Student understanding of the first law and second law of thermodynamics

Benjamin Brown and Chandralekha Singh

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA
15260, United States of America
E-mail: clsingh@pitt.edu

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Abstract
We discuss common student difficulties with the first and second laws of thermodynamics found using a validated conceptual multiple-choice survey called the survey of thermodynamic processes and first and second laws suitable for introductory physics courses. The analysis of data from more than a thousand students using the validated survey at six different colleges in the US shows that not only introductory but also advanced physics students have many common difficulties with these concepts after traditional lecture-based instruction in relevant concepts. The findings of the common student difficulties with the first and second laws of thermodynamics discussed here can be useful for developing effective curricula and pedagogies in order to reduce student difficulties.

Keywords: thermodynamics, first law, second law, validated survey, student difficulties

Introduction
Since many physics courses focus on both conceptual understanding and problem solving [1–8], research-validated conceptual multiple-choice surveys [9–20] can be invaluable. In order to assess whether a particular curriculum or pedagogy is effective in helping introductory physics students learn the fundamental concepts related to thermodynamic processes and the first and second laws, we developed, validated and administered a 33-item conceptual multiple-choice test called the survey of thermodynamic processes and first and second laws.
(STPFaSL) to students at six different colleges in the US. The details pertaining to the development, validation and administration of the survey can be found elsewhere [22]. The final version of the validated survey can be found here [21, 22] or in the supplementary materials (https://stacks.iop.org/EJP/42/065702/mmedia) for this paper [23]. This research was carried out in accordance with the principles outlined in University of Pittsburgh Institutional Review Board (IRB) ethical policy.

Several prior studies have focused on student understanding of thermodynamics [23–51]. Here we discuss the common college student difficulties with the first and second laws of thermodynamics found using the STPFaSL survey before and after traditional lecture-based instruction in relevant concepts in college introductory physics courses as well as by administering the survey to advanced students (upper-level physics majors in thermodynamics course after relevant instruction and to first year post-graduate students in physics PhD program before they took statistical mechanics course). As discussed in the survey validation paper [22], although earlier versions of the survey have been given to several thousand students, including the six US colleges that participated, the final version of the survey was administered to 1087 introductory physics students in calculus-based (mainly physical science and engineering majors) or algebra-based (mainly biological science majors) physics courses, and 192 students in advanced physics courses. The six institutions varied in size. The average survey scores of introductory students before and after college instruction in relevant concepts were 29% and 37%, respectively, which implies that traditional college instruction did not improve introductory student understanding of these concepts significantly [22]. The average overall survey scores of advanced students was approximately 56%. What is also interesting is that when the survey questions are separated into first law and second law questions, student scores on each of these subsets (first law and second law) are comparable. While discussing the percentages of students with certain difficulties in the tables in this paper, we keep the algebra-based and calculus-based introductory and advanced students as separate groups since instructors are often mainly interested to compare their students’ scores with a comparable group. Moreover, we conducted hour long interviews with 34 students individually from introductory to advanced levels (24 introductory 10 advanced) using a think-aloud protocol at various stages of test development. Some of the earlier interviews asked students more open-ended questions to develop good alternative choices to the survey questions while the later interviews asked students to explain their reasoning for each of their survey responses while thinking aloud. Students were not interrupted while they were thinking aloud during these interviews but later were asked for clarifications of points they had not made clear. These interviews were very valuable for understanding student reasoning and will be alluded to while discussing student difficulties.

We note that there are different views regarding the statement of the first law of thermodynamics. Most introductory physics texts define it as a relation between change in internal energy of the system, thermal energy transfer and work done by the system in a thermodynamic process. Since our focus is on introductory physics content, for the purposes of this paper, we will refer to this relation as the first law although it is a consequence of the first law. In particular, we emphasize that a consequence of the first law is a relation among three quantities of different nature and that only one (internal energy) is a state variable of the system and that the other two are contributions to the change of internal energy coming from different mechanical and non-mechanical (thermal) interactions to which the system is subjected. Also, the word ‘variable’ in this paper does not necessarily refer to state variables but any variable.

Since the in-class study presented here uses a validated survey with 33 items spanning 19 contexts, some of which have been taken from previous studies while others are new, and involves a large number of students from introductory physics to advanced levels, it provides
Table 1. Prevalence of incorrect use of compensation heuristic in first law problems. (In order to see the context dependence, table 4 in the appendix shows the breakdown of the percentages of students with a difficulty for each question separately.) The item numbers which have an asterisk on them are not included in tabulating the prevalence of a particular difficulty because it was not possible to tease out the percentage of students exhibiting a particular difficulty from the data due to the prevalence of other difficulties.

| Difficulties                                                                 | Item # | Upper Post | Calc. Post | Calc. Pre | Algebra Post | Algebra Pre |
|------------------------------------------------------------------------------|--------|------------|------------|-----------|--------------|-------------|
| An increase in one quantity implies a decrease in another quantity           | 2, 9, 10, 14* | 21         | 23         | 22        | 20           | 17          |
| Two of the three quantities in the first law are zero in a process           | 17, 21, 27, 29* | 16         | 28         | 34        | 30           | 30          |

Table 2. Prevalence of difficulties with entropy change in reversible processes. $S_U$ is the entropy of the Universe and $S_{\text{system}}$ is the entropy of the system under consideration.

| Correct answer in bold, difficulties unbolded | Item # | Upper Post | Calc. Post | Calc. Pre | Algebra Post | Algebra Pre |
|----------------------------------------------|--------|------------|------------|-----------|--------------|-------------|
| Reversible adiabatic process                 |        |            |            |           |              |             |
| $\Delta S_{\text{system}} = 0$ (correct)    | 1      | 24         | 28         | 19        | 29           | 24          |
| Reversibility (alone) $\Rightarrow \Delta S_{\text{system}} = 0$ | 1 | 39 | 29 | 16 | 36 | 19 |
| $\Delta S_{\text{system}} > 0$              | 1      | 28         | 32         | 51        | 29           | 46          |
| Reversible isothermal compression           |        |            |            |           |              |             |
| $\Delta S_{\text{system}} < 0$ (correct)    | 4      | 31         | 28         | 37        | 32           | 44          |
| $\Delta S_{\text{system}} = 0$              | 4      | 42         | 36         | 25        | 43           | 20          |
| $\Delta S_{\text{system}} > 0$              | 4      | 23         | 26         | 23        | 12           | 19          |
| Reversible isothermal expansion            |        |            |            |           |              |             |
| $\Delta S_{\text{system}} > 0$ and $\Delta S_U = 0$ (correct) | 28 | 34 | 40 | 36 | 42 | 27 |
| $[\Delta S_{\text{system}} = 0]$ and $\Delta S_U = 0$ | 28 | 26 | 27 | 23 | 30 | 33 |
| $\Delta S_{\text{system}} > 0$ and $\Delta S_U > 0$ | 28 | 40 | 33 | 41 | 28 | 40 |

an opportunity to investigate the robustness of previous findings and context dependence of the difficulties. Moreover, it provides an opportunity to investigate the degree to which the difficulties students had decreased from the pretest (before instruction) to posttest (after traditional lecture-based instruction) in the introductory courses and from introductory level to advanced level using a validated survey.

The goal of this paper is to describe different types of common difficulties that prevented many students from answering various survey questions about the first and second laws of thermodynamics correctly. In all of the tables in the following sections (tables 1–3), if the number of students across different questions with a similar type of difficulty is averaged, the corresponding tables in the appendix (tables 4 and 5) provide the breakdown for the number of students with that difficulty for each question separately. These tables display whether the percentage of students at a particular level with a particular type of difficulty is stable across
Table 3. Prevalence of difficulties with entropy change in irreversible processes (see table 5 in the appendix for the breakdown of the percentages of students with a difficulty for each question separately).

| Correct answer in bold, difficulties unbolded | Prevalence (average %) by level |
|---------------------------------------------|--------------------------------|
| Item # | Upper Calc. | Calc. Algebra | Calc. Algebra |
| Not all processes have $\Delta S_{\text{Isolated}} = 0$ (correct) | 16 | 58 | 27 | 19 | 27 | 16 |
| $\Delta S_{\text{Isolated}} = 0$ for all processes | 16 | 42 | 73 | 81 | 73 | 84 |
| | | | | | | |
| Irreversible isochoric process | | | | | | 
| $\Delta S_U > 0, \Delta S_{\text{System}} > 0$ (correct) | 29 | 68 | 43 | 35 | 57 | 40 |
| $\Delta S_U = 0, \Delta S_{\text{System}} > 0$ | 29 | 16 | 31 | 30 | 20 | 28 |
| $\Delta S_U = 0, [\Delta S_{\text{System}} = 0]$ | 29 | 9 | 8 | 15 | 10 | 17 |
| | | | | | | |
| $\Delta S_{\text{Isolated}} > 0$ for a spontaneous process (correct) | 12, 14, 24, 32 | 84 | 61 | 56 | 62 | 59 |
| $[\Delta S_{\text{Isolated}} = 0]$ for a spontaneous process | 12, 14, 24, 32 | 16 | 39 | 44 | 38 | 41 |
| Free expansion process | | | | | | 
| $\Delta S_{\text{Isolated}} > 0$ (correct) | 14 | 89 | 77 | 69 | 79 | 72 |
| $\Delta S_{\text{Isolated}} = 0$ | 14 | 11 | 23 | 31 | 21 | 28 |
| Spontaneous heat transfer | | | | | | 
| $\Delta S_{\text{Isolated}} > 0$ and $\Delta S_{\text{Cold}} > 0$ (correct) | 12, 24 | 63 | 31 | 24 | 32 | 30 |
| $[\Delta S_{\text{Isolated}} = 0]$ and $\Delta S_{\text{Cold}} > 0$ | 12, 24 | 16 | 41 | 42 | 41 | 41 |
| $\Delta S_{\text{Isolated}} > 0$ and $\Delta S_{\text{Cold}} > 0$ but also $\Delta S_{\text{Hot}} > 0$ | 12, 24 | 14 | 13 | 13 | 11 | 12 |
| $\Delta S_{\text{Isolated}} > 0$ and $[\Delta S_{\text{Cold}} = 0]$ | 12, 24 | 6 | 9 | 13 | 11 | 11 |
| Spontaneous mixing | | | | | | 
| $\Delta S_{\text{Isolated}} > 0$, and each $\Delta S_{\text{subsys}} > 0$ | 32 | 62 | 37 | 33 | 40 | 27 |
| $\Delta S_{\text{Isolated}} > 0$, but each $[\Delta S_{\text{subsys}} = 0]$ | 32 | 21 | 23 | 21 | 22 | 31 |
| $[\Delta S_{\text{Isolated}} = 0]$, and each $[\Delta S_{\text{subsys}} = 0]$ | 32 | 8 | 21 | 23 | 18 | 16 |
| $[\Delta S_{\text{Isolated}} = 0]$, but each $\Delta S_{\text{subsys}} > 0$ | 32 | 6 | 13 | 15 | 15 | 13 |
| Second law (correct) | 13, 25, 33 | 88 | 63 | 58 | 72 | 53 |
| First law | 13, 25, 33 | 25 | 53 | 60 | 40 | 54 |
| Newton’s 2nd law | 13, 25, 33 | 4 | 13 | 17 | 11 | 25 |

Different questions on the survey or sensitive to the context of the questions. Also, the item numbers in all of the tables which have a star (asterisk) on them are not included in tabulating the prevalence of a particular difficulty because it was not possible to tease out the exact percentage of students with a particular difficulty from the data due to the prevalence of other difficulties. We also note that in some of the tables below, for comparison, the percentages of students in a particular group with the correct answer are provided (in boldface) before the percentages of students who have a certain type of difficulty are presented. Thus, all of the tables below display the average scores for the following groups: advanced students who had instruction in thermodynamics beyond introductory physics (upper-post, total number of students $N = 192$) and pre-test (before instruction, $N_{\text{calculus}} = 705$, $N_{\text{algebra}} = 218$) and post-test (after instruction in relevant concepts, $N_{\text{calculus}} = 507$, $N_{\text{algebra}} = 382$) performance of students in the calculus-based and algebra-based introductory physics courses.

Also, the details pertaining to how each group of students performed on each problem on the survey can be found elsewhere [22], however, as noted earlier, even advanced students’ average score was only 56%. Analyzing advanced students’ performance on individual questions,
we note that only on 11 problems on the survey, at least two thirds of the advanced students provided the correct response. These problems on which the students performed well were related to the change in internal energy in a cyclic process depicted on a PV diagram (problem 5), whether internal energy of a system can change in an insulated case in which it is isolated from everything else (problem 11, students performed the best on this problem of the survey), which law will be violated if spontaneous net heat transfer were to take place from an object at a lower temperature to another at a higher temperature (problems 13 and 25), the relation between the change in internal energy and temperature of an ideal gas (problem 17), identifying processes in which there is no net heat transfer between the system and the surroundings (problem 18), work done by an ideal gas in constant pressure and constant volume processes (problem 21), identification of state variables (problem 22), change in internal energy, net heat transfer and work done by an ideal gas in an isothermal expansion (problem 27), change in entropy and internal energy in a constant volume irreversible process (problem 29) and which law will be violated if a spontaneous process were to occur in which gas A and gas B mixed uniformly throughout the entire volume were to end up with gas A in one chamber and gas B in another chamber (problem 33).

1. Difficulties with the first law of thermodynamics

A number of difficulties related to the first law of thermodynamics have been documented in prior research [24, 25, 36–43]. For example, Loverude et al [24] investigated student understanding of the first law of thermodynamics in the context of how students relate work to the adiabatic compression of an ideal gas. In one problem used to investigate student understanding in their study, students were asked to consider a cylindrical pump containing an ideal gas such that the piston fit tightly and no gas could escape. In one version, students were asked what will happen to the gas temperature and why if the piston is quickly pressed inward. Another type of problem posed in the same study provided a cyclic process on a PV diagram in which part of the cyclic process was isothermal, isochoric and isobaric. Students were asked whether the work done in the entire cycle was positive, negative or zero and explain their reasoning. Loverude et al [24] reported that students had difficulty in discriminating between related concepts, sometimes considered only two of the three variables in the first law, and sometimes confused heat and internal energy or had confusion among work, heat and internal energy. A different study of students’ understanding of heat, work and the first law of thermodynamics in an introductory calculus-based physics course by Meltzer [25] asked several conceptual problems some of which involved the PV diagrams. For example, one problem in their study involved two different processes represented on the PV diagram that started at the same point and ended at the same point. Students were asked to compare the work done by the gas and the heat absorbed by the gas in the two processes and explain their reasoning for their answers. Meltzer [25] reported that students often incorrectly claimed that $W = 0$ and $Q = 0$ in a cyclic process and had difficulty distinguishing between state variables and process-dependent variables. Leinonen et al investigated the pre-knowledge of introductory thermal physics at the university [39]. They focused on student understanding of adiabatic compression of an ideal gas [40] and how hints and peer instruction during lecture might help students [46]. Most of their findings were consistent with Loverude et al [24] and Meltzer [25] and using evidence-based approaches helped with student understanding. Meltzer also investigated upper-level students’ understanding of these concepts using similar measures and found that they also had similar difficulties (e.g. $W = 0$ and $Q = 0$ in a cyclic process) but these difficulties were reduced [43]. In particular, upper-level students demonstrated superior qualitative reasoning
skills than introductory students and were better at interpreting the meaning of diagrams and graphs [43].

Our findings described below from more than a thousand students including introductory and advanced levels using a validated survey with 33 items, which span 19 contexts, are consistent with the previous findings. Moreover, the contexts of some of our items are the same as those in previous investigations while others are new. Thus, our research validates the previous findings in new contexts and points to the robustness of the previous findings. We also find that student reasoning is context dependent (similar to that found in the contexts used in prior research) as discussed below. We note that the tables provide quantitative data pertaining to difficulties although we emphasize the interviews in the narrative below since they helped us understand these difficulties better.

Before we discuss student difficulties after traditional instruction in relevant concepts, we note that in a brief thermodynamic knowledge survey administered before instruction (pre-test) on these topics in an introductory physics course, about half of the students had responses along the lines that energy is conserved although they did not specify the details of energy conservation. Another common response was that ‘heat’ itself is conserved with 15% of the students making statements such as ‘there is no loss of total heat in the Universe.’ While only mentioning energy conservation does not provide a good picture of student understanding of the first law and the statements that students made about the conservation of heat are not accurate, such responses suggest that students in the introductory physics courses have had previous instruction regarding the laws of thermodynamics (e.g. from high school physics courses, high school and college chemistry courses, and preparatory materials for the medical exam that includes these topics) before learning those concepts in the introductory physics course.

Some instructors who administered the survey noted that since the first law of thermodynamics is a conservation of energy law similar to those students have encountered in earlier courses, it will be easier for students than the second law. They noted that the second law was difficult partly because it was the first time students had encountered a quantity that was not necessarily conserved in a process for an isolated system. These instructors predicted that the form of the second law that states that the change in the entropy of the Universe is always greater than or equal to zero in a process will be more challenging for students than applying the first law in different situations. Contrary to those instructors’ prediction, students struggled with both laws. In particular, we find that while many students struggled with the second law and incorrectly assumed, e.g. that entropy of various systems or sub-systems is conserved across a variety of problems, others used the opposite heuristic and incorrectly assume that $\Delta S > 0$ in all situations for the individual system or sub-systems, and/or the combined system or Universe. Below, the difficulties with the second law will be discussed after the first law.

Individual interviews suggest that even after instruction, many introductory physics students only recalled fragments of the first law instead of a coherent statement of energy conservation involving work done by the system $W$, heat transfer to the system $Q$ and the change in the internal energy of the system $\Delta E$. Evidence of the prevalence of difficulties with the first law is widespread throughout the responses to the STPFaSL survey. In particular, 14 of the 33 conceptual problems on the STPFaSL can be solved using the first law, although some of them can also be solved using an alternative reasoning not requiring the first law. For example, on items 14, 23 and 31 on the survey involving different types of spontaneous processes (free expansion, spontaneous heat transfer and spontaneous mixing, respectively), one can use the first law to correctly conclude that if there is no heat transfer between the system and the surroundings ($Q = 0$) and the work done by the system is zero ($W = 0$), the change in the internal energy, $\Delta E$, is zero as well. However, the fact that the change in the internal energy must be zero can also be inferred without the use of the first law by simply noting that the
internal energy of an isolated system cannot change. Similarly, on the same items 14, 23 and 31 on the survey, if a student recognizes that $Q = 0$ and $\Delta E = 0$, that student can use the first law to correctly conclude that work $W = 0$. However, the use of first law is not mandatory to reason correctly that $W = 0$ in these problems if one recognizes, e.g. that there is no work done in any of these situations because the overall volume of the system is fixed. We also note that three other items on the survey (items 13, 25 and 33), related to why spontaneous processes do not occur in the opposite direction, include possible ‘violation of the first law’ as a choice, although this choice is incorrect. The average scores for students in different groups on these problems that touched upon the first law in some manner or another ranged from 29% to 59%.

We find that the fact that the relation between three thermodynamic quantities is involved in the first law makes it challenging for students, who are not adept at reasoning about three quantities simultaneously. In particular, when prompted about how they would describe the first law of thermodynamics to another student, some students only recalled one of the three quantities involved in the first law. For example, one introductory student after instruction stated: ‘heat cannot appear and disappear out of nowhere it is gotta come from somewhere. Is that conservation of heat?’ The above student did not have a good understanding of the first law and omitted work and internal energy in his description of the first law of thermodynamics. In individual interviews, we also find that the same students reasoned about the first law by considering two of the three quantities in the first law and ignoring the third one, but depending upon the question, a different quantity is ignored in the ‘two-quantity at a time’ reasoning involving the first law. In particular, some interviewed students only mentioned two of the three quantities involved in the first law, as in the following response from an introductory student after instruction in relevant concepts: ‘conservation of energy when there’s no work being done on a system’. Even after further prompting, this introductory physics student omitted $Q$ from the discussion and continued to claim that the first law says that ‘energy’ does not change when no work is done on a system. Another introductory student who ignored the changes in the internal energy of the system stated: ‘I still do not know how you would connect the work and the heat done’. When prompted further about what else the student could say about the first law, the student added: ‘I know that all the heat that you have in a system cannot go into doing work for the system’. This type of statement shows that there may also be confusion between the first and second laws. One reason students may be using this type of ‘two-quantity at a time’ reasoning is that it can help them manage their cognitive load during problem solving even though they are likely to arrive at an incorrect conclusion, having left out one of the three quantities in the first law.

Below, we describe some difficulties found with the first law although these categories are not mutually exclusive.

1.1. Inappropriate use of a compensation heuristic

Many items on the survey have an explicit description of a process and students must use the first law of thermodynamics to reason about a target quantity ($W$, $Q$, or $\Delta E$) using the information inferred from the description of the problem situation. As noted earlier, in these types of problems, some students ignored a quantity, especially if it is not explicitly mentioned in the problem. Moreover, interviews suggest that in some cases, even if all the three quantities involved in the first law are mentioned in the problem in some form or another (e.g. items 21 and 27), some students used a compensation heuristic to determine the target variable using only two of the three quantities. The students with this type of reasoning generally claimed that an increase in one quantity must lead to a decrease in another quantity and vice versa. The various cues in the problem often determine how a particular student may proceed, which quantity the
student focuses on first and then which quantity the student makes an inference about based upon the compensation heuristic. While it is not possible to obtain exact percentages of the use of compensation heuristics in written responses, table 1 provides an estimate of the prevalence of the responses in which an increase in one quantity is paired with a decrease in another quantity incorrectly (to see the context-dependence of this difficulty, please see breakdown by individual questions in table 4).

1.1.1. Difficulties in situations in which the relevant quantities are not zero. This difficulty is related to the preceding one discussed. For example, on item 9, both processes shown on the PV diagram involve an expansion in which positive work is done by the system (see figure 1). The problem asks students to make a comparison between $W_1$ and $W_2$ and between $Q_1$ and $Q_2$, which are the work done by the system $W$ and heat transfer to the system $Q$ for two different processes. For this problem, students are provided both a PV diagram (figure 1) and a verbal description. In order to solve this problem, a student must make use of the first law correctly. However, interviews suggest that after determining a relation between one pair (e.g. inferring that $W_1 > W_2$ correctly by discerning the areas under the curves on the PV diagram), some students used a compensation heuristic instead of using the first law to determine the remaining relationship. For example, in this case, they often incorrectly concluded that since $W_1 > W_2$, then $Q_1 < Q_2$ to compensate for it. On the other hand, some students who first correctly reasoned that $Q_1 > Q_2$ often used a compensation heuristic to incorrectly infer that $W_1 < W_2$ (this latter group of students generally did not know how to infer the work done by the system using the area under the curve in a PV diagram). Thus, there is a pattern to their reasoning.

Another situation in which some interviewed students used a compensation heuristic is item 10, which is one version of the Meltzer [25] problem, in which two expansion processes start and end at the same initial and final states on a PV diagram (see figure 2). The most common incorrect response from upper-level students was $Q_1 < Q_2$ since $W_1 > W_2$. Such a response was also quite common among introductory students. Similarly, on item 2, which asks about the change in the internal energy and work done by the gas in an adiabatic expansion, some interviewed students used a compensation heuristic to incorrectly reason that the internal energy of
the system must increase and the work done by the gas must be negative after they decided on
the increase or decrease in one of those variables incorrectly.

1.1.2. If one quantity is zero, another quantity is also zero. A special case of the compensation
heuristic, which was as prevalent in interviews as the cases in which students reasoned that
a higher value of one quantity must be compensated by a lower value of another quantity
in a process, is one in which students conclude that if one thermodynamic quantity is zero,
then another thermodynamic quantity is zero as well (see table 1). This difficulty was often
apparent in the interviews and individual discussions when students reasoned about some of
the conceptual problems that involve the first law. For example, on both items 17 and 21 (for
which the diagrams provided within the problems are displayed in figure 3), one common
difficulty was concluding that in an isochoric process, since there is no change in the volume
of the system, no work is done, and hence there is no change in the internal energy of the system
(we note that some interviewed students directly concluded that no change in the volume of
the system implies no change in the internal energy even without reasoning about the fact that
$W = 0$ in an isochoric process). Some of these students in one on one discussion did not realize
that they should also be considering the net heat transfer to the system in this process and the
fact that if two of the variables (internal energy of the system and work done by the system)
are zero then the net heat transfer will also be zero in the isochoric process as described by
them. In fact, on question 21, almost all of the interviewed students with this type of reasoning
thought that only the work done by the gas and the change in the internal energy of the system
are zero but the net heat transfer between the system and the surroundings is not zero. Even
when some of them were explicitly asked about the net heat transfer in the isochoric process,
they did not know how to reason about it and some did not appear to be very concerned about
the fact that the first law of thermodynamics is a relation between three quantities in which
only two of the three quantities were zero according to their reasoning. Similarly, on question
21, another common difficulty was that in the isochoric process, there is no work done by the
system and the many students concluded that there is no net heat transfer between the system
and the surroundings but there is a change in the internal energy of the system. In individual
discussions, many of these students also used the reasoning that if the work done by the system
is zero then the net heat transfer should be zero as well and they generally did not remember
that the first law is a relation between three quantities in which only two of the three quantities
cannot be zero for a process. We note that 52% of introductory students in an algebra-based
course pre-instruction noted an energy-conservation principle as the first law. However, the use
of a compensation heuristic concluding that two quantities are zero in a process suggests that many students do not have a deep understanding of the first law.

We note that on item 27 related to an isothermal expansion of an ideal monatomic gas, one common incorrect response is that there is no heat transfer between the system and surroundings, the internal energy does not change but the work done by the gas is positive. Unlike the responses of students who claimed that the internal energy must change in this isothermal process because $Q = 0$, the type of response in which students claim that $Q = 0$ and $\Delta E = 0$ in an isothermal process shows a lack of understanding of the first law of thermodynamics as a relation between three thermodynamic quantities. If the students knew how to reason about the first law correctly using all three quantities involved, they would have realized that it is impossible to have a situation in which two of the quantities in the first law are zero while the third quantity is non-zero.

1.2. Inferring an incorrect sign of a physical quantity using the first law

When students use an algorithmic approach and attempt formula fitting to solve problems that can be solved using the first law, they often get the sign of a physical quantity wrong. For example, on item 2 related to a reversible adiabatic expansion, the internal energy of the system must decrease in the expansion. However, on this question, the most common incorrect answer among students at all levels was that the internal energy should increase and the work done by the system should also be positive (correct) in this adiabatic expansion. Interviews suggest that students with this kind of reasoning incorrectly reasoned that the change in the internal energy of the system is equal to the work done by the gas and both changes must be positive in this case. These students did not reason conceptually about the fact that the work done by the gas should decrease the internal energy of the system in this adiabatic expansion. They often focused on an algorithmic approach and claimed that both the left-hand side and right-hand side of the formula they were using should have the same sign.

Another common incorrect response for item 2 from students at all levels is that the internal energy of the gas must increase and the work done by the gas must be negative (both signs incorrect). In individual interviews and discussions, many students did not think conceptually about the work done by the gas and they had difficulty in distinguishing between the work done by the gas and the work done on the gas. In particular, many students in both introductory and upper-level courses could not reason conceptually that the work done by the gas will decrease
the internal energy of the gas and the work done on the gas will increase the internal energy of the gas. These interviewed students, who did not reason conceptually about these issues and made use of some equation form of the first law of thermodynamics (correct or incorrect form), were very likely to get the sign of the work done by the gas wrong. The difficulty in conceptual reasoning about the work done by the system can also lead students to incorrectly answer questions related to heat transfer between the system and the surroundings because these two quantities are intertwined in many problems through the conservation of energy (for example, in items 3, 8, 10, 15, 27 for the relation between work and heat transfer).

Interviews suggest that on item 3, which is about a reversible isothermal compression of a monatomic ideal gas, some students made an incorrect inference about the sign of \( Q \) (whether net heat transfer is to or from the system) using the first law often because they were not thinking conceptually about the process. Even those students who correctly reasoned that \( \Delta E = 0 \) for the process did not realize that in a compression, work is done on the system by the surroundings so to keep the internal energy constant there must be net heat transfer from the gas.

On item 27, some interviewed students incorrectly noted that there is no heat transfer between the system and the surroundings for an isothermal process. However, some of them used a correct chain of reasoning to conclude that if the work done by the gas is positive and there is no heat transfer, the internal energy of the gas must decrease. The students who stated that the internal energy decreases essentially provided the correct reasoning using the first law for an adiabatic expansion (their mistake was assuming that a constant temperature process implies there is no heat transfer between the system and the surroundings). On the other hand, some interviewed students who did not reason conceptually and made use of the first law equation, incorrectly inferred that the work done by the gas should be positive and the internal energy of the gas should increase as well since there is no heat transfer between the system and surroundings for the isothermal process in item 27.

These types of conceptual difficulties may at least partly be responsible for student difficulties with the relation between work, heat transfer, and internal energy changes in items 9, 21, 29, and 30.

1.3. Using first law as the first line of reasoning when other reasoning should precede it

Similar to previous findings of expertise research, we find that many students immediately focus on whatever the question is asking about instead of making an overall plan to systematically approach the problem solving process [1–8]. In many of the problems, reasoning using the first law of thermodynamics is not the first line of reasoning students should use. However, in many situations, some students often invoke the first law right away when they are asked for a relation between any combination of \( E, W \) and \( Q \). For example, on item 10, even before invoking the first law of thermodynamics, a physics expert would first focus on the fact that both processes depicted on the PV diagram have the same initial and final states and conclude that the change in internal energy of the system is the same (see figure 2). Next, the physics experts would note that the work done by the system is larger for process 1 than for process 2 (as given by the area under the curve for each process on the PV diagram). Then, they would invoke the first law of thermodynamics to reason that from the conservation of energy, there should be larger net heat transfer to the system in process 1 than in process 2 if both systems start and end in the same states. Individual interviews and discussions suggest that some students immediately start thinking about the net heat transfer to the system using some version of the first law (not necessarily correct) and do not reason systematically about the fact that the changes in the internal energy are the same in both processes and work done by the system is larger in process 1 before invoking the first law.
2. Difficulties with the second law of thermodynamics

Previous investigations have shed light on student difficulties with the second law, e.g. see references [26–29, 34–38, 42, 43, 45]. For example, a study by Cochran and Heron [26] investigated heat engines and the second law of thermodynamics. In one question in that study, students were provided the diagram of a proposed heat engine and asked if the device as shown could function and why. They found that students had difficulty with most aspects of heat engine. In another investigation, Bucy et al [27] focused on student understanding of entropy in the context of comparison of ideal gas processes. For example, students were asked to compare the change in the entropy of an ideal gas in an isothermal expansion and free expansion into a vacuum and also explain whether the change in entropy of the gas in each case is positive, negative or zero in each case and why. They found that students confuse entropy of the Universe with the entropy of the system. Moreover, they had difficulty with the concept of entropy as a state variable. In another investigation by Christensen et al [28], students’ ideas regarding entropy and the second law of thermodynamics in an introductory physics course were studied. These studies found that students struggled in distinguishing between entropy of the system and the surrounding and had great difficulty with spontaneous processes. Meltzer [43] also investigated upper-level students’ understanding of the second law and found that although a larger proportion of students provided correct responses, they also had difficulty with the fact that the entropy is a state variable and often claimed that the system entropy must always increase even when that was not the case or it was not possible to infer it from the context given. Another investigation by Smith et al [29] focused on student difficulties with concepts related to entropy, heat engines and the Carnot cycle and found that student difficulties were similar to the earlier studies and the understanding was improved using research-based tools.

Many of the findings in our investigation using a validated survey are consistent with the earlier findings. However, many of our problems are in contexts different from those used before. Thus, our results show the robustness of prior findings in new contexts. Interviews and written responses suggest that many students did not remember the various forms of the second law of thermodynamics correctly (Clausius statement, Kelvin–Planck statement, and the change in the entropy of the Universe should be greater than or equal to zero in any thermodynamic process, etc) [29]. Similar to prior research, many students also had difficulty with the fact that the entropy is a state variable. One common difficulty was that students often overgeneralized the second law. For example, in individual interviews, many students after instruction echoed the statement of this introductory physics student: ‘second law says that the entropy always increases’. This type of common overgeneralization of the second law suggests that many students do not have a clear understanding of this form of the statement of the second law and they are confusing the system with the Universe and/or are unable to distinguish between reversible and irreversible processes.

On the brief survey of thermodynamics given before instruction on relevant topics for bonus points on an exam in an algebra-based introductory physics course, students were less likely to make a correct or incorrect statement about entropy and the second law (28%) than they were to make statements about the first law (52%). Even in these responses from students before instruction, the most common statements about the second law were the well-known overgeneralizations of the law as conveyed by the following statements from students: ‘entropy increases always (and/or everywhere)’ or ‘energy is always moving toward disarray’ (the latter statement suggests confusion between energy and entropy). Examples of the prevalence of the difficulties with the second law can be found in the written responses to the survey questions.
Since many of the survey problems that involved the second law were framed in terms of entropy, difficulties with those problems were often associated with difficulties with the concept of entropy. As noted, many prior investigations have focused on student understanding of entropy [27, 28, 34–36, 38, 45, 47]. Our findings in many different contexts are consistent with earlier studies with advanced students having similar difficulties to introductory students but with lower percentage of students displaying those difficulties. Confusion about the system and the Universe is often responsible for student difficulties with the second law as it relates to entropy. Some students claimed, e.g. that the entropy of the system (not the Universe) increases for irreversible, but stays constant for reversible, processes. Another common difficulty with the second law as it relates to entropy is that the entropy cannot change for an isolated system. Students often incorrectly claimed that even in an irreversible process, the entropy of an isolated system does not change. For reversible processes, some students claimed that entropy is conserved for the system (or both the system separately and the Universe). On the other hand, some students claimed that the entropy of the Universe increases even in a reversible process since they did not know the relevance of the word ‘reversible’ in this context. These difficulties will be discussed in more detail in the following sections.

2.1. Difficulties with heat engines

Several prior investigations have focused on student understanding of heat engines and some have also focused on learning tools that can help students develop a coherent understanding of heat engines [26, 37, 38]. We find that most students in all groups had great difficulty with the two problems about heat engines on the survey. Many answered them by resorting to memorized information about heat engines. On item 16, students had to recognize the correctness of the following two versions of the second law that were related to heat engines (directly or indirectly): ‘no heat engine can be more efficient than a reversible heat engine between given high temperature and low temperature reservoirs’ and ‘the net heat transfer to the system from a hot reservoir cannot be completely converted to mechanical work in a cyclic process’. Students had great difficulty with these. Interviews suggest that some students did not have a clear understanding that in heat engines, as the cyclic process is repeated, there is net heat transfer to the working substance (system) from the hot reservoir, some of this energy is used to perform work by the system and the rest transfers to the cold reservoir. All of the difficulties discussed earlier in the context of a cyclic process were observed in interviews (e.g. not recognizing that $\Delta S = 0$ for both the system and the environment in a complete cycle if the process is reversible but $\Delta S = 0$ only for the system and that $\Delta S > 0$ for the environment so that the entropy of the Universe increases consistent with the second law of thermodynamics for an irreversible complete cycle). Some interviewed students had difficulty with articulating how the operation of the heat engine involves both the first and second laws of thermodynamics consistent with earlier findings.

2.2. Difficulties with entropy as a state variable

Consistent with prior research, many introductory and advanced students had difficulty with the fact that entropy is a state variable and incorrectly believed that the system entropy must increase in a given process. For example, items 7 and 15 on the survey ask students about the change in entropy of the system in a cyclic process for one complete cycle. These problems are two of the most challenging problems on the survey even for advanced students with only 41% and 40% of the advanced students providing the correct response that the entropy of the system is unchanged. On items 7 and 15, respectively, 36% and 35% of the advanced students incorrectly answered that the entropy of the system increases for one complete cycle.
2.3. Difficulties with $\Delta S$ in a reversible process

The common difficulties with the concept of reversibility of a process can be classified into two categories. One difficulty was overgeneralizing the statement that reversibility implies that $\Delta S = 0$ for the Universe to reversibility implies $\Delta S = 0$ for the system. The second difficulty was to disregard the word ‘reversible’ in a question and let the other details of the problem dictate the reasoning (these students often claimed that entropy of the system and/or the Universe increases in a reversible process). The analysis of the survey data suggests that students sometimes performed better on problems involving irreversible processes than they did on problems involving reversible processes partly because of these two difficulties.

Table 2 shows the prevalence of student difficulties with entropy in a reversible process across various items on the survey. The table shows that one of the most common difficulties on item 1 about a reversible adiabatic expansion of a gas is that the entropy of the system remains constant for a reversible process regardless of whether the process is adiabatic or not. Table 2 shows that the entropy of the system remains constant for a reversible process is one of the most common difficulties also on item 4 (isothermal reversible compression) and item 28 (in item 28, a gas undergoes an isothermal reversible expansion). As noted, this type of response is often due to the confusion between the system and the Universe.

Table 2 also shows that another common conceptual difficulty with items 1 and 4 is that the entropy of the system increases in the reversible processes described in the problems (the correct response is that the entropy of the system does not change in item 1 and it decreases in item 4). Interviews suggest that students with this type of a response either incorrectly thought that the entropy of the system increases because it is an expansion process or that the entropy of the system increases in all processes.

On the other hand, on item 28, a common incorrect response was that the entropy of the Universe increases (see table 2). Interviews suggest that students with this type of difficulty often did not recognize the relevance of the word reversible and assumed that entropy increases in all processes.

2.4. Difficulties with $\Delta S$ in an isolated system

Some prior studies have investigated student difficulties with an isolated system [28, 38]. Our findings are consistent with these studies. A number of the survey questions contain a system (sometimes consisting of two subsystems) which cannot exchange energy in any form with the surroundings (e.g. items 11, 12, 14, 16, 23, 24, 13, and 32 all require reasoning about isolated systems). The entropy of an isolated system increases if it undergoes an irreversible process. However, for questions related to isolated systems for which neither particles nor energy are being exchanged with the surroundings, some students thought that the entropy of the system cannot change. Table 3 shows student difficulty with such questions. For example, on item 16, more than 80% of the students before instruction and 73% of students after instruction in introductory courses selected an incorrect choice consistent with the claim that the entropy of any system that cannot exchange energy with its surrounding environment must remain unchanged (see table 3). In upper-level courses, the corresponding average percentage is 42%. Some interviewed students with this difficulty claimed that if there is no exchange of energy, there is no heat transfer between the system and the surroundings so there cannot be any change in the entropy of the system since the change in entropy depends on $Q$. Also, some interviewed students explicitly tried to consider a process in which there is no energy exchange between the system and surroundings and the entropy of the system increases, but they often could not come up with any appropriate process. Those who did make a connection generally considered $\Delta S$ in the free expansion process in which the entire system is insulated from the surroundings.
Most of those students concluded that since the entropy of the isolated system increases in the free expansion process, $\Delta S$ can be greater than zero for an isolated system.

2.5. Difficulties with $\Delta S$ in an irreversible isochoric process

Even though there are 11 items on the survey that require knowledge of irreversible processes, item 29 is the only problem on the survey with the word ‘irreversible’ in it. In this irreversible isochoric process, the most common difficulty was manifested by selecting that the entropy of the gas increases but the entropy of the system and reservoir taken together does not change (see table 3). Interviews suggest that some students exhibiting this type of reasoning thought that the entropy of the system and the reservoir taken together cannot change because the gas was in a closed container. The second most common difficulty exhibited by the section of choice was that the entropy is conserved both for the system alone and also for the system and the reservoir taken together. Interviews suggest that some of these students thought that the entropy of the gas cannot increase when it is in a closed container.

2.6. Difficulties with $\Delta S$ for a free expansion process

Table 3 shows that on item 14 on the survey, the most common mistake related to entropy is that it is conserved for the free expansion process. Approximately 20%–30% of introductory students from calculus-based and algebra-based courses even after instruction and 10% of students from upper-level courses selected this option. Interviews suggest that a common reason for this difficulty is assuming that entropy cannot change for an isolated system.

2.7. Difficulties with $\Delta S$ in spontaneous mixing of two gases

Table 3 shows that on item 32 the most common mistake was that the entropy of the combined system increases if two inert ideal gases in adjacent chambers are allowed to mix spontaneously but the entropy of each of the sub-systems does not change (the combined system is in an insulated case). Interviews suggest that this type of response was often based upon over-generalization of memorized knowledge. Table 3 also shows that the second most common mistake on item 32 is that the entropy of the combined system and the entropy of each of the sub-systems do not change (each is conserved) if two inert ideal gases in adjacent chambers are allowed to mix spontaneously. Interviews suggest that at least for some of the students, this difficulty is due to the fact that the combined system is in an insulated case. Table 3 also shows that the third most common mistake on item 32 is that the entropy of the combined system does not change (is conserved) but the entropy of each of the sub-systems increases. Interviews suggest that some students with this type of mistake thought that since each gas is allowed to mix, each component will have an increased entropy but since the combined system was in an insulated case, there is no change in the entropy of the combined system. In this type of reasoning, students are inconsistent in their response to different parts because it amounts to $1 + 1 = 0$.

2.8. Difficulties with $\Delta S$ in spontaneous heat transfer between two solids at different temperatures

Tables 3 and 5 in the appendix show that on item 12, the most common mistake was that for a closed system, the entropy of the sub-system at a lower temperature increases but that of the combined system does not change if there is spontaneous heat transfer from one part of the system to another when two solids at different temperatures are placed in contact. Interviews suggest that some students with this mistake thought that the entropy of the combined system
cannot change for an isolated system. Table 5 in the appendix also shows that on item 12, the second most common mistake was that for a closed system, the entropy of each sub-system and the combined system all increase if there is spontaneous heat transfer from one part of the system to another when two solids at different temperatures are placed in contact. Interviews suggest that at least some of these students thought that the entropy always increases for everything, at least in an irreversible process. In addition, table 5 shows that on item 12, the third most common mistake was that the entropy of the combined system increases but the entropy of the cold sub-system does not change when two solids at different temperatures are in contact. Interviews suggest that at least some of these students thought that the second law of thermodynamics says that the entropy of the combined system increases but the entropy of each sub-system does not change in such processes.

2.9. Difficulties with $\Delta S$ in spontaneous heat transfer between two gases at different temperatures

Tables 3 and 5 in the appendix show that on item 24, the most common mistake was that for a closed system, the entropy of the sub-system at a lower temperature increases but that of the combined system does not change if there is spontaneous heat transfer from one part of the system to another. Table 5 also shows that on item 24, the second most common mistake was that for a closed system, the entropy of each of the sub-systems and the combined system all increase if there is spontaneous heat transfer from one part of the system to another. Table 5 shows that on item 24, the third most common difficulty was that for a closed system, the entropy of the combined system increases if there is spontaneous heat transfer from one part of the system to another but the entropy of each sub-system does not change. Interviews suggest that common reasons for these difficulties were analogous to those for spontaneous heat transfer between two solids at different temperatures in contact that was discussed in the preceding section.

2.10. Difficulties with the relation between entropy change, heat transfer, and temperature

Several prior investigations have focused on student difficulties with the relation between entropy, heat transfer and temperature [27, 28, 38, 45]. Our findings are consistent with these studies. While some of the interviewed students did not recall the relationship between heat transfer to the system and the change in entropy of the system, even those interviewed students who remembered (often vaguely) that the change in the entropy of the system is somehow related to the net heat transfer between the system and the surroundings, generally appeared not to be able to exploit this information effectively to solve the survey problems. In fact, some of the students who remembered the relation between entropy and net heat transfer noted that if there is no heat transfer between the system and the surroundings, the entropy of the system must be conserved (including for irreversible processes). They argued that if $Q = 0$, then the entropy of the system cannot change. Also, some interviewed students did not know that the relation between the change in entropy, heat transfer and temperature applies only for a reversible process, but since entropy is a state variable, in order to find the change in entropy for an irreversible process, one can carry out the integral over a reversible process that takes the system from the initial state to the final state.

2.11. Difficulty with the law governing the direction of spontaneous processes

Prior research indicates that students do not always connect the second law of thermodynamics with spontaneous processes that occur in nature [28, 34, 35, 38, 45]. Items 13, 25, and 33 on the survey ask students to choose why a spontaneous process occurs in a certain direction
and which law(s) will be violated if a spontaneous process took place in the reverse direction. On these questions, students had to identify that the second law of thermodynamics will be violated if a spontaneous process took place in the opposite direction. Items 13 and 25 pertain to situations in which there is net heat transfer from a solid at a higher temperature to a solid at a lower temperature in contact or from a gas at a higher temperature to a gas at a lower temperature in adjacent chambers. Question 33 focuses on mixing of two inert ideal gases in adjacent chambers. Apart from the second law of thermodynamics, students could select the first law and/or Newton’s second law. These laws were chosen based upon our earlier interviews that suggested that some students thought that the first law of thermodynamics prevents a process from happening in reverse. Table 3 shows the percentages of students who selected different options. Some interviewed students explicitly noted that since the first law relates to the conservation of energy, it will always be violated if a spontaneous process took place in a direction opposite to that observed.

In the interviews, some students claimed that the reason the first law (energy conservation) or Newton’s second law is violated is because the momentum conservation is violated in these types of processes. In some cases, students reasoned about heat transfer as though it involved transfer of particles from one region to another. In interviews, some students spent a significant amount of time trying to determine if these processes violate Newton’s second law. Introductory students taking the written survey as a pretest often claimed that Newton’s second law is violated in such processes, but the fraction of students who claimed this by the end of the semester on posttest is markedly lower.

### 2.12. Difficulties related to distinction between system and universe

Most of our findings are consistent with prior research studies that have investigated the confusion between the system and the Universe [28, 34, 37, 38]. In order to solve problems about changes in the entropy of the system or the Universe using the second law of thermodynamics, one must understand the law as it pertains to the entropy change of the Universe in a particular process. For example, students should understand that one version of the second law of thermodynamics states that the entropy of the Universe increases in an irreversible process and remains constant in a reversible process, and it is possible for the entropy of the system alone to decrease or increase in a particular thermodynamic process regardless of whether the process is reversible or irreversible. Many students had difficulty with the survey problems related to entropy because they could not make a clear distinction between the system and the Universe and how the second law formulated in terms of entropy applies to various systems, subsystems and the Universe.

Some interviewed students also treated ‘cyclic processes’ and ‘reversible processes’ in a very similar manner in some problems (not necessarily all since student reasoning is context dependent) as though the word ‘cyclic’ has the same meaning as the word ‘reversible’. They did not realize that a cyclic process can be irreversible and in such a process the change in the entropy of the system will be zero but the change in the entropy of the environment will be greater than zero because it is the system that returns to the initial state after a complete cycle but the final state of the environment is different from the initial state after a complete cycle. Thus, the entropy of the Universe increases in an irreversible cyclic process. The fact that some students are unclear about the distinction between the system, environment and the Universe makes these concepts challenging for them.
3. Discussion

We investigated student difficulties related to the first and second laws of thermodynamics using a validated 33-item conceptual multiple-choice survey. We find that these thermodynamic concepts, which were at the level typically covered in introductory physics courses, were very challenging for both introductory and advanced students after traditional instruction. We note that a limitation of the study is that the distractors provided on the survey will significantly impact the difficulties observed, and therefore, this approach could miss other significant difficulties that were not included as distractors on the survey. Thus, the difficulties identified in this manner may not be complete and may be influenced by the design of the survey itself. However, we also note that this is a validated survey [22] and research on student difficulties was used as a guide to develop the survey. Thus, similar to other validated surveys on other topics, this survey can be very valuable for instructors. We also note that sometimes students have some knowledge but it does not get invoked or applied correctly in a particular context. Thus, if students did not answer a question correctly, all we can conclude is that they did not activate the knowledge or apply it correctly in the particular context of the problem even though they may have had the knowledge.

Our findings from more than a thousand students including those from the introductory and advanced levels using a validated survey with 33 items are largely consistent with the previous findings in the contexts used in previous studies and they also point to similar difficulties in new contexts not investigated earlier. Also, unlike some of the previous studies which were only focused on students at one level, our findings are for both introductory and advanced students with a sizable student number in each group. The conceptual difficulties revealed in the posttest after instruction across all levels indicate that traditional instruction is not successful in reducing student difficulties and helping them build a coherent knowledge structure even after an advanced undergraduate thermodynamics course. We note that while there were quantitative differences across contexts used in different items in terms of the percentages of students at a particular level who provided the correct response or had certain difficulty, that level of nuanced analysis is out of the scope of this paper.

We find that student responses to similar topics across different contexts are often inconsistent. In fact, student responses depend not only on the physical context of a problem, but they also depend on the wording of a question, particularly because the alternative choices to the multiple choice questions include the common difficulties of students. Moreover, in thermodynamics, there are many physical quantities, processes, and types of systems that one must consider to solve a problem in addition to the principles and laws that govern each situation in the problem posed. It is possible that certain information given in the problem statement (e.g. whether a process is reversible or not) is actually relevant in one situation to solve the problem but not in another. We find that many students did not appropriately recognize or distill the underlying principles and concepts relevant in a problem appropriately or did not know how to systematically exploit them to solve the conceptual survey problems effectively [1–8].

Individual interviews also reveal that while solving conceptual problems on the survey, students often ignored information they did not want to consider or did not know how to consider to solve the problems, which led to mistakes. While certain information in the problem may in fact be irrelevant, students often ignored important information and hoped that they would still be able to solve the problem correctly. We find that in addition to the information given in individual questions that many students ignored, some also ignored the information provided on the cover page of the survey. For example, the cover page contains the relation between the internal energy and temperature of an ideal monatomic gas and the definition of the term ‘adiabatic’. However, many students at all levels answered various survey questions as though...
they had not read or did not remember or did not find relevant this type of information on the cover page of the survey that was useful for solving problems. For example, on item 18, which explicitly asks students to identify the processes that involve no heat transfer between the system and surroundings, approximately two-thirds of the calculus-based and one-fourth of the algebra-based introductory physics students, even after instruction, did not use the information on the cover page that an ‘adiabatic’ process fits this category. In fact, the average student performance at each level was very similar for the problems which required knowledge of the fact that there is no heat transfer between the system and the surroundings in an adiabatic process when this definition was given on the cover page of the survey compared to an earlier version administered in the past in which this information was not provided.

We also note that certain information provided in a problem gives clarity to physics experts and facilitates their reasoning process while solving the problem. For example, if the problem statement says that a thermodynamic process is reversible and the problem is about changes to the entropy of the system or the Universe, such information facilitates expert reasoning that the entropy of the system can increase or decrease but the entropy of the Universe will not change. On the other hand, many students who had alternative conceptions about what the word reversible means, concluded that the entropy of the system will also not change. Similarly, on problems related to cyclic processes, physics experts immediately note that the state variables will be unchanged but other physical quantities are not zero in general after a complete cycle. However, the phrase ‘cyclic process’ led many students to conclude that none of the thermodynamic quantities changed in such a process after a complete cycle. Thus, the information that the process is reversible or cyclic derailed their reasoning. The same kind of difficulty was observed on survey problems that used the word isothermal. As noted, in interviews, students often interpreted the word isothermal to mean that either both the temperature was constant and net heat transfer between the system and surroundings was zero or at least $Q = 0$ even if they did not explicitly mention anything about the change in temperature. The rest of their reasoning was impacted by this initial interpretation of an isothermal process.

We find that many students in all groups did not have the expertise to solve the conceptual survey questions in an expert-like manner and they did not invoke appropriate concepts in the order in which they should be invoked to solve a problem. Unlike experts, constraints on a process were often ignored or used incorrectly by students. Students’ responses were also often context dependent in that they did not give consistent answers to various questions involving the same underlying concepts.

Most thermodynamics problems on the survey cannot be solved using a plug and chug approach with memorized algorithms. We find that students often used heuristics that were too simplistic such as using only two quantities in the first law instead of reasoning with all three quantities or using a compensation heuristic to solve problems involving the relation between the internal energy of the system, work done by the system and net heat transfer to or from the system. They often assumed that when some quantity increases, another must decrease or if some quantity does not change then another should not change either without considering other aspects of the problem correctly. Interviews suggest that sometimes the same student reasoned about two of the three quantities in the first law, choosing a set of two out of three quantities depending upon the cues of the problem statement, without realizing that he/she may have neglected a quantity that should be included in the reasoning involving conservation of energy. Expertise research suggests that such a problem solving strategy is typical of students who do not have a robust knowledge structure in the domain [1–8].

On many problems, students were unable to distinguish between the system, environment and the Universe. Instruction should be designed carefully to help students learn, e.g. that in a cyclic process since the initial and final states of the system are the same in a complete cycle,
there is no change in any state variable including the entropy for the system. On the other hand, all we can say about the environment is that there is no change in the internal energy of the environment in the complete cycle due to the conservation of energy, but the initial and final entropy of the environment will be the same only if the cyclic process is reversible. In particular, if the cyclic process is irreversible, the final entropy of the environment must be greater than its initial entropy so that the entropy of the Universe (which is the sum of the entropies of the system and environment) increases, consistent with the second law of thermodynamics. Helping students learn to treat changes to the system, environment and the Universe due to various thermodynamic processes instead of mainly focusing on discussions of the changes to the system will not only help students apply the second law of thermodynamics correctly in various situations but also reduce the confusion between, e.g. a cyclic and a reversible process.

We also found that many students at all levels confused ‘closed container’ with an ‘isolated system’ in which there is no heat transfer between the system and the surroundings. Interviews suggest that some of the worst performance on the survey questions was on items in which a gas in a closed container was heated because students treated such a system as an isolated system. It is possible that this difficulty will decrease if instructors do not use the terms ‘isolated system’ and ‘closed system’ interchangeably because this type of language can give students the impression that ‘closed container’ and ‘isolated system’ are the same.

4. Conclusion

The findings presented here suggest that even though instructors cover the STPFaSL survey content in introductory physics, it is challenging even for advanced students. In particular, to apply the fundamental laws of thermodynamics appropriately in diverse situations, students must be provided guidance and support to discern the differences between different types of thermodynamic systems, quantities, processes, etc. Moreover, effective curricula and pedagogies should help students learn how to systematically focus on relevant information provided in the problems and reason about them. Instructors can view the variety of situations encountered in relation to the topics in thermodynamics covered in STPFaSL as an opportunity for developing students’ problem solving and reasoning skills. Also, in order to help students learn to make sense of the thermodynamic processes and correctly apply the first and second laws of thermodynamics, instructors should consider using physics education research based instructional approaches. The findings presented here for student difficulties in traditionally taught introductory courses can be compared with courses in which innovative curricula and pedagogies are used in order to gauge the level of improvement in introductory and advanced students’ understanding of these concepts.

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Appendix

See tables 4 and 5.
Table 4. Prevalence of incorrect use of a compensation heuristic in first law problems for each item. The item numbers which have an asterisk on them are not included in tabulating the prevalence of a particular difficulty because it was not possible to tease out the percentage of students exhibiting a particular difficulty from the data due to the prevalence of other difficulties.

| Difficulties | Prevalence (average %) by level |
|--------------|---------------------------------|
|              | Upper | Calc. | Calc. | Algebra | Algebra |
| An increase in one quantity implies a decrease in another quantity. (Additional question 14*) | 2 | 10 | 16 | 14 | 15 | 13 |
| Two of the three quantities in the first law are zero in a process. (Additional question 29*) | 17 | 11 | 18 | 23 | 24 | 18 |

Table 5. Prevalence of difficulties with entropy change in irreversible processes for each item. Bold text indicates a correct statement, which was given as part of a response. Statements in brackets are the interpretation of student response informed by interview. For instance, ‘[\(\Delta S_{\text{Isolated}} = 0\)]’ represents a case where students did not select \(\Delta S_{\text{Isolated}} > 0\).

| Correct answer in bold, difficulties unbolded | Prevalence (average %) by level |
|---------------------------------------------|---------------------------------|
|                                             | Upper | Calc. | Calc. | Algebra | Algebra |
| Not all processes have \(\Delta S_{\text{Isolated}} = 0\) (correct) | 16 | 58 | 27 | 19 | 27 | 16 |
| \(\Delta S_{\text{Isolated}} = 0\) for all processes | 16 | 42 | 73 | 81 | 73 | 84 |

Irreversible isochoric process

| \(\Delta S_{\text{Isolated}} > 0, \Delta S_{\text{System}} > 0\) (correct) | 29 | 68 | 43 | 35 | 57 | 40 |
| \(\Delta S_{\text{Isolated}} = 0, \Delta S_{\text{System}} > 0\) | 29 | 16 | 31 | 30 | 30 | 28 |
| \(\Delta S_{\text{Isolated}} = 0, [\Delta S_{\text{System}} = 0]\) | 29 | 9 | 8 | 15 | 10 | 17 |

| \(\Delta S_{\text{Isolated}} > 0\) for a spontaneous process (correct) | 12 | 81 | 55 | 50 | 57 | 57 |
| 14 | 89 | 77 | 69 | 79 | 72 |
| 24 | 83 | 53 | 50 | 51 | 48 |

| \(\Delta S_{\text{Isolated}} > 0\) for a spontaneous process | 32 | 83 | 60 | 54 | 63 | 59 |
| 12 | 19 | 45 | 50 | 43 | 43 |
| 14 | 11 | 23 | 31 | 21 | 28 |
| 24 | 17 | 47 | 50 | 49 | 52 |

| \(\Delta S_{\text{Isolated}} = 0\) for a spontaneous process | 32 | 17 | 40 | 46 | 37 | 41 |

Free expansion process

| \(\Delta S_{\text{Isolated}} > 0\) (correct) | 14 | 89 | 77 | 69 | 79 | 72 |
| \(\Delta S_{\text{Isolated}} = 0\) | 14 | 11 | 23 | 31 | 21 | 28 |
Table 5. Continued

| Spontaneous heat transfer | 12 | 62 | 31 | 24 | 32 | 29 |
|---------------------------|----|----|----|----|----|----|
| $\Delta S_{\text{isolated}} > 0$ and $\Delta S_{\text{Cold}} > 0$ (correct) | 12  | 17  | 40  | 44  | 41  | 39  |
|                           | 12  | 17  | 40  | 44  | 41  | 39  |
| $[\Delta S_{\text{isolated}} = 0]$ and $\Delta S_{\text{Cold}} > 0$ | 24  | 15  | 42  | 39  | 41  | 43  |
| $\Delta S_{\text{isolated}} > 0$ and $\Delta S_{\text{Cold}} > 0$ but also $\Delta S_{\text{Hot}} > 0$ | 24  | 14  | 12  | 12  | 11  | 7   |
| $\Delta S_{\text{isolated}} > 0$ and $[\Delta S_{\text{Cold}} = 0]$ | 12  | 6   | 10  | 13  | 12  | 11  |
| Spontaneous mixing        | 24  | 5   | 9   | 13  | 9   | 11  |
| $\Delta S_{\text{isolated}} > 0$ and each $\Delta S_{\text{subsys}} > 0$ | 32  | 62  | 37  | 33  | 40  | 27  |
| $\Delta S_{\text{isolated}} > 0$ but each $[\Delta S_{\text{subsys}} = 0]$ | 32  | 62  | 37  | 33  | 40  | 27  |
| $[\Delta S_{\text{isolated}} = 0]$ and each $[\Delta S_{\text{subsys}} = 0]$ | 32  | 8   | 21  | 23  | 18  | 16  |
| $[\Delta S_{\text{isolated}} = 0]$ but each $\Delta S_{\text{subsys}} > 0$ | 32  | 6   | 13  | 15  | 15  | 13  |
| Second law (correct)      | 33  | 88  | 62  | 52  | 67  | 42  |
| First law                 | 33  | 88  | 62  | 52  | 67  | 42  |
| Newton’s 2nd law           | 33  | 88  | 62  | 52  | 67  | 42  |

**ORCID iDs**

Chandralekha Singh [https://orcid.org/0000-0002-1234-5458](https://orcid.org/0000-0002-1234-5458)

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