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Comparison of Student Responses to Easy and Difficult Thermodynamics Conceptual Questions during Peer Instruction*

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This study investigates the use of Peer Instruction in an upper division chemical engineering thermodynamics course. Peer Instruction is a technology-supported active learning pedagogy where each student in the class participates; it is often used with classroom response systems (clickers). In its typical implementation, the students are asked a multiple-choice conceptual question, they respond individually, self-select small groups to discuss the answer, and then respond again individually. The instructor can then display the results and lead a class-wide discussion. In order to apply this pedagogy most effectively, a better understanding of student thinking during Peer Instruction is needed. In this study, students were asked to provide short written explanations with their multiple choice responses. Through analysis of these responses, catalogued by group, we seek to identify how the student–student interactions during Peer Instruction influence conceptual development. Two questions where students needed to apply an energy balance are compared. In one of the questions, few students answered correctly while many students answered the other question correctly. In both cases, approximately one-quarter of the students' written explanations improved after group discussion; however, in the case of the difficult problem, a significant portion of other students' explanations got worse. Analysis of the written explanations showed that in both cases many students failed to identify that an energy balance was needed and instead resorted solely to the ideal gas law in their explanation. Results are discussed in the context of a cognitive resources-based framework and in terms of a sociocultural perspective of learning.

Keywords: peer instruction; educational technology; active learning; thermodynamics

1. Introduction

Many engineering classes use lecture based instructional delivery and emphasize algorithmic problem-solving skills. However, such instruction tends to reinforce rote learning rather than conceptual understanding [1, 2]. It has been shown that this lack of conceptual understanding severely restricts students' abilities to solve different types of problems based on the same concepts, since they do not have the functional understanding to use their knowledge in new situations [3]. Streveler *et al.* [4] argue that the construction of conceptual knowledge is central to the development of expertise in engineering. Active, student centered learning environments are more effective than traditional lecture based methods at promoting conceptual understanding [5–7]. In this study, the ability of students to learn from their peers is examined as part of one active learning technique, Peer Instruction. While the study presented in this paper specifically uses Peer Instruction, the results can apply to other similar formative assessment pedagogies including the conceptual conflict collaborative group method [8], technology-enhanced formative assessment [9], and Assessing-to-Learn [10].

Peer Instruction is a structured questioning process that actively involves all students in the class [11]. In this technique, a multiple choice 'conceptest' or 'clicker question' is presented to the class. The class first answers the question individually. Depending on the aggregate response, students can be encouraged to discuss the answer in small groups and then individually submit a final answer. This sequence is then typically followed by a class-wide discussion. In this way, the instructor can dynamically adjust the pace and extent of coverage to match student learning. Peer Instruction prompts students to actively engage in their own learning, to think critically about the material during class, and to learn from and teach each other. This instructional technique is well established in the sciences [12–14]. For example, in one study of 30 introductory science classes across 11 universities, an average normalized gain of 0.39 was measured [15]. Peer Instruction has begun to be incorporated into the engineering instruction in Australia [16], Europe [6, 17], and the United States [18].

The effectiveness of Peer Instruction depends critically on the quality of the conceptual question. Such questions are designed to be conceptually challenging and typically require little or no computation so that students cannot mechanically rely on equations to obtain the answer. They focus on

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the most important concepts in a subject. Concept questions can be designed towards several objectives: to elicit or reveal pre-existing thinking in students, to have students apply ideas in new contexts, to ask students to qualitatively predict what will happen, to use examples from everyday life, or to have students relate graphical and mathematical representations [19]. The use of concept questions assists students in obtaining a deeper learning experience, improves their understanding and ability to apply learning to new situations, enhances their critical thinking, and increases their enthusiasm for science and learning. Concept questions extend assessment beyond 'What does a student remember?' and 'What can a student do?" to "What does a student understand?' [20]. Effective concept questions improve students' understanding and ability to apply learning to new situations, enhance their critical thinking, and increase their enthusiasm for science and learning. Researchers have sought to establish the effectiveness of Peer Instruction. Most commonly, multiple choice pre- and post- tests, typically administered at the start and end of the term (often using reliable and valid concept inventories), are used to compare learning gains in courses taught using Peer Instruction with more traditional pedagogies [8, 13, 17]. While these studies offer compelling evidence that Peer Instruction results in learning gains, they integrate the effects over the entire term, and do not specifically elucidate the changes students undergo in a specific instance.

In this study, we seek to examine changes in student thinking that result directly from group discussion more extensively. Reflective written explanations are collected as students answer questions individually before group discussion and then as they answer after group discussion. In addition, the members of each group are identified so that the complete set of responses of each team can be compared. The observation of changes from members within specific groups is intended to identify the effect of student–student interaction on conceptual development. This study seeks to relate the reflective cognitions of students before and after group discussion and compare them with other members in the group.

2. Theoretical framework

In investigating the effectiveness of Peer Instruction in the classroom, it is useful to consider both the constructivist and sociocultural perspectives of student learning. From a constructivist view, students arrive in the classroom with prior knowledge and preconceptions about how the world works. The construction of knowledge is viewed to be the result of a student's use of existing knowledge to make sense of new experiences. Consequently, effective teaching must engage and confront those preconceptions and leads both to the modification of concepts and the reorganization of knowledge structures [3]. Draper *et al.* [21] suggest that during Peer Instruction, students learn since they are required to engage in a level of cognitive processing or reprocessing of the lecture material. From Clark's [22] point of view, students 'hold multiple conceptual elements and ideas at various levels of connection, contradiction and organization' and gains in understanding occur by the process of their restructuring of their ideas. This viewpoint is reinforced by the novice/expert literature, which shows that experts differ from novices not only in the extent of their domain-specific knowledge but also in the organization of that knowledge [23].

Taber [24] has developed a typology to categorize erroneous student thinking according to whether they are missing knowledge (the 'null' category) or have a misconception substantiated by previously learning (the 'substantive' category). Substantive learning impediments tend to be persistent and difficult to correct. Alternatively, Hammer *et al.* [25] present a *resources-based* framework where the ability to answer a conceptual question correctly reflects a cognitive state that involves activating multiple resources. When viewed from this perspective, incorrect answers can arise either from a lack of resources or from the students' inability to activate the resources that they have. While there are clearly similarities between this view and Taber's null and substantive misconceptions, the resources-based framework rejects a unitary view of misconceptions, but rather decomposes the answer of a conceptual question into activation and coordination of appropriate resources. A key difference is that in the unitary view concepts are 'pre-compiled', whereas the resource-based perspective attributes compilation as context-dependent and occurring in real time as students answer questions or solve problems. Lobato [26] discusses the role of *focusing phenomena*, features of the classroom environment that direct students towards particular patterns or ways of thinking, as central in the context-dependent activation of resources.

The sociocultural perspective views learning as a process of transforming participation in valued sociocultural activities [27, 28]. Learning is socially mediated and intimately influenced by the culture and activities in which the learning is situated. Penuel *et al.* [29] suggest that the sociocultural perspective can place into context key elements of student learning using active, technology-based pedagogies like Peer Instruction where the nature of classroom interactions fundamentally change.

They identify the key role of tools such as language in mediating cultural activities and that engagement in the talking and writing of science coincides with participation in a community of practice and, thereby, develops expertise. From this perspective, learning in engineering requires dialog about the concepts. In the case of the study described in this paper, both group discussion and written explanations play a critical role in allowing students to participate in the activity, to 'talk science,' and to elaborate on their conceptual understanding. As students integrate into the Peer Instruction environment, they become more comfortable 'taking risks' and their identity in participation shifts from peripheral roles with limited responsibility to fuller roles with more responsibility. This shift is captured by a change from students 'showing their smarts' in the traditional classroom culture to 'showing their thinking' in the active classroom. Ultimately, a new type of 'community plane' can emerge from these interactions where learning becomes 'a shared endeavor among students and the instructor . . . where students and teachers are looking together at the problem of learning' [29]. In this study, the written reflections of students immediately before and after group discussion and the observation of these changes from all members within specific groups are intended to identify the effect of student–student interaction on the use of language and conceptual development.

Smith *et al.* [30] apply Peer Instruction and compare student responses to conceptual questions in genetics before and after group discussion. By examining student responses to the identical conceptual question and also an isomorphic question, a question on the same concept with different surface features, they show group discussion enhances understanding, even when none of the students in the group has the correct answer initially. Nicol and Boyle [31] compare Peer Instruction with the technique of class-wide discussion. The authors argue that Peer Instruction is more effective. Since students first think about the question individually, they construct their own ideas and are better able to engage in dialogue and defend their answers or identify gaps in their thinking when interacting with their peers. As a consequence, these students are less likely to adopt the reasoning given by the more dominant students. Singh [32] performed a controlled study and showed that students in pairs outperformed individuals in conceptual questions. In some cases, the pair was able to determine a correct answer even when both individuals were initially wrong. She attributes this outcome to co-construction of knowledge. Additionally, she found that the pair performance score was similar whether they first responded individually or not.

Research on self-explanation suggests that in formulating arguments and presenting them to others, students come to a deeper understanding of concepts [33]. Thus, it has been argued that a key attribute of Peer Instruction is the facilitation of student-to-student and student-to-instructor interactions that allow students to negotiate meaning and construct understanding [34]. However, researchers are only beginning to systematically measure and understand how teaching and learning unfold in this environment. Van Dijk *et al.* [17] showed that Peer Instruction without the group discussion step produced significantly lower scores on a content post-test than with group discussion. Turpen and Finkelstein [35] reported a large variation in instructors' techniques when implementing Peer Instruction (whether they walked around the class during discussion, whether they answered questions, and if there was an explicit individual response before group discussion), and that these techniques can greatly impact the opportunity for student learning. The intent of this study is to examine responses to two specific questions and to characterize changes in student multiple choice answers and written reflections that result from group discussion. Furthermore, the changes for each student are examined based on the initial conceptions of the other students in the group.

3. Methods

This study examines student responses in a junior-level undergraduate Chemical Engineering Thermodynamics course at a large public university. A total of 122 students participated in the study. The research was approved by the Institutional Review Board and participants signed informed consent forms.

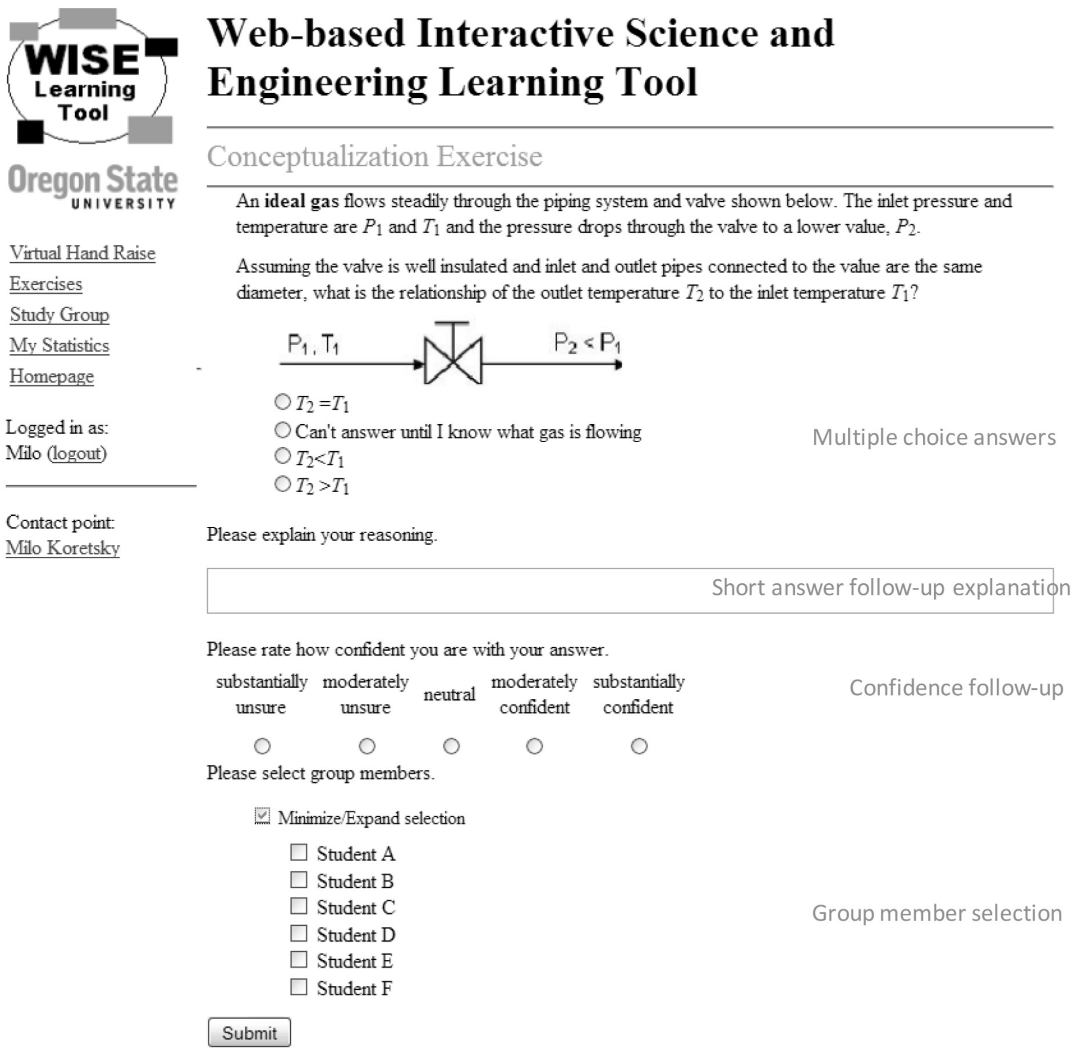
Students submitted responses using the Web-based Interactive Science and Engineering (WISE) Learning Tool [36]. WISE is enabled through a Wireless Laptop Initiative, which mandates that every student own a laptop computer. In the class studied in this paper, WISE was used once a week in a two-hour recitation section that the entire class attended. WISE allows for a wide variety of question and response types. This study reports results when the Peer Instruction technique was used; however, other types of technology-driven active pedagogies were also used during these recitation sections.

For the two questions analyzed in this study, conceptual exercises were assigned using WISE. Students first were asked to answer individually, without consulting their neighbors or the instructor. They chose a multiple choice answer, wrote a short answer explanation, and reported their confidence.

After answering individually, students in the class self-selected into groups of two or three students to discuss their answers. During this group discussion, the instructor did not interact with the groups directly except to answer general questions to the entire class. Therefore, the responses were entirely composed of the co-construction within the student group. After group discussion, the question was assigned again and students again responded individually. In addition to the responses above, students identified the members of their Peer Instruction group. In all cases, a class wide discussion followed.

The time spent on each conceptual question averaged 18 minutes in total and is longer than is typical for Peer Instruction [11], largely because students are asked to provide short answer written explanations of why they selected an answer. This method prompts the students to be reflective; they are encouraged to think about their reasons for an answer. It also provides insight into their thought processes and how those processes change with Peer Instruction. This difference should be kept in mind when considering the results presented in this paper. Students received full credit for participating, but also received extra-credit for correct answers. This approach is intended to encourage student discussion by decreasing the stakes [37, 38]; yet it still provides incentive for students to respond correctly.

In this paper, a subset of two question pairs labeled *Throttling Valve* and *Adiabatic Air* are analyzed. The questions, as they appeared to students, are shown in Figs. 1 and 2, respectively. Both questions have been modified from items taken from thermodynamics concept inventories [39, 40].



Source: Ron Miller

Fig. 1. The *Throttling Valve* question as it appeared to students. The short-answer explanation box has been reduced in size to consolidate the presentation in this paper. The group member selection provides a list of all the students registered for the class.

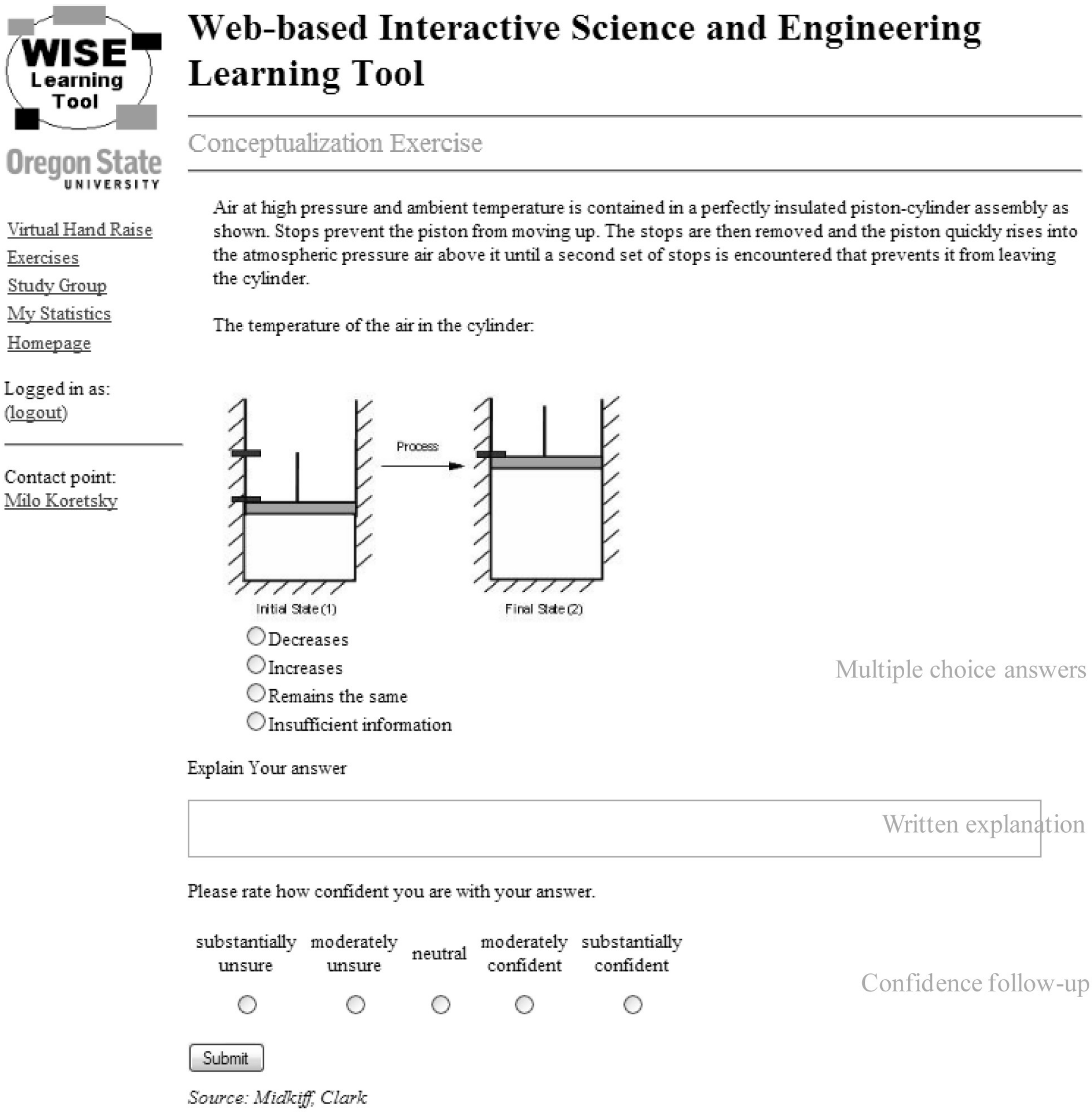


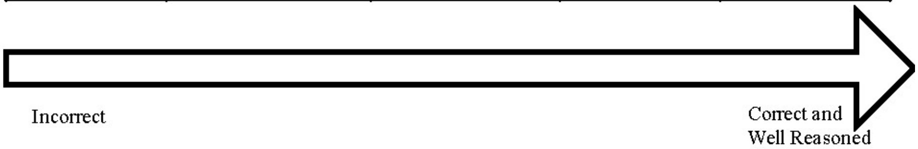
Fig. 2. The *Adiabatic Air* question.

The mixed methodological basis of this research is grounded in a phenomenological perspective of ascertaining how student multiple choice and short answer explanations reflect conceptual understanding and how that understanding changes as a result of group discussion. Coding the free response short answer explanations involved open coding, a process used to infer categories of meaning using a technique similar to that of Newcomer and Steif [41] in their analysis of written explanations to a concept question in statics. The process involves proposing a code, coding individually, comparing amongst the coders, modifying the code, and repeating until convergence. Three researchers, including a chemical engineering thermodynamics textbook author participated in this process. A hierarchical coding scheme was created for each question that incorporates and ranks the important concepts and misconceptions. Table 1 describes the coding scheme that was used for the two questions. Codes ascend from 1 (incorrect) to 4 (correct and well reasoned) with a higher code indicating a more appropriate explanation. Two graduate student researchers coded the written explanations. Both researchers have undergraduate degrees in chemical engineering, are former thermodynamics teaching assistants, and are pursuing Ph.D. degrees in chemical engineering focusing on engineering education. The inter-rater reliability using the Cohen's Kappa (κ) statistic is 0.80, indicating reasonable agreement.

Written responses were cataloged by group, and qualitatively analyzed, comparing answers of each member in the group before and after group discussion. Particular attention was paid to instances when ideas propagated from a single contributor

Table 1. Coding scheme for conceptual questions

Code	1	2	3	4
Throttling Valve	Ideal gas law – implicit constant volume assumption	Ideal gas law – explicit constant volume assumption	Incorrect energy balance	Proper energy balance
Adiabatic Air	Generally incorrect, e.g., adiabatic means no temperature change	Ideal gas law – P is directly proportional to T	Implicit energy balance – system does work, losing "heat"	Explicit energy balance – molecular kinetic energy converted to work



to all group members or when students with strong initial written explanations reverted to less sound reasoning. Self-reported student comments were also collected at the end of the course. After the Likert-scale based assessment of the WISE learning tool, students were asked the following free-response question, 'Write any additional comments or thoughts.' Comments reflecting the cognitive or social aspects of the learning environment were noted.

4. Multiple choice responses and coding of written explanations

Table 2 shows a summary of the distribution of multiple choice responses for each question pair. It includes the percentage of correct and the percentage of students who chose each incorrect response. The questions labeled 'before' are based on the initial individual student responses and those labeled 'after' are individual responses after group discussion. The *Throttling Valve* question was difficult, with only 13% of the students initially choosing the correct answer before group discussion and 19% after. The percentage response of the popular incorrect answer, labeled 'Wrong A%,' also increased from 64% initially to 76% after group discussion. For *Adiabatic Air*, a majority of 88% initially chose the correct multiple choice answer. This value increased to 98% after group discussion.

Figure 3 shows the code values assigned to the written explanations associated with the multiple choice responses, before and after group discussion. The highest number of students on the difficult *Throttling Valve* question had the lowest code value (1), both before and after group discussion. The number of responses that were coded (1) and (2) stayed approximately constant while the number coded (3) slightly decreased and (4) slightly increased. The most common code for *Adiabatic Air* was the highest code value (4) followed by (2). After group discussion, the number of responses that were coded (1) and (2) decreased while the number coded (3) and (4) increased. From these data it appears that there were more learning gains from the easier question than the more difficult one.

Figure 4 shows the percentage of students whose written explanations by question pair improved (+ code), declined (- code), or did not change (no change) in code value *after group discussion*. Each question shows improvement in roughly one quarter of the student's written explanations. However, while 18% of codes showed a decrease for the difficult question only 3% decreased in the easier question. The differences between the two questions noted in Fig. 3 can be attributed to this decrease.

Table 2. Answer distribution summary for the two questions examined in this study

Question	Correct %	Wrong A%	Wrong B%	Wrong C%
Throttling valve—before	13	64	22	1
Throttling valve—after	19	76	5	0
Adiabatic Air—before	88	7	3	2
Adiabatic Air—after	98	2	0	0

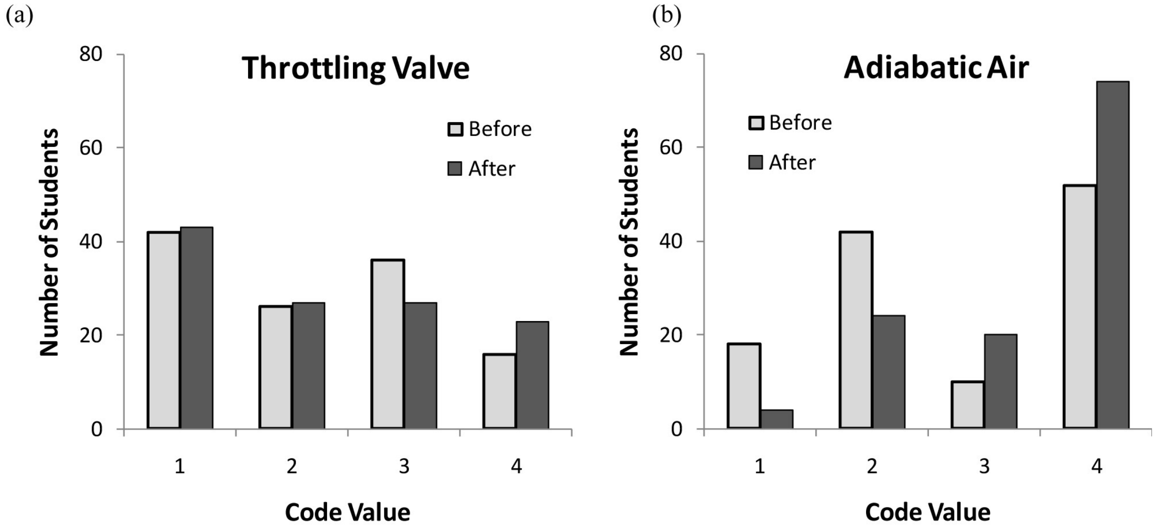


Fig. 3. Number of students vs. assigned code value of their short answer explanation (1 = poorest explanation; 4 = best explanation) when they first answered individually 'before' group discussion, and 'after' group discussion for (a) *Throttling Valve* and (b) *Adiabatic Air*.

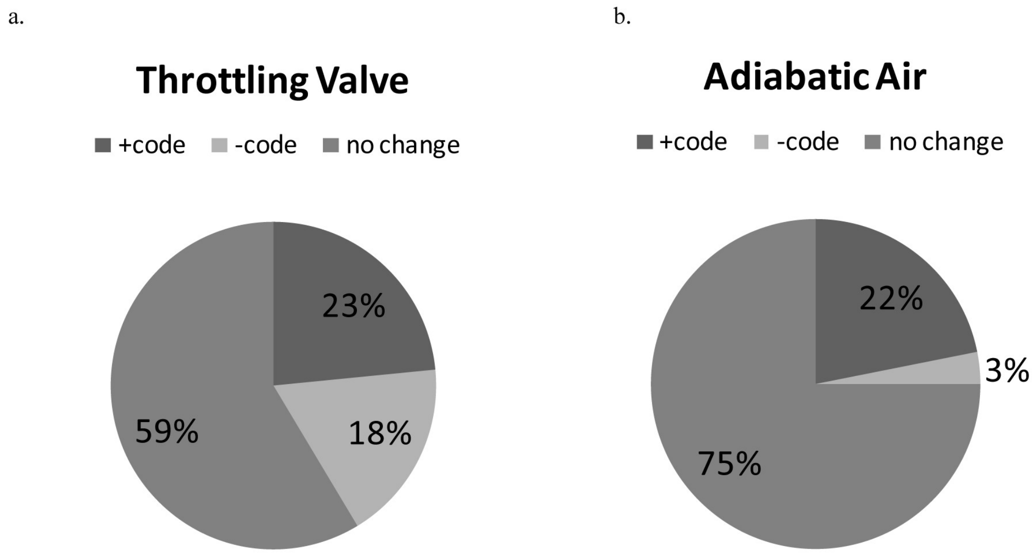


Fig. 4. Percentage of students per question whose explanations improved (+ code), got worse (- code), or stayed the same (no change) for (a) *Throttling Valve* and (b) *Adiabatic Air.*

5. Relation of answer choices to knowledge structures

It is useful to consider the individual written explanations from the perspective of Hammer's *resource-based* perspective presented earlier. Consider, the *Throttling Valve* question (Fig. 1). The correct answer is '$T_2 = T_1$'. To answer this question, students needed to activate and coordinate different distinct resources. A top-rated answer could be written as follows: first, the steady-state energy balance across the valve shows that the enthalpy of the exit state, 2, equals the enthalpy of the inlet state, 1, i.e., it is an isenthalpic process; second, the enthalpy change of an ideal gas depends on temperature only. Therefore, since the enthalpy does not change, neither does the temperature.

The common errors represented by the written explanations on *Throttling Valve* may be attributed to an inability to activate a critical resource. The proper reasoning involves applying an energy balance; however, 57% of student written responses failed to consider any aspect associated with energy. The context in which this question was delivered illustrates how deep rooted such misconceptions can be. Students were asked to turn in a homework assignment on the same day that the *Throttling Valve* conceptual question was posed in class. In one problem, they were asked to solve numerically for the exit temperature of steam flowing through a throttle valve. The primary difference was that the numerical homework problem contained a real gas and the qualitative conceptual problem used an ideal gas; however, the surface features were identical. Over 90% of the students answered the numerical homework question correctly and the majority explicitly demonstrated application of an energy balance in a procedural (or algorithmic) manner in their solution. Evidently, this solution was not adequately compiled into the mental models of many students. Therefore, they did not activate that resource even though the surface features of the calculation-based homework problem and the conceptual-based Peer Instruction questions were identical. They did not identify the need to apply an energy balance to answer the similar qualitative conceptual problem.

Additionally, the responses can be interpreted in terms of a *focusing phenomenon* prompted by the ideal gas 'cue' in the question (see Fig. 1), which is triggered both by a combination of the students' prior classroom experiences with ideal gases and faulty reasoning with multi-variable relationships. In their prior courses at the university and before that, students have been asked to solve many problems applying the ideal gas law. Of the three intensive properties, temperature, pressure and molar volume, they typically solve for one given a change in the second, while holding the third constant. It can be argued that these experiences condition students to apply this type of solution, when they see the cue *Ideal Gas*, even in cases where it is not valid. From this perspective, in the *Throttling Valve* conceptual question, students were able to activate the *Ideal* Gas resource on which they exclusively focused, but failed to consider another needed resource, the energy balance. Students argue that '$T_2 < T_1$', since the outlet pressure (state 2) is less than the inlet pressure (state 1), failing to recognize (either implicitly or explicitly) that the molar volume also changes. Faulty reasoning due to an inability to account for multi-variable relationships using the ideal gas law has been reported in physics classes [42, 43]. In the *Throttling Valve* problem solution, the inability to account properly for multi-variable relations confounds the inability to identify a resource (energy balance).

While the example above illustrates the students' inability to activate resources in the more 'difficult' question, similar evidence of faulty reasoning is seen in the 'easier' *Adiabatic Air* question. The written responses can again be considered in the framework of activating resources. Again the response of temperature must be determined. The correct multiple choice answer is that the temperature decreases and a correct written explanation could be as follows: the internal energy of the system decreases as the gas does work on the surroundings and, since the internal energy of the ideal gas decreases, the temperature decreases. 88% of the students initially selected the correct multiple choice response. From this result, it would appear that the majority of the students demonstrated a conceptual understanding of the first law of thermodynamics for closed systems. However, in coding the written explanations, it was determined that 49% of those students only activated the *Ideal Gas* resource as described above and did not consider an energy balance. The proportion is approximately equal to the *Throttling Valve* question even though the 'cue' is far subtler, the problem statement does not indicate that air is an ideal gas. In this case, however, exclusive use of the ideal gas law can inadvertently lead to the correct multiple choice response (i.e., since P decreases then T decreases). In a sense, the *Adiabatic Air* and *Throttling Valve* questions represent isomorphic questions: they both require students to activate the energy balance resource to predict the resulting temperature and they both can elicit the ideal gas focusing phenomena. In the case of *Adiabatic Air*, the proportion of students failing to use an energy balance reduces to 23% after group discussion. It is unclear to what degree this decrease represents true learning, and to what degree students are parroting others in the group.

These students possessed the required resources but failed to activate them in the context of the conceptual question. This example suggests that role of Peer Instruction is to provide explicit cases where students can practice activating resources in different contexts. Put another way, the major pedagogical opportunity afforded by Peer Instruction is not in introducing content but is rather the critical task of knowledge integration. Instructors who possess this *resource-based* perspective can reinforce such knowledge integration in the class-wide discussion that follows the second round of answers.

6. Relation of changes in answers to group discussions

Previous studies of Peer Instruction, found that participation in a discussion group alone led to learning gains even if no one in the group originally knew the correct answer [30, 32]. These results indicate the critical role of the group discussion process in the construction of individual student knowledge. In order to examine more closely the role that the members of a group have in one another's thinking, it is instructive to examine the individual written responses of each of the members of a specific group both before and after group discussion. Such responses can provide evidence of the extent that individual responses are influenced by group discussion and the possible effect of the ideas of the other members of the group on each individual's response.

Tables 3–5 show the written responses to the *Throttling Valve* question of three representative groups, labeled Group 1, Group 2, and Group 3. Each student is labeled by a letter from A to I. These groups were selected to illustrate representative examples of different overall influence of group discussion, but other than that they were randomly selected and not filtered to show a best case. The initial multiple choice responses for the students A, B and C in Group 1 are all different. Student A initially explains his/her response with the ideal gas focusing phenomenon discussed above. Student B, considers the energy balance and essentially has the correct explanation (flow work is not zero, but the flow work of the inlet and the outlet are the same). This view apparently influenced Student A whose response after group discussion demonstrates a significant improvement in reasoning. The written explanation even appears richer than Student B's final explanation, suggesting real learning took place. Specifically, Student A explicitly recognizes the volumetric flow rate is changing and thereby accounts for the constant volume misconception. This response provides evidence of cognitive restructuring to account for the cognitive conflict to reconcile thoughts with student B. However, Student A exhibits a low self-confidence score (2/5). Student B indicates the social nature of the group discussion, stating, 'my group members wouldn't fight me on this.' While Student C maintains his/her original multiple choice answer, the written explanation is also improved. This example shows an effective influence of group discussion.

Table 4 shows similar data for Group 2. However, the impact of group discussion appears to be opposite. In this case, all three students initially have incorrect multiple choice responses. Student D's initial explanation correctly identifies the internal energy across the valve is constant but he/she mistakenly reasons temperature will go up. On the other hand, both Students E and F employ the common ideal gas focusing phenomenon to argue

Table 3. Group 1 explanations for the *Throttling Valve* question

Student	Pre-Discussion Explanation	Post-Discussion Explanation
A	PV/T = PV/T Due to pressure drop, the energy must be going somewhere so temperature will probably increase	Since no work if (sic) being done and the system is adiabatic we see no change in internal energy. No change in internal energy for an ideal gas means that temperature has not changed, no change in temperature means the volumetric flow rate must be changing. T1 must be equal to T2.
B	NO WORK IS DONE, AS THE PRESSURE DECREASES THE VOLUMETRIC FLOW RATE WILL INCREASE PROPORTIONALLY. U REMAINS THE SAME THEREFORE T REMAINS THE SAME. ALSO THIS IS AN IDEAL GAS AND THEREFORE WE HAVE NO FLOW WORK.	I STILL CAN'T SEE ANY OTHER WAY OF DOING THIS ONE, AND MY GROUP MEMBERS WOULDN'T FIGHT ME ON IT, SO I GOT TO SAY THAT THEY ARE EQUAL BECAUSE THERE IS NO WORK BEING DONE!!!! U=Q+W Q=0
C	There is less internal energy if the pressure decreases	Flow work is done the same amount of particles esscap (sic) as are inputed (sic) rlaying (sic) that there is an increase in velocity which is removed from the temperature of T1 and thus to T2 is less than that of T1

Table 4. Group 2 explanations for the *Throttling Valve* question

Student	Pre-Discussion Explanation	Post-Discussion Explanation
D	since well insulated and no work is being done, delta U has to equal zero. This means that the energy lost from the drop in pressure would lead to an increase in temperature.	Pv=RT .. therefore if pressure decreases while volume remains the same then temperature must decrease as well.
E	The ideal gas equation explains the relationship between pressure and temperature. There is no change in molar amount or volume between the two states. Only thing changing is pressure, and from that temperature changes in the following way; If pressure goes down, temperature must go down as well for the equation to remain equal, PV=nRT.	The ideal gas law shows that temperature changes directly proportional to pressure. If pressure goes down, temperature goes down. Based on this observation it can be shown that T2 < T1.
F	Using Ideal gas law, if pressure decreases, then the temperature must also decrease.	Do (sic) to ideal gas law. If the pressure goes down, then the temperature must go down.

that temperature will go down. Student D is persuaded by the other two students and ignores the energy balance argument after the group discussion, lowering the quality of his/her response.

The impact of group discussion in Group 3, shown in Table 5, is more complex. In this case, all three students have different answers to the initial multiple choice question. Student G employs the common ideal gas focusing phenomenon. The response of student I shows an inclination towards the ideal gas focusing phenomenon, but that is corrected as he/she then recognizes the need to account for energy. Such a change demonstrates the usefulness of the reflective free response explanation to justify the multiple choice response. After group discussion, all three students believe the temperature will lower. However, all students' conceptualizations contain reference to energy. Student G even identifies explicitly that enthalpy is constant, before reverting to the ideal gas focusing phenomenon. It is reasonable to believe that the class wide discussion would be critical to further help the students in this group to develop conceptual understanding.

The influence of group discussion on learning during Peer Instruction is also evident in self-reported end of course student comments. While care must be taken not to over-interpret such comments, they can offer triangulating evidence. Twenty-two percent of the students who participated in the study had responses that contained references to learning within a group even though they were only asked to comment on the technology (WISE) and not the pedagogy (Peer Instruction). One student wrote, 'I like trying to answer the question on my own and then reasoning through the question with group members.' Another student wrote that Peer Instruction '. . . allows us to try and explain our views on the topic and fight for what we think is right in class.' One student specifically writes, 'I learned a lot with the whole discussion part that happened in-between answering by myself and answering after talking with a group.' Additional student commentary reflected the ways in which active pedagogy influenced the culture of the classroom by creating a learning community. For example, one student emphasized, 'It was good to see what the rest of the class thought about certain solutions. It helped me not to get frustrated when I realized half the class didn't understand a concept either so I know how I did compared to them.' Another student observed a change in his/her relation to instructor, 'The teacher can see conceptual misunderstandings that students would never talk about with ease. He can then tailor discussion to alleviate those common misconceptions.' The examples above resonate with a sociocultural perspective and were typical of most comments; however, a few students described a learning process that occurred within their own heads, i.e., a constructivist perspective. Examples include, 'It was a great way to build off of what was taught in lecture. It really helped my mind make deep conections (sic),' and, 'I feel like it allows you to take the knowledge that has been presented and actually understand it through use before sending it to the back of your mind. Generally classes present materials in lecture and I don't look at that material again until I have to use it in homework assignments and that time in between looking at it diminishes what I learn.'

Comparison of the written explanations before and after group discussion coupled with reflective written comments at the end of the course indicates that the student interaction is central to the learning environment of Peer Instruction. During this interaction, students have the opportunity to actively 'talk like an engineer' as they defend their positions and explore the views of others. They also can be 'primed' to possible paths of reasoning and recep-

Table 5. Group 3 explanations for the *Throttling Valve* question

Student	Pre-Discussion Explanation	Post-Discussion Explanation
G	An ideal gas is represented by PV=nRT, which shows a directly proportional relationship between P and T. If P lowers, T lowers.	The enthalpy is the same when an ideal gas moves through a valve, but the internal energy may not be the same. It is still governed by PV=nRT.
H	Because the pressure drops across the valve, and assuming that flow rate does not change, the energy due to the pressure drop must go to heating the gas.	The energy lost due the pressure drop is going towards raising temperature. the enthalpy across the valve is the same, and delH=delU and delPV. P decreases so U increases.
I	P1/T1=P2/T2 so if P2 decreases to keep the proportionality true it is necessary for the ideal gas to decrease in its temperature. The total internal energy is the same because no work or heating were done; however, according to Boyles and Charles and simple PV T relationships it seems that T should decrease. I might almost say that the temperature remains the same . . .thats just intuition. No wait if internal energy is unchanged then their can be no change in temperature.	If there was flow work done by pv term then internal energy may not be the same and since I am not confident that internal energy is zero. I will agree with the simple relationships. It just seems that temp should be zero in change

tive to explanations that did not originally occur to them. By having access to the class multiple choice responses and written reflections (if they are available), instructors can observe general patterns of students' misinterpretation, lack of prior knowledge, or incomplete logic. These items can be addressed in the class-wide discussion that follows, in future class periods, or with additional assignments and conceptual questions. However, as illustrated by the changes in the written explanations in the three groups discussed above, there is a wide range of directions that the group discussion can take. The heterogeneity of the group discourse and the differences within specific groups must be considered by the instructor during delivery of Peer Instructions so that the discussion intended to integrate conceptual themes does its best to resonate with the many and varied perspectives of the individual students in the class.

7. Conclusions

This study analyzes students' responses during Peer Instruction to two question pairs in chemical engineering thermodynamics, labeled *Throttling Valve* and *Adiabatic Air*. This study infers evolving conceptions that result from group discussion by examining reflections of sets of students prior to and after group discussion. However, the actual discussion has not been recorded. Moreover, the results are reported for delivery within the instruction and content of a specific class. The results from this study should be interpreted in the context of these limitations.

The *Throttling Valve* question was difficult, with only 13% of the students initially choosing the correct multiple-choice answer, while for *Adiabatic Air* 88% initially chose correctly. Students were asked to provide short answer written explanations, which were then coded. While the explanations to the easier question were generally assigned greater code values, approximately one quarter of the students' written explanations improved in code value in both cases. While only 13% of the students chose the correct answer to the *Throttling Valve* exercise, 90% had answered a similar numerical homework problem correctly. Examination of written responses shows that in both questions a significant proportion of students focused solely on the ideal gas cue, and used improper reasoning of multivariate relationships to deduce their answer choice. Moreover, the dynamics within particular groups varied widely.

It is proposed that the ability to activate appropriate resources is context-dependent and that students need practice synthesizing conceptual answers in different contexts. In this regard, relatively quick conceptual questions and pedagogies like Peer Instruction are very useful instructional tools. Instructors should identify explicitly the different resources needed and design questions that address similar resources in different contexts and even different courses, if possible. Additionally, in synthesizing the results during class-wide discussion, the instructor should be cognizant of the various dynamics within the groups.

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