working collaboratively on problem-based design activities; and applying technological knowledge and ability to real-world situations (International Technology Education Association, 2000; International Society for Technology in Education, 2002). These skills are increasingly recognised by business, higher education, and policy leaders as critical for tomorrow's workforce (Business – Higher Education Forum, 2005).

Further, the technical systems around us are becoming increasingly integrated, both technically as well as socially. Systems thinking and engineering gives students a toolbox and an approach to see the larger picture, both when designing technological solutions for society, as well as in considering how the different elements of a solution produce behaviours and characteristics of the system as a whole.

2 Previous efforts of the authors in implementing systems approach

In an attempt to address the challenges of teaching a systems approach to design, the authors redesigned and pilot-tested the fundamental engineering design undergraduate courses at Stevens Institute of Technology (Stevens) to include a systems approach to design. Some of these modifications and enhancements included tools, techniques, and case studies which were already being used for the graduate design courses. As a result of this experience the authors realised that the fundamental concepts of system design have not been identified explicitly even though their subject matter has been taught in existing design courses in almost all engineering disciplines.

At the graduate level a systems approach to design is an integral part of teaching System Engineering (SE). This systems approach is addressed through the lifecycle approach to SE. However, any attempts to define the underlying fundamental concepts of systems design that can be abstracted to apply across domains have been non-existent. Therefore, it has been difficult to translate the elements of a systems approach to design to the undergraduate or lower levels. Based on their experiences from graduate-level design courses the authors abstracted and selected five underlying design concepts and built teaching materials for the undergraduate design labs. These five fundamental concepts of system design were context, abstraction, interdisciplinarity, value, and tradeoffs (Jain et al., 2008). Further work in addressing systems concepts in different ways in the undergraduate curriculum has been ongoing (Sheppard et al., 2007; Jain et al., 2006). An aggregated view of all the different initiatives was shared in a Best Paper Award at an ASEE conference (Jain et al., 2008).

3 Systems approach for high school level design

The most recent initiative in applying systems concepts to design at Stevens led to the SAGE (Systems and Global Engineering) project. Stevens Institute of Technology partnered with the New Jersey Technology Education Association to introduce systems concepts and approaches to high school technology, engineering, and science students. *The five concepts of a systems approach mentioned above were applied in creating the design projects for the high school students*. As part of the SAGE project, students in classrooms around the world have the opportunity to design a solution to a complex problem. Students apply science and mathematics principles in the development of an engineered product or system; utilise state-of-the-art industrial software to collaborate on the design; practice inventive thinking and problem-solving to develop designs; collaborate in class-based and worldwide teams; and develop and present a final product. Students are introduced to a systems-thinking approach via the application of the above five concepts that encourages them to see their design effort in a larger context. They have to reflect on the problem they are trying to solve, the resources that are available, and assess the desirable as well as potentially undesirable impacts their design will have in its intended environment. Local as well as worldwide collaboration fosters teamwork, innovation and invention, effective communication, and other 21st century workforce skills.

Over the course of three years, this project will develop, pilot, and disseminate, via face-to-face and online professional development, four high school level curriculum modules that elucidate systems engineering concepts and that assess different approaches to curricula implementation that will enable effective global collaboration among schools and classrooms world-wide. The SAGE curricula include one introductory module and three additional modules that focus on issues of global sustainability. The modules are as follows:

- Introduction to the core concepts of systems engineering
- Water purification
- Home lighting in developing countries
- Biodynamic farming.

The first module introduces basic concepts of systems engineering in the context of a simple and relatively short reverse engineering activity. Students are challenged to identify and explain the five fundamental concepts of systems engineering as it pertains to the system that is disassembled and reassembled in this activity. The remaining modules build on students' systems engineering knowledge by engaging them in longer, more intensive design experiences in which they apply their understanding of the five fundamental concepts to the solution of a specific design challenge.

During the first year of the project, these modules were developed and 20 high school teachers were trained to use them in their classes. Currently in its second year, pilot testing of all of the modules has been completed and findings from the fall 2008 implementation of the module *Introduction to the Core Concepts of Systems Engineering* are now available.

4 Pilot test results

First year

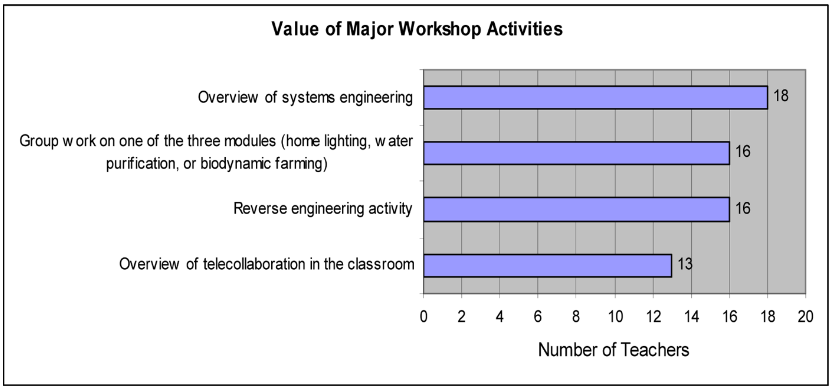
In the first year the focus was on identifying the design projects to be piloted through SAGE and providing professional development to the selected teachers who would then pilot test the materials in their classrooms during the 2008–2009 school year. The module topic identification, curriculum development, teacher selection, and teacher professional development efforts occurred over many months and involved a team of faculty and educators (McKay et al., 2008).

Teacher training

Pilot teachers were selected to represent a range of school socio-economic circumstances, achievement levels, and geographic locations. Each pilot teacher selected received a grant of up to $1,000 for the purchase of needed materials. Pilot teachers received four days of professional development at Stevens in August, 2008 to introduce them to the four curriculum modules that were implemented during the 2008–2009 school year.

The four-day pilot teacher workshop consisted of four major activities. Teachers were asked to rate how valuable each of the activities was to them. More than 70% of the respondents stated that each of the four activities was very valuable as shown in Figure 1. All of the respondents stated that the overview of systems engineering was very valuable. Teacher responses to the items related to self-efficacy suggest that systems engineering is the topic in the project with which teachers have the least familiarity and confidence. It is reasonable, then, that they would find this aspect of the workshop very valuable in preparation for teaching modules that incorporate systems engineering as a primary component.

Figure 1 The number of teachers responding 'very valuable' when asked about the value of each of the major workshop activities ($N = 18$) (see online version for colours)

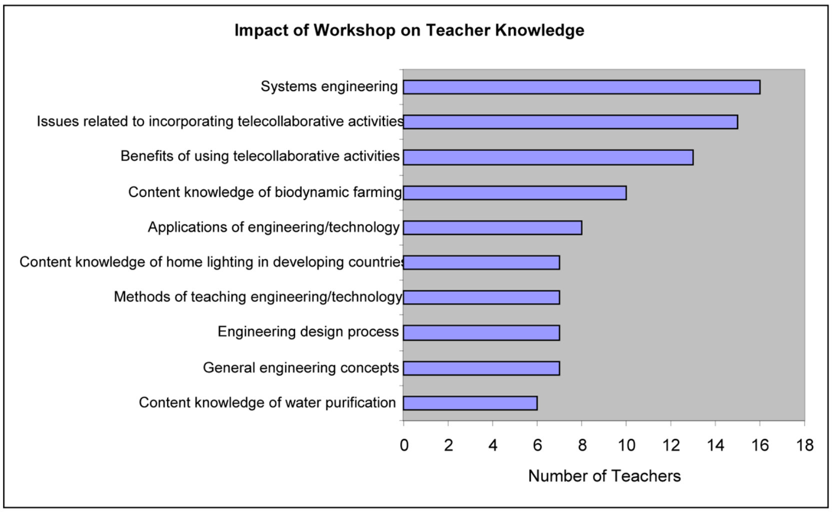


Training impact

Pilot teachers were then asked to what extent their awareness or knowledge of specific relevant topics was increased as a result of participating in the workshop activities. Again, systems engineering ranks at the top of the list, with 16 of the 18 teachers completing this part of the survey stating that their knowledge of this topic increased considerably (Figure 2).

While teachers' perceptions of workshop activities and their self-reported impact on teacher knowledge of content and pedagogy were overwhelmingly positive, an efficacy scale score was used as a more reliable measure of workshop impact. Teachers were asked for their confidence in the classroom pre- and post-workshop on 11 statements, some of which were presented in the negative form (to increase reliability of this measure). Each of the 11 statements corresponded to an efficacy scale that is related to one of three focal areas in the workshop, namely, Content knowledge (1 statement); Tele-collaboration (three statements) and Engineering (seven statements).

Figure 2 The number of teachers stating that their knowledge of each of the listed topics was increased considerably as a result of workshop activities ($N = 18$) (see online version for colours)



An efficacy scale score was calculated for each teacher in each of the three focal areas for both the pre- and post-workshop surveys. The pilot teachers' level of confidence increased significantly in all three of the focal areas as evidenced by p values ≤ 0.010.

Second year

Pilot testing of the curriculum modules and module refinement were the focus of the second year of the project. Teachers were required to pilot at least one module but encouraged to pilot two or more. Each pilot teacher received one classroom visit to observe and assist with implementation. Based on the results of the pilot test, the module materials have been refined and finalised.

Module implementation in classrooms

During the fall of 2008, pilot testing for one module, *Introduction to the Core Concepts of Systems Engineering* (http://www.stevens.edu/ciese/sage/curriculum.html) (introductory module), was implemented. This online collaborative project was designed to provide students in grades 9–12 technology education, engineering, or science courses with an orientation to systems engineering concepts. It provides the background needed to encourage teachers and students to participate in more advanced collaborative design activities; namely, the other three SAGE modules. In the introductory module, students were provided with an overview of systems thinking including the systems model. Through guided activities students reverse-engineered a common device, a disposable camera that contained both electrical and mechanical components and then created a systems diagram for the deconstructed device. Students created reassembly instructions and diagrams that partner schools then used in their attempt to reconstruct the device. Two different brands of single use cameras were used. In each class, half the students disassembled a Fuji camera and half the class disassembled a Kodak camera. Later, students reassembled the *other device* using reassembly instructions that a different school created.

The learning objectives for introducing some of the initial concepts of systems engineering (the introductory module) include:

- analyse the component systems and subsystems of a device and classify them as mechanical or electrical
- classify the component parts of the device according to their materials and recycling ability
- create a systems diagram to describe the operation and control of the device
- identify the purpose of subsystems as input, process, output, or feedback
- explain product lifecycle in terms of technological impacts
- follow instructions and diagrams created by others to reassemble a common product.

The module contains activities, assignments, and deliverables, each with a specific due date. Of all of the developed modules, this is the shortest in terms of length of class time needed to devote to the project; approximately two weeks. Similarly, the level of collaboration is also the simplest. Classes are expected to share information in *Collaboration Central*, the online discussion forum, and to learn from other classes' postings. However, completion of the module does not hinge on the participation of any one class. This was designed purposely to attract the greatest number of participating classes – those that wished to learn about systems engineering and engage in a collaborative experience without a large commitment of class time.

Pilot test teachers received all of the equipment necessary to implement this particular module; in this case, enough disposable cameras for their students to work in groups of four. Classes were encouraged, but not required, to use a Computer-Aided Design (CAD) software tool for their designs in order to provide students with a real-world engineering design experience.

Evaluation

Evaluation of the SAGE project is ongoing and primarily of a formative nature at present. Both quantitative and qualitative data are being collected to evaluate and inform revisions of various aspects of the project as well as to measure student learning as a result of completing the curriculum modules.

Twenty-three teachers committed to implementing the introductory module in the fall of the 2008–2009 academic year. Sixteen of these implemented the module in widely varying degrees. Teachers were requested to administer pre- and post-tests to their students and to respond to a brief online survey after completion of the module. Only half of the teachers returned answer sheets for both the pre- and post-tests for their students. Thirteen teachers completed the online survey. The following sections illustrate the analysis of the responses collected from these teachers and their students.

5 Effectiveness of the SE module and pedagogy: student assessment

Validated instruments to assess high school students' knowledge of systems engineering concepts are currently not available. The authors have attempted an assessment of student knowledge of and ability to apply systems engineering concepts by developing an instrument based on their own subject knowledge of the discipline.

The assessment is composed of 23 multiple choice items, two of which have more than one correct response. Each correct answer on a single-answer item was awarded one point. Each of the two items that had more than one correct answer was worth two points; partial credit was awarded for these unique items.

Each of the items was assigned a level based on cognitive demand. Level 1 items are those intended to require students to recall information that they should have encountered while completing the module. Level 2 items are application items. Students should not have directly encountered the information in items at this level; instead, they are expected to apply information or concepts from the module to a new example or situation. Level 3 items are analysis items and require a more sophisticated understanding of the concepts in the module. An example item at each cognitive level and the corresponding count of items is shown in Table 1.

Table 1 Examples of items on the assessment and count of items by cognitive level

Level	*Count*	*Item text*
1	12	Which statement best describes a system? A It is a complex way of completing a task B It is a group of unrelated parts within a product C It consists of models for a product that is to be made D It consists of parts that work together to meet a need Key: D
2	9	The design and operation of the controls in the cockpit of airplanes have been standardised to avoid pilot confusion when flying different planes. Which term best describes this process? A Human factors integration B Product improvement C Systems integration D Systems optimisation Key: A

Table 1 Examples of items on the assessment and count of items by cognitive level (continued)

Level	*Count*	*Item text*
3	2	Note: Background information on the Building America Program, a program to build energy-efficient homes that uses a systems engineering approach, was provided for a set of questions related to this program. Also, the directions stated that this item may have more than one correct answer. Why might a systems engineering approach be beneficial for designing and constructing these energy-efficient homes? A Modifications in the materials and methods used to construct the shell will impact the heating and cooling system required for the homes B Constructing the homes in a factory and moving them to the building site will require additional energy for transportation C Information from trial projects with energy-efficient homes using different materials and components will allow for improvements D Less time and money will need to be invested for building the homes Key: A, C and D

Teachers administered the assessment prior to implementing the module in their classes and again at the conclusion of the module. The gains or difference between pre- and post-test scores indicate an improvement in the high school students' ability to comprehend and apply systems engineering concepts. Twelve of the 16 teachers who implemented the module returned pre- and post-tests for a total of 327 students. Of these, both pre- and post-tests were received for 271 students. The mean gains for each of the classes for which both pre- and post-tests were administered are shown in Table 2.

Table 2 Student performance on the assessment by teacher

Teacher ID	*No. of students*	*Mean gain*
1	24	0.35
2	56	2.13**
3	32	0.20
6	19	3.00**
7	17	0.20
8	18	0.98
9	18	–2.68*
12	25	3.71**
15	15	2.04*
18	6	0.55
19	22	2.62**
23	19	2.83**
Total	*271*	*1.48***

*$p < 0.01$; **$p < 0.001$.

Results from a paired *t*-test indicate that significant positive gains were achieved by half of the classes. The results for one class, Teacher 9, indicate a significant *negative* gain, a clear outlier among these data. After reviewing the student answer sheets, it is considered likely that the answer sheets for pre- and post-tests were reversed, thereby resulting in the large negative gain. Data from this class have been omitted from all subsequent analyses because the data are a clear outlier, but conclusive evidence regarding a reversal is lacking.

Results from the paired *t*-test demonstrate that students had significant gains overall and specifically in the recall of systems engineering concepts and their application (item Levels 1 and 2) as shown in Table 3. Gains were not significant, however, for the highest cognitive level questions: Level 3, analysis. Not only are there too few items to accurately measure achievement at this level, these items are much more challenging and are likely to require a longer period of instruction for students to show significant gains.

Table 3 Student performance on the assessment as a function of cognitive level of the items ($N = 253$)

Items	*Maximum possible score*	*Mean raw score*		*Significance*
		Pre-test	*Post-test*	
All	*25*	12.81	14.59	<0.001
Level 1	*12*	6.46	7.59	<0.001
Level 2	*10*	4.93	5.65	<0.001
Level 3	*3*	1.42	1.35	–0.079

As mentioned previously, it would have been preferable to use an assessment that had been created from items on existing assessments with established validity. Since this was not possible due to a lack of assessments related to systems engineering for high school students, the items on the internally developed assessment are being analysed individually to collect data regarding their suitability for such an assessment in addition to collecting data regarding student performance.

A significant increase in correct responses on the post-test as compared to the pre-test was observed for 12 of the 23 items. Table 4 lists the rate of correct responses on the pre- and post-test by item for each of the items that had a single correct response and the overall mean score for the two 2-point items that had more than one correct response.

Table 4 Student assessment results for the pre- and post-tests by item ($N = 253$)

Cognitive level	*Item no.*	*Percent correct response*	
		Pre-test	*Post-test*
1	1	83	89*
	2	45	66***
	5	18	31***
	6	29	39**
	7	50	59*
	9	80	82
	12	59	60

Table 4 Student assessment results for the pre- and post-tests by item ($N = 253$) (continued)

Cognitive level	*Item no.*	*Percent correct response*	
		Pre-test	*Post-test*
1	14	53	69***
	15	80	76
	17	32	47***
	18	45	66***
	19	71	74
2	3	21	34***
	4	75	83*
	8	73	72
	10	68	72
	11	15	38***
	13	49	49
	16	66	73
	20	33	53***
	22	0.91[1]	0.90[1]
3	21	49	49
	23	0.93[1]	0.87[1]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

[1]Items 22 and 23 had more than one correct response and were scored on a partial credit model. Data reported here represent the mean raw score based on 2 points, the point value of these items.

Several of the items that did not show an increase in the rate of correct responses on the post-test are likely to elicit a correct response based on general knowledge alone rather than specific knowledge of systems engineering concepts. One such example is Item 9, which is shown in Figure 3.

Figure 3 Example of an item for which there was no improvement

Money and time may hinder an engineering team from achieving the design goals for a system. Which term best describes money and time?

A. Constraints
B. Criteria
C. Guidelines
D. System attributes

It is likely that high school students would be familiar with the term 'constraints' and therefore would be able to answer this item correctly without benefit of instruction in systems engineering concepts. In fact, approximately 80% of the students answered this item correctly both before and after they completed the module.

6 Teachers' experience of piloting the SE module

The range of responses provided by 13 teachers through an online survey provides some insight into student test results and some formative information for consideration in revising the module. Two of the teachers stated that they had prior experience introducing systems engineering and/or reverse engineering in their classes and four of the teachers reported having prior experience incorporating an Internet-based collaborative project in their classes. The relative comfort level and ability of teachers to facilitate the online collaboration is likely to affect the students' level of success in the reverse engineering activity.

Gain in students' assessment scores would certainly be directly affected by the amount of classroom time spent on the module and this value varied widely among the respondents. Three teachers reported spending one class period of 42–44 min on the module, while two teachers devoted 640–680 min (16 classes of 40 minutes and eight classes of 85 min, respectively). The average amount of time spent based on the reports of the 13 teachers responding to the survey was 278 min, or approximately 6.5 class periods of 42 min each.

When asked what changes, if any, teachers would recommend being made before the module is used again with students, seven teachers made recommendations, but only one of those teachers referred to the subject matter content of the module. This teacher recommended that additional papers be included to introduce core concepts. Other teachers commented on logistical issues pertaining to implementation of the module. The remaining recommendations referred to collaboration (three comments), the product being reverse engineered (2 comments), the amount of time allowed for the project (1 comment), and additional online features that might be included (1 comment). A subsequent question specifically asked how teachers would describe the extent to which systems engineering concepts are presented in the module. Twelve of the thirteen teachers responding selected the response "Coverage is about right". The one teacher who selected "Too little is presented" also recommended that additional papers be included to introduce core concepts.

7 Conclusions and recommendations

The results from the student assessment and completed teacher surveys from this pilot implementation of the SAGE introductory module demonstrate that systems engineering concepts and activities are suitable for high school level courses in technology, engineering, and science. Significant student gains on the assessment indicate that high school students can comprehend and apply systems engineering concepts. Teacher responses demonstrate an interest in incorporating these concepts and activities on a continuing basis as 12 of the 13 teachers responding to the survey reported that they were either very likely (8) or somewhat likely (4) to use this module again. Without the ability to correlate student achievement with teacher responses on the survey, the conclusions that can be reached are limited. It would be desirable to have evidence linking classroom time and student performance, among other correlations, before making sweeping changes to the module. This limitation will be remedied for the next implementation of the module by creating and assigning teacher codes that will also be used by students to allow data from both sources to be linked.

While the preliminary results from the student assessments and teacher surveys are promising, consideration will be given to making revisions to the content of the module, the online collaboration experience, and the student assessments. Teacher feedback regarding the content of the module was overwhelmingly positive and students scored significant gains in the comprehension and application of systems engineering concepts. It should be noted, however, that the overall mean score on the post-test does not demonstrate mastery of the concepts by a large number of students. Although this assessment has a different purpose than a classroom assessment and therefore is not expected to result in the positively skewed results often obtained on classroom assessments, it was expected that the mean score on the post-test would have been higher than the approximately 60% mean that was obtained. This is likely due, at least in part, to the relatively short time devoted to this introductory SE module by several of the teachers, but this does not explain the small (or negative) gains seen in many instances. In order to improve student gains, the module's objectives, activities, and assessment will be reviewed and revised based on feedback and analysis.

Also, modifications of the collaborative experience will be considered as suggested by some of the teachers. Specifically, the schedule for required activities and deliverables will be extended to give teachers more flexibility during project implementation and to account for varying school schedules, holidays, and unexpected school closings.

8 Future and ongoing work

Pilot implementation of the other three SAGE modules commenced in the spring, 2009, and results from that study are currently being analysed. Based on students' assessment data and teachers' feedback we will have a better understanding of the relevance and appropriateness of SE concepts in high school level education. The findings and outcomes of the SAGE project will be used to enhance and disseminate our other similar initiatives on designing and implementing SE curriculum at different levels of education. Stevens will also develop an online short course for each of the modules, comprised of 3–5 sessions, that will be used to supplement face-to-face teacher professional development and also for online, asynchronous professional development. This optional online course will serve to prepare teachers from a wide geographic spectrum and with a wide diversity of backgrounds to implement any of the global engineering modules.

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