AC 2009-410: SYSTEMS AND GLOBAL ENGINEERING: RESULTS OF A PILOT STUDY FOR HIGH-SCHOOL STUDENTS AND TEACHERS

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Systems and Global Engineering: Results of a Pilot Study for High School Students and Teachers

Abstract

This three-year project is designed to engage high school classes in New Jersey and elsewhere 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. This paper presents the findings from the first part of the pilot study; results of the fall 2008 implementation of the module *Introduction to the Core Concepts of Systems Engineering*.

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. Stevens Institute of Technology has partnered with the New Jersey Technology Education Association to introduce concepts and approaches of systems and global engineering to high school technology, engineering, and science students. As part of the Systems and Global Engineering (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 toward the development of an engineered product or system; utilize 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 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. 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 is underway and findings from the fall 2008 implementation of the module *Introduction to the Core Concepts of Systems Engineering* are now available.

Rationale

The current U.S. engineering workforce is facing an urgent problem. Trends reported by the National Science Board show that there are not enough engineering students in the pipeline today to support the workforce of tomorrow. The number of students earning bachelor's degrees in engineering dropped by 17% between 1985 and 2005, despite modest gains between the low in 2001 and 2005[1]. In 2005, less than 5% of those earning bachelor's degrees were in engineering disciplines. In addition, females and minorities have not been completing degrees in engineering at the same rate as males and other groups[2]. The decreasing numbers of students completing degrees in engineering could have a serious effect on the science and engineering workforce of the United States unless more sufficiently prepared students, especially females and minorities, begin studying engineering in college[3].

There is a pressing need to excite and attract students to engineering. Also of critical importance in the contemporary workforce are such technological literacy skills as designing, developing, and utilizing technological systems; working collaboratively on problem-based design activities; and applying technological knowledge and ability to real-world situations[4,5]. These skills are increasingly recognized by business, higher education, and policy leaders as critical for tomorrow's workforce[6]. Furthermore, 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 behaviors and characteristics of the system as a whole.

Thomas Friedman's book, *The World is Flat,* illustrated the globalized and interconnected world in which today's students will work. It is important that students are not only aware of this trend, but are also trained in the skills of virtual collaboration. This is not only a matter of distance, but also of culture, language, skills and many other factors. In addition, the systems and products we create have, to a larger extent than ever before, the potential for global reach. This means that better understanding of potential "foreign" user communities and environments are needed.

Students participating in the *Introduction to the Core Concepts of Systems Engineering* have engaged in a first-hand experience integrating systems engineering and global collaboration as part of an effort to increase the number of students who will go on to pursue engineering education and careers and to provide them with workforce skills for the 21st century.

Pilot Test Description

The two major components addressed during the first year of the SAGE project were to 1) identify and develop the four systems and global engineering curriculum modules and 2) provide professional development on those modules to selected teachers who would then pilot test the materials in their classrooms during the 2008-09 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[7]. Ultimately, four modules that focused on global sustainability issues were developed:

- Introduction to the Core Concepts of Systems Engineering
- Water Purification
- Home Lighting in Developing Countries
- Biodynamic Farming

Each module also incorporates a different type of student collaboration approach (e.g. sharing, mentorship, workflow, or interdependent subsystems) in order to determine the benefits and shortcomings of each[8]. Twenty practicing high school teachers from a diverse mix of New Jersey schools were selected as pilot teachers and during the summer 2008 were trained to implement one or more of the modules in their classrooms as part of the pilot test effort during the 2008-09 school year.

During the fall of 2008, pilot testing for one module, *Introduction to the Core Concepts of Systems Engineering*[9] (introductory module), commenced. 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 which are scheduled for piloting in the spring 2009. 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 introductory module addresses many of the National Science Content Standards, ITEA Standards for Technological Literacy, and New Jersey Core Curriculum Content Standards while introducing students to systems engineering concepts and global collaboration experiences necessary to meet 21st Century learning expectations. The specific learning objectives include:

- Analyze 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 2 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 but 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 CAD/CAE software tool for their designs in order to provide students with a real-world engineering design experience.

Pilot Test 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-four teachers committed to implementing the introductory module in the fall of the 2008-09 academic year. One of these teachers rescheduled classroom implementation to the spring semester. Of the remaining 23 teachers, 16 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. Twelve teachers returned answer sheets for both the pre- and post-tests for their students. Thirteen teachers completed the online survey. The following sections refer to the data collected from these teachers and their students.

Results from the Student Assessment

An assessment to measure student knowledge of and ability to apply systems engineering concepts was developed internally. While use of items from existing assessments with established validity is desirable, a lack of existing courses and assessments for systems engineering at the high school level necessitated development of an assessment for this module. The SAGE project director and an individual with substantial experience in assessment development worked collaboratively to create the assessment, which was then reviewed by two Stevens systems engineering faculty members. Revisions to the assessment were made based on reviewers' recommendations.

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 standardized 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 optimization Key: A
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 serve as an indication regarding 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. 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 has been omitted from all subsequent analyses because the data is 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 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****

*$p < .01$. **$p < .001$.

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 analyzed 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 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	< .001
Level 1	**12**	6.46	7.59	< .001
Level 2	**10**	4.93	5.65	< .001
Level 3	**3**	1.42	1.35	- .079

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 1. 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.

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
	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	.91[1]	.90[1]
3	21	49	49
	23	.93[1]	.87[1]

*p < .05. **p < .01. ***p <.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.

Figure 1: 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

Results from the Teacher Survey

Teachers were requested to complete an online survey after implementing the module in their classes in addition to administering the pre- and post-tests to their students. Thirteen teachers completed the online survey, which provided feedback regarding their experiences with the module and additional information used in interpreting the results from the student assessments.

Unfortunately, teachers were not provided unique identifiers to be used for the survey site and student assessments, so survey responses cannot be correlated with student test results. In several instances, such as prior experience with the content or pedagogy incorporated in the module and the amount of time spent implementing the module, it would be more informative to have the ability to correlate teacher responses with student test results. Despite not having the ability to make this connection, the range of responses provided on the survey provide some insight into student test results and, in any case, provide 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. Considering the extent to which online collaboration figures in completing this module, any challenges that teachers face in this regard are especially important to address. Not surprisingly, of the four teachers who stated that they had prior experience incorporating an Internet-based collaborative project with their classes (not necessarily with their current students, however), all were much less likely to identify any challenges related to collaboration in this project. While the teachers who were new to online collaboration were more likely to report challenges related to this aspect of the project, these teachers were also much more likely to comment on the benefits of collaboration as they perceived them. Table 5 summarizes the comments made regarding both the benefits and challenges posed by the online collaboration.

Table 5: Benefits and challenges of the online collaboration component cited by teachers.

Experience w/ Online Collaboration	**No. of Teachers**	**Comments Related to Online Collaboration**	
		No. of Teachers Commenting	**Comments**
Yes	4	1 cited challenges	Login issues in the early days of the project Converting class work to an online format
		1 cited benefits	Other students' work can be used in self evaluation Commitments to other students requires planning Demonstrates importance of documentation
No	8	4 cited challenges	Timing of interactions Preferring direct contact / work in forum was difficult Prefer assigned school partner / knowing partner school Face time *(no further explanation provided)*
		6 cited benefits	Increased student interest and motivation (cited 4 times) Students considered another perspective Feedback was useful
No Response	1	N/A	N/A

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. It is not clear, however, how this might impact students' gain scores from the pre- to post-test since items related to the process of collaboration and reverse engineering, the focal activity of the collaboration, were not included on the assessment.

Conversely, gain scores on the assessment 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 minutes on the module, while two teachers devoted 640-680 minutes (16 classes of 40 minutes and 8 classes of 85 minutes, respectively). The average amount of time spent based on the reports of the 13 teachers responding to the survey was 278 minutes, or approximately 6.5 class periods of 42 minutes 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 referred to the subject matter content of the module. This teacher recommended that additional articles be included to introduce core concepts. The remaining recommendations referred to collaboration (3 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" is the same respondent who recommended in the previous question that additional articles be included to introduce core concepts.

Examples of Student Work

An asynchronous online discussion forum, Collaboration Central, provided the primary means for student collaboration during the pilot test of this module. This was for two reasons: (1) participating classes might be held at different times during the school day and may also (eventually) be located in different time zones around the world. It was important that all required collaboration take place in an asynchronous mode; (2) In order to effectively assess the strengths and challenges of collaboration in this pilot project, there needed to be a written record of all the collaboration that transpired between schools and classrooms. In the survey, some teachers stated that direct contact with other participants would be desirable rather than having all contact within Collaboration Central. Although the reasons for funneling all contact through Collaboration Central were explained explicitly in the online module and re-iterated a number of times during the teacher professional development, consideration will be given to providing other means of collaboration once the module(s) are ready for formal dissemination.

Collaboration Central was open only while the project was running and required a teacher username and password to access. This was to minimize the amount of SPAM and inappropriate postings made to the discussion forum. Different types of documents, files, images, recordings, and links could be uploaded to Collaboration Central. Students initially shared Letters of Introduction which served to describe their school and geographic location as well as any goals and expectation they may have had for the project. An example of a class Letter of Introduction is shown in Figure 2. Classes later used Collaboration Central to post reassembly instructions for one of the cameras and to provide feedback on another group's posted reassembly instructions after attempting to reconstruct one of the cameras. Figures 3, 4 and 5 depict examples of student reassembly instructions posted to Collaboration Central. Some instructions included engineering drawings, some photos and corresponding directions. Some video clips were also shared.

Figure 2: Class Letter of Introduction

Class Letter of Introduction

Hello, we are from NVOT Regional High School. This class is level one Innovations and Inventions, section two, grades nine through twelve. Northern Valley Regional High School at Old Tappan is located in Old Tappan New Jersey. Our latitude and longitude is 41.01001 and -73.974414. Our school strengths come from sports. Our Varsity baseball program 2007-2008 won the sectional three State Championship. Also, we have a 100% graduation rate and our school was the 18th ranked public high school in New Jersey out of 314 schools according to the New Jersey Monthly magazine. However, one of our weaknesses this year is that our network has failed on us multiple times. At times there is no access to the network, Internet, etc. Our classroom has 24 Mac G5's, containing Photoshop, Vector Works, and Google Sketchup. Our technology classroom has a dedicated workshop. In this workshop we have a variety of hand and machine tools. Moreover, to this effort we can contribute clear and thorough sketches, enabling vivid pictures and concise directions for rebuilding the camera. Our goals in participating include working on projects as engineers do in the real world, improving our communication skills through sketching and learning about system engineering, so we can apply it to our next project. From this first meeting, we wish to learn others weakness's and try to help them with the problem they have. Also from this project, we would want to see how other schools conduct their own projects. In closing, we look forward to this upcoming project, meeting and sharing our ideas to work through this experiment.

Figure 3: Kodak Assembly Drawing

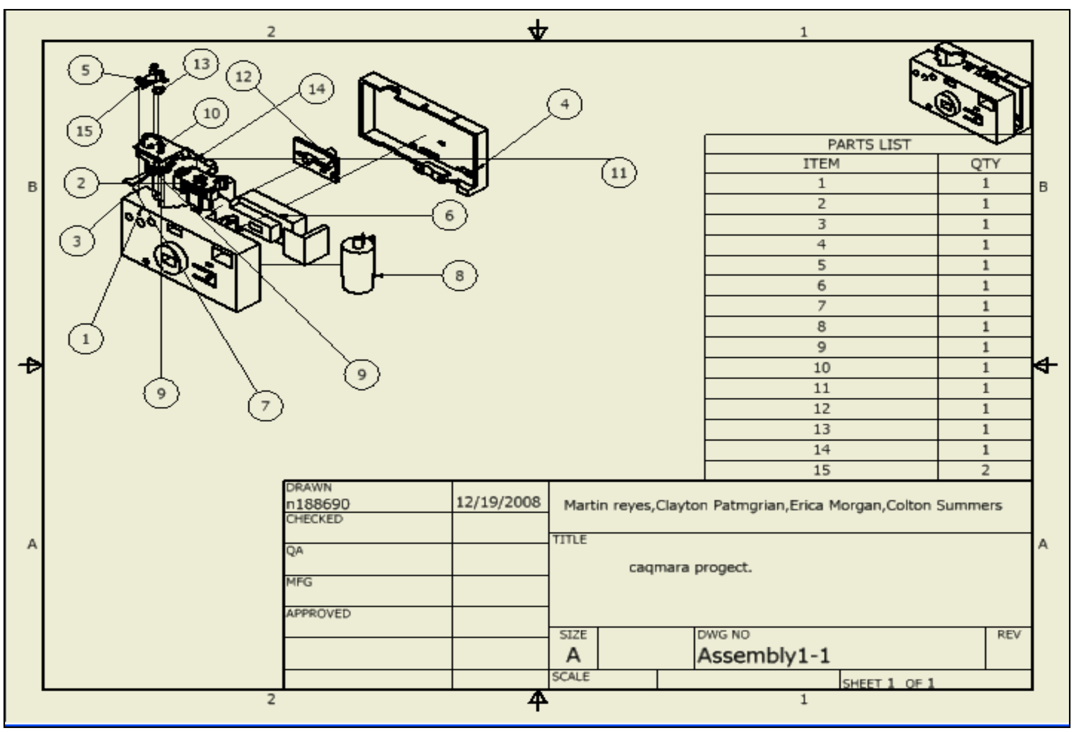
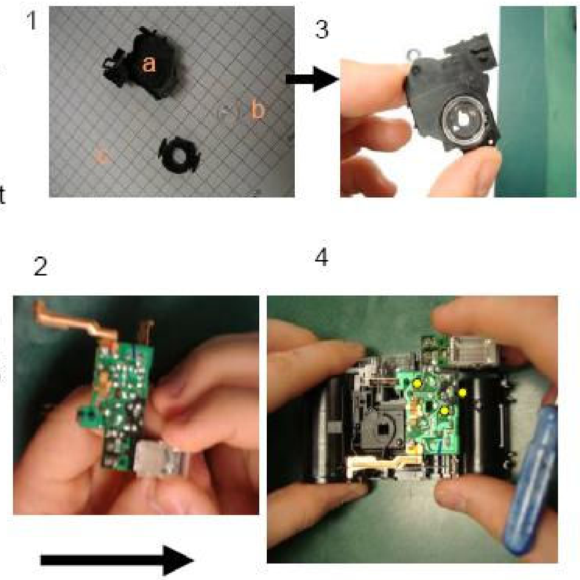


Figure 4: Fuji Assembly Directions (partial)

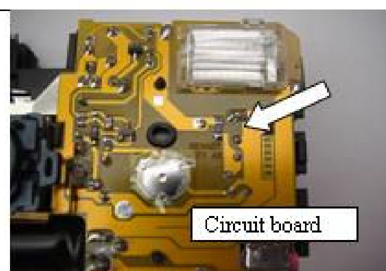
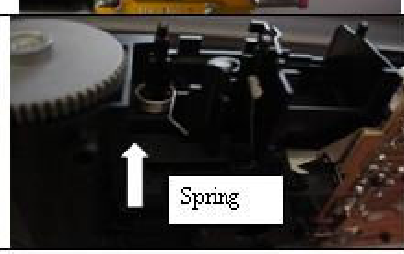
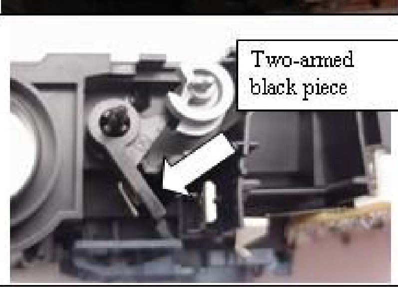
- Number one is the lens assembly and is put together as the letter indicate “a” the “b” then “c”
- And the “b” the lens is placed on “a” the base “c” the cover will twist on to “a” and lock c the lens in place finished it will look like picture three
- Two will be placed on to the main back piece. It should slide on to a few rods facing up, the will line up with corresponding holes



Holes indicated with yellow dots

Figure 5: Kodak Reassembly Instructions (partial)

KODAK CAMERA ASSEMBLY

1	Place circuit board on the frame	
2	Put the spring inside the camera	
3	Place the two-armed black piece on top of the spring.	

Conclusion 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 both appropriate and desirable 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 the module by several of the teachers, but this does not explain the small (or negative) gains seen in many instances. Several recommendations will be considered to address this issue:

- Conduct an internal review of the stated objectives for the module
- Compare the stated objectives to the activities in which students will be engaged to determine the extent to which these are matched
- Revise the objectives and/or the activities based on the review of the objectives and the correlation between objectives and activities
- Analyze assessment results by item, including an analysis of student responses
- Compare the assessment items to the stated objectives and student activities
- Revise the assessment based on the analysis of student responses and the comparison to the objectives and student activities
- Strengthen the systems engineering content by providing additional online resources such as current news articles and optional in-class activities

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.

Next Steps

As the project progresses and the other three modules are piloted in the spring 2009, additional data collected from student assessments, teacher surveys, and classroom visitations will provide more complete information regarding the impact of the project; specifically, on teacher classroom practices as a result of implementing one or more of the SAGE modules. The resulting modular curriculum will be disseminated, via workshops, presentations, and articles in relevant journals and magazines, to other high schools throughout New Jersey and nationwide. These modules will form an important resource in a major statewide initiative that Stevens is leading in New Jersey to ensure that all K-12 students experience engineering as an integral component of their K-12 education, not merely as an elective or extracurricular activity.

In conjunction with the pilot test, 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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