The Effect of Inquiry-Based Activities and Prior Knowledge on Undergraduates' Understanding of Reversibility

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Abstract

Research has shown evidence of problems understanding heat, temperature, and energy concepts. Even after instruction, undergraduate engineering students have been found to still hold misconceptions about thermodynamic concepts. The prior knowledge students bring to the classroom can also represent a challenge when trying to alter these misconceptions. One promising pedagogical approach is the use of inquiry-based activities. However, the way these activities are implemented can impact outcomes. This NSF funded (DUE 0717536) quasi-experimental study investigated the use of inquiry-based activities and their method of implementation, as well as the role of prior knowledge, in reducing misconceptions in five key areas of thermodynamics (Entropy, Reversibility, Equilibrium and Steady State, Internal Energy, and Enthalpy), with a more detailed focus on reversibility. Pre-post data from 26 different undergraduate thermodynamics classes from multiple institutions was analyzed. The Concept Inventory for Engineering Thermodynamics (CIET) and its Reversibility Sub-Test were used to measure conceptual understanding and change. Some classrooms used a series of inquiry-based activities in each key concept area as part of their instruction and some did not. Data was also collected on whether students had previously taken fluid dynamics and heat transfer courses. Finally, instructors were asked to indicate how they had implemented a packet of inquiry-based activities specifically designed to teach reversibility. Results showed that conceptual understanding of thermodynamics (five concept areas) as measured on the CIET was significantly higher for the inquiry-based activities group than the no activities group, although the effect size was small. Post-test scores were significantly higher for students who had previously taken courses in fluid dynamics and heat transfer when compared to those who had not. There was a significant difference between the activities and no activities groups on students' understanding of reversibility, with a small effect size. A survey of faculty revealed that reversibility activities were implemented by some in ways that differed from the directions provided. Finally, understanding of reversibility was impacted by students' previous coursework in fluid dynamics and heat transfer.

Introduction and Background

Conceptual difficulties with heat, temperature, and energy have been documented at all educational levels.[4, 17, 23, 31, 34] Thomaz et al. found that secondary level physics students had difficulty discriminating between heat and temperature.[34] Carlton found that many teacher education students, when their prior knowledge was assessed, defined temperature as "…a measure of how hot or cold something feels" (p. 102).[4] Some students have been found to believe that there is no difference between heat and temperature or that heat is a form of energy.[9, 10, 30, 35] Even after instruction, some individuals have been found to have incorrect understandings of these concepts, or what have been labeled misconceptions.[3] A key reason behind these misconceptions is that terms like heat, temperature, and energy are also used in daily life to identify other processes.[30] In other words, when students come to science classes they are not "blank slates," but are informed by scientific knowledge that comes from out-of-class settings as well as previous courses.[3]

These same conceptual difficulties have been found in undergraduate engineering students.[21, 25, 28] For example, Prince and Vigeant found that many engineering undergraduates viewed heat and temperature as equivalent entities.[25] Self et al. determined that almost 30% of chemical and mechanical engineering seniors could not, "…logically distinguish between temperature and energy in simple engineering systems and processes" (p. S2G-1).[28]

The field of thermodynamics examines interchanges of energy in chemical and thermal systems, particularly changes between heat and work, making it key to many engineering disciplines. The content of undergraduate thermodynamics courses can be especially difficult for students to grasp due to its equation-based abstract nature. This makes conceptual change challenging, because it has been shown that students are able to get the math correct even when their conceptual understanding is incorrect.[14] Reversibility, defined by the degree "…the system and all parts of its surroundings can be exactly restored to their respective initial states after the process has taken place" (p. 212), is especially challenging.[22] As can be seen in Table 1, misconceptions are regularly found in the learning of thermodynamics.[37]

Table 1:
Misconceptions Regularly Found in Thermodynamics

Concept Area	**Misconception**
Entropy	Students often misconstrue the impact of entropy on the efficiency of real systems, believing if a system is reversible, frictionless, and appropriately adiabatic, it can have thermal efficiency of 100%. That is, they often assume the thermal efficiency of a Carnot engine is 100% regardless of heat source and sink temperatures.
Reversibility	Students often assume reversible behavior for real systems where such an assumption is inappropriate. That is, students fail to grasp what reversibility would mean for the behavior of a real system.
Steady State vs. Equilibrium	Students confound steady state and equilibrium, believing they are synonyms or that one necessarily implies the other for a given system.
Internal Energy vs. Enthalpy	Students confound internal energy and enthalpy, assuming they are interchangeable. Students often conflate "flow work" (that which distinguishes enthalpy from internal energy) with kinetic energy.
Reaction Equilibrium vs. Reaction Rate	Students often believe that a reaction that favors products strongly will react rapidly. That is, they confound factors that impact reaction rate with the factors that impact how much product is produced.

There is an increasing understanding that prior knowledge acts as a filter for new learning.[29] This prior knowledge can interfere with concept mastery. There is also a broad realization that meaningful learning of science content requires conceptual understanding rather than memorization of facts and formulas [2, 19], as well as a growing understanding that traditional instructional methods can be ineffective at altering students' misconceptions.[33] Consequently, the challenge in teaching is to make academic knowledge of real value by constructing it in a meaningful way so that the students learn and understand the concept correctly.[27]

Interactive pedagogy can help facilitate the remediation of misconceptions and the learning of new concepts.[8, 14, 20, 26, 39] Use of inquiry-based activities is one way that instruction can be more interactive and engaging.[5, 6] Inquiry-based activities allow students to participate in hands-on activities, which can permit the students to experience the information being presented in a more meaningful way.[5] This can help them to better grasp the complexity of these different thermodynamic concepts.[1]

Purpose of the Study

The purpose of this research was to investigate whether inquiry-based activities affected undergraduate engineering students' conceptual knowledge and understanding of thermodynamic concepts, especially reversibility, as measured by the Concept Inventory for Engineering Thermodynamics.[37] It also investigated whether the way reversibility activities were implemented affected students' knowledge of this concept. Finally, it looked at the influence of prior knowledge on participants' understanding of thermodynamics concepts. For the purposes of this study, prior knowledge was operationally defined as having previously taken courses in fluid dynamics and heat transfer. It was anticipated that students with some prior knowledge from other engineering courses would have a better understanding of thermodynamics concepts.

Methods

A quasi-experimental design with intact groups was used to assess learning gains prior to and after instruction. There was an inquiry-based activities group and a group taught under normal conditions, without the use of supplemental activities. Descriptive statistics examined changes in knowledge as measured by the scores on the Concept Inventory for Engineering Thermodynamics (CIET), as well as on its Reversibility Sub-Test.[37] Oneway analysis of variance (ANOVA) was used for hypothesis testing to examine the differences between pre- and post-test scores of the two groups (no activities and activities). When there were more than two levels of an independent variable examined, Tukey's HSD post hoc tests were used to determine the source of the differences. Eta Squared, utilized for Analysis of Variance models [7], was employed to determine the effect size when oneway analysis of variance was computed. Effect sizes indicate, "…the size of the difference or relationship" (p. 121) and are currently required by many professional organizations, including the American Psychological Association, when stating the results of hypothesis testing.[7] Finally, the Kuder-Richardson Formula #20 (KR20) was computed on the post-test to estimate the internal consistency reliability of the Concept Inventory of Engineering Thermodynamics (CIET) and the Reversibility Sub-test by itself.[37] The KR20 was used because it could not be assumed that all of the questions in the CIET were of equal difficulty and this approach is recommended when that is the case.[13]

A convenience sample of 938 individuals from 26 different undergraduate, thermodynamics classes from multiple institutions were used in the current study. The majority was male (n = 681), white (n = 723), juniors (n = 523), and chemical engineering majors (n = 489). Table 2 shows the demographic characteristics of the participants.

Table 2:
Demographic Characteristics of Participants

Demographic Variable		**n**	**Percentage**
Gender	Female	258	27.48
	Male	681	72.52
Major	Chemical Engineering	489	52.10
	Mechanical Engineering	299	31.80
	Environmental Engineering	3	0.30
	Civil Engineering	30	3.20
	Other	118	12.60
Ethnicity (major 3 groups)	White	723	77.00
	Asian/Pacific Islander	94	10.00
	Other	25	2.70
Year in School	Freshman	20	2.10
	Sophomore	276	29.40
	Junior	532	56.70
	Senior	110	11.70
	Grad Student	1	0.10
GPA	below 2.00	2	0.20
	2.00-2.49	41	4.40
	2.50-2.99	211	22.50
	3.00-3.49	320	34.10
	3.50-4.00	365	38.90

The Concept Inventory for Engineering Thermodynamics (CIET) was used in the current study.[37] This instrument, patterned after concept inventories used in other disciplines such as the Force Concept Inventory [16], was designed to document conceptual change and the presence of previously identified misconceptions in thermodynamics.

The CIET has 35 multiple choice questions targeting five key concept areas: Entropy, Reversibility, Equilibrium and Steady State, Internal Energy versus Enthalpy, and Reaction Rate versus Reaction Equilibrium. Seven questions specifically address Reversibility. The questions on the CIET came from a number of sources. For three of the five concept areas, 18 questions were drawn primarily from the Thermal and Transport Concept Inventory (TTCI).[21, 24, 32] There were also two questions drawn from the TTCI and modified. A single altered question was drawn, with permission, from the Thermodynamics Concept Inventory (TCI).[11, 12] The researchers constructed the rest of the questions. Appendix A provides sample questions from the CIET.

Inquiry-based activities have been defined in multiple ways.[6, 36] For the purposes of this study, they were defined as open-ended, student-centered, and hands-on activities that fully engage the participants in the concept area that is being discussed.[6] The framework adopted for the inquiry-based activities developed and used in this study drew heavily on the Workshop Physics Model.[18] Laws et al. noted that there was improvement in student learning when the following were incorporated in instruction:

- "use peer instruction and collaborative work;
- keep students actively involved by using activity-based guided-inquiry curricular materials;
- use a learning cycle beginning with predictions;
- emphasize conceptual understanding;
- let the physical world be the authority;
- evaluate student understanding;
- make appropriate use of technology…" (p. 4).[18]

Ten inquiry activities, two per concept area, were provided to the participating professors at the beginning of the semester along with homework and concept questions. Activities for Reaction Rate versus Reaction Equilibrium were not available in the early part of this investigation so those doing the activities initially were given eight activities. Two activities were designed for Reversibility.

Both activities designed for Reversibility involve computer simulations and are meant to clearly show that most realistic situations are irreversible. There is a Mixing Simulation and a Pump Simulation. Appendix B provides more details about these two inquiry-based activities.

The participants completed an electronic version of the Concept Inventory for Engineering Thermodynamics (CIET) during the first two weeks of the course. Instructors in the activities group were provided with inquiry-based activity packets which they could use with students throughout the semester. Each inquiry activity had pre-activity questions, observations to be taken during the activity, and analysis questions for homework after the completion of the activities. When activities were done in the class, the professors were instructed to have the students form teams of about three members and have the teams complete the activities. When no activities were completed, the teacher taught the class as usual. During the final portion of the study, the participants were asked to again complete the CIET during the last two weeks of their classes. The same set of instructions was given to the participants. At the end of the semester, instructors who had used the activities were asked to indicate how they had been implemented, especially those addressing Reversibility.

Results and Discussion

There were 520 students who used inquiry-based activities and 231 who were taught without the supplemental activities. Out of the 520 participants who used the activities, only 205 completed activities for all the five concept areas. This resulted in a variation among participants in the number of activities completed in the "Yes" group, a limitation in the current study.

Inquiry-Based vs. No Activities Comparison on the CIET[37]

Mean pre-test scores on the Concept Inventory for Engineering Thermodynamics (CIET) were similar for the activities (Yes) and no activities groups (No). However, after instruction, the inquiry-based activities group had a higher mean score than the no activities group. The mean score for the activities group increased approximately 15% from pre- to post-test while the no activities group increased almost 10%. Table 3 provides information about the mean scores.

Table 3:
Differences in Mean Scores between Inquiry Activities and No Activities Groups

	Mean Pre-Test Score	**Mean Post-Test Score**
No Inquiry-Based Activities (No)	15.50 or 44.3% n = 271	18.88 or 53.9% n = 231
Inquiry-Based Activities used (Yes)	15.78 or 45.1% n = 649	21.23 or 60.7% n = 520

Oneway analysis of variance (ANOVA) showed that there was no significant difference on the pre-test between the activities/no activities groups however, there was a significant difference on the post-test between the two groups with a small effect size, $F (1, 749) = 23.57$, $p < .01$, $\eta^2 = .03$. The mean post-test score of the activities group was significantly higher than the no activities group, showing that the use of inquiry-based activities did make a difference in the understanding of thermodynamics concepts.

Impact of Inquiry-Based Activities on Understanding of Reversibility

When scores on the seven Reversibility questions were examined separately by activities/no activities groups, it was found that while both groups had approximately the same mean score on the pre-test, the mean post-test score for the activities group was higher. As can be seen in Table 4, the mean score for the activities group increased approximately 15% from pre- to post-test while the no activities group increased about 6%. Oneway analysis of variance (ANOVA) showed that there was no significant difference between the two groups on the pre-test and that the activities group scored significantly higher on the post-test than the no activities group, although the effect size was small, $F (1, 749) = 25.59$, $p < .01$, $\eta^2 = .03$.

Table 4:
Differences in Mean Scores for Reversibility between Inquiry Activities and No Activities Groups

Reversibility Sub-test	No Inquiry-Based Activities		Inquiry-Based Activities	
	Pre-Test (n = 271)	Post-Test (n = 231)	Pre-Test (n = 649)	Post-Test (n = 520)
	3.61 (51.6%)	4.02 (57.4%)	3.62 (51.7%)	4.64 (66.3%)

While the improvement in reversibility by the broad categories was promising, it was unclear whether all the students in the activities group had actually completed the Reversibility activities, which could account for the smaller effect size. An attempt was made to clarify this by looking at only those who had done the Reversibility activities versus those who had not. If instructors had indicated they did "some" of the inquiry-based activities but it was unclear whether the students had actually done the Reversibility activities, they were not included in this analysis[1]. Oneway analysis of variance (ANOVA) revealed that there was a significant difference on the Reversibility Post-test between those who had completed the Reversibility activities and those who had not, but the effect size remained small; $F(1, 665) = 19.59$, $p < .01$, $\eta^2 = .03$. Descriptive statistics seen in Table 5 showed that the inquiry-based group who had completed the Reversibility activities had a significantly higher mean post-test score than the group which had not done the Reversibility activities.

Table 5:
Mean Reversibility Post-test Scores by Activity Level

Reversibility Activities	**Mean Reversibility Post-Test Score (out of 7 points total)**	**n**	**Standard Deviation**
YES	4.65	363	1.54
NO	4.11	304	1.58

Finally, the researchers examined how the Reversibility activities were implemented, to determine whether the activities had been carried out as intended and to discern whether this could provide further insight into the small effect size. It was found that engineering instructors implemented the Reversibility activities in a number of different ways. Some had conducted the activities during a laboratory or class period, where faculty or TAs were available to directly coach students (as intended); some assigned the activities instead as homework which was completed either in student teams or individually. There was also a group for which there was no specific information on how the activities were implemented. However, as can be seen in

[1] There are 84 cases from some of the initial schools that said they did inquiry-based activities but didn't say which ones were included, so they were omitted in this analysis.

Table 6, mean scores were higher when Reversibility activities were used, regardless of implementation method, than when no Reversibility activities were done.

Table 6:
Mean Reversibility Post-test Scores by Method of Implementation

Ways Reversibility Activities Implemented	Mean Post-Test Scores (out of 7 points total)	n	Standard Deviation
Student Teams in Class or Lab[2]	4.42	174	1.52
Student Teams for Homework	4.19	42	1.76
Students Individually Completing Homework	4.27	41	1.83
Activity Implemented, No Specific Information	5.12	190	1.29
No Reversibility Activities Used	4.11	304	1.58

Oneway analysis of variance (ANOVA) with implementation condition (student teams class/lab, student teams homework, students individually doing homework, no information, and no activities done) as the independent variable, yielded a significant difference in the Reversibility Post-test scores with a medium effect size; $F (4, 746) = 13.29$, $p < .01$, $\eta^2 = .07$.

Impact of Prior Knowledge on Understanding Thermodynamics Concepts

The impact of prior knowledge was also examined in the current study. Prior knowledge was operationally defined as having taken a Fluid Dynamics and/or a Heat Transfer course prior to taking the current course where participants were learning thermodyamics concepts. Table 7 illustrates the mean differences among those who had taken, were currently in, or had not taken a course in Fluid Dynamics. As can be seen in that table, the group who had previously taken a course in Fluid Dynamics had the highest mean post-test score on the Concept Inventory for Engineering Thermodynamics (CIET) [37].

Table 7:
Differences in Mean Post-Test Scores on the CIET [37] for Prior Fluid Dynamics Coursework

Fluid Dynamics Coursework	Mean	n	Standard Deviation
Had Not Taken the Course	19.71 (56.3%)	504	6.15
Currently in the	21.38	80	5.66

[2] This was the way that researchers indicated the inquiry-based activities should be implemented.

Course	(61.1%)		
Previously Took the Course	22.49 (64.26%)	167	6.23

Oneway analysis of variance (ANOVA) determined there was a significant difference among the groups although the effect size was small, $F(2,748) = 13.85$, $p <.01$, $\eta^2 = .04$. Tukey's HSD post hoc tests indicated that those who had previously taken a course in Fluid Dynamics scored significantly higher on the entire post-test than those who had not taken such a course.

This same pattern was also seen when looking at the Reversibility Sub-test by itself. Table 8 shows the mean differences in the Reversibility Post-Test scores among those who had taken, were currently in, or had not taken a course in Fluid Dynamics. The mean post-test score of those who had taken a course in Fluid Dynamics was higher than those in the other groups.

Table 8:
Differences in Mean Post-Test Scores on Reversibility Sub-Test for Prior Fluid Dynamics Coursework

Fluid Dynamics Coursework	**Mean**	**n**	**Standard Deviation**
Had Not Taken the Course	4.30 (61.42%)	504	1.58
Currently in the Course	4.66 (66.57%)	80	1.55
Previously Took the Course	4.80 (68.57%)	167	1.50

Oneway analysis of variance (ANOVA) with course condition (had not taken, currently taking, previously took) as the independent variable revealed a significant difference with a very small effect size among the mean scores of the different groups, $F(2, 748) = 17.38$, $p < .01$, $\eta^2 = .02$. Tukey's HSD post hoc tests showed a significant difference between those who had previously taken a course in Fluid Dynamics and those who had not taken such a course. The mean Reversibility Post-test score of those who had previously taken a course in Fluid Dynamics was significantly higher than those who had not taken this course.

Table 9 illustrates the mean differences among those who had taken, were currently in, or had not taken a course in Heat Transfer. As can be seen in that table, the group who had previously taken a course in Heat Transfer had the highest mean post-test score on the Concept Inventory for Engineering Thermodynamics (CIET). Those who had taken a course in Heat Transfer previously scored approximately 14% higher than those who had not taken this course.

Table 9:
Differences in Mean Post-Test Scores on the CIET [37] for Prior Heat Transfer Coursework

Heat Transfer Coursework	**Mean**	**n**	**Standard Deviation**
Had Not Taken the Course	19.92 (56.91%)	521	6.07
Currently in the Course	19.98 (57.09%)	143	6.02
Previously Took the Course	24.91 (71.17%)	87	5.67

Oneway analysis of variance (ANOVA) determined there was a significant difference with a moderate effect size among the groups, $F (2,748) = 26.31$, $p < .01$, $\eta^2 = .07$. Tukey's HSD post hoc tests indicated that those who had previously taken a course in Heat Transfer scored significantly higher than those who had not taken this course or were in a course that semester. This same pattern was again seen when looking at the Reversibility Sub-test questions by themselves.

Table 10 shows the mean score differences on the Reversibility Sub-test among those who previously took, were taking or had not taken a course in Heat Transfer. As can be seen in this table, those who had previously taken a course in Heat Transfer had the highest mean score.

Table 10:
Differences in Mean Post-Test Scores on Reversibility Sub-Test for Prior Heat Transfer Coursework

Heat Transfer Coursework	**Mean**	**n**	**Standard Deviation**
Had Not Taken the Course	4.27 (61.0%)	521	1.57
Currently in the Course	4.59 (65.57%)	143	1.58
Previously Took the Course	5.30 (75.71%)	87	1.25

Oneway analysis of variance (ANOVA) revealed a significant difference with a small effect size among the coursework groups, $F (2, 748) = 17.48$, $p < .01$, $\eta^2 = .05$. Tukey's HSD post hoc tests indicated that those who had previously taken a course in Heat Transfer scored significantly higher than those who had not taken this course or were in a Heat Transfer course that semester.

Internal Consistency Reliability

The estimate of internal consistency reliability of the CIET post-test was .83, high as measured by the Kuder-Richardson Formula 20. The estimate of internal consistency reliability for the Reversibility post-test was .55, moderate as measured by the Kuder-Richardson Formula 20.

Whereas the internal consistency reliability of the entire instrument was acceptable for research purposes, the reliability of the Reversibility Sub-Test should be higher. It has been noted that for research purposes, the reliability coefficient should be at least .70.[13] Future research should examine ways to raise the internal reliability of this sub-test.

Conclusions

Misconceptions resistant to change through traditional teaching methods are of particular interest to engineering educators, especially when these misconceptions concern important concepts found in core engineering courses. In the current study, both the inquiry-based and the no activity groups showed improvement in understanding from pre- to post-test on both the entire Concept Inventory for Engineering Thermodynamics (CIET)[37] and the Reversibility Sub-test although the mean post-test scores were lower for both groups than most instructors would prefer. In addition, it is not known whether conceptual understanding was maintained. Thomaz et al.[34] has recommended the use of a delayed post-test to see whether conceptual changes are maintained. This should be done in future studies.

The activities group showed the greatest improvement. This could be due to the multiple modalities used to learn the target concepts, a form of elaboration. Elaboration helps in remembering material and builds connections to prior knowledge.[38] The greater improvement from pre- to post-test with the activities group could be the result of increased elaboration as students' encoded the new information in multiple ways, e.g., through questions and dialogue, experiments, computer simulations, reading text, etc. However, even with the significantly greater mean post-test scores of the inquiry-based group when compared with the no activities group, the effect sizes tended to be small. A more detailed examination of the implementation of Reversibility activities revealed a possible reason for the small effect sizes. The researchers could only verify that 23.1% of the total group used and completed the Reversibility activities as recommended. Henderson, Finkelstein, and Beach have noted that failure to implement new strategies in STEM fields could be the result of university faculty not having a meaningful role in the creation of the new strategies or the new pedagogies being incompatible with the teaching norms of individual institutions.[15] Further investigation is needed to determine how inquiry-based activities and other innovative pedagogies can best be implemented as designed.

Prior knowledge of students can impact performance in current coursework. In the present study, prior knowledge was operationalized as having taken courses in Fluid Dynamics and Heat Transfer. Since the findings related to prior knowledge may be reflective of the number of courses previously taken in the engineering program or participants' years in school, one of these variables should be controlled in further analyses to see whether the differences found in this study are maintained. Other prior coursework of relevance to conceptual understanding should also be explored such as Physical Chemistry. In addition, the examination of the order in which courses are taken could provide insight into the learning of difficult concepts and the reduction of misconceptions. However, more information is needed.

There are a number of limitations in the current study. The first is the use of a convenience rather than a random sample. Even though care was taken to obtain participants from a variety of institutions and locations, samples of convenience still remain unrepresentative of the population.[13] Future research should attempt to obtain a random sample. In addition, it is not known how instructors in the no activities group taught the targeted concepts. Future research should examine the specific strategies used by those not using the inquiry-based activities.

While the findings in the current study are very encouraging, there is a need for more research. Continuing research should focus on how the inquiry-based activities are implemented to determine which parts of the teaching strategy result in the most conceptual understanding of thermodynamics concepts. In addition, the use of other assessments of students' conceptual understanding such as concept maps or semi-structured student interviews would provide a fuller picture of the effectiveness of the inquiry-base activities.

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Appendix A

Sample Questions from the Concept Inventory of Engineering Thermodynamics (CIET) [37]

12. Table salt is slowly added to a beaker of water that is being stirred. Initially, all the salt dissolves in the water. As more salt is added, the water eventually becomes saturated with salt and some solid salt remains undissolved. Once solid salt is observed in the bottom of the beaker, no additional salt is added.

Assuming the beaker contents are still well-stirred, even though salt addition has stopped, we can say that:

a. Salty water and solid salt are in equilibrium and the beaker system is at steady-state
b. Salty water and solid salt are in equilibrium but the beaker system is <u>not</u> at steady-state
c. Salty water and solid salt are <u>not</u> in equilibrium but the beaker system is at steady-state.
d. Salty water and solid salt are <u>not</u> in equilibrium and the beaker system is <u>not</u> at steady-state.

13. because:

a. salt is always being dissolved on a molecular level so the system can never come to equilibrium
b. equilibrium and steady-state are related – you can't have one without the other
c. maximum amount of salt is dissolved (so net dissolution rate is zero) and conditions in the beaker (temperature, pressure, composition) are not changing with time
d. once the water is saturated, salt dissolution stops so system can't be at steady-state

Appendix B

Information About Reversibility Inquiry-Based Activities

Activity #1: Mixing Simulation (student sheet follows)

This activity has a 2-D molecular dynamics simulation that shows the mixing of two hard-sphere fluids. Guided by 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 believe 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 takes reversiblility into the domain of machines and cycles. Students predict how much work they might extract from a pump that is allowed to free-wheel backwards when water is pushed 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.

Inquiry-Based Activity 1: Mixing Simulation

Student Name or Number __________________________

The program models the entropy changes involved in several types of mixing, including mixing hot and cold water, water and oil, and water and dye. Answer the question on the first page of the program, then run the simulation. You can set the hot water temperature from 25-100 °C.

Materials:

A computer with Macromedia Flash Player 8 or later

Internet access.

Directions:

1. Make predictions about how the operation you are about to simulate will work.
   a. You have two cups, each containing the same mass of liquid water. In one cup, the water is 80ºC, and in the other the water is at 10ºC. If the *system* is the water, is the entropy of the system higher, lower or the same *after* you mix the two cups together? Why?

2. Start up the simulation by accessing the following website.: http://www.facstaff.bucknell.edu/mvigeant/thermo_demos/mixing_page.html

3. What happens to the entropy when you mix hot and cold water?

4. Experiment with different temperatures for the hot and cold water. What happens as the temperatures approach one another?

5. What happens to the entropy when you mix water and oil?

6. What happens to the entropy when you mix water and dye?

7. Click on the "what's happening" window to watch a representation of how this works at the molecular level.

Analysis – to do after class/lab and hand in:

1. Revisit your predictions in question 1 of Directions. Were you right? Compare your initial predictions to what actually happened.
2. If the simulation results do not match your initial predictions, come up with a new explanation of the results. In your explanations, you *must* pay particular attention to why your original arguments were not correct and how you had to revise your thinking to explain what happened.

3. Give three examples of changes that a system could undergo that would result in a zero change of entropy for the system. What are some of the characteristics shared by each of these changes?
4. Is there any way to do the hot / cold water experiment and realize a zero change in system entropy? Why?
5. You should discuss your answers with at least 2 other students and agree on what happened and why.
6. Hand in your original prediction and your comparison to question 1 above, specifically noting if and how your thinking has changed with respect to the experiment. What, if anything, did you learn?
7. Remember to put your name or identifying student number on each page of your response.