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Intelligent Tutoring System Using Decision Based Learning for Thermodynamic Phase Diagrams

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ABSTRACT

Students learn when they connect new information to existing understanding or when they modify existing understanding to accept new information. Most current teaching methods focus on trying to get students to solve problems in a manner identical to that of an expert. This study investigates the effectiveness of assessing student understanding related to context specific problem solving decisions, prescribing feedback based on the assessment, and improving student understanding to the point where they can make correct decisions. Students were given a refrigeration problem unlike their prior problems and were asked to draw the cycle on a T-v diagram using a tutor system. Every group tested (a total of 373 students) showed a significant improvement in their understanding ($p<0.0001$, Cohen's $d>0.8$) using a single 40 minute tutor activity.

Key words: Thermodynamics, intelligent tutoring, misunderstanding

INTRODUCTION

It is well established that thermodynamics is a major challenge for undergraduate engineering students in terms of their ability to understand and properly use the concepts and principles at a level that is necessary to solve engineering problems (Miller, 2006; Streveler et al., 2008, Prevost et al., 2012). In addition, students develop misconceptions about thermodynamics that lead them to incorrect solutions. Chi (2008) and Reiner, et al. (2000) address the question of why some misconceptions are particularly prevalent and difficult to correct. Their results suggest that particularly problematic misconceptions may be based on metaphors to physical phenomena that are similar but not quite right, e.g. thinking of electrical current as a fluid. Or, difficult misconceptions are based on phenomena with unobservable components or relationships.

One approach to improving student understanding of thermodynamics was to create more interactive instructional materials using computer-based instruction to supplement traditional textbooks (Anderson et al., 2005; Taraban, 2003). Interactions included answering multiple choice and short answer questions as well as controlling simulations of device and system behaviors. However, their results did not indicate significant improvement in student understanding.

Researchers have attempted to define and test student understanding of the set of concepts needed to solve problems in thermal-fluids courses (Streveler 2003; Prince 2012). Turns & Van Meter (2011) argued that how students structure their declarative knowledge is strongly linked to their problem framing ability. They recommended explicit explanations of the essential concepts and the problem solving process along with mechanisms for engaging students in problem solving. To identify students' misconceptions about thermodynamics, Beall (1994) posed conceptual questions to the students and asked them to write a response. This assessment of student understanding was used to clear up misconceptions in subsequent lectures.

Building on this work, Prevost et al. (2012) scaled the approach to large classes using automated text analysis to provide instructors with an analysis of students' constructed responses. The goal was to automatically generate a report for instructors so that they could address any problems by the next class meeting by providing feedback to students or modifying instructional materials.

Although there is wide variation in student understanding, typical instruction targets the average student because of limited resources. An intelligent tutoring system (ITS) is one approach to providing personalized learning that is easily scalable to many students and is available 24/7.

An ITS contains multiple interdependent components: the domain model, the student model, the expert model, the tutor model, the user interface, and any training media (Beck, Stern & Haugsjaa, 1996; Sottilare & Proctor, 2012). The domain model is critical to the effectiveness of the tutor because it contains information (e.g., facts, concepts, principles) for a specific knowledge domain. The student model contains information on each student's status in terms of understanding at different points in time. The tutor model reconciles the domain model with the student model to determine what learning activities are most appropriate for a student. The expert model represents the solution to a problem and is used by the tutor to make comparisons with the students' solutions. The interface includes the screens and user dialogs that students use to interact with the tutor.

The remainder of this paper is organized as follows. In the next section, we describe previous work on student learning that provides insights on how an ITS could facilitate student learning. This is followed by a description of the basis of the ITS domain model - decision based learning. We then describe how the domain model was implemented. Then in the next section, we describe the methodology used in this study to determine its effectiveness. Finally, results of the study are presented followed by our conclusions.

Related LIterature on Learning

Haile (1997-1998) identified two fundamental components of learning, namely, that learning involves developing useful neural firing patterns in the brain (Freeman 1994, Searle 1992) and that learning can only begin from things a student already knows. Given that learning involves developing beneficial patterns, students must learn cues that re-create useful patterns so that they can use the patterns to solve problems. Intelligent thinking involves the identification of alternate patterns and choosing from them. This cannot be done quickly. Correcting misunderstandings from earlier learning requires not only the development of a new pattern, but the suppression of the formation of the old erroneous pattern. The domain and tutor models in an ITS need to be consistent with the nature of learning (i.e., creating useful patterns and suppressing erroneous patterns).

Haile (1997, 1998) proposed that technical understanding should be organized into the hierarchy shown in Table 1. Alternative structures have also been proposed to develop student understanding (Fuller et al., 2007) such as Bloom's taxonomy, Niemierko's ABC taxonomy, Tollingerova's taxonomy, and Bespalko learning objectives. While there are variations in the content of these structures, they

Table 1. Haile's Hierarchy of Understanding.

Level	Name	Description
1	Making Conversation	Properly use names of objects and concepts, even if they are not correctly understood
2	Identifying Elements	The typical or common use of the object as well as situations where the object is not useful/fails.
3	Recognizing Patterns	Relations that impart meaning to a set of objects, concepts, and processes
4	Solving Problems	Getting successful answers
5	Posing Problems	Learning the procedure of problem solving through repetition
6	Making Connections	Generalizing pattern, problem context, and solution to other domains
7	Creating Extensions	Modifying generalizations to attack other problems

tend to be hierarchical in nature. Haile (2000) also showed that his proposed hierarchy fits into the more general hierarchies developed by Donald (1991) and Egan (1997).

DOMAIN MODEL

The fundamental structure of our domain model for the ITS is a hierarchical set of decisions that students need to make as they solve a problem. This set of decisions is consistent with Haile's hierarchy (1998). For example, for a thermodynamic cycle, students need to decide how many different pressures exist in the system. A student who cannot make the correct decision lacks fundamental understanding in the domain. By evaluating a student's solution using the decision set, the tutor can make an assessment of student's understanding. The evaluation process proceeds sequentially through the decision set and makes a determination of the level of understanding for each decision. The decision set is designed by the instructor so that decisions proceed from general domain decisions to problem specific decisions (i.e., students must understand fundamental principles as well as the elements of the problem).

The ITS is designed to help students solve problems without full expertise and to improve their conceptual understanding and expertise through the decision making/feedback loop. Students decisions give the tutor specific knowledge about the students (i.e., the student model) so that the tutor can provide individualized feedback in the form of additional questions or activities. The feedback was designed to develop a student's understanding to the point where they can make the correct decision, based solely on the student's thought process.

Lacking expertise, students will make errors in their decisions. Some of these errors are related to student misconceptions. Misconceptions are addressed by introducing problems where the student's thought processes does not work, and by using existing student understanding to eliminate the misconception. After successfully completing a problem, the student should have better understanding, although they are still not an expert. Students gain expertise by refining their understanding as they practice making these same decisions for a variety of problems.

Domain Model for T-v Phase Diagrams

To illustrate the implementation of the domain model, we use the context of drawing a T-v phase diagram in a thermodynamics course. We designed a general set of decisions that could be used for any thermodynamic cycle.

1. Is a vapor dome needed? (Are there phase changes in the cycle?)
2. How many pressures are in the cycle?

3. How is a pressure line drawn on a T-v diagram?
4. How should phase change P and T be labeled on the diagram?
5. What are the P, T, v relations for each component in the cycle?
6. In which phase region should each state be located?

In this study, we focused on the question – does this domain model increase student understanding of component relations?

METHODOLOGY

An online problem solving activity was implemented using an intelligent tutoring system to collect student T-v drawing data for a previously unseen refrigeration cycle problem. The tutor was initially used for statics problems and is described in Amin-Naseri (2013). A total of 373 students participated in the tutor activity. While student demographics were not collected for this study, the majority of the students in the thermodynamics courses are sophomores and juniors. Approximately 55% of the students are usually from mechanical engineering with the remainder coming from aerospace (22%), industrial engineering (14%), and other disciplines. Almost 100% of the students in Thermo 2 are in mechanical engineering. The activity was assigned as a homework problem in the courses.

This study included 7 sections of thermodynamics (six Thermo 1 sections and one Thermo 2 section) from 4 different instructors. Thermo 1 covers the zeroth, first and second laws of thermodynamics, properties and processes for ideal gases and solid-liquid-vapor phases of pure substances, and applications to vapor power cycles. In Thermo 2, students learn about gas power cycles, fundamentals of gas mixtures, psychrometry, and thermochemistry. Students apply concepts in these topics to one-dimensional compressible flow, refrigeration, air conditioning and combustion processes. The data collection consisted of a pre-test, 40 minutes working on the tutor, followed immediately by a survey and post-test. In some cases, students did not solve the entire problem within 40 minutes.

Activity Description

In Figure 1, the problem statement is on the left including a system drawing showing how all the components are connected for this previously unseen type of refrigeration cycle, along with problem specific information. On the right, is the drawing area for the T-v diagram (a phase diagram with temperature on the y axis and specific volume on the x axis) and a set of drawing tools for selecting objects, drawing and labeling points and line segments, and drawing a vapor dome. The vapor dome separates pure liquid, liquid-gas, and pure gas states. Students use the “Submit Drawing” button to receive feedback on their most recent drawing.

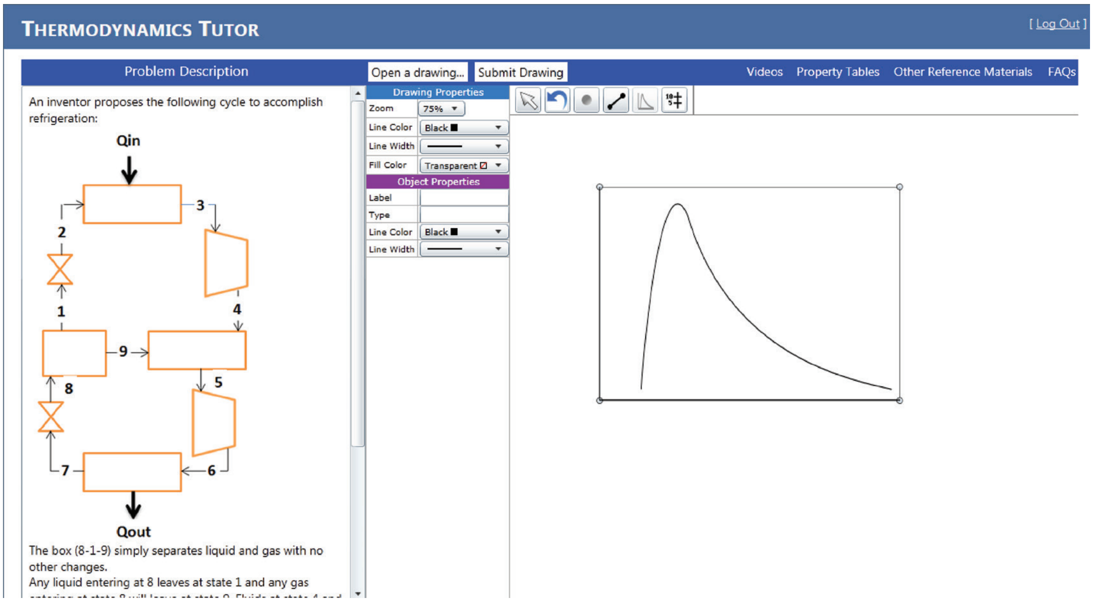

Figure 1. The activity for (P, T, v) relations.

Feedback from the tutor model for phase change labeling was improved throughout the study based on the student responses to the feedback. The general tutor process involving a student can be described by the decision tree in Figure 2. A student begins the process by drawing an initial T-v diagram and submitting it for evaluation. Figure 3 shows an example of an incorrect initial submission. Based on the decision tree, the student answers the pressure question in Figure 4. If the answer is incorrect, the student answers component pressure questions for each component in the system. Figure 5 shows the question for a compressor. If a component answer is incorrect, the student is redirected to an instructional video about the behavior of the component.

After successfully answering all the questions, the student can revise the T-v diagram and resubmit for tutor evaluation. If the diagram does not have all the states in the system (e.g., Figure 6) the tutor provides feedback that all states need to be included. When all states are present, the tutor will check the P, v, and T relations for each component based on the location of the states. For example, in Figure 7 the state relations for the compressor are incorrect because the specific volume should decrease from 3 to 4.

The student answers three questions about the P, T, and v relations in the component. If any of the answers is incorrect, the student is redirected to an instructional video about the component. When all three answers are correct, the student revises the diagram and re-submits. Finally, when all the component relations are correct, the student has successfully completed the problem.

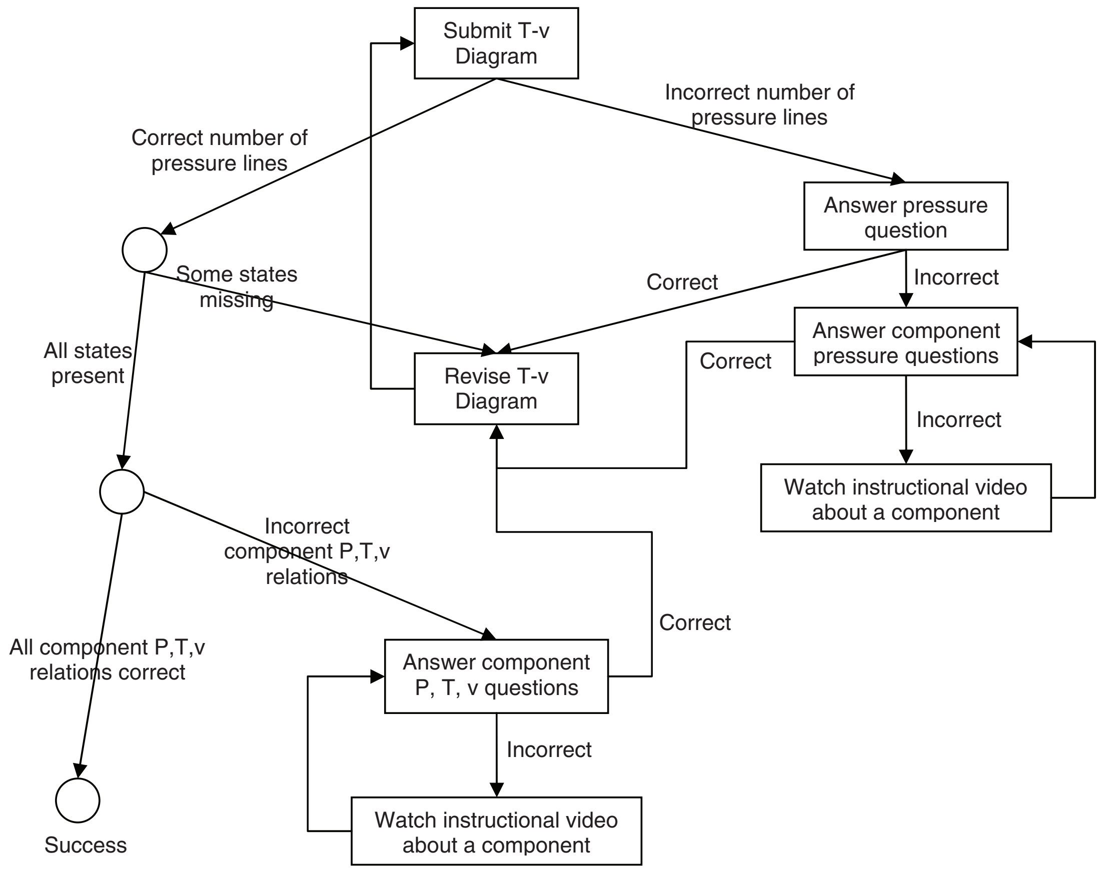

Figure 2. General tutor process.

After correctly completing the drawing activity, the student is immediately sent to a post-test that asked the same component property relations questions as the pre-test (see Appendix A). Two multiple choice questions were worded incorrectly on the initial set of students, and these two questions were thrown out, resulting in pre/post test scores out of 16 questions for the first set of students.

RESULTS

A paired t-test on the test scores was performed for each group of students to evaluate the effectiveness of the tutor. Two of the pre/post test questions were incorrectly worded in the initial Thermo 1 data set, resulting in maximum pre/post test scores of 16 points. Removing these two answers did not significantly alter the results for this initial group. As shown in Table 2, every group

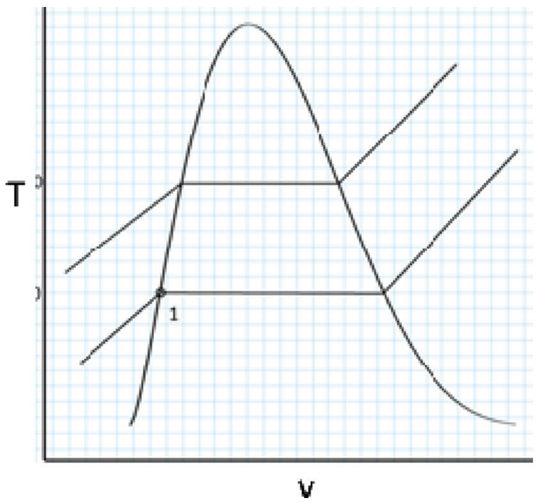

Figure 3. Initial student T-v submission.

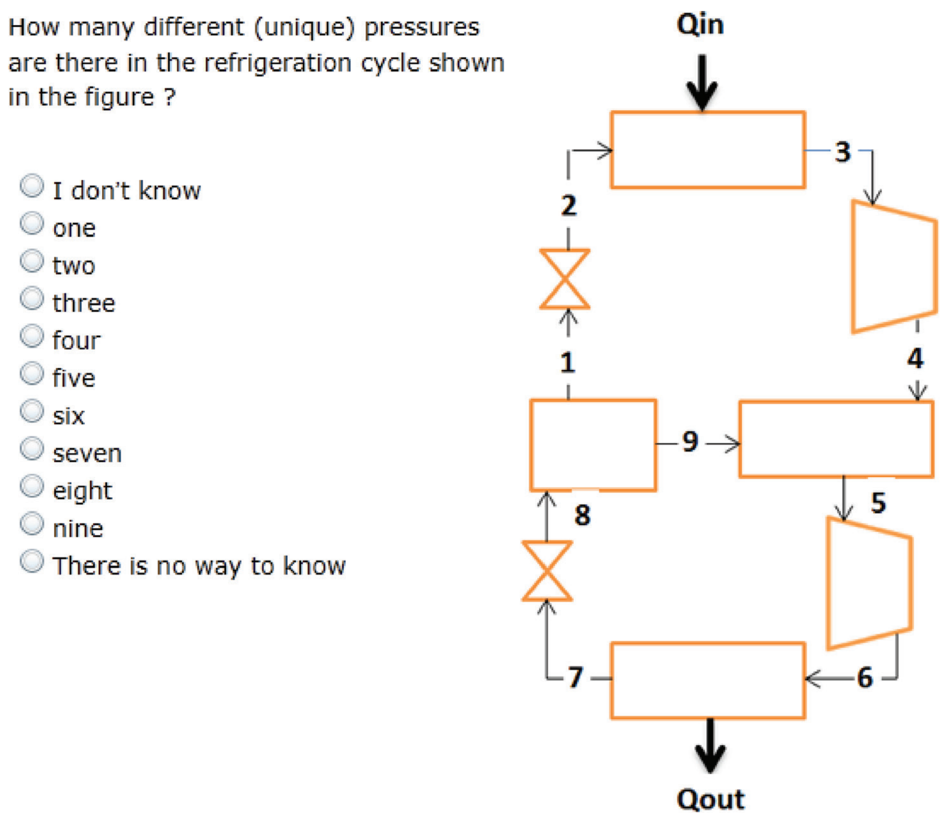

Figure 4. Pressure question.

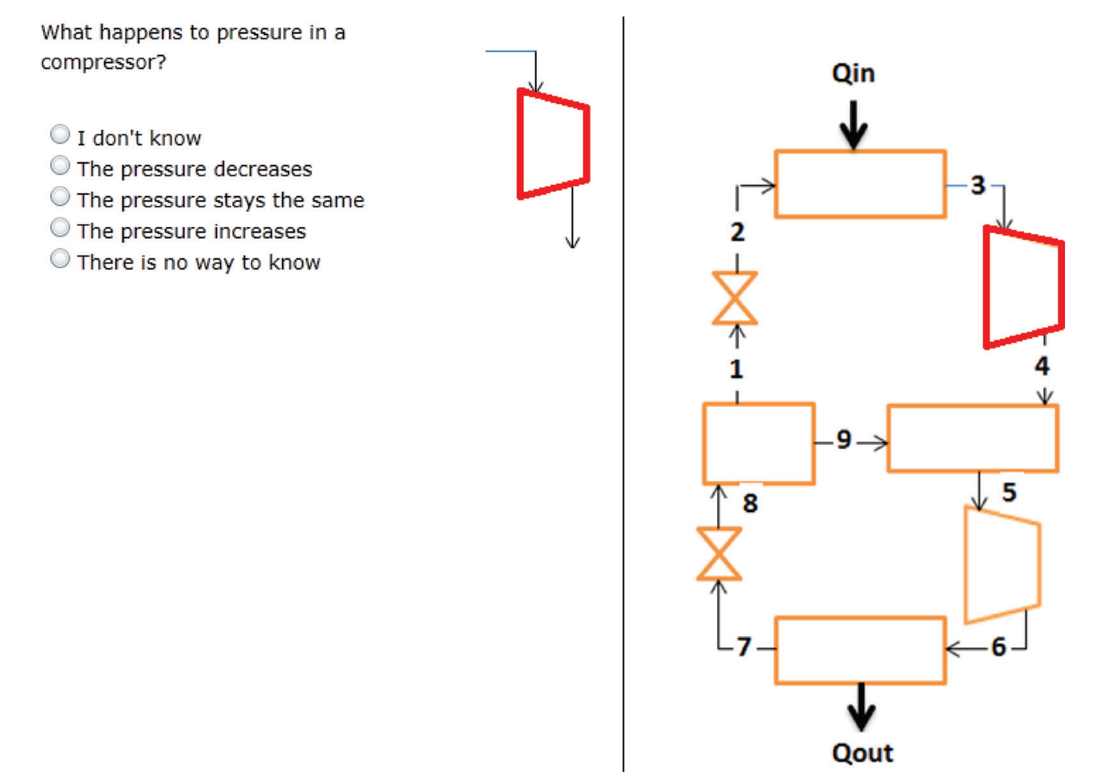

Figure 5. Component pressure question.

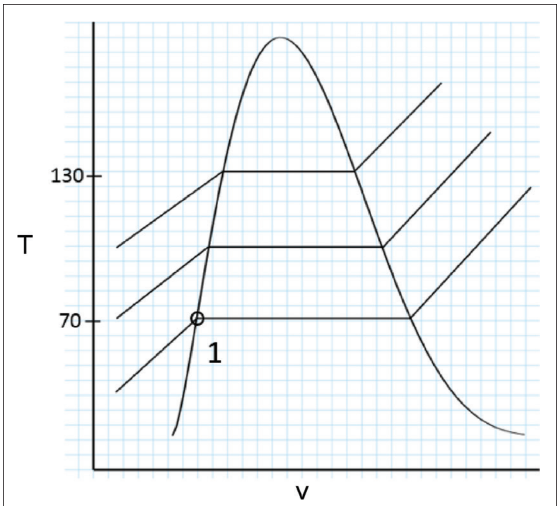

Figure 6. Drawing after pressure activity.

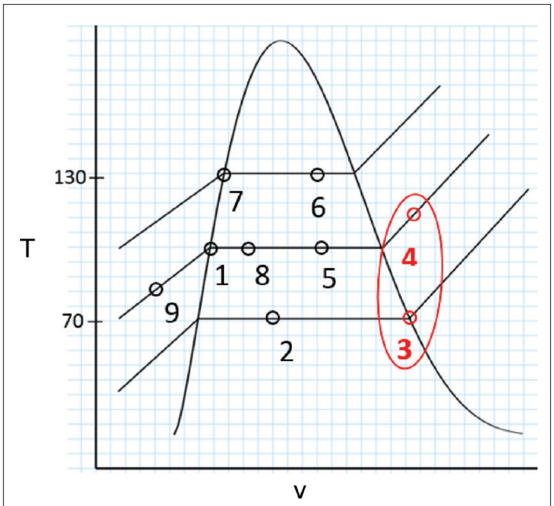

Figure 7. Compressor component failure.

Table 2. Tutor Results All Users.

Course	# of students	Pre test Mean	Pre test SD	Post test Mean	Post test SD	Retention Mean	Retention SD	Cohen's d (Effect size)**
Summer 2013 Thermo 1*	88	9.72	2.73	14.09	2.16	N/A	N/A	1.77
Summer 2013 Thermo 2	42	12.28	3.03	15.85	2.11	14.33	2.57	Pre-post: 1.36 Retention: 0.73
Fall 2013 Thermo 1	53	7.62	2.60	10.79	3.36	N/A	N/A	1.05
Fall 2013 Thermo 1	50	8.60	2.42	11.36	3.35	N/A	N/A	0.95
Spring 2014 Thermo 1	12	8.92	2.31	12.83	2.95	N/A	N/A	1.48
Spring 2014 Thermo 1	98	8.70	2.99	11.39	3.15	N/A	N/A	0.87
Summer 2014 Thermo 1	30	10.87	3.06	13.67	2.45	N/A	N/A	1.01

* Summer 2013 – Thermo 1 students' score is out of 16 possible points due to poorly worded pre/post questions. The rest of the scores are out of 18 possible points.
** An effect size of 0.8 or greater is considered a large effect. Between 0.5 and 0.8 is considered medium.

of students tested had a large improvement in understanding, regardless of instructor or class size. The difference between the post-test and pre-test scores was significant (with $p< 0.0001$) for all groups. The t-test results indicate that students were better able to answer P, T, v questions immediately after working on the activity. The effect size was calculated using Cohen's d (0.2 = small, 0.5 = medium, 0.8 = large) (Cohen 1988). The level of improvement ($d>0.8$) indicates a large (short-term) improvement in student understanding of P, T, v relations for the components in the refrigeration problem. All of this improvement was the result of a single 40 minute activity in which students made decisions and received individualized assistance from the tutor.

The Thermo 2 group was tested for retention 4 weeks after the tutor activity, with no additional coverage of refrigeration cycles. Even after 4 weeks, Thermo 2 students knew a medium amount more ($0.6 < d < 0.8$) about cycle components than they did at the completion of course coverage of refrigeration cycles, solely due to a single 40 minute tutor activity.

Four separate instructors were used for the Thermo 1 test groups. Therefore, the results were not pooled across all groups because of possible instructor differences. The average initial understanding of each component relationship varied by instructor from 28 to 62%, while the number of components correctly understood (all 3 correct property relationships) varied from 0 to 25%, depending on the instructor and the semester. Figure 8 takes a closer look at how initial understanding is related to the amount of learning from using the tutor for a single activity. The Y axis is the increase in the

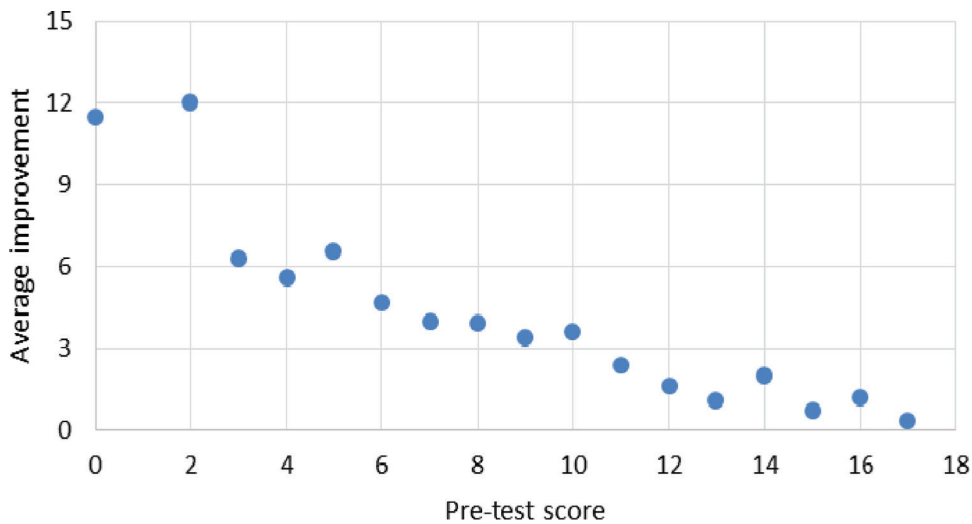

Figure 8. Learning vs Initial Understanding.

students' scores from the pre-test to the post-test. Students learned approximately ½ of what they didn't know about component relations, regardless of their level of initial understanding. Students who needed the most help benefitted the most from the activity.

Table 3 shows the variation in pre-test scores. The amount of improvement is inversely proportional to the pre-test score. The relatively low number of low (and high) scores seems to indicate that most students gave an honest attempt at the pre/post test questions. Random guessing would give an average pre-test score of 3.6. Removing students below some threshold (say removing those with a pre-test score of 5 or less) does not significantly alter any of the reported results.

Table 3. Pre Test Distribution.

Pre Test	Number of Students	Average Improvement	Pre Test	Number of Students	Average Improvement
0	2	11.5	10	30	3.6
2	1	12.0	11	49	2.4
3	7	6.3	12	29	1.7
4	7	5.6	13	23	1.1
5	11	6.5	14	12	2.0
6	38	4.7	15	15	0.7
7	41	4.0	16	5	1.2
8	48	3.9	17	3	0.3
9	51	3.4	18	1	0.0

Instructor Effects

Data shows that students having the same instructor for Thermo 1 and 2 had higher pre-test scores (t value: 2.07, p = .049), but interestingly there is no statistically significant difference in post test score (t value = 1.007, p= 0.324) based on Thermo 1 instructor. These results indicate that students benefit regardless of the instructor.

Survey Results

An ANOVA was conducted on first time users to study the effects of self-assessment on student performance. The ANOVA results ($F_{3,25}$) = 0.577, p = 0.636) indicate that the level of improvement due to tutor use is independent of the student self-assessment. Improvement appears to be independent of background, self-efficacy, initial pre-test score, or prior instruction for these students.

Component Results

To see why the tutor is working, a more in depth analysis was performed for the 88 students in the summer 2013 Thermo 1 course. While this initial group of students had some of the best results, the areas of difficulty are typical of all 373 students evaluated. Most of the 88 students needed help at various points in this activity. Fifteen students hit the submit button without a vapor dome on initial submission (16%). After drawing a vapor dome, 26 students submitted a drawing without 3 pressures lines (29%). After receiving enough help, if any, to get a vapor dome, 3 correctly drawn pressure lines, and 9 labeled states, 67% of the components were initially drawn correctly by the students. The initial component drawing results do not perfectly measure initial drawing success because some students had already received assistance regarding the correct property relations through completion of the pressure activity. With the assistance of the tutor, 89% of students (78/88) were able to complete the entire drawing activity, and 92% of the components were correctly drawn. Completion of the activity requires all components and states to be correctly drawn. Student performance for components is summarized in Table 4.

An important goal of the decision set is to find and remove misconceptions. A common student misconception about pressure is that heating or cooling an open system at steady state will raise or lower the pressure. When 88 students were asked about a heat exchanger, pre-test results showed that only 38% of students had correct initial understanding while 53% of the students had a misconception. At the end of the activity, the post-test showed that 80% of the students had the correct understanding of pressure while 16% of the students still had this misconception.

Comparing the pre-test scores with the first drawing submissions, there does not appear to be a good correlation between initial drawing success and initial component understanding. Students may have trouble with their initial drawing because they do not understand a component, or they may have understanding but simply have trouble connecting what they know to drawing a diagram.

Table 4. Component performance.

Comparison	Knowledge		Drawing	
	Pre-test	Post-test	First submission	Last submission
Compressor	82%	96%	64%	92%
Mixing chamber	49%	88%	50%	91%
Separator	32%	93%	74%	91%
Condenser	57%	82%	76%	94%
Expansion valve	68%	90%	48%	91%
Evaporator	58%	83%	89%	93%
Average of all components	61%	88%	67%	92%

The reverse is also true: students may have a correct drawing because they understand component behavior or they may memorize what a particular component looks like on a diagram.

Specific volume was the least understood property (49% correct), followed by pressure (56% correct) and then temperature (78% correct). Not surprisingly, students had trouble with temperature, pressure, and specific volume for the components they had not seen before (mixing chamber and gas-liquid separator). What might be surprising is the degree of misunderstanding in components that had been used repeatedly to solve thermo problems (i.e., compressor, condenser, evaporator, and expansion valve). Students initially had all three P, T, v relations correct for only 25% of the previously seen components.

Overall understanding of all three properties was much better after the tutor activity, increasing from 61% to 88% (9.74/16 to 14.09/16). The pre-test was taken immediately before the drawing activity and the post-test was taken immediately after completing the drawing activity. Therefore, the changes in student performance can be attributed solely to the tutor activity.

Some important points about the tutor include the following:

1. Pre-test results were not linked to the help students received on the activity.
2. Help with P, T, v relationships occurred only when the drawing was incorrect.
3. Students were never directly told what the drawing should look like.
4. Students had never seen this specific cycle prior to the activity.

Not all student misunderstandings (identified by the pre-test) were necessarily addressed by the activity. Student misunderstanding was only addressed when it was helpful in completing the current problem (drawing a correct diagram). The idea is to have all help be relevant to a task, rather than trying to correct everything that is wrong.

For the initial two groups of students (summer 2013), phase change labeling was allowed but was not evaluated. The initial two groups of students have the biggest improvement because nearly all of the students got through the component checks. On later versions of the tutor, students were required to correctly label phase change temperatures and pressures before component relations were addressed. Some students got stuck in how to correctly label a diagram, and quit before they received the component help portion of the activity. Other students spent enough time to get proper labelling that they lost interest and quit when they reached the component portion of the activity. It is clear from our experience that an ITS needs to rapidly provide students with the help that they need or students will not use it. An ITS requiring extensive student (or instructor) training is likely doomed to failure.

CONCLUSIONS AND FUTURE WORK

"Good teaching meets students at their current level of understanding and attempts to push them to higher levels … One of an instructor's goals is to find the level of understanding at which students are balanced between perplexity and confidence; at the point of creative tension, teaching is most effective and learning is most rapid. The goal is relatively easy to achieve for a single student (graduate student), but exceeding difficult to achieve for a group of heterogeneous talents and personalities (undergraduate class)." Haile (2000)

The ITS using a domain model based on a hierarchical decision set was designed to address the goal described by Haile. A domain model based on a decision set can be used for a class of problems such as T-v diagrams described in this study. The results show that student understanding significantly increased for all students regardless of their initial understanding. Given these promising results, the authors are in the process of creating/testing/making available multiple decision sets and problems using the ITS. Another advantage of the ITS is that it provides a means to collect detailed information about students, the effectiveness of the domain model, the success or failure of tutor feedback, retention and accreditation information, and as a means to share/test decision sets without requiring instructors to change the way they teach.

All groups of students benefited from the activity, regardless of their background, instructor, or the type of help they received. Students learned roughly ½ of the component relations they didn't know from a single activity, regardless of their initial understanding. Students improved in a similar manner regardless of their preference for watching instructor videos, guessing until they get the right answer, or thinking through their own understanding.

The success of this approach suggests that future research should focus on the following

1. Having additional instructors create, share, and test general to specific decision sets so the truly universal decision sets can be shared through multiple courses.

2. Finding the simplest sets of general decisions that novices can use to solve problems, without the instructor directly providing answers.
3. Using an ITS to integrate multiple decision sets into multiple domain models throughout an entire course.
4. Providing/testing/sharing an appropriate set of problems that challenges students, eliminates misconceptions, and builds understanding through pre-existing understanding.
5. Providing/testing/sharing help with specific decisions through group work, in-class activities, and online tools.

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REFERENCES

Amin-Naseri, M., Guo, E. Gilbert, S. B., Jackman, J., Hagge, M., Starns, G., & L. E. Faidley, Authoring a Thermodynamics Cycle Tutor Using GIFT, Proceedings of the Workshops at the 16th International Conference on Artificial Intelligence in Education (AIEDws 2013), Edited by: Erin Walker, Chee-Kit Looi,Memphis, USA, July 9-13, 2013, pp. 45–53.

Anderson, E. E., Taraban, R., Sharma M. P. 2005. "Implementing and Assessing Computer-Based Active Learning Materials in Introductory Thermodynamics." International Journal of Engineering Education. 21, 1168-1176.

Beall, H. 1994. "Probing Student Misconceptions in Thermodynamics with In-Class Writing," Journal of Chemical Education. Vol. 71, 1056–1057.

Beck, J., Stern, M., & Haugsjaa, E. (1996). Applications of AI in Education. Crossroads, 3(1), 11–15.

Chi, M. T. H. "Three types of conceptual change." In Vosniadou (ed.). 2008 International Handbook of Research on Conceptual Change., New York: Taylor & Francis, pp. 61–81.

Cohen J. (1988). Statistical power analysis for the behavioral sciences (2nd ed.). Hillsdale, NJ: Lawrence Earlbaum Associates.

Donald M. (1991). Origins of the Modern Mind, Harvard University Press, Cambridge MA.

Egan K. (1997) The Educated Mind, University of Chicago press, Chicago IL.

Freeman, W.J. (1994), "Role of Chaotic Dynamics in Neural Plasticity", Progress in Brain Research 102, 319.

Fuller, U., Johnson, C. G., Ahoniemi, T., Cukierman, D., Hernán-Losada, I., Jackova, J., & Thompson, E. (2007, December). Developing a computer science-specific learning taxonomy. In ACM SIGCSE Bulletin (Vol. 39, No. 4, pp. 152–170). ACM.

Haile, J.M. (1997), "Toward Technical Understanding. 1. Brain Structure and Function", Chemical Engineering Education 31, 152–157.

Haile, J.M. (1997), "Toward Technical Understanding. 2. Elementary Levels", Chemical Engineering Education 31, 214–219.

Haile, J.M. (1998), "Toward Technical Understanding. 3. Advanced Levels", Chemical Engineering Education 32, 30–39.

Haile, J.M. (2000), "Toward Technical Understanding. 4. A General Hierarchy Based on the Evolution of Cognition", Chemical Engineering Education 34, 48–54.

Haile, J.M. (2000), "Toward Technical Understanding. 5. General Hierarchy Applied to Engineering Education", Chemical Engineering Education 34, 138–143.

Miller, R. L., R. A. Streveler, B. M. Olds, M. T. H. Chi, M. A. Nelson, and M. R. Geist. 2006. Misconceptions about rate processes: preliminary evidence for the importance of emergent conceptual schemas in thermal and transport sciences. In Proceedings, American Society for Engineering Education Annual Conference. Chicago, IL.

Prevost, L.B., Haudek, K.C., Urban-Lurain, M., and J. Merrill. 2012. Examining student constructed explanations of thermodynamics using lexical analysis. Proceedings of the 2012 Frontiers in Education Conference, Seattle, WA.

Prince, M., Vigeant, Margot A.S.; and Nottis, K. (2012), "Development of the Heat and Energy Concept Inventory: Preliminary Results on the Prevalence and Persistence of Engineering Students' Misconceptions." Journal of Engineering Education 101, no. 3 : 412–438.

Searle, J. (1992), "The Rediscovery of the Mind", MIT Press, Cambridge MA.

Sottilare, R. A., & Proctor, M. D. (2012). Passively Classifying Student Mood and Performance within Intelligent Tutors. Educational Technology & Society, 15(2), 101–114.

Streveler, R.A., Litzinger, T.A., Miller, R.L., Steif, P.S., (2008). Learning conceptual knowledge in the engineering sciences: Overview and future research directions. Journal of Engineering Education, 97(3), 279–294.

Streveler, R. A., B. M. Olds, R. L. Miller, and M. A. Nelson. (2003). Using a delphi study to identity the most difficult concepts for students to master in thermal and transport science. In Proceedings, American Society for Engineering Education Annual Conference. Nashville, TN.

Taraban, R., Anderson, E. E., Sharma, M. P. and A. Weigold (2003) Developing a model of students' navigations in computer modules for introductory thermodynamics, In Proceedings, American Society for Engineering Education Annual Conference. Nashville, TN.

Turns, S. R., Van Meter, P. N. "Applying Knowledge from Educational Psychology and Cognitive Science to a First Course in Thermodynamics." In Proceedings of the American Society for Engineering Education Annual Conference. 2011. Vancouver, British Columbia.

AUTHORS

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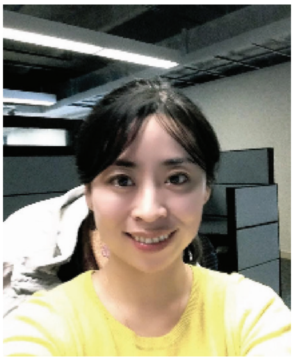
Mostafa Amin-Naseri is pursuing his PhD in Industrial Engineering at Iowa State University with a minor in statistics. His research interest is applying data science and analytics to various domains. In addition to educational data, he has been working on traffic data. His current research involves spatiotemporal anomaly detection and traffic prediction, leveraging crowdsourced data.

John Jackman, Associate Professor, Industrial and Manufacturing Systems Engineering at Iowa State University, conducts research in advanced manufacturing and engineering education. In manufacturing, he is currently working on wind turbine blade inspection techniques that characterize the variability in blade geometry and detect surface flaws. Dr. Jackman has extensive experience in computer simulation, web-based immersive learning environments, and data acquisition and control. His work in engineering problem solving has appeared in the Journal of Engineering Education and the International Journal of Engineering Education. He is currently investigating how to improve students' problem framing skills using formative assessments.



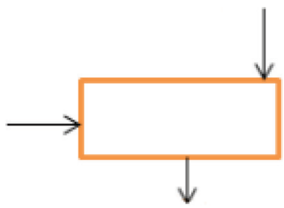
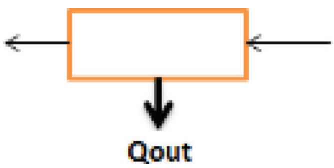
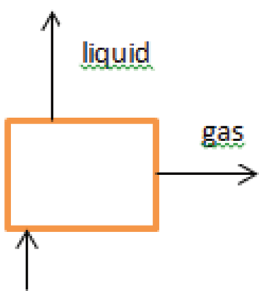
Enruo Guo received her PhD in 2015 at Iowa State University in both Computer Science and Human Computer Interaction. She now works as a software developer and user experience designer in industry.

Stephen B. Gilbert is assistant professor in the Industrial and Manufacturing Systems Engineering department at Iowa State University, as well as Associate Director of ISU's Virtual Reality Application Center. His human factors research interests focus on technologies to reduce cognitive load, including augmented and virtual reality, intelligent tutoring systems, and cognitive engineering. He is a member of IEEE and ACM and works closely with both industry and NSF and DoD on research contracts.

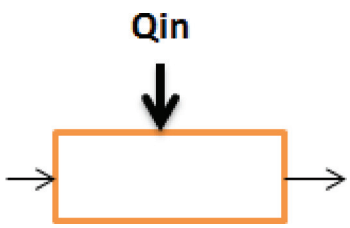
Gloria Starns is a Senior Lecturer at Iowa State University. Her research interests in engineering education includes the science of learning and application of Design Thinking to pedagogy. Optimization and kinematics are areas of interests in mechanical engineering.

LeAnn Faidley is an Associate Professor of Engineering Science at Wartburg College in Waverly IA where she teaches Freshman Engineering, the Engineering Mechanics sequence, Engineering Materials, and the Design sequence. She has a passion for Engineering Education and is currently engaged in implementing a number of research-based pedagogies in her classrooms including a flipped dynamics classroom, service learning design projects, concept based assessment in statics, and guided inquiry in Materials.

APPENDIX A PRE- POST-TEST QUESTIONS

	I don't know	Increases	Decreases	Stays the same	No way to know
What happens to the pressure in a compressor? 	○	○	○	○	○
What happens to pressure when two fluid streams mix together into a single stream with an open system? 	○	○	○	○	○
What happens to pressure in a heat-exchanger when heat is removed? 	○	○	○	○	○
What happens to pressure in an expansion valve? 	○	○	○	○	○
What happens to pressure when liquid and gas are separated? 	○	○	○	○	○

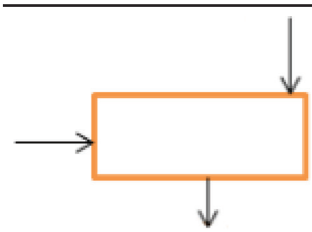
	I don't know	Increases	Decreases	Stays the same	No way to know
What happens to pressure in a heat exchanger when heat is added?	○	○	○	○	○



Please answer the following questions about specific values of Temperature and Volume in a compressor.

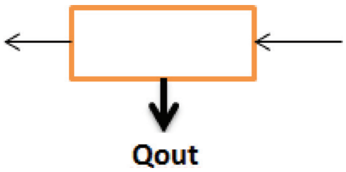
	I don't know	Increases	Decreases	Stays the same	No way to know
What happens to temperature in a compressor?	○	○	○	○	○
What happens to specific volume in a compressor?	○	○	○	○	○

What happens to specific values of Temperature and Volume when two fluid streams mix together into a single stream with an open system?



	I don't know	Increases	Decreases	Stays the same	No way to know
Temperature	○	○	○	○	○
Specific volume	○	○	○	○	○

What happens to specific values of Temperature and Volume in a heat-exchanger when heat is removed?

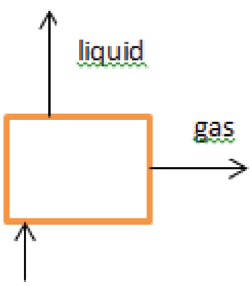


	I don't know	Increases	Decreases	Stays the same or increases	Stays the same or decreases	Stays the same	No way to know
Temperature	○	○	○	○	○	○	○
Specific volume	○	○	○	○	○	○	○

Please answer the following questions about specific values of Pressure, Volume and Temperature in an expansion valve.

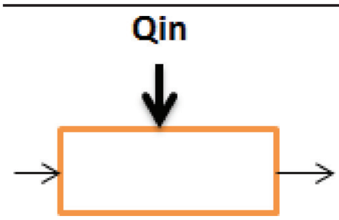
	I don't know	Higher	Same	Lower	No way to know
What happens to temperature in an expansion valve?	○	○	○	○	○
What happens to specific volume in an expansion valve	○	○	○	○	○

How does the temperature coming INTO a gas-liquid separator compare to the two exiting ones?



	I don't know	More than that of the two exiting fluids	Between that of the two exiting fluids	Less than that of the two exiting fluids	No way to know
Specific Volume	○	○	○	○	○

What happens to specific values of Temperature and Volume in a heat exchanger when heat is added?



	I don't know	Increases	Decreases	Stays the same	Stays the same or increases	Stays the same or decreases	No way to know
Temperature	○	○	○	○	○	○	○
Specific volume	○	○	○	○	○	○	○