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# Development and Implementation of Interactive Virtual Laboratories to Help Students Learn Threshold Concepts in Thermodynamics - Year 3

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**Introduction:**
Thermodynamics is a difficult subject for chemical and biological engineering students to master. One reason for the difficulty is the diverse and challenging set of threshold concepts that they must coherently synthesize and be able to apply in a diverse range of contexts. Based on our experience and from reports in the literature, we have identified a set of threshold concepts we propose are critical for mastery of thermodynamics. The goal of this NSF TUES project is to develop a corresponding set of *Interactive Virtual Laboratories* to help students identify and learn these threshold concepts. The intent of this project is not to develop a comprehensive list of all the threshold concepts needed to master thermodynamics. Rather we would like to examine a subset of threshold concepts and illustrate, first, that they can form a design basis for development of *Interactive Virtual Laboratories* where students can actively experience multiple representations, and, second, that experience with these virtual laboratories helps students learn.

The *Interactive Virtual Laboratories* are being developed based on best practices in engineering education pedagogy and sound multimedia development principles. Year 3 progress is reported. Beta versions of six laboratories have been completed and are available to the engineering community through integration into the *AIChE Concept Warehouse*, another NSF supported project.[1] Three of the IVLs have been delivered in a thermodynamics with over 1,000 sets of student responses. We are investigating the ways that to use gathered information to understand learning, supply formative feedback, and provide accountability. To achieve that end, we have audio-recorded 25 students as they have worked individually (10 students) or in groups (15 students) in a think-aloud protocol to understand more completely the various types of thinking that are elicited in this environment.

**Threshold Concepts**
Meyer and Land[2] have recently introduced *threshold concept theory* as a lens through which to view learning, assessment, and curriculum development. In their application, the term “concept” should be viewed broadly to include both the fundamental principles and the procedural capabilities that are core to understanding and progressing in a discipline. Meyer and Land identified four qualities of a threshold concept: troublesome, transformative, irreversible, and integrative. By troublesome, they mean the concept or capability is difficult for students to learn; for example, it may be conceptually complex. By transformative, they mean it changes the way the student views the discipline and knowledge of the subject. By irreversible, they mean once the student “sees” this new view, she/he will not revert to a more naïve perspective that she/he previously had.  Finally, by integrative, they mean it allows the student to see connections between elements that were previously disjointed.

Development of curriculum based on the identification of threshold concepts has recently been enacted in engineering.[3] However, in addressing threshold concepts, we must be mindful that many approaches to instruction do not fundamentally reform students faulty conceptions.[4] We suggest that threshold concept theory is a useful framework for identifying content for the development of *Interactive Virtual Laboratories*, and reflexively, *Interactive Virtual Laboratories* are appropriate for enabling students to learn threshold concepts.

**Design of IVLs**

The *Interactive Virtual Laboratories* are a series of two-dimensional simulations designed to address targeted threshold concepts. We followed design principles for educational multimedia while developing the IVLs. We used Mayer's[5] approach involving cognitive load theory, which asserts that students have a maximum information processing capability. Excess information overloads the student's learning channels and reduces information processing. We also incorporated the findings of Scalise et al.[6] from a synthesis of the results of 79 studies of virtual laboratories to find best practices for virtual laboratory design, including an emphasis on focal points rather than step-by-step instructions, basing design to minimize cognitive load, and introducing scaffolding with fading. Finally, we kept in mind the design principles suggested by Mayer and Moreno[7]:

- *Multiple representation principle:* Explanation in the form of a combination of words and pictures are more effective than words or pictures alone.
- *Contiguity principle:* Simultaneous presentation of words and pictures works better than presentation in succession.
- *Spatial contiguity principle:* Closer proximities of text and image enhance the learning outcome.
- *Personalization effect:* Deeper learning can be achieved by conversational style text rather than formal style text.

Individual labs consist of examining the effect of different processes on the molecules, such as compressing or heating them, while performing numerical computations and answering discussion questions. Each individual simulation targets a single threshold concept and adheres to a scaffolded design following the predict-observe-explain technique proposed by Gunstone and Champagne.[8]

Before interacting with the simulation, students are asked to predict what will happen if they make a change, such as raising the temperature or increasing pressure. Students then perform and observe the virtual experiment and, afterwards, explain if their prediction was accurate and what effects the change had using information present in the simulations. The goal of the simulations is to allow students to describe molecular and macroscopic thermodynamic phenomena in terms of the underlying physical behavior using conceptual knowledge. In real experiments, students cannot see molecular interactions, and their understanding often becomes abstract and removed, existing only in the form of equations. The *Interactive Virtual Laboratories* allow students to see how molecular interaction gives rise to the phenomena described by mathematical equations.

**Development of IVLs**

The activity in Year 3 has been directed towards integration into the Concept Warehouse, pilot delivery, think-aloud research, and development of automated assessment practices. An overview of project activity is shown in Table 1 which also identifies the content each IVL with the concepts they address. Screenshots of sample frames from six IVLs are shown in Appendix A. The IVLs are written in JavaScript and HTML for easy incorporation into student laptops and web browsers. They make use of the HTML5 Canvas element to draw two-dimensional objects for simulating molecular behavior. Each simulation depicts ideal gas molecules as perfectly elastic spheres. Four IVLs have been delivered in class and completed over 1000 times which have garnered nearly 20,000 recorded question responses.

**Table 1.** Summary of the IVLs

| IVL | Concepts | Status | Implementation | Think-Aloud |
|---|---|---|---|---|
| Cv/Cp | Definition of heat capacity; difference between $c_v$ and $c_P$. | Available on Concept Warehouse. | 237 students have completed | 2 Teams (8 students) |
| Work | Pv work as an energy transfer process | Available on Concept Warehouse. | 390 Students have completed | 6 individuals |
| Reversibility | Definition of a reversible process; difference between reversible and irreversible processes | Available on Concept Warehouse. | 388 Students have completed | 4 individuals 2 Teams (7 students) |
| Hypothetical Path – I | Hypothetical Paths, state functions, enthalpy of vaporization. sensible heat, PT phase diagram, | Final Refinement | | |
| Hypothetical Path - II | Hypothetical Paths, state functions, enthalpy of reaction, sensible heat, | Final Refinement | | |
| Reaction Rate and Equilibrium | Difference between rate and equilibrium. | Available on Concept Warehouse. | 151 students have completed | |
| Single Component Phase Equilibrium | Sensible Heat, Latent Heat, PT Phase Diagram, Change in heat of vaporization with temperature, Change in saturation pressure with temperature | In Development | | |
| Two Component Phase Equilibrium | Two Suffix Margules Equation, Azeotropes, Activity coefficients | Final Refinement | | |

We believe the capability of IVLs to generate large amounts of data present opportunity to understand student learning and provide formative feedback and adaptive instruction. Therefore, using a think aloud protocol, we have audio recorded 25 students as they worked through three different IVLs in an attempt to examine student thinking processes and determine rationale that commonly leads students to submit wrong answers (see Table 1). We have analyzed the transcripts of the audio recordings to uncover the student thinking process that led them to the answers they input in IVL. We especially tried to recognize (1) common misconceptions that led students to common wrong numerical answers of procedural questions; (2) productive discussion in conceptual questions regardless of whether answers to procedural questions were accurate; and (3) reasoning that was canonical and also led students to arrive at the correct answers to procedural questions. This analysis provided us a spectrum of student thinking and responses, in continuum, from wrong-answers with wrong-reasoning, to partly-correct reasoning, to correct-answers with correct-reasoning.

## Results and Discussion

Our analysis allowed us to examine student thinking processes as they worked through the IVLs. We discovered errors and/or misconceptions some students have regarding thermodynamic principles. We were easily able to determine how many students might have shared the errors and/or misconception by looking at their numerical answers.

Using the information gained from analysis of the Work IVL think aloud analysis and looking at the bigger scale of student answers of 241 total students, we were able to identify a set of students that made calculation errors similar to one of one of the students studied. Based on the student answers submitted for the Work IVL, 32 of the total 240 students who participated made a unit error in their calculations and 7 of those 240 students read the PV graph incorrectly. Thus, approximately 16% of the students who answered incorrectly did so most likely because of calculation errors as opposed to misconceptions.

We were able to observe and describe misconceptions of a think aloud group in the Heat Capacity IVL. For example, by examining the answers students submitted for the Heat Capacity IVL, we discovered that 24 of the total 237 students answered “6.93” for the change in volume. We speculated with confidence that these other students solved for the change in volume by using the same equation as the 3 students in Group 1. Therefore, from this information we can assume that approximately 10% of the students have these misconceptions involving internal energy.

Working toward the automatic grading system as one of our ultimate products of this project, we wanted to understand the thinking processes that led students to the answers they put in the boxes in the IVL. We have found that sometimes even students’ final answers were not accurate, but there are still productive ideas behind the answers. Therefore, the next challenge is to accommodate theses thought processes into the grading system.

The detailed results of the think-aloud studies are reported in another paper from this conference as well as a previous publication.[9, 10]

## Acknowledgements

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## Appendix A: Sample screenshots of the IVLs

Screenshots of six IVLs listed in Table 1 are shown in this appendix. All these IVLs are available for use on the AIChE Concept Warehouse (cw.edudiv.org).


**Figure A1.** **$c_v/c_P$.** In this part of the $c_v/c_P$ IVL, students compare how much energy it takes to heat a constant pressure and constant volume system by 100 K.

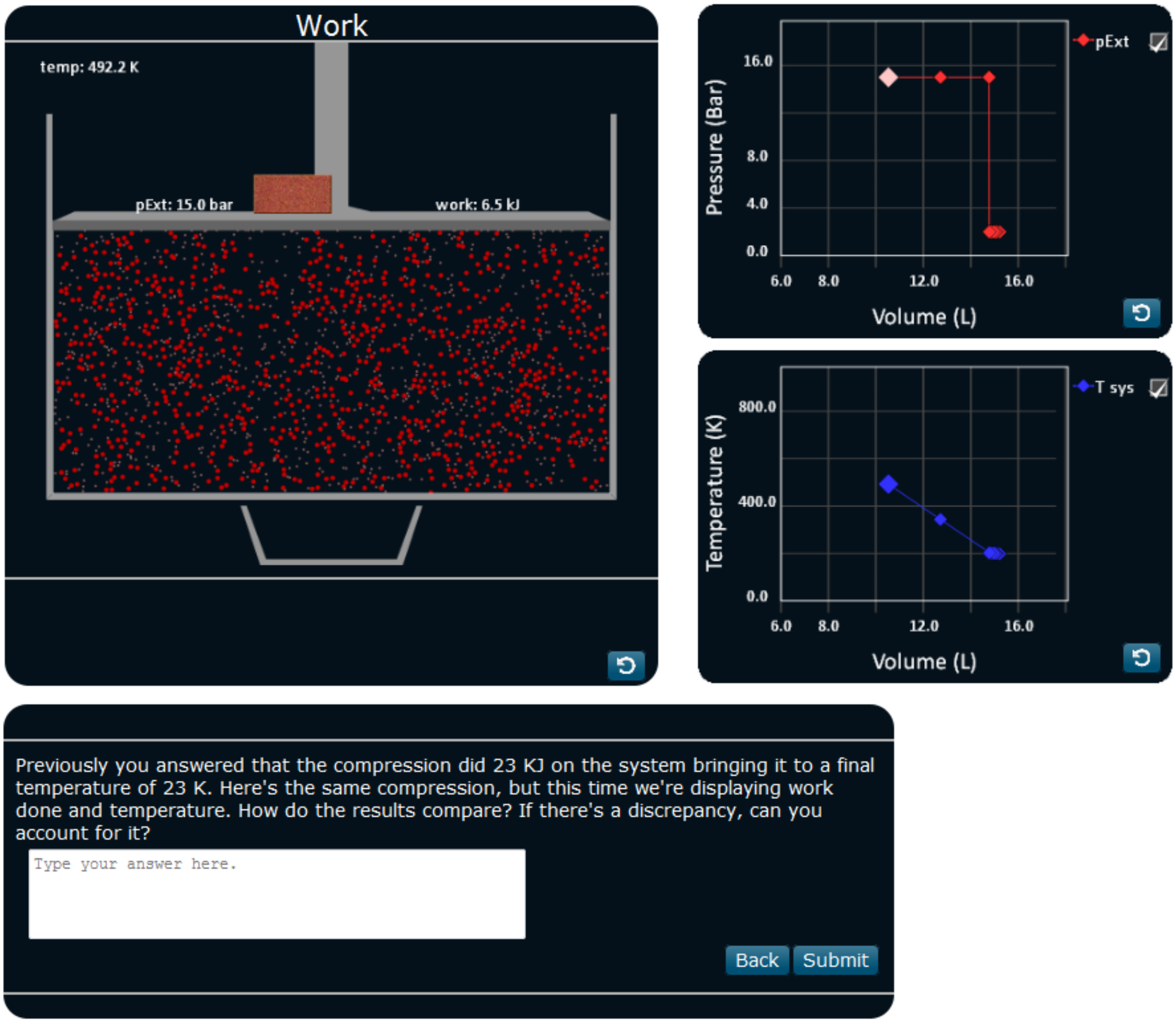


**Figure A2.** **Work.** In this part of the work IVL, students compare calculated and observed values for work.

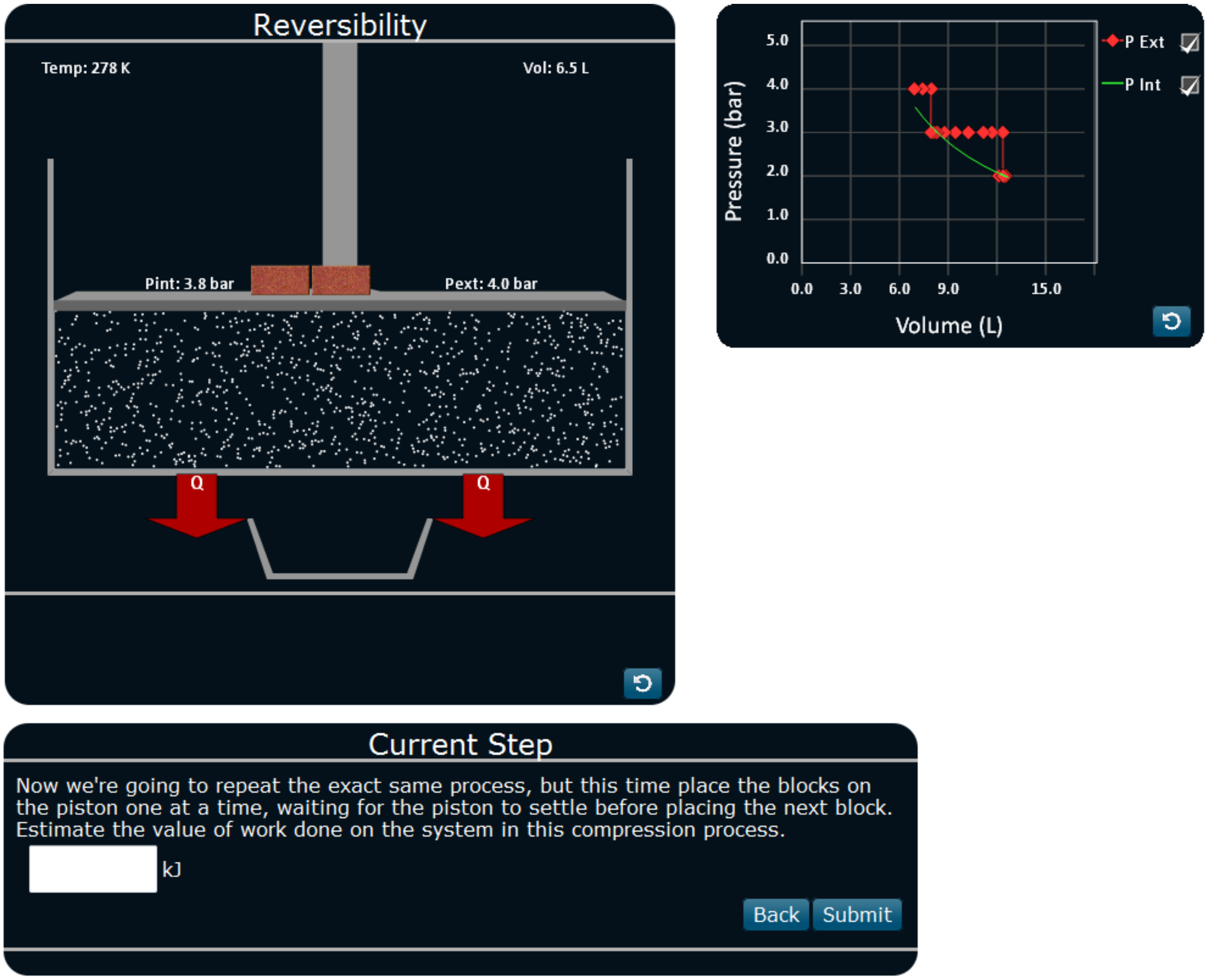


**Figure A3.** **Reversibility.** In this part of the reversibility IVL, students examine the work needed when a compression process is broken into steps.

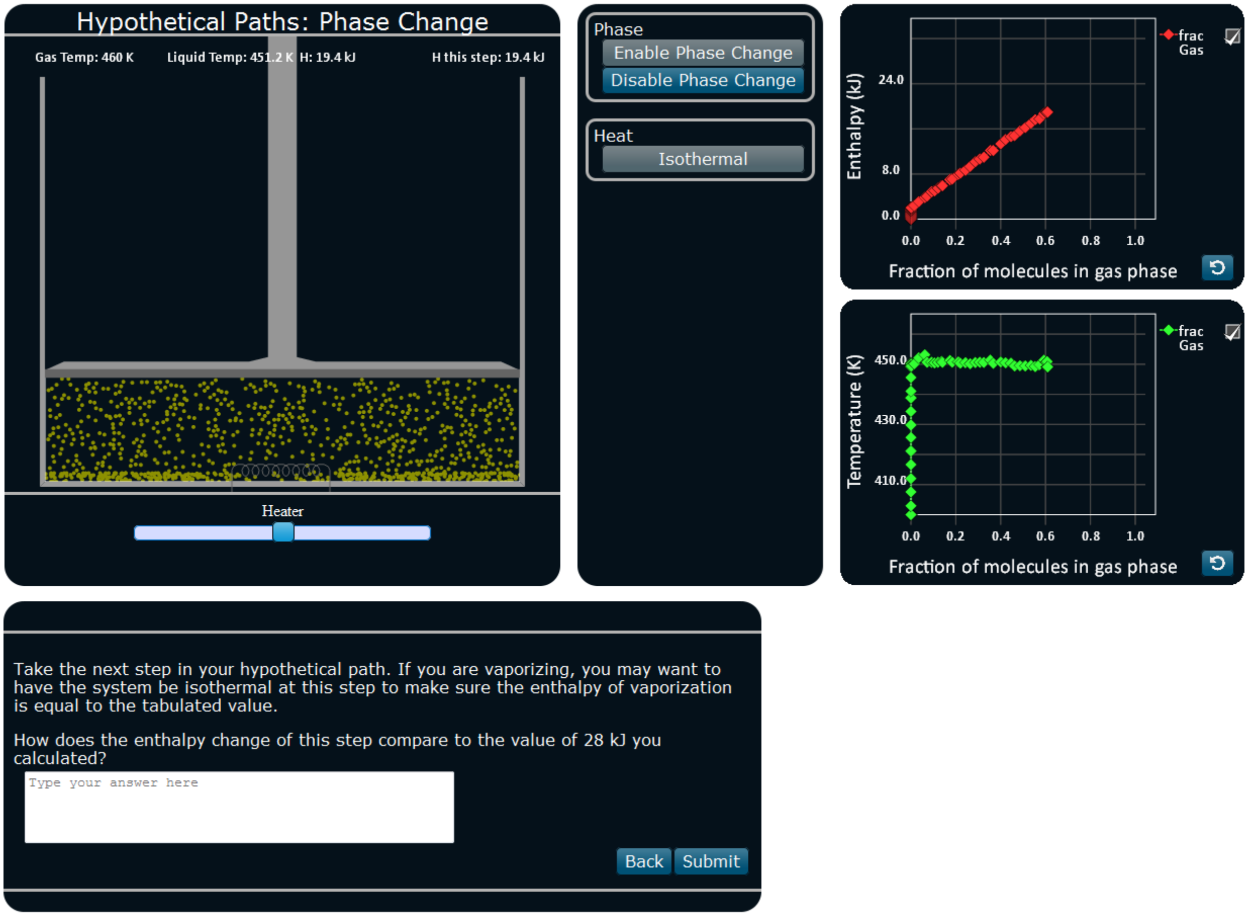


**Figure A4. Hypothetical Path – I.** In this part of the Hypothetical Path – I IVL**,** students test a hypothetical path they created earlier to determine the heat of vaporization of a substance at a temperature where the value is unknown. In this particular step, they vaporize a liquid at a temperature where the heat of vaporization is known.

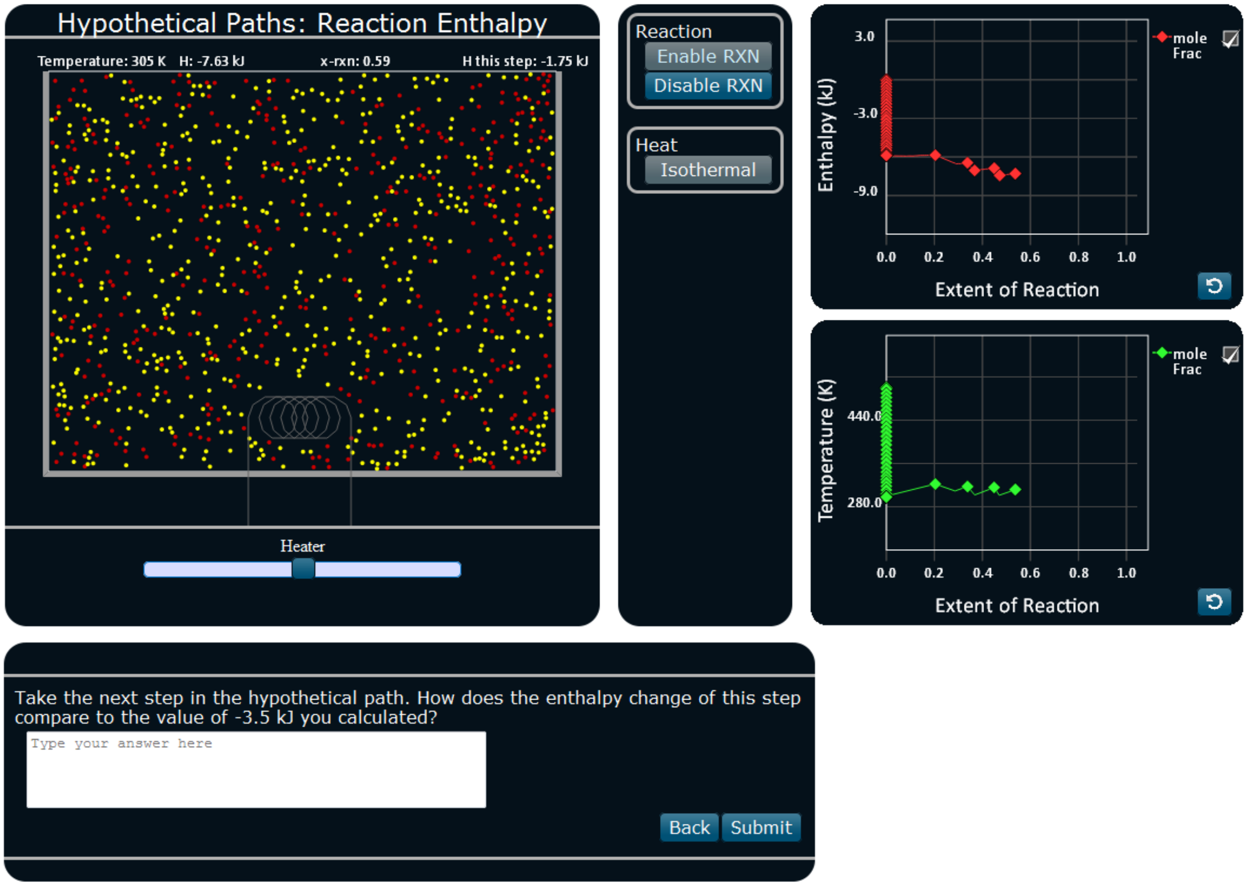


**Figure A5. Hypothetical Path – II.** In this part of the Hypothetical Path – II IVL**,** students test a hypothetical path they created earlier to find the heat of reaction at a temperature where it is unknown. In this step, students enable an isothermal reaction at a temperature where the heat of reaction is known. The parallel between this IVL and Hypothetical Path-I is deliberate.

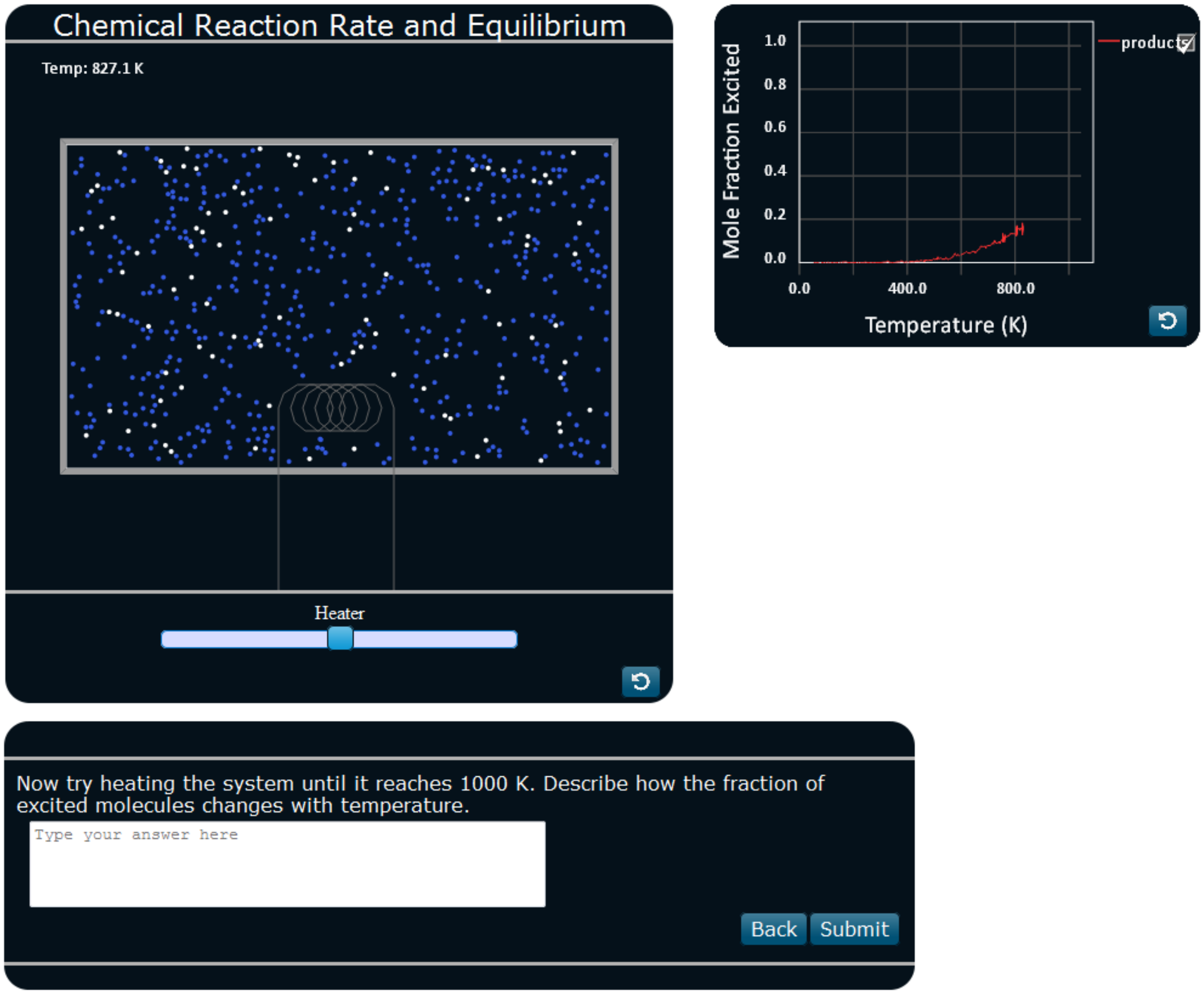


**Figure A6. Reaction Rate vs. Equilibrium.** In this part of the Reaction Rate vs. Equilibrium IVL**,** students heat a system to see how the fraction of "excited" molecules that have enough energy to promote reaction changes with temperature. The white dots represent excited molecules.

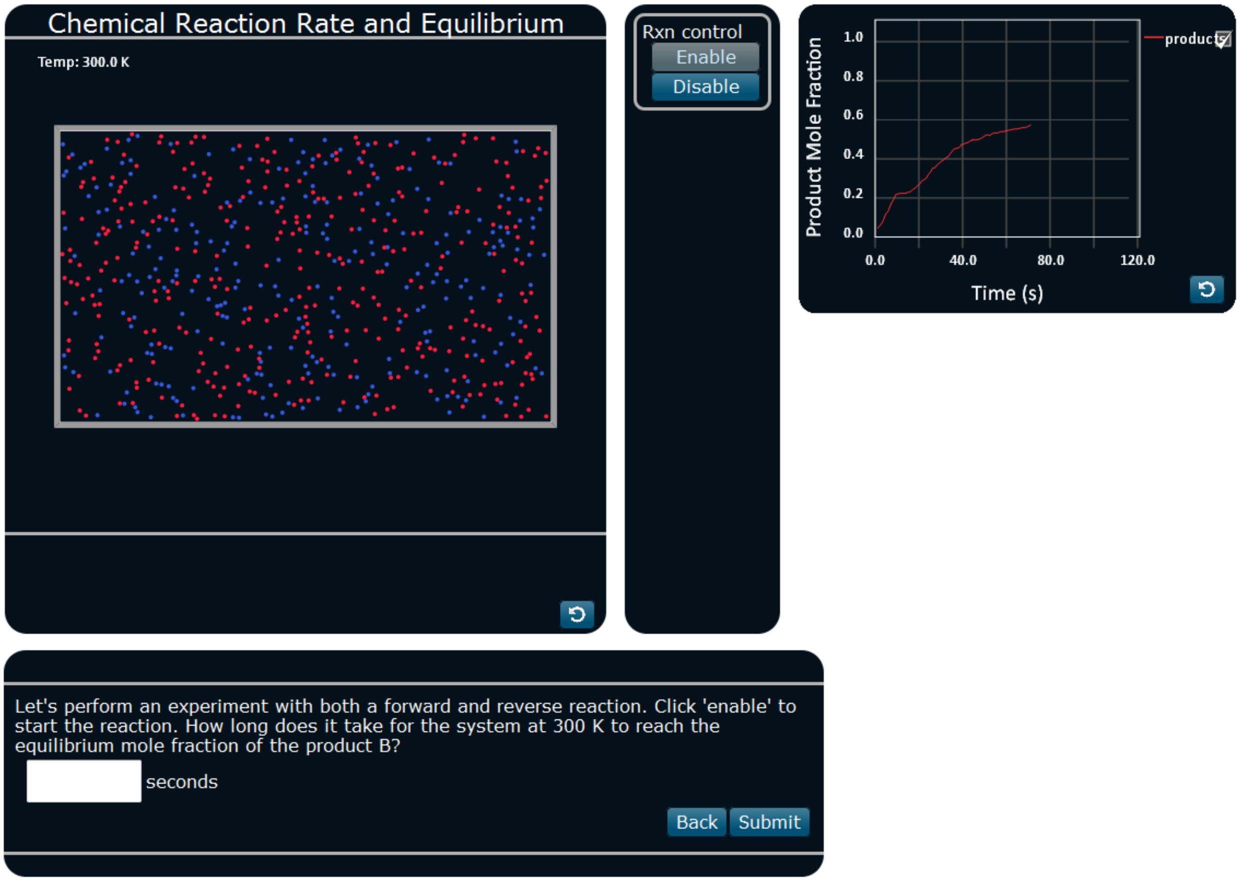


**Figure A7. Reaction Rate vs. Equilibrium.** In this part of the Reaction Rate vs. Equilibrium IVL**,** students explore the difference between reaction rate and equilibrium by performing the same reaction at three different temperatures. The reaction is exothermic, so as temperature increases, the equilibrium shifts to the reactants but the rate increases. This reaction takes place at 300 K.