121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #10253

An Inventory to Assess Students' Knowledge of Second Law Concepts

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Abstract

Concept inventories are tools to help instructors and students assess student knowledge and retention of important concepts for various disciplines of study. In thermodynamics, several concept inventories exist that center on energy, heat transfer, and temperature principles; the authors were not able to find, however, a concept inventory centered solely on second law concepts. A second law concept inventory is important since the interaction of entropy and energy is an important skill for students to have when pursuing design and development of advanced energy conversion technology. In addition to the seemingly non-existence of a second law concept inventory centered on engineering thermodynamic applications and the importance of having equal strengths of knowledge in first and second law concepts, the development of the concept inventory is also motivated by the need to assess a redesign of the first thermodynamics course for engineers that aims to increase the learning and retention of second law concepts. The objective of this study is to develop a second law concept inventory and assess the effectiveness of the concept inventory in terms of its robustness and clarity.

The article describes the early stages of development and preliminary testing of an inventory to assess students' learning and retention of second law concepts (including ideas of entropy, reversibility, impossibility, and specific topics including Kelvin-Planck and Clausius statements, heat engines, heat pumps, and Carnot cycles). The article describes the concept inventory and assesses its effectiveness by evaluating student responses (both the correctness of the students' responses as well as their assessment on the clarity of the question). The concept inventory was administered to a diverse group of students, in terms of curriculum, with some students not having had thermodynamics before, some students having only the first thermodynamics course before, and graduate students (with presumably at least one course of thermodynamics).

In general, the concept inventory seems to capture the relevant second law concepts for a first thermodynamics course. Improvements to the wording of some of the multiple choice questions (and their responses) have been identified for future versions of this concept inventory. In a separate activity, attempts to assess the clarity of the individual questions were found not to be effective. This finding is based on the poor correlation between the students' responses regarding clarity, and the students' class groups.

Introduction

Concept inventories are useful tools for several reasons[1]. They allow instructors to assess students' core knowledge of understanding of a concept / subject (as opposed to rote repetition or following a prescribed methodology via a known solution pathway). They reveal what common misconceptions students may have about a particular topic (via a consistent selection of a wrong answer)[2-4]. They suggest to students what is really believed to be the most important fundamental concepts of a given subject. They can also, in a way, be used to assess or track changes to a course. For example, in a redesign of the choice and delivery of conceptual topics in a course, a concept inventory might be one way to indicate changes in the effectiveness of the redesign effort. The concept inventory presented in this paper is meant to provide all the above-mentioned purposes; it's development, however, was motivated largely by the need to use a concept inventory as partial assessment in the major redesign of the first thermodynamics course (FTC) for engineers.

There is a large number of concept inventories in thermodynamics[4-9]. Many of the concept inventories focus mostly on first law, energy, and property concepts; very few, if any at all, have a primary emphasis on second law concepts (reversibility, impossibility, entropy, and exergy). For example, the comprehensive and well-designed thermodynamics concept inventory that emerged from the Foundation Coalition (FC) effort, written by Midkiff, et al.,[5, 7], has room for only two questions centering on second law concepts and only one that connects entropy to the usefulness of energy (i.e., exergy). A non-FC concept inventory related to thermodynamics emphasizes concepts related to temperature and thermal transport,[6]. A concept inventory designed from a Delphi study[10] determining concepts of high importance but with little student-understanding[8] does not assess second law concepts, even though the Delphi study revealed a second law concept (reversibility) to be ranked 7th among 28 concepts (very few students understand it but experts generally consider it important). During the development of second-law oriented tutorials, Cochran and Heron observed severe deficiencies of students' second-law understanding[11]. A concept inventory, however, did not emerge from this study[11] as the objective was to develop tutorials on second law, not develop a second law concept inventory. Some concept inventories[2, 4, 12] include questions on second law concepts (such as reversibility and maximum thermal efficiency of a heat engine), but these questions are a subset of a larger concept inventory covering the broader context of thermodynamics and heat transfer. For the purposes of specifically assessing student knowledge of second law concepts there is a need for a concept inventory centered on second law concepts.

What are second law concepts and how do they differ from first law concepts? Second law concepts are, of course, those related to the second law of thermodynamics which is a difficult law to concisely state in one sentence. In a simple way, the second law is that which suggests natural processes will proceed in a given direction; that direction is one which ultimately increases the net entropy of an isolated system / surroundings interaction. A process may proceed in a different direction, but this will require some other interaction to occur between the system and surroundings; no process can proceed in a fashion that decreases net entropy of the isolated system/surroundings. These truths lead to many corollary statements that are nothing more or less than alternative versions of the same second law.

First law concepts are, of course, those related to the first law of thermodynamics. Unlike the second law, the first law does seem to have a simple statement; it's the conservation of energy principle and states that energy is neither created nor destroyed. Thus, first law concepts center on those that mandate energy be conserved. The first and second laws are not necessarily isolated from each other. In fact, combination of second law concepts with first law concepts reveals the effect that entropy has on energy. That is, the second law recognizes, by virtue of the increase in net entropy principle, the ability of energy to do useful work (exergy) necessarily decreases. This is the important concept that engineers must learn[13].

A concept inventory on second law concepts is important because engineers need to have as strong of an understanding of second law as they do first law[8, 11, 13]. First law concepts ensure engineering analysis is done correctly. It ensures energy is balanced properly, control systems are chosen wisely when doing analysis, and proper decisions are made when sizing systems or ensuring highest efficiency of a given design. Second law concepts, however, allow engineers to understand the parameter space they work within and the limitations that may naturally be imposed on them. They allow engineers to recognize that various types of energy have better uses in different applications. Second law concepts enable engineers to make proper decisions about how to allocate resources for developing and advancing various energy-related technology[13].

The objective of this study is to design and assess a preliminary concept inventory that quantifies students' knowledge and conceptualization of second law concepts. In addition to describing the development of the second law inventory, the study evaluates its effectiveness in both clarity of question and appropriateness of question for quantifying student understanding of the second law. It should be noted that this is a preliminary development and is not meant to represent a final deployable concept inventory; rigorous reliability and validity testing[9, 14] has not taken place which would be necessary for this concept inventory to work effectively across a broad spectrum of students and disciplines.

Choice of Concepts to be Assessed

The constraints on deciding on the specific questions for this concept inventory include: 1) the number of questions be limited to 20, 2) each concept needed to have at least two questions, and 3) the most basic and fundamental concepts be assessed. Constraint number 2 is needed so that the students' understanding of a given concept is independent of the wording of only one question. The major concepts that were considered important to evaluate include such items as statements of the second law (classical and other), entropy, exergy, cycles, reversible processes, and Carnot principles. Certainly, many other related concepts could have been included. This second law concept inventory is one version of what could be a series of such inventories.

Description of Concept Inventory

The current form of the concept inventory is shown in the appendix. It is noted that this is the first draft of the concept inventory, and some of the questions may have ambiguity or non-uniqueness. Those questions requiring revisions are noted in the comments following the indication of the intended correct answer. In summary, the general Second Law concepts, and the corresponding concept inventory questions, that are assessed include the following:

1. Statements of the second law – Questions 1, 6, 7, 10, 11, 12, 15, 16, 17, 18

2. Carnot Principles – Questions 2, 7, 9, 20
3. Reversible / Irreversible Concepts – Questions 3, 4, 6, 13, 14, 18
4. Cycle Concepts – Questions 4, 8, 13, 16
5. Entropy Concepts – Questions 5, 15, 17, 18
6. Exergy Concepts – Questions 6, 7, 11

General concept #1 (statements of the second law) has the most questions mostly because there are so many corollary statements of the second law. Specifically, questions #1 and #16 are related to the Kelvin-Planck Statement, questions #6, #11, and #17 are types of Increase in Entropy Principle statement, questions #7, #15, and #18 capture many of the corollary statements of the second law, and questions #10 and #12 are related to the Clausius Statement.

General concept #2 (Carnot principles) focuses on the ideas of the Carnot postulates; specifically, that 1) the ideal cyclic device is composed entirely of reversible processes and 2) the ideal cyclic device maximum efficiency is only a function of the surrounding reservoir temperatures. Questions #2, #9, and #20 center on heat engine efficiency, and recognizing that ideal (Carnot) heat engine efficiency is necessarily higher than any actual heat engine device efficiency. Question #7 partially relies on Carnot principles, as one of the corollary statements of the second law.

General concept #3 (reversible / irreversible concepts) relates to identification of reversible / irreversible processes and how these affect cyclic operation and exergy. Question #3 links the idea of reversibility to the second law. Questions #4 and #13 assess an understanding of both cycles (definition of a cycle) and why heat engine / pump cycle efficiencies are necessarily less than 100% (as opposed to ever equaling 100%). Question #6 links the effect of entropy on energy (i.e., availability of useful work, or exergy). Question #14 assesses an ability to identify irreversible processes. Question #18 links the effect of irreversibility on entropy.

General concept #4 (cycle concepts) captures the basic definition of a thermodynamic cycle, the constraints of the Kelvin-Planck / Clausius Statements (i.e., cycle efficiencies must be less than 100%), and the relationship between cycle efficiency and reservoir temperature (Carnot principles). Specifically, Questions #4 and #13 address both the definition of the cycle as well as the Kelvin-Planck / Clausius Statements. Question #8 addresses the imposition of Carnot principles on cycle efficiency. Question #16 captures Kelvin-Planck Statement for a cyclic device (see comment following question).

General concept #5 (entropy concepts) captures the relationship between entropy and second law concepts. For example, Question #5 explicitly addresses this relationship. Questions #15, #17, and #18 assess the connection between irreversibility, entropy generation, and system entropy (as well as knowledge of the second law "balance" equation).

Finally, General concept #6 captures the relationship between energy and entropy; that is, the effect of entropy on the ability of energy to do useful work, or exergy. This is explicitly done with both Questions #6 (on a system-level) and #11 (on a global or "universe" level). Question #7 requires one to understand the connection between exergy and second law.

Concept Inventory Effectiveness

The concept inventory was first used during the spring 2013 semester at the conclusion of the first thermodynamics course. This course enrolls a diverse group of students from several engineering majors, including mechanical engineering, petroleum engineering, civil engineering, industrial engineering, and nuclear engineering. When considering the total student population in engineering at Texas A&M University, roughly 63% of engineering students take the FTC of mechanical engineering. Additionally, the grade level of students varies from as young as sophomores (mostly mechanical and nuclear engineering students) to as old as graduating seniors (mostly civil and industrial engineering students). The average grade level for the course is junior-level.

In addition to Spring 2013, the concept inventory was also used during the summer 2013 semester in the FTC and as a "pre-quiz" at the start of Fall 2013 semester in the FTC, two separate sections of the second thermodynamics course (all undergraduate mechanical engineering students), and a graduate-level thermodynamics course (all graduate mechanical engineering students, but with some varied undergraduate education). The administration of the concept inventory is summarized in Table 1. In some instances, the second law concept inventory was administered to both assess the concept inventory itself as well as provide some feedback on a parallel effort to redesign the FTC. The redesign of the FTC is described elsewhere [15].

Administering the concept inventory to FTC students at the start of the semester reveals any background information students may have, the potential misconceptions they may bring into the course, and the typical "guessed" response. Administering the concept inventory to second-thermodynamics-course and graduate-thermodynamics-course students at the start of the semester reveals students' retention of concepts from FTC and any misconceptions they may bring into the course. In all three cases (FTC, second thermodynamics course, and graduate thermodynamics course), students were asked to assess the clarity of the question.

Table 1: Summary of the administration of the second law concept inventory and the purpose for administration.

Identifier	Course	Semester	Purpose
FTC-2013a-RD	Redesigned FTC	Spring 2013	First use of concept inventory; used to assess concept inventory and redesign of FTC
FTC-2013b-1 and FTC-2013b-2	Conventional FTC (two sections)	Summer 2013	Assess concept inventory and redesign of FTC
FTC-2013c-pre	Pre Conventional FTC	Fall 2013	Assess concept inventory
STC-2013c-pre-1 and STC-2013c-pre-2	Pre Second Thermodynamics Course (two sections)	Fall 2013	Assess concept inventory
GTC-2013c-pre	Pre Graduate Thermodynamics Course	Fall 2013	Assess concept inventory

The first data to present are the students' interpretations on the clarity of the question; these are shown in Figure 1. There is much data in this figure, so a brief introduction of how to interpret is provided. First, the data shown quantify the percent of students who felt a given question (x-axis) was unclear. Each series of data correspond to the group of students taking the concept inventory (summarized in Table 1), excluding the students taking the redesigned FTC. Thus, high values for a given question among all groups might indicate an unclear question while low values for a given question among all groups might indicate a clear question.

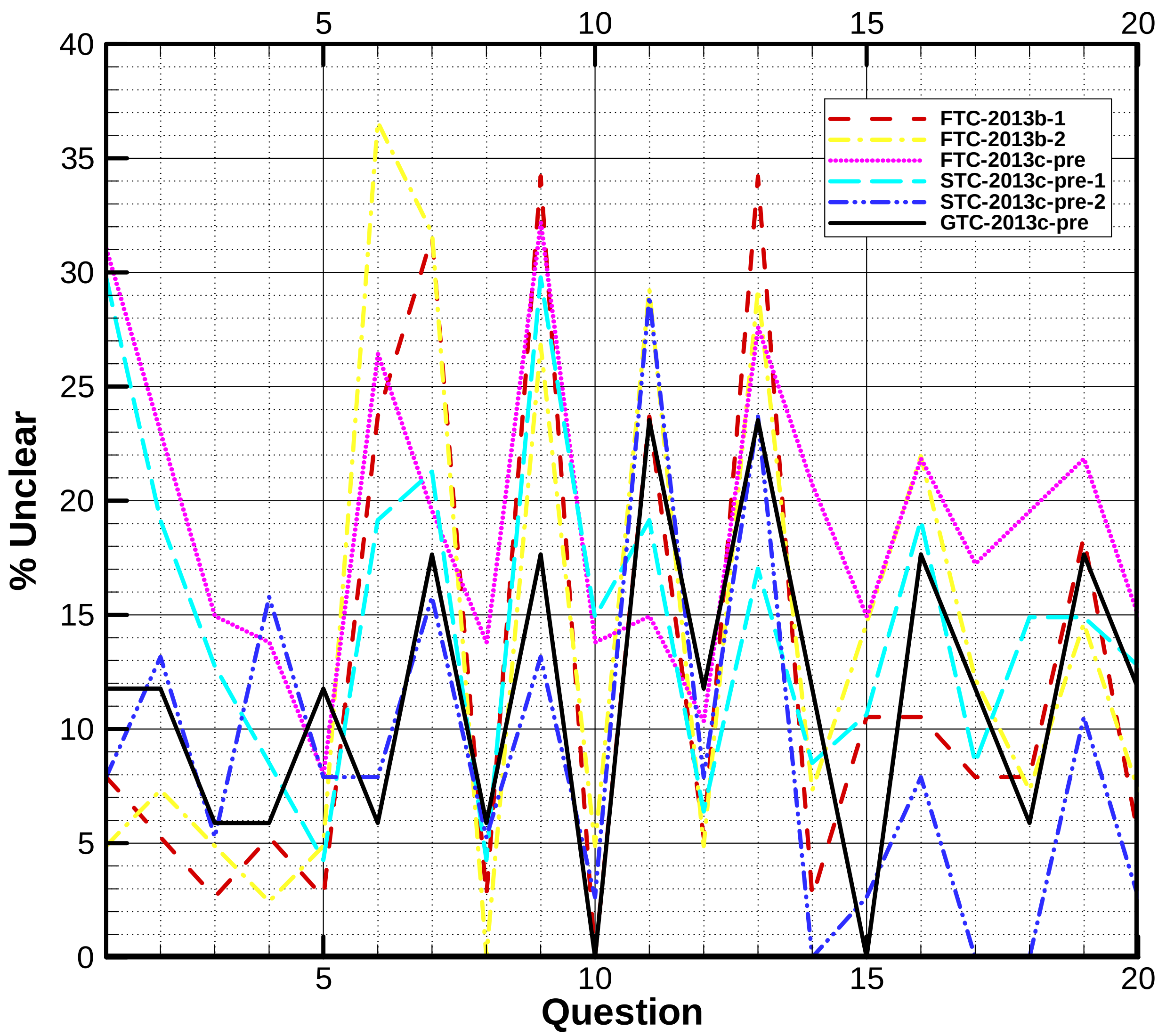

Figure 1: Percent of students who felt the question was unclear, organized by class; refer to Table 1 for a summary of the class legend identifiers.

Overall, it appears the vast majority of students found most of the questions clear. Specifically no single question was unclear to more than 37% of the students; most of the questions were clear to more than 80% of the students. If 20%-unclear is arbitrarily chosen as a threshold, it appears some students found questions 1, 2, 6, 7, 9, 11, 13, 14, 16, and 19 unclear. Of these questions, the authors have identified potentially confusing language in either the question or the response options in questions 2, 7, 13, 14, 16, and 19. There are wording changes suggested for these questions, which are included in the comments in the concept inventory provided in the appendix.

The remaining questions identified as unclear are dissected as follows. Question #1 was largely marked unclear by students seeing thermodynamics for the first time, or revisiting thermodynamics for the first time, at the start of the semester. Thus, it is possible students were unable to determine an obvious response because of non-familiarity or struggling to remember the material. Question #6 uses a term that students may not have been exposed to (i.e., exergy and the opportunity to do useful work); thus, this may have created some clarity issues. Question #9 may be confusing due to the combination of high / low "input" temperatures (i.e., confusing language about a high T_H versus a low T_H). Question #11 was marked unclear by a large percent of graduate students (about 23% graduate students marked the question unclear); this may be due to the use of the word "global", which is interchangeable with several other words / terms (e.g., universal, system/surrounding interaction, and net). No wording changes for these questions are proposed at the current time, since it's not precisely determined why the question may be unclear.

The level of clarity of each question among the different groups of students was evaluated, but no real consensus could be determined (except in the rare cases when all groups agreed upon clarity, such as Questions 8 and 10). It may be argued that the graduate student data are best indicative of question clarity, since graduate students will have been the most exposed to the concepts based on prior undergraduate study. A similar argument, however, could be made regarding students taking the second thermodynamics course. In comparing these three groups of students (STC-2013c-pre-1, STC-2013c-pre-2, and GTC-2013c-pre), it is clear there is very little consistency. There is large disparity even between the two sections of the second thermodynamics course. Consequently, these types of comparisons are not rigorously pursued here.

The next set of data to evaluate are the percentage of students from each of the six groups answering a given question correctly. These data are shown in Figure 2. There seem to be both obvious and subtle trends in the data. First, Questions #4, 13, 16, and 19 may have problematic wording, as all six class groups have very low (i.e., less than 50%) percentages of students answering the questions correctly. Question #4 is a very subtle question that probes the understanding of both a cycle and irreversibility; interestingly, Cochran and Heron also discovered student misconception regarding cycle behavior [11]. In the current concept inventory, the question asks what entropy of the system will be after the last process of an irreversible cycle, relative to the initial value at the start of the cycle. Because the system is operating on a cycle, the initial and final values will be the same, regardless of the reversibility of the cycle. This in fact is a critical concept to understand from thermodynamics; the return of system entropy to a cycle's initial value is necessary for the cycle to operate. Otherwise, entropy would accumulate in the system and eventually cause the cycle to stop. This concept, along with entropy's effect on energy being converted to useful work, render the existence of Kelvin-Planck and Clausius statements.

Question #13 is very similar (same basic concepts) as Question #4; the only difference is that a substance (gas) is specified. Further, the question states that the gas varies in temperature and pressure through the process. The coincidence of students getting both Questions #4 and 13 wrong is likely indicative of misconceptions about both cycles and reversibility. It is noted, however, that the authors believe Question #13 is too wordy, which could compound the issue. Referencing Figure 1, it is noted that a high percentage of students felt Question #13 is unclear (as low as 17% and as high as 34% among the studied class groups).

Question #16 is meant to assess two major concepts: 1) students realize that the environment can / does serve as a thermal reservoir and 2) the presence of the Kelvin-Planck / Clausius statements. It is not immediately clear why a large percentage of students answered this question incorrectly, but there are some postulations. First, as noted in the comment following the question in the Appendix, it is not specifically stated in the question statement that the device is meant to be a cyclic device. Even though it is obvious from the responses that the device is intended to be cyclic, this missing piece of information could cause confusion (i.e., it is in fact possible for a non-cyclic device to interact with just one reservoir and produce work). Second, referencing Figure 1, a high percentage of students do identify Question #16 as being unclear (i.e., as few as 8% to as high as 22% among class groups). It is also noted, in combining results of Figure 1 and Figure 2 that the class group having the lowest percentage of students finding the question unclear (STC-2013c-pre-2 at 8% unclear) have the highest percentage of students answering the question correct (STC-2013c-pre-2 at 35% correct). This may just be a coincidence, since a similar trend does not exist for the class group having the highest percentage of students finding the question unclear. Finally, it is worth noting that students may not recognize the connection / sameness among “reservoir”, “environment”, and “surroundings.”

Question #19, in terms of percentage of students answering the question correctly, is not as low as Questions #4, 13, and 16. Regardless, the highest percentage of students answering the question correctly among the class groups is only 45% (FTC-2013b-1 and STC-2013c-pre-2), therefore some discussion is merited. Question #19 is similar in concept to Question #16; it is meant to assess knowledge of the environment acting as an environment in addition to knowledge of the Kelvin-Planck / Clausius statements. As noted in the comment following the question in the Appendix, the question may be clarified by specifying that work is produced using a cycle heat engine with just one reservoir (thus, rendering what is now a possibly correct response clearly incorrect). Further, referencing Figure 1, a high percentage of students among all class groups marked the question as unclear (as low as 10% to as high as 22%). Again, it is not immediately clear why students marked the question unclear, but it is possible it is related to the possibility that response “c” could be correct. Similar to Question #16, it is also possible that students do not fully understand the sameness among “reservoir”, “environment”, and “surroundings”.

Some of the subtle features of Figure 2 are related to differences among class groups. For example, the class group presumably never exposed to thermodynamic concepts before (FTC-2013c-pre) scored very low on questions #1, #2, #3, #9, #10, and #11 (all questions were answered correctly by less than 40% of the students). In reviewing these questions, it is clear why this may be true, since the questions focus on higher-level concepts of thermodynamics that are not necessarily discussed in first-level chemistry and physics courses (i.e., Kelvin-Planck / Clausius statements, Carnot concepts, reversibility, and net increase in entropy principle). Thus, from an educator’s point of view, it is refreshing to see groups of students who have been exposed to thermodynamics answering such questions correctly! In a similar context, it is interesting to note that the same group of students (FTC-2013c-pre) did have a relatively high percentage of students answer some second law concepts correctly. Specifically, over 60% of such students answered Question #5 correctly, which addresses the connection between entropy and the second law. This perhaps is reasonable, since students are likely exposed to basic discussions of entropy and second law in their first courses of chemistry and physics. Somewhat confusing, however, is the even-higher percentage of this student group answering Question #8 correctly, since this involves subtleties of heat engines and the correct answer is in fact a combination of two potential responses.

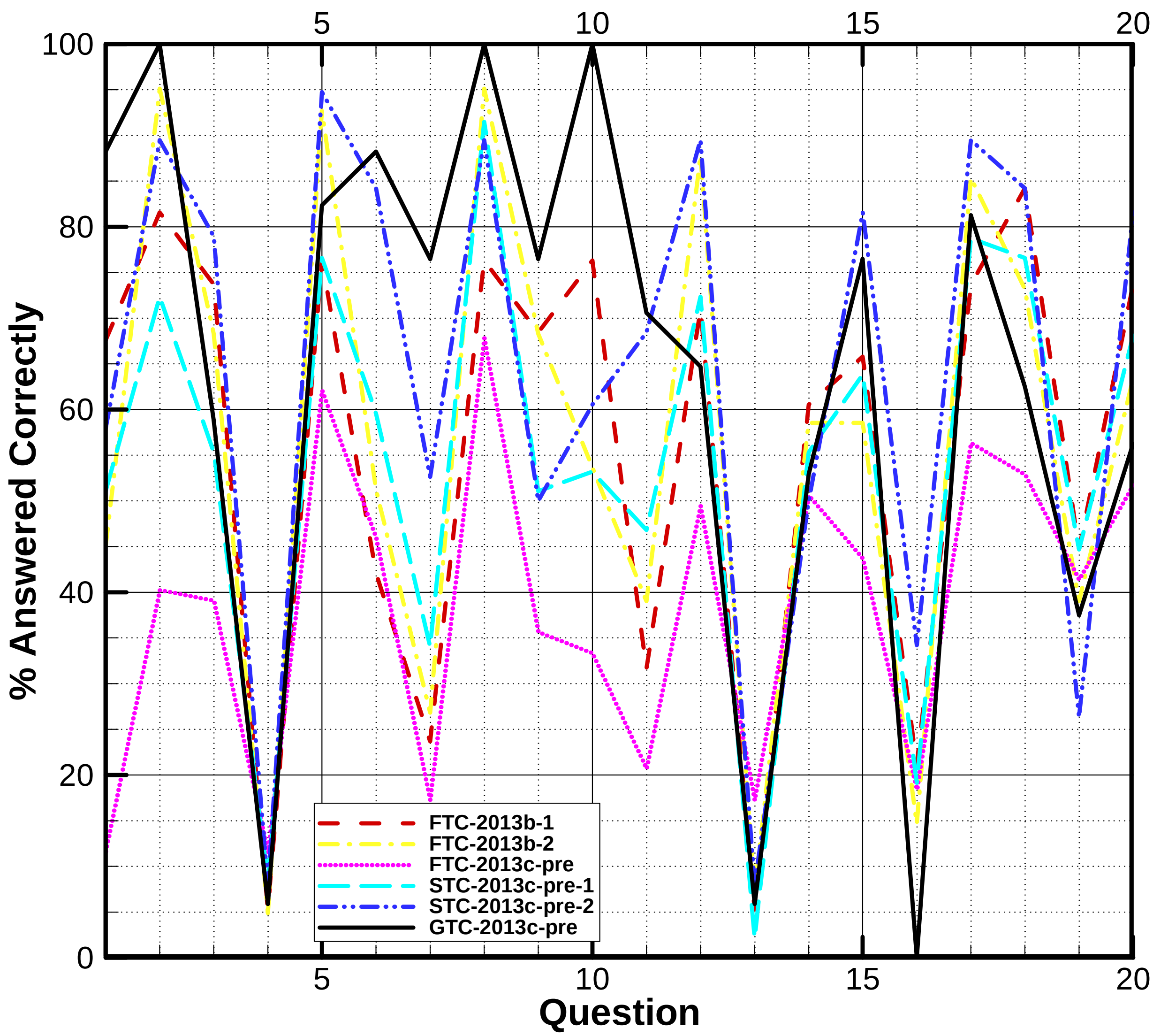

Figure 2: Percent of students who answered the question correctly, organized by class; refer to Table 1 for a summary of the class legend identifiers.

Another subtle feature of Figure 2 is a non-changing percentage of correct responses among student groups as the question number increases. That is, as noted above, concepts are assessed with multiple questions to help identify potential issues with wording relative to issues with conceptual understanding. The fact that there is not an increasing trend of percentage of correct responses as question number increases suggest that, for the most part (i.e., except where noted), the questions are written clear and concisely and students incorrectly answering questions likely have conceptual misunderstandings.

Specific Comments from Advisory Workshop

The preliminary concept inventory for the second law of thermodynamics was presented to an advisory council composed of thermodynamic experts from industry, academia, and governmental laboratories during a one day workshop evaluating the redesign of the FTC effort [15]. The advisory council members were enthusiastic about the inventory, and in general felt that this preliminary version captured the basic concepts that they felt were important. Several of the members had specific comments about the wording of certain questions, and a valuable dialog was conducted that should help improve future versions of the inventory. Many of their comments are integrated into those included in the Appendix for each question.

Summary Discussion

In summary, there are several key elements that have been learned in this preliminary development of an inventory of second law concepts. The first is that the rigorous exercise of using the concept inventory with a large number of students at various levels of exposure to thermodynamics has offered substantial opportunities to improve its wording. The obvious opportunities to improve wording are included as comments in the concept inventory appended in this article. Further, areas of further investigation to understand either student concerns with question clarity and / or high rates of incorrect answering on questions are identified. With respect to the latter (high rates of incorrect answering on questions), future work will involve probing the students' specific responses to questions are consistently answered incorrectly to identify if the high rate is due to wording or due to students' misconceptions. The next step for the authors is to modify the concept inventory accordingly and retest student control groups. Further, the concept inventory is intended to eventually be used to partially assess a redesign of the first thermodynamics course that centers on improving student learning and retention of second law concepts [15].

Another observation made in this study is the effectiveness (or lack thereof) of the approach used to have students gauge the clarity of the questions. In referencing Figure 1 and the surrounding discussion it is apparent that there is very little consistency in students' perception of question clarity and a connection between this and their ability to answer the question correctly (referencing Figure 2). There are likely better ways to probe students' perception of question clarity, but the approach used in this study is not effective. Consequently, it will be dropped in future efforts of assessing the effectiveness of the concept inventory.

Conclusion

This study describes the early stages of development and preliminary testing of an inventory to assess students' learning and retention of second law concepts (including ideas of entropy, reversibility, impossibility, and specific topics including Kelvin-Planck and Clausius Statements, heat engines, heat pumps, and Carnot cycles). The concept inventory's development is motivated by the seemingly non-existence of one centered on engineering thermodynamic applications, the importance of having equal strengths of knowledge in first and second law concepts, and the need to assess a redesign of the first thermodynamics course for engineers that aims to increase the learning and retention of second law concepts. The article describes the concept inventory and assesses its effectiveness by evaluating student responses (both the correctness of the students' responses as well as their assessment on the clarity of the question). The concept inventory was administered to a diverse group of students, in terms of curriculum, with some students not having had thermodynamics before, some students having only the first thermodynamics course before, and graduate students (with presumably at least one course of thermodynamics).

In general, the concept inventory seems to capture the relevant second law concepts for a first thermodynamics course. This conclusion is based on the percentage of students who answer the questions correctly, particularly those who have had the first thermodynamics course. In spite of this, there are several opportunities to improve the wording of the question and / or their responses. Some of these opportunities were identified by very high rates of incorrect answering by students. The authors intend to further refine the concept inventory based on this preliminary data and analysis.

Another general conclusion from the study is the ineffectiveness of the approach taken to directly assess students' impression of the clarity of the question. Students were asked directly to assess if they felt a question were clear or not. Very few questions were identified as being unclear by the students and there was no correlation between students' impression of the clarity and the correctness of the responses. Further, there was no correlation between students' impression of the clarity and their presumptive number of years of exposure to thermodynamics.

Acknowledgements

The authors wish to acknowledge several organizations and persons who have made this work possible. The National Science foundation is acknowledged for providing the financial support for the first thermodynamics course redesign effort (NSF Grant #1044875). The opinions and or our views expressed in this article are solely those of the authors and not necessarily those of the sponsoring agency. Further, the authors wish to acknowledge members of the project's Advisory Panel for their feedback on both the course redesign and the concept inventory. The panel members include Dr. William Cannella (Chevron Corporation), Dr. Philip Caruso (General Electric Water and Power), Dr. C. Stuart Daw (Oak Ridge National Laboratory), (Chevron Corporation), Professor David Foster (UW-Madison), Dr. Kevin Kirtley (General Electric Water and Power), and Professor Robert Lucht (Purdue University). The co-principal investigators on the project, Dr. Jeffrey Froyd and Professor K. Rajagopal, are acknowledged for their contributions and assistance to the concept inventory. Faculty colleagues at Texas A&M University Department of Mechanical Engineering are acknowledged for their assistance in administering the concept inventory to their respective courses; these colleagues include Professor Michael Pate, Professor David Staack, Professor Andrea Strzelec, Mr. Joshua Bittle, and Dr. Jacob McFarland. Finally, the data processing and preliminary analysis were greatly aided by the assistance of Mr. Timothy McDonald, undergraduate student at Texas A&M

University Department of Mechanical Engineering and one of the first students to be exposed to the redesigned first thermodynamics course for mechanical engineers.

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Appendix

The following are the questions of the currently developed concept inventory (along with the corresponding answers).

Please select the “best” choice:

1. A device is proposed that receives energy from a hot reservoir and produces work with no other interaction.
    a. This violates the first law of thermodynamics.
    b. This violates the second law of thermodynamics.
    c. This violates the state principle of thermodynamics.
    d. This does not violate any part of thermodynamics.
    e. a & b

    Correct answer = b.

2. Consider a Carnot heat engine operating between a high temperature reservoir and a low temperature reservoir and producing work. The thermodynamic efficiency of this heat engine may be determined
    a. Knowing only the low temperature
    b. Knowing only the high temperature
    c. Knowing only the work output
    d. Knowing only the energy leaving the high temperature reservoir
    e. a & b

    Correct answer = e.

    Comments: The use of the word “only”, particularly in options “a” and “b”, makes the choice of option “e” confusing. It is suggested the word “only” be removed from every choice.

3. In thermodynamics, the idea of a “reversible” process is most closely associated with
    a. The first law of thermodynamics
    b. The second law of thermodynamics
    c. The state principle of thermodynamics
    d. Work interactions
    e. a & b

    Correct answer = b.

4. For an irreversible cycle, the ending value of the system entropy
    a. is less than the starting value
    b. is equal to the starting value
    c. is greater than the starting value
    d. depends on the type of process
    e. depends on the working fluid

    Correct answer = b.

5. Entropy is a thermodynamic property most closely associated with
    a. The first law of thermodynamics
    b. The second law of thermodynamics
    c. The state principle of thermodynamics
    d. Work interactions
    e. a & b

    Correct answer = b.

6. Consider all the energy associated with an irreversible process:
    a. energy is conserved and its potential to do work (i.e., exergy) has increased
    b. energy is conserved and its potential to do work (i.e., exergy) has not changed
    c. energy is conserved and its potential to do work (i.e., exergy) has decreased
    d. energy is not conserved and its potential to do work (i.e., exergy) has not changed
    e. energy is not conserved and its potential to do work (i.e., exergy) has decreased

    Correct answer = c.

7. All the following are consequences of the second law of thermodynamics *except*:
    a. Determines the maximum ideal efficiency of a heat engine.
    b. Specifies the direction of heat transfer.
    c. Specifies criteria for equilibrium conditions.
    d. Provides the thermodynamic path to convert all heat transfer into work.
    e. Provides the means to determine the portion of energy which may ideally produce work (exergy).

    Correct answer = d.

    Comment: Choice "d" is the correct answer because, in fact, the second law recognizes that it's impossible to completely convert heat energy to work energy. Thus, in a way, d is correct because it's impossible to do it by virtue of the second law. The correct response is confusing. It may be better to provide a first law concept (such as, energy is conserved), to make the response options less confusing.

8. Consider an irreversible heat engine operating between a high temperature reservoir and a low temperature reservoir and producing work. What system parameter would you change to increase the work output?
    a. Increase the low temperature reservoir temperature
    b. Increase the high temperature reservoir temperature
    c. Decrease the high temperature reservoir temperature
    d. Decrease the low temperature reservoir temperature
    e. b and d

    Correct answer = e.

    Comment: The wording of the question, "what system parameter. . ." is constraining since it implies there is only one parameter, when in fact there are two (hence, option "d" being correct). It is suggested the word "parameter" be replaced with "parameter(s)".

9. If 100 kJ is supplied to a heat engine, the work produced would be highest for
    a. the highest input temperature (T_H) for an irreversible heat engine
    b. the highest input temperature (T_H) for a reversible heat engine
    c. the lowest input temperature (T_H) for an irreversible heat engine
    d. the lowest input temperature (T_H) for a reversible heat engine
    e. any input temperature (T_H) for a reversible heat engine

    Correct answer = b.

10. A device is proposed that requires no work input, and moves energy from a cold reservoir to a hot reservoir.
    a. This violates the first law of thermodynamics.
    b. This violates the second law of thermodynamics.
    c. This violates the third law of thermodynamics
    d. This violates the state principle of thermodynamics.
    e. This does not violate any part of thermodynamics.

    Correct answer = b.

11. On a global basis,
    a. energy is conserved and its potential to do work (i.e., exergy) has not changed
    b. energy is conserved and its potential to do work (i.e., exergy) has increased
    c. energy is conserved and its potential to do work (i.e., exergy) has decreased
    d. energy is not conserved and its potential to do work (i.e., exergy) has not changed
    e. energy is not conserved and its potential to do work (i.e., exergy) has decreased

    Correct answer = c.

12. A device has been proposed that allows energy to be moved from a low temperature reservoir to a high temperature reservoir. This device
    a. Violates the first law of thermodynamics
    b. Violates the second law of thermodynamics
    c. Is possible.
    d. Is only possible with a work input.
    e. Answer depends on the nature of the device.

    Correct answer = e.

    Comment: In this question, "e" is the correct answer because simply providing work input only satisfies the Clausius Statement, but does not necessarily satisfy the Carnot cycle constraint. That is, there is a minimum work that must be supplied for the device to work properly. There is too much subtlety between options "d" and "e". It is suggest that option "d" be stated as "Is only possible with a minimum work input" and option "e" be stated as "Is possible with any work input."

13. Consider a gas that undergoes an irreversible cyclic process which consists of a series of changes in pressure and temperature. For each complete cycle,
    a. The beginning and ending temperatures are the same, but the beginning and ending entropy values are different.
    b. The beginning and ending temperatures and the beginning and ending pressures are the same, but the beginning and ending entropy values are different.
    c. The beginning and ending temperatures are the same and the beginning and ending entropy values are the same.
    d. The beginning and ending temperatures are different and the beginning and ending entropy values are different.
    e. The beginning and ending temperatures and the beginning and ending pressures are different and the beginning and ending entropy values are different.

    Correct answer = c.

Comment: The responses for this question are too long. The goal of this question is to assess students' understanding that what makes a cyclic heat engine / heat pump necessarily less than 100% efficient is the requirement that unusable entropy must be rejected from the system (hence, the cyclic nature of the device); therefore, entropy of the system cannot increase and the starting value of entropy must always be the same (if the device is to operate cyclically). The responses can be simplified by removing the pressure property, and making the responses more concise.

14. All the following are examples of irreversible processes except:
    a. Mixing of identical fluids initially at different pressures.
    b. Unrestrained expansion of a fluid.
    c. Heat transfer across a finite temperature difference.
    d. Spontaneous chemical reactions.
    e. All the above are irreversible processes.

    Correct answer = e.

    Comment: There is an inconsistency between the problem statement (suggesting that one of the options is not an example) and the correct response (indicating that in fact all the responses are correct). It is suggested that the question be reworded as: "Which of the following is an / are irreversible process(es).

15. An adiabatic tank is divided into two equal volumes by an internal partition. On one side is oxygen gas and on the other side is nitrogen gas. Both gases are at the same temperature and pressure. The partition is removed. After sufficient time,
    a. All properties remain unchanged.
    b. The internal energy increases.
    c. The internal energy decreases.
    d. The entropy increases.
    e. The entropy decreases.

    Correct answer = d.

16. Assume that the environment is available as a high temperature reservoir. To use this source and produce work, a device would need
    a. At least one other thermal reservoir at any temperature
    b. At least one other thermal reservoir at a higher temperature
    c. At least one other thermal reservoir at a lower temperature
    d. At least one other thermal reservoir at the environment temperature
    e. This source can never produce work.

    Correct answer = c.

    Comment: The responses make it clear the "device" in the question is meant to be cyclic. Regardless, it would be clearer to specify the device is a cyclic device, so as to avoid confusion with the subtlety that a device could interact with just one reservoir and produce work non-cyclically. Further, technically response "b" could be true (even though the question states "as a high temperature" reservoir, implying T_H); it is suggested that the question and responses be reworded appropriately.

17. As time progresses,
    a. The energy and entropy of the universe increases
    b. The energy and entropy of the universe decreases
    c. The energy of the universe decreases
    d. The entropy of the universe decreases
    e. The entropy of the universe increases

    Correct answer = e.

18. The specific entropy of a closed thermodynamic system may
    a. increase due to internal irreversibilities
    b. increase due to heat transfer into the system
    c. decrease due to internal irreversibilities
    d. decrease due to heat transfer into the system
    e. a and b

    Correct answer = e.

19. Consider the earth's "reservoirs" such as the oceans, the atmosphere and the rivers.
    a. These reservoirs do not contain energy
    b. These reservoirs do contain energy
    c. By using only one of these reservoirs, and not interacting with any other reservoir, work may be obtained
    d. a and c
    e. b and c

    Correct answer = b.

    Comment: Response "c" could technically be correct, if the interaction is not meant to be a cyclic system. Given this subtlety, and the slight cumbersomeness of the response, it is suggested that response "c" be reworded as follows: "By using only one of these reservoirs, work may be obtained using a cyclic heat engine."

20. A device is proposed that receives 10 kJ of energy from a hot reservoir (T_H = 1000K), delivers 7 kJ of energy to a cold reservoir (T_L =500K), and produces 3 kJ of work with no other interaction.
    a. This violates the first law of thermodynamics.
    b. This violates the second law of thermodynamics.
    c. This violates the state principle of thermodynamics.
    d. This does not violate any part of thermodynamics.
    e. a & b

    Correct answer = d.