CycleTalk: Toward a Dialogue Agent that Guides Design with an Articulate Simulator

Carolyn P. Rosé[1], Cristen Torrey[1], Vincent Aleven[1], Allen Robinson[1], Chih Wu[2], and Kenneth Forbus[3]

[1] Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh PA, 15213
{cprose,ctorrey,aleven}@cs.cmu.edu,alr@andrew.cmu.edu
[2] US Naval Academy, 121 Blake Rd., Annapolis MD, 21402-5000
wu@usna.edu
[3] Northwestern University, 1890 Maple Ave., Evanston IL, 60201
forbus@cs.northwestern.edu

Abstract. We discuss the motivation for a novel style of tutorial dialogue system that emphasizes reflection in a design context. Our current research focuses on the hypothesis that this type of dialogue will lead to better learning than previous tutorial dialogue systems because (1) it motivates students to explain more in order to justify their thinking, and (2) it supports students' meta-cognitive ability to ask themselves good questions about the design choices they make. We present a preliminary cognitive task analysis of design exploration tasks using CyclePad, an articulate thermodynamics simulator [10]. Using this cognitive task analysis, we analyze data collected in two initial studies of students using CyclePad, one in an unguided manner, and one in a Wizard of Oz scenario. This analysis suggests ways in which tutorial dialogue can be used to assist students in their exploration and encourage a fruitful learning orientation. Finally, we conclude with some system desiderata derived from our analysis as well as plans for further exploration.

1 Introduction

Tutorial dialogue is a unique, intensely dynamic form of instruction that can be highly adaptive to the individual needs of students [15] and provides opportunities for students to make their thinking transparent to a tutor. In this paper we introduce early work to develop a novel tutorial dialogue agent to support guided, exploratory learning of scientific concepts in a design scenario. Current tutorial dialogue systems focus on leading students through directed lines of reasoning to support conceptual understanding [16], clarifying procedures [21], or coaching the generation of explanations for justifying solutions [19], problem solving steps [1], predictions about complex systems [9], or computer literacy [11]. Thus, to date tutorial dialogue systems have primarily been used to support students in strongly directed types of task domains. We hypothesize that in the context of creative design activities the adaptivity of dialogue has greater impact on learning than the impact that has been demonstrated in previous comparisons of tutorial dialogue to challenging alternative forms of instruction such as an otherwise equivalent targeted "mini-lesson" based approach (e.g., [12]) or a "2nd-generation" intelligent tutoring system with simple support for self-explanation (e.g., [1]).

We are conducting our research in the domain of thermodynamics, using as a foundation the CyclePad articulate simulator [10]. CyclePad offers students a rich, exploratory learning environment in which they apply their theoretical thermodynamics knowledge by constructing thermodynamic cycles, performing a wide range of efficiency analyses. CyclePad has been in active use in a range of thermodynamics courses at the Naval Academy and elsewhere since 1996 [18]. By carrying out the calculations that students would otherwise have to do by more laborious means (e.g., by extrapolation from tables), CyclePad makes it possible for engineering students to engage in design activities earlier in the curriculum than would otherwise be possible. Qualitative evaluations of CyclePad have shown that students who use CyclePad have a deeper understanding of thermodynamics equations and technical terms [4].

In spite of its very impressive capabilities, it is plausible that CyclePad could be made even more effective. First, CyclePad supports an unguided approach to exploration and design. While active learning and intense exploration have been shown to be more effective for learning and transfer than more highly directed, procedural help [7,8] pure exploratory learning has been hotly debated [3,13,14]. In particular, scientific exploratory learning requires students to be able to effectively form and test hypotheses. However, students experience many difficulties in these areas [13]. Guided exploratory learning, in which a teacher provides some amount of direction or feedback, has been demonstrated to be more effective than pure exploratory learning in a number of contexts [14].

Second, CyclePad is geared towards explaining its inferences to students, at the student's request. It is likely to be more fruitful if the students do more of the explaining themselves, assisted by the system. Some results in the literature show that students learn better when producing explanations than when receiving them [20]. Thus, a second area where CyclePad might be improved is in giving students the opportunity to develop their ability to think through their designs at a functional level and then explain and justify their designs.

A third way in which CyclePad's pedagogical approach may not be optimal is that students typically do not make effective use of on-demand help facilities offered by interactive learning environments (for a review of the relevant literature, see [2]). That is, students using CyclePad may not necessarily seek out the information provided by the simulator, showing for example how the second law of thermodynamics applies to the cycle that they have built, with a possibly detrimental effect on their learning outcomes. Thus, students' experience with CyclePad may be enhanced if they were prompted at key points to reflect on how their conceptual knowledge relates to their design activities.

We argue that engaging students in natural language discussions about the pros and cons of their design choices as a highly interactive form of guided exploratory learning is well suited to the purpose of science instruction. In the remainder of the paper, we present a preliminary cognitive task analysis of design exploration tasks using CyclePad. We present an analysis of data collected in two initial studies of students using CyclePad, one in an unguided manner, and one in a Wizard of Oz scenario. We present preliminary evidence from this analysis that suggests how tutorial dialogue can be used to assist students in their exploration. Finally, we conclude with some system desiderata derived from our analysis as well as plans for further exploration.

2 CycleTalk Curriculum

A thermodynamic cycle processes energy by transforming a working fluid within a system of networked components (condensers, turbines, pumps, and such). Power plants, engines, and refrigerators are all examples of thermodynamic cycles. In its initial development, the CycleTalk curriculum will emphasize the improvement of a basic thermodynamic cycle, the simple Rankine cycle. Rankine cycles of varying complexities are used in steam-based power plants, which generate the majority of the electricity in the US.

At a high level, there are three general modifications that will improve the efficiency of a Rankine cycle:

Adjusting the temperature and pressure of the fluid in the boiler will increase efficiency, up to the point where the materials cannot withstand the extreme conditions.

Adding a reheat cycle reheats the working fluid before sending it through a second turbine. This requires extra energy to the second heater, but it is balanced by the work done by the second turbine.

Adding a regenerative cycle sends some of the steam leaving the turbine back to the water entering the boiler, which decreases the energy required to heat the water in the boiler.

These modifications can be combined, and multiple stages of reheat and regeneration are often used to optimize efficiency, though the cost of additional parts must be weighed against the gains in efficiency.

3 Exploratory Data Collection

We have begun to collect data related to how CyclePad is used by students who have previously taken or are currently taking a college-level thermodynamics course. The goal of this effort is to begin to assess how tutorial dialogue can extend CyclePad's effectiveness and to refine our learning hypotheses in preparation for our first controlled experiment. In particular we are exploring such questions as: (1) To what extent are students making use of CyclePad's on-demand help? (2) What exploratory strategies are students using with CyclePad? Are these strategies successful or are students floundering? Do students succeed in improving the efficiency of cycles? (3) To what extent are student explorations of the design space correlated with their observed conceptual understanding, as evidenced by their explanation behavior?

At present, we have two forms of data. We have collected the results of a take-home assignment administered to mechanical engineering students at the US Naval Academy, in which students were asked to improve the efficiency of a shipboard version of a Rankine cycle. These results are in the form of written reports, as well as log files of the student's interactions with the software. In addition, we have directly observed several Mechanical Engineering undergraduate students at Carnegie Mellon University working with CyclePad on a problem involving a slightly simpler Rankine cycle. These students were first given the opportunity to work in CyclePad independently. Then, in a Wizard of Oz scenario, they continued to work on the problem while they were engaged in a conversation via text messaging software with a graduate student in Mechanical Engineering from the same university. For these students we

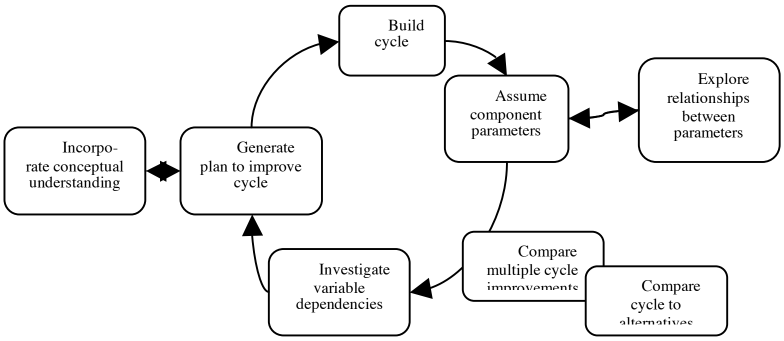

Figure 1: Task analysis of exploring a design space with CyclePad

have collected log files and screen movies of their interactions with CyclePad as well as transcripts of their typed conversation with the human tutor.

We have constructed a preliminary cognitive task analysis (See Fig. 1) describing how students might use CyclePad in the type of scenario they encountered during these studies (i.e., to improve a simple Rankine cycle).

Creating the cycle and defining key parameters. When creating a thermodynamic cycle according to the problem description, or modifying a given thermodynamic cycle, students must select and connect components. Further, they must provide a limited number of assumed parameter values to customize individual cycle components and define the cycle state. CyclePad will compute as many additional parameters as can be derived from those assumptions. When each parameter has a value, either given or inferred, CyclePad calculates the cycle's efficiency. In order to be successful, students must carefully select and connect components and be able to assume values in ways that acknowledge the relationships between the components.

Investigating Variable Dependencies. Once the cycle state has been fully defined (i.e., the values of all parameters have been set or inferred), students can use CyclePad's sensitivity analysis tool to study the effect of possible modifications to these values. With this tool, students can plot one variable's effect on another variable. These analyses may have implications for their redesign strategy. For example, when a Rankine cycle has been fully defined, students can plot the effect of the pressure of the output of the pump on the thermal efficiency of the cycle as a whole. The sensitivity analysis will show that up to a certain point, increasing the pressure will increase efficiency. The student can then adjust the pressure to its optimum level.

Exploring Relationships among Cycle Parameters. Setting appropriate assumptions given a specific cycle topology can be difficult for novice students of thermodynamics. For any specific cycle topology, it is important for students to understand which parameters must be given and which parameters can be inferred based on the given values. In order to help in this regard, CyclePad allows students to request explanations that articulate the relationships between parameters, moving forward from a given parameter to conclusions or backward to assumptions. For example, CyclePad will answer questions such as "Why does P(S2) = 10,000 kPa?" or "What follows from P(S2) = 10,000 kPa?". Here, P(S2) specifies the pressure of the working substance at a particular stage in the cycle.

Comparing Multiple Cycle Improvements. Students can create their redesigned cycles, and, once the cycle states are fully defined, students can compute the improved cycle efficiency. Comparing cycle efficiencies of different redesigns lets students explore the problem space and generate the highest efficiency possible. Suppose a student began improving the efficiency of the Rankine cycle by including a regenerative cycle. It would then be possible to create an alternative design which included a reheat cycle (or several reheat cycles) and to compare the effects on efficiency before combining them. By comparing alternatives, the student has the potential to gain a deeper understanding of the design space and underlying thermodynamics principles and is likely to produce a better redesign.

3.1 Defining Cycle State

Despite CyclePad's built-in help functionality, we have observed that a number of students struggle when defining the state of each of the components in the cycle. On the take-home assignment, 19 students were asked to improve the efficiency of a shipboard version of a Rankine cycle. The work of only 11 students resulted in the ability to compute the efficiency of their improved cycle using CyclePad, even though these students had two weeks to complete the assignment and ample access to the professor. Of the 11 students who were able to fully define their improved cycle, 3 students created impractical or unworkable solutions and 3 other students did not improve the efficiency of the cycle in accordance with the problem statement. From the efforts of these students, we have seen that implementing one's redesign ideas in the CyclePad environment should not be considered trivial.

Because we only have the artifacts of these students' take-home assignments, it is difficult to speculate as to exactly what these students found difficult about fully defining each state of their improved cycle. It seems likely however that the greater complexity of the redesigned cycles that students constructed (on average, the redesigned cycles had 50% more components than the cycle that the students started out with) made it more difficult for students to identify the key parameters whose values must be assumed. We have informally observed that our expert tutor is capable of defining the state of even complicated cycles in CyclePad without much, if any, trial and error. Perhaps he quickly sees a deep structure, as opposed to novice students who may be struggling to maintain associations when the number of components increases (see e.g., [5]). As we continue our data collection, we hope to investigate how student understanding of the relationships between components affects their ability to fully define a thermodynamic cycle.

We did observe the complexity of implementing a redesigned cycle directly through several Wizard-of-Oz-style studies where the student worked first alone, then with a tutor via text-messaging software. In unguided work with CyclePad, we saw students having difficulty setting the assumptions for their improved cycle. One student was working for approximately 15 minutes on setting the parameters of a few components, but he encountered difficulty because he had not ordered the components in an ideal way. The tutor was able to help him identify and remove the obstacle so that he could quickly make progress. When the tutoring session began, the tutor asked the student to explain why he had set up the components in that particular way.

Student: I just figured I should put the exchanger before the htr
[The student is using "htr" to refer to the heater.]
Tutor: How do you think the heat exchanger performance/design will vary with the condition of the fluid flowing through it? What's the difference between the fluid going into the pump and flowing out of it?
Student: after the pump the water's at a high P
[P is an abbreviation for pressure.]
Tutor: Good! So how will that affect your heat exchanger design?
Student: if the exchanger is after the pump the heating shouldn't cause it to change phase because of the high pressure
…
Tutor: But why did you put a heat exchanger in?
Student: I was trying to make the cycle regenerative
…
Tutor: OK, making sure you didn't waste the energy flowing out of the turbine, right?

After the discussion with the tutor about the plan for the redesign, the student was able to make the proposed change to the cycle and define the improved cycle completely without any help from the tutor. Engaging in dialogue forces students to think through their redesign and catches errors that seem to be difficult for students to detect on their own. By initiating explanation about the design on a functional level, the tutor was able to elicit an expression of the student's thinking and give the student a greater chance for success in fully defining the improved cycle.

3.2 Exploring Component Relationships

As mentioned, in order to gain an understanding of how cycle parameters are related (crucial to fully defining the state of a cycle) students can ask CyclePad to explain the relations in which a given parameter takes part. Without guidance from a tutor, however, students tended not to take advantage of this facility, consistent with results from other studies [1]. Investigation of the log files from the take-home assignment reveals very limited use of CyclePad's explanation features. Only one log file indicated that a student had used the functionality more than ten times, and the log files of 8 of 19 students contained no evidence that the functionality was ever used. (We cannot rule out the possibility that students used the explanation features on CyclePad files they did not turn in or that they chose to ask their professor for help instead.) Similarly, in our direct observation of students working independently with CyclePad, we saw that students often set parameter values that contradict one another, causing errors that must be resolved before continuing. One student encountered numerous contradictions on a single parameter over a short length of time, but still did not ask the system to explain how that parameter could be derived.

By contrast, students working with the tutor did seek out CyclePad's explanations, for example when the tutor asked them a question to which they could not respond.

Tutor: What does your efficiency depend on?

…

Student asks CyclePad for “What equations mention eta-Carnot?”

(eta-Carnot refers to the hypothetical efficiency of a completely reversible heat engine. The student is asking a theoretical question about how efficiency would be determined under ideal conditions.)

CyclePad displays eta-Carnot(CYCLE) = 1 – [Tmin(CYCLE)/Tmax(CYCLE)]

Student: the definition of carnot efficiency

Tutor: What can you deduce from that?

Student: that the lower Tmin/Tmax, the higher the efficiency of the cycle; ie, the greater the temperature difference in the cycle the more efficient

Tutor: Is there any way you can modify your cycle accordingly?

The challenges faced by students working with CyclePad could be opportunities for learning. CyclePad has the capacity to explain how the cycles are functioning, but students do not seem to utilize CyclePad’s articulate capacities spontaneously. When students are prompted to explain themselves and they receive feedback on their explanations, they are more likely to utilize CyclePad’s helpful features in productive ways. Furthermore, as part of the discussion, the tutor may explicitly direct the student to seek out explanations from CyclePad.

3.3 Investigating Variable Dependencies

One of the most useful tools that CyclePad offers students is the sensitivity analysis. A sensitivity analysis will plot the relationship between one variable (such as pressure or temperature) and a dependent variable (such as thermal efficiency). Information like this can be very useful in planning one’s approach to a redesign.

There were two students who performed large numbers of sensitivity analyses, as evidenced from their log files, but the comments from the professor on these students’ written reports were critical of their process. They did not seem to document a well-reasoned path to their solution. From the relatively large numbers of sensitivity analyses in quick succession, one could speculate that these students’ use of the sensitivity analysis tool was not purposeful. Rather, these students appeared to take a blanket approach in the hope that something useful might turn up. In contrast, we observe the tutor assisting students to interpret sensitivity analyses and apply those interpretations to their designs in a systematic way, as illustrated in the following dialogue:

Student: I have recreated the basic cycle and am now in the sensitivity analysis

Tutor: Go ahead. Let's stick to eta-thermal

[student sets up the efficiency analysis in CyclePad]

Tutor: So what does this tell you?

Student: the higher the temperature to which the water is heated in the heater, the higher the thermal efficiency

Tutor: So do you want to try changing the peak temperature?

Student: to improve the efficiency, yes

3.4 Comparing Multiple Cycle Improvements

CyclePad makes it relatively easy for students to try alternative design ideas and thereby to generate high-quality designs. However, students working independently with CyclePad tended not to explore the breadth of the design space, even if they seemed to be aware of design ideas that would improve their design. Although students who did the take-home assignment were aware of both the reheat and regenerative strategies through course materials, only 8 of these 19 students incorporated both strategies into their redesigned cycles. Also, in the written report associated with the take-home assignment, the students were asked to explain the result of each strategy on the efficiency of the cycle. 15 of 19 students correctly explained that regeneration would improve the efficiency of the cycle. However, only 10 of 19 students used a regeneration strategy in their redesigned cycle.

In contrast, students working with the tutor are prompted to consider as many alternative approaches as they can and they are encouraged to contrast these alternatives with one another on the basis of materials and maintenance cost, in addition to cycle efficiency. This explicit discussion of alternatives with the tutor should produce an optimal design. Here is an example dialogue where the tutor is leading the student to consider alternative possibilities:

Tutor: Yes, very good. How do you think you can make it better? i.e. how will you optimize the new component?

Student: we could heat up the water more

Tutor: That's one, try it out. What do you learn?

Student: the efficiency increases pretty steadily with the increased heating - should i put the materials limitation on like there was earlier? or are we not considering that right now

Tutor: OK, how about other parameters? Obviously this temperature effect is something to keep in mind. Include the material effect when you start modifying the cycle

Student: ok

Tutor: What else can you change?

Student: pump pressure

Tutor: So what does the sensitivity plot with respect to pump pressure tell you?

Student: so there's kind of a practical limit to increasing pump pressure, after a while there's not much benefit to it

Tutor: Good. What other parameters can you change?

Student: exit state of the turbine

Tutor: Only pressure appears to be changeable, let's do it. What's your operating range?

Student: 100 to 15000. right?

Tutor: Do you want to try another range? Or does this plot suggest something?

Student: we could reject even lower, since its a closed cycle

Tutor: Good!

4 System Desiderata

Our exploratory data collection illustrates that CyclePad's significant pedagogical potential tends to be underutilized when students do not receive tutorial guidance beyond what CyclePad itself can offer. Our data suggests that the goals of CyclePad are realized more effectively when students have the opportunity to engage in tutorial dialog. In particular, we see a need for a tutorial dialogue agent to engage students in learning activities including (1) thinking through their designs at a functional level, (2) seeking out explanations from CyclePad, (3) reflecting on implications of sensitivity analysis and efficiency measurements for their designs, and (4) weighing trade-offs between alternative choices.

In order to fulfill these objectives, we have designed CycleTalk as a tutorial dialogue agent that monitors a student's interactions with CyclePad in search of opportunities to engage them in the four learning activities just mentioned. This tutor agent will contain a detailed knowledge base of domain-specific pedagogical content knowledge as well as mechanisms that allow it to build up detailed student models. We plan to reuse much of the functionality that has been developed in the context of previous CyclePad help systems such as the RoboTA [10]. As the student is interacting with CyclePad to build thermodynamic cycles and perform sensitivity analyses, the tutor agent will monitor the student's actions, building a detailed student model that keeps track of which portions of the space of design choices the student has already explored, which analyses have already been performed, and what the student is likely to have learned from them. When the tutor agent determines based on its observations or by detecting a request from the student that a dialogue with the student is necessary, it formulates a dialogue goal that takes into consideration the student model and the state of the student's design. The latter information is maintained by CyclePad's truth maintenance system.

5 Conclusions and Current Directions

In this paper we have presented an analysis of a preliminary data collection effort and its implications for the design of the CycleTalk tutorial dialogue agent. We have argued in favor of natural language discussions as a highly interactive form of guided discovery learning. We are currently gearing up for a controlled study in which we will test the hypothesis that exploratory dialogue leads to effective learning. During the study, students will work on a similar design scenario as the ones presented in this paper. On a pre/post test we will evaluate improvement of students' skill in creating designs, in understanding design trade-offs, and in conceptual understanding of thermodynamics, as well as their acquisition of meta-cognitive skills such as self-explanation. In particular we will assess the value of the dynamic nature of dialogue by contrasting a Wizard-of-Oz version of CycleTalk with a control condition in which students are lead in a highly scripted manner to explore the design space, exploring each of the three major efficiency enhancing approaches in turn through step-by-step instructions

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