ATLANTA
120th ASEE Annual Conference & Exposition
FRANKLY, WE DO GIVE A D*MN
June 23-26, 2013

Paper ID #6305

Development of an Intervention to Improve Students' Conceptual Understanding of Thermodynamics

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Introduction

Engineering thermodynamics is a very complex domain. Students encounter many basic concepts, such as heat, work, system, properties, state, control volume, surroundings, among others, which are needed to build a larger framework; this larger framework includes the ability to use the state principle and state relations, and to apply the overarching conservation principles for mass and energy. Many of these concepts are predicated on a precise mathematical representation and understanding. In applying all of this to problem solving, many assumptions and approximations are often invoked, yielding special cases of general principles. Furthermore, students must become proficient with the use of extensive tabular data and/or software to obtain thermodynamic properties. Pitfalls abound as students struggle to consolidate conceptual understanding and develop procedural knowledge.

Students are introduced to some of the basic concepts of thermodynamics in pre-college and introductory college chemistry and physics courses. There is a broad literature describing the difficulties encountered and the misconceptions students develop in these courses.[1-6] Meltzer,[1, 2] for example, has recently reported "that 20% or fewer (students) were able to make effective use of the first law of thermodynamic even after instruction." Many of these foundational weaknesses are retained in students' study of engineering thermodynamics. Concept inventories in thermodynamics and thermal-fluids have identified several specific concepts that are problematic for students.[7-13] For example, students exhibit confusion about the differences between temperature and internal energy and how to properly relate the two.[10, 11] Students have similar difficulties in distinguishing steady-state processes from equilibrium processes.[10] Various strategies have been employed to improve students' learning of engineering thermodynamics. These include computer-based instructional modules,[14-18] problem-based learning,[19-21] active learning,[22] visually-oriented "engineering scenarios",[23-25] and the multi-faceted approach of Chen.[26] Work specifically addressing problem solving in thermodynamics includes the seminal work of Bhaskar and Simon,[27] studies focusing on procedural or prescriptive approaches,[28-30] and McCracken and Newstetter's [31] work on representational transformations. Henk[16] addresses improving students' thermodynamics problem-solving skills with the use of on-line personalized homework problems. Despite the variety of pedagogical tools that have been investigated, the literature provides little information that links students' foundational needs to the instructional methods that can address them. We addressed this issue in previous work,[32] outlining several ways that knowledge from cognitive science could be applied to improve thermodynamics learning. The present paper describes an intervention that we derived from our previous work and presents the results from a pilot test of that intervention.

Focus of the Intervention

Our intervention focuses on the application of the first law of thermodynamics to ideal-gas processes for fixed-mass systems. This focus encompasses several of the concepts identified as very important (i.e., ranking 9 or 10 on a 10-point scale of importance) by experts in the

Streveler et al.[33] Delphi study: the first law of thermodynamics, adiabatic versus isothermal processes, and the ideal gas law. Experts cited these concepts to be of the highest importance and, moreover, ranked students' mastery of these concepts to be relatively high (i.e., ranking 8 on a 10-point scale of importance). However, results from think-aloud and other studies conducted as part of our research showed that, for many students, the understanding of these concepts was very shallow, and not much, if at all, beyond a plug-and-chug level. Considering the importance of these concepts, our intervention efforts focused on them.

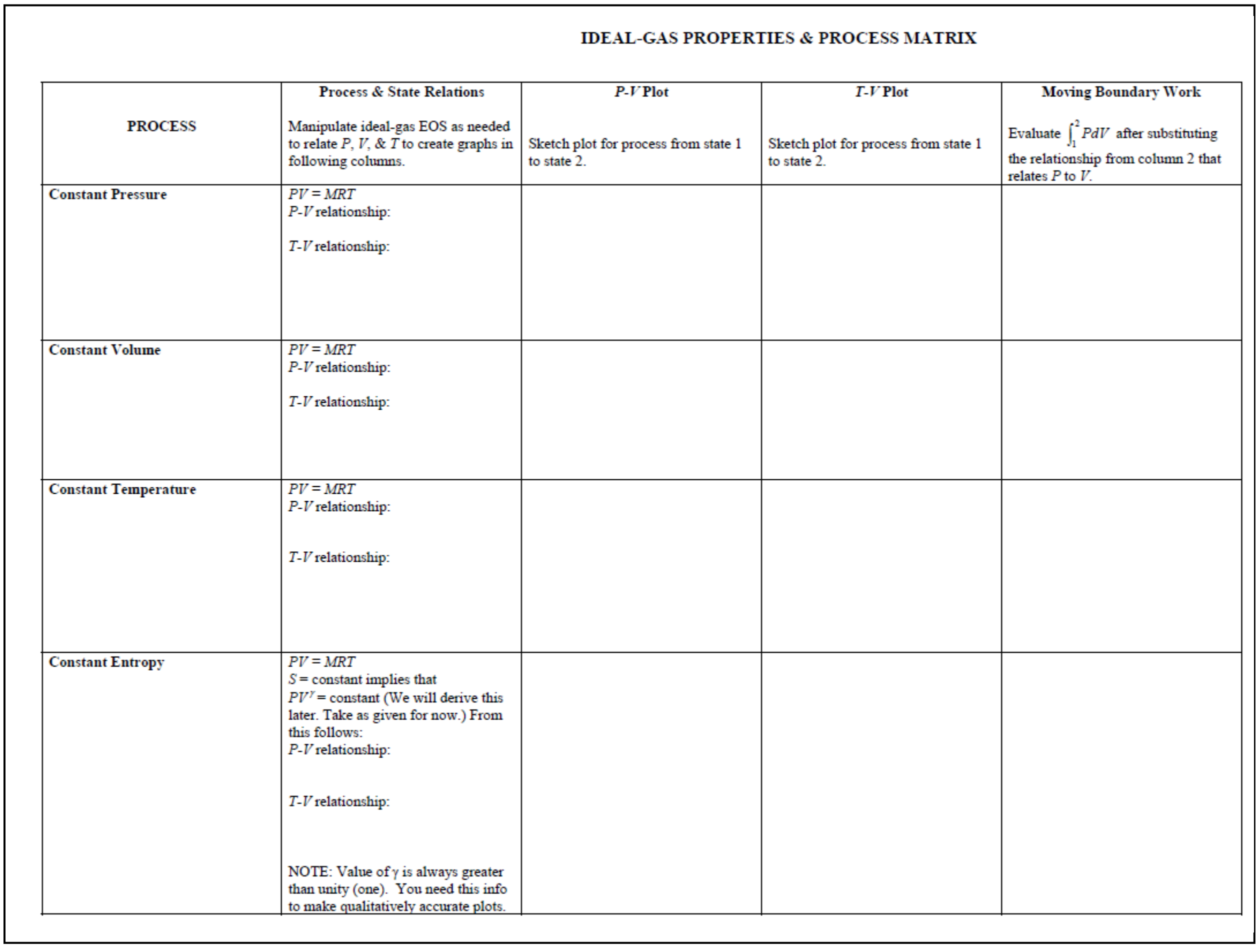
Description of the Intervention

The exercises we developed have their roots in the concept of matrix notes[34, 35] because we believe the structure of this learning strategy is well matched to the demands of thermodynamics learning. This structure provides an organizational framework that allows a learner to see ideas in relation to one another; specifically, information is organized in rows and columns. Because of this row-column structure, we refer to our exercises as *matrix exercises*. As the information that the students must supply includes verbal statements, diagrammatic depictions, and mathematical expressions, the specific format of the exercise also supports the representational transformations required for thermodynamics problem solving.[31] For the pilot study discussed below, the intervention comprises two exercises that students completed out of class. The instructor discussed how to complete the exercises in class.

In the first matrix exercise (Fig. 1), students consider the four ideal-gas processes presented in four rows: (i) a constant-pressure expansion, (ii) a constant-volume process in which the pressure increases, (iii) a constant-temperature expansion, and (iv) an adiabatic, reversible (constant entropy) expansion. Prompts written in the columns required students to (i) write a mathematical expressions for the relation of pressure-to-volume and the relation of temperature-to-volume, (ii) create a plot of pressure versus volume, (iii) create a plot of temperature versus volume, and (iv) develop and enter an expression for moving boundary work.

In the second matrix exercise (Fig. 2), students consider the same four ideal-gas processes with column prompts designed to elicit information to correctly apply the first law of thermodynamics. The first column repeats the four processes, and the second column repeats the generic formulation of the 1st law. In the third column, students define the process in terms of the state variables P, V, and T (essentially as done in the first exercise), but now they must add the calorific equations of state, which for an ideal gas are simply: $\Delta U = Mc_{\mathrm{v,avg}}(T_2 - T_1)$ and $\Delta H = Mc_{\mathrm{p,avg}}(T_2 - T_1)$. Students are instructed to simplify these where possible; for example, ΔU and ΔH are zero for the isothermal process. In the fourth column, students enter an expression for the moving boundary work. This is a repetition of the last column of the first matrix exercise (Fig. 1). The last column is the culmination the exercise. To complete this column, students must simplify the 1st law (column 2) by inserting the process-appropriate expressions for the internal energy change (column 3) and the moving-boundary work (column 4), and rearrange their result to determine the process heat transfer. Students then enter their expressions for the heat transfer in the last column.

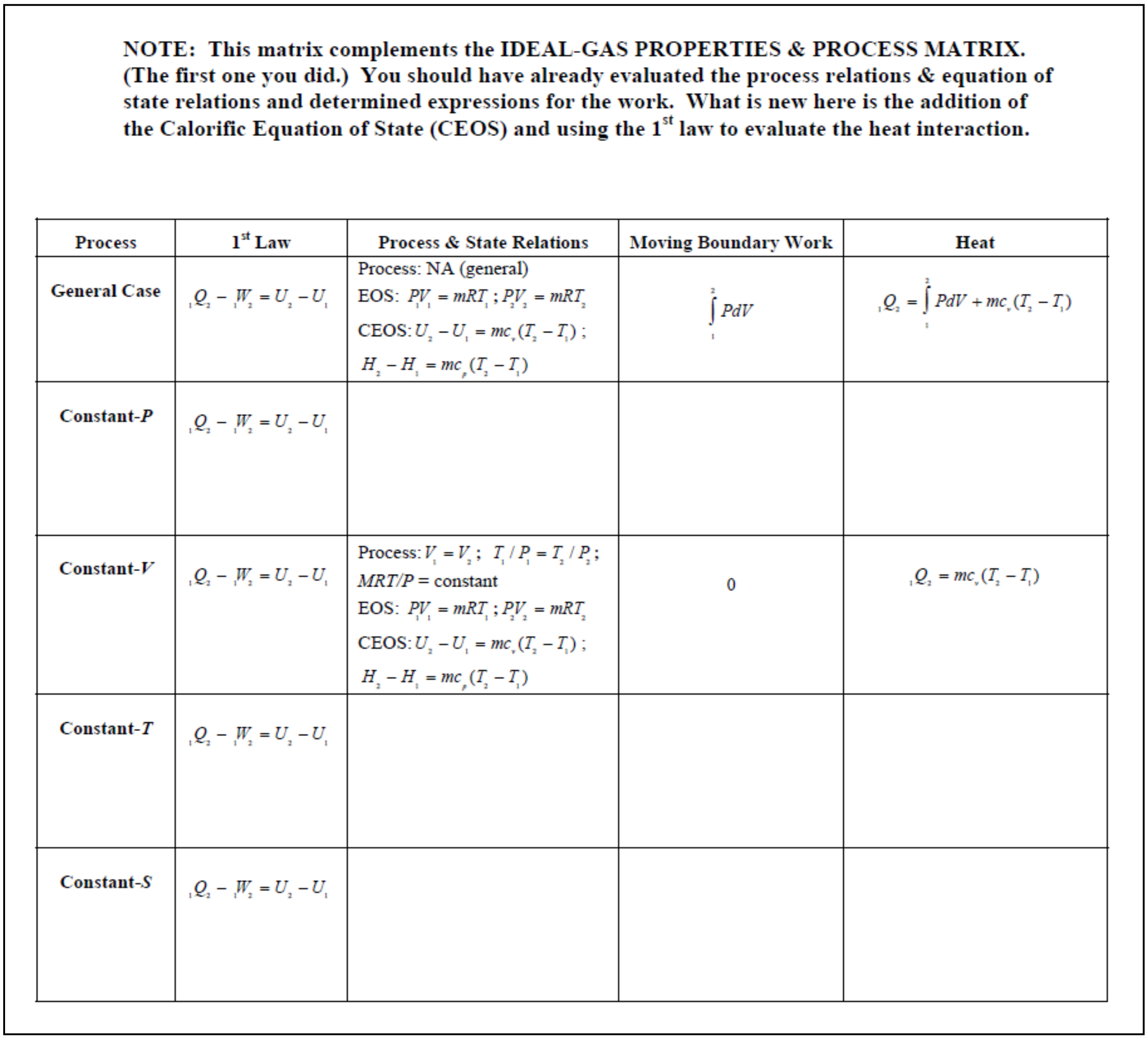
The intended educational benefit of this exercise is for students to see how general principles apply to specific cases, emphasizing one form of the 1st law, which can be recast depending on the specific process considered. Students are required to grapple with the details of each process successively, with the intent to help them organize their knowledge. Furthermore, students can see from an examination of the *P*-*V* plots for the three expansion processes (constant-*P*, constant-*T*, and constant-*S*) that the amount of work delivered by these processes decreases in the same order, i.e. the constant-*P* process delivers the most work, whereas the constant-*S* process delivers the least work for the same increase in volume. With this knowledge and a careful examination of the final column, students will be able to see how the input energy (heat) is transformed into work and internal energy. For example, students can see that the constant-*P* process required the greatest amount of heat, as this process produced the greatest amount of work and required additional heat to maintain the pressure constant as the volume increased. The corresponding *T*-*V* plot from the first exercise shows that the internal energy of the system increased because of the increased temperature at the final state. Similar analyses can be performed for the constant-*T* and the constant-*S* (adiabatic reversible processes). We found, however, that students needed to be prompted to gain these insights.



IDEAL-GAS PROPERTIES & PROCESS MATRIX

PROCESS	**Process & State Relations** Manipulate ideal-gas EOS as needed to relate P, V, & T to create graphs in following columns.	**P-V Plot** Sketch plot for process from state 1 to state 2.	**T-V Plot** Sketch plot for process from state 1 to state 2.	**Moving Boundary Work** Evaluate $\int_1^2 PdV$ after substituting the relationship from column 2 that relates P to V.
Constant Pressure	$PV = MRT$ P-V relationship: T-V relationship:			
Constant Volume	$PV = MRT$ P-V relationship: T-V relationship:			
Constant Temperature	$PV = MRT$ P-V relationship: T-V relationship:			
Constant Entropy	$PV = MRT$ S = constant implies that PV^γ = constant (We will derive this later. Take as given for now.) From this follows: P-V relationship: T-V relationship: NOTE: Value of γ is always greater than unity (one). You need this info to make qualitatively accurate plots.			

Figure 1. First matrix exercise – Ideal-Gas Properties and Processes.



NOTE: This matrix complements the IDEAL-GAS PROPERTIES & PROCESS MATRIX. (The first one you did.) You should have already evaluated the process relations & equation of state relations and determined expressions for the work. What is new here is the addition of the Calorific Equation of State (CEOS) and using the 1st law to evaluate the heat interaction.

Process	1st Law	Process & State Relations	Moving Boundary Work	Heat
General Case	${}_1Q_2 - {}_1W_2 = U_2 - U_1$	Process: NA (general) EOS: $P_1V_1 = mRT_1$; $P_2V_2 = mRT_2$ CEOS: $U_2 - U_1 = mc_v(T_2 - T_1)$; $H_2 - H_1 = mc_p(T_2 - T_1)$	$\int_1^2 PdV$	${}_1Q_2 = \int_1^2 PdV + mc_v(T_2 - T_1)$
Constant-*P*	${}_1Q_2 - {}_1W_2 = U_2 - U_1$			
Constant-*V*	${}_1Q_2 - {}_1W_2 = U_2 - U_1$	Process: $V_1 = V_2$; $T_1 / P_1 = T_2 / P_2$; *MRT/P* = constant EOS: $P_1V_1 = mRT_1$; $P_2V_2 = mRT_2$ CEOS: $U_2 - U_1 = mc_v(T_2 - T_1)$; $H_2 - H_1 = mc_p(T_2 - T_1)$	0	${}_1Q_2 = mc_v(T_2 - T_1)$
Constant-*T*	${}_1Q_2 - {}_1W_2 = U_2 - U_1$			
Constant-*S*	${}_1Q_2 - {}_1W_2 = U_2 - U_1$			

Figure 2. Second matrix exercise – 1st law Applied to Ideal-Gas Closed Systems used in pilot study.

Students Qualitative Evaluation of the Exercise

Students were asked to evaluate the intervention both at mid-semester and at the end of the semester. Students' evaluations of the exercise was highly favorable. As can be seen from Table 1, students were overwhelmingly positive in responding to the statement *"I found the matrices helpful in my preparation for exams."* Here we see that 68% of the students agreed or strongly agreed with the statement. Adding the agree-somewhat responses yields 94% of the students had a positive response to the matrices being helpful. Only 6% disagreed, or somewhat disagreed, with the statement. The anonymous end-of-semester survey yielded comparable results.

Table 1. Student Ratings of Helpfulness of the Intervention

N = 95 (Mid-semester survey)	No. of Responses	% of Responses
a. agree strongly	24	25%
b. agree	41	43%
c. agree somewhat	24	25%
d. disagree somewhat	4	4%
e. disagree	2	2%
f. strongly disagree	0	0%

Students' answers to a question asking about the purpose of the matrix exercises indicated that they had a clear understanding that the matrix exercises were to help them to organize their knowledge of thermodynamics. The following are a few typical thoughtful responses:

- *I think the purpose is to get an overview of the important material and to draw connection between concepts.*
- *The purpose is to help us understand the laws of thermodynamics in a neat and orderly way. The matrices ended up as very helpful references for homework problems and studying.*
- *I think it helps to gain a deeper understanding of concepts presented in class. It also keeps everything neat and organized for easy reference.*
- *To organize information and show how different situations either have similar, the same or different results. Also to make sure the theory is understood.*
- *To help us understand conceptually how to relate equations to each other. To help orient related thermodynamic ideas and principles. They allow us to think critically & are a helpful learning tool.*

In response to the open-ended request for comments related to the use of the matrix exercises in the class, 58 comments were provided by 95 students. These comments were categorized as follows:

Table 2. Categorization of Open-Ended Comments

Comment Category	No. of Comments	% of Comments[†]
Positive	26	45%
Negative	4	7%
Suggestion for Improvement	21	36%
Neutral	5	9%
Expressed Confusion	6	10%
Not Applicable	3	5%

[†] Sum exceeds 100% as a few comments fell into two categories.

The two most common types of comments were either positive comments or comments that offered suggestions for improvement. Samples of positive comments are the following:

- *Super excellent way to understand all the concepts of thermodynamics.*
- *Very efficient way to learn and think anything related in thermodynamics.*
- *They are a good assignment. They work in steps which made me think in steps, and overall I think it made both homework and the exam easier to complete.*
- *The matrices are very useful. They contain a lot of the important information for the course. If I understand them, homework, tests, and quizzes are much easier. It is nice to have that amount of information organized in a way that is understandable and accessible.*
- *I find them very helpful to be honest. It made understanding the fundamentals a lot easier and it provided a guideline to how to approach problems. I would actually enjoy having one for each possible section.*

Pilot Study to Test the Efficacy of Matrix Exercises

Although students believed the matrix exercises to be helpful, their comments do not necessarily indicate that the exercises provide better learning outcomes. To test the hypothesis that the exercises increase learning, we conducted a pilot test with two sections of an introductory engineering thermodynamics course. Students in both sections completed the Ideal-Gas Properties & Processes exercise shown in Fig. 1, first as an individual assignment, and second, as a team assignment during the third and fourth weeks of the semester. The second matrix exercise was administered during the sixth and seven weeks of the semester as follows: One section of students completed the intervention (Fig. 2) after the first examination and immediately before a quiz. Students in this section completed the matrix exercise as a homework assignment outside of class. The instructor did not discuss the exercise nor return it to students prior to the in-class quiz. The second section served as a “business-as-usual” control and did not complete the second matrix. Scores on the first examination served as the index of prior ability, and quiz scores were the dependent variable. The first exam covered properties and property relationships. This exam included concept questions, which were asked in a multiple-choice format, and problem solving questions that required calculations. Scores on this exam were used to divide all students into three ability level groups of low, medium, and high ability. This separation allowed us to determine if the matrix exercise was equally effective for students at all ability levels, an important consideration when designing a classroom-based intervention.

The quiz that served as the dependent variable is shown in Fig. 3. Because this quiz was used as part of a research study, students received credit for completing the quiz, but not for the accuracy of their response. Student responses on this quiz were scored for evidence that the students could apply the 1st law of thermodynamics, understood the definition of work and could evaluate the work resulting from the problem, rearrange the elements to perform the algebraic calculations, recognize the definition of enthalpy, and apply the calorific equation of state. Students received one point for correctly addressing each of these six elements so that quiz scores could range from zero to six.

NO-COUNT QUIZ 4

1st Law Applied to Ideal-Gas Closed Systems

Consider a fixed-mass (closed system) of an ideal gas contained in a piston-cylinder assembly. Derive that ${}_1Q_2 = Mc_p(T_2 - T_1)$ for a constant-pressure process, where the subscripts 1 and 2 refer to the initial and final states, respectively. Start with the 1st law of thermodynamics. Assume that the specific heats can be treated as constants and that the process is performed quasi-statically, i. e., the process is a quasi-equilibrium process. Show every step in your derivation.

Figure 3. Quiz used in pilot study of matrix exercises.

This pilot test examined two research questions:

1. Does completing the matrix exercise improve students' performance on related quiz questions?
2. Are the effects of the matrix exercise different for students at different ability levels?

Pilot Study Results

Exam 1 scores were compared across the two sections to ensure that the two groups were equivalent prior to the matrix exercise experience. A one-way ANOVA comparing these scores did not find a significant effect of section on these scores: $F(1, 99) = 0.012$; $p = 0.914$. This comparison demonstrates that there were no significant ability differences between the two sections prior to the experimental period. Average scores for this exam, across the two sections and by each ability level tested in the intervention, are shown in Table 3.

The effects of the matrix exercise intervention were evaluated in a two-by-three ANOVA [(Experimental vs. Control Section) and (Ability Level: High, Medium, Low)] with quiz scores as the dependent variable. Table 3 contains means and standard deviations for these scores for each ability level in the two conditions. Not surprisingly, there was a significant effect of ability level, $F(2, 95) = 14.83$, p < 0 .001, and partial $\eta^2 = 0.24$[†]. Follow-up comparisons using Tukey's HSD (Honestly Significant Difference) procedure revealed that the low prior-ability students obtained significantly lower scores on the quiz than did students in either the medium or high prior-ability groups. The difference between the medium and high prior-ability groups was not significant, however.

The average quiz score for participants who completed the matrix exercise was 2.6 (std. dev. = 1.9); the average score for participants in the control condition was 2.0 (1.4). This difference was marginally significant; $F(2, 95) = 3.72$; $p = 0.057$, and partial $\eta^2 = 0.04$. The interaction

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[†] Partial η^2 is a measure of effect size. The greater the effect size indicator, the greater the magnitude of the experimental effect.

between ability and intervention was not significant, $F(2, 95) = 3.88$, $p = 0.16$, and partial $\eta^2 = 0.038$. Although this interaction was not significant, an inspection of the mean scores suggests that the intervention was of greater benefit for students in the high and medium ability groups than it was for students in the low prior-ability group. Whereas experimental students in both the high and medium ability groups obtained higher quiz scores than their control comparison peers, lower ability students in the experimental condition actually had a slightly lower mean score than their peers in the control group. It is likely that there was insufficient power in this six group study to detect a statistically significant interaction at the 95% confidence level. Given the practical nature of this research, however, we do not believe that the pattern of differences in mean scores should be overlooked.

Table 3. Exam 1 (Grouping Variable) and Quiz Scores (Dependent Variable) for the Three Ability Groups in the Control and Intervention Condition

	Exam 1 Score		Quiz Score	
Prior Ability	Control Section Mean (Std. Dev.)	Expt. Section Mean (Std. Dev.)	Control Section Mean (Std. Dev.)	Expt. Section Mean (Std. Dev.)
Low	64.0 (12.4) *N* = 21	64.4 (8.3) *N* = 14	1.4 (1.3)	1.2 (1.2)
Medium	83.8 (3.1) *N* = 16	84.1 (3.4) *N* = 17	1.9 (1.4)	2.94 (1.6)
High	94.4 (3.2) *N* = 20	93.2 (2.6) *N* = 13	2.8 (1.3)	3.7 (1.8)

Conclusions

The results of this pilot study are encouraging and suggest that the matrix exercise has the potential to improve students' understanding of these fundamental thermodynamics concepts. Students' positive attitudes toward this exercise, as well as their comments indicating that the intended benefits were understood, suggest that this exercise is one that could be used in thermodynamics classes with a high likelihood that students would execute them as intended. There are, however, aspects of our findings that bear deeper consideration. First, the statistical analysis of quiz reveals that the matrix exercise had only a very small effect on students' quiz performance. In addition, the pattern of means scores across ability levels raises concerns that this exercise does not have its intended effect on lower ability students.

These concerns have led our team to conduct additional examinations of the matrix exercise and to make revisions based upon our findings. For instance, we had thermodynamics students come into the lab individually and think aloud while working through the matrix exercise. From these think alouds, we found that students were not attending to the relationships across cells within rows and columns but rather thought about each cell in isolation. Such piecemeal thinking did not lead to the elaborations necessary for students to fully realize the relations across cells and to monitor their understanding of those relations.

It was this information that led to the transformation of the early version of the second matrix exercise (Fig. 2) to the current version (Fig. 2A) shown in Appendix A. Furthermore, this motivated our development of a third exercise consisting of a set of questions related to prompting students to draw connections among the rows and columns. The enhancements incorporated in both the revised and new exercise were designed to stimulate not only the learning processes of organization, but also elaboration and metacognitive monitoring.

Extended and Future Efforts

The current forms of the two matrix exercises are shown in Appendix A. Note that the constant entropy (adiabatic, reversible) process has been eliminated. This has been done to help students focus on the more easily dealt with processes and also makes the exercise more consistent with the typical order of topics in thermodynamic textbooks, as many instructors may not wish to introduce the isentropic process until after a discussion of the second law.

In order to create a "stand-alone" intervention package requiring minimal involvement from the instructor, we also developed a series of videos that discuss the purpose of the exercises and assist students in their completion of the exercises. The videos are screen-casts of the instructor working on a tablet PC within PowerPoint. Figure 1A shows the constant-pressure process row as developed in the video as an example. The videos provide instruction on how to complete each of the two matrix exercises. Students are instructed to complete the first exercise before proceeding to the second matrix exercise and its associated video. Because most students want to know if they have correctly completed the exercise, we have developed an online quiz-like instrument with personalized feedback that students can use to check their work. We have been careful not to present a completed matrix as the availability of this could prevent many students from working through the exercise.

The second exercise (Fig. 2A) has also evolved. Specifically, the exercise has been modified such that the column headings now elicit the desired organization, elaboration, and metacognitive monitoring. The new third exercise builds on the knowledge and skills that students have acquired from completing the first two matrix exercises. This exercise asks a series of questions in which students are asked to compare and contrast various aspects of the three processes. We hope to report on the efficacy of the complete intervention package (three exercises and six short screen-cast videos) in a later publication. We are also in the process of developing a thermodynamics reasoning inventory, which will be used in a pre-test/post-test evaluation of our intervention.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. DUE-1043833. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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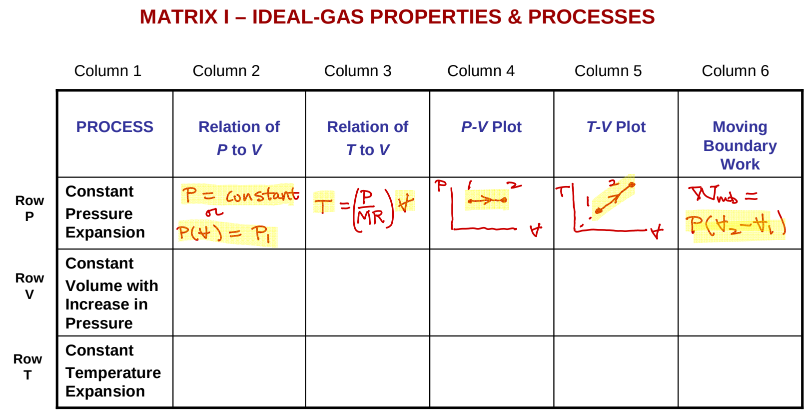
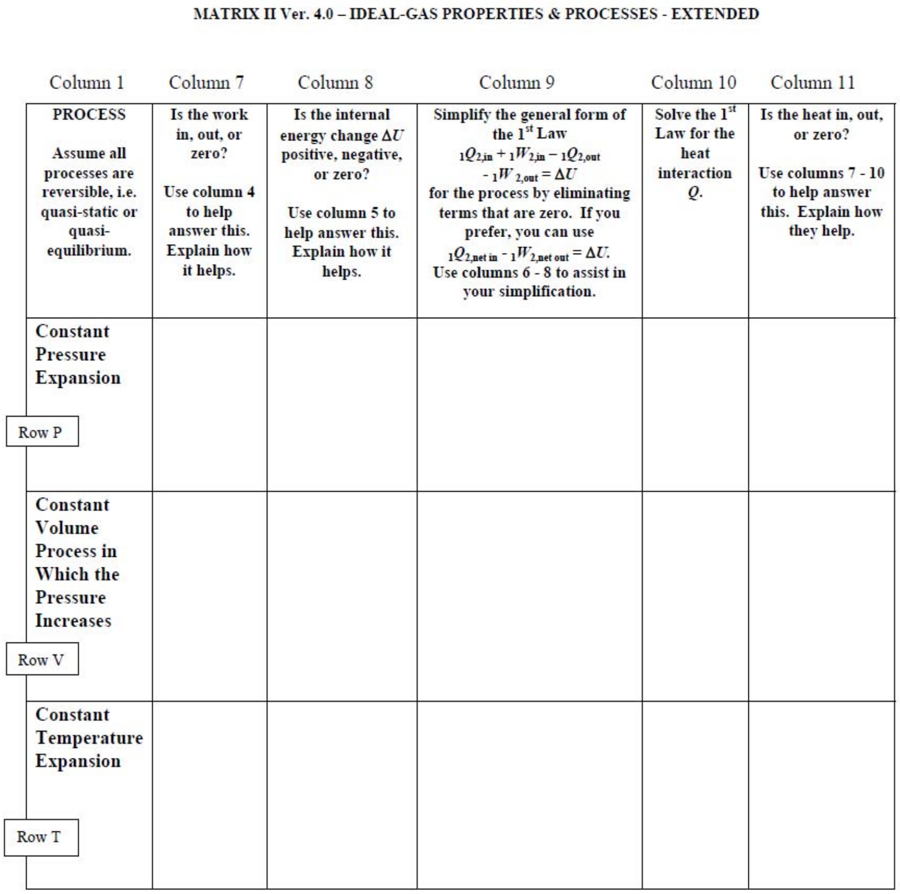
APPENDIX A



MATRIX I – IDEAL-GAS PROPERTIES & PROCESSES

	Column 1	Column 2	Column 3	Column 4	Column 5	Column 6
	PROCESS	Relation of *P* to *V*	Relation of *T* to *V*	*P-V* Plot	*T-V* Plot	Moving Boundary Work
Row P	Constant Pressure Expansion	$P = \text{constant}$ or $P(\forall) = P_1$	$T = \left(\frac{P}{MR}\right)\forall$	P 1 2 $\forall$	T 1 2 $\forall$	$W_{mb} =$ $P(\forall_2 - \forall_1)$
Row V	Constant Volume with Increase in Pressure					
Row T	Constant Temperature Expansion					

Figure 1A. Current version of Matrix Exercise I – Ideal-Gas Properties and Processes. Image from video screen capture.



MATRIX II Ver. 4.0 – IDEAL-GAS PROPERTIES & PROCESSES - EXTENDED

	Column 1	Column 7	Column 8	Column 9	Column 10	Column 11
	PROCESS Assume all processes are reversible, i.e. quasi-static or quasi-equilibrium.	Is the work in, out, or zero? Use column 4 to help answer this. Explain how it helps.	Is the internal energy change ΔU positive, negative, or zero? Use column 5 to help answer this. Explain how it helps.	Simplify the general form of the 1st Law ${}_1Q_{2,\text{in}} + {}_1W_{2,\text{in}} - {}_1Q_{2,\text{out}} - {}_1W_{2,\text{out}} = \Delta U$ for the process by eliminating terms that are zero. If you prefer, you can use ${}_1Q_{2,\text{net in}} - {}_1W_{2,\text{net out}} = \Delta U$. Use columns 6 - 8 to assist in your simplification.	Solve the 1st Law for the heat interaction Q.	Is the heat in, out, or zero? Use columns 7 - 10 to help answer this. Explain how they help.
Row P	Constant Pressure Expansion					
Row V	Constant Volume Process in Which the Pressure Increases					
Row T	Constant Temperature Expansion					

Figure 2A. Current version of Matrix Exercise II – Ideal-Gas Properties and Processes – Extended.