
AC 2011-312: TIERED SCAFFOLDING OF PROBLEM-BASED LEARNING TECHNIQUES IN A THERMODYNAMICS COURSE

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Tiered Scaffolding of Problem-Based Learning Techniques in a Thermodynamics Course

Abstract:

Problem-Based Learning (PBL) holds the promise of training students to tackle ill-defined, ill-structured problems and enhance transference of student knowledge from typical classroom activities to real-world design and analysis. However, some educational researchers (e.g. Kirschner, Sweller et. al.^{1,2}) contend that minimal guidance techniques such as PBL fail to account for “human cognitive architecture” and produce exceedingly high cognitive loads, resulting in less learning than guided instruction. This paper addresses the gap between high-level, high cognitive load PBL techniques by presenting a tiered scaffolding approach ranging from highly guided to entirely un-formed (student-formed) problems in a Thermodynamics course. This approach includes short, structured in-class problems, a version of Challenge-Based Instruction (CBI) carried out as ill-structured problems in class, and student-developed Thermodynamic Inquiry Projects carried out outside of class time. In addition to details of the approach, data on pre/post test assessments and student surveys will be presented.

Introduction:

Problem-based learning (PBL), in which students solve ill-defined, ill-structured problems, aims to give students the experience of using course material in manner closer to that encountered in a “real-world” setting, thus increasing transference of course material outside of “textbook” examples. Analyses of published studies on the effectiveness of PBL show that it results in more positive student attitudes, a deeper conceptual understanding of course material, ability to apply material (transference) and improved retention of knowledge as compared to traditional instruction^{3,4}.

While most educational studies agree on the definition of problem-based learning, the detailed implementation can vary widely from virtually no guidance or formal class time to moderate guidance during formal class time^{3,4}. It may be versions of PBL at the minimal-guidance extreme that led Kirschner et. al.¹ to name PBL as an example of an “instructional procedure that ignores the structures that constitute human cognitive architecture,” or more specifically, an instruction method that “proceed[s] with no reference to the characteristics of working memory, long-term memory, or the intricate relations between them.” The tax on working memory during minimally guided instruction, Kirschner et al. argue, is great enough that students use all working memory in their attempts to search for problem solutions, blocking their ability to truly learn the material via the accumulation of knowledge in long-term memory.

However, as noted in Hmelo-Silver et. al.’s response to Kirschner et al.⁵, many PBL strategies do employ scaffolding that reduces the load on working memory and allows for material to reach the long-term memory. Although scaffolding has a variety of definitions in educational literature, common characteristics amongst the nearly all scaffolding models include contingency based on students’ level of competence, fading of support over time, and eventual transfer of responsibility to the learner⁶. For example, Reiser,

Quintana, and co-workers^{7,8} have done extensive work on using software tools to support inquiry learning by structuring the task (including decomposing complex tasks and focusing effort) and “problematizing” aspects of subject matter (leading students to engage with important ideas or processes); while inquiry learning does differ from problem-based learning, this type of scaffolding could easily be applied to PBL. Hmelo and Guzdial⁹ also worked in the area of software-based scaffolding, and introduced the idea of black-box vs. glass-box scaffolding: black-box scaffolding guides students through an efficient path to achieve a goal, but does not facilitate learning how to perform that goal independently or when conditions might differ from the original task. On the other hand, glass-box scaffolding also supports student learning, but is designed to gradually decrease support so that students are able see “implicit models made explicit” and begin to construct their own learning. While Hmelo and Guzdial’s work was focused on software, this concept can clearly be applied universally.

The aim of the approach presented in this paper is to maintain PBL’s advantages in training students to address ill-defined real-world problems while providing sufficient scaffolding (in a manner similar to Hmelo and Guzdial’s glass-box scaffolding) to address cognitive architecture concerns raised by Kirschner et al. and Sweller et al.^{1,2}.

Tiered Scaffolding Approach

The six-tiered approach shown in Figure 1 below was used to prepare students for PBL (here in the form of challenge problems and Thermodynamics Inquiry Projects) by moving them up the levels of Bloom’s Taxonomy¹⁰. While the course generally proceeded from Tier 1 through 5 for each challenge (Thermodynamic Inquiry Projects or TIPs were ongoing throughout the semester; more detail below), the basics of the relevant challenge were presented at the outset of each section to motivate student learning.

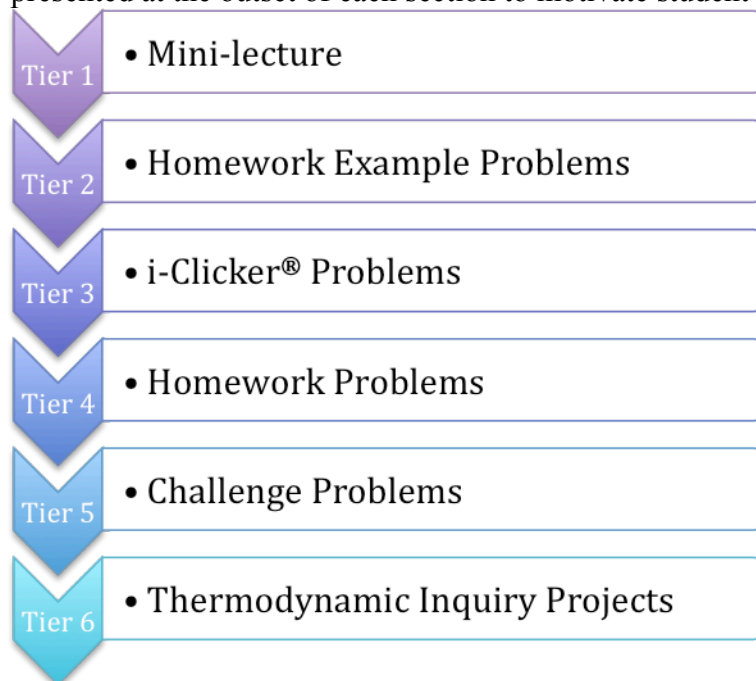


Figure 1: Six Tiers of Scaffolding

The details of this particular tiered scaffolding approach were designed to fulfill the goals and objectives of E82: Chemical and Thermal Processes. This course is required of all Engineering majors (Harvey Mudd College has a general Engineering degree) and covers mass and energy balances and thermodynamics. It is the only chemical engineering course and the only thermodynamics course required for HMC Engineering majors (other chemical engineering and thermodynamics courses may be taken as electives). As such, the goals of this course are to:

1. Familiarize students with challenges that can be solved by chemical engineers and thermodynamicists.
2. Provide students with enough knowledge in thermodynamics and mass balances to analyze, evaluate, and design related engineering processes and systems and to teach themselves more advanced concepts in these areas where necessary.
3. Connect students with the real-world physical roots and implications of the course material, particularly thermodynamics.
4. Develop students' technical writing skills.

The course outcomes (with related ABET outcome noted in parentheses) are:

1. Students will be able to identify and formulate problems involving mass balance and thermodynamics (ABET E).
2. Students will be able to choose, justify, and correctly apply appropriate equations of state or data tables to solve thermodynamic problems (ABET A, C).
3. Students will be able to interpret and explain the physical meaning of thermodynamic equations and concepts (as well as mass balances).
4. Students will be able to use mass balances and thermodynamics to solve engineering problems, including the selection and justification of appropriate assumptions (ABET A, C, E).
5. Students will be able to use thermodynamics and mass balances to design and evaluate processes and systems (ABET A, C, E).
6. Students will be able to clearly communicate problems, methods, and solutions involving thermodynamics and mass balances (ABET G).
7. Students will demonstrate understanding of the impact of their work on society (ABET F, J).

Tier 1: Mini-Lectures

After motivating the material by introducing or reminding students of the current challenge problem (see Tier 5 for further discussion of challenge problems), a short “just-in-time” lecture would be given on a portion of the relevant material. The lecture time never exceeded 10 minutes and generally the instructor spent less than 5 minutes lecturing before moving on to either a Homework Example Problem (Tier 2) or an i-Clicker question (Tier 3)

Tier 2: Homework Example Problems

For each major concept presented in the mini-lecture, the instructor stepped students through a corresponding “Homework Example Problem”. This was simply an end-of-chapter book problem, parallel to example problems used in most courses. Calling this a “Homework Example Problem” seemed to clue students in to reviewing the problem and

solution when working on their own homework in a way that simply discussing similar example problems without the moniker did not: while exact numbers are not available, previously frequent comments requesting more problems like the homework problems all but disappeared from minute papers (used at the end of each class session) and course evaluations.

The instructor always began the solution by addressing the following three items:

System Definition: Is the system open or closed? What is the selected control volume (for an open system) or control mass (for a closed system)?

Assumptions: The instructor asked students to think about reasonable models they might select for the substance (e.g. ideal gas, incompressible liquid) and terms they might be able to neglect (e.g. negligible change in kinetic energy).

Physical Laws: In this section, the instructor wrote out a common version of the first law, second law entropy balance, and/or mass balance (if reactions or multiple units were present) and asked the class to help cancel out terms based on the assumptions and/or problem statement.

Again, this tier is certainly not particularly innovative, but was intended to provide a “worked example” for students to follow while attempting other problems, with the hope of benefitting from Cooper and Sweller’s worked example effect¹¹ wherein students showed marked improvement after studying problems solved by an instructor.

Tier 3: i-Clicker[®] Questions

i-Clickers[®] are a particular brand of real-time audience-response systems. In this course, i-Clicker questions ranging from entirely conceptual (aimed at addressing major misconceptions) to those requiring design calculations were posed with multiple-choice solutions. Problems that required calculation typically were related (but not formulaically similar) to the immediately preceding Homework Example Problem, hopefully beginning the benefits of the worked example effect. A wide body of literature has addressed the benefits of such systems, so this paper will not go into detail other than to state that the real-time feedback on student comprehension was extremely valuable and employed immediately to either spend additional time on concepts and/or methodologies for solving problems or to confidently move on to the next subject.

Tier 4: Homework Problems

Homework removed the immediate assistance of the instructor available for the i-Clicker[®] questions and brought the students another step closer to autonomy. The homework problems assigned for the course were mainly typical end-of-chapter book problems, but did include several concept questions each week to help students think about the physical meaning and implications of thermodynamic concepts rather than simply applying equations. The formatting of problem solutions used in class (System Definition, Assumptions, and Physical Laws - see “Homework Example Problems” for details) was required on the homework. In addition to giving students a rigorous method for approaching problems, this format was meant to address student complaints regarding the inability get started when solving problems.

Tier 5: Challenge Problems

Challenge-Based (CBI) is (or, at least, can be framed as) a variant of PBL: rather than approaching course material as a sequence of topics, CBI presents material through a series of specific challenges or modules. The development of CBI was inspired by advances in learning science brought forward in the 2000 book “How People Learn”¹², and is centered around a learning cycle (typically the STAR.Legacy learning cycle developed at Vanderbilt University). After presenting the challenge, students reflect on initial thoughts, then receive information in the form of perspectives and resources; they then apply what they have learned and are assessed in some form, and finally, the challenge is solved either by the student or an expert or some collaboration between both. At its best, CBI results in student-driven learning as the instructor guides students in solving the challenge and an environment characterized by active participation and involvement in a learning community. A great body of educational research and materials on CBI in biomedical engineering has been developed by the VaNTH ERC (Vanderbilt-Northwestern-Texas-Harvard-MIT Engineering Research Center)¹³⁻¹⁵.

For this course, a series of challenges motivated the learning thermodynamic concepts with the aims of increasing student interest in chemical engineering and learning in thermodynamics, presenting students with a tangible real-world problem in an what is often a severely abstract subject, and, of course, the typical PBL goals of equipping students to solve ill-formed real-world problems. While the full CBI format was not followed, each challenge was presented with a good deal of information, some extraneous and some necessary that students must sort through to solve the challenge. Additionally, in some cases less information was given than necessary and students must make reasonable assumptions (with help from the instructor on an as-needed basis) to complete the challenge. Students solved the problems in small groups while the instructor walks through the room answering questions; we then went over the solution as a class.

The specific challenges are listed below, with the thermodynamic or other subjects addressed by the challenge in parentheses (for more details including full challenge problems and supporting materials, please e-mail the author):

1. **Design and Cost-Savings for a Solar Batch Water Heater** (internal energy changes for incompressible liquids, heat transfer, economic evaluation, alternative energy);
2. **Solar Bag Time to Lift-off** (internal energy changes for ideal gases, heat transfer, P-V work);
3. **Sizing a Solar Electric Generation System (SEGS) for HMC** (enthalpy changes for incompressible liquids and use of steam tables, technical feasibility via space requirements, introduction to power cycles, alternative energy);
4. **Economic Feasibility and Environmental Analysis of Pumped-Hydro Storage** (isentropic efficiencies, economic feasibility, overall energy costs, seemingly-alternative energy);
5. **Feasibility of Large Ocean Thermal Energy Conversion (OTEC) Power Plant** (power cycles, use of thermodynamic tables, isentropic efficiencies, alternative energy, technical feasibility);

- 6. Economics and Energy Costs for Hydrogen Production via Steam Methane Reforming** (mass balances on reactive processes, energy balances on reactive processes, alternative energy, economic and energetic analysis). *Please note that there was not enough time to finish this final challenge in the two semesters in which the tiered scaffolding approach was implemented; hopefully this will be covered in Spring 2011.*

Tier 6: Thermodynamic Inquiry Projects

The uppermost tier, the Thermodynamics Inquiry Projects, or TIPs, required students not only to think about thermodynamics beyond the textbook, but also to formulate their own problems in thermodynamics. In pairs, the students investigated two inquiries of their choosing over the course of this semester (one focused on the first law of thermodynamics and the other focused on the second law of thermodynamics) and for each inquiry, wrote a short (3 pages or less) paper on the inquiry, investigation, and results, and presented a mini-poster (standard letter size paper). The short length of the papers and small size of the posters were designed to help students think about the most important elements of the work and also reduce workload. The students were instructed to look for a topic that isn't necessarily serious or important, but 1) does have reasonable scope (not too big, not too small), 2) is original, and 3) requires thermodynamic analysis. It was suggested that they look for steady-state processes (or processes that can be approximated as steady-state, such as solar energy collection during the day) to simplify their analysis (the course focused on steady-state processes with only minimal coverage of transient processes). If the solution to their inquiry (or a very similar one) could be found online or in the literature, they were required to choose a new topic. For the first project (focused on the first law of thermodynamics), they were strongly encouraged to choose inquiry topics that required the calculation of an internal energy or enthalpy change. To aid students in topic selection, they were required to meet with the instructor to discuss their ideas. This helped eliminate inquiries that could be solved with simple algebra, were solvable with freshman physics concepts, or were too complicated for the scope of the class. Some sample effective topics included calculating the efficiency (in terms of heat directly resulting in drying versus total work input) of a clothes dryer on campus, calculating the internal temperature Superman would reach if he actually stopped a train dead in its tracks, determining the isentropic efficiency of the human heart, and determining the power production potential of sunburned students (via a power cycle).

Students were required to turn in a rough draft of their TIP report one week before their final draft. This rough draft served several purposes: first, it forced students to abide by "good practice" of writing and editing multiple drafts. Second, students could not put the final report together entirely the night before it was due (while they could put the draft together the night before it was due, they needed to come back to the report at a later date to review their work before turning in the final version). Finally, students received feedback from an instructor on any misconceptions evidenced in the report, and were required to act to correct these misconceptions for the final draft. This was preferable to

the typical summative feedback received with grades, which students may or may not read in depth and do not need to work to correct.

Students were evaluated using a rubric (appended to this paper) in the following categories inspired by ABET outcomes:

1. Ability to communicate effectively (via the TIP report).
2. Ability to communicate effectively (via the mini-poster).
3. Ability to Identify and Formulate Engineering Problems in Thermodynamics.
4. Ability to Apply Knowledge and Solve Engineering Problems in Thermodynamics.
5. Demonstration of an understanding of the impact of the inquiry area and inquiry solution in a global, economic, environmental, and/or societal context (as relevant).

Assessment:

The main form of direct evidence for achievement of student outcomes was the TIP rubric evaluation. The rubric scores showed a strong performance on the TIPs (see Figure 2). As mentioned above, students were scored on written communication in the paper, communication via the mini-poster, their ability to identify and formulate the problem, their ability to solve the problem, and their demonstrated understanding of the implications (technical, environmental, and societal) of their work. As shown in Figure 2, students received an average between 4 (“Very Good”) and 5 (“Exemplary”) on all items. These high scores were certainly due in part to review process: most students responded to comments on their drafts, either by coming in for a meeting to discuss the material or correcting the errors on their own, and thus received a high score. Scores for the mini-poster were the lowest, presumably because virtually no guidance was given for the posters (other than a brief mention in class of what they should contain and the sample posters). As these scores were assigned by the instructor and therefore potentially biased, future assessment for this course will hopefully include analysis by an outside evaluator.

As additional direct evidence, students took the Thermodynamics Concept Inventory¹⁶ as a pre- and post-test for bonus homework credit. Unfortunately, this data is not available at the time this paper was written; it should be available in time to be included in the oral presentation. Additionally, to more closely assess the design-based and concept learning outcomes and the long-term effects of the course format, in Spring 2011 a new pre-test/post-test will be piloted that includes longer-form open-book problems and essay answers related to key thermodynamics concepts. This test will also be administered to students who took the course in previous semesters, either using this approach or an approach without CBI (gift certificates will be offered as compensation for their time) to examine retention of the course material. This data may also be available for the oral presentation.

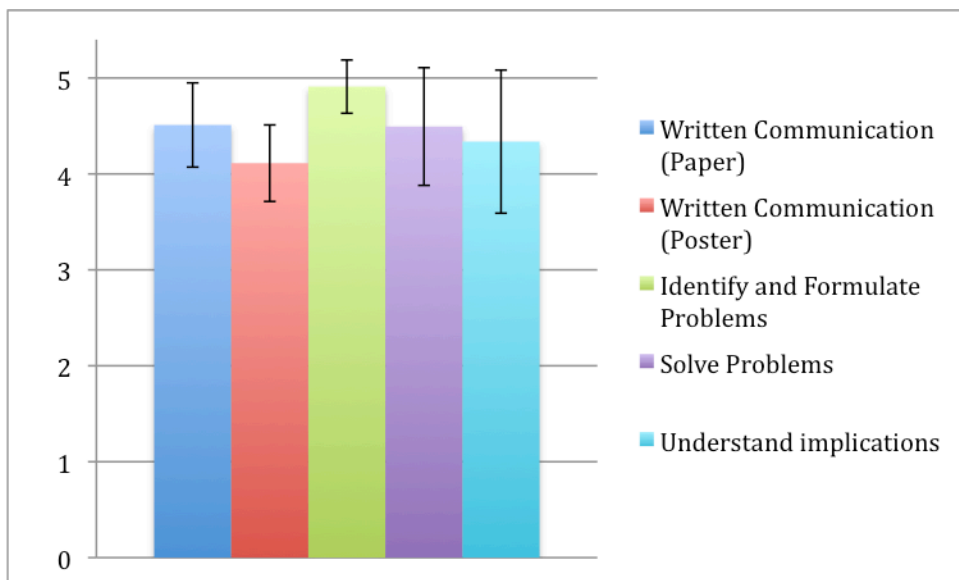


Figure 2: Sample rubric scores for the TIP (5= Exemplary, 4 = Very Good, 3 = Acceptable, 2 = Needs Improvement, 1= Poor; please see the appended rubric for a full description of each category). Error bars represent the standard deviation.

In the realm of indirect and anecdotal evidence, the TIPs led to many conversations with students that brought to light and allowed the instructor to clear up misconceptions about thermodynamics that may have only become evident when grading exams, if at all. The majority of students also saw the benefit of the TIP, as seen below in comments from an anonymous online end-of-semester survey:

“You really had to be comfortable with the concepts in order to write a TIP report. It wasn't something that you could have a hazy understanding of and still expect to get a good grade, so in that way it forced you to sit down and really work through all the intricacies of whatever concept(s) your TIP covers.”

“The best aspect of the TIP projects was that they really made you think about how the topics discussed in lecture apply to real-world applications beyond those discussed in textbook problems. The process of applying concepts to an open problem helped solidify my understanding of the material.”

“It was no longer a contrived problem out of a textbook. There weren't things we were necessarily supposed to do, steps to follow, or equations that were 'supposed' to be used for that type of problem. Instead, since everything was decided by us, we had to deal with all aspects of the problem and decide if the assumptions made were reasonable. It was much more realistic than other problems and homework sets.”

Regarding indirect/anecdotal evidence regarding the success of CBI and the tiered approach leading up to the CBI, instructor observations confirm that students eagerly and

successfully tackled these complex, ill-defined problems after moving up through the lower tiers of scaffolding. Furthermore, when speaking to students about their TIP, homework, or general study questions, they often referred to the challenge examples instead of the more “standard” examples provided in class or the textbook. For example, when analyzing design choices for a new vapor power or refrigeration cycle, many students mentioned how it was “just like that OTEC [Ocean Thermal Energy Conversion] cycle challenge we did in class.” The following student comments regarding these challenges are taken from an anonymous online survey administered in Spring 2010:

“I think the best thing about [the challenges] was how they combined a lot of concepts/equations/material and served as very distinct separators in the curriculum. You could really get a feel for how much you understood the material after doing the challenge problem since they were so cumulative. They were also real-world problems; projects that people deal with today so that made it interesting. Finally, they gave a sense for what solving the problem would be like out in industry: particularly sifting through the enormous amounts of material available to find only the info you needed to solve the problem.”

“They were taken directly from real world problems. It put the coursework in perspective in relation to how it is used in the real world.”

“I liked how interesting they were. The [i-Clicker problems] are somewhat interesting and help to learn sections of the material better. But the challenge problems really test your understanding, and how to apply everything together. I really enjoyed learning how the things we’ve learned in class can be applied to real world problems.”

As a final note on assessment, many instructors worry that implementing active learning techniques will adversely affect student evaluations of teaching. The various tiers of this approach were added over the course of several semesters to reach the final operating version, and student evaluations (of the instructor and of the course) have risen steadily with the additions. For the Fall 2010 semester, “The course was effectively organized to promote the learning objectives.” was rated an average of 6.50 on a 7-point Likert scale (7 = “strongly agree”); “The course stimulated my interest in the subject matter.” was rated a 5.89/7 (recall that this is a required course for students including those most interested in somewhat divergent fields such as electrical engineering); and “I learned a great deal in this course.” received an average score of 6.30/7.

Conclusions:

The tiered scaffolding approach employed in this course was designed to maintain the benefits of ill-formed problems posed by PBL techniques while addressing concerns about the tax on working memory during learning. Preliminary evidence suggests that the course outcomes can be successfully achieved via this method; future assessment data

will further clarify areas of greatest strength and need for improvement. The author would be happy to share materials related to this work upon request.

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Thermo Inquiry Project: Grading Rubric

Partner Team: _____ and _____
TIP # _____

Each aspect of the project below will be rated using the following 5-point scale and weighted as shown in the Grade Summary:

- 5** – Exemplary
- 4** – Excellent
- 3** – Acceptable
- 2** – Needs Improvement
- 0-1** – Poor

Ability to Communicate Effectively (Paper)

<i>Criteria</i>	The paper is well-organized, follows formatting guidelines laid out in the assignment sheet, is written clearly and concisely in a single, appropriate scientific voice, transitions well from one section to another, and is free or nearly free of grammatical errors.
<i>Your score</i>	
<i>Comments</i>	

Ability to Communicate Effectively (Mini-Poster)

<i>Criteria</i>	The mini-poster is clear, engaging, and appropriate for the intended audience. The most important aspects of the inquiry and inquiry solution are presented accurately and sufficiently.
<i>Your score</i>	
<i>Comments</i>	

Ability to Identify and Formulate Engineering Problems in Thermodynamics

<i>Criteria</i>	The inquiry requires a thermodynamic solution. It is clearly stated and appropriate background information has been provided.
<i>Your score</i>	
<i>Comments</i>	

Ability to Apply Knowledge and Solve Engineering Problems in Thermodynamics

<i>Criteria</i>	The system and appropriate subsystems have been properly defined and thorough 1 st law (both TIPs) and 2 nd
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	law (required for Second TIP) balances have been correctly carried out. Efficiency has been defined and calculated where reasonable.
<i>Your score</i>	
<i>Comments</i>	

Demonstration of an understanding of the impact of the inquiry area and inquiry solution in a global, economic, environmental, and/or societal context (as relevant).

<i>Criteria</i>	The paper shows understanding of the strengths and weaknesses of the solution to the inquiry and the impact of the inquiry and inquiry solution in a global, economic, and/or societal context, as relevant. Ties are made to other potential applications of analysis applied in the paper.
<i>Your score</i>	
<i>Comments</i>	

Grade Summary

	Raw Score	Weighting	Final Score
Ability to Communicate Effectively (Paper)		1	
Ability to Communicate Effectively (Poster)		1	
Ability to Identify and Formulate Engineering Problems in Thermodynamics		3	
Ability to Apply Knowledge and Solve Engineering Problems in Thermodynamics		5	
Demonstration of an understanding of the impact of inquiry in a global, economic, environmental, and societal context.		1	
TOTAL	--	--	____/55