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Development and Implementation of Interactive Virtual Laboratories to Help Students Learn Threshold Concepts in Thermodynamics – Year 1

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Overview and Objectives:

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 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 following specific project objectives have been constructed to achieve this goal:

1. Validate a set of at least six proposed threshold concepts in thermodynamics.
2. Develop *Interactive Virtual Laboratories* to provide students multiple representations and help them experientially explore these threshold concepts. Develop the virtual laboratories based on engineering education best practices and multimedia development principles to provide students structured engagement, such as incorporating the “predict, observe, explain” technique.
3. Deliver the *Interactive Virtual Laboratories* in classes using the studio architecture recently implemented at the home institution.
4. Assess the perception and effectiveness of the *Interactive Virtual Laboratories* through
    a. Classroom observation, student surveys, and instructor and student focus groups
    b. Measurement of learning gains on the *Throttling Valve question* and the *Technician question*, two conceptual questions that have been historically difficult for students
5. Incorporate the *Interactive Virtual Laboratories* as resources in the *AIChE Concept Warehouse* so that they are broadly available for engineering and science instructors to use.

The *Interactive Virtual Laboratories* are being developed based on best practices in engineering education pedagogy and sound multimedia development principles. Year 1 progress is reported including the following. Beta versions of three laboratories have been completed and are available to the engineering community through integration into the *AIChE Concept Warehouse*, another NSF supported project.[1] Two laboratories have been investigated in a clinical study and two have been piloted in a thermodynamics studio class of approximately 150 students.

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. It is transformative in that it changes the way the student views the discipline and knowledge of the subject. It is irreversible in that once the student "sees" this new view, she/he will not revert to a more naïve perspective that she/he previously had. Finally, it is integrative in that 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 primary activity in Year 1 has been software development. The status of eight IVLs is shown in Table 1, together with the concepts they address. Screenshots of the first six 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.

Table 1. Summary of the IVLs developed in Year 1

IVL	Concepts	Status	Clinical	Implementation
Cv/Cp	Definition of heat capacity; difference between c_v and c_P.	Available on Concept Warehouse.		Fall 2013; 155 students for 50 min studio
Work	Pv work as an energy transfer process	Available on Concept Warehouse.	4 students interviews, reflections	Fall 2013; 155 students for 50 min studio
Reversibility	Definition of a reversible process; difference between reversible and irreversible processes	Available on Concept Warehouse.	4 students interviews, reflections	
Hypothetical Path – I	Hypothetical Paths, state functions, enthalpy of vaporizationsensible heat, PT phase diagram,	Preliminary version available on Concept Warehouse.		
Hypothetical Path - II	Hypothetical Paths, state functions, enthalpy of reaction, sensible heat,	Preliminary version available on Concept Warehouse.		
Reaction Rate and Equilibrium	Difference between rate and equilibrium.	Preliminary version available on Concept Warehouse.		
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	In Testing		

Implementation and Data Collection

Clinical Studies

The first set of studies was performed using preliminary versions of the *Work* and *Reversibility* IVLs. We investigated how students experienced the laboratories and whether the students perceived the simulations are beneficial towards learning. Eight participants took part in the clinical study outside of the engineering classroom. All students had previously taken a thermodynamics course and had access to a thermodynamics textbook and the internet as they completed the laboratory. A "think aloud" protocol was used where students were audio recorded as they verbally described their actions in completing the laboratory. The transcribed audio recordings together with video recordings of the computer screen on which they worked were analyzed. After completing the laboratory, a semi-structured interview asked participants about their perceptions of the simulation's effectiveness, their previous thermodynamics experience, and a brief assessment of what they learned. All interviews were transcribed for analysis.

The participants generally responded positively to the simulations. Seven out of eight students explicitly stated that the dynamic simulations helped them visualize and engage with the processes more than they could with the static depictions in books or lecture. However, some difficulties were observed, including interacting with the interface and understanding specifically what a question was asking. One participant found the interactivity to be unintuitive. We also noticed a relation between how the participants framed knowledge and their approach to completing the laboratory. Students who activated more sophisticated frames typically completed the simulation more quickly and accurately than those with more naive frames. Students who did not do as well tended to focus on trying to identify equations they had used in the past, even going so far as to use them in an unsuitable context. On the other hand, students who completed the simulations accurately and more quickly appeared to integrate what they were seeing on the screen with their foundational conceptual knowledge to form new understanding. The results are described in more detail in another paper at this conference.

Classroom Implementation

The c_V/c_P and Work IVLs were used for in a junior level thermodynamics class of 155 students in Fall 2013. Data collected include numerical answers, discussion answers, and time stamps. We also have time stamps when a student refreshed a page or performed certain events like hitting the single molecule with the sliding wall. A researcher observed and took notes. These data have not yet been analyzed.

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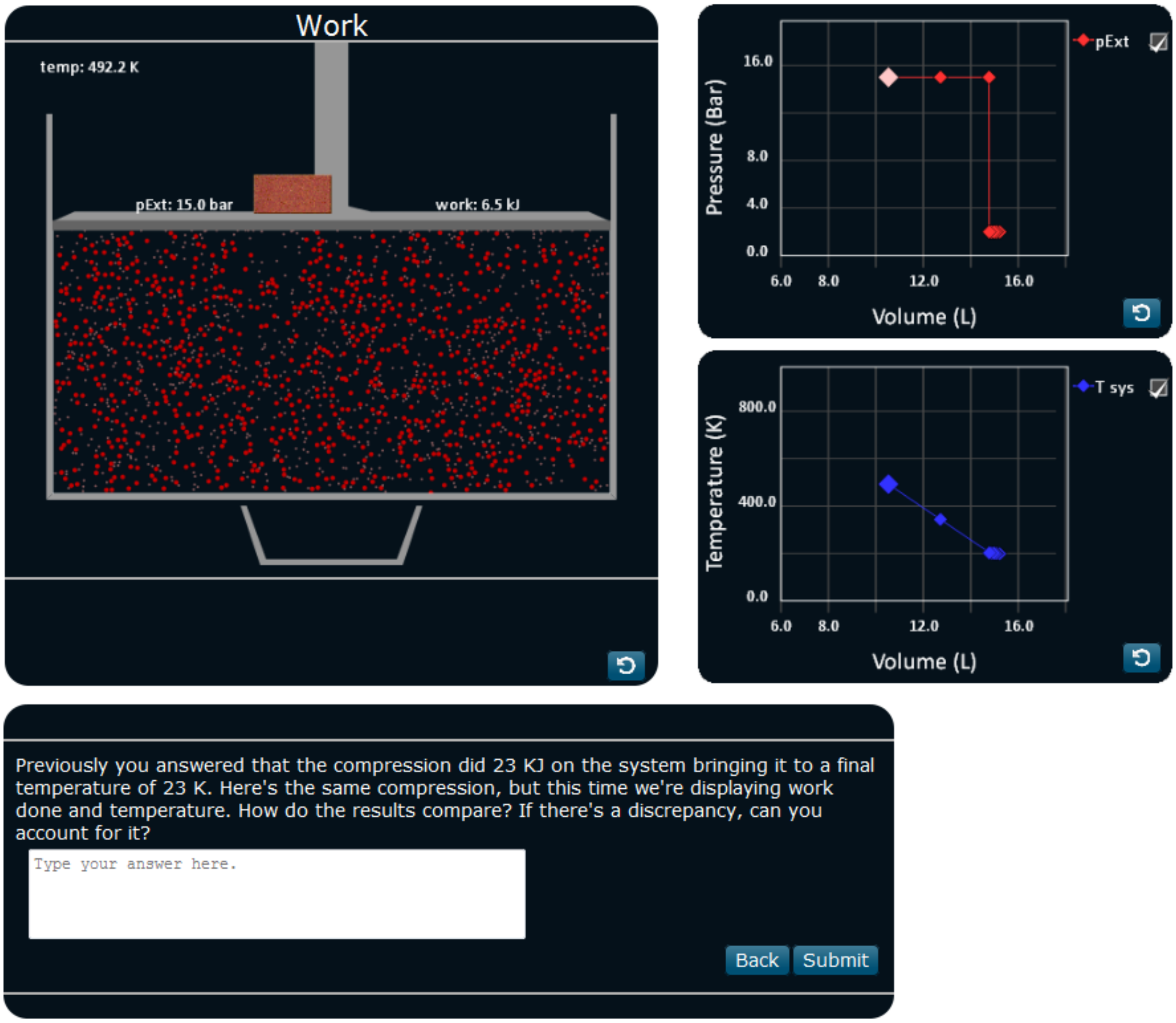
Appendix A: Sample screenshots of the IVLs

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).

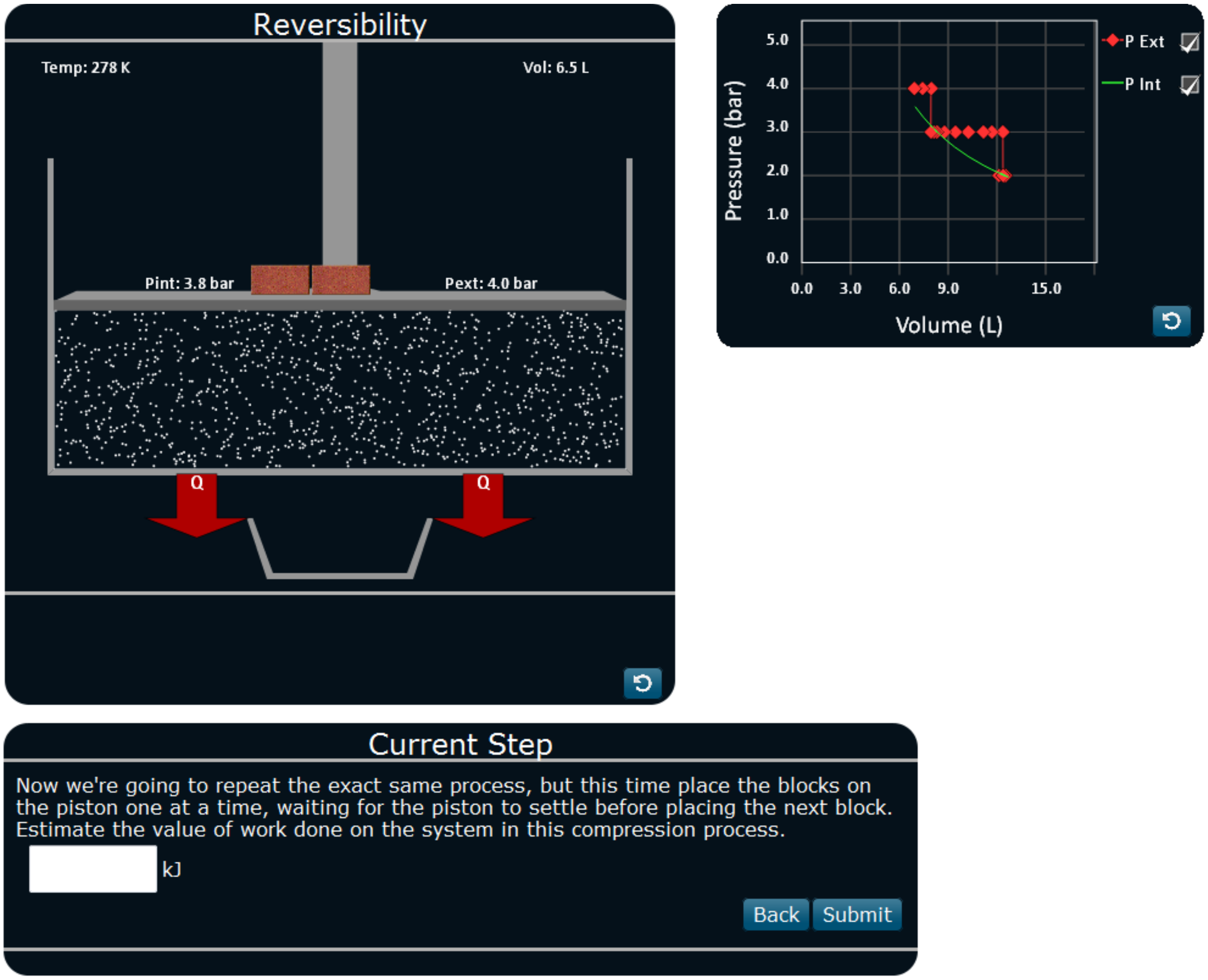
Here is the constant pressure version of the system filled with one mole of the ideal monatomic gas. Heat the system by 100 K. How does the value compare to the constant volume heating value of 0.62 kJ?

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.



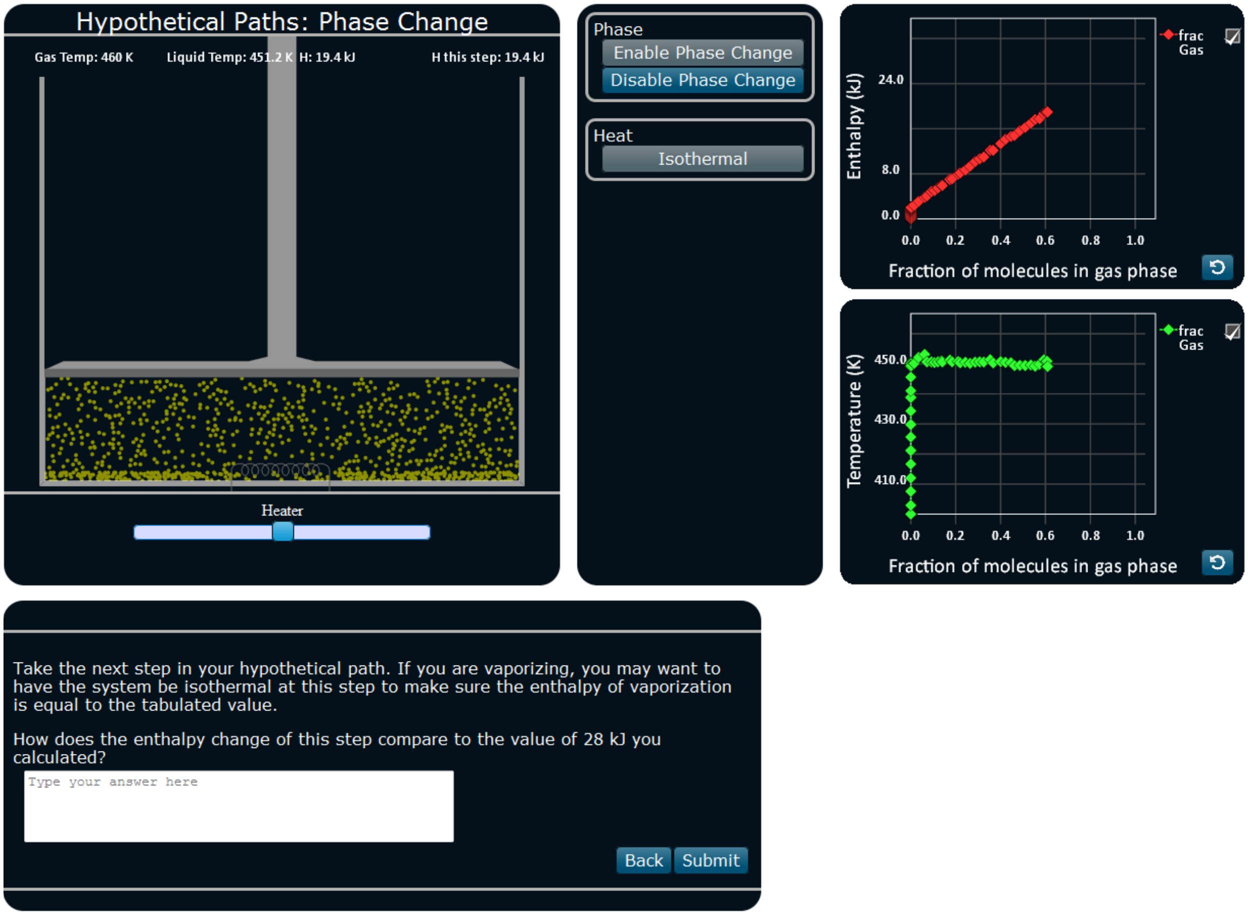
Previously you answered that the compression did 23 KJ on the system bringing it to a final temperature of 23 K. Here's the same compression, but this time we're displaying work done and temperature. How do the results compare? If there's a discrepancy, can you account for it?

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



Now we're going to repeat the exact same process, but this time place the blocks on the piston one at a time, waiting for the piston to settle before placing the next block. Estimate the value of work done on the system in this compression process.

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



Gas Temp: 460 K

Liquid Temp: 451.2 K

H: 19.4 kJ

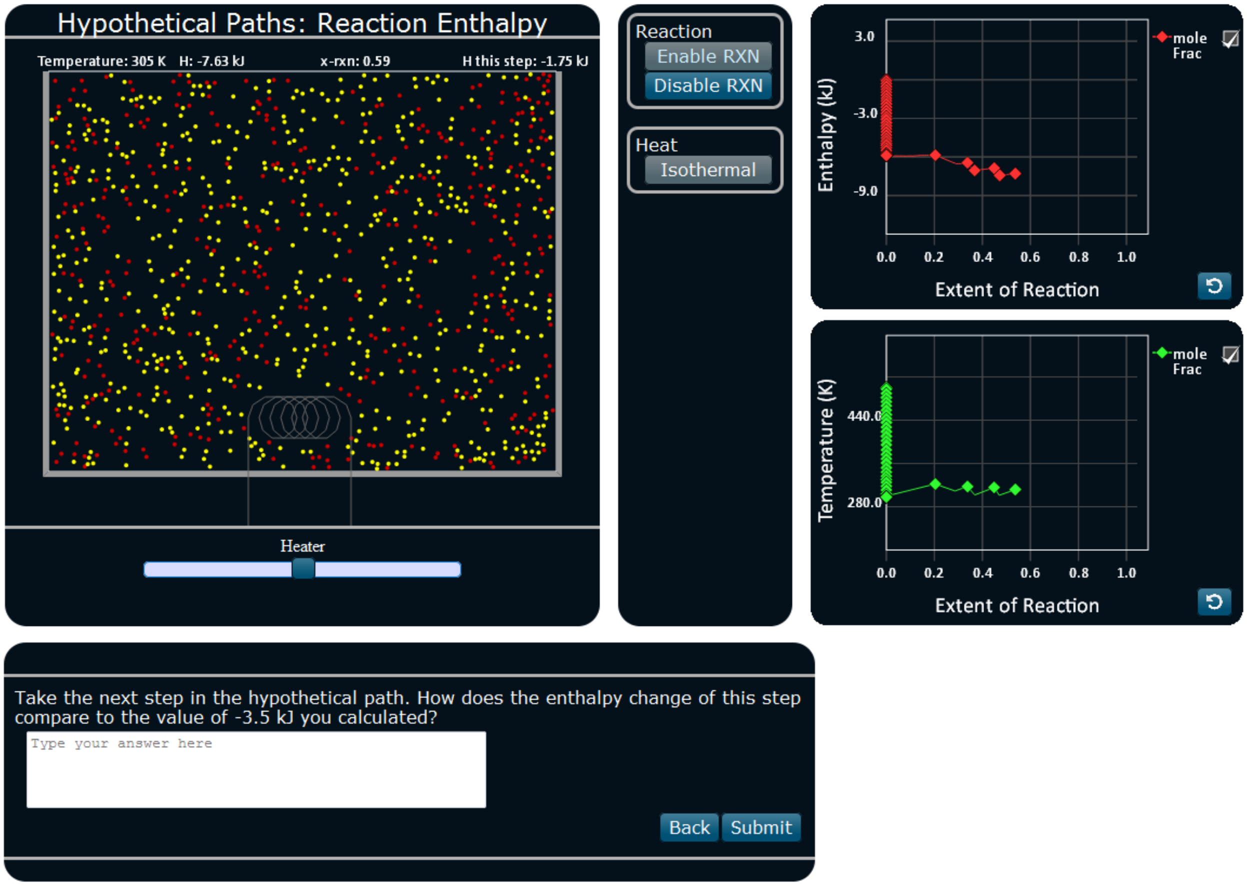
H this step: 19.4 kJ

Take the next step in your hypothetical path. If you are vaporizing, you may want to have the system be isothermal at this step to make sure the enthalpy of vaporization is equal to the tabulated value.

How does the enthalpy change of this step compare to the value of 28 kJ you calculated?

Type your answer here

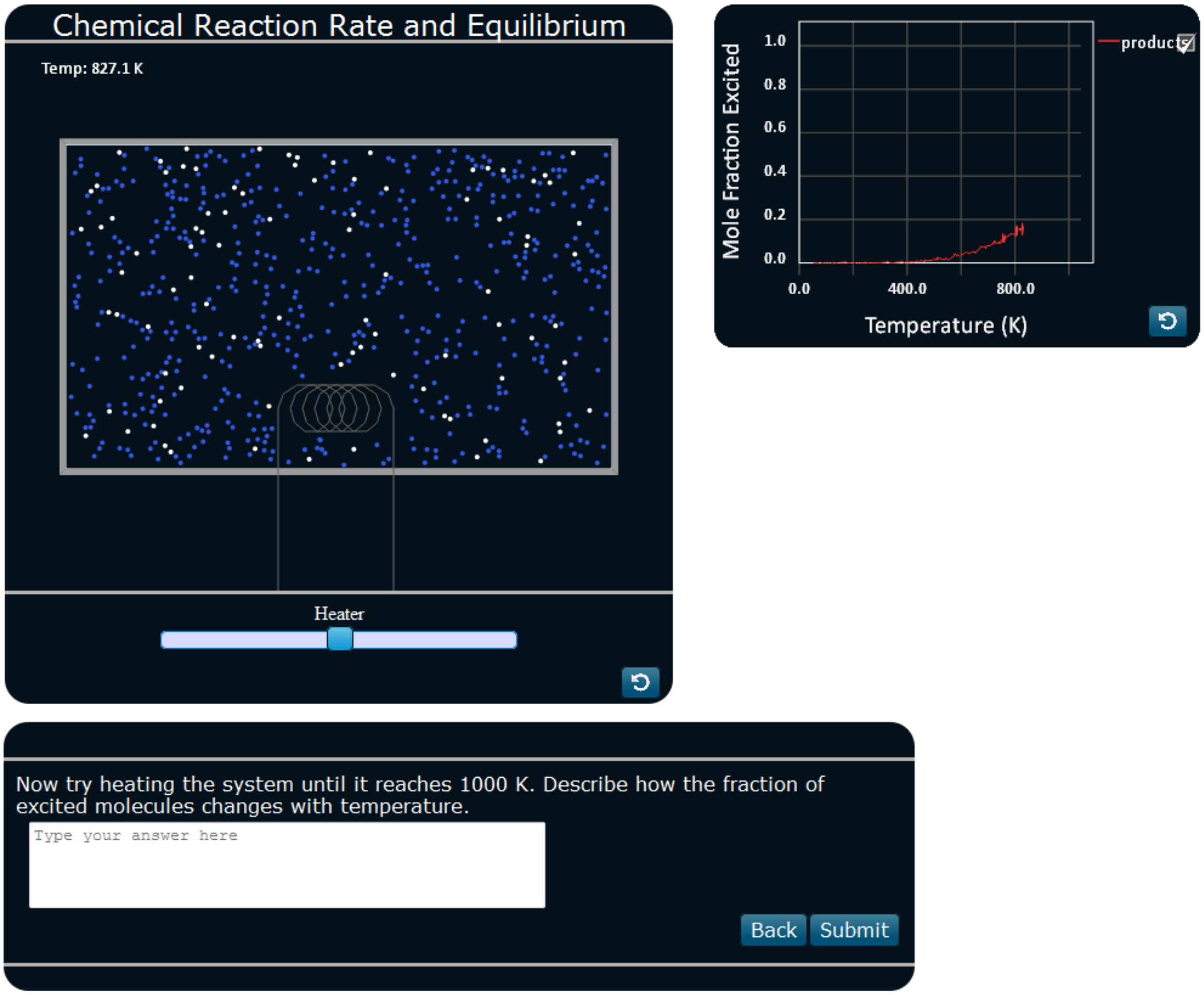
Figure A4. **Hypothetical Path – I.** In this part of the Hypothetical Path – I IVL**,** students test a hypothetical path they created earlier to determine the heat of vaporization of a substance at a temperature where the value is unknown. In this particular step, they vaporize a liquid at a temperature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



Take the next step in the hypothetical path. How does the enthalpy change of this step compare to the value of -3.5 kJ you calculated?

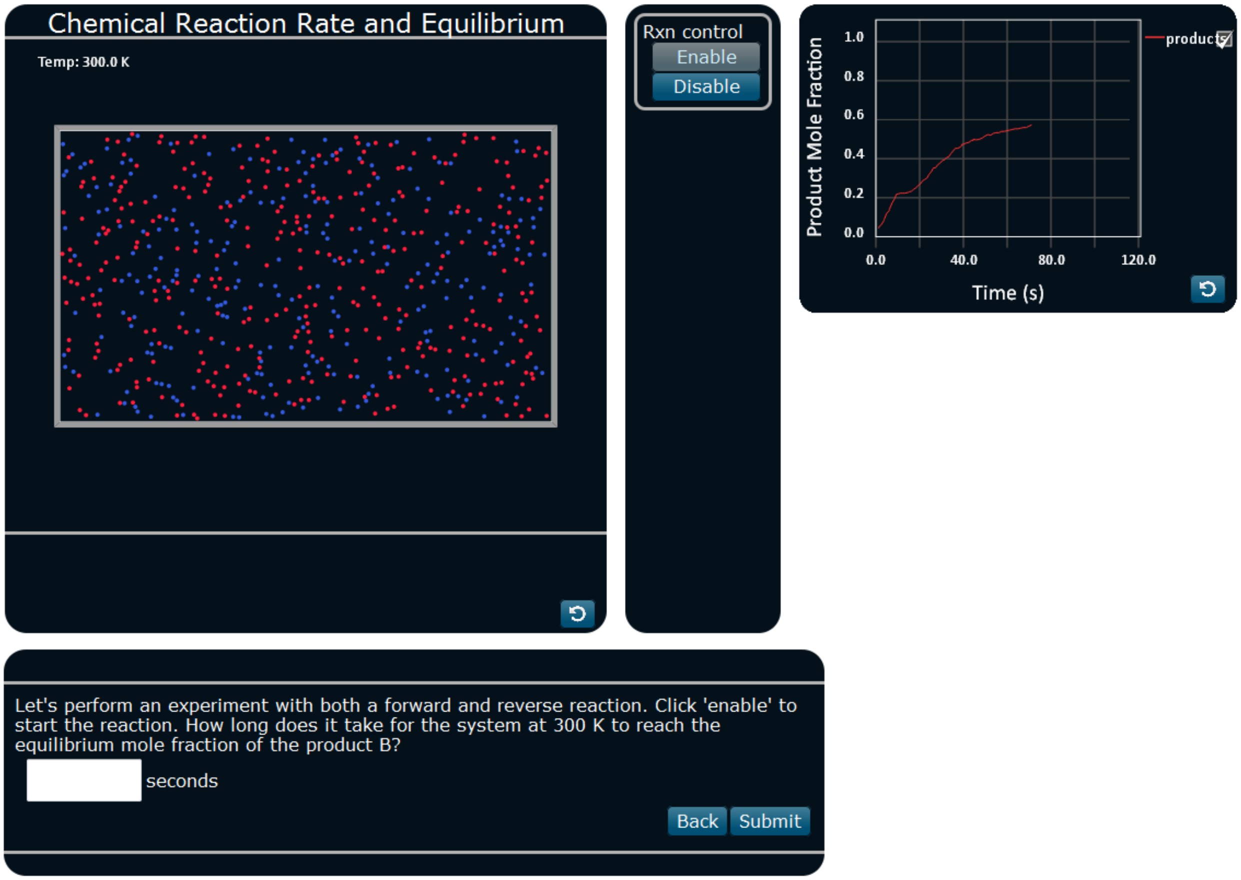
Type your answer here

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.



Now try heating the system until it reaches 1000 K. Describe how the fraction of excited molecules changes with temperature.

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.



Let's perform an experiment with both a forward and reverse reaction. Click 'enable' to start the reaction. How long does it take for the system at 300 K to reach the equilibrium mole fraction of the product B?

seconds

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.