Massachusetts was the first state in the nation to introduce engineering as part of the K-12 education frameworks. In the middle schools, the engineering framework is tested as part of the compulsory Massachusetts Comprehensive Assessment System (MCAS) exam. The engineering framework requirement provides an opportunity to introduce problem-based learning modules on engineering and technology, to motivate students to pursue math, science and engineering careers, and to increase technical literacy of students. Studies show that middle school is a critical intervention point for encouraging the study of math and science, especially for girls.\textsuperscript{1,2} The goal of the NSF-sponsored 4 Schools for WIE (Women in Engineering) project is to use the Massachusetts engineering framework requirement to infuse the curriculum with gender-neutral modules and activities that focus on engineering and technology.

\textit{4 Schools for WIE} is a partnership of four engineering colleges in Massachusetts: Northeastern University, Boston University, Tufts University, and Worcester Polytechnic Institute. Each partner school has a STEM (Science, Technology, Engineering, Mathematics) Team composed of one engineering faculty member, two middle school teachers, one or more professional engineers, and one or more graduate or undergraduate engineering college students. \textit{4 Schools for WIE} uses these all-female (when possible) STEM Teams to help teachers develop engineering education modules, and to serve as in-class resources for teachers in the greater Boston area. Each STEM Team is responsible for developing and piloting a project-based module that meets the goals of \textit{4 Schools for WIE} and that can be disseminated throughout Massachusetts and the United States. More information about the NSF-sponsored \textit{4 Schools for WIE} endeavor can be found in a separate article ("Schools for Women in Engineering: Innovative Approaches to Increase Middle School Students Interest in STEM" by Reisberg, \textit{et al.}) as part of these proceedings.

\textbf{The Great Orange Squeeze} is the module developed by the Northeastern University STEM Team, a joint effort between Northeastern University, Raytheon Corporation, the Josiah Quincy Middle School and the Grover Cleveland Middle School. While the module is designed to meet Massachusetts state requirements, the incorporation of engineering principles into 8\textsuperscript{th} grade curricula and the discussion of engineering careers with middle school students can benefit school systems nationally by helping the students understand the value of math and science and encouraging more students to consider engineering as a career. It further benefits the engineering profession by generating interest in the field.
The Great Orange Squeeze is a hands-on, open-ended problem that illustrates both the differences and the interdependence of science and engineering in defining a problem and creating a solution. The students are posed with the challenge: “How can we get nutritious, good-tasting orange juice from Florida to kindergarten breakfast programs in Boston Public Schools for $0.15 an 8-ounce glass?” The module leads students through six activities that illustrate the engineering design process presented in the MCAS and shown in Figure 1. In order to prepare students for the engineering strand of the MCAS exam, many of the Massachusetts Science and Engineering Frameworks are incorporated in the module’s activities. Those criteria that are addressed in the module are listed in Figure 2. The Massachusetts Science and Technology/Engineering Curriculum Framework can be found on the world wide web at: http://www.doe.mass.edu/frameworks/current.html.

Figure 1: Eight-step Engineering Design Process as presented in the Massachusetts Comprehensive Assessment System (MCAS) Guide.

1. Identify the need or problem
2. Research the problem
3. Develop possible solutions
4. Select the best possible solution(s)
5. Construct a prototype
6. Test and evaluate
7. Communicate the solution(s)
8. Redesign

Figure 2: List of Massachusetts Science and Engineering Framework Requirements that are addressed in The Great Orange Squeeze module. The numbering system below is aligned with the numbering of the framework requirements.

1) Earth and Space Science-Heat Transfer in the Earth System
2) Life Science-Energy and Living Things
3) Physical Sciences
   a) Properties of Matter
   b) Elements, Compounds, and Mixtures
   c) Heat Energy
4) Technology/Engineering
   a) Materials, Tools, and Machines
   b) Engineering Design
   c) Communication Technologies
   d) Manufacturing Technologies
   e) Transportation Technologies
The goals of *The Great Orange Squeeze* module are to:

- involve student interest in an enjoyable and equitable way,
- build a connection between engineering careers and helping society,
- illustrate as many engineering framework criteria as possible,
- illustrate both the differences between Science and Engineering and their interdependence in solving technical problems that benefit society, and
- incorporate active learning, experience-oriented tasks and inquiry-based design.

These goals reflect the benefits to student learning by incorporating active learning and inquiry-based design into activities.\(^3\) They incorporate the findings that female students are likely to be interested in pursuing careers that they can see as helping society.\(^4\) Because middle school students and teachers often have little experience with engineering or engineers, the project makes an effort to illustrate the differences as well as the interdependencies between science and engineering. In addition, *The Great Orange Squeeze* meets the overall *4 Schools for WIE* goals of supporting the MCAS engineering strand requirements, encouraging girls to pursue engineering careers, and producing modules that can be shared throughout and beyond Boston.

*The Great Orange Squeeze* is a series of six activities: “Manufacturing and Transportation of Orange Juice”, “Heat Transfer in the Production of Orange Juice”, “Flowsheets and Procedures: Engineer’s Communication Tools”, “Orange Concentration Prototype I”, “Orange Concentration Flowsheet and Prototype II”, and “Orange Concentration Process: Test, and Retest”. The module is intended to be flexible and adaptable so that some activities may be left out or expanded upon depending upon what aspects of the science and engineering criteria the teacher wishes to emphasize. All activities are designed for groups of two to five students. From start to finish the entire module takes approximately 4 weeks of Science classes. The equipment necessary for a moderately sized classroom (20 to 25 students) is approximately seven hundred dollars.

In the sections below, each activity is described in more detail and related to both the engineering design steps (Figure 1) and the framework requirements (Figure 2). The complete module has been developed, documented, pilot tested, and modified based on feedback from the pilot test. The second pilot test, which includes assessment activities, is scheduled for April 2004. Additional assessment of the impact of the module on student performance (as measured by MCAS exam scores) and student interest in engineering careers (as measured by student surveys and interviews) is also in progress, and preliminary findings will be available in Summer of 2004.

**activity 1: “manufacturing and transportation of orange juice”**

The first activity includes an introduction on engineering and engineering careers. Then the students are asked to be engineers and are presented with a challenge, which is designed to generate student interest and require them to use both science and engineering concepts to solve the problem. The challenge is as follows:

In the United States, many school children do not receive proper nutrition. Vitamin C is especially important for growing children. This important vitamin is needed every day for a strong immune system, to resist
infection and to maintain the body’s ability to heal itself. An 8-ounce glass of orange juice contains 100% of the daily-required vitamin C.

As an Engineer at Tropicana® you are trying to sell your OJ to the Director of Food Services for Boston Public Schools breakfast program. However, due to recent budget cuts the director will not buy it unless it meets the budget constraint of $0.15 per student.

How can we get nutritious, good-tasting orange juice from Florida to the breakfast programs in Boston in an affordable way?

In this activity students are introduced to the engineering design process (Figure 1) and they work on the first 4 steps: identify the need or problem, research the problem, develop possible solutions, and select a best possible solution. First the students identify the problem from the challenge. Then research different transportation systems that will be able to deliver orange juice to the final destination as well as determine the cost associated for each system to see if any meet the budget constraint. They also research the different types and costs of commercial orange juice to see how that influences their decision. From their research, they develop many possible solutions in both forms of orange juice (fresh, pasteurized, frozen concentrate) and modes of transportation (plane, train, truck). They must choose the best possible solution based on their analysis of cost and quality (orange juice spoilage with transportation time).

By the end of the activity the students must conclude that due to budget constraints the best possible solution is to provide concentrated orange juice to the schools. Note that the challenge can be adapted to any scenario that sets a cost goal, leads students to explore both types of orange juice and modes of transportation, and leads to the conclusion that concentrated orange juice is the most desirable option. The module provides student worksheets to facilitate the research and cost analysis. An example worksheet is provided in Figure 3. The module has been piloted as independent group work and as interactive classroom discussions with break-out activities; both with equal success.

In addition to Engineering Design, this activity covers the Transportation Technologies aspect of the Science and Engineering Frameworks. There are options to expand the activity that are outlined in the module documentation and include: the impact of orange juice on nutrition that connects with the Life Science framework, and discussions of the different processes that produce the different types of orange juice that connect with both the Manufacturing Technologies, and Physical Sciences frameworks.

activity 2: “heat transfer in the production of orange juice”

Once students decide that the concentrated orange juice leads to the best quality orange juice within the budget constraint, they are faced with a new challenge: how to concentrate the orange juice from 100% fresh juice to a concentrate with 50% of the volume of fresh juice. This takes them through the first four steps of the design process again to find the best possible solution for evaporating water from fresh orange juice. For the research step, students need to turn to science to gather information about heating and evaporation in order to design the best possible solution.
for the concentration of orange juice. Activity 2 leads the students to investigate different forms of heat transfer and discover how they work.

In “Heat Transfer in the Production of Orange Juice,” students use science to gather the heat transfer information needed to solve the engineering challenge of removing water from the orange juice mixture. After suitable background information, the students experiment with evaporating water from a cup of fresh orange juice using possible heating systems: a hair dryer (convective heat transfer), a hot plate (conductive heat transfer), and a heat lamp (radiation heat transfer). They measure initial and final volume and mass of the orange juice, and they measure the temperature of the juice with time during heating. An example of this experimental setup is shown in Figure 4.

From the experiments, students identify the different types of heat transfer and observe the evaporation rate using the different methods. They also observe and account for the impact of evaporation on the volume and density of the liquid mixture to illustrate the concept of “concentration” of the orange juice. Costs in dollars per minute are also applied to each heating method so that the students can evaluate the relative economics of using the three heating methods to evaporate 50% of the initial liquid volume. Using samples prepared ahead of time, the students also taste reconstituted juice from slightly, moderately, and highly concentrated juices. Because of the tools provided in the kit, conduction heat transfer using the hot plate is the most efficient and economical method to concentrate the orange juice. Students also discover
that reconstituted orange juice does not taste as good as the fresh orange juice, and the taste gets worse with greater levels of concentration. (This observation becomes important in the prototype design.)

Figure 4: Experimental setup for Activity 2: discovering the science of heat transfer (convection, radiation, conduction) needed to solve and engineering problem (how to concentrate orange juice efficiently).

In addition to showing the interdependence of science (discovering the differences in the three forms of heat transfer) and engineering in solving a problem, this activity addresses both the Engineering Design and the Physical Science Frameworks. There are several options for expansion of this module including mathematical analysis, computer spreadsheets and graphing, boiling points of mixtures, and mass balance (conservation of mass).

activity 3: “flowsheets and procedures: engineer’s communication tools”

Once the students discover that the hot plate is the most efficient and economical tool to use to concentrate the orange juice, the next step is to design a process to concentrate the orange juice. However, the students are not necessarily aware of “manufacturing processes” or tools used to communicate about processes, like flowsheets and procedures. Every manufacturing process, independent of the complexity of the process, must have a flowsheet and a procedure. In this activity the students develop a flowsheet and a procedure for a simple process based on their experience and interest. A favorite topic for this module is producing a creative new snack product.

“Flowsheets And Procedures: Engineer’s Communication Tools” introduces the students to manufacturing processes and to the use of flowsheets and procedures as important communication tools by using examples the students can identify such as the back of a cake mix
or the directions for hooking up a new computer. These examples are presented as processes to make a product (a cake or a working computer). They both have instructions of how to make the product, and these instructions include both symbols pictorially representing the idea and written words giving information and directions. These instructions are examples of flowsheets and procedures. It is even possible to point out the importance of safety as part of flowsheets and procedures in processes such as hot mitts pictured on the back of prepackaged cake mixes and electrical connections in connecting computer equipment. A key aspect of flowsheets and procedures is that they must be followed exactly as presented in order to ensure that the final product is the product that the process was designed to create.

After this background, the students are exposed to an industrial-scale manufacturing orange juice concentration process (through either a tour or a virtual tour), and then given the following challenge:

**New Snack Challenge:**
You are a design engineer for the Holiday Candy Company. Your job is to create a new holiday treat for 8th graders across the globe. You must design the snack and how to make it (the snack process) so that your company can produce your snack. As a good engineer, you know that first you must create possible snack ideas and then choose the best one. Then, you need to design your snack process and test your snack process to see if it works. To test your snack process you must create a flowsheet of your process and see if the senior process engineer (another group) can make your snack according to your intended design.

The students, in groups of 2, create a flowsheet for making a new snack food with a variety of provided supplies. The groups then swap flowsheets and try to follow the other group’s procedure to make the desired product (a snack food). Oral presentations of the intended snack and the actual result of following the flowsheet can be both amusing and a valuable learning experience.

Activity 3 builds the students’ frame of reference for engineering by providing them with an experience with the design process and with communicating ideas through flowsheets and procedures. From Figure 1, design steps 3 (Develop possible solutions), 4 (Select the best possible solution(s)), 5 (Construct a prototype), 7 (Communicate the solution(s)), and 8 (Redesign) all involve creating and testing ideas and communicating those ideas to others. For the Massachusetts framework requirements (Figure 2), the Engineering Design, Manufacturing Technologies, Communication Technologies, and Materials, Tools, and Machines Frameworks are addressed in the module. Through the “mini-project” of designing and communicating their design of a snack product, the students are ready to approach the design and communication of their orange juice concentration process.

**activity 4, “orange concentration prototype I”**

The students have already discovered the science of heat transfer (Activity 2) and learned that conduction is the most efficient way to transfer heat to the orange juice with the tools provided. They have experienced creating and using flowsheets and procedures to communicate design
solutions (Activity 3). They are now ready to use this information and these skills to help them solve the challenge.

In “Orange Concentration Prototype I”, the students design a prototype (Step 5 of the Engineering Design Process) of a process to concentrate orange juice using their best heat transfer method. They also create a flowsheet and procedure for their process. As they create the flowsheet and procedure, the students discover the need for more science and experimentation in order to understand the process variables needed to complete their flowsheet. This activity also introduces the impact of process design choices on product cost and quality, which is reinforced in Activity 5.

This activity begins with a PowerPoint slide presentation of an actual orange juice concentration process. Various aspects of process design are discussed such as worker safety, environmental protection, and waste management. For example, evaporated and condensed water from the concentration process is reused as wash water for the incoming fruit, and peels and excess pulp are added to cattle feed. Simple economics of the process are introduced, such as processing time having a cost in labor and utilities, the cost of raw materials, and the cost value of recycling streams or selling undesired side-products. The students are told that manufacturers solve the quality problem of poor tasting reconstituted juice by adding a small amount of fresh juice to the concentrate before the freezing process.

After this background (and some background on condensation if necessary for the students), the students are given the materials and tools for the prototype design shown in Figure 5. Then, using their current knowledge, the students construct a preliminary flowsheet and prototype for their best solution of a concentration process. They then evaluate their solution and realize that they need more information about process variables in order to solve the problem (Step 6 of the design process in Figure 1). The students need to know how long to heat their orange juice to produce the desired concentration and they need to know how much fresh juice to add in order to produce a good quality product. To find the answers to these questions, Activity 5: “Orange Concentration Flowsheet and Prototype II” allows the students to “go back to science” and discover the time, volume and taste relationships with heating the orange juice to remove water.

Figure 5: Materials and tools for the prototype design.

<table>
<thead>
<tr>
<th>Item</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermometer</td>
</tr>
<tr>
<td>Stainless Steel Funnel</td>
</tr>
<tr>
<td>Stainless Steel Cup</td>
</tr>
<tr>
<td>Hot Plate</td>
</tr>
<tr>
<td>Timer</td>
</tr>
<tr>
<td>Measuring Cup</td>
</tr>
<tr>
<td>Straws</td>
</tr>
<tr>
<td>Ice</td>
</tr>
<tr>
<td>Duct Tape</td>
</tr>
<tr>
<td>Cardboard Tubes and Sheets</td>
</tr>
<tr>
<td>Paper Towels</td>
</tr>
<tr>
<td>Oven Mitts</td>
</tr>
<tr>
<td>Safety Glasses</td>
</tr>
</tbody>
</table>
This activity addresses the Engineering Design, Materials, Tools and Machines, Communication Technologies, and Manufacturing Technologies Frameworks (Figure 2). There may be several variations in design of the prototype. This illustrates the concept of multiple correct solutions to problems. However, the kit comes with a stainless steel cup and funnel that fit together to collect the water vapor evaporating from the juice. This part of the prototype is standard for all groups to ensure at least partial success in concentrating the juice. One possible flowsheet prototype is shown in Figure 6. Note the insulation on the "evaporator". The more materials options provided for the prototype design, the more varied the designs will be.

Figure 6: Example of portion of possible prototype flowsheet.

activity 5, “orange concentration flowsheet and prototype II”

In Activity 5, “Orange Concentration Flowsheet and Prototype II”, the students must experimentally determine the correlation between the time of heating and the volume reduction for their prototype and determine the amount of fresh juice to add to different concentrations of orange juice to meet the taste quality requirement. With this new science information and the cost information, the students can optimize their design to balance the quality of the juice and minimize the cost of the juice. At the end of this activity, the students have produced a final flowsheet and procedure for their concentration process and have calculated the cost of their product per 8 oz glass of reconstituted juice.

The experimentation to determine the correlation between the time of heating and the volume reduction for the prototype takes several trials of starting with an initial volume and heating at the desired rate for different amounts of time. The condensing part of the process is not necessarily needed during this step, but the funnel and cup combination that catches the water vapor can influence the net evaporation rate and should be part of this experimentation. It is not
uncommon during this experimentation for students to modify their prototype design as they gain experience in running their system. This can be used to strengthen the concept of the design, test and evaluate, and redesign loop of the Engineering Design process (Steps 5 through 8 in Figure 1) and to discuss the evolution of manufacturing processes from laboratory scale to pilot scale to full scale.

The experimentation to determine the amount of fresh juice to add to the concentrate to produce “good-tasting” orange juice is best done with stocks of various concentrated juices that are prepared by the teacher in a way that ensures that the samples may be safely tasted. This has been done by simply heating fresh orange juice in a cooking pot on a home stove and reducing the volume by 10%, 25%, and 50%. The determination of taste is, of course, qualitative and a matter of opinion. Because a consequence of heating the orange juice is the destruction of vitamin C, a quantitative option for this step is to measure the vitamin C content of the juice after the various amounts of heating, and adjust the amount of fresh juice addition to meet a range of acceptable vitamin C content in the reconstituted juice. Simple iodine-based test procedures for vitamin C (ascorbic acid) content are available and adaptable to the classroom environment.

This activity addresses the Engineering Design, Materials, Tools and Machines, Communication Technologies, Manufacturing Technologies, and Physical Sciences Frameworks. Exploration of vitamin C content may be used to incorporate the Life Science Framework. An additional expansion of the activity would be to include the freezing step of the process. There may be several variations in design of the prototype. The development of the economic analysis can also be expanded to stress developing mathematical relationships and using a spreadsheet to plot changes in cost with changing process conditions such as heating time.

As with Activity 5, each group’s design will be different, especially in terms of the process variables of heating time and amount of fresh juice addition. This translates to different costs for an 8 oz glass of reconstituted juice. The more materials options provided, the more varied the process designs will be. Once the students have a completed flowsheet with procedures, they are ready to build their complete process and produce their product.

activity 6: “orange juice concentration process: test, and retest”

In “Orange Juice Concentration Process: Test, and Retest”, the students must demonstrate their process by following their flowsheet and procedure from Activity 5, and evaluate their product’s ability to meet the challenge of providing cost effective, good-tasting orange juice to Boston Public Schools. The students present their solution to the class, which includes their flowsheet and procedure, cost for an 8oz glass of constituted juice in Boston, a qualitative taste rating, and any recommendations they have for improvements to their own process design. By the end of the module, students are able to identify and use the Engineering Design Process of Figure 1. They are able to effectively communicate an engineering design with a flowsheet and procedure. They can describe what engineers do, and can discuss the differences and interdependence of science and engineering in solving societal problems.
initial pilot implementation results and future plans

The module was first piloted during the 2002/2003 school year. Student interest in the project was higher than expected and very rewarding. The most popular activity was the flowsheet exercise in Activity 3, and the second most popular aspect of the module was, surprisingly to us, the economic analysis of the process. The assessment processes to determine student learning from each activity varied among the teachers, and was mostly qualitative. Although the activities seemed successful in meeting their objectives, assessment methods are now included as part of the modules and will be tested as part of the second pilot implementation.

There were several concrete and practical changes that came from the first pilot implementation. The time requirements of the activities was largely unknown prior to the first pilot, and will still be refined in the second pilot. Activity 4 was initially designed to require the students to design their prototype on paper before being given materials to build their prototype. However, the design, flowsheet, and prototype process became much less frustrating and more efficient when the students were provided the materials for the prototype right away. The first pilot helped to revise the student worksheets to make them more valuable and more worksheets have been added to the module. The teachers requested more detailed background information and, with input from the teachers, the documentation for the module has been expanded and modeled after the Full Option Science System (FOSS) module format. Specific assessment tools have been added to the module.

The second pilot implementation of the module is scheduled for April of 2004. In addition to the module assessment, additional assessment through the 4 Schools for WIE program will be performed. This includes the impact of the module on student performance as measured by MCAS exam scores, and the impact of the module on student interest in engineering careers as measured by student surveys and interviews. These efforts are being lead by a team external to the STEM team and are in progress. Preliminary findings from these assessments will be available in the summer of 2004. The impact of the module as determined by these assessment tools will be published in a later paper.

Engineers use science to make products that solve our society’s problems. Many products are made through a manufacturing process. In The Great Orange Squeeze, the students, as engineers, make concentrated orange juice through an evaporation and condensation manufacturing process to provide low cost, good tasting orange juice to Kindergarten Breakfast Programs in the City of Boston. The module covers several aspects of both the Science and Engineering MCAS Frameworks, and is flexible enough for teachers to use individual activities or the entire module. The concepts included in them module are aligned with the American Association for the Advancement of Science (AAAS) recommended science education standards and can be used in any 8th grade classroom.

The Great Orange Squeeze enriches the student’s exposure to the design process and to engineering, and increases their technical awareness. It is hoped that through this interactive, gender-equitable learning activity and through the use of this activity to expose students to women engineers, more girls will develop an interest in science and engineering careers.
more 8th graders become interested in science, math, and engineering, the more future engineers and scientists will be available to meet our technical and societal challenges.

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Bibliography
6. FOSS is a research-based science curriculum for grades K-8 developed at the Lawrence Hall of Science, University of California at Berkeley. It is an ongoing research project dedicated to improving the learning and teaching of science and can be found on the world wide web at: http://lhsfoss.org/index.html.

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