AC 2012-4671: MAKING THEIR BRAINS HURT: QUICK AND EFFECTIVE ACTIVITIES FOR THERMODYNAMICS

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Making their Brains Hurt: Quick and Effective Activities for Thermodynamics

Abstract

Nearly half of the students starting engineering thermodynamics believe that the thermal efficiency of a typical engine is nearly 100%. This belief is challenging to displace, even for students who demonstrate faculty with mathematical descriptions of efficiency. While traditional lecture is not highly effective at reversing students' misconceptions, several supporting approaches such as clicker-questions and inquiry-based activities have been demonstrated to be effective in changing students' minds.

In this work, we developed two inquiry-based activities to address each of five areas identified as important yet challenging for students: Entropy, Reversibility, Confusion between Enthalpy and Internal energy, Confusion between Equilibrium and Steady State, and Confusion over factors impacting Chemical Equilibrium and Reaction Rate. The activities each start by setting up a situation where students' most common misconceptions lead them astray, and ask them to make a prediction. This is followed by a hands-on experiment (when possible) or an interactive simulation (when not) in which students directly interact with the situation that provoked their prediction. These situations are designed so that the predictions based upon the most common misconceptions fail to explain what is observed. Students are allowed and encouraged to "mess with" the experiment to verify that the surprising result isn't a trick. Finally a series of follow-up and reflection questions encourages students to incorporate the new information into their existing understanding. Each activity is designed to take about 15 minutes and use materials found commonly in chemical engineering laboratories or available at Wal-Mart.

These activities have been shown to improve students' concept inventory scores another 10 percentage points over lecture alone. In the following paper, we will present a summary of each activity and its implementation, as well as further evidence for the effectiveness of the approach.

Introduction

Meaningful learning requires that students master concepts, not simply memorize facts. Understanding concepts and the connections among concepts is one of the primary distinctions between experts and novices [1, 2]. Conceptual understanding is also a prerequisite for transfer of classroom learning to new settings [1, 2]. While the importance of conceptual learning is widely recognized, an extensive body of research shows that traditional instruction often does little to promote conceptual change [3, 4].

A number of research-based instructional approaches have been developed that significantly improve students' conceptual understanding relative to traditional instruction. These approaches, including the use of concept inventories, in-class concept questions and inquiry-based activities, were originally developed for science education [3-10]. More recently, engineering education has built on this success by developing and testing similar approaches in some of the core engineering sciences [11-21]. In our work [22-24] we have developed validated concept inventories and inquiry-based activities that were effective at promoting and assessing conceptual learning in heat transfer and thermodynamics.

The model for inquiry that we applied was that of Laws et al [9], originally developed and applied to physics education as Workshop Physics. A typical inquiry-based activity is a short experiment with a surprising result that directly engaged a students' misconception. For example, measuring the temperature of both a tile and carpet surface and demonstrating that they are identical despite the students' assertion that the tile is 'colder'. Our activities are based on the elements of inquiry detailed by Laws et al [9] – collaboration, emphasis on the conceptual, use of experiment whenever possible, beginning with predictions, work inductively. We have also appended the need to reflect, in writing, on any differences between what was predicted and what was observed. We found that without written reflection students too easily dismiss the results as 'Oh, sure, I thought that would happen.' Each inquiry-based activity developed in this work consists of a written prediction (I), an action (II, either experiment or simulation), and written post-processing (III). While the core of each activity is the action, in order to direct students' attention to the 'ah ha!' part of the experiment/simulation there are typically a number of prompts and written observations to be made over the course of the activity itself as well.

A key aspect of our interpretation of 'inquiry' is that students must have some agency over the action (step II). Students can 'play' with any of the experiments and simulations and convince themselves that a) they've tried everything they want to try and b) there are no hidden tricks.

In order to engage students' well-known misconceptions, most of the activities contain a real or simulated version of a situation from one of the concept inventory questions. In this way, the activity engages the students' interest by having a surprising result. Because there are at least five questions in each concept area, we can also examine how well students transfer their understanding to new situations they have not directly observed.

These activities' effectiveness has been assessed with the concept inventory for engineering thermodynamics (CIET) that targets the same five concepts as the activities themselves. The CEIT, described more fully in [21, 25, 26], is a combination of questions from the TTCI and original questions with a single question from the TCI, used with permission. The CIET has been tested for reliability, and has a post-test overall KR20 of 0.81. KR20 is a estimate of the reliability of an instrument, and its values range from 0 to 1.0. A research instrument should typically have a KR20 of 0.7 to be useful.

Activities Summary

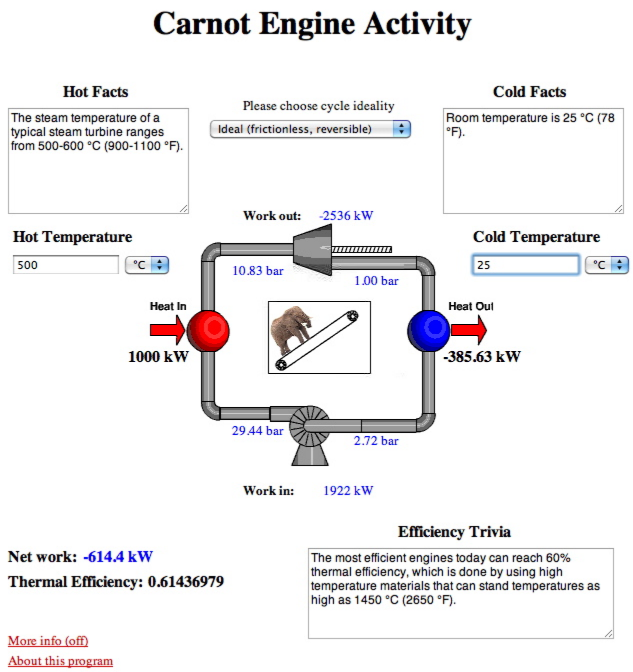
Below are descriptions of each of the ten activities. For full activity packets (including student handouts and setup instructions), please contact the corresponding author.

Entropy

Students' most significant reoccurring misconception in this area is that many believe that most systems, including heat engines, can reach a thermal efficiency of 100% if friction is removed and insulation is good.

Activity #1: Carnot

This activity begins by asking students' to predict the thermal efficiency of a Carnot cycle that suffers no losses from friction or poor thermal insulation. They then work with a simulation of a power cycle operating on a Carnot cycle, inputting a consistent amount of heat. Students work with the simulation to determine which conditions result in the greatest work output. In early iterations of this simulation, we discovered that most students had no conception of a 'reasonable' temperature for a boiler, so the simulation provides temperature-based 'trivia' to help calibrate students' expectations. While it is possible to nearly approach a 100% efficient cycle, it requires a heat source or sink at unreasonable temperatures. Questions guide students to the discovery that at reasonable operating conditions, even the most efficient engine loses 40% of its energy as waste heat.



Carnot Engine Activity

Hot Facts

The steam temperature of a typical steam turbine ranges from 500-600 °C (900-1100 °F).

Please choose cycle ideality: Ideal (frictionless, reversible)

Cold Facts

Room temperature is 25 °C (78 °F).

Hot Temperature: 500 °C

Cold Temperature: 25 °C

Work out: -2536 kW

Heat In: 1000 kW

Heat Out: -385.63 kW

Work in: 1922 kW

Net work: -614.4 kW

Thermal Efficiency: 0.61436979

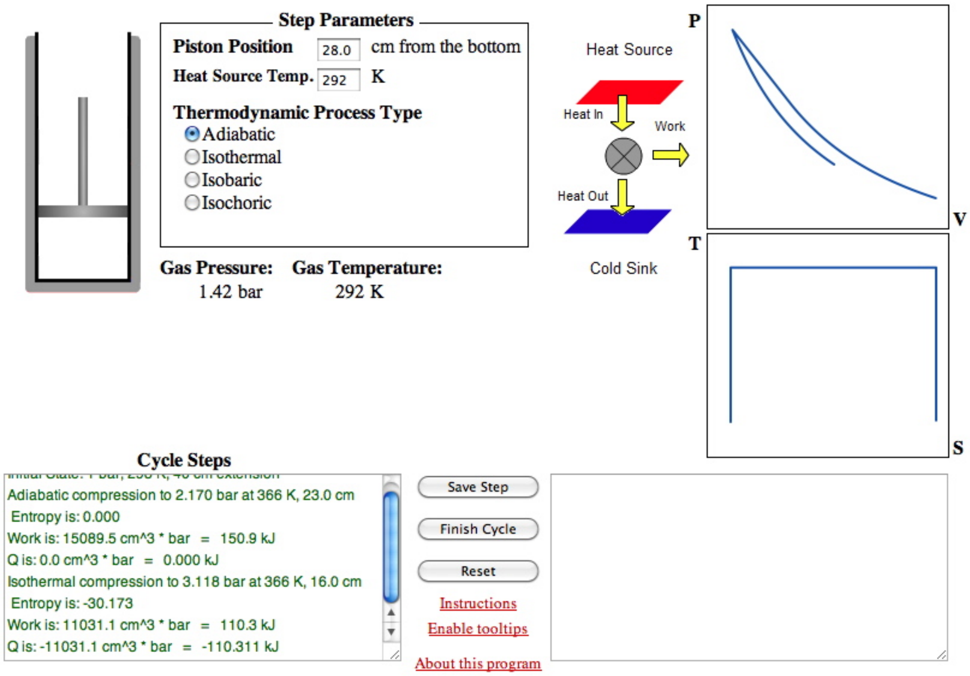
Efficiency Trivia

The most efficient engines today can reach 60% thermal efficiency, which is done by using high temperature materials that can stand temperatures as high as 1450 °C (2650 °F).

Figure 1: Screenshot of Carnot simulation

Activity #2: Piston

While constructing the concept inventory, we collected many open-ended responses to questions about entropy and efficiency. A suggestion that occurred many times was that engine cycles should omit the step rejecting waste heat, and thereby approach 100% efficiency. This activity asks students to predict if they can do so, and then invites them to try. The core action is a simulation where the students can use a piston-cylinder system to construct an arbitrary cycle. Students may choose that steps are isochoric, isothermal, adiabatic, or isobaric. As seen in Figure X, PV and TS plots track the cycles' progress as students discover that they cannot close the shape without rejecting some energy as heat.



Step Parameters

Piston Position 28.0 cm from the bottom

Heat Source Temp. 292 K

Thermodynamic Process Type

- ● Adiabatic
- ○ Isothermal
- ○ Isobaric
- ○ Isochoric

Gas Pressure: 1.42 bar

Gas Temperature: 292 K

Cycle Steps

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Adiabatic compression to 2.170 bar at 366 K, 23.0 cm
 Entropy is: 0.000
Work is: 15089.5 cm^3 * bar  =  150.9 kJ
Q is: 0.0 cm^3 * bar  =  0.000 kJ
Isothermal compression to 3.118 bar at 366 K, 16.0 cm
 Entropy is: -30.173
Work is: 11031.1 cm^3 * bar  =  110.3 kJ
Q is: -11031.1 cm^3 * bar  =  -110.311 kJ
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Figure 2: Screen shot of piston-cylinder simulation

Reversibility

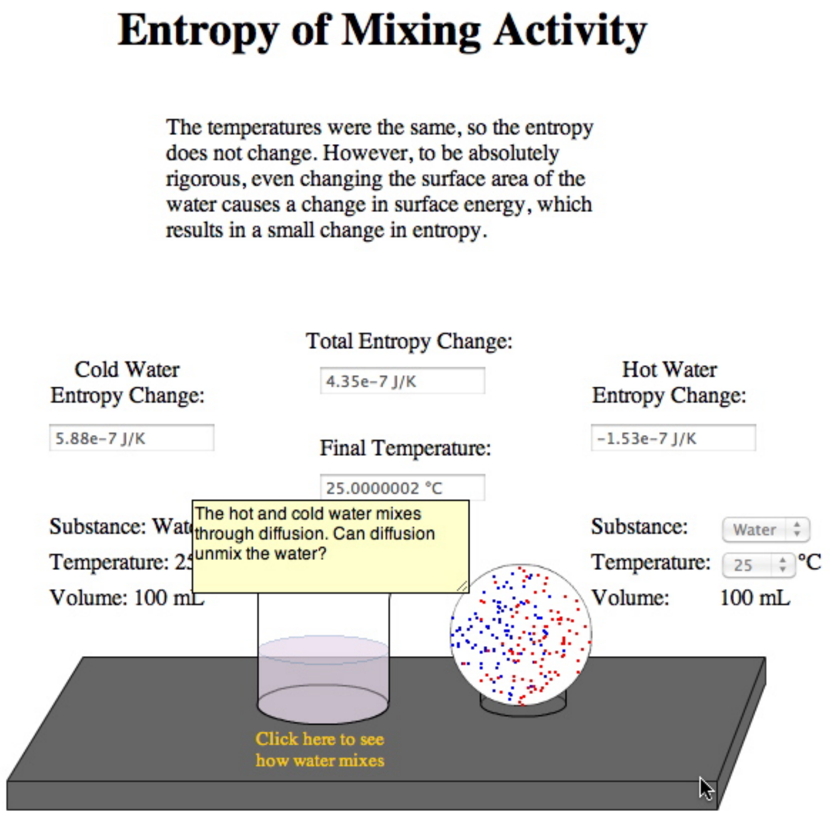
Students' misconception about reversibility is that it is something that they can readily invoke in any situation. Students with this misconception might propose that making an automobile engine reversible is a good idea for improving miles per gallon. The activities in this case are both simulations and are meant to clearly demonstrate that most realistic situations are irreversible.

Activity #1: Mixing Simulation

This rather simple activity has at its core a 2-D molecular dynamics simulation, showing the mixing of two hard-sphere fluids. Guided by the questions, students predict whether or not the entropy of a warm and cold water mixture is higher, lower, or the same as the waters' entropy just prior to mixing. Many students assert that entropy is conserved in this situation, but after playing with the simulation can see that the mixing is not reversible, resulting in a higher net entropy.

Activity #2: Pump Simulation

This activity brings reversiblility into the realm of machines and cycles. This simulation is currently available as a Excel spreadsheet, but is being re-interpreted in a more visual manner in Javascript, to be available by the time of the conference. In the activity, students will virtually pump water from a ground-level tank to an elevated storage tank, choosing the rate at which a variable-speed pump works. Students predict how much work they might extract from a pump that is allowed to free-wheel backwards when the water is propelled through it by gravity. In the activity, they find that they can get nearly what they put into pumping the water up into a tower if they do so very slowly and neglect frictional losses in the pipes. However, if they want the water to move up into the tower at an appreciable rate, they deviate from nearly reversible operation.



Entropy of Mixing Activity

The temperatures were the same, so the entropy does not change. However, to be absolutely rigorous, even changing the surface area of the water causes a change in surface energy, which results in a small change in entropy.

Total Entropy Change: 4.35e-7 J/K

Cold Water Entropy Change: 5.88e-7 J/K

Hot Water Entropy Change: -1.53e-7 J/K

Final Temperature: 25.0000002 °C

Substance: Wat

Temperature: 2

Volume: 100 mL

The hot and cold water mixes through diffusion. Can diffusion unmix the water?

Substance: Water

Temperature: 25 °C

Volume: 100 mL

Figure 3: Screen shot of the mixing simulation.

The distinction between Enthalpy and Internal Energy

This is a subtle distinction that might be restated as "many students confound flow-work with kinetic energy". This is the most challenging misconception of the five because neither internal energy nor enthalpy is amenable to direct observation. Both activities in this area therefore require calculation, in addition to observation, to connect observed temperature changes to the goal concept.

<u>Activity #1: Hair dryer</u>

Using air as a readily available ideal gas, students are asked to predict what the temperature of air exiting from a hair dryer will be if the heating element is turned off. Students then measure the temperature difference and find that the exit stream is warmer. Doing calculations based on air flow and energy input, it is possible to determine some of the change is due to the motor being warm, but also that some of it is due to the flow-work done on the system. This experiment helps get students thinking about flow work and temperature, which play key roles in activity #2.

Activity #2: Filling tank

Students are asked to imagine an evacuated insulated tank that is allowed to fill with air until the inside and outside pressures are equal, and to predict the temperature of the interior air. Many students say it is the same as the exterior air (it's at the same pressure) and some say that it's lower because of the Joule-Thompson effect. Students then enact the actual experiment using a vacuum desiccator with a clear top, into which a digital thermocouple has been placed. They can then directly observe the significant temperature increase that accompanies the introduction of air to the system. This experiment takes only one minute, so most students choose to replicate it several times to be sure the temperature rise isn't a fluke.

The distinction between Steady State and Equilibrium

Many students equate both equilibrium and steady state systems, considering them to be interchangeable terms describing something that does not vary with time. However, a system at steady-state is not necessarily at equilibrium ; a thermal example would be that a steam-pipe could be consistently at a temperature higher than its immediate surroundings.

Activity #1: Hot pot

When presented with a metal pan with a metal handle, many students conflate the equilibrium system temperature (ex. everything is 100ºC if the pot is full of boiling water) with the steady-state temperature (where the handle is actually at a touchable temperature). The experiment portion of the activity has students log temperatures from three locations (side, base of handle, handle grip) on a stainless-steel pot full of boiling water. Students can even lift the pot at the end to convince themselves that the handle really is at a significantly lower temperature. The development of this particular activity was described in depth here [25].

Activity #2: Cough drop

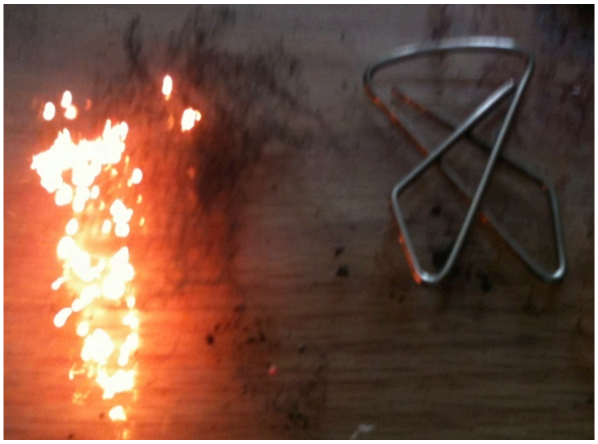
This activity extends the concept of steady-state and equilibrium to a mass-transfer system. Students are asked to predict whether a flow-system of dissolving cough-drops in water can reach steady-state and/or equilibrium. Students then position a Buchner funnel below a tap, and control the flow rate of the water in, as well as the rate at which they unwrap and add red menthol cough drops. They then continuously collect samples of the outflow, and compare the color to a chart to determine if they have achieved either steady-state or equilibrium. For comparison, we also provided a static system of a large number of cough drops in a relatively small amount of water that had been allowed to mix overnight. Our observation is that many students find this rather simple activity fun and choose to run several different flow rates to attain the full range of steady-state outflow colors. It also smells nice, a fairly unusual facet for a chemical engineering experiment.

The distinction between factors affecting Rate of Chemical Reaction and Extent of Chemical Reaction

This area closely mimics a misconception area uncovered by colleagues working with heat transfer and with electrical concepts. Students are often confusing factors that make a reaction produce large amounts of product with those that produce product quickly. For example, students might predict that a reaction with a large, negative DG would both significantly favor products (amount) as well as be explosive (rate).

Activity #1: Explosive Reactions

In this activity, students are first asked to calculate the free energy change for the reaction of three elements with oxygen: iron (to form rust), silicon (to form silicon dioxide), and carbon (to form carbon dioxide). They are then asked to predict if these reactions are favorable and how fast they think they might occur. For the action, they are then exposed to a selection of these elements in an oxygen atmosphere and asked to observe them closely. This does not take too long once they realize that they are quite familiar with the graphite in their pencils being stable at room temperature. Finally, they are given several samples of steel, which they know to be mainly iron and carbon, and a match. They observe that fine steel wool will ignite, while nails, spoons, etc will not. In their reflection, they then consider what factors besides thermodynamic favorability play into the rate of a given reaction. Students are typically quite fascinated to see that steel will indeed burn.



Activity 2: Volcano

This activity is meant to complement the first by demonstrating a reaction that is not highly favorable thermodynamically, but still proceeds at an appreciable rate at room temperature. Students are given information about the reaction of acetic acid and sodium bicarbonate to product carbon dioxide and sodium acetate in aqueous solution. Once again, they are asked to predict what will happen, and they are then presented with the ingredients to conduct the experiment. As many of them know from prior experience, the reaction is reasonably rapid (and can be used to make model volcanoes in grade school, hence the name).

Results

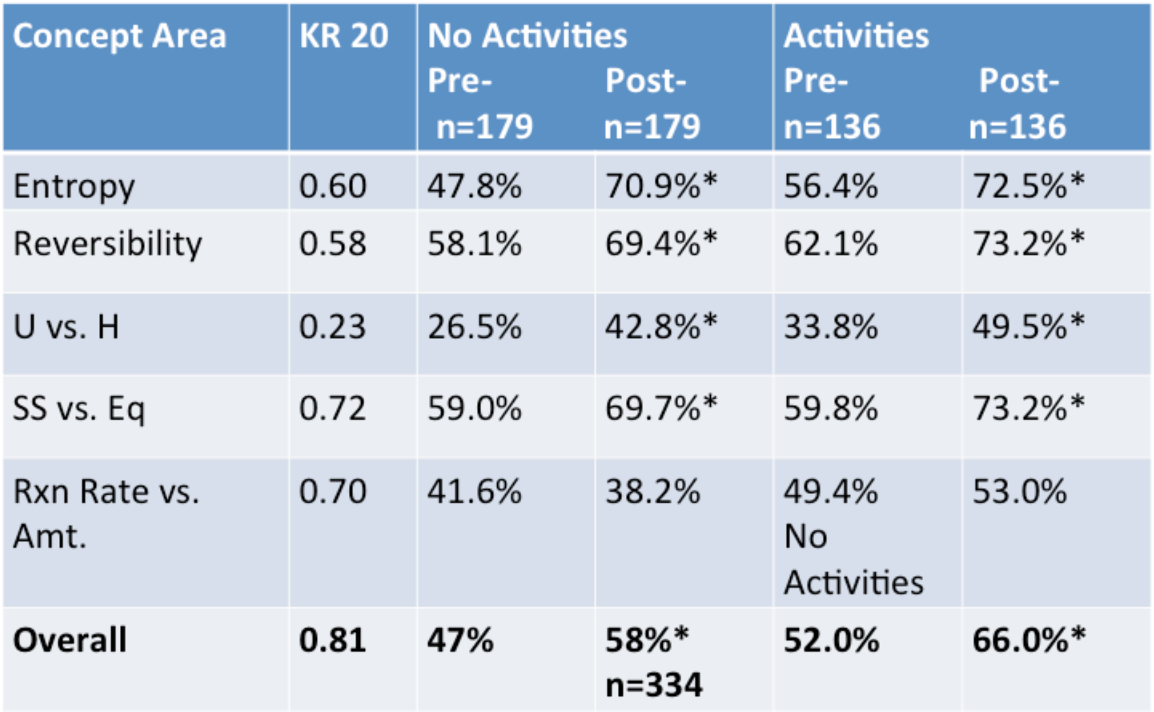
Activities were implemented in thermodynamics courses at 11 colleges and universities. While testing is ongoing, the results in Table 1 are for tests through Fall semester of 2010. The "control" data are from courses at six institutions. All participating courses were engineering thermodynamics for undergraduate students in the United States. Schools were geographically diverse and represented both private and public institutions. "Control" schools gave the CIET in the first two weeks of their thermodynamics course, then again in the final two weeks. "Activities" schools followed the same protocol, but also performed both activities in each concept area covered by their course. Faculty were allowed to implement activities in a way that best fit their course, either as in-class activities or homework, directly performed by students or as demonstrations. All students were expected to complete the pre- and post- activity questions. Testing is ongoing as of this report.

The data in Table 1 are complicated by the fact that not every course addresses every concept area, and therefore the results are a mix of institutions that performed every available activity and those that performed only a relevant sub-set. Future data analysis will separate these results by concept area. Note that as of this data set, results from activities addressing "reaction rate vs. reaction equilibrium" were unavailable.

In Table 1, the data are broken down by concept area. However, as the "activities, post-" data includes schools that may or may not have performed activities in a given concept area, the most meaningful comparison is based on the Overall scores in the bottom row. The 14% improvement in scores for those schools performing activities in at least some concept areas is significantly better than the 11% increase for schools without activities. The magnitude of the improvement is only moderate, although the results presented in Table 1 mask the true extent of improvement. This data set contains all students who completed at least two activities (both from a given concept area). Because not every thermodynamics course uses all five of these concepts or has access to sufficient space or equipment for the experiments, some participating schools completed only some of the activities. The first version of our data analysis was not set-up to accommodate variability in concept area, and re-assessment of data in light of this additional variable is ongoing.

The activities for "Reaction Rate vs. Amount" is the most recent addition, and assessment is still ongoing although preliminary results suggest positive outcomes, concept inventory results from these tests is still under analysis.

Table 1: Summary results for CIET. *Designates significant improvement at $p<0.01$



Concept Area	KR 20	No Activities Pre- n=179	Post- n=179	Activities Pre- n=136	Post- n=136
Entropy	0.60	47.8%	70.9%*	56.4%	72.5%*
Reversibility	0.58	58.1%	69.4%*	62.1%	73.2%*
U vs. H	0.23	26.5%	42.8%*	33.8%	49.5%*
SS vs. Eq	0.72	59.0%	69.7%*	59.8%	73.2%*
Rxn Rate vs. Amt.	0.70	41.6%	38.2%	49.4% No Activities	53.0%
Overall	**0.81**	**47%**	**58%* n=334**	**52.0%**	**66.0%***

Conclusions and Future Work

While the activities are effective at repairing students' misconceptions, and students report that they are fun, further analysis is needed to more clearly demonstrate the contribution of particular activity pairs to students' understanding. Also ongoing is the conversion of the existing simulations that were realized in Flash and Excel to Javascript so that they may be more universally accessible to anyone with a web-browser.

Acknowledgements

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