Teaching and Assessing Critical Thinking in Engineering Thermodynamics

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Introduction

"Critical thinking" has recently been adopted as a proficiency in the University's proposed outcomes-based core curriculum. Once the new core is approved, each program in the university will be required to demonstrate that its students satisfy the associated critical thinking outcomes either through additional courses or existing courses that have been modified to satisfactorily address the outcomes. The impending imposition of critical thinking outcomes has typically been greeted by engineering faculty members with comments such as "Of course we can meet those outcomes: engineering is all about critical thinking!" This may be true, but as is often the case in engineering program assessment, rigorously demonstrating that a given course satisfies the outcomes is not a trivial matter. In this paper we present a plan for the teaching and assessment of a formal critical thinking component in a thermodynamics course. The course structure has been redesigned to address critical thinking through the introduction of the principles of logic and a mandatory problem solving procedure. The critical thinking outcomes are assessed through specially designed assignments and with the help of a scoring rubric tailored to the problem solving methodology. The paper addresses questions such as: What is critical thinking and why is it important? What are the characteristics of a critical thinker? How can critical thinking skills be taught and assessed in engineering courses in general, and particularly in thermodynamics? The paper will show how the concepts of thermal efficiency, reversibility, work and heat, properties, and the 1st and 2nd Laws can be used to help students apply the principles of sound argumentation, identify and avoid informal fallacies, determine relevant assumptions, and evaluate results and their implications. Contemporary challenges related to energy conservation, fossil fuel use, alternative energy sources, and global warming will provide a context for application of critical thinking skills.

What is critical thinking, how can it be taught, and why is it important?

Brookfield[1] defines critical thinking as a process which consists of identifying assumptions, checking the validity of assumptions, considering ideas and actions from diverse viewpoints, and taking informed action. Edward Glaser[2] identified three elements of critical thinking: (1) an attitude of being disposed to consider in a thoughtful way the problems and subjects that come within the range of one's experiences, (2) knowledge of the methods of logical inquiry and reasoning, and (3) some skill in applying those methods. It is interesting to note that both these descriptions imply that critical thinking involves more than just thought: it also includes an aptitude for action based on that thought. Facione[3], in a discussion of the results from the American Philosophical Association Delphi Report, defines it as the "purposeful, reflective judgment which manifests itself in reasoned consideration of evidence, context, methods, standards, and conceptualizations in deciding what to believe or what to do." Paul and Elder[4] define it as simply "the art of analyzing and evaluating thinking with a view to improving it." They go on to describe the critical thinker as one whom

> • raises vital questions and problems, formulating them clearly and precisely;
> • gathers and assesses relevant information, using abstract ideas to interpret it effectively;
> • comes to well-reasoned conclusions and solutions, testing them against relevant criteria and standards;
> • thinks openmindedly within alternative systems of thought, recognizing and assessing, as need be, their assumptions, implications, and practical consequences; and
> • communicates effectively with others in figuring out solutions to complex problems.

Claris and Riley[5] assert that critical thinking is not merely the use of a set of skills, but a questioning of power relations within engineering. Young college students often fall victim to uncritically believing that what the professor says must be true because of her position, experience, qualifications, etc. To address this, Riley and Claris[6] described a project intended to promote critical understanding of issues in engineering thermodynamics, including an activity where students critique analogies for the concept of entropy found in a popular thermodynamics textbook.

Giancarlo and Facione[7] suggest that critical thinking must consist of not only cognitive skills, but of a *disposition* towards critical thinking. They cite seven attributes that dispose a person towards critical thinking: truthseeking, open-mindedness, analyticity, systematicity, critical thinking self-confidence, inquisitiveness, and maturity of judgment. Interestingly, they also point the negative manifestations of these characteristics: intellectually dishonest, intolerant, inattentive, haphazard, mistrustful of reason, indifferent, and simplistic. They also presented results from a student study that showed the critical thinking attributes were either maintained or increased in strength over four years at a liberal arts university, suggesting that, at least to some extent, critical thinking can be taught.

Ralston and Bays[8] discuss the Paul-Elder Critical Thinking Framework[4], presenting the associated intellectual traits of a critical thinker as: intellectual humility, intellectual autonomy, intellectual integrity, intellectual courage, intellectual perseverance, confidence in reason, intellectual empathy, and fair-mindedness. These are developed by applying the "elements of thought," posited as purpose, point of view, information, concepts, questions, assumptions, inferences, and implications. They cite a study by Paul et al.[9] that showed 89 percent of 140 faculty members at 38 public and 28 private colleges claimed CT as a primary objective in their teaching, while only 9 percent were explicitly teaching critical thinking skills. They assert that

> Any conscientious engineering educator must ask:
>
> - How am I teaching/developing critical thinking in my students by modeling critical thinking skills, intentionally incorporating critical thinking skills in learning activities, and providing diverse opportunities for students to apply critical thinking skills in real world situations?
> - Are students aware they are learning critical thinking skills?
> - Are students even aware of the need for critical thinking skills?

The authors present the development, application, and initial validation of a rubric used to assess critical thinking skills for engineering assignments.

How can critical thinking be taught? While some educators believe that a problem solving methodology may promote critical thinking, others criticize such a strategy for being too discipline specific. Many educators link the philosophical study of logic to critical thinking. In fact, at the University, the first course to be approved for the critical thinking proficiency area was a philosophy course entitled *Introduction to Logic*. Meyers[10], however, questions the belief that understanding logic skills carries over into critical thinking in disciplines other than philosophy. He goes on to assert that both the study of logic and problem solving methods have limitations in teaching critical thinking, and proposes a more holistic approach that addresses attitudes about raising questions, suspending judgment, and "enjoyment of mysteries and complexities."

Cooney et al.[11], in a review of approaches to teaching critical thinking in engineering and technology, identify two best practices used in the classroom: writing for reflection and problem-based learning. They also describe the disconnect between what faculty think they are teaching their students in terms of critical thinking and student perceptions of how much critical thinking they are being taught.

Siller[12] describes the application of a "reflective judgment development model" to a freshman level design course on sustainable development. He mentions the difficulty with assessing success for such a project. Switzer et al.[13] present a hierarchical cognitive model that fosters lower level cognitive skills early in a student's academic career in order to provide a solid foundation for the development of high level cognitive skills. They present results that demonstrate the effectiveness of their approach in improving low level skills.

Lewis et al.[14] emphasize that students should be aware that they are being taught critical thinking skills, and describe a class where critical thinking is incorporated through 1) an explicit lecture on critical thinking using the Paul-Elder Framework as a guide, 2) a critical thinking "breakout session" where student groups apply critical thinking approaches to specific "word" problems, 3) a critical thinking assignment, followed by a quiz covering the critical thinking elements of thought, 4) case studies in which students prepare reviews using critical thinking principles, and 5) a pre- and post-assessment instrument involving multiple choice, Likert scale, and open ended questions covering student understanding and application of critical thinking skills.

Why is critical thinking important? At the very least it helps to avoid embarrassment that can happen when a young engineer proposes an unworkable solution to a team of experienced engineers - an unfortunate episode that could have been avoided if the engineer had only performed a "reality check." Much of the pedagogical effort in critical thinking is geared towards equipping students to keep themselves from getting hoodwinked by politicians or advertising, or to rationally approach hot-button issues like global warming or abortion. As Brookfield[1] states,

> So critical thinking is not just an academic process that leads to good scores on SATs, elegantly argued essays, or experimental hypotheses that can stand the toughest scrutiny. It is a way of living that helps you

> stay intact when any number of organizations (corporate, political, educational, and cultural) are trying to get you to think and act in ways that serve their purposes.

Such lofty goals may seem far removed from the "mundane" study of thermodynamics, but as we shall see, the critical thinking outcomes we address find application both within the discipline and in broader contexts.

At first glance it seems that some aspects of critical thinking as typically proposed, such as empathy, have little relevance to engineering problem solving. Perhaps it is straightforward to think of relevant examples in a design class, where customer needs are identified as part of the design process, but what about an engineering science class like thermodynamics? How can the ability to consider viewpoints other than one's own be useful in the analysis of a steam power cycle? I would argue that perhaps the most useful application of empathy is in communication of results and conclusions. When asked to compare two results, for instance, students may unthinkingly present them serially, in a seemingly unconnected fashion. If they consider the recipient of the results, however, they would present the results as juxtaposition, either graphically or in a table. In fact, presenting the development of an engineering analysis in a logical, readable, and orderly fashion is in itself demonstrating an appreciation for the viewpoint of the reader.

Regardless of all the attention given to defining critical thinking in the literature, in this paper I necessarily constrain myself to viewing critical thinking in terms of the University's core outcomes. In essence, these consist of a set of abilities that together, in the view of the collective wisdom of the faculty at the University, characterize a critical thinker.

The critical thinking outcomes for the new University core consist of the following:

Students will be able to:

1. Identify the assumptions, methods, and standards of evidence in various fields of study.
2. Recognize the discipline-specific language of signs and symbols and their role across disciplines.
3. Apply the fundamentals of sound argumentation in order to critically analyze the evolving aspects of human knowledge and experience.
4. Compare different opinions and claims of knowledge, and recognize the limitations of their own perspectives.
5. Discriminate between results and conclusions, and evaluate their implications.

In the next section I address the following questions: how can the content of the course be used to address these outcomes, and how can student proficiency at meeting the outcomes be assessed?

Satisfying the University outcomes in thermodynamics

Below I describe course content specific to each of the five critical thinking outcomes, and give sample assessment exercises along with expectations for student responses.

Outcome (1). Identify the assumptions, methods, and standards of evidence in various fields of study. *Assumptions* are critical to engineering analysis. Just as in dynamics the student must assume the absence of friction, or in statics that a body behaves rigidly, most thermodynamic analyses require simplifications to make problems tractable. Commonly employed assumptions include the specification of adiabatic and/or reversible processes, steady state behavior, neglect of kinetic and potential energy terms, heat transfer with isothermal reservoirs, and uniform flow properties at inlets and exits. In fact, thermodynamics is typically the first place where the engineering student is exposed to the concept of irreversibility and learns how unrestrained expansion, spontaneous chemical reactions, electric current flow through a resistance, inelastic deformation, heat transfer through finite temperature differences and other deviations from "perfect" behavior are linked to 2^{nd} Law considerations.

The *method* applied in thermodynamic analysis is introduced as a problem solving methodology outlined in Table 1. This methodology consists of listing given information, succinctly paraphrasing the problem statement, identifying assumptions, drawing a schematic, identifying the general governing equation, analyzing the problem by simplifying the governing equation and performing necessary calculations, highlighting the results, and drawing conclusions. The *standards of evidence* include thermodynamic properties or system characteristics such as velocity, power production, or rates of heat transfer. These quantities appear as either inputs or calculated outputs in any given analysis. An important standard of evidence is the thermodynamic water and refrigerant tables. Students become proficient at performing single and even double interpolation to estimate properties at states intermediate to the discrete values found in the tables.

Significant class time is devoted to example problems done by the instructor on the board and by the students during inclass exercises individually and in groups. The problem solving methodology indicated below in Table 1 is followed in all examples, where assumptions, methods, and standards of evidence are addressed. Time is also spent discussing the validity of assumptions and the effect on results if the assumptions are violated (as, in fact, they invariably are).

Table 1. Solution methodology and scoring rubric for thermodynamic problems. All eight parts of a problem solution are scored with numerical values 0 – 3. Scores for relevant task descriptions are used to assess CT outcomes 1 and 5.

	3	2	1	0
Givens	All givens necessary for solving the problem are stated along with units; givens noted in the problem statement but not necessary for solving the problem have been eliminated.	All givens necessary for solving the problem are stated along with units; some irrelevant givens are listed, or givens are stated without accompanying correct units. Some givens confused with assumptions.	Given list is incomplete.	Givens are not explicitly listed.
Problem statement	Problem statement is clear and thorough.	Problem statement is clear but missing some important variables.	Problem statement is ambiguous or misses critical unknowns.	Problem statement not included.
Assumptions	Assumption list is complete, including assumptions such as adiabatic, steady, constant property, reversible, frictionless.	Some assumptions are missing or confused with givens.	Most assumptions are missing, or simply implied in the calculation section.	No assumptions are listed.
Schematic (if appropriate)	Drawing is clear and properly labeled.	Drawing exists, but is somewhat unclear or has missing information (state labels, dimensions, etc.)	Drawing ambiguities hinder the problem solution.	No relevant drawing exists.
Governing equations	All relevant governing equations are given in full form.	Some key equations are missing or erroneous, or reduced form of governing equations are given.	Most key equations are missing.	All given equations are wrong.
Analysis	Equations are properly reduced according to assumptions, and algebraically manipulated correctly to solve for the unknown on the left in terms of knowns on the right (if possible). Steps in the analysis are easy to follow. Unit conversions are explicit and correct.	Some errors in reduction, algebra, or units cancellations exist. Analysis steps are somewhat difficult to follow.	Many errors in reduction or algebra exist. Units are ignored. Analysis is messy and hard to follow.	Analysis is irrelevant or unreadable.
Results	Results are clearly indicated, correct, and thorough.	Results are given but not clearly highlighted, or some key results are missing, or some results are erroneous.	Results are incomplete, wrong, or difficult to identify.	No results found.
Conclusions	Correctness of the results is judged (“reality check”). Validity of answer in terms of assumptions is discussed. “What if” scenarios are considered.	Correctness of the results is judged (“reality check”). Validity of answer in terms of assumptions is discussed.	Erroneous results are improperly judged to be reasonable, or assumptions not reflected upon.	No conclusions are drawn.

Outcome (1) specifies that students must identify assumptions, methods, and standards of evidence in *various* fields of study. This means students should have exposure outside thermodynamics. In class the plan is to introduce students to the social sciences using information from a text such as that from OpenStax College[15]. DeLittle[16] highlights the assumptions, methods, and standards of evidence in the social sciences. For instance, he cites the example of a social scientist using Mill's method of agreement to determine a necessary and sufficient condition for the success of union organizing drives. He cites sources of evidence for social sciences to include census data, historical archives, interviews, and observations of practice. And he describes the two divergent views of peasant rebellion in China based on researcher's assumptions about peasant rationality and religious motivations.

Following the brief introduction to social sciences, the students will be given an exercise such as that given in Table 2. Two scenarios are presented in which students will be asked to explicitly identify the assumptions, the method of inquiry, and the standards of evidence used in the study.

Table 2. Exercise used to assess outcome (1) for various disciplines.

Scenario	Expectations
1) *A group of sociology students want to test the following hypothesis: A disproportionate number of African American drivers in the city of Pleasantville are stopped for traffic violations. The group of students decides to test the hypothesis by making observations in court and at several busy intersections. They will use census data to determine the proportion of African Americans in Pleasantville.*	Students will identify the assumption that the observation times chosen are representative of the behavior of traffic police; they will identify the method as observation, and the evidence as the number of convicted African Americans compared to the total number of convicted violators.
2) *Students want to design an experiment to confirm the pressure at which water will boil at room temperature as given in their text. They place a mercury thermometer in one orifice of a two-holed stopper fitted to the throat of an Erlenmeyer flask. A vacuum pump and pressure gauge are connected through a tube to the other orifice. After all parts are in place, the vacuum pump is turned on and readings are recorded after steady state has been reached.*	Students will indicate that assumptions include the absence of leaks around the tubes where they penetrate the stopper or between the stopper and flask, that the point of temperature measurement is representative of the entire water temperature, and that the measurement devices are calibrated correctly. Method is the design of an experiment using engineering measurement devices to confirm the textbook data on saturation values. Evidence includes pressure and temperature measurements.

Outcome (2). Recognize the discipline-specific language of signs and symbols and their role across disciplines. "Signs and symbols" is interpreted as word definitions and symbols for concepts as employed in various disciplines. I plan to focus on the concepts of efficiency and entropy. These are two terms that are used extensively both inside and outside technical circles, and comparing meanings and interpretations across disciplines, and even within a single discipline, is valuable for clarifying student thought.

For most thermodynamic applications, students use the definition of efficiency as the ratio of energy (or power) desired to energy (or power) spent. In some cases a more useful definition might be desired output divided by input, but in all cases it should be defined as a unitless quantity (or percentage) whose upper limit is unity (or 100 percent). For this outcome, we present students with several common usages of efficiency in everyday life, and ask them to provide a technical definition. This makes them think specifically about the ambiguity of the word in general usage in contrast to the necessity of a narrow well defined meaning in energy contexts. Students are also asked to critique several misapplications of thermodynamic efficiency that they may come across.

Efficiency is often used loosely, and can accompany sloppy thinking. Students are taught to recognize this. For example, a consumer may hear from the salesperson a comment like "this vacuum cleaner is extremely efficient." Although impressively worded, the consumer should pursue the real meaning behind the statement. Does it mean that the device is more effective at removing filth from shag carpeting? Does it mean that the devices uses less electricity, and thus costs less to operate? If so, does it do as good a job at removing loose dirt and dust as its competition? Pressed to define an efficiency for a vacuum cleaner, the attentive thermodynamics student will conclude that it needs to be expressed as a ratio of two measurable effects, as a desired output divided by an input. This precise definition is imperative if various vacuum models are to be compared. For instance, one possible definition is the volume of debris removed over the electrical energy expended. Students should recognize that this definition is not unitless, but has units of volume over energy (for instance, gallons over kWh). When pressed to come up with an efficiency that is unitless (which must be done if the efficiency is to be expressed as a percent), students may define an efficiency as volume of debris collected over volume of air passing through the machine.

Other examples of student exercises are given in Table 3. The third example covers the multidisciplinary aspect reflected in the outcome statement.

Table 3. Exercises used to assess outcome (2) regarding the use of "efficiency."

Problem	Expectations
You are at a trade show for residential heating systems. You listen to a salesperson claim that his company's heat pump is "400 percent efficient" as opposed to his competitor's high efficiency natural gas furnace which is "only" 90 percent efficient. Evaluate the salesperson's claim regarding comparative efficiencies.	Students will recognize that the salesperson is confusing coefficient of performance with an engineer's understanding of efficiency, which is energy desired over energy spent, and which can never be greater than 100 percent.
Develop a meaningful definition for the efficiency of an electric hair drier.	Students will recognize that the definition of efficiency as the ratio of energy desired to energy spent is meaningless for an electric resistance device used to produce heat. Per this definition, such a device always has an efficiency of 100 percent (sales literature will sometimes state that an electric resistance heater is 100 percent efficient!). Students will recognize that the purpose of a hair is not to heat up the hair, but to dry it. A reasonable definition may be the ratio of the rate of evaporative energy transfer (which is proportional to the rate at which liquid water is removed from the hair) to the electric power input. Although this definition depends on hair type and hair drying technique (orientation with respect to head and speed at which the dryer is moved over the head), it lends itself to a reproducible test where a specimen of a certain hair type and configuration is wetted with a known mass of water

	and placed with a certain orientation to the dryer outlet is used.
Look up an economist's definition of efficiency and compare and contrast it with efficiency as used in thermodynamics.	Students will discover that economic efficiency concerns the production of goods at the lowest possible cost, while the thermodynamic first law efficiency is the ratio of energy desired to energy spent.

Other exercises for assessing this outcome will be related to thermodynamic versus popular understandings of entropy. This is ripe ground for exploring the ambiguities and misunderstandings surrounding this highly elusive "sign and symbol," and future work will entail the development of exercises to help students recognize these misunderstandings. (See Jeppsson et al.[17] for a discussion of the controversy surrounding teachings about entropy.)

Outcome (3). Apply the fundamentals of sound argumentation in order to critically analyze the evolving aspects of human knowledge and experience. The fundamentals of arguments as typically taught on a course on logic will be presented (see, for example, the textbook by Hurley[18]). I will present material defining and giving examples for deductive and inductive arguments, and provide tools for establishing the validity of deductive arguments. Students will also learn how to identify arguments versus nonarguments, premises and conclusions, and strong versus weak inductive arguments.

Students are taught that the laws of thermodynamics are inductive: all our experience to date indicates that energy can neither be created nor destroyed, and thus we expect that in all future situations energy will be conserved. Corollaries, on the other hand, use statements of thermodynamic laws to deductively argue various conclusions. For instance, the 2^{nd} Law states that it is impossible for a heat engine operating on a thermodynamic cycle to produce a net work output while exchanging heat with a single thermal reservoir. Given this statement as a premise along with additional premises having to do with heat engine reversibility, it can be concluded that all reversible heat engines operating between thermal reservoirs at the same high and low temperatures must have the same efficiency.

An example of an invalid deductive argument is as follows: The integral of the quantity $\delta Q/T$ along a reversible path between two states is independent of path. The integral of a property between two states is independent of path. Therefore, $\delta Q/T$ is a property. Restated as a valid deductive argument this becomes: The integral of the quantity $\delta Q/T$ along a reversible path between two states is independent of path. Any quantity whose change in value between two states is independent of path is a property. Therefore, $\delta Q/T$ is a property. In the teaching of classical thermodynamics the understanding of this logic is a vital foundation for subsequent use of entropy in engineering calculations (although it, arguably, lends little physical insight into what entropy actually is). Table 4 gives several other examples of exercises used to assess this outcome.

Table 4. Exercises used to assess outcome (3) regarding the nature of arguments.

Problem	Expectations
Analyze the following argument by addressing the subsequent questions: An adiabatic, reversible process is isentropic. Process A is isentropic. Therefore, process A is adiabatic and reversible. a) Is this argument deductive or inductive? b) if the argument is deductive, judge its validity. If the argument is inductive, state whether it is strong or weak. c) prove the truth or falsity of the initial premise.	Students will determine the argument to be deductive and invalid. This argument illustrates a common error made by students, that "isentropic" means reversible and adiabatic. Another exercise involves students demonstrating that an irreversible process in which cooling occurs can also be isentropic.
State whether the following passage is an argument or a nonargument: The Orthodox Church of America has long been a proponent of environmental stewardship. Lately the Church leadership has issued a communication calling for local governments to institute community recycling programs.	Students will recognize a nonargument.
Indicate the premise(s) and conclusion in the following argument: Increasing transportation efficiency is the best place to start efforts to reduce emissions of carbon dioxide (CO_2), which is a primary culprit in global warming. Of all CO_2 emissions in the United States, about 33 percent comes from transportation. (Mother Earth News).	Conclusion is "transportation efficiency is the best place to start efforts . . ." Premise is 33 percent of CO_2 emissions is from transportation.

Outcome 4. Compare different opinions and claims of knowledge, and recognize the limitations of their own perspectives. This outcome is addressed by teaching students about informal fallacies as applied to inductive arguments. As opposed to formal fallacies - which can only occur in deductive arguments and can be identified simply through examination of the argument form - an informal fallacy can only be determined by examination of the argument content. Students will learn about informal fallacies classified into five categories (following Hurley[18]): fallacies of relevance, fallacies of weak induction, fallacies of presumption, fallacies of ambiguity, and fallacies of grammatical analogy. Within each of these groups, we identify several fallacy types and cite examples. There does not appear to be a standard classification of informal fallacies; other groupings can be found in the form of taxonomies[19] or lists[20]. See Figure 1 for a partial list of the 22 informal fallacies identified by Hurley and used in the thermodynamics examples presented here.

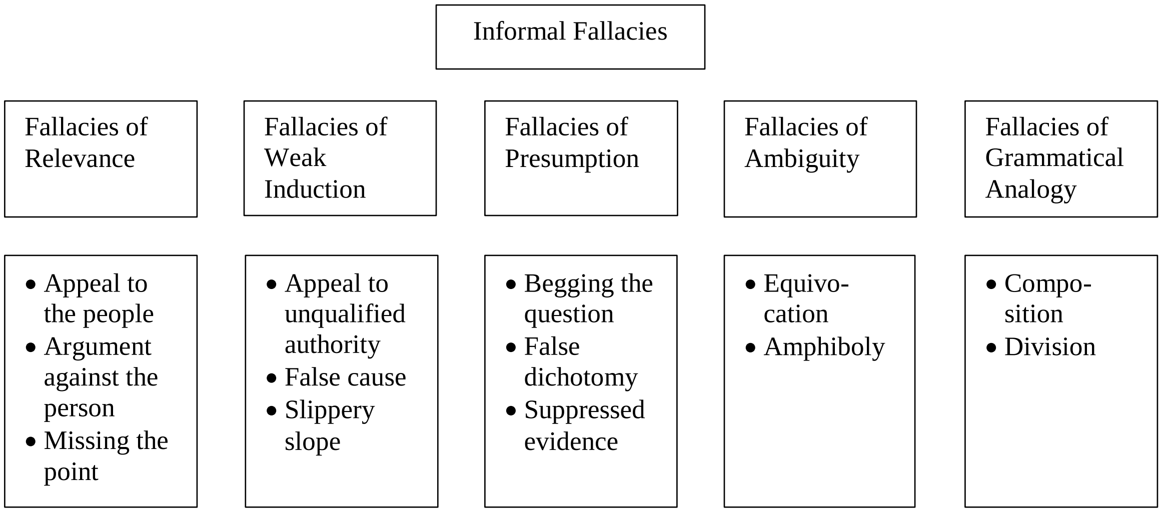

Figure 1. A classification of informal fallacies, following Hurley[18].

It is through the study of informal fallacies, accompanied by copious examples, that arguably students learn the most important skills for critical thinking. One topic that is particularly conducive to teaching about fallacies is climate change. The argument for climate change due to manmade emissions is an inductive one, and exercises can be developed not so much for demonstrating the truth of any given proposition, as for analyzing the variety of boiled down arguments for and against a conclusion in an effort to develop critical thinking about the subject. By breaking the arguments into a series of syllogisms, we demonstrate the variety of informal fallacies that can arise while at the same time describing the role of thermodynamics in the controversy. The following argument is that put forth by someone who is against taking action to mitigate global warming:

> Global warming is a hoax perpetrated by those who want to see the coal industry in this country destroyed. They conveniently ignore evidence such as the facts that average annual temperatures in the Midwest have actually decreased over the last three years, and that manmade emissions are tiny compared to the emissions from natural processes.

Here the arguer has committed several fallacies: an argument against the person (an attempt to discredit proponents of climate change by ascribing ill-intent), appeal to unqualified authority (the arguer appears to stand behind unnamed authorities who have the "true" scientific take on events), suppressed evidence (average annual temperatures in the Midwest are different than average annual global temperatures; there are many natural absorbers of CO_2 that kept CO_2 levels relatively constant for thousands of years).

Of course, a brief argument for the existence of manmade climate change could also consist of informal fallacies. For instance, consider the following syllogism:

> Many studies report that atmospheric levels of carbon dioxide have been rising over the last century.
> A recent report showed that average global temperatures have also been rising over the last century.
> Therefore, we should burn fewer fossil fuels if we want to halt catastrophic climate change.

Taken alone, this inductive argument commits two informal fallacies, however unintended by the arguer: false cause (coincidence of two phenomena does not mean that one caused the other), and begging the question (the stated premises are inadequate for linking increasing CO_2 levels to manmade emissions). In order to bolster the argument, the arguer could include the premise that increased CO_2 traps heat in a phenomenon known as the greenhouse effect, could provide other evidence that trapped heat is causing climate change (like melting glaciers and polar ice), and could supply evidence that increasing CO_2 levels are most likely due to burning of fossil fuels.

Table 5 lists other possible student exercises regarding informal fallacies.

Table 5. Exercises used to assess outcome (4) regarding informal fallacies.

Problem: identify the fallacies in the following arguments	Expectation
1) You should support the building of the Perry Nuclear Power Plant. Not only does it produce zero carbon emissions, but a recent poll indicated that over 80 percent of people living near a nuclear power plant were in favor of nuclear power as an energy source.	Students will respond with "begging the question" or "suppressed evidence," and "appeal to the people."
2) We learned in thermodynamics that a thermal reservoir is one which can absorb or reject heat indefinitely without its temperature changing. Therefore, any power plant rejecting heat to Lake Erie will not result in the lake's temperature increasing.	Students will respond with "missing the point."
3) Over the last decade, the level of Lake Erie has decreased by an inch. At the same time, the number of coal burning power plants has increased by 25%. We must halt the building of coal plants if we are to stop the lowering water levels.	"False cause."
4) If you approve the installation of wind turbines at Mr. Smith's farm, it will only lead to an influx of tall unsightly towers sprinkled across the countryside, and before we know it, our blue skies and rolling hillsides will be forever blemished by hordes of these noisy, mechanical machines.	"Slippery slope."
5) Scientists believe that the most economical and fastest way out of our energy crisis is through energy conservation. Do your part by purchasing an energy-conserving Toyota hybrid for your next vehicle.	"Equivocation."

Outcome (5). Discriminate between results and conclusions, and evaluate their implications. Students often stop after an answer pops up on their calculator, circling it without a thought towards its reasonableness. This is particularly true in thermodynamics, where many students are unfamiliar with quantities such as heat, work, mass and volumetric flowrates, the properties of refrigerants and steam – and their associated units. The energy in a flow of high pressure and high temperature steam is not nearly as tangible for the student as the energy in locomotive barreling down into the valley. A mass flowrate of 700 kg/s may be reasonable for a power plant cooling tower, but not for the airflow through a desktop computer.

All examples done in class conclude with a discussion of the results, where students are asked to judge their reasonableness, aided by coaching that encourages students to make comparisons with tangible phenomenon they are likely familiar with. For instance, I often compare calculated heat transfer rates to the output of a 100 watt incandescent bulb (although this comparison becomes less useful as more and more students grow up with CFLs!).

As with outcome (1), the problem solving methodology students use in their homework problems addresses this outcome. In the final part of the procedure, students are asked to draw conclusions about their results. The ideal conclusion will be one where correctness of the results is judged, validity of the answer in terms of assumptions is discussed, and "what if" scenarios are considered.

Embedding Critical Thinking into the Course Curriculum: Teaching and Assessment

The engineering curriculum is full and leaves little, if any, room for an extra course from the philosophy department in critical thinking. It is therefore imperative that the outcomes be incorporated into other courses that engineers are required to take. Thermodynamics is a required course for mechanical, civil, and architectural engineering students at the University. The fact that almost all engineering students take the course, combined with the necessity to develop logical processes for employing abstract principles to the solution of practical problems and the relevance of energy issues to the society at large, make a class in thermodynamics an excellent choice for addressing of the critical thinking proficiency area.

In order for the class to qualify as a critical thinking course, the material needs to be not only addressed through student exercises, but taught explicitly in the classroom. The trick is to incorporate the material without sacrificing other important content. Invariably this will mean a portion of the learning of the traditional material will be shifted to the students, where exposure to some thermodynamic subtleties may be left to reading assignments and explorations during homework problem solution. My experience is that if you cover the material too thoroughly during lectures, students will find no value in reading the text. Learning through reading is an important lifelong skill that students need to develop, and skipping some points in lecture may in the long run be healthy.

The plan is to devote three class periods throughout the course of the term to coverage of critical thinking topics. Not only does this lecture coverage introduce students to concepts necessary for critical thought, but it highlights the fact that they are being taught critical thinking. This addresses a problem discussed by Cooney et al.[11] regarding engineering students' lack of awareness that they are being taught critical thinking. Accordingly, the first week of class includes a lecture on the classification, evaluation, and analysis of arguments. In this lecture I will cover deductive and inductive arguments, identification of arguments and nonarguments, premises and conclusions, strong versus weak inductive arguments, and establishing validity. In the second week there is a 20-minute quiz covering the argumentation material using exercises similar to those discussed previously. In the middle of the term I will insert a lecture covering informal fallacies. This will involve introduction of fallacies presented in Figure 1, and presentation of examples of fallacious arguments for classroom discussion. In the week after this lecture, students will take their second critical thinking quiz. A third class near the end of the term will be devoted to inclass critical thinking exercises, followed by the third critical thinking quiz. In addition to the quizzes, there will be a small number of critical thinking questions in each of the two midterm exams, and also on the final exam. The weekly homework will occasionally include short answer critical thinking exercises either from the text or as given in the examples above.

In every weekly homework assignment, students will be required to formally present the solution to at least one homework problem according to the methodology outlined in Table 1. This problem will be scored according to the rubric shown. The scores for the "Givens," "Problem Statement," "Assumptions," "Schematic," "Governing Equations," and "Analysis" tasks will be used to assess outcome (1), and the scores for the "Results" and "Conclusions" tasks will be used to assess outcome (5). With each of the outcomes clearly assessed by specific quiz, homework, and exam problems, the overall assessment of critical thinking core outcomes should be straightforward.

Conclusion

Critical thinking has been defined by the University faculty in terms of five student outcomes. In order for any university class to qualify as a "critical thinking" course, it must address these outcomes explicitly both in instruction and assessment. Although (arguably) most other engineering courses require students to employ critical thinking skills, this claim is unverifiable without clear topical coverage as outlined in the syllabus and without rigorous assessment. Thermodynamics, with its emphasis on application of abstract principles and relevance to many contemporary issues outside the classroom, is an excellent place to incorporate such an effort.

The plan outlined in this paper will be implemented for the first time in the Fall 2015 offering of *Thermodynamics I*. Future work will include the development of assessment tools to measure the impact of the course on students' critical thinking skills.

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