Personalized Learning Tool for Thermodynamics

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***Abstract*—This Research-Work-in-Progress presents a significant advance in the development of a personalized learning tool for students of science, technology, engineering, or mathematics (STEM) who are struggling to learn how to solve difficult word problems. Developing the skill to solve word problems is required to do well on exams, to complete the STEM degree, and to have a successful STEM career. There have been several efforts to develop tools that focus on predefined explanations of concepts or trying to determine the point of error in predefined problems. What is new and different about our tool called Pathway is its use of artificial intelligence (AI) to derive multiple solution paths to custom word problems that are created by the student. This paper presents a proof-of-concept of Pathway's ability to solve word problems; that is, it is the first word-problem solver. The first course we have chosen to apply Pathway to is Engineering Thermodynamics because it is a well-known weed out course, and mechanical engineering has a low 49% retention rate. Presently, Pathway shows students how to set up their word problems and assumptions and describes symbolic step-by-step solutions paths. Once the development of Pathway is complete and fully tested, we will investigate its effect on the exam scores of students. A study conducted with our prior e-learning tool resulted in an increase in exams scores of a letter grade and a half for Engineering Thermodynamics. However, since it used a limited set of predefined word-problems, the tool could not be used by other instructors who cover a different sequence of topics or used by students who want to explore what-if scenarios. Pathway is being developed to address those challenges.**

Keywords—automated tutoring, personalized learning, Pathway, e-learning, word problem solver.

I. Introduction

Increasing the number of professionals in science, technology, engineering, or mathematics (STEM) greatly increases the rate of prosperity [1]. STEM attraction and retention are two areas that are expected to have a significant impact on increasing the number of STEM professionals [1]. Currently, 93% of high school students do not go on to major in STEM. Of the 7% that major in STEM, only 52% of them complete the degree [2]. The retention rate varies across majors and demographic groups [4].

A STEM weed-out course is a very difficult course that must be successfully passed before completing the degree. Rigorous expectations include heavy cognitive loads and large numbers of study hours. These courses have the lowest exam scores and result in the highest rates of Ds, Fs, and Ws. Thermodynamics is such a course. However, since thermodynamics is the science of energy conversion and transmission, its understanding is important for a variety of engineering and science disciplines. **Figure 1** plots the national passing rates of thermodynamics over an eleven-year period for the majors of mechanical, civil, and electrical engineering [5], [35]. The majority of passing rates fall between 40% to 65% (the red bars). Students perform similarly in other countries [6]-[15]. Several studies point to misconceptions of concepts and principles as persistent issues that are resistant to change [16]-[20].

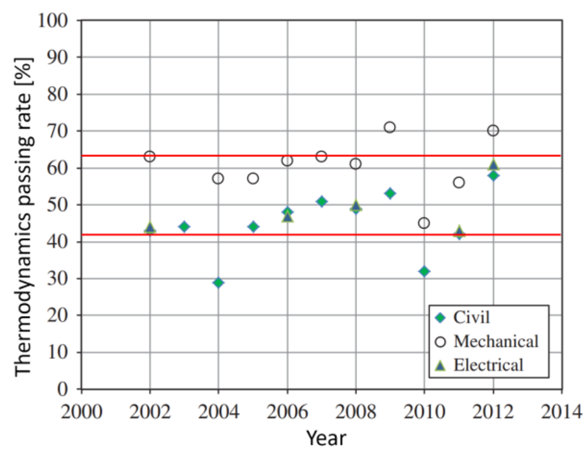

Figure 1: Passing rates for thermodynamics in the U.S. Data from the National Council of Examiners for Engineering and Surveying [35].

Efforts to improve student performance include inquiry-based [18] and [21], problem-based [22]-[24], and project-based [25]-[28] learning techniques. In particular, e-learning tools have been received positively by students. Multimedia methods include hypertext, animation, simulation, and videos. Some YouTube videos on thermodynamics receive over a million views. Examples of software tools include a web-based self-assessment tool [28], a highly-interactive e-book [29], and a tool that allowed parametric studies of textbook examples [30]. Although such methods have shown promise and have been welcomed by students, such efforts to date have not been comprehensive nor have shown widespread improvements in student performance [37].

Improvement in exam scores through scaffolding is the objective of this research-work-in-progress. Our prior study showed how the scaffolding of selected exercises can

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significantly improve exam scores. The difference with this new tool is that it allows the user to customize their problem, which accommodates all thermodynamic courses.

In Section II we discuss our prior work in the e-learning of engineering thermodynamics. In Section III we describe a prototype of our new personalized learning tool. And in Section IV we compare its solution method to the official solution. We summarize in Section V.

II. Prior Results

Research results on the efficacy of our prior e-learning tool support the hypothesis that immediate and unpenalized feedback while practicing solving word problems for homework improves exam scores. The tool was tested on 600 undergraduate students divided across five sections of engineering thermodynamics at a Research I university. Each section (1-5) had 120 students and was taught by a different mechanical engineering professor. The students enrolled in Section 5 were the experimental group, while the other four sections were the control group. The five instructors used the same textbook, covered the same topics, and assigned the same type of homework. Although each section was taught at different times during the week, all sections took the same exams at the same times throughout the semester. The most senior professor (of Section 3) was assigned to create all exams. The other four instructors were not allowed to see the exam before the date of the exam to prevent the possibility of biasing the students about which concepts to focus on most during their preparation for the exam. The senior professor created the solutions. TAs helped the professors with grading.

Figure 2 shows the average exam score of each section for the three midterms. Each of the three midterms of the experimental group was significantly higher than the other sections. The standard deviation (uncertainty) was 3.7 percentage points, the average exam score of the experimental group was 14 percentage points (a letter-grade-and-a-half) higher than the average of other sections, which is well above uncertainty. Although there were differences in teaching styles, it was not enough difference to account for the significant increase found in exams scores of the experimental group. That is, during semesters when the e-learning tool was not used, the instructor's exam scores were on par with all other sections. Further details of the study, including quantitative and qualitative results, can be found in [31]. Although more analysis is warranted, cognitive load theory and cognitive theory of multimedia [32]-[34] may help explain the improvement in exam scores. These constructs help explain the effectiveness of working memory and knowledge acquisition in a traditional classroom instruction with virtual learning environments.

Despite the significant increase in exam scores, the widespread use of our prior tool is severely limited to a particular sequence of concepts and homework sets. That is, its set of word-problem exercises and solutions are hard-coded and relatively few in number. As seen in the online syllabus/schedules of instructors of the course, the sequence and rate of concepts covered can vary. Different textbooks also vary in the sequence and rate of coverage. For example, textbook authors Moran et al., Chengel et al., and Chavan et al. introduce the concept of the second law of thermodynamics in Chapters 5, 6, and 3, respectively. Textbooks often have a large variety of problems to choose from for homework assignments.

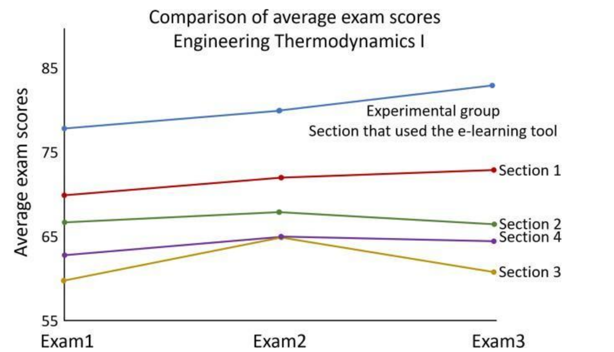

Figure 2: Exam scores of the experimental and control groups. Each group had about 120 each. The experimental group used the tutorial tool while the control group (Sections 1-4) did not. The experimental group scored on average 14.0 percentage points higher than other sections over the three midterm exams. Standard deviation is 3.7 percentage points.

III. New Prototype

Our present tool's design is similar to Mayer's [3] cognitive principles of multimedia learning but will more comprehensively and directly address the large variety of word problems that students may encounter in homework, may find to practice with, or create themselves to better understand particular concepts and to improve their problem-solving skills. To address this grander challenge, we are developing the first word-problem solver (called Pathway).

Several tiered scaffolding [22] approaches will be incorporated in the tool, such as the use of models, video demonstrations, hints, encouraged reflection and metacognition, and problem-solving strategies [36]. Furthermore, according to Bandura [37-38] "the ability to persist in the face of aversive experiences and obstacles is dependent on the strength of personal self-efficacy" [37-38] and personal self-efficacy begets intrinsic motivation which leads to desirable student learning outcomes [37]. We hypothesize that Pathway's scaffolding approaches will enhance the strength of student's self-efficacy and intrinsic motivation which is especially needed when students get stuck or can't even get started on solving a problem. Pathway allows students to easily input the specifications of their word problem and it outputs a variety of step-by-step solution paths. The key difference between our old tool and this new tool is that the old tool was severely limited to covering the solutions of only a small set of predefined hard-coded exercises, while the new tool is being developed to solve just about any problem on a particular subject matter. Pathway does so by using our custom-built AI engine

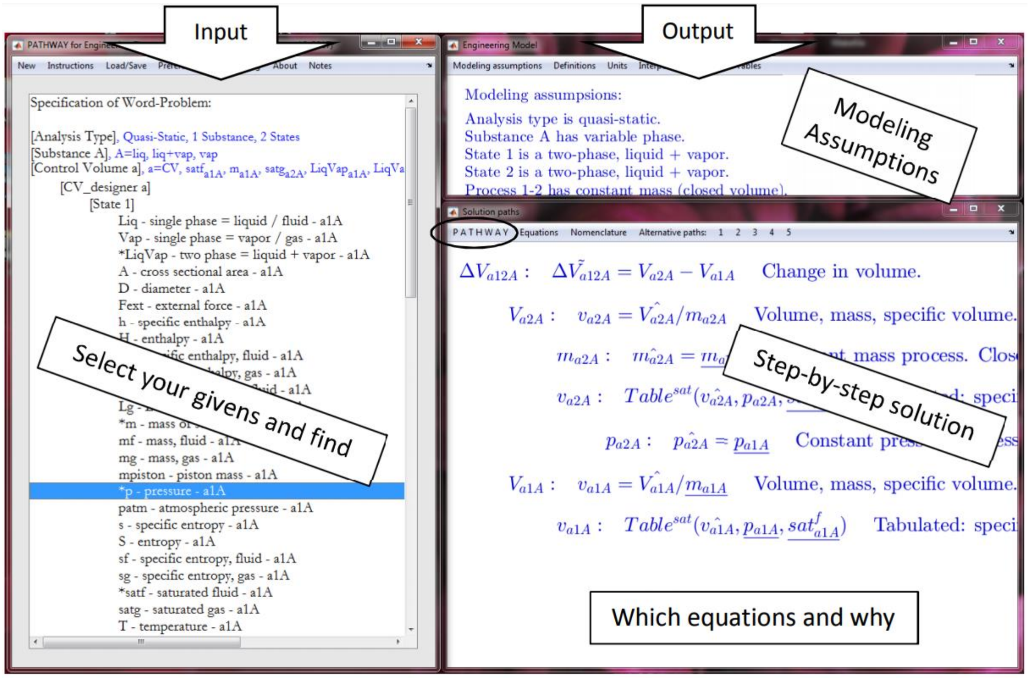

Figure 3: Pathway prototype. To get unstuck, a user inputs their word-problem *specifications* into the right window using the expandable menus. Then after pressing the Pathway button in the lower-right window, Pathway outputs a *step-by-step solution path* and *modeling assumptions* in its lower- and upper-right widows.

for solving general STEM word problems. The engine appears to find all solution paths, which may benefit students' understanding and problem-solving development.

Pathway is expected to be used as follows. Once a struggling student reaches a mental impasse, they will be able to go online to access Pathway. The graphical user interface (GUI) of the Pathway prototype consists of one input window and two output windows. They will use a mouse or touch- screen to input their word-problem *specifications* using Pathway's expandable menus. Each menu heading expands to all possible symbolic quantities or relations that can be asked about in the subject, which in this case is Engineering Thermodynamics. That is, each STEM subject has a finite number of types of variables, relational concepts, and constraints. The student is able to select: the type of analysis (static, steady-state, cyclic, or transient); the type of substances (ideal to non-ideal types, liquid, solid, multi-phased, etc.); the number of states; the number and types of control volumes; the states variables at each input/output port between each control volume; and select the unknown they wish to solve for. The goal of the input method is to be able to accommodate the specifications of every type of problem that the course can conjure up. As the user selects each specified quantity, the label of the quantity is added to the list of specified quantities located to the right of the heading (in blue text). The subscripts are used to discern one quantity from another quantity that is of the same type. The three-character subscripts are used to identify the substance, port, and component for which the quantity is associated with (see the left window in **Figure 3**).

Once the word problem has been specified, the student presses the Pathway button (circled in the lower-right window). Pathway then outputs a *step-by-step solution path* and *modeling assumptions* in its lower- and upper-right widows. Pathway's solution path is always displayed in a systematic outline format, which begins by being seeded with the unknown quantity that is to be determined. Each equation line includes the quantity that is being solved for, a mathematical relation, and a short phrase describing the purpose of the relation. To help the user follow along, a tilde over each quantity in an equation identifies the quantity that is being solved for, an underline identifies which quantities are known in the equation, and a hat identifies which quantity should be substituted into the equation above it (see the lower- right window in **Figure 3**). That is, if all equations were substituted into each other, from the bottom to the top, the results would be a single equation consisting of a single unknown (identified by a tilde) and several other underlined known quantities. Last, the upper-left window displays the modeling assumptions that were applied to the problem. Assumptions are often absent in the solutions of beginning STEM students; however, assumptions are a critical aspect of a word-problem solution.

IV. Solution Path Validation

As seen in **Figure 3**, Pathway presents the solution path in a way that may be perceived as "backward and lengthy" when compared to how people with expert knowledge and insight typically begin and skip steps while solving problems. However, Pathway's solution path is much more logical and intuitive for learners. For example, in the following test case, shown in **Figure 4**, a student is asked to solve for temperature; however, the textbook's solution shows the first equation to be something that does not include temperature. To find temperature, most beginning students would not consider using an equation that does not include the temperature variable. Official solutions often skip steps and offer no explanations as to why particular equations are chosen. Struggling students often ask the professor to explain the solutions. Such issues have been alleviated in Pathway: it always begins with the quantity to be determined, no steps are skipped, and each step is explained.

Our method of validation proceeds as follows. Beginning with a problem from a popular engineering thermodynamics textbook, say, problem 6.13 (**Figure 4**, left), we enter the problem's specifications (**Figure 4**, right) into Pathway. The solutions by the textbook's author versus Pathway are shown in **Figures 5** and **6**, respectively. Although the textbook author's solution has a smaller number of steps, the solution path is not very clear to many non-experts. The solution begins with a nonintuitive equation that does not contain the temperature variable, which is to be determined. There are no explanations of the purpose of each equation nor the conditions for which each equation is allowed to be used. Several steps are skipped. The textbook's solution appears to be written for the professor, not for struggling students. Conversely, Pathway begins (as always) with the variable that is to be determined, explains what each equation is for, tracks each new unknown variable that is introduced in a logical outline format, and uses unique variable symbols with special subscript label identifiers that specify which variables are known, unknown, substituted, etc. See insets in **Figure 6**. Once labeling and hierarchy are understood, then all Pathway solutions are easy to follow.

After validation of the textbook's problem, then what-if scenarios are explored, where other quantities are chosen to be solved. An example of a what-if scenario is shown in **Figure 7**, where the *number of moles* is chosen as the quantity to be determined. Although no problems in Chapter 6 of this particular textbook asks students to solve for the number of moles, such a quantity is fair game for an exam question, or for a curious student.

V. SUMMARY

This effort demonstrates a preliminary proof-of-concept for a personalized tutorial tool for Engineering Thermodynamics. Further testing and development are ongoing. The overarching goal of this project is to help struggling students improve their engineering problem-solving skills, which will be reflected in an improvement in exam scores, and eventually an improvement in the passing rates of students learning engineering thermodynamics. Open questions include: Can Pathway show significant improvement in exam scores like our prior tool? And in what ways should students be recommended to use, and not misuse Pathway.

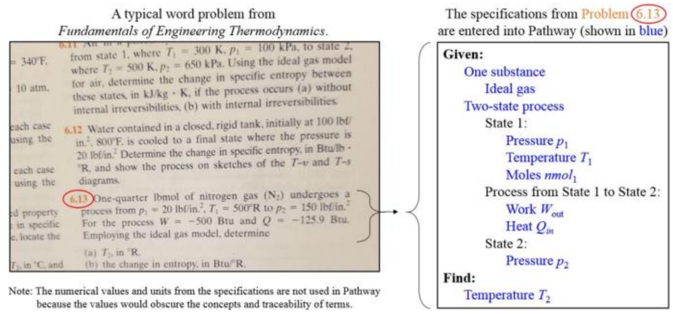

Figure 4: Validation test case. Word problem specifications are symbolically entered into Pathway. The box on the left is a Pathway representation of the word problem, aside from numerical values, which detract from the learning process.

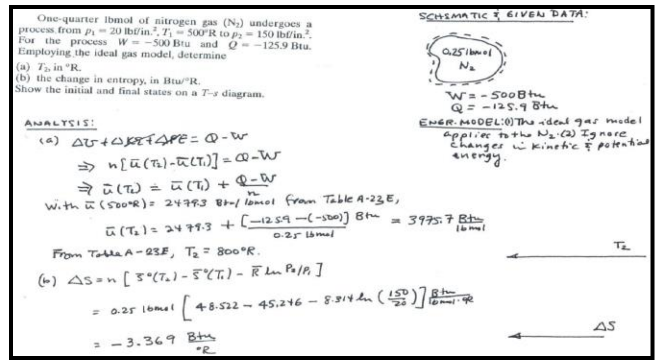

Figure 5: The official solution to problem 6.13 given by the textbook's authors.

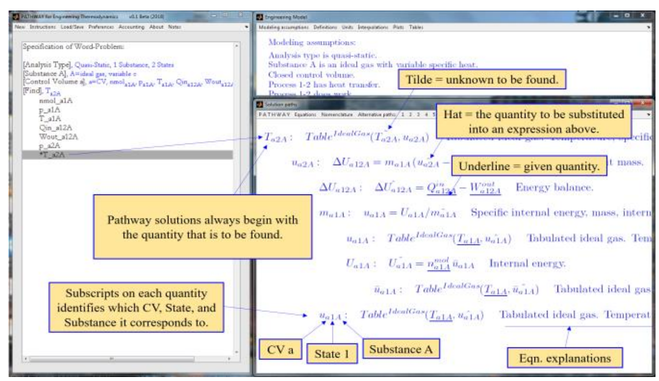

Figure 6: Pathway's version of the solution to problem 6.13.

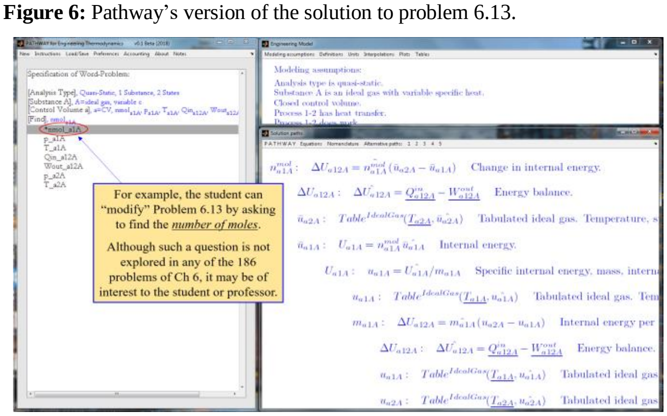

Figure 7: Validation of what-if scenario. Unlike textbooks, Pathway's problems can be greatly modified from textbooks. Student or professors can make up their own problems from scratch within Pathway.

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