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An investigation of student thinking regarding calorimetry, entropy, and the second law of thermodynamics

Warren Michael Christensen
Iowa State University

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An investigation of student thinking regarding calorimetry, entropy, and the second law of thermodynamics

by

Warren Michael Christensen

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Physics

Program of Study Committee:
David E. Meltzer, Co-major Professor
Craig A. Ogilvie, Co-major Professor
Thomas J. Greenbowe
Steven D. Kawaler
Howard N. Shapiro

Iowa State University

Ames, Iowa

2007

UMI Number: 3274888

UMI

Dedication

To my mom

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Acknowledgments

It is my wife's honest opinion that I should take some time and care with the acknowledgements since, "it's the only part of your thesis some people might read." Also, this is the only section that David has unleashed me from the reins of his "formal and appropriate" writing style. In addition, I like to talk, and being that this is the only space where I can just be me, I'm going to take the time to acknowledge a lot of people. I apologize in advance for any of those who are choosing to only read this part of my thesis and might be angered to find that they weren't mentioned. I will invariably forget more people than I'll remember, and for those that aren't mentioned, well, thanks to you too.

First and foremost I'd like to thank my mom. She was good. I don't know if a kinder, bubblier, more warming person has ever lived before or since. She was my buddy, always ready for a quick dance around the kitchen even when she was tired or not feeling well. She was always extremely supportive of everything I did, both in school and theater. I strive to embody the spirit of my mother every day and I'm very glad to report that despite being put through the wringer of grad school, I think that spirit of fun and playfulness still exists in me. I know that she has been watching over me, and I miss her very, very much.

My dad is no slouch either! He has been an amazing source of support ever since my mom passed away. He's been very giving and caring every step along the way. He's had a far more difficult row to hoe than I have in a lot of ways, and I'm really proud of the person that he is today. He was the inspiration for this whole rollercoaster ride of

grad school, as some of my earliest recollections of him are happily discussing the classes

he was teaching and the students he was working with while teaching at KSC (that's the

former Kearney State College in Nebraska).

It is very clear to me that I would never have finished this process if it were not

for my wife Katie and my son Drew. I never really understood why people don't finish

their dissertation, but I understand now. In short, it's painful. Having proper motivation

to put oneself through that pain is essential. Katie puts up with all my tension and

procrastination, of which there is plenty of both. Drew is one cool kid. I'm looking

forward to many evenings fishing with him this summer and for many summers to come.

Their love and support has been essential for getting this thesis done on time. Of course,

having a second child due four days after I turn this in doesn't exactly give me a lot of

leeway. I can't really comprehend how Katie is able to put up with all of this, teach over

140 high school students, and grow another person, but that's why moms get all the

credit; because they deserve it.

Larry Engelhardt was my right-hand man for most of school. Struggling to study

for the comprehensive Ph.D. Qualifying Exam, we became very good friends, and

enjoyed spending long hours torturing one another with qualifier problems that neither of

us really understood. I'm 100% certain that I would not have passed the qualifying exam

if Larry would not have been there to walk that line with me. We shared the common

goal of improving life for physics graduate students at Iowa State, and together we helped

establish a Graduate Student Colloquium, which provides physics graduate students a

forum in which they are able to give talks about their research and engage fellow

graduate students in discussions. We also spent two summers developing a Qualifying

Exam Preparatory Course to guide other incoming graduate students on key topics and

successful methods for study; it is this achievement in graduate school for which I am

most proud.

Robby Bruner is my best friend. As best friends do, we tend to get at one

another's throat from time to time, but he always helps pick me up when I feel down. His

recent phone calls have been incredible, and I can't remember the last time I laughed so

hard. Along with Robby comes a major topic of our conversations. The WFL, the

fantasy football league that I created for my friends, is now entering its 12th year and is

easily the best and worst distraction that can be.

Derek Wilke is without a doubt the worst running coach I've ever had. For those

interested in some of Derek's sagely advice here is his plan to start for someone who is in

absolutely no physical shape at all: "The first day try to get in four miles. Then the

second day, go for four miles again." Yep. I've drank more coffee with Derek than all

other living people I've drank coffee with combined. I don't know if I'm exactly grateful

for that, since I'm pretty worthless without a strong cup of joe in the morning, but it's a

fact so it's worth mentioning. Derek, Larry and I did a lot of running around especially

in the first few years of school. We had lots of picnics at the park; grilling meat and

drinking beer make for some of the best times in past five years without a doubt.

Matt Tillman is my taco and poker compadre. We've chatted at length about all

things concerning cards, and I'm pretty sure he's one of the unluckiest people I know.

He's been a regular fixture during all of my most recent trips to see college friends, as

they all get along him very well. I'm pretty sure I still owe him about 30 lunches for all

the times he spotted me when I was short of cash, but he never seems to mind and always has a little extra for me.

Michael Yakes and I are very different people. He prefers traditional instruction and I despise it. He works a strict 9-5 work day, and I don't think I ever put those hours in at school. How do these two people become such good friends? It's a combination of two loves: the NFL and statistical analysis. We've spent an inordinate amount of time discussing heights, weights, 40-times, and hip fluidity; and he and I both respect the NFL Draft as a being one of the top three holidays on the calendar.

Matt Egger is the reason I attended graduate school at Iowa State. I don't know if that means I should thank him, but it's definitely worth acknowledging. The summer after I graduated from school, he almost on whim suggested that I move with him to Ames, Iowa and try to get into graduate school as he was planning to do. He's been a friend since 6th grade, and the only person from my high school that I still associate with on any level. Don't bother getting into a conversation about movies with Matt and I in the room about any movie made before 2001, your opinion is not likely to be correct and ours most certainly will be.

Ngoc-Loan Nguyen was my early mentor in graduate school. He was a key reason that I was able to make it through the coursework during my first semester of school. He gave willingly of his time and his talents to help others succeed where he had not. He passed away suddenly and unexpectedly in November of 2005. I'm very proud to have been a small part of the creation and dedication of the Ngoc-Loan Nguyen Memorial Library, which serves as an open-access library for physics graduate students using Loan's old textbooks as well as donations from other faculty members and friends.

Tom Stroman also provided valuable contributions to this research during his summer working in our group. His savvy with Excel and attention to detail helped in the entry and analysis of several sets of data as well as the redrafting of several questions.

David Meltzer is quite obviously my mentor for physics education research. While working with him I have learned an incredible amount about the field, the work, and the people in it. I don't know of a single other graduate student who was given as many opportunities to attend national meetings, give talks, and interact with their peers as I was. I've only been involved in PER for five years, and not only have I already heard nearly every leader and major participant in my field give talks about their research, I've interacted with them, had dinners with them, and in many cases talked shop with the likes of Joe Redish and Paula Heron over beers. It's an amazing community of which I would not be a part if not for David's generosity and desire for me to learn. It should also be mentioned that David and I can eat more than nearly any other two men who could easily find. I cherish the culinary experiences he and I have had together, and I look forward to many more to come.

Craig Ogilvie is my Co-Major Professor so by necessity he is issued some space in the acknowledgements. But I wanted to go beyond formalities to extend a very personal thanks for really stepping up for me at a time when I was really unsure of my lot in life at Iowa State. For a guy who has so many interests and pursuits, he really goes above and beyond what any other physics professor at Iowa State had done. Believe me Criag that I will pay it forward. As I continue on toward becoming a professor I will keep my eyes open for situations were I can come through for students as much as you've come through for me.

Tom Greenbowe is the head of the Chemical Education Research Group at Iowa State University. He has been extremely generous with his time and support both as a committee member, fellow scientist, and as a friend who is on the lookout to help. He opened up his group's meetings for me to attend, and gave me unique opportunities to discuss discipline-based education research on a weekly basis.

Steve Kawaler and his family are wonderful people. He's been a helpful guide and friendly ear throughout my time at Iowa State. Always laid back and insightful, Steve displays the style and demeanor I hope to carry with me as a professor.

The Physics Department secretaries are an AMAZING group of women. I'm convinced they work harder than anyone else in the building, and never get enough credit for what they do. There are always asking about Drew and giving well-wishes. I especially wanted to thank Gloria and Lori. Lori always knows or knows how to find the answers to all my questions and takes so much weight off the shoulders of the graduate students she should get a medal. To Gloria, for being so positive, giving me candy, and opening up her family to mine for a wonderful day of picking corn and digging up potatoes

Dr. See was my mentor during my undergraduate years. He acted as a concerned parent, delighted grandfather, and supportive friend throughout my days at Central Missouri State University. My experience in acting with him during Death of a Salesman will always be one my greatest moments in life.

Also special thanks to all of the faculty that allowed valuable classtime for testing our materials: Craig Ogilvie, David Johnston, John Hill, Anatoli Frishman, David Atwood, Eugene Levit, Paula Herrera-Siklody, Paul Canfield, Bert Crawley, Rolf

Hansen, and Art Meyers. In addition there have been dozens of faculty, graduate-student, and post-doc TAs that assisted in administering the material and I thank them as well.

Also for the final acknowledgement, I'd like to thank Taco Bell. I have a special connection with the fast food eatery. Throughout my college years it served as the pinnacle of late night cuisine in Warrensburg, MO, and during graduate school I've had countless lunches there. The walk there was often the only legitimate exercise I could get and, at times, it served as the only means for getting out in the sunshine. Lots of laughs and great conversation were had whilst consuming $0.49 tacos and bean burritos.

Chapter 1: Introduction

1.1 Motivation for study

Our primary goal in this work is to lay the framework for the creation of instructional materials that improve student understanding of heat and thermal physics. In particular, we have targeted concepts related to calorimetry, entropy, and the second law of thermodynamics. These topics include some of the most fundamental principles in the thermal physics portion of the introductory physics curriculum.

One of the most fundamental laws of physics is that total energy is conserved in all processes. In order to strengthen student facility with this concept, we must present problems related to it and assess students' understanding of it in multiple contexts. Research has shown that students in introductory physics courses face substantial difficulty in applying the first law of thermodynamics, which is simply the thermodynamic statement of energy conservation. Because basic algebraic relationships and common life experiences are incorporated in introductory calorimetry problems, this topic is often covered in high school physics and physical science courses, and it is also among the first thermodynamics topics discussed in introductory chemistry courses. For these same reasons, calorimetry is a common topic in both introductory algebra- and calculus-based physics courses. It could serve as a opportunity to strengthen students' understanding of energy conservation and proportional reasoning skills, as both are essential to solving qualitative questions concerning calorimetric concepts.

While energy is always a conserved quantity, the first law of thermodynamics gives no guidance about which processes may occur naturally. The second law of

thermodynamics (in its various forms) limits the direction of any naturally occurring processes to that which causes an overall increase in entropy. Although the concepts of energy and entropy are often taught sequentially, some curricula aim at teaching the two simultaneously to build on this strong link between the concepts.

The concepts of entropy and the second law of thermodynamics are of key relevance in the world today, particularly in view of the increased emphasis on energy efficiency. The fact that, even under ideal conditions (e.g. in a reversible cycle), there exists a limit on the amount of usable work that can be gained from a given amount of heat energy is an idea of which more people should be aware. The concept of maximum engine efficiency is closely related to the idea that the entropy change in the universe associated with any spontaneous process must be positive. By defining the property called "entropy" we can, in the simplest way possible, characterize and describe what processes may actually occur for any arbitrary real system, however complex, by constraining the entropy of the system plus that of the surroundings to increase. It is this key idea that helps explain the course of natural phenomena in a wide variety of contexts.

There is very little published research about student understanding of entropy and related thermal physics topics at the introductory calculus-based level, and we feel that the methods of physics education research (PER) pioneered by Lillian McDermott and the PER group at the University of Washington (UW) can shed some much needed light on this topic.

1.2 Research Questions

This work is an investigation into students' thinking regarding certain concepts in thermal physics. Our first objective is to identify students' conceptual and reasoning difficulties related to entropy and the second law of thermodynamics. The second objective is to find ways of addressing these difficulties with more effective instructional methods.

The investigation revolves around the following central research questions:

1) How does students' understanding of thermodynamic concepts evolve during their studies in the introductory general-physics course? Specifically, what are students' initial, pre-instruction ideas regarding:

    a) the conservation of energy and the role of specific heat in heat transfer processes involving two substances at different initial temperatures, and

    b) entropy and second-law concepts, including those involved with spontaneous processes and the state function property of entropy,

and what is the nature of students' thinking after instruction has been completed?

2) What are the primary conceptual and reasoning difficulties that students encounter when studying calorimetry, entropy, and second-law concepts in an introductory general-physics course?

3) How can these difficulties be addressed more effectively to help improve student learning of these topics?

The primary criterion for assessing the success of our work regarding questions 1) and 2) is the consistency with which specific student ideas can be identified, when observations are made a) repeatedly in multiple offerings of the same course, with varied

instructors and varied student samples, b) in diverse physical and representational

contexts as expressed in a variety of problems, questions, and assignments, and c) with

diverse forms of probes, including multiple-choice questions, written free-response

questions, verbal responses to problems posed during one-on-one interviews, and

responses submitted to questions posed through a computer either on-line or in-class.

The primary criteria for assessing the success of our work regarding question 3)

are: a) the degree to which our new instructional materials can be administered in actual

instructional situations (in-class, on-line, or as homework) so as to fit in seamlessly with

other instructional activities, such that students are observed to work cooperatively and

efficiently with the materials with no apparent negative outcomes, and b) the degree to

which student learning is improved when using the new materials in comparison to cases

when the materials have not been used.

1.3 Context of study

1.3.1 Introductory calculus-based physics course at Iowa State University

The bulk of this study was conducted with students in a second semester (of a

two-semester sequence) calculus-based introductory physics course at Iowa State

University (ISU, a large, research-based institution in the Midwest). The calculus-based

physics sequence at Iowa State usually has 700-800 students per calendar year, most of

whom are engineering majors, with handfuls of physics majors and computer science

majors. The course content varies slightly as the individual instructor has some

flexibility of topics. However, in general, the first semester course covers kinematics,

dynamics, and fundamentals of electricity while the second semester typically covers magnetism, AC circuits, waves, fluids, and thermal physics.

1.3.2 Upper-level Thermal Physics courses

Several semesters of data were taken from students in upper-level undergraduate thermal physics courses at Iowa State University and the University of Washington. These courses were both taught by David Meltzer. The ISU course is a one-semester junior-level course which focuses entirely on thermodynamics and statistical physics; data from this course are not discussed in this dissertation. The UW course is a sophomore-level course that is the fourth quarter of a four-quarter introductory sequence. As such it covers a good deal more thermal physics than ISU's introductory course, but not as much as the advanced course due to a significant section on waves and fluids. The course is made up primarily of physics majors and typical enrollment is around forty.

1.3.3 Introductory algebra-based physics course at Iowa State University

Students in a first semester (of a two-semester sequence) algebra-based introductory physics course at ISU are primarily life-sciences majors, often pre-medical or pre-veterinary medicine students, along with other students having majors that require algebra-based physics.

1.4 Overview of Physics Education Research

1.4.1 Methods

The work discussed in this thesis is modeled on those methods employed at UW. The essence of these methods is to make use of both qualitative and quantitative assessment of students' ideas about physics. Researchers attempt to probe student thinking using questions that ask for student explanations. By analyzing student responses, from large-scale written samples and smaller-scale interview samples, we determine the breadth and depth of student understanding. Interviews provide a researcher/student dialogue that allows us to deeply probe student understanding. Large-scale samples of students who provide written explanation of their reasoning can give us numbers sufficient for meaningful statistical analysis.

1.4.2 General Overview and Findings of PER

In his book, Five Easy Lessons (Knight 2004), Randall Knight accurately and succinctly describes PER as having two major thrusts:

- studying the concepts that students hold about the physical world and how those concepts are altered as a result of various methods of instruction, and
- studying the problem-solving techniques and strategies of students.

He describes PER work as following a two-step methodology. (This is in fact a highly simplified version of actual practices). The first step involves interviewing a small number of students about a particular topic. The students are typically presented with a table-top apparatus and some questions. Students are asked questions about their

understanding and interpretation of what is happening with the apparatus and their reasoning for why it occurs. These interviews can yield a great deal of insight into student thinking as it relates to the particular apparatus and the relevant physical concepts. The use of predict-and-explain questions with a specific apparatus or concrete problem is done deliberately in PER (e.g., PEG 2007) and other discipline-based education research.

Knight describes the second step as consisting of researchers drafting multiple-choice questions that are conceptual in nature and possess both the correct answer and "attractive distracters." These distracters are incorrect answers that are consistent with those misconceptions that were observed during the first step of the process. While this is the mode of several successful published studies, many studies rely on free-response questions that ask for student explanations. In our observations, giving students the opportunity to use their own words is a more reliable assessment technique than providing them only with limited descriptions of a particular answer.

Knight goes on to highlight four key findings from PER that pervade nearly all physics instruction:

- "Students enter our classroom not as 'blank slates'…but filled with many prior concepts…By the standards of physics, their concepts are mostly wrong. Even so, they are the concepts by which students make decisions about physical processes.

- "Students' prior concepts are remarkably resistant to change…

- "Student knowledge is not organized in any coherent framework…

- "…As a result, most students don't develop a functional understanding of physics, they can't apply their knowledge to problems or situations not previously encountered, and they can't reason correctly about physical processes" (Knight 2002, p. 25).

The general idea is that if we hope to impact student thinking or student learning, we need to recognize how humans interpret, assimilate, organize, and recall information. This requires the gathering of information about students' thinking during all phases of the instructional process. To put this in context, it is interesting to consider the response offered to us by an experienced physics professor when we requested that diagnostic questions on entropy be administered to his physics class before instruction. This instructor said, "Well, they don't know anything about entropy; we haven't taught them yet." Although it may seem obvious that students do in fact have ideas before instruction, it's often not apparent just how resistant to change these ideas can be, or how poorly organized is the knowledge (both conceptual and procedural) that is held by many students.

(In Chapter 3, we will present a more in-depth discussion of those points mentioned above that are most directly relevant to this work.)

Knight also lays out "five easy lessons" for instruction that are drawn from the PER literature. They are, to quote directly:

1. Keep students actively engaged and provide rapid feedback.

2. Focus on phenomena rather than abstractions.

3. Deal explicitly with students' alternative conceptions.

4. Teach and use explicit problem-solving skills and strategies.

5. Write homework and exam problems that go beyond symbol manipulation to

    engage students in qualitative and conceptual analysis of physical phenomena.

This list is attractive in its brevity and directness, but the ordering scheme should

not necessarily be accepted as bearing some hierarchical significance. The importance of

students' "active engagement" appears to receive the most attention across all forms of

education, but in terms of learning physics, research suggests that the specific content of

the instructional activities is likely to be among the most important aspects of the process.

In particular, instruction based on research that addresses students' specific learning

difficulties has been found more effective than other forms of instruction in which

students may still be actively engaged. For example, Cummings (2001) and her

collaborators reported on an investigation that examined the impact of a "studio"

classroom (in comparison to a large lecture hall environment) and found that if research-

based instruction was not employed, learning gains were still small. Still other work

suggests that classes can feature many "active-learning" techniques and yet still have

minimal impact on student thinking if students' learning difficulties are not explicitly

addressed (Kraus 1997).

1.4.3 History and Major Findings

For the purposes of this discussion I will be considering the era of physics

education research that began with Arnold Arons and Lillian McDermott's work at the

University of Washington. Portions of the material in this section are drawn directly from

summaries prepared by the Physics Education Group at the University of Washington.

Other parts of this section summarize the most important work of other leaders in the field.

"In 1968 Arons came to UW to create a physical science course for pre-service elementary school teachers. McDermott followed shortly thereafter with a similar course for future high school teachers.

"The Physics Education Group (PEG) at UW began conducting research on student thinking in the 1970s, graduating its first Ph.D. in physics for research in physics education in 1979. This dissertation presented results from student interviews concerning two balls rolling on a straight and inclined track. Analysis of these interview responses, which were subsequently confirmed with written tests on a larger scale, revealed significant student difficulties with concepts of velocity and acceleration. The papers resulting from this research were published in the American Journal of Physics and were the first of their kind. (Trowbridge 1980, 1981) The investigation also guided the creation of the first Physics by Inquiry module on kinematics. (Physics by Inquiry… is a full-course curriculum targeted at instruction for pre-service teachers.)

"In 1991, the PEG began work on a curriculum for their university's introductory physics sequence for majors and engineers…Over a long time span the PEG has shown through pre- and post-instruction testing that many students, with varied educational backgrounds, possess similar conceptual and reasoning difficulties for many topics. These findings have been found to be reproducible and consistent across semester, instructor, and institution. This same model of research informing instruction continues to guide the curriculum [development of the PEG] …to this day" [PEG 2007].

Ibrahim Halloun and David Hestenes of Arizona State University provided a key step in the dissemination of PER when they created a survey to test students' conceptual knowledge in Newtonian mechanics. The Force Concept Inventory (FCI) has gained international renown for the extent to which it exposed the failings of traditional physics instruction (Halloun 1985). The FCI and its predecessor, the Mechanics Diagnostic Test (MDT), were some of the first assessments of their kind. Consisting of physically and conceptually simple questions, this diagnostic proves extremely challenging for students even after completing an introductory course in physics. It's worth noting that the FCI has faced criticism for its reliance on multiple-choice questions and a few unrepresented concepts (e.g., Huffman 1995).

Halloun and Hestenes were also among the first to show that most students in traditional courses fail to gain significant understanding of Newtonian mechanics, independent of the identify or popularity of the instructor who is teaching the course.

Richard Hake began work in physics education research after several decades of research in condensed matter physics. His seminal work "Interactive Engagement vs. Traditional Methods: A six-thousand-student survey of mechanics test data for introductory physics courses," is one of the largest (6500 students) and most extensive (62 institutions) studies conducted in PER. (Hake 1998) Hake provided strong evidence that students whose courses used "interactive-engagement" instructional methods (see Chap. 3) showed substantial (far greater than mere statistical significance) pre- to post-instruction gains versus those gains in which there was little to no interactive engagement.

Alan Van Heuvelen, now at Rutgers University, published seminal work on research-based instructional strategies in a course that emphasized problem solving (Van Heuvelen 1991a and Van Heuvelen 1991b). He stressed the importance of developing qualitative understanding through the use of multiple-representation problem-solving techniques, and on the formulation of a hierarchical knowledge structure.

E.F. (Joe) Redish of the University of Maryland became active in physics education research in 1992. He collaborated with many universities in creating the Physics Suite, a collection of curricular materials that incorporates the *Tutorials in Introductory Physics* with other research-based ideas for lecture, homework, etc. One of Redish's most significant contributions to PER is his insight into student learning that he sought to bring over from the perspective of cognitive science. (Redish 1994) Redish has provided PER with some of the most lucid explanations of constructivism and knowledge structure (on which I will elaborate in Chapter 3) using research on learning theory to support claims, and continues to be on the forefront of research on learning theory in physics education. Another of Redish's achievements is his ground-breaking work on students' expectations and attitudes in physics. The Maryland Physics Expectation Survey (MPEX) found that most physics courses (both those that emphasized traditional, and those that emphasized interactive environments) moved students *away from*, rather than towards, those attitudes that physicists are hoping to instill or cultivate in their students. (Redish 1999) This is touched on further in Chapter 4 below, in a discussion about students' beliefs regarding their role in the physics classroom.

Recently, there has been an increasing focus on upper-level physics curriculum in areas of quantum mechanics, mechanics, electricity & magnetism, and thermal physics,

the latter being the work of David Meltzer, John Thompson, their collaborators, and the author of this thesis. Although much of this work is in its preliminary stages, the initial results are promising; many of the same techniques and methodologies used successfully with introductory students also appear applicable with advanced students.

This enumeration of significant work could be substantially extended, but the review here covers the many of the early pioneers in the field.

Notes for Chapter 1

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Chapter 2: Literature Review

There have been a large number of textbooks and articles written about thermodynamics and statistical physics, many laying out novel methods for explaining various thermal relationships. Despite this impressive volume of material there has been, by comparison, relatively little research done on student understanding and learning of thermodynamic concepts. This chapter serves to review that literature which is most directly relevant to the research contained within this thesis. Further discussion of the literature on specific topics can be found in Chapters 4 and 5.

2.1 Research on Learning of Calorimetry Concepts

Cochran has recently investigated student understanding of concepts related to calorimetry. Cochran (2005) found among other things that: 1) students' difficulty distinguishing between heat and temperature may impair their ability to recognize that objects at thermal equilibrium are at the same temperature, and 2) students often associate the amount of heat transfer as being solely dependent on a single property in the interaction, without accounting for multiple variables such as mass and specific heat. Jasien and Oberem (Jasien 2002) conducted a study across various groups of college-level students. They report significant student difficulties with concepts involving thermal equilibrium, heat capacity, and specific heat, with no significant correlation between observed difficulties and the number of physical science courses that students had taken.

There is additional discussion of research on student learning related to calorimetry in Chapter 4.

2.2 Research on Learning of the First Law of Thermodynamics

In a seminal study at the University of Washington (UW), Loverude *et al.* (Loverude 2002) probed student thinking on the first law of thermodynamics. A wide range and depth of student confusion were observed. The study revealed a strong tendency for students to inappropriately apply the ideal-gas law in a wide variety of problem contexts. Even after interviewers suggested use of the first law of thermodynamics, students more often kept trying to apply the ideal gas law, despite its inadequacy for finding answers to the given questions. The authors suggest that this result might be traced, in part, to the emphasis on a microscopic model for thermodynamics often utilized when covering the kinetic theory of gases. The study also found that difficulties in understanding the concept of mechanical work could prevent a student from correctly applying the first law.

David Meltzer's study of student understanding of the first law of thermodynamics (Meltzer 2004) ran in parallel with Loverude's paper. Meltzer confirmed Loverude's findings that students emerge from the introductory calculus-based physics course with numerous fundamental reasoning difficulties with the first law of thermodynamics, as well as with difficulties understanding the definition and meaning of thermodynamic work. Meltzer's study further explored student difficulties related to the process-dependent nature of work and heat transfer, and highlights student confusion

with this idea during cyclic processes. A remarkable achievement of these two papers is how accurately they reflect some of the same misconceptions using different questions over similar material.

Recent papers by Meltzer have shed light on student thinking in an upper-level thermal physics course. Meltzer (2005; 2007) probed the extent to which junior and senior physics majors shared those difficulties observed in students in the introductory courses. Although upper-level students' pre-instruction performance was slightly better than the post-instruction performance of the introductory students on some questions, most students displayed the same difficulties encountered in the introductory course. Many students persisted with these difficulties even after instruction.

Kautz *et al.* (Kautz 2005a) conducted a study at UW among students in introductory calculus- and algebra-based physics courses, and in a sophomore-level thermal physics course. They found that many students were unable to properly interpret the macroscopic quantities in the ideal gas law, and that difficulties with mechanics concepts severely limited students' ability to relate the ideal-gas law to physical situations. From this study on student understanding of the macroscopic variables in the ideal gas law, Kautz, *et al.* determined that an investigation into student understanding of the microscopic perspectives was necessary. Many of the student difficulties observed at the macroscopic level were linked to misconceptions at the microscopic level (Kautz 2005b). This study cautioned against overreliance on use of microscopic models to introduce thermodynamics, since many students treated ideal gas particles like macroscopic objects that themselves have pressure and temperature.

2.3 Research on Learning of the Second Law of Thermodynamics

Kesidou and Duit (Kesidou 1993) conducted thirty-four clinical interviews with 15- and 16-year-old students who had received four years of physics instruction. They report that after instruction most students have ideas about processes going in one direction only and the energy being used up, but these notions were largely based on intuitive ideas about everyday life and were not in the "physicist's framework" that they were taught in class. In this context, the physicist's framework refers to the structure and linking of ideas that most experts would likely have. Kesidou and Duit conclude that student difficulties with heat and temperature are impeding student learning on the second law.

Bucy *et al* (Bucy 2005) reports on an investigation which has shed light on how students think about entropy in an upper-level thermal physics course at the University of Maine. Before instruction students appear to link entropy to concepts they are already familiar with such as temperature and energy, or to some notion of "disorder." The study found that students showed a poor grasp of entropy's state-function property. While instruction apparently resulted in strong learning gains on questions about the thermodynamic definition of entropy, student ideas about the state-function property remained largely unchanged.

The paper by Cochran and Heron (Cochran 2006) represents the only substantial published study of student understanding of entropy and the second law of thermodynamics in university-level physics. Their investigation focused on students' inability to accept or reject the possible existence of certain heat engines based on considerations of the second law of thermodynamics. In the development of their

research-based instructional materials (a "tutorial"; see Chapter 3), Cochran did a great

deal of research regarding proposed statements of the second law of thermodynamics.

(Cochran 2005). Reviewing numerous textbooks, Cochran demonstrated the vast array of

potential descriptions and pinpoints the advantages and pitfalls of each method.

Notes for Chapter 2

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Chapter 3: Methodology

3.1 Scientific and methodological basis for our work

The primary charge of physics education research is the development and assessment of effective and efficient instructional methods in physics. This section will describe the methodology we employ in conducting this work.

Researchers in physics education face constraints which are somewhat analogous to those encountered by early physicists in their studies of bulk materials. Such early research had to focus on macroscopic properties, until the time when direct probes of atomic and sub-atomic properties became possible (e.g., in work by Rutherford and Thompson). Analogously, physics education researchers do not yet possess the capability of making direct probes of students' brain structure to look for actual physiological indicators of students' thought processes. We are forced instead to rely on macroscopic manifestations of students' ideas, in the sense that students' answers to questions we pose are taken to be those "macroscopic" indicators of students' thought structures.

3.1.1 The framework in which we understand student learning

As we intend to draw conclusions about student knowledge from student responses to physics questions, it is important that we explicitly address our model of knowledge, that is, how it is organized and how it is changed. A useful model for students' knowledge structure has been proposed by Redish (Redish 1994, 2003). This

model is represented by an archery target that consists of three concentric rings shaded black, gray, and white.

The central black bull's-eye of the target describes those things that students know well; it represents a tightly linked network of well-understood concepts. The middle gray ring describes students' partial and imperfect knowledge. This is analogous to Vygotsky's "Zone of Proximal Development" (Vygotsky 1978). Knowledge in the gray region is in a developmental stage: some concepts and links are strong, while others are weak. The outer white region represents what students don't know at all, typically consisting of disconnected fragments of poorly understood concepts, terms and equations.

It is important to recognize the types of response patterns we expect to see when probing the different regions of knowledge. When questions are posed regarding knowledge in the central black region, students answer rapidly, confidently and correctly, regardless of the context or representation in which the question is posed. Questions posed regarding gray-region knowledge yield correct answers in some contexts and in some representations but not in others; explanations may be incomplete or partially flawed. Responses that are characteristics of questions posed to white-region knowledge consist mostly of noise; that is, answers are highly context-dependent, inconsistent and unreliable, and explanations are either deeply flawed or totally incorrect. (These response characteristics have profound implications for question development, which is discussed further in Section 3.2.)

The effectiveness of instruction also varies substantially by knowledge region. It is difficult to make significant relative gains in the black region of knowledge due to pre-existing high levels of understanding. Instruction in this region typically aims to polish

or refine these well-established ideas that are already present. Learning gains in the white region are generally minor, infrequent, and difficult to retain. Our model suggests that ideas in the white region lack anchors to regions which contain well-understood ideas. Teaching is most effective when targeting the gray region. Similar to a substance near a phase transition, a few key concepts and links can catalyze substantial leaps in student understanding.

3.1.2 Conducting research on student learning

The ultimate goal for much of PER is the development of effective and efficient curricular materials and instructional methods. The crucial first step in this process is a broad and deep investigation concerning student thinking and learning for the topic of interest. If we hope to increase student understanding via new instructional methods, we must first determine what ideas students are bringing to the classroom, as well as those ideas that they possess after instruction. If our aim is to improve this understanding, we must meticulously analyze student ideas about the topic in question, as well the underlying or supporting notions that may influence responses to the targeted concept.

3.1.3 Development of effective instructional methods

In recent years there have been numerous attempts at improving curriculum throughout the educational system, using various innovations for teaching and learning. Classrooms that traditionally have been taught via passive lecture now often include students working in small groups interacting with one another, with the instructor acting as a participant in the students' learning rather than merely as an authority figure who passes on information. There is a great deal of evidence that instructional methods of this

type can be effective at improving student understanding (e.g., Bransford 1999). The philosophy of the PER community is that rigorous testing of instructional innovations and methods, to assess the extent of their impact on student learning, is needed in order to make concrete statements about those impacts.

Research-based instruction can be defined as instruction that is based directly or indirectly on the findings of education research. Typically, though not always, such instructional methods are carefully tested to assess their effects on student learning. In order to determine productive approaches for creating instructional methods and materials, we must first consider how people learn and, more specifically, how they learn physics.

If we consider the implications of our model for knowledge structure, we are led to assume that students are not blank slates on which we can simply "write" correct knowledge and reasoning. Rather, students are likely to have a knowledge structure that is at least partially filled with incorrect, and/or incomplete notions, or correct ideas connected with weak, or broken links. If we want to help students develop a strong and well-organized knowledge structure, we must help them modify their incorrect or incomplete ideas and build on their correct understanding.

It's insufficient to simply collect a list of student "misconceptions," and then attempt to dispel all incorrect notions via a lucid and intelligent lecture. While instruction of this type may assist a few students, research has shown that most students gain relatively little through this approach (e.g., McDermott 1991). In its stead, PER offers many useful strategies. One such strategy will be the focus of this thesis,

specifically, the creation of research-based tutorial-style worksheets that employs many of the strategies covered in the following section.

3.1.4 Research-based instructional methods

There have been a large number of instructional strategies reported in the PER literature. The umbrella-term used to describe many of these methods is "interactive-engagement instruction." In an attempt to paint the landscape of this catch-all phrase, we can look to the literature and try to extract common features of these various strategies.

Interactive-engagement instructional methods are, either explicitly or implicitly, informed and guided by knowledge both of students' pre-instructional ideas (McDermott 1991, 1993, 1997, 2001; Halloun 1985; Hake 1987, Goldberg 1995) and of the ways in which those ideas are changed via instruction (Thornton 1992; Meltzer 2005). This feature is a direct consequence of an awareness that students come to class with previously-formed ideas and understanding. Instruction can then guide students to elicit and address known student difficulties, whether this is described as direct "confrontation" of those difficulties (McDermott 1991, 1993, 1997, 2001) or as carefully guided revision of previously-held concepts (Elby 2001). The former is one formal way of describing cognitive conflict, by which students are guided to recognize the flaws in their reasoning and helped to reconcile their understanding by modifying their ideas. The latter approach aims to avoid direct conflicts with students' thinking that might tend to discourage them from science learning, and emphasizes instead a restructuring of students' current ideas.

Instruction that emphasizes student "discovery" to the extent that it is practical and appropriate can in certain contexts be very effective. For example, the University of

Washington's *Physics by Inquiry* curriculum guides students to reason out key ideas through "guided inquiry," which is a process of questioning and discussion with student peers and the instructor. (McDermott 1997)

Another key component is instruction that leads students to express their reasoning explicitly both in verbal form (via student-instructor interactions and student-student interactions), or in written form on free-response homework problems, or on quiz or exam questions that ask for written explanations. (McDermott 1991, 1993, 1997, 2001; Hake 1987; Goldberg 1995; Minstrell 1989; Arons 1976; Redish 1994; Leonard 1996; Heller 1992) These types of activities are often best accomplished by allowing students to work in small groups, so that they can effectively comment on, listen to, and provide critiques for each other's ideas and reasoning. (McDermott 1997, 2001; Goldberg 1995; Hake 1992; Heller 1992) These methods also benefit from the rapid feedback that instructors are able to provide to the students, particularly in problem-solving activities (Reif 1995; Hake 1998) Again, this feedback can be provided from the instructor or from other students in the class.

Instruction that emphasizes students' qualitative and conceptual thinking rather than simply the mastery of algebraic or algorithmic techniques is another effective element of interactive engagement. (McDermott 1991, 1993, 1997, 2001; Reif 1995; Hake 1987; Goldberg 1995; Arons 1976; Redish 1994; Leonard 1996) By making use of non-quantitative means for solving problems, students can often strengthen their understanding of fundamental principles. Lastly, instruction that provides exposure to and practice with problems in wide variety of contexts and representations (verbal, graphical, pictorial, tabular, etc.) can develop more robust understanding (McDermott

1990, 1993, 2001; Reif 1995; Goldberg 1995; Hake 1992; Minstrell 1989; Arons 1976; Redish 1994; Leonard 1996; Heller 1992; Etkina 2001, 2006; Van Heuvelen 1991; Hestenes 1997; Meltzer 2005) .

Unlike some other techniques occasionally offered as potential teaching innovations (often based only on perfunctory assessment), these research-based methods of physics instruction have significant, reproducible success at improving student understanding of physics. For some of these methods, evidence of success has been accumulating for over 30 years. Some studies which advocate alternative instructional methods caution that certain instructional strategies (such as cognitive conflict) may negatively impact students' attitudes about science in certain contexts (Redish 1998). Redish notes that traditional instructional methods also face this same problem, so it would appear that while cognitive conflict may sometimes, in some cases, negatively impact certain students' attitudes about science, at least it can be successful in improving their understanding (unlike traditional instruction). This is not to suggest that these are the only instructional methods that are capable of improving student understanding. Rather, there are likely many methods that *might* work, but there is clear evidence that those methods described above *do* work.

The development of the interactive-engagement teaching methods embraced by physics education researchers can be traced most directly to those educational innovations that began after World War II. The Physical Science Study Committee project in 1956 by MIT physicists Jerrold Zacharias and Francis Friedman was one of the earliest steps in this long chain of developments (Finley 1962). Leading to the re-thinking of the high-school physics curriculum, this project emphasized the communication of

deep conceptual understanding of the pervasive underlying themes of physical principles. After the launch of Sputnik, the National Science Foundation began to support similar developments in physics and in other disciplines as well, and with the help of the National Academy of Sciences a joint meeting with scientists and leading psychologists produced more work (Bruner 1960 and Schwab 1962).

Soon, work by prominent physicists Philip Morrison (Morrison 1963) and Robert Karplus (Karplus 1964) along with many other workers in a variety of fields was being developed and applied to new instructional methods and materials aimed at the elementary school level. This work strongly emphasized the principles of guided-inquiry instruction based on an understanding of students' pre-existing knowledge and ideas. Arnold Arons (Arons 1976) and Lillian McDermott (McDermott 1975, McDermott 1976) of the University of Washington put these instructional methods into action at the university level with pre-service and in-service K-12 science teachers, pushing for students to express their reasoning in written and spoken form.

Modern ideas about guided inquiry are traceable in part to the three-phase "learning-cycle" that was developed by Karplus and his collaborators (Atkin and Karplus 1962). The work of Karplus, in turn, was very directly motivated by over 30 years of work published by Piaget and his followers, who were among the first to utilize notions of active learning associated with "disequilibrating" students' thinking through confrontation with surprising or unexpected physical phenomena (e.g., Piaget 1935). Science educators (e.g., Driver 1973 and Novick 1976) began to see the pedagogical significance of those ideas that students brought with them into the classroom, something that had been emphasized by Piaget who stressed that that new ideas must be

"accommodated" into students' previously existing understanding (Piaget 1935). The guiding notion that students must create their own understanding of new concepts by testing new experiences against previously developed ideas came to be known as "constructivist" pedagogy (Bodner 1986; McDermott 1991). Many further developments and implementations of these ideas are discussed and referenced in the compendia by Gabel (1994) and Bransford (1999).

In the late 1970s physics education groups in France (Viennot 1979) and the US (Trowbridge 1980) began to systematically study student understanding of specific science concepts at the university level, which led to the creation and implementation of research-based instructional materials in specific disciplines. This theme was also being implemented by researchers in chemical education (e.g., Herron 1986) and, to a more limited extent, in other fields as well.

3.2 Data collection methods

Before we can deeply analyze our students' thinking, we need to have a firm understanding about the methods by which we are assessing our students' understanding. As discussed above, we utilize students' responses to physics questions as a means of inferring information about their knowledge. We employ multiple questioning strategies and techniques through which we can assess student thinking.

As we probe ideas that exist in the "gray" region, we must consider the response characteristics which our model suggests will be encountered. Student knowledge in this region is often inconsistent and context-dependent, so we need to craft our questions such

that they yield the most precise possible picture of students' ideas. Therefore, the best questions for probing students' conceptual knowledge: 1) have little technical language that might otherwise serve as a distraction for a student, 2) have a clear description of the problem and the physical process in question, 3) are solvable with few numerical calculations. From this standpoint, I will look at the benefits and shortcomings of one-on-one interviews, free-response questions, and multiple-choice questions.

3.2.1 One-on-one interviews

One-on-one interviews are our deepest available probe of student understanding, because they allow a dialogue to occur between the researcher and the student. They are typically one hour in length and usually feature a series of related questions. Interviews are conducted with student volunteers and are either recorded with audio or video equipment. Students are asked to respond to a question using a "think-aloud" method, in which the students describe their reasoning as they go about solving a problem. This can assist the researcher in tracking how the student is attempting to solve the problem, and which elements of knowledge and experience are being activated in the process. Researchers can ask clarifying questions if the student's explanations are inconsistent or unclear.

For all the advantages interviews provide, they consume substantial amounts of time both to conduct and to analyze. This drawback leads to sample sizes that are smaller than with other methods (typically on the order of 10-30). Another consequence of using student volunteers is that the students in the interview sample are self-selected, and they

typically represent a high-achieving subset of the entire student population we are investigating. (For an example of this from our own work, see section 5.5.2.)

3.2.2 Free-response questions

Free-response questions are another important method for probing student ideas. Questions of this type explicitly ask for an explanation of the student's answer. This can provide valuable insight into what ideas led a student to their response. The administration of several free-response questions can be very time efficient. Students are expected to answer these questions without any input or assistance from an instructor, so the amount of data that can be collected is not constrained by time. Analysis of these data can be time consuming, depending on the length of the questions and the depth of student explanations. The key shortcoming of free-response questions is the absence of any instructor-student dialogue. Researchers are only able to work with what students give them, however brief or incomprehensible it may be. (Examples of this type of response can be seen in Chapter 4 and Chapter 5.)

3.2.3 Multiple-choice questions

Multiple-choice questions are one of the most widely used forms of student assessment in large-enrollment courses. Unfortunately there are many drawbacks when using them to probe student thinking. Instructors may erroneously associate certain responses with a particular line of student thinking. Even if a group of physicists might agree that a particular answer seems to correspond to a particular student idea, a researcher isn't confident of this connection unless there is strong interview and free-response data to support the relationship. Forcing students to respond in one of only four

or five ways, as dictated by the question, may not allow for an alternative conception that students are actually using.

Use of multiple-choice questions is highly tempting to an instructor due to the ease of grading a large number of students in a brief period of time. Development of effective and reliable multiple-choice questions, or sets of such questions such as the FCI (Hestenes 1992), or the FMCE (Thornton 1998), requires many years and numerous test samples of significant size. Even then, such question sets can be held up for criticism due to various presumed inadequacies (e.g., Huffman 1995). (For an example from this study of difficulties involving interpretation of multiple-choice questions, see section 5.6.2.2.)

3.3 Data analysis methods

PER uses many specific data analysis methods as means of investigating student thinking. Our goal is to accurately and fairly represent student ideas, with as little interference and making as few assumptions as possible. In this way PER aims to be highly robust with respect to its claims, in the sense that findings should be reproducible across diverse student populations in a wide variety of instructional contexts, including different instructors..

3.3.1 Categorization of responses

It is very common when writing a physics question to speculate about possible student responses. As researchers who are interested in assessing what students are thinking, we want to write the best questions possible in hopes of getting accurate

determinations of students' ideas. Making an initial hypothesis regarding anticipated student responses may help us, after it is first administered, to determine whether a question needs revisions. This practice may guide a question's construction, but it doesn't restrict us in our analysis of the responses.

In analyzing free-response or interview data, it is a standard practice in PER to first allow student responses to filter into what could be called "natural" categories. These categories are determined by the data which are obtained, as opposed to being predetermined by the researcher before any observations are made. Initially, student responses are recorded by using actual student language whenever possible. After having analyzed approximately fifty student responses, we look for common themes among the student explanations. These themes are used to generate new categories, which are then employed throughout the analysis with frequent checks to ensure a good fit to the observations. Often, an "other" category is used to group less-popular responses. Often, the initial categorization is inadequate for describing the details of student understanding and so revisions will occur. This may lead to a re-categorization of all data to keep analysis consistent.

3.3.2 Testing for reliability of question responses across semesters

As with all scientific fields, PER strives for reliable results when probing student thinking. There is an expectation that administering the same question at the same relative time in a semester (e.g., before all instruction) will yield very similar results from one year to the next. However we must explicitly check for this if we want to claim that the question is reliably assessing our population. After taking multiple data samples, we

are able to report our results including an explicit calculation of a confidence interval for these data. .

If a question is shown to be unreliable, we use student explanations to assess what ideas might be cueing specific student responses. We can further probe student thinking on these issues through one-on-one interviews. Again, although we might speculate in advance as to what the defects in the question might be, we always use our data to draw our conclusions.

3.3.3 Correlating individual responses across various questions

Our model for student thinking supposes that knowledge is a large collection of ideas (with all shades of grey from completely correct to utterly incorrect) that are connected and organized with various associations and relationships. This model then assumes that a student response on one particular question isn't simply a measure of one completely separable and independent notion, but rather an understanding that is, in some way, critically linked to their thinking on various concepts that they associate with the particular question. By correlating individual responses across various questions we attempt to map out some of these related ideas. (For instance, a student may get an incorrect answer concerning the relative temperature changes of an object and a liquid in a calorimeter cup, not due to a misunderstanding about specific heat capacity, but due to a notion that energy isn't conserved in the process.)

This analysis provides many challenges as we can't possibly analyze all possible correlations, so we must make use of our expert understanding of the topic along with insight garnered from student interviews and free-response data. It is common to

investigate those correlations among question responses that might characterize the thinking of an expert, since we would hope students are developing expert-like knowledge structures. However it is vital that the scope of ideas and understanding we analyze is not limited to these expert-like threads of reasoning alone. The notions students bring to a physics problem have the potential to be extremely broad and diverse, so it's realistic that in checking a limited number of correlations among responses we are failing to detect certain patterns in student knowledge structures. Allowing student responses from interviews and free-response questions to inform our analysis is a key aspect of our investigation, and often informs our study by leading us to develop new questions for probing student thinking.

3.3.4 Comparing responses across question type

There is strong evidence that student responses on a given topic are linked to the context and representation in which a question is presented. Students with robust understanding are able to answer content questions in any number of formats (pictorial, graphical, diagrammatic, text-based, etc.) with little difficulty, while a student whose knowledge is more disorganized is likely to provide inconsistent responses. The important point is that while important information is provided by the proportion of students who answer a particular question correctly, it's naive to believe that a correct-response rate for a single question alone provides a complete picture of what students are thinking.

3.3.5 Using interviews to deepen understanding of students' thinking

One focus of PER is the use of large samples of answers to free-response questions that could potentially provide significant findings. However, free-response data does lack a researcher-student dialogue which could allow for deeper probing of student understanding. Free-response explanations have the potential to be misleading because eventually they require an interpretation, since student answers can be incomplete or unclear.

In a one-on-one interview we can further question students about the explanations they provide, probing those ideas that led to their answer, and ask follow-up questions that are tailored to the explanation and to the ideas presented by a particular interviewee. In so doing, we attempt to assess how their thinking is organized and what resources are activated when approaching a problem. (As used here, the term resource refers to any idea, algorithm, equation, feeling, experience, etc. that might be employed, or drawn upon from long-term memory when considering a particular problem.) Due to time constraints, we rarely conduct enough interviews for statistical tests. However, the purpose of the interviews is more often to provide an in-depth probe of the diverse ideas that may be present in a student population.

3.4 Statistical review

This section will give an overview of the statistical assumptions that we make in analyzing our population, and will describe some of the statistical tests we use.

3.4.1 Statistical assumptions

If we consider the population of students enrolled in all calculus-based introductory physics courses at major universities with substantial engineering programs in the United States, this group numbers in the several hundred thousand each year. For statistical purposes this population is essentially infinite. If we were able to administer a series of questions to every individual in this entire population we could determine the mean score and the distribution for all students. We will define the mean score of the entire population to be μ, and the standard deviation of the distribution to be σ. The spread of this distribution is primarily due to the variation in individual responses, though a small error portion is due to the imperfect reliability of the instrument. We will ignore the latter effect since we expect it to be much smaller than the true variations among the individual students.

Suppose we now choose a random collection of subsamples from our entire population each with a sample size of N students (where N is roughly 500). For each of these subsamples there exists a subsample mean and subsample standard deviation. This collection of subsample means have a distribution of its own. This distribution will have its own mean and standard deviation. The mean of the collection of subsamples will be equal to μ, the mean of the entire population, but the standard deviation is NOT equal to the standard deviation of the entire population; rather it is equal to $\dfrac{\sigma}{\sqrt{N}}$, (often referred to as the standard error). If we obtain one such subsample (i.e. subsample A) we can determine the mean μ_A, and standard deviation σ_A, where μ_A and σ_A are expected to be good estimators of μ and σ, respectively. We can thereby estimate that the mean of the

total unobserved population is equal to $\mu_A \pm$ *1.96* $\frac{\sigma_A}{\sqrt{N}}$ with 95% confidence. (the 1.96

factor holds for samples of infinite size, while smaller samples have larger prefactors.

The factor corresponding to $N = 4$ is 3.18.) That is, we expect 95% of subsamples of size

N to fall within two standard errors of the observed mean, when the standard error is

calculated using N and the observed σ_A (Guilford 1965).

If we have two N-sized subsamples (e.g. Fall 2005 course, Spring 2006 course),

we would expect that, if the subsamples received identical treatments, their means should

be within two standard errors of one another 95% of time. If they are not that close, we

might suspect the presence of some uncontrolled variables that are causing deviations

greater than those we would expect from statistical fluctuations.

If our diagnostic instrument is a binomial type—that is, one that requires either a

yes or no response, or one that is classified as correct or incorrect without some

percentage score—we assume the standard error is equal to $\sqrt{\frac{p_A(1 - p_A)}{N}}$. Here p_A is the

percentage of correct responses in the entire subsample, and for the limiting case of an

infinite sample size the standard error equals zero. It is interesting to consider how this

estimated standard error would compare to the actual standard error that could be

obtained from an equivalent multi-question instrument. For an instrument of that type,

score variances and standard errors based on those variances could be calculated. Those

standard errors might or might not be equal to those obtained by estimating from the

binomial proportions formula.

Our procedure then consists of making multiple observations and checking whether the resulting means fall within intervals of two standard errors. If they do, we conclude that any observed differences are the result of random sampling fluctuations, If the scores are not within the intervals, we would suspect that the method of instruction or perhaps the instructors themselves might be having some effect. In the case of identical instructors, we might suspect that the diagnostic question(s) is (are) triggering some context-dependant response that cause a variation in student response that is outside previously observed intervals.

3.4.2 Confidence intervals

We are able to calculate confidence intervals on questions which we have administered multiple times at (approximately) the same time during a course (e.g. before all instruction, after all instruction, etc.). These intervals are calculated by $\mu \pm t_{df} \dfrac{\sigma_{actual}}{\sqrt{N}}$ where μ is the mean value, the t_{df} value is read from Student's t-value tables (e.g., Guilford 1965) depending on the desired level of confidence and the number of degrees of freedom (df, which we calculate from the number of samples minus 1, $[N - 1]$). The σ_{actual} is the standard deviation we calculate from the variances of our samples,

3.4.3 Two-sample t-test

We use a two-sample t-test to determine the statistical significance of the difference in mean values of two samples of data. More formally, we are testing the null hypothesis: the two measured samples have equal means. The two-tailed t-test requires a calculation of a t-statistic from the data of the two samples:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\dfrac{\sigma_1^2}{\eta_1} + \dfrac{\sigma_2^2}{\eta_{21}}}}$$

where $\overline{x_1}$ and $\overline{x_2}$ are the mean values of the samples 1 and 2, σ_1 and σ_2 are the standard

deviations of samples 1 and 2, and η_1 and η_2 are the sample size for sample 1 and 2. If

the *t*-statistic is greater than that corresponding to the *p*-value that corresponds to the

desired level of confidence (95%, for instance) and the degrees of freedom ($\eta_1 + \eta_2 - 2$)

in the samples, then we can reject the null hypothesis with the specified level of

confidence.

3.5 Difficulties and limitations of our research

PER, as with any field of scientific research, faces challenges and limitations in

certain aspects of its experimental design and analysis. This section will examine some

of these difficulties, look at how they impact this work, and describe how we work within

and around these limitations to engage in rigorous scientific study.

3.5.1 Sample Size Difficulties

In section 3.4, the statistical approach for conducting this research was described.

The strength of this work is its emphasis on statistically significant results due to

adequately sized samples of students. However, if an effect is sufficiently small and the

sample is *not* sufficiently large, even a real effect could be seen as "not statistically

significant" in a given investigation. As convenient as it would be, we are not afforded

the luxury of going into our lab and "cooking-up" an ensemble of students. The constraints on our ability to access real students enrolled in actual classes form one of the most significant limitations on this work. This constraint can sometimes be due to obstacles that develop between a researcher and his or her desired sample; these can occur at multiple levels: researcher/instructor conflict, researcher/departmental conflict, researcher/Institutional Review Board (IRB) conflict, researcher/testing site conflict, etc.

3.5.2 Instructor Difficulties

Since we are assessing students who are actually enrolled in a course, the researcher must secure time from the class and the permission of the instructor to administer materials. Not all instructors welcome a study in their course that could potentially show the students aren't learning the material very well. And, regardless of the specific reasons, some instructors simply don't feel they can allocate the amount of time for testing that researchers might desire. Even if the instructor is open to the investigation, the timeline for the course is often restrictive (due to published syllabi and course schedules) and may impede the collection of data. For instance, if a topic is covered during the first and last week of class, data collection could be particularly difficult.

At the department and university level, researchers may be forced to justify the aims of their study and the form of impact that is expected. Tasks such as adding additional researchers to the project, conducting interviews, collecting data with different samples of students, etc. may hamper the timeliness and effectiveness of a particular project.

3.5.3 Human Subjects Testing Difficulties

Much of PER involves the assessment of student thinking, and is therefore inextricably linked to real students in physics classes. The department and the Institutional Review Board (IRB) of the university may have concerns about using actual students in a course as test subjects. As such the researcher is often required to work through the university's IRB, which can be extremely limiting if the researcher wants to maintain flexibility in his or her experiment. As a general rule most of the testing procedures that are utilized by PER are within what would normally be asked of a student (typically asking them physics questions), and as such these procedures should be exempt from Human Subjects Testing concerns. However, since categorization is left up to the discretion of each school's board, these problems can be amplified as we attempt to test materials at other universities. This difficulty had a direct impact on our investigation, as we had collaborators at other universities collect data that we were ultimately not allowed to use in our study due to IRB restrictions at the collaborating institution. This experience suggests that before collecting data, a researcher would be well-advised to consult the off-site's IRB to ensure that the time and effort of collecting data will not be wasted.

An alternate concern with off-site testing is the ethical and practical concern of sending out raw materials that haven't been adequately refined or tested. In a rush to net the largest possible sample size it is often tempting to distribute materials right away. However, if we are very unsure of the potential effectiveness of our questions, it isn't appropriate to ask other institutions to use valuable class time to administer them. This would be analogous to an experimentalist in condensed matter physics sending out crystal

samples to be used in experiments with apparatus at different institutions, before

checking that the sample materials are properly made and capable of yielding useful data.

3.5.4 Theoretical Difficulties

At this time, the methods of PER don't allow for precise theoretical "predictions"

in the sense that physicists ordinarily understand that term. Although some PER groups

are making a few early steps that might lead in the direction of this kind of theory, there

is nothing available at the present time. The only method we have for determining that

an effect has occurred is to collect data and analyze them. The theoretical "framework"

or model which we do have gives a foundation for our methods and procedures that are

shown to be successful. We can't be sure that we are using the best method; in fact, it is

unlikely that there is any "best" method, but rather a range of acceptable methods some

of which can be shown to be better than others in certain contexts. The best prediction

we can make is that using the well-tested methods outlined in seminal papers in the PER

literature, it may be possible to improve students' conceptual understanding more than

ordinarily occurs with traditional means of instruction.

We are also limited in our studies by what our data tell us. We can only report on

those things that we measure: human responses, whether they be verbal, written, gestures,

or other forms of communication. Humans are complex systems, and any particular

instruction might have other effects than those which we are assessing.

Notes for Chapter 3

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Chapter 4: Student understanding of calorimetry

4.1 Overview of calorimetry in introductory physics

Unlike some of the other more complicated topics in introductory physics calorimetry only requires relatively straightforward application of a few fundamental principles, namely energy conservation and specific heat, along with basic algebraic acumen. Typical coverage of thermodynamics in introductory physics begins with a brief introduction to thermodynamic systems, and quickly proceeds to discussions of temperature and temperature scales. Linking temperature to other system properties such as length and volume follows with the formulation of thermal expansion relationships. Then, relationships among pressure, volume, and temperature with the various "named" laws (e.g. Boyle's Law, Charles's Law, etc.) are brought together to form the ideal gas law.

Calorimetry is often the next topic discussed and depending on the instructor's preference, students might be asked to use a relationship for specific heat, $Q = mc\Delta T$ or molar specific heat $Q = nc_{molar}\Delta T$. The definition of specific heat does not vary significantly from textbook to textbook, with most simply describing it similarly to Reese, "You can think of specific heat as the heat transfer to one kilogram of the material needed to raise its temperature by one Kelvin."

4.2 Overview of previous research on calorimetry topics

The most robust and insightful investigation concerning student thinking on calorimetry is the work of Matt Cochran and his collaborators at the University of Washington. As is carefully discussed in his dissertation, Cochran (2005) surmised that: 1) students have extensive difficulty distinguishing between heat and temperature and that this may impair their ability to understand other thermodynamic concepts, such as the ability to recognize that objects at thermal equilibrium are at the same temperature, 2) students occasionally focused on *rates* of heat transfer or temperature change when it wasn't appropriate to do so, and 3) students would commonly associate the amount of heat transfer as being solely dependent on a single property in the interaction. For example, the change in temperature of a hot copper block in water was thought to be due *only* to the specific heat or initial temperature of the block, ignoring the role of the mass.

Greenbowe and Meltzer (2003) conducted research on student thinking about calorimetric concepts for chemical solutions in introductory chemistry courses at Iowa State. They reported similar difficulties regarding student confusion between heat and temperature, and found that these misconceptions were not easily dislodged.

Jasien and Oberem (2002) conducted a study across various groups of college-level students using multiple-choice questions. They report significant student difficulties with concepts involving thermal equilibrium, heat capacity, and specific heat, with no significant correlation between observed difficulties and the number of physical science courses that students had taken.

4.3 Concepts we are assessing

In this section we specify a set of concepts, the understanding of which we attempted to assess during our investigation of student thinking on calorimetry.

4.3.1 There in no heat transfer between the inside and the outside of a perfectly insulated container

A necessity for qualitative and quantitative comparison of temperatures changes, between objects in thermal contact, is that we can assume that energy is conserved as the objects exchange energy in their approach to thermal equilibrium. The physical constraint we typically impose on the objects is to put them into a calorimeter container that we assume does not allow energy to escape or enter.

4.3.2 When two objects are in an insulated container, the magnitude of heat transfer from one object is equal to the magnitude of heat transfer to the other object

One of the most fundamental physical principles we hope to teach students in introductory physics is that energy is conserved in any physical process. Students are expected to transfer to other physics topics, ideas about energy conservation that they may have learned as part of their studies on mechanics (e.g. where total mechanical energy is the conserved quantity).

4.3.3 The specific heat is the amount of energy per unit mass required to change the temperature of some object

The most common quantity students work with in calorimetry is the specific heat capacity. This quantity is useful for analyzing energy transfers to something that undergoes a change in temperature, and is relatively simple to apply as long as no phase transition occurs.

4.4 Questions used to probe student ideas on calorimetry

4.4.1 Object in Liquid, free response

The specific heat of water is greater than that of copper.

A piece of copper metal is put into an insulated calorimeter which is nearly filled with water. The mass of the copper is the same as the mass of the water, but the initial temperature of the copper is higher than the initial temperature of the water. The calorimeter is left alone for several hours.

During the time it takes for the system to reach equilibrium, will the temperature change (number of degrees Celsius) of the copper be more than, less than, or equal to the temperature change of the water? Please explain your answer.

Figure 4.1 Object in Liquid, free response

Description: This question (and the various versions of it; see Appendix) describes an object and a liquid in which it is immersed, such that the two are initially at different temperatures. The question asked about the change in temperature of the object and the liquid during the time it takes for them to reach equilibrium, that is, a common final temperature. This question was presented in several different versions which varied the relative specific heats and relative initial temperatures of the object and liquid. In addition, a wording change was introduced in later versions to address concerns about student understanding of the word "equilibrium"; see Section 4.6.2.

Physics Principle: Students are expected to recognize that since this process occurs inside a calorimeter and energy is conserved, we can assume that there is no heat transfer aside from that between the object and the liquid. Therefore, all energy that is lost by the one will be gained by the other. For equal changes in energy and equal masses, the temperature change of each item will be inversely proportional to the specific heat capacity of that item. Algebraically:

$$Q = mc\,\Delta T$$
$$\left|Q_{Cu}\right| = \left|Q_{Water}\right| \ \ and \ \ m_{Cu} = m_W$$
$$\Rightarrow c_{Cu}\left|\Delta T_{Cu}\right| = c_W\left|\Delta T_W\right|$$
$$\left|\Delta T_{Cu}\right| = \frac{c_W}{c_{Cu}}\left|\Delta T_W\right|$$
$$c_W > c_{Cu} \Rightarrow \left|\Delta T_{Cu}\right| > \left|\Delta T_W\right|$$

What this question attempts to probe: The extent to which students can determine relative temperature changes for two substances that conserve energy between them, have equal masses, and have different specific heats.

What this question does not attempt to probe: The question does not explicitly ask for whether or not the heat transfers are equal, and this may be an underlying cause of incorrect student answers. (See further discussion in Section 4.6.4.)

Issues: As mentioned below in the discussion of 4.6.2, the use of the word "equilibrium" was addressed during the course of the investigation. There also were some concerns about students misinterpreting the question and thinking that, since the higher temperature had to decrease, it must therefore have a "smaller" temperature change since

it had a negative change in temperature. However, analysis of students' written and

verbal explanations indicated that this form of misinterpretation was very rare.

4.4.2 Two Liquids, free response

Suppose we have two *separate* containers: One container holds Liquid A, and another contains Liquid B. The mass and initial temperature of the two liquids are the same, but the *specific heat* of Liquid A is *two times* that of Liquid B. Each container is placed on a heating plate that delivers the *same rate of heating* in joules per second to each liquid beginning at initial time t_0.

    a) On the grid below, graph the temperature as a function of time for *each* liquid, A and B. Use a separate line for each liquid, even if they overlap. Make sure to clearly <u>label</u> your lines, and use proper graphing techniques.

Temperature

Liquid A   Liquid B

Heating Plate

t_0 Time   The specific heat of A is greater than the specific heat of B.

    b) Please **explain** the reasoning that you used in drawing your graph. (Please continue on the back of the page.)

Figure 4.2 Two Liquids, free response

Description: Two liquids of equal masses and different specific heats are heated at equal

rates. Students are asked to sketch a graph of temperature change over time for the two

liquids, and to explain their answer. (Different versions of this question varied the ratio of

$c_A{:}c_B$.)

Physics Principle: The liquids are being heated at equal rates and have equal masses;

therefore the liquid with the higher specific heat will have a smaller increase in

temperature as compared to the liquid with the lower specific heat over that same period.

What this question attempts to probe: The extent to which students can determine relative temperature changes over time for two substances that have equal masses, receive equal rates of heating, but possess different specific heats. This question also probes students' ability to represent their answer in different contexts e.g., graphical form.

What this question does not attempt to probe: This question does not directly probe whether students understand that there is an equal amount of energy transferred per unit time to the two liquids. (We aimed to address this issue in other questions.)

Issues: This question also probes students' ability to report their answer in a graphical form which may interfere with their ability to give a completely correct response. See section 4.6.2 for more discussion of this issue.

4.4.3 Object in Liquid, text multiple-choice

An object is immersed in a liquid within a sealed and insulated container. The mass of the object is the same as the mass of the liquid. The initial temperature of the object is lower than the initial temperature of the liquid, but the specific heat of the object is *greater* than that of the liquid. The calorimeter is left alone for several hours until it reaches equilibrium. Which of the following is true? *Note: Here, "temperature change" means "number of degrees Kelvin increased or decreased."*

   A. The energy transfer to the object is *not* equal to the energy transfer away from the liquid, and the temperature change of the object is greater than the temperature change of the liquid.

   B. The energy transfer to the object is *not* equal to the energy transfer away from the liquid, and the temperature change of the object is less than the temperature change of the liquid.

   C. The energy transfer to the object is equal to the energy transfer away from the liquid, but the temperature change of the object is greater than the temperature change of the liquid.

   D. The energy transfer to the object is equal to the energy transfer away from the liquid, and the temperature change of the object is equal to the temperature change of the liquid.

   E. The energy transfer to the object is equal to the energy transfer away from the liquid, but the temperature change of the object is less than the temperature change of the liquid. **(correct)**

Figure 4.3 Object in Liquid, text multiple-choice

Description: This question is almost identical to our object in liquid, free response question. Students are offered possible answers that allow for equal and unequal heat transfers, and for correct and incorrect rankings of changes in temperature, including equal temperature change.

Physics Principle: Heat transfers between an object and a liquid inside a calorimeter are equal and opposite of one another, and specific heat determines the amount of energy it takes to change the temperature of a given mass.

What this question attempts to probe: The extent to which students can determine relative temperature changes for two substances that conserve energy between them, have

equal masses, and different specific heats. This question also probes the extent to which students understand that heat lost by one substance will be gained by the other substance.

Issues: A few students complained about the extensive "legalese," or wordiness of this question, and there were concerns that this wordiness might lead to student confusion. This led to our development of a similar question with a more compact formulation; see Question 4.4.4 and the discussion in 4.6.4

4.4.4 Object in Liquid, symbol multiple-choice

Object A has mass m_A, specific heat c_A, and initial temperature $T_{initial\ A}$. Liquid B has mass m_B, specific heat c_B, and initial temperature $T_{initial\ B}$. Object A is immersed in Liquid B within a sealed and insulated container (i.e., a calorimeter). We are given the following information:

$$m_A = m_B$$
$$c_A > c_B$$
$T_{initial\ A} < T_{initial\ B}$ but after a long time, $T_{final\ A} = T_{final\ B}$

Which of the following is true? [Q is heat transfer; $\Delta T \equiv T_{final} - T_{initial}$]

A. $Q_{to\ A} \neq Q_{away\ from\ B}$; $|\Delta T_A| > |\Delta T_B|$
B. $Q_{to\ A} \neq Q_{away\ from\ B}$; $|\Delta T_A| < |\Delta T_B|$
C. $Q_{to\ A} = Q_{away\ from\ B}$; $|\Delta T_A| > |\Delta T_B|$
D. $Q_{to\ A} = Q_{away\ from\ B}$; $|\Delta T_A| = |\Delta T_B|$
E. $Q_{to\ A} = Q_{away\ from\ B}$; $|\Delta T_A| < |\Delta T_B|$ **(correct)**

Figure 4.4 Object in Liquid, symbol multiple-choice

Description: This question is almost identical to our object in liquid, free response question and to the object in liquid, text multiple-choice question. Students are offered possible answers that allow for equal and unequal heat transfers, and for correct and incorrect rankings of changes in temperature, including equal temperature change.

Physics Principle: As with 4.4.1, students are expected to recognize that this process occurs inside a calorimeter, and that therefore we can assume that all energy that is lost by the object or the liquid will be gained by the other. For equal changes in energy and

equal masses, the temperature change of each entity will be inversely proportional to the specific heat capacity of that entity. Algebraically:

$$Q = mc \, \Delta T$$
$$\left| Q_A \right| = \left| Q_B \right| \quad and \quad m_A = m_B$$
$$\Rightarrow c_A \left| \Delta T_A \right| = c_B \left| \Delta T_B \right|$$
$$\left| \Delta T_A \right| = \frac{c_B}{c_A} \left| \Delta T_B \right|$$
$$c_B < c_A \Rightarrow \left| \Delta T_A \right| < \left| \Delta T_B \right|$$

What this question attempts to probe: The extent to which students can determine, using a symbolic notation, relative temperature changes for two substances that conserve energy between them and have equal masses and different specific heats., This question also probes the extent to which students understand that the amount of energy lost through heating by one substance will equal that gained by the other substance.

4.4.5 Two Liquids, multiple-choice

Suppose we have two *separate* containers: One container holds Liquid A, and another contains Liquid B. The mass and initial temperature of the two liquids are the same, but the specific heat of Liquid A is *four times* that of Liquid B. Each container is placed on a heating plate that delivers the same rate of heating in joules per second to each liquid beginning at initial time t_0.

On the grids below are four graphs that represent the temperature-versus-time plots for liquid A and liquid B, with liquid A represented by a solid line and liquid B by a dashed line. Indicate the graph whose temperatures are plotted most accurately for liquid A versus liquid B.

Figure 4.5 Two Liquids, multiple choice

Description: Two liquids of equal masses and different specific heats are heated at equal rates. Students are asked to choose a graph that is consistent with the temperature change over time for the two liquids.

Physics Principle: The liquids are being heated at equal rates and have equal masses; therefore, the liquid with the higher specific heat will have a smaller increase in temperature, as compared to the liquid with the lower specific heat over that same period.

What this question attempts to probe: The extent to which students can determine relative temperature changes over time for two substances that have equal masses, receive equal rates of heating, but possess different specific heats. This question also probes students' ability to represent their answer in graphical form.

What this question does not attempt to probe: This question does not directly probe whether students understand that there is an equal amount of energy transferred per unit time.

Issues: This question also probes students' ability to report their answer in a graphical form, which may interfere with their ability to give a completely correct response. See section 4.6.2 for more on this issue.

4.4.6 Object in Liquid, graphical

Suppose that a mass of aluminum (Al) is heated to a high initial temperature. At time t_0 it is placed in an insulated container of water that is at a lower initial temperature. The mass of the aluminum is the *same* as the mass of the water. (Note: The specific heat of water is higher than that of aluminum.)

a) On the grid below, graph the temperature as a function of time of the aluminum and water separately. Make sure to clearly <u>label</u> your graphs. (Note: t_1 represents a time shortly after the initial time, before equilibrium is reached.)

ASSUME THAT THE SPECIFIC HEAT OF WATER IS *FOUR* TIMES THAT OF ALUMINUM

b) Please explain the reasoning that you used in drawing your graph.

Figure 4.6 Object in Liquid, graphical

Description: This question describes an object and a liquid that are initially at different temperatures. Students are asked to graph the changes in temperature for the object and the liquid with respect to time, when the object is immersed in the liquid.

Physics Principle: Students are expected to recognize that because the process occurs inside a calorimeter, we can assume there is no heat transfer apart from that between the aluminum and the water. Therefore, all energy that is lost by one will be gained by the other. For equal changes in energy and equal masses, the ratio of the temperature changes will be inversely proportional to the ratio of the respective specific heat capacities. Algebraically:

$$Q = mc\Delta T$$

$$\left|Q_{Al}\right| = \left|Q_{Water}\right| \quad and \quad m_{Al} = m_W$$

$$\Rightarrow c_{Al}\left|\Delta T_{Al}\right| = c_W\left|\Delta T_W\right|$$

$$\left|\Delta T_{Al}\right| = \frac{c_W}{c_{Al}}\left|\Delta T_W\right|$$

$$c_W = 4c_{Al} \Rightarrow \left|\Delta T_{Al}\right| = 4\left|\Delta T_W\right|$$

What this question attempts to probe: The extent to which students can determine relative temperature changes for two substances that conserve energy between them, have equal masses, and different specific heats. The extent to which students can represent their understanding in a graphical representation is probed as well.

What this question does not attempt to probe: The question does not explicitly ask whether or not the heat transfers are equal which may be an underlying cause of incorrect student answers.

Issues: This question also probes students' ability to report their answer in a graphical form which may interfere with their ability to give a completely correct response. See section 4.6.2 for more on this issue. A variety of "acceptable" answers are shown in the Appendix.

4.5 Inventory of Calorimetry Data

Table 4.5.1 Inventory of Calorimetry Data Collection

	Summer 2002	Spring 2003	Spring 2004	Fall 2005	Spring 2006
4.4.1 Object in Liquid, free response	After all Instruction	After Lecture Instruction		Before all Instruction and After Lecture Instruction	After all Instruction
4.4.2 Two Liquids, free response	After all Instruction	After Lecture Instruction		After Lecture Instruction	
4.4.3 Object in Liquid, text multiple-choice		After all Instruction	After all Instruction		
4.4.4 Object in Liquid, symbol multiple-choice			After all Instruction		After all Instruction
4.4.5 Two Liquids, multiple-choice			After all Instruction		
4.4.6 Object in Liquid, graphical		After all Instruction			

Table 4.5.1 Inventory of Calorimetry Data Collection

4.5.1 Free-Response Data

Before All Instruction

Fall 2005 – Administered during the first recitation of the semester before all instruction on calorimetry

After Lecture instruction

Spring 2003 – Administered at the beginning of recitation that was to cover calorimetry, which was after lecture instruction

Fall 2005 – Administered at the beginning of recitation that was to cover calorimetry, which was after lecture instruction

Spring 2006 – Administered during lab in the second week of class after instruction on calorimetry was complete

After all instruction

Summer 2002 – Administered during a recitation period after all instruction on calorimetry was complete

Spring 2003 – Administered during a mid-term exam after all instruction on calorimetry was complete

4.5.2 Multiple-Choice Data

After all instruction

Spring 2003 – Administered on a final exam after all instruction on calorimetry was complete.

Spring 2004 – Administered the object in liquid, text multiple-choice, and two liquids, multiple-choice questions on a mid-term exam after all instruction on calorimetry was complete; administered the object in liquid, symbol multiple-choice question on the final exam after all instruction on calorimetry was complete

Spring 2006 – Administered on a mid-term exam after all instruction on calorimetry was complete

4.5.3 Interview Data

Fall 2003 – Conducted ten interviews with student volunteers after all instruction on calorimetry was complete

Summer 2003 – Conducted two interviews with student volunteers after all instruction on calorimetry was complete

4.6 Analysis of data

We administered our free-response questions before and after instruction throughout the introductory calculus-based courses over the course of five semesters between the summer of 2002 and the spring of 2006. This section will cover the stages of student thinking on calorimetry 1) before all instruction, 2) after lecture but before recitation instruction, and 3) after all instruction. We will look at students' rule-based reasoning across a question's varied representational formats and contexts, and follow up with insights we derived from student interviews.

4.6.1 Before All Instruction

We administered the object in liquid, free-response question before all instruction on thermodynamics in the Fall of 2005; results are shown in Table 4.6.1. In other semesters it was used after lecture instruction but before recitation instruction (see Sec 4.6.2). It's worth noting that even before any instruction on thermodynamics, students' previous exposure to this material was evident. Half of all students (exactly 50%) answered correctly that the substance with the lower specific heat would have greater temperature change than the substance with the higher specific heat, and 80% of those that gave a correct answer gave acceptable explanations.

Correct explanations fell under one of three distinct categories: 1) Students who used the definition of specific heat to justify their answers:

"Object A *will change less than liquid* B *because the specific heat of object* A *is*

greater so it takes more heat to change its temperature by one degree."

2) Students who used the equation $Q = mc\Delta T$ to mathematically arrive at a

proportion for their answer or showed some algebraic manipulation as part of the

solution:

Replication of student work:

$$q_A = mc_A\Delta T_A \qquad \frac{q_A}{mc_A} = \Delta T_A$$

$$q_B = mc_B\Delta T_B \qquad \frac{q_B}{mc_B} = \Delta T_B$$

Student's written response: *"Less than because the specific heat is higher"*

3) Students who made a specific indication that a substance with a smaller heat

capacity would have a greater change in temperature:

"Less than, the object has a higher specific heat so it takes more energy to change

its temperature."

An in-depth analysis of incorrect answers and explanations is presented in Section

4.6.2.

Table 4.6.1 Before all instruction, Object in liquid, free response: Fall 2005

	Fall 2005
	$N = 479$
Greater c, Smaller ΔT	50%
Correct with Correct Explanation	*40%*
Equal ΔT	38%
Greater c, Greater ΔT	12%

Table 4.6.1 Before all instruction, Object in liquid, free response: Fall 2005
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have the smaller change in temperature; "*Correct with Correct Explanation*" corresponds to the proportion of all students who gave the correct answer with correct reasoning. "Equal ΔT" corresponds to the proportion of students who answered that both the object and the liquid would have the same change in temperature. "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature

4.6.2 After Lecture Instruction Before Recitation Instruction

Object in Liquid, free response

As seen in the Table 4.6.2, 63% of students answered that the substance with the lower specific heat would have a greater temperature change than the substance with the higher specific heat. Those students giving a correct answer with a correct explanation (53%), relied on the equation $Q = mc\Delta T$, or the definition of specific heat to explain their answer (see 4.6.1 for more on students' correct explanations).

Nearly one quarter of all students (22%) stated that the temperature change of the object and the liquid would be the same. Explanations for this response include the idea that equal energy transfer is assumed to imply equal temperature change. For example, here is one student's argument:

"Same. The system will reach an equilibrium since the copper will gain the heat that the water gives up, they will both change the same amount of °C."

A different justification was offered by this student:

"The temperature change of the copper and the water will be the same. Any heat lost by the copper will be gained by the water, or any heat gained by the copper will lost from the water. So ΔT of both are the same."

The remaining 18% of students answered that the substance with the lower specific heat would have a smaller temperature change than the substance with the greater specific heat. Most students with this type of response indicated that the temperature change was proportional to the specific heat. For instance:

"The temperature change of copper will be less than that of the ΔT of the water, because the specific heat of water is greater, and the masses are the same."

Table 4.6.2a After lecture instruction before recitation instruction, Object in liquid, free response: Spring 2003, Fall 2005, Spring 2006

	Spring 2003	Fall 2005	Spring 2006	All Semesters
	$N = 359$	$N = 427$	$N = 250$	$N = 1084$
Greater c, Smaller ΔT	64%	61%	64%	$63 \pm 4\%$
Correct with Correct Explanation	*55%*	*51%*	*53%*	*53 ± 5%*
Equal ΔT	21%	25%	20%	$22 \pm 7\%$
Greater c, Greater ΔT	15%	14%	16%	$15 \pm 2\%$

Table 4.6.2a After lecture instruction before recitation instruction, Object in liquid, free response: Spring 2003, Fall 2005, Spring 2006
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a smaller change in temperature; "*Correct with Correct Explanation*" corresponds to the proportion of students who gave the correct answer with correct reasoning. "Equal ΔT" corresponds to the proportion of students who answered that both substances would have the same change in temperature. "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature.
The statistics reported in the "All Semesters" column represent the 95% confidence interval of student performance for each answer category, based on score variances among the three classes.

Table 4.6.2b After lecture instruction before recitation instruction, Object in liquid, free response Explanation Breakdown: Spring 2003, Fall 2005, Spring 2006

	Object in Liquid Spring 2003	Object in Liquid Fall 2005	Object in Liquid Spring 2006
	$N = 359$	N = 427	N = 250
Correct (Greater c, Smaller ΔT)	64%	61%	64%
With correct explanation	*55%*	*51%*	*54%*
With incorrect explanation:			
temperature change is larger because initial temperature is higher (or lower)	3%	1%	<1%
Other explanations	6%	7%	8%
Incorrect (Equal ΔT)	21%	25%	20%
…because energy transfers are equal	8%	6%	2%
…because system goes to equilibrium	6%	7%	7%
…because masses are equal	3%	5%	4%
other explanations	3%	8%	7%
Incorrect (Greater c, Greater ΔT)	14%	14%	16%
… because specific heat directly proportional to rate of temperature change	6%	4%	6%
"correct" explanation and incorrect answer	1%	1%	1%
other explanations	9%	8%	8%

Table 4.6.2b After lecture instruction before recitation instruction, Object in liquid, free response explanation breakdown: Spring 2003, Fall 2005, Spring 2006
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a smaller change in temperature; "*Correct with Correct Explanation*" corresponds to the proportion of students who gave the correct answer with correct reasoning. "Equal ΔT" corresponds to the proportion of students who answered that both substances would have the same change in temperature. "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature

Approximately one third of students who believed the temperature changes for the object and the liquid would be equal justified their answer by stating that the object and the liquid go to "equilibrium." This word does have a specific scientific definition and there were concerns that these students may be confused by this technical language. To

address this issue we administered the object in liquid, free-response question with a

change in the wording for the Fall 2005 and Spring 2006 courses.

This change was as follows: The phrase "*During the time it takes for the system to reach equilibrium...*" was changed to, "*During the time it takes for the object and the liquid to reach a common final temperature...*" in an attempt to alleviate any possible confusion. However, this change didn't appear to affect the student response pattern in any significant way.

Two Liquids, free-response question

Additionally, there was a free-response graphing portion where students were

asked to graph the temperature over time of two liquids with different heat capacities

both placed on a heating plate that delivered constant and uniform heating.

An issue concerning what constituted a correct answer for this question needed to

be addressed. Since a portion of the answer for this problem depends on the ability to

properly graph two lines, we decided that as long as students had the slope of $B > A$ it

would be considered correct. (Interviews backed up this reasoning as many students

failed to draw an accurate graph, but admitted that it wasn't perfect and almost always

drew a proper one when pressed on the idea.)

With this rubric in place we found that 68% of students correctly identified the

slope of the liquid with the lower specific heat being greater than that of the liquid with

the greater specific heat. 57% gave a correct explanation along with the correct response.

29% of students stated that the slope of B would be less than the slope of A, and there

were essentially zero students who answered that the slope of the two liquids would be the same, despite the fact that 22% of students gave this answer on the previous problem.

There isn't any clear evidence as to why students are making such a dramatic shift from the "temperature changes are equal" response between the two questions; however, we will address students' perceived use of "rule-based reasoning" in Section 4.6.3.

Table 4.6.3 After lecture instruction before recitation instruction, Two Liquids, free response: Spring 2003, Fall 2005

	Spring 2003	Fall 2005
	$N = 361$	$N = 427$
Greater c, Smaller ΔT	70%	73%
Correct with Correct Explanation	*50%*	*65%*
Equal ΔT	2%	0%
Greater c, Greater ΔT	28%	26%

Table 4.6.3 After lecture instruction before recitation instruction, Two Liquids, free response: Spring 2003, Fall 2005
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the liquid with the greater specific heat would have a smaller rate of temperature change (i.e., smaller slope on graph);"*Correct with Correct Explanation*" corresponds to the proportion of students who gave the correct answer with correct reasoning. "Equal ΔT" corresponds to the proportion of students who answered that both liquids would have the same rate of temperature change (i.e., equal slopes)."Greater c, Greater ΔT" corresponds to the proportion of students who answered that the liquid with the greater specific heat would have a greater rate of temperature change (i.e., larger slope on graph).

4.6.3 Rule-based Reasoning

As shown in section 4.6.2 we observed inconsistent responses between those students who answered that the change in temperatures would be equal on the object in liquid, free-response question (22%) and in the two liquids, free-response question (0%). We tracked student responses across these two questions to try and determine the consistency of student thinking (see Table 4.6.4). We found that a high proportion (82%) of those students who answered the object in liquid, free-response question correctly *also*

answered the two liquids, free-response question correctly; a relatively small number (15%) switched to an incorrect answer of "Greater c, Greater ΔT".

Students who stated that the temperature changes were equal for the object in liquid, free-response question, split their answers among the correct answer "Greater c, Smaller ΔT" (48%) and the incorrect answer "Greater c, Greater ΔT" (45%) on the two liquids, free-response question. It's striking that none of these students offered a consistent answer from the first to the second question.

Similarly, students who gave an answer consistent with "Greater c, Greater ΔT" for the object in liquid, free-response question, split their answers among the correct answer "Greater c, Smaller ΔT" (51%) and the incorrect answer "Greater c, Greater ΔT" (47%) on the two liquids, free-response question.

These findings suggest that students are employing context-dependent reasoning in answering these questions. It could be called "rule-based" reasoning because students typically justify their answers by citing one or another presumed "rules," which they tend to employ instead of trying to arrive at an answer by reasoning from more elementary principles. This is discussed further in the Conclusion, Section 4.9.

Table 4.6.4 After Lecture Instruction Before Recitation Instruction, Object in Liquid, free response, and Two Liquids, free response; Spring 2003 and Fall 2005

	Object in Liquid: Greater c, Smaller ΔT		Object in Liquid: Equal ΔT		Object in Liquid: Greater c, Greater ΔT	
	Spring 2003	Fall 2005	Spring 2003	Fall 2005	Spring 2003	Fall 2005
Number of students in category	*230*	*262*	*77*	*107*	*50*	*58*
Two Liquids: Greater c, Smaller ΔT	84%	81%	40%	54%	52%	50%
Two Liquids: Equal ΔT	0%	0%	0%	0%	0%	0%
Two Liquids: Greater c, Greater ΔT	15%	15%	55%	38%	46%	47%

Table 4.6.4 After Lecture Instruction Before Recitation Instruction, free-response questions: Object in Liquid vs. Two Liquids: Spring 2003 and Fall 2005
Columns correspond to answers given by students to the object in liquid, free-response question. "Number of students in category" corresponds to total number of students in each course who gave the answer specified in the column heading. "Two liquids: Greater c, Smaller ΔT" corresponds to the proportion of students that gave a (correct) answer on the two liquids, free-response question (consistent with "greater specific heat implies smaller change in temperature")."Two liquids: Equal ΔT" corresponds to the proportion of students who gave an answer on the two liquids, free-response question that was consistent with temperature changes for both liquids being equal. "Two liquids: Greater c, Greater ΔT" corresponds to the proportion of students who gave an answer on the two liquids, free-response question that was consistent with greater specific heat implying greater change in temperature.

4.6.4 Post-Instruction Results

Our first opportunity to probe student thinking was during the summer of 2002 after all instruction was complete. We administered the object in liquid, free-response and two liquids, free-response questions to thirty-two students during recitation to develop a baseline of data on student thinking after instruction was complete. Student responses (see Table 4.6.5 and Table 4.6.6) were roughly consistent with responses we measured after lecture instruction but before recitation instruction (see Table 4.6.2 and Table 4.6.3).

Table 4.6.5 After all instruction, Object in Liquid, free response: Summer 2002

	Summer 2002
	$N = 32$
Greater c, Smaller ΔT	72%
Correct with Correct Explanation	*63%*
Equal ΔT	22%
Greater c, Greater ΔT	6%

Table 4.6.5 After all instruction, Object in Liquid, free response: Summer 2002
Row "Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat will have a smaller change in temperature; Row "*Correct with Correct Explanation*" corresponds to the proportion of students who gave the correct answer with correct reasoning; Row "Equal ΔT" corresponds to the proportion of students who answered that both substances will have the same change in temperature; Row "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat will have a greater change in temperature

In addition to testing student thinking using our two liquids, free-response question after all instruction was complete in the summer of 2002, we created what we felt was the multiple-choice equivalent of the question (see Section 4.4.5) for use on a mid-term exam after all instruction was complete in the Spring 2004 course. We felt that the subtle difference between choices *A* and *B* on this question (see Figure 4.5) might be lost on the students, and so following the protocol we laid out in Section 4.6.2 on the two liquids, free-response question, we report in Table 4.6.6 (Spring 2004 column) all those students who gave an answer that was consistent with greater specific heat implying smaller change in temperature; this is the sum of the number that answered *A* and *B*. Similarly, we categorized both *C* and *D* as being incorrect under the same heading of "greater specific heat implies greater temperature change."

The results show very similar proportions of responses on the free-response and multiple-choice versions of the two-liquid question, across all three answer categories. Yet again, responses that are consistent with the liquids having equal changes in

temperature are non-existent, compared to such answers given to questions governed by

the same underlying principles but in a different context.

Table 4.6.6 After all instruction, Two Liquids, free response: Summer 2002; Two Liquids, multiple choice: Spring 2004

	Two Liquids, free response Summer 2002	Two Liquids, multiple choice Spring 2004
	$N = 32$	$N = 447$
Greater c, Smaller ΔT	69%	73%
Correct with correct explanation	*59%*	--
Equal ΔT	0%	1%
Greater c, Greater ΔT	22%	26%

Table 4.6.6 After all instruction, Two Liquids, free response: Summer 2002; Two Liquids, multiple choice: Spring 2004
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat will have a smaller change in temperature (i.e., responses *A* or *B* on the multiple-choice version); "*Correct with Correct Explanation*" corresponds to the proportion of students who gave the correct answer with correct reasoning on the free-response version; "Equal ΔT" corresponds to the proportion of students who answered that both substances will have the same change in temperature (i.e., response *E* on the multiple-choice version); "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat will have a greater change in temperature (i.e., responses C or D on the multiple-choice version).

A later follow-up with the object in liquid, text multiple-choice question (Figure

4.3), which had similar wording to the free-response question, was carried out at the time

of the final exam. Despite instruction, student performance seems strikingly similar to our

free-response quiz. The results of this textual question when taken at face value may

appear different (see Table 4.6.7), but when we analyze the multiple-choice responses

according to categories we find patterns consistent with answers on the free-response

question (see Table 4.6.8). The categories identify the temperature changes involving the

higher-specific-heat substance as being greater than, less than, or equal to the temperature

change of the lower-specific-heat substance; also included are categories corresponding

to heat transfer *away* from one object being equal to or not equal to the heat transfer *to*

the other object (see Table 4.6.9).

In Table 4.6.9, we see that the proportion of correct responses on the multiple-

choice questions (~68%) is highly consistent with that on the corresponding free-

response question (63%) which was given after lecture instruction but before recitation

(compare with Table 4.6.2a). However, on the multiple-choice questions, the "Equal ΔT"

response frequency (~11%) was lower than that seen on the free-response question

(22%). By contrast, the "Greater c, Greater ΔT" response was somewhat more popular

than it was on the free-response question (22% vs. 15%).

The text multiple-choice question was given on a midterm exam during Spring

2004, while the symbol multiple-choice question was given on a final exam in the same

course. Responses in each category were very similar, with a discrepancy ≤6% on each of

the five categories (Table 4.6.8).

Table 4.6.7 After all instruction, Object in Liquid, text multiple-choice: Spring 2003, Spring 2004, All semesters summary; Object in Liquid, symbol multiple-choice: Spring 2004, Spring 2006, All semesters summary

	Object in Liquid, Text MC			Object in Liquid, Symbol MC		
	Spring 2003	Spring 2004	Average Response	Spring 2004	Spring 2006	Average Response
	$N = 299$	$N = 461$	$N = 760$	$N = 420$	$N = 311$	$N = 731$
A.	4%	8%	6%	10%	6%	8%
B.	13%	16%	15%	9%	6%	8%
C.	13%	18%	16%	16%	14%	15%
D.	12%	13%	13%	7%	7%	7%
E.	57%	44%	51%	56%	68%	62%

Table 4.6.7 After all instruction, Object in Liquid, text multiple-choice: Spring 2003, Spring 2004, All semesters summary; Object in Liquid, symbol multiple-choice: Spring 2004, Spring 2006, All semesters summary
Rows lettered A-E correspond to student response rates on Object in Liquid, text multiple-choice (first three columns) and Object in Liquid, symbol multiple-choice (last three columns), see Figure 4.4.3 and 4.4.4 for precise answers. In Spring 2004, the Text MC question was given on a midterm exam while the Symbol MC question was given on the final exam.

Table 4.6.8 After all instruction, Object in Liquid, text multiple-choice: Spring 2003, Spring 2004; Object in Liquid, symbol multiple-choice: Spring 2004, Spring 2006*

	Object in Liquid, Text MC			Object in Liquid, Symbol MC		
	Spring 2003	Spring 2004	Average Response	Spring 2004	Spring 2006	Average Response
	$N = 299$	$N = 461$	$N = 760$	$N = 420$	$N = 311$	$N = 731$
Greater c, Smaller ΔT	71%	60%	66%	66%	73%	70%
Equal ΔT	12%	13%	13%	8%	7%	8%
Greater c, Greater ΔT	17%	27%	22%	26%	20%	23%
Heat transfers are not equal	17%	25%	21%	19%	12%	16%
Heat transfers are equal	83%	75%	79%	81%	88%	85%

Table 4.6.8 After all instruction, Object in Liquid, text multiple-choice: Spring 2003, Spring 2004; Object in Liquid, symbol multiple-choice: Spring 2004, Spring 2006
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a smaller change in temperature (i.e., the sum of answers *B* and *E*). "Equal ΔT" corresponds to the proportion of students who answered that both substances would have the same change in temperature (i.e., answer *D* only). "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature (i.e., the sum of answers *A* and *C*). "Heat transfers are not equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance does not equal the heat transfer to the low-temperature substance (i.e., the sum of answers *A* and *B*). "Heat transfers are equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance is equal to the heat transfer to the low-temperature substance (i.e., the sum of answers *C*, *D*, and *E*).
*In Spring 2004, the Text MC question was given on a midterm exam while the Symbol MC question was given on the final exam.

Table 4.6.9 After Lecture Before Recitation Instruction, Object in Liquid, free response: All semesters; After all instruction, Object in Liquid, text multiple-choice: averaged data (Spring 2003 and Spring 2004); Object in Liquid, symbol multiple-choice, averaged data (Spring 2004, Spring 2006)

	Object in Liquid, Free Response All Semesters	Object in Liquid Text MC Average Response	Object in Liquid Symbol MC Average Response
	$N = 1084$	$N = 760$	$N = 731$
Greater c, Smaller ΔT	63 ± 4%	66%	70%
Equal ΔT	22 ± 7%	13%	8%
Greater c, Greater ΔT	15 ± 2%	22%	23%
Heat transfers are not equal	--	21%	16%
Heat transfers are equal	--	79%	85%

Table 4.6.9 After Lecture Before Recitation Instruction, Object in Liquid, free response: All semesters; After all instruction, Object in Liquid, text multiple-choice: Spring 2003, Spring 2004; Object in Liquid, symbol multiple-choice: Spring 2004, Spring 2006
"Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a smaller change in temperature (i.e., the sum of answers *B* and *E*). "Equal ΔT" corresponds to the proportion of students who answered that both substances would have the same change in temperature (i.e., answer *D* only). "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature (i.e., the sum of answers *A* and *C*). "Heat transfers are not equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance does not equal the heat transfer to the low-temperature substance (i.e., the sum of answers *A* and *B*). "Heat transfers are equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance is equal to the heat transfer to the low-temperature substance (i.e., the sum of answers *C*, *D*, and *E*).

4.6.5 Interview data regarding students' mathematical errors

We conducted twenty-six one-on-one student interviews during the course of three different semesters. Interviews consisted of the above questions and related questions on energy, temperature, and specific heat capacity. Students succeeded with the interview tasks at a high level (~80%), with only two identifiable tendencies regarding incorrect reasoning. Four of the twenty-six students stated that the initial temperature would affect the magnitude of the temperature change. The most striking finding was that a surprising number of student mathematical errors were observed.

Nearly one quarter of all interviews (26%) involved students making algebraic errors while working problems. For instance, while answering the object in liquid, free-response question, students would set up a correct expression comparing heat transfers to and from the object and the liquid, but after determining a correct expression that related the magnitudes of temperature change with the specific heat capacities, students would incorrectly interpret the proportional relationship as greater specific heat implying a greater change in temperature. This response was not observed among the free-response explanations and, consistent with other research on the mathematics/physics connection, it seems that simple algebra skills might be a significant source of student difficulties with calorimetry problems.

These mathematical errors as discovered via interviews consistently interfered with correct conclusions even when other, intuitive reasoning approaches eventually allowed the students to arrive at a correct answer. Meltzer's previous work had examined analogous correlations between algebraic skills and physics performance. Apparently, mathematical errors even on basic linear equations can completely derail a certain segment of the student population, even on a relatively simple topic such as calorimetry.

4.7 Curriculum Development

(See Appendix 2.1 for the full Calorimetry Worksheet)

The Calorimetry Worksheet was designed by Ngoc-Loan Nguyen, a former graduate student in the PER group at ISU, to address the specific relationships among internal energy, heat transfer, changes in temperature, mass, and specific heat capacity.

Students are first presented with two gases that are separated by a thermal wall which prevents them from physically mixing, but allows for heat transfer. Students are given a partially completed set of bar charts describing the energy transfer during the process, and the initial and final temperatures on an absolute temperature scale. Students are guided to realize that the final temperatures will always be equal to one another, and the energy transfer from one object equals the energy transfer to the other object. The worksheet proceeds to more complicated arrangements, which make the task of figuring out the final and/or initial temperatures progressively more challenging.

4.7.1 Testing methodology

During the spring of 2003, we identified an intervention group that received our research-based worksheet in an attempt to improve their understanding of calorimetry. We carried out post-instruction testing, and compared traditional instruction and instruction using worksheets. Using a random number generator we identified seven recitation sections that received our research-based worksheet. To alleviate the need for TA training, the investigators of this project (Warren Christensen, Ngoc-Loan Nguyen, and David Meltzer) became guest TA's in those recitations where the research-based tutorial was administered. All students who attended recitation answered the "object in liquid, free-response" and the "two liquids, free-response" questions.

Most students did not complete the worksheet, and the TAs felt that students were slightly tentative in employing the very different and unfamiliar mode of instruction they

were being guided to use. (The students had not previously had any similar

worksheet/tutorial instruction during their physics course).

4.7.2 Student performance and feedback

An unanticipated methodological problem arose when we compared pre-

instruction performances of the intervention and control groups. Even before any

instruction on the relevant topics had taken place, there was a significant difference in

performance of the two groups. The control group had a significantly higher correct-

response rate on both the object in liquid, free-response and the two liquids, free-response

questions (Table 4.7.1). The reason for this discrepancy is not clear.

Table 4.7.1 After Lecture Before Recitation Instruction, Object in Liquid, free response and Two Liquids, free response, Intervention Group and Control Group before recitation instruction

	Intervention Group, Pre-Instruction	Control Group, Pre-Instruction
	$N = 128$	$N = 171$
Proportion of correct answers on Object in Liquid, free response	46%*	60%*
Proportion of correct answers on Two Liquids, free response	43%*	55%*

Table 4.7.1 After Lecture Before Recitation Instruction, Object in Liquid, free response and Two Liquids, free response, Intervention Group and Control Group
Percentages give the proportion of correct responses on the Object in Liquid Question (row 1) and the Two Liquids Questions (row 2) for the randomly selected Intervention Group (column 1) and the Control Group (column 2).

* Statistically significant difference between the Control and Intervention Group using a binomial proportions test, (p < 0.05).

After all instruction was complete, students were given the object in liquid,

graphical question (see Table 4.7.2), and the object in liquid, text multiple-choice

question (see Table 4.7.3) on a mid-term examination that covered all thermodynamic topics. Students who received our Calorimetry Worksheet performed statistically the same as those students who received traditional instruction on the object in liquid, graphical question. One might consider this a success, in view of the fact that those students in the intervention group had significantly lower pre-instruction scores than those in the control group.

Performance on the object in liquid, text multiple-choice question was not encouraging as the proportion of students giving correct answers that were consistent with "greater c, smaller ΔT" was statistically higher for those students in the control group than for those in the sections that used our Calorimetry Worksheet.

Table 4.7.2 Post-Instruction, Object in Liquid, graphical, Intervention Group performed Calorimetry Worksheet and Control Group received traditional instruction

	Intervention Group Performed Calorimetry Worksheet	Control Group Performed Traditional Recitation Instruction
	$N = 128$	$N = 171$
Correct Responses	55%	52%

Table 4.7.2 Post-Instruction, Object in Liquid, graphical, Intervention Group performed Calorimetry Worksheet and Control Group received traditional instruction
Proportion of correct response for the Intervention and Control Groups for the Object in Liquid, graphical question that was administered on a mid-term exam. There was no statistically significant difference between intervention and control groups on proportion of correct responses.

Table 4.7.3 Post-Instruction, Object in Liquid, text multiple–choice, Intervention Group performed Calorimetry Worksheet and Control Group received traditional instruction

	Intervention Group Performed Calorimetry Worksheet	Control Group Performed Traditional Recitation Instruction
	$N = 128$	$N = 171$
Greater c, Smaller ΔT	65%*	76%*
Equal ΔT	13%	11%
Greater c, Greater ΔT	22%**	13%**
Heat transfers are not equal	20%	15%
Heat transfers are equal	80%	85%

Table 4.7.3 Post-Instruction, Object in Liquid, text multiple-choice
The Intervention Group performed the Calorimetry Worksheet and the Control Group received traditional instruction. "Greater c, Smaller ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a smaller change in temperature (i.e., the sum of answers *B* and *E*). "Equal ΔT" corresponds to the proportion of students who answered that both substances would have the same change in temperature (i.e., answer *D* only). "Greater c, Greater ΔT" corresponds to the proportion of students who answered that the substance with the greater specific heat would have a greater change in temperature (i.e., the sum of answers *A* and *C*). "Heat transfers are not equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance does not equal the heat transfer to the low-temperature substance (i.e., the sum of answers *A* and *B*). "Heat transfers are equal" corresponds to the proportion of students who answered that the heat transfer from the high-temperature substance is equal to the heat transfer to the low-temperature substance (i.e., the sum of answers *C*, *D*, and *E*).

* Statistically significant difference ($p < 0.04$) between intervention and control group, using a test for Binomial proportions
 ** Statistically significant difference ($p < 0.04$) between intervention and control group, using a test for Binomial proportions

4.8 Implications for Instruction

Our model of student knowledge identified three regions of student thinking (See Chapter 3). The innermost region (i.e. the black bull's eye region) contains ideas that students know well, and that they are able to answer correctly regardless of context or representation. After observing more than half of all students provide correct answers

with correct explanations on questions in different contexts, even after only lecture instruction, we conclude that for many students the concepts of calorimetry in a physics context are relatively easily grasped. For some students, rule-based reasoning (in contrast to reasoning from first principles) seems to dominate their thinking, and it is possible that we could design curricular materials to help these students improve their reasoning in this area.

Following the model of instruction that we laid our in Chapter 3, effective curriculum must explicitly address student difficulties. It would seem that exercises which guide students to recognize the interplay among mass, specific heat, temperature change, and heat transfer are essential. Ensuring that students can resolve any inconsistency in their answers, especially across representations that elicit non-uniform responses (such as our object in liquid and two-liquids questions), would likely be beneficial for those that are utilizing some kind of rule-based reasoning.

4.9 In-depth comparison to Previous Research

Calorimetry findings

In his Ph.D. dissertation, Cochran reported findings that are consistent with those of our own investigation. Using a variety of questions involving different substances exchanging heat with each other and approaching a mutual equilibrium temperature, Cochran probed student difficulties as reflected in rankings of temperature changes and magnitudes of heat transfers. Several of the questions used by Cochran are very similar to those used in our investigation. For example, Cochran administered the following

question to students in an algebra-based physics course after all instruction on thermal physics was completed (Cochran 2005, p. 62):

A block of lead at 100°C is put into an equal mass of cold water at 0°C in a perfectly insulated container. The specific heat of water is much greater than that of lead. The lead and the water are allowed to come to thermal equilibrium.

1. Is the magnitude of heat transfer from the lead *greater than*, *less than*, or *equal to* the heat transfer to the water. Explain.

2. Is the temperature change of the lead *greater than*, *less than*, or *equal to* the temperature change of the water? Explain.

Cochran found that 70% of the students gave a correct answer to Question #2, while 20% of students responded that the temperature changes would be equal. Also, 10% stated that the temperature change of the higher specific heat substance (the water) would be greater (Cochran 2005, Table 6.1, p. 63). These results are remarkably similar to those on the *non-graphical* questions in our investigation, such as those reported in Table 4.6.2a (correct response: 63%; equal temperature change: 22%; greater change for higher specific heat: 15%) and Table 4.6.5 (correct response: 72%; equal temperature change: 22%; greater change for higher specific heat: 6%). Similarly, Cochran found that 10% of the students responded to Question 1 by claiming that the heat transfer magnitudes would *not* be equal; this may be compared to our findings on a similar question as reported in Table 4.6.8, in which 16-21% of students made a similar incorrect assertion.

Cochran reported results on several other similar but more complicated questions. The results are similar to those given above, but can not be compared directly because additional conceptual issues were involved in these questions.

Cochran notes that while most students are able to give correct answers to fundamental questions on calorimetry, a significant minority of introductory physics students show persistent problems. He cites specific student difficulties with calorimetry as including 1) student confusion between the quantities of heat and temperature (previously reported by Kautz (2005), and by many others) and 2) students' tendency to focus on one particular variable (while ignoring the others) in the equation $Q = mc\Delta T$, thereby attributing a determining influence either to mass, or to specific heat, or to initial temperature, in order to justify answers regarding heat transfers or temperature changes.

For instance, on a question involving the immersion of two identical blocks into different volumes of water at the same temperature (the blocks had equal masses, specific heats, and initial temperatures), Cochran reports that 20% of the students identified the changes in temperature of the two blocks as being equal.

An excerpt from his dissertation shows findings nearly identical to our own:

We were surprised to see some student difficulties with the concept of temperature on this question. About 20% of the students incorrectly answered that the final temperatures would be equal in each experiment. The responses of these students often suggested that they viewed temperature as a measure of amount of heat. The sample response below illustrates this type of reasoning.

"They both start at the same temperature and heat is neither gained or

lost in the process so both of the temperatures reached in the process should be

the same."

Other responses suggested that students though[t] the blocks applied heat as

ovens do.

"I think the calorimeters will reach the same equilibrium because they

both start at the same temperature and are warmed by a block that is at 100 °C.

Experiment 2 will warm faster."

A few students claimed that the final temperatures were equal because

thermal equilibrium was reached and, "…*thermal equilibrium is when heat lost*

equals heat gained." In many cases, we found it difficult to interpret the

reasoning of these students. Some difficulties appeared related to the fact that

students were asked to compare two experiments [Cochran 2005, pp. 72-73].

One key feature uncovered by our study and not reported by Cochran was the

striking disappearance of "equal temperature change" answers on our graphical ("Two

Liquids") questions. It appears that the graphical nature of this task might have altered

student responses, since similar questions failed to show this pattern of responses.

Rule-Based Reasoning

Published work by other researchers suggests that the behavior we have called

"rule-based reasoning" originates from perceptions that students have regarding their role

in the classroom. A "rule-learner" has been described by Herron and Greenbowe as a student who views their primary task as memorizing rules and algorithms which are then practiced until they can be applied flawlessly. Herron and Greenbowe point out that successful problem solvers may utilize a similar pattern, but more often include a step where they check the validity of their answer or evaluation method before reporting a final answer (Herron 1986).

The Maryland Physics Expectations Survey (Redish 1998) and the Colorado Learning Attitudes about Science Survey (Adams 2006) both probed student expectations and attitudes about science and science learning. Both studies found that a substantial number of students both before and after instruction feel that they must *memorize* all the information, and then simply *find* the right equation to solve a problem. It would seem that this notion of needing to "determine the rule" often leads students to try to learn the material without bothering to search for any underlying conceptual framework or unifying ideas.

4.10 Conclusion

Students' correct explanations generally involved very basic stripped-down "rules-of-thumb," rather than detailed elaborate arguments. An example of such a rule might be, "greater specific heat so temperature change is more [or less]." Many students employed algebraic calculations to justify their answers, although students didn't seem to show an overwhelming preference for the algebraic method. Instead, many simply employed a straightforward qualitative argument involving rather perfunctory rule-based reasoning.

It was clear that some students had been misled by mistaken rules-of-thumb such as "equilibrium means equal temperature change" or "rate of temperature change is directly proportional to specific heat." Students' ideas about what *should* happen appeared to lead them to form conclusions to fit their expectations.

Despite performing at a statistically lower level than the control group on the pretest, the intervention group in the end showed no statistically significant difference in performance on our post-instruction free-response question, although some differences on multiple-choice data were noted. The implication of the results is uncertain, but they suggest that in the time allotted, our Calorimetry Worksheet had no significant effect on student learning as far as we could determine.

Focusing on developing and refining this rule-based reasoning, and giving students more practice at using it correctly, might be an efficient way to promote improved problem solving with calorimetry. In addition, problems should be developed that confront students with the failure of incorrect ideas, so that they can be aware of their imperfect understanding and thereby be more apt to modify their thinking.

Notes for Chapter 4

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Chapter 5: Student understanding of entropy and the second law of thermodynamics

5.1 Overview of entropy in introductory physics

5.1.1 Textbook presentation of the topic

Entropy and the second law of thermodynamics are topics which are invariably mentioned in introductory general-physics and general-chemistry textbooks. The specific terminology and formulations used to present the concepts vary somewhat among the different texts. Here we present a sample of such formulations from a variety of different texts.

Physics:

Cutnell and Johnson: "…the process of spontaneous heat flow is irreversible. In fact, all spontaneous processes are irreversible… The word 'universe' means that $\Delta S_{universe}$ takes into account the entropy changes of all parts of the system and all parts of the environment…***any irreversible process increases the entropy of the universe***… The total entropy of the universe does not change when a reversible process occurs ($\Delta S_{universe} = 0$) and increases when an irreversible process occurs ($\Delta S_{universe} > 0$)."

Giancoli: ". . . the most general statement of the second law of thermodynamics can be restated as: the total entropy, S, of any system plus that of its environment increases as a result of any natural process: $\Delta S > 0$."

Halliday, Resnick and Walker: "**The Second Law of Thermodynamics:** This law, which is an extension of the entropy postulate, states: If a process occurs in a closed system, the entropy of the system increases for irreversible processes. It never decreases. In equation form, $\Delta S \geq 0$."

Knight: Second Law, formal statement: "The entropy of an isolated system never decreases. The entropy either increases, until the system reaches equilibrium, or, if the system began in equilibrium, stays the same."

Tipler: "The entropy of a system can increase or decrease, but the entropy of the universe or of any other isolated system never decreases. . . The statement that for any process the entropy of the universe can never decrease is a statement of the second law of thermodynamics that is equivalent to the heat-engine and refrigerator statements."

Young and Freedman: "An important statement of the second law of thermodynamics is that the entropy of an isolated system may increase but can never decrease. When a system interacts with its surroundings, the total entropy change of the system and surroundings can never decrease."

Serway: ". . . increase in entropy applies to the system *and* its surrounding. When two objects interact in an irreversible process, the increase in entropy of one part of the system is greater than the decrease in entropy of the other part. Hence, we conclude that the change in entropy of the Universe must be greater than zero. . ."

Chemistry:

Tro: "Second law of thermodynamics: For any spontaneous process, the entropy of the universe increases ($\Delta S_{univ} > 0$)… The entropy change for the universe is just the sum of the entropy changes for the system and the surroundings: $\Delta S_{univ} = \Delta S_{sys} + \Delta S_{surr}$."

Woodbury: "Irreversible processes in an isolated system are spontaneous in one direction and not spontaneous in the other direction. For the spontaneous direction, the entropy increases: $\Delta S > 0$."

Atkins: "The universe is divided into two parts, the system and its surroundings. A system is the part of the world in which we have a special interest. When matter can be transferred through the boundary between the system and its surroundings the system is classified as open; otherwise it is closed. An isolated system is a closed system that has neither mechanical nor thermal contact with its surroundings…The entropy of an isolated system increases in the course of a spontaneous change: $\Delta S_{tot} > 0$ where S_{tot} is the total entropy of the isolated system that contains the system of interest."

Engineering Thermodynamics:

Moran and Shapiro: "An enlarged system comprising a system and that portion of the surroundings affected by the system as it undergoes a process… Since all energy and mass transfers taking place are included within the boundary of the enlarged system the enlarged

system can be regarded as an *isolated* system. Since entropy is produced in all actual process, the only processes that can occur are those for which the entropy of the isolated system increases."

Elliott and Lira: "Irreversible processes will result in an increase in entropy of the universe. Reversible processes result in no increase in entropy of the universe."

Jones and Dugan: "The entropy of an isolated system always increases or, in the limiting case of a reversible process, remains constant with respect to time… with the understanding that time is the independent variable, this statement is usually written $\Delta S_{\text{isolated system}} \geq 0$."

5.1.2 Topical coverage in introductory physics

The standard introductory physics course includes entropy in a unit on thermal physics. This unit typically starts with a discussion of the ideal gas law, those macroscopic quantities that comprise it, and an introduction to the kinetic theory of gases. This is followed by a treatment of various forms of temperature scales, different forms of heat transfer, and the role of various material properties such as density, thermal conductivity, specific heat, etc. Next is typically an introduction to thermodynamic work, which is then related to the previous topics of heat and internal energy to deduce the first law of thermodynamics. It is at this time that textbooks frequently cover ideal-gas processes (e.g. isobaric, isochoric, isothermal, and adiabatic), and cyclic processes as well.

Entropy and the second law of thermodynamics typically follow, starting with the principal of increasing entropy (i.e. the change in entropy of the universe is always

greater than zero for any real process) along with methods for calculating entropy

changes by starting from $\Delta S \equiv \int \frac{\delta Q_{reversible}}{T}$. This relationship is often reformulated into

simplified equations that can be applied for each of the previously mentioned ideal-gas

processes. Textbooks cover heat engines and always discuss the Carnot cycle, which

defines the maximum efficiency for any heat engine. Refrigerators are also touched

upon, often described as "heat engines that are run backwards." The Kelvin-Planck and

the Clausius statements of the second law are sometimes covered, depending on the

instructor's preference. The second law may be followed by a treatment of the "third

law" which states that absolute zero is the temperature at which the entropy of any

system is equal to zero.

5.1.3 Early exposure to entropy concepts

We conducted a brief background survey in the fall of 2006 regarding students'

previous instruction on the relevant concepts. This was an attempt to cast additional light

on students' background and prior exposure to entropy concepts before entering physics.

The survey was distributed before any instruction on entropy or thermodynamics had

begun. We found that 64% of students self-reported studying entropy in a previous

course, primarily in one of a number of introductory chemistry courses. Inconsistencies

in the courses' topical coverage as recorded in the more recent semesters' syllabi make it

difficult to determine the accuracy of this self-reporting, but it's worthwhile to look at

topical coverage in introductory chemistry courses.

The chemistry courses that students take prior to taking the introductory calculus-based physics course vary in terms of content, but there is a general thread of topical coverage concerning thermodynamics. Most thermodynamic processes that introductory chemistry students encounter involve chemical interactions (e.g., salts dissolving in water forming ionic solution). Chemistry places considerable emphasis on the quantity of enthalpy (that is, heat transfer at constant pressure) in discussions of these various interactions. Enthalpy, like entropy, is a state function, even though, generally speaking, heat transfer is not. We saw no descriptions or use of the term enthalpy among our free-response and interview data, but students' study of that quantity could very well have impacted their understanding and learning of thermodynamic concepts. Students are introduced to ideas about specific heat and molar heat capacity, but a substantial emphasis is placed on solution calorimetry.

Students are typically introduced to entropy and the second law in the context of spontaneous processes, in order to recognize that the second law defines the inherent direction in which processes occur. This direction is that which results in an increase in the entropy of the universe, which in turn is comprised of any arbitrary system and its surroundings. Chemistry texts are very explicit in the use of the formulation "system plus surroundings equals universe" (more so than many physics books). Students are also exposed to discussions on entropy and cursory arguments about entropy and the "disorder" of a system, without any rigorous proof or explanation of what disorder actually is.

We will address concerns about the validity of pre-instruction testing in Section 5.8.1

5.2 Overview of pertinent research in the field

There is very little previous research on student understanding of entropy and the second law of thermodynamics at the introductory university level. The few papers that address student thinking on the second law to any extent are briefly discussed here. For a more in-depth discussion of several background papers related to PER work on thermodynamics, see Chapter 2 of this thesis.

Kesidou and Duit (Kesidou 1993) conducted thirty-four clinical interviews with 15- and 16-year-old students who had received four years of physics instruction. They report that after instruction most students have ideas about processes going in one direction only and the energy being used up, but these notions were largely based on intuitive ideas about everyday life and were not in the "physicist's framework" that they were taught in class. In this context, the physicist's framework refers to the structure and linking of ideas that most experts would likely have. Kesidou and Duit conclude that student difficulties with heat and temperature are impeding student learning on the second law.

Ruth Ben-Zvi (1999) reports on use of curricular materials she developed that deal with energy and the quality of energy. She asserts that, in a course for non-science majors, approximately one-quarter of the students had developed some understanding of entropy concepts. Specifically, Ben-Zvi states that some students recognized that in processes involving energy transfer, some energy is always lost through a heat transfer process, and thereby loses its ability to do work.

In the context of chemistry, Granville (1985) reported that chemistry students sometimes became confused when applying the principle that $\Delta S > 0$ for a spontaneous process, where S refers to the entropy of the system plus that of the surroundings. Granville notes that in some contexts discussed in the introductory chemistry course, S refers to the entropy of the system plus that of the surroundings, or of an isolated system. In other contexts, however, S refers to the entropy of the system only.

Thomas and Schwenz (1998) investigated "prevalent alternative conceptions" on equilibrium and thermodynamics among 16 college-level physical chemistry students. Among the findings they reported was a strong tendency for students to believe, incorrectly, that the second law of thermodynamics *required* the entropy of "the system" to increase even in a context where other evidence showed that would not be the case.

Cochran and Heron (2006) investigated student thinking on entropy and its role in constraining possible heat-engine efficiencies. This investigation is, to date, the only published study of student learning related to entropy and the second law of thermodynamics in university-level physics. Although their investigation has similarities to our own work (see Chapter 2), we are here addressing very different conceptual issues than did Cochran and Heron.

However there is some direct overlap between our work and that of Cochran and Heron with regard to the state-function property of entropy, which is discussed in Section 5.1 of Cochran's Ph.D. dissertation (Cochran 2005). Cochran and Heron's initial findings were that 65% of students (50% with correct explanation) showed facility, after instruction, with entropy's state function property. Only 20% could correctly rank the absolute value of entropy change of a gas that underwent either an isothermal or adiabatic

expansion. (The isothermal expansion involves a heat transfer to the gas, while the adiabatic expansion does not; therefore, the former involves an increase in entropy while the later does not.) In a different context, about 50% of the students were unable to correctly compare entropy changes in two different free-expansion processes that had identical initial and final states. Cochran notes that "many students do not utilize the fact that entropy is a function of state." He ascribes most of the difficulties encountered by students on these questions to underlying conceptual problems with more fundamental notions such as equilibrium and the first law of thermodynamics. He does note, however, that some students failed to realize that the relationship $\Delta S = \int \frac{dQ}{T}$ is only valid for a reversible process.

5.3 Concepts Under Investigation

As can be seen in Section 5.2, there has been very little published work on university students' understanding of entropy and the second law of the thermodynamics. The only directly applicable study (completed very recently) was an investigation of students' understanding of second-law constraints on heat engine efficiencies (Cochran 2006). With so very little of this broad area having been previously explored, it was necessary for us to identify some of the concepts that are central in traditional physics instruction on these topics. The work presented here focuses on student understanding of three fundamental and interrelated ideas that comprise the principle of increasing entropy, as well as the key notion of the state-function property of entropy.

5.3.1 The entropy of the universe increases during any real ("spontaneous") process

The above statement, which is often referred to as the principle of increasing entropy, states that the change in entropy of the universe is positive during any real process. Some physics textbooks use similar language to set constraints on the increase in entropy of an isolated system during any real process, in which an "isolated" system is defined as one that can not exchange energy or mass with its surroundings. In the present investigation we chose to focus on the entropy of "the universe" or of "the system and surrounding environment," since many physics textbooks (and textbooks from other scientific disciplines, such as chemistry) use this language (see Section 5.1.1).

5.3.2 The universe can be represented as a combination of an arbitrarily defined system plus that system's surroundings (or, "surrounding environment")

One may arbitrarily define any chosen object, collection of objects, or region of space to be a "system." Although it is quite common to specify a particular item or collection of items as comprising a system in any particular situation, the specification of what is encompassed by any given system is completely arbitrary. A "system" is nothing other than a particular region of interest, along with its contents, that is arbitrarily defined. The "surroundings," however, are inextricably linked to and determined by a

particular system in that the surroundings comprise everything in the universe that is not included in the given system.

5.3.3 There is no specific constraint on the change in entropy of an arbitrary system or surroundings during a real ("spontaneous") process, so long as the total entropy of system + surroundings increases

In 5.3.1 we see that the principle of increasing entropy establishes a requirement that the entropy of the universe must increase during any real process. In 5.3.2 we discussed the concept that system and surroundings are intimately linked [system + surroundings = universe] but ultimately either one can be arbitrarily defined, so long as the other is defined to constitute "everything else" in the universe. Taken together we can conclude that since the system is arbitrarily defined, we may be able to identify some system in any real process such that the entropy of that system is *not* increasing. Depending on the process, the entropy of this system may well decrease or stay the same. This leads us to the conclusion that there can be no specific constraint on the change in entropy of an arbitrarily defined system (or surroundings) during a real process, so long as the total entropy (system + surroundings) increases.

5.3.4 Entropy is a function of the state of the system, and therefore entropy differences between system states are independent of the process connecting those states

State functions characterize the equilibrium state of a system. Thermodynamic quantities, such as Temperature, Volume, Pressure, Internal Energy, and Entropy only depend on the current state of the system and its surroundings, not on the way in which the system arrived at the current state.

5.4 Diagnostic Questions

This section provides an overview of the diagnostic questions that we used, including the concepts targeted by each question and issues related to the administration of the questions.

5.4.1 General-Context Question

> For each of the following questions consider a system undergoing a naturally occurring process. The system can exchange energy with its surroundings.
>
> a) During this process, does the entropy of the <u>system</u> [S_{system}] *increase, decrease, remain the same*, or is this *not determinable* with the given information? *Explain your answer.*
>
> b) During this process, does the entropy of the <u>surroundings</u> [$S_{surroundings}$] *increase, decrease, remain the same*, or is this *not determinable* with the given information? *Explain your answer*
>
> c) During this process, does the entropy of the system *plus* the entropy of the surroundings [$S_{system} + S_{surroundings}$] *increase, decrease, remain the same*, or is this *not determinable* with the given information? *Explain your answer.*

Figure 5.1 General-Context Question

Description: This question is written to be very general with minimal technical language, and with no details offered regarding either the "system" or the "process."

Physics Principle: The entropy of the universe will always increase due to the occurrence of any real process. The universe can be divided into two intimately connected parts, the system and its surroundings. The system can be arbitrarily defined as any volume of space and its contents, and the surroundings will be defined as everything in the universe that isn't explicitly defined as the system.

What this question attempts to probe: This question probes students' ideas about the change in entropy of a system and its surroundings. The correct answer is that the change in entropy of the system and surroundings is not determinable from the given information, because we aren't given any specifics about the process that is occurring. The only physical constraint is that the entropy of the system plus the entropy of the

surroundings must increase, since the system plus the surroundings constitutes "the universe."

What this question does not attempt to probe: This question does not attempt to probe whether students understand the terminology that establishes "system + surroundings = universe." (The word "universe" does not appear in the question.) It also does not attempt to probe student understanding of the idea that the entropy of "the universe" increases during every real process. Students may use that information to aid in answering this question, but the idea is not directly probed. This question does not address the context in which a person can answer these types of questions other than in this particular, highly general form. Student understanding of the concepts of "isolated" or "closed" systems is not probed by this question.

Issues: Student understanding of what, precisely, *defines* a "system" and its "surroundings" could be a cause a source of confusion. Students may have some understanding of entropy, but uncertainty regarding terminology can cause errors on this question. Part (c) of the question is a bit subtle in that students may grasp the idea that the entropy of the universe increases, but at the same time may not understand the relationship "system + surroundings = universe," and therefore still arrive at incorrect answers.

5.4.2 Concrete-Context Question

An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures. The object and the air in the room are allowed to exchange energy with each other, but the air in the room does not exchange energy with the rest of the world or with the insulating walls.

a) During this process, does the entropy of the **object** [S_{object}] *increase, decrease, remain the same,* or is this *not determinable* with the given information? *Explain your answer.*

b) During this process, does the entropy of the **air in the room** [S_{air}] *increase, decrease, remain the same,* or is this *not determinable* with the given information? *Explain your answer.*

c) During this process, does the entropy of the object *plus* the entropy of the air in the room [$S_{object} + S_{air}$] *increase, decrease, remain the same,* or is this *not determinable* with the given information? *Explain your answer.*

d) During this process, does the entropy of the **universe** [$S_{universe}$] *increase, decrease, remain the same,* or is this *not determinable* with the given information? *Explain your answer.*

Figure 5.2 Concrete-Context Question

Description: This question is written in a concrete context with minimal technical language. Students should recognize that the object and the air in the room are the only two things inside the insulated room. Since the object and the air in the room are initially at different temperatures, the higher temperature entity (object or air) will transfer energy in the form of heat to the lower temperature entity. The question does *not* specify whether the object's temperature is higher than that of the air in the room.

Physics Principle: The entropy of the universe must increase due to the occurrence of any real process, i.e. one that is irreversible, such as heat flow. While the entropy change of the object and the entropy change of the air in the room aren't separately constrained, the sum of the two must be positive.

What this question attempts to probe: Students' understanding that high-temperature entities transfer energy to low-temperature entities, so long as they can exchange energy with each other. The idea that an object or entity that loses energy through heating will decrease in entropy while one that gains energy through heating will increase in entropy, assuming that volume changes are negligible.

What this question does not attempt to probe: This question does not probe students' ability to solve problems regarding entropy in a quantitative context, and students are not expected to perform any calculations to answer this question.

Issues: It's possible that students were making assumptions about which entity was at the higher temperature (object or air) without explicitly stating their assumption, for instance some students stated that they had assumed the object's temperature was higher than that of the air, even though this is not stated in the problem.

5.4.3 Cyclic-Process Question

Consider a heat engine that uses a fixed quantity of ideal gas. This gas undergoes a *cyclic process* which consists of a series of changes in pressure and temperature. The process is called "cyclic" because the gas system repeatedly returns to its original state (that is, same value of temperature, pressure, and volume) once per cycle.

Consider one complete cycle (that is, the system begins in a certain state and returns to that *same* state).

a) Is the *change* in temperature (ΔT) of the gas during one complete cycle *always equal to zero for any cyclic process* or *not always equal to zero for any cyclic process*? Explain.

b) Is the *change* in internal energy (ΔU) of the gas during one complete cycle *always equal to zero for any cyclic process* or *not always equal to zero for any cyclic process*? Explain.

c) Is the *change* in entropy (ΔS) of the gas during one complete cycle *always equal to zero for any cyclic process* or *not always equal to zero for any cyclic process*? Explain.

d) Is the net heat transfer to the gas during one complete cycle *always equal to zero for any cyclic process* or *not always equal to zero for any cyclic process*? Explain.

Figure 5.3 Cyclic-Process Question

Description: This question deals with a cyclic process, which is clearly defined as one that repeatedly returns to its original state. It explicitly states that the initial and final temperatures, pressures, and volumes are the same.

Physics Principle: Temperature, pressure, volume, internal energy, and entropy are state functions in that specific values of these quantities characterize any particular state of a gas system. The difference in magnitude of any state function between the initial and final state of a process is the same regardless of the path taken by the process, and the net change in any state function during a cyclic process is zero. However, the net heat transfer during a cyclic process is not, in general, zero.

What this question attempts to probe: This question was written to assess the extent to which students could apply their knowledge of state functions to a very general process.

Issues: The question is very generic, and doesn't describe any particular concrete process. A very small number of students (< 5%) remarked that the words "during one complete cycle" meant that throughout the process the temperature or other quantities might change, but that from the initial to final state they would remain the same.

5.4.4 Spontaneous-Process Question, Versions **A** *and* **B**

A subsystem A is in thermal contact with its environment B, which together comprise an isolated system. Consider the following situations:

I.   Entropy of system increases by 5 J/K; entropy of the environment decreases by 5 J/K.
II. Entropy of system increases by 5 J/K; entropy of the environment decreases by 3 J/K.
III. Entropy of system increases by 3 J/K; entropy of the environment decreases by 5 J/K.
IV. Entropy of system decreases by 3 J/K; entropy of the environment increases by 5 J/K.

Which of the above four situations can actually occur in the real world?

    A. I only
    B. II only
    C. III only   Version *A*
    D. II and III only
    E. II and IV only

Figure 5.4 Spontaneous-Process Question, Version *A*

A system is in thermal contact with its environment and together they are undergoing a naturally occuring process. Consider the following situations:

I.   Entropy of environment decreases by 4 J/K; entropy of the system increases by 7 J/K.

II.   Entropy of environment increases by 4 J/K; entropy of the system decreases by 7 J/K.

III. Entropy of environment increases by 7 J/K; entropy of the system decreases by 7 J/K.

IV.   Entropy of environment increases by 7 J/K; entropy of the system decreases by 4 J/K.

Which of the above four situations can actually occur?

a. III only

b. IV only

c. I and IV only

d. I, III and IV only

e. I only

Version *B*

Figure 5.5 Spontaneous-Process Question, Version *B*

Description: This question was written for administration on a large-sample, multiple-choice mid-term or final exam. It describes four processes that involve a change in the entropy of a system and its environment. Students are asked to decide which of the processes can actually occur "in the real world." Version *B* of this question includes an answer option (response *d*) that corresponds to the total entropy either increasing *or* remaining the same. Version *A* of the question does not include an answer option that combines those two possibilities. (Note: The instructor for the course in which this question was first used employed the terminology "isolated system," so the question was written to include that language in Version *A*.)

Physics Principle: The entropy of the universe (or, as in Version *A*, an isolated system) must increase for any real process. The universe is comprised of an arbitrarily defined system and that system's surroundings (or environment). There is no constraint on the change in entropy of either of these two arbitrarily defined entities, so the information that the entropy of the "system" or of the "environment" might be increasing or

decreasing does not determine the possibility of that particular process. However the sum of the two entropy changes must be positive, which means that processes II and IV (in Version *A*) or I and IV (in Version *B*) are possible, but that the other processes are not possible.

What this question attempts to probe: (1) The extent to which students give an answer consistent with the total entropy remaining unchanged; (2) the extent to which students give an answer consistent with the total entropy increasing *along with* the entropy of the "system" increasing; and (3) the extent to which students given an answer consistent with correct understanding.

Issues: The wording of Version *A* involves the terminology "isolated system," which was not a focus of our research. We also found that the distracters in Version *A* may not be accurate representations of student thinking, and this was the motivation for creating Version *B*. (For more discussion of this issue, see Section 5.6.2.2.)

5.4.5 PV-*Diagram State-Function Question, Versions* A and *B*

This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that undergoes three different processes in going from state A to state B:

Rank the change in entropy of the system for each Process.

NOTE: ΔS_1 represents the change in entropy of the system for Process #1, etc.

A. $\Delta S_3 < \Delta S_2 < \Delta S_1$
B. $\Delta S_1 < \Delta S_2 < \Delta S_3$
C. $\Delta S_1 = \Delta S_2 < \Delta S_3$
D. $\Delta S_1 = \Delta S_2 = \Delta S_3$
E. Not enough information
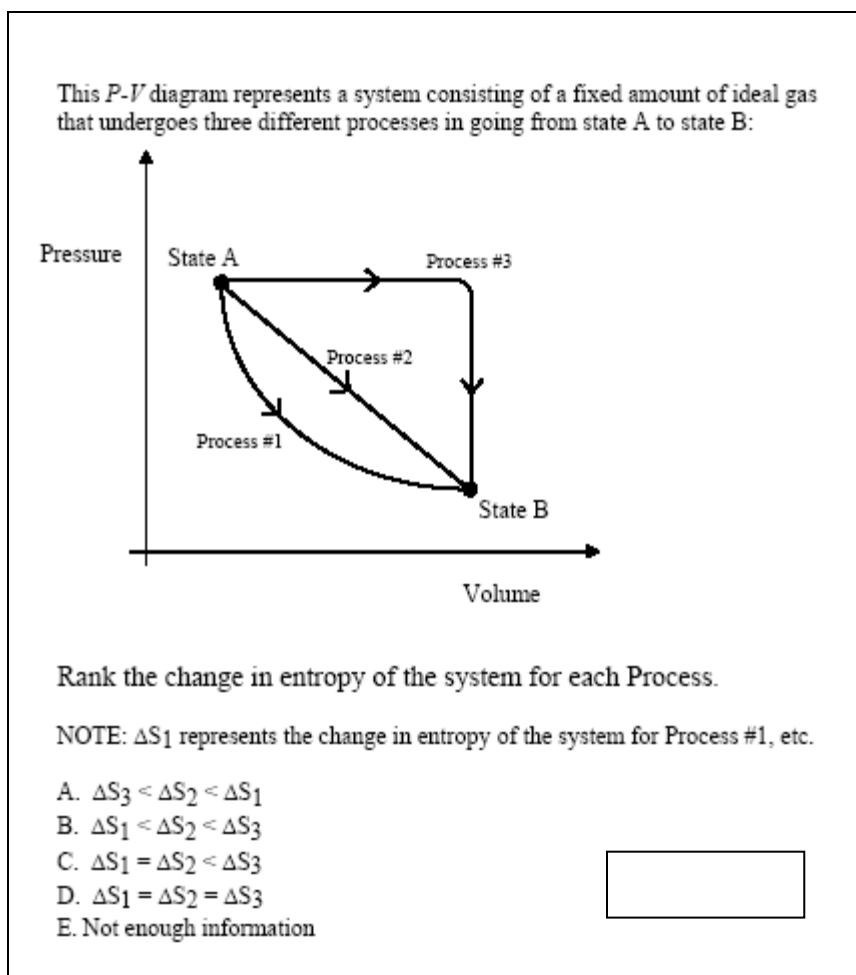
Figure 5.6 *PV*-Diagram State-Function Question Version *A*

This *P-V* diagram represents a system consisting of a fixed amount of ideal gas that is initially in state A and ends up in State B. Process #1 is an isothermal expansion, and Process #2 consists of two parts: an adiabatic expansion and an isochoric heating of the system (process at constant volume). The arrows indicate the direction of each process.

Pressure   State A

Which of the following statements about the change in entropy of the system is true?

NOTE: ΔS_1 represents the change in entropy of the system for Process #1, etc.

Process #1

State B

Process #2

Process #2

Volume

a. $\Delta S_1 > \Delta S_2$
b. $\Delta S_1 < \Delta S_2$
c. $(\Delta S_1 = \Delta S_2) \neq 0$
d. $(\Delta S_1 = \Delta S_2) = 0$
e. Not determinable

Figure 5.7 *PV*-Diagram State-Function Question Version *B*

Description: The *PV*-Diagram State-Function Question was written for administration to a large sample of students during a multiple-choice mid-term or final exam. It is similar to a question used by Meltzer in his investigation of student thinking regarding state-function properties of other thermodynamic quantities (Meltzer 2004). Version *A* asks students to rank the relative entropy changes of three processes that have identical initial and final states. Version *B* deals with only two different processes, but provides details about the nature of the processes and also asks students to determine whether or not the entropy change was zero.

Physics Principle: Entropy is a state function, so the change in entropy between state *A* and state *B* is the same independent of the process by which the gas's state changed. In Version *B* the isothermal expansion of the ideal gas involves no change in internal energy; therefore, the positive work done by the gas in its expansion implies a positive

heat transfer to the gas. A positive heat transfer at constant temperature means that the entropy change of the gas will be positive as well.

What this question attempts to probe: (1) Student thinking that is consistent with "change in entropy is directly related to area under the curve," or "change in entropy is inversely related to area under the curve"; (2) The extent to which students identify correctly that entropy is a state function; (3) Students' ability to identify non-zero changes in entropy.

Issues: Version *B*, while it does probe the same concepts as the original Version *A*, includes the additional task of identifying zero and non-zero changes in entropy. This may add considerably to the question's difficulty, and in any case requires students to consider more than merely the state-function property of entropy.

5.4.6 Metal in the Ocean Question

A very hot 1 cm³ piece of metal is thrown into the ocean; several hours pass.

  a) During this time does the entropy of the metal *increase, decrease, remain the same*, or is this *not determinable with the given information*?

  b) Does the entropy of surroundings *increase, decrease, remain the same*, or is this *not determinable with the given information*?

  c) Does the entropy of the metal plus the surroundings *increase, decrease, remain the same*, or is this *not determinable with the given information*?

Figure 5.8 Metal in the Ocean Question

Description: Students are expected to realize that since the temperature of the metal is greater than that of the ocean, there will be a net heat transfer from the high temperature metal to the low temperature ocean. The positive heat transfer to the ocean will not

change its temperature, but will cause an increase in its entropy. The net heat transfer away from the metal results in a decrease in entropy of the metal. The overall process occurs spontaneously (i.e., independent of any external influence), so the entropy of the universe will increase.

Physics Principle: The entropy of the universe must increase due to the occurrence of any real process, i.e. one that is irreversible.

What this question attempts to probe: This question is meant to probe student understanding that total entropy increases during a real-world process, in the case of a concrete example that explicitly incorporates two entities with differing temperatures. This question was posed in the context of "the ocean" (rather than a smaller body of water such as a bathtub) to shed additional light on a small percentage of students that argued that size of an object would have an effect on its change in entropy.

What this question does not attempt to probe: This question does not test students' abilities to perform numerical calculations to provide a result. It also does not include language about "the universe," so the concept that entropy of the universe always increases due to any real process is also not directly addressed.

Issues: As written (see above), the question states that the metal is "very hot," but it fails to explicitly specify its temperature in relation to that of the ocean. During interviews several students asked about this detail, so later versions will be altered to make the language unambiguous by stating that the very hot metal is initially at a higher temperature than that of the ocean. Additionally, the question is unclear as to what processes are occurring in the surroundings that might change the entropy of the surroundings. We only want students to consider the change in entropy due to the heat

transfer process between the metal cube and the surroundings. There was no evidence from our interview data that this caused confusion for students, but it should be corrected in later versions.

5.4.7 Free-expansion Question

Consider a sealed cylindrical container consisting of perfectly thermally insulating material, such that there can be no heat transfer between the container and *anything* else, outside or inside. Within the container, a thin plastic sheet divides the container in half. Two moles of an ideal gas are confined inside the container to one half of the container, at a temperature of 300 K.

The plastic divider is suddenly removed and the gas expands to fill the container; no other changes are made. Because it is a free expansion of an ideal gas (no work is done on or by the gas), the final temperature of the gas is *also* 300 K.

a) Does the entropy of <u>everything outside the container</u> *increase, decrease, remain the same,* or is this *not determinable with the given information*? **Explain.**

b) Does the entropy of the gas *increase, decrease, remain the same,* or is this *not determinable with the given information*? **Explain.**

c) Does the total entropy of the gas <u>plus</u> everything outside the container *increase, decrease, remain the same,* or is this *not determinable with the given information*? **Explain your answer.**

Figure 5.9 Free-expansion Question

Description: The plastic divider is removed and the gas expands to fill the container, but no work is done, no heat is transferred, and the temperature of the gas remains constant. The process of the gas expanding to fill the entire container is irreversible, since it can not spontaneously revert back to its original state unless there is an interaction with something external to the gas system (such as energy being added to the gas through a piston doing work on it, etc.).

Physics Principle: The entropy of the universe must increase due to the occurrence of any real process, i.e. one that is irreversible. No changes occur outside the container due to the expanding gas, so the entropy outside the container is unchanged. This implies that
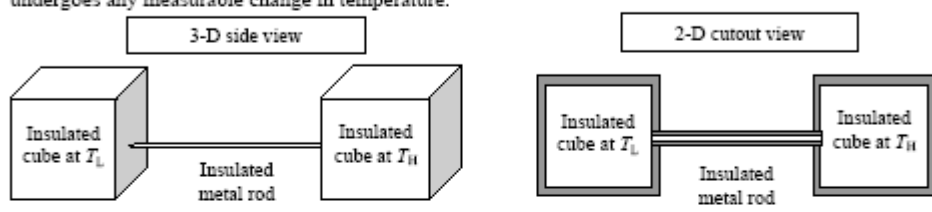
the entropy of the gas increases because the sum of the entropies of the gas and

everything outside the container (i.e., the "entropy of the universe") must increase.

What this question attempts to probe: This question was written to give students an

opportunity to consider a gas that was undergoing a spontaneous process that involved no

heat transfer. Other than the general-context question, all other questions we asked

involved some explicit use or assumed use of entropy changes due to heat transfers.

Issues: The question should ask if "the entropy of <u>everything outside the container</u> *due to*

the process of the expanding gas inside the container increases, decreases, etc." As

written and administered there is no evidence that students were drawn away from correct

responses to part (a) as a result of this question's wording (see Table 5.7.6), nor did the

wording seem to detract from overall correct responses.

5.4.8 Entropy Spontaneous-Process Worksheet Question

A metal cube, one meter on each side, is enclosed in a thermally insulating jacket. Another metal cube of the same size is enclosed in its own insulating jacket. The temperature of this second cube is higher than the temperature of the first cube. We'll refer to the high-temperature cube as "H," and the other as "L," and their temperatures as T_H and T_L, respectively. The only connection between the cubes is through a narrow metal rod that has a very small mass. Heat transfer to or from the cubes can take place only through this narrow metal rod. We will assume that when heat transfer does take place, the rate of energy change is so small that neither of the metal cubes undergoes any measurable change in temperature.

3-D side view

Insulated cube at T_L Insulated cube at T_H Insulated metal rod

2-D cutout view

Insulated cube at T_L Insulated cube at T_H Insulated metal rod

Is it reasonable to assume the temperature of the two cubes will remain constant:
A quantitative argument: Suppose we have two different copper blocks each with volume of 1 m³; assume that the temperature difference between the blocks is 50 K and that they are connected by a copper rod 20 cm long, with diameter 1 cm. There would be 8 joules of energy transferred each second through heat conduction. However, given the mass of the blocks (each weighs roughly 10 tons), it would take almost 12 days before the temperature of the blocks changed even by *one* kelvin.

a) Consider the system consisting *only* of the low-temperature cube. While the two cubes are connected with the rod, does the entropy of this system *increase, decrease,* or *remain the same*?

b) During the same process, does the total entropy of the high- and low-temperature cubes together *increase, decrease,* or *remain the same*? Explain your reasoning.

c) State whether the following quantities are conserved during this process: (i) energy; (ii) entropy.

Figure 5.10 Entropy Spontaneous-Process Worksheet Question

Description: This question is on the first page of our Entropy Spontaneous-Process tutorial. The problem describes two metal blocks that are at different temperatures and explains that the blocks are so massive that over the interval of one minute there is no substantial temperature change of either block.

Physics Principle: For a spontaneous process, the entropy of the universe must increase, but that there is no constraint on the change in entropy of an arbitrarily defined system or its surroundings.

What this question attempts to probe: This question probes the extent to which students can recognize that total entropy must increase during a spontaneous process.

5.5 Administration of Diagnostic Questions

In this section we provide details regarding the time and circumstances of administration of each of our diagnostic questions.

5.5.1 Free-response and Multiple-choice data collection

The chart below shows in which courses and at what times (i.e., before or after instruction) the various diagnostic questions were administered. Below the chart we provide a more detailed enumeration of the timing and circumstances for each administration.

Table 5.5.1 Inventory of Entropy Data Collection

	Fall 2004	Spring 2005	Fall 2005	Spring 2006
5.4.1 General-Context Question	Before Instruction Only	Before and After Instruction	Before Instruction Only	Before and After Instruction
5.4.2 Concrete-Context Question		Before and After Instruction	Before Instruction Only	Before and After Instruction
5.4.3 Cyclic-Process Question	Before Instruction Only	Before and After Instruction		
5.4.4 (a) Spontaneous-Process Question, Version *A*,	After Instruction Only			
5.4.4 (b) Spontaneous-Process Question, Version *B*,		After Instruction Only		After Instruction Only
5.4.5 (a) *PV*-Diagram State-Function Question Version *A*		After Instruction Only		After Instruction Only
5.4.5 (b) *PV*-Diagram State Function Question Version *B*				After Instruction Only
5.4.6 Metal in the Ocean Question				After Instruction Only (interviews)
5.4.7 Free-expansion Question				After Instruction Only

Table 5.5.1 Inventory of Entropy Data Collection

Before all instruction

Fall 2004 – Administered during the first recitation of the semester before all instruction on thermodynamics.

Spring 2005 – Administered during the first and second week of labs before all instruction on entropy.

Fall 2005 – Administered during the first recitation of the semester before all instruction on thermodynamics.

Spring 2006 – Administered during the second week of labs before all instruction on entropy.

After all instruction

Fall 2004 – Administered multiple-choice question on the final exam after all instruction on entropy was complete.

Spring 2005 – Administered multiple-choice questions on mid-term exam after all instruction on entropy was complete; administered free-response questions during one week of labs after all instruction and mid-term exam on entropy was complete.

Spring 2006 – Administered multiple-choice questions on mid-term exam after all instruction on entropy was complete; administered free-response questions during one week of labs after all instruction and mid-term exam on entropy was complete

5.5.2 Interviews

Fall 2004: 7 interviews; post-instruction; course utilized traditional instruction.

After all instruction and exam testing for the course were complete, we conducted seven one-on-one interviews with student volunteers whom we solicited via e-mail after the course was complete. Students were asked a combination of calorimetry and entropy questions. The students in this sample had completed a course that utilized traditional instruction methods. The purpose of these interviews was to shed some initial light on student thinking on entropy and the second law of thermodynamics.

Spring 2005: 18 interviews; post-instruction; students performed the "Entropy State-Function" tutorial worksheet in recitation during the week in which they were covering entropy and the second law of thermodynamics during lecture.

After all instruction and exam testing on entropy in the course were complete, we conducted 18 one-on-one student interviews. Students were solicited for interviews during lecture and asked to sign up for 60-90-minute interviews. The Spring 2005 course utilized research-based curricular materials and instructional methods both in lecture and during recitation. Recitation periods (one hour per week) were split between research-based tutorials and research-based Group Problem-Solving exercises. During the week entropy was covered, the materials for recitation comprised a research-based tutorial that we had created to address student understanding of entropy (for more on this, see section 5.7.3). The purpose of these interviews was to shed additional light on our free-response question data, probe student thinking on entropy more deeply and also to ensure that our students were not having substantial difficulties in interpreting our questions. Students answered questions on calorimetry and several entropy topics.

Fall 2005: 9 interviews; post-instruction; course utilized traditional instruction

These interviews were conducted with student volunteers from the Fall 2005 second-semester calculus-based physics course. Student volunteers were contacted via an e-mail list from the course, and asked to consent to a one-on-one interview lasting 60-90 minutes that would require them to answer physics questions and work through physics problems for educational research purposes. The students were compensated financially for their time. Interviews were carried out in January 2006, after the entire

fall-semester course was complete. Students in the Fall 2005 course received almost purely traditional instruction. Only one reformed instruction innovation was used. (An electronic personal-response system or "clickers" were used once or twice per lecture, using basic quantitative questions with little conceptual content.) No research-based instructional materials were used in the course.

The students who were interviewed were asked to work through a research-based tutorial that our group had created (see section 5.7.3). Our objective was to present the students with a basic context for discussing heat transfer that would allow them to confront issues concerning incorrect preconceptions about entropy.

S*pring 2006*: 20 interviews; post-instruction, completed Entropy Spontaneous-Process Worksheet

In the spring semester of 2006 we conducted twenty one-on-one student interviews after all instruction on thermodynamics was complete. Our self-selected student sample had statistically higher final exam scores (76.6%) than students in the course taken as a whole (70.1%), ($p < 0.02$ using a two-tail t-test). This is consistent with previous studies that have found a similar trend among self-selected student interview subjects (e.g., Loverude 2002; Meltzer 2004). Interviewees were asked to consent to a 60-90 minute interview where they would answer physics questions and discuss their ideas. The Spring 2006 course spent two 50-minute lecture periods and one 50-minute recitation period on entropy. The recitation was spent working through a research-based tutorial on entropy concepts, our Entropy Spontaneous-Process Worksheet.

5.6 Student concepts related to entropy

In this section we will discuss students' ideas related to entropy and the second law of thermodynamics, as revealed by their responses to our diagnostic questions. In Section 5.6.1, we look at the proportion of students who were able to give correct answers on questions related to the entropy-increase principle *before* instruction on these topics had begun in their general physics course. In Section 5.6.2, we focus on student ideas (both pre- and post-instruction) related to an apparent belief in the existence of a conservation principle for entropy. In Section 5.6.3, we discuss students' apparent preference for believing that any generic "system" must increase in entropy, rather than decrease, during any spontaneous process. Students show a similar belief in regards to the behavior of the "surroundings." In Section 5.6.4, we comment on student notions that entropy change is linked to the size of an object, which come into play only when considering very large objects. In Section 5.6.5, we explore student understanding of the state-function property of entropy in two different contexts, and finally, in Section 5.6.6, we summarize all of the results of Section 5.6.

5.6.1 Students' pre-instruction performance on questions related to the entropy-increase principle

We administered the general-context and concrete-context questions during four and three different semesters, respectively, of the second-semester calculus-based

introductory physics course. The questions were administered before all instruction on entropy and the second law of thermodynamics.

For the general-context question, the data show that almost half of all students (42%) answered correctly that the entropy changes of the system and the surroundings would not be determinable from the given information. A smaller proportion of students (19%) gave the correct "increases" answer for the entropy change of the system plus surroundings, and almost no one (4%) gave a correct response for all three parts of the question.

The concrete-context question yielded similar results. Half of all students stated that the change in entropy of the object, and the entropy change in the air in the room would not be determinable (50% and 49% respectively). The proportion of students (14%) who gave the correct response on part (c) (that is, that the entropy of the object plus the air in the room increases) was similar to the proportion who gave a correct response on the corresponding part (c) for the general-context question. A similar proportion (15%) correctly stated that the entropy of the universe would increase. The proportion of students who gave a correct answer for all three parts (*a*, *b*, and *c*) was nearly identical (5%) to those who gave correct answers on the three corresponding parts on the general-context question.

Table 5.6.1 Pre-instruction Correct Responses on General- and Concrete-Context Questions

	Pre-Instruction General-Context Cumulative Results		Pre-Instruction Concrete-Context Cumulative Results
Correct Answers	$N = 1184$	*Correct Answers*	$N = 609$
Entropy of system *is not determinable*	$42 \pm 10\%$	Entropy of object *is not determinable*	$50 \pm 11\%$
Entropy of surroundings *is not determinable*	$42 \pm 6\%$	Entropy of air in the room *is not determinable*	$49 \pm 3\%$
Entropy of the system + surroundings *increases*	$19 \pm 5\%$	Entropy of the object + air in the room *increases*	$14 \pm 9\%$
		Entropy of the universe *increases*	$15 \pm 18\%$
All Correct	**$4 \pm 1\%$**	**All Correct (Part a-c)**	**$5 \pm 3\%$**

Table 5.6.1 Proportion of correct responses on the General- and Concrete-Context questions, before all instruction on entropy

Figures shown are mean values and 95% confidence intervals, based on score variances among the four samples for the general-context question and three samples for the Concrete-Context question; see detailed data in Appendix 5.1 & 5.2. About 90% of students who gave a "not determinable" response on part (a) (the system/object) also gave a "not determinable" response on part (b) (the surroundings/air), on both the general-context and concrete-context questions, both before and after instruction..

5.6.2 Overall entropy remains the same

5.6.2.1 Pre-instruction Analysis

Many students gave pre-instruction answers consistent with a belief that entropy is a conserved quantity (see Table 5.6.2). Two-thirds of all students stated that the "entropy of the system plus the entropy of the surroundings" stays the same for the general-context question. A statistically identical proportion of students stated that the entropy of the object plus the air in the room stays the same for the concrete-context question.

When we analyze the answers of the students who gave these "entropy remains the same" responses on the general-process question in more detail, we find that 90% of

them fall into one of two specific categorizations. (These categories are referred to as "*A*" and "*B*," respectively, in Table 5.6.2.) The first category ("*A*") consists of students who believe that the change in entropy of the system is not determinable and the change in entropy of the surroundings is not determinable, but the entropy of the system *plus* that of the surroundings remains the same (26% of all responses). 65% of the students who fall in this category specifically cited some type of conservation rule as their reasoning for entropy remaining the same. Many are unclear about what exactly is being conserved, but entropy, energy, and heat are the most commonly cited quantities. The second category ("*B*") consists of a nearly equal proportion of students (25% of all responses) who display a similar chain of reasoning, i.e.: the system entropy increases [decreases] and the surroundings' entropy decreases [increases], but the entropy of the system *plus* that of the surroundings remains the same.

It's conceivable that some students are confused about what is being asked due to the very general language of the general-context question. However, the results for our concrete-context question yield strikingly similar results. Before instruction approximately 70% of all students had some notion that the entropy of the object plus the entropy of the air in the room (hereafter referred to as the "total entropy") does not change during a spontaneous process. More than half (60%) of all responses on the concrete-context question included a series of answers consistent with total entropy being conserved during a spontaneous process (see category (C) in Table 5.6.2).

It is conceivable that some students may simply confuse the word "entropy" with the word "energy." The words are spelled similarly, and the two concepts are tightly linked together. But while there may be some word confusion among the students, there

is no clear evidence from their responses that students actually believe energy and

entropy are the same thing.

Table 5.6.2 Pre-Instruction Responses Related to Overall Entropy Change on General- and Concrete-Context Questions

	222 Pre-Instruction General-Context Cumulative	222 Pre-Instruction Concrete-Context Cumulative
	$N = 1184$	$N = 609$
Total entropy *[of (system + surroundings)/(object + air in the room)]* remains the same	**$67 \pm 8\%$**	**$71 \pm 7\%$**
A. Entropy of (system *and* surroundings)/(object *and* air) not determinable, but total entropy remains the same	$26 \pm 12\%$	$38 \pm 8\%$
B. Entropy of (system/object) increases [decreases] and entropy of (surroundings/air) decreases [increases], but total entropy remains the same	$25 \pm 10\%$	$22 \pm 6\%$
C. Students with one of these notions of entropy conservation (sum of A and B above)	*$51 \pm 7\%$*	*$60 \pm 13\%$*

Table 5.6.2 Responses related to overall entropy change on the general-context and concrete-contest questions, before all instruction on entropy.
Figures shown are mean values and 95% confidence intervals, based on score variances among the four samples for the general-context question and three samples for the Concrete-Context question; see detailed data in Appendix 5.3 & 5.4.

Figures in the first row (*"Total entropy…remains the same"*) correspond to students who answered "remain the same" to part (c) of each question, respectively. Figures in the second row (*"A. entropy of…"*) correspond to students who responded "not determinable" to parts (a) and (b), but "remain the same" to part (c) of each question, respectively. Figures in the third row (*"B. Entropy of (system/object) increases [decreases]…"*) correspond to students who answered *either* "increase" *or* "decrease" to part (a), but gave the opposite answer (i.e., "decrease" or "increase") to part (b), and who *also* answered "remain the same" to part (c) of each question, respectively. Figures in the last (fourth) row are the sums of figures in rows two and three.

5.6.2.2 Post-instruction and interview analysis

Free Response Questions

After all instruction was complete in Spring 2005 we were able to administer free-response questions to students during one week of lab classes. Responses to these questions are shown in Table 5.6.3, where students' post-instruction responses are

compared to their pre-instruction responses. These students had performed our research-based Entropy State-Function Worksheet during recitation. For the General-Process Question, many students continued to state, post-instruction, that entropy of the system plus that of the surroundings stays the same (50% of all responses); nearly 80% of this group fell into one of our two conservation categories (41% overall). The only statistically significant difference ($p < 0.01$) between pre- and post-instruction responses in this Spring 2005 sample was the decrease in the conservation category A (i.e., "entropy of system is not determinable, entropy of surroundings is not determinable, total entropy remains the same"). The direct cause for this shift is not entirely clear and deserves more attention in future work.

The concrete-context question yielded responses that were nearly identical before and after instruction. If we compare post-instruction data across questions, it appears that in some cases students were applying different reasoning to problems in general and concrete contexts, respectively. Students stated that total entropy would remain the same on the concrete-context question (70%) more often than they did on the general-context question (50%, difference significant at $p < 0.001$ using a test for binomial proportions). Both questions had a high proportion of students that fell in one of the two conservation categories when considering the "total entropy remains the same" responses. When looking at a proportion of the whole sample, the concrete-context question again showed a higher proportion of conservation arguments (60%) as compared to the proportion of conservation arguments for the general-context question (41%, difference significant at $p = 0.001$).

Table 5.6.3 Pre- and Post-Instruction Responses Related to Overall Entropy Change, General- and Concrete-Context Questions (Matched Sample, Spring 2005)

	222 Pre-Instruction General-Context Spring 2005	222 Post-Instruction General-Context Spring 2005	222 Pre-Instruction Concrete-Context Spring 2005	222 Post-Instruction Concrete-Context Spring 2005
	N = 153	*N = 153*	*N = 131*	*N = 131*
Total entropy *[of (system + surroundings)/(object + air in the room)]* remains the same	60%	50%†	69%	70%†
A. Entropy of (system *and* surroundings)/(object *and* air) not determinable, but total entropy remains the same	32%*	18%*†	38%	36%†
B. Entropy of (system/object) increases [decreases] and entropy of (surroundings/air) decreases [increases], but total entropy remains the same	18%	24%	21%	24%
C. Students with one of these notions of entropy conservation (sum of A and B above)	50%	41%†	60%	60%†

Table 5.6.3 Pre- and Post-Instruction Responses related to Overall Entropy Change, General- and Concrete-Context Questions (Matched Sample, Spring 2005)
*Significant difference (p < 0.01) between *pre-* and *post*-instruction rates on general-context question, based on binomial proportions test.
$\dagger$ Significant difference (p ≤ 0.001) between *concrete*-context and *general*-context rates on post-instruction questions, based on binomial proportions test.

Pre- and Post-Instruction responses given by students to the General-Context (Fig. 5.1) and Concrete-Context (Fig. 5.2) questions in Spring 2005. The same group of students (the "matched sample") responded to the questions both pre-instruction and post-instruction. See detailed data in Appendix 5.7.

Figures in the first row (*"Total entropy…remains the same"*) correspond to students who answered "remain the same" to part (c) of each question, respectively. Figures in the second row (*"A. entropy of…"*) correspond to students who responded "not determinable" to parts (a) and (b), but "remain the same" to part (c) of each question, respectively. Figures in the third row (*"B. Entropy of (system/object) increases [decreases]…"*) correspond to students who answered *either* "increase" *or* "decrease" to part (a), but gave the opposite answer (i.e., "decrease" or "increase") to part (b), and who *also* answered "remain the same" to part (c) of each question, respectively. Figures in the last (fourth) row are the sums of figures in rows two and three.

There was no significant difference between general- and concrete-context question responses pre-instruction, but such differences did appear post-instruction as indicated by the "†" symbol. The only significant difference between pre- and post-instruction responses on same-context questions was with Category *A* on the general-context question.

Multiple-choice Questions

The two different versions of the Spontaneous–Process Question were administered after all instruction on thermodynamics was complete in the Fall 2004 and Spring 2005 semesters. After administering Version *A* of the question in the Fall 2004 course, we conducted seven interviews (see Sec 5.5.2) in which we asked this question in a free-response format, simply asking students to identify which processes would be possible for a spontaneous process. Four of the seven students stated that total entropy must either increase *or* remain the same. We therefore re-cast the multiple-choice options to reflect this change in Version *B*, administered in the Spring 2005 course. (We were unable to administer this question again in the fall-semester course due to logistical difficulties.) Responses to both version of this question are shown in Table 5.6.4.

Table 5.6.4 Post-Instruction Responses on Spontaneous-Process Question

	222 Fall 2004 Post-Instruction (Version *A*)	222 Spring 2005 Post-Instruction (Version *B*)
	N = 539	*N* = 341
A. Total entropy remains the same	54%	36%
B. Total entropy increases and system entropy increases	5%	12%
C. Total entropy decreases and system entropy increases	7%	2%
D. Answers B & C	4%	--
E. Total entropy increases and system entropy can increase *or* decrease *[correct]*	30%	27%
E.* Total entropy increases *or* remains the same	--	23%

Table 5.6.4 Post-instruction responses on Versions *A* and *B* of the spontaneous-process question
Only Version *B* contains the option of total entropy either increasing *or* remaining the same.
Column 1 descriptions are characterizations of the actual numerical response options in the
original question; see Section 5.4.4 for the actual response options.

It's unclear to what extent the students in the Fall 2004 course would have

preferred an "increases *or* remains the same" answer, but in both semesters over half of

all students (54%, Fall 2004; 59%, Spring 2005) gave a response consistent with a belief

that entropy should (or at least could) remain unchanged during a spontaneous process.

(The proportion of correct responses was not significantly different on the two versions

of the question.)

Interview Data

One-on-one student interviews provide some of the richest insight into student

thinking. The following data are identified by semester and year, and by the question to

which the students are responding. Representative examples of student responses are

shown; the full set of relevant interview quotes can be found in Appendix 5.10.1.

Spring 2004, Post-instruction (traditional instruction), General-Context Question:

Two out of eight students answered that the entropy of the system plus the surroundings would remain the same. We found that both students reasoned in a manner consistent with our groupings of "conservation ideas":

SA2 "I knew that the entropy of everything has to be at equilibrium, so that'd be remain the same [for part c]. I kinda guessed that [system] was decreasing, if it's at equilibrium the surroundings would have to increase. It could be increases [for system] and decreases [for surroundings], but irreversible gives it away… at first I thought it was not determinable, but then I thought there were different processes, like irreversible and reversible."

I: What do you mean by *everything*?

SA2 "I want to say the entire system; the system that is undergoing the irreversible process and the surroundings is everything around it."

I: What if this were a reversible process, how would that change your answers?

SA2 "If it was a reversible I would put not determinable because it could go one way or the other."

SA7 "We need to know more about the process to determine what the change in entropy was, it depends on whether it is endo- or exothermic. The total entropy would remain the same. Because one [of system or surroundings] is increasing and one is decreasing."

Spring 2005, Post-instruction (performed Entropy State-Function Tutorial), General-Context Question:

Seven out of eighteen students responded to part (c) of the general-context question by stating that the total entropy remained the same. By examining their answers to parts (a) and (b) of this question, we were able to determine that all seven students fell into one of our two defined conservation categorizations.

SC3 "I think for the irreversible process… I actually started with step (c)… I was thinking that the entropy of the system plus surroundings equals zero. So it would remain the same… I know these two would be opposite of each other… I wasn't 100% sure, but I was thinking the system would decrease… and the surroundings would increase"

SC11 "… [c] it remains the same because the surroundings and system is like the universe and entropy of the universe is constant"

Fall 2005, Post-Instruction (Traditional Instruction), Entropy Spontaneous-Process Tutorial Question:

Four of nine students gave explanations consistent with the total entropy remaining the same. Of the four students, two argued that the low-temperature block would increase in entropy (which is correct) and that the total entropy would remain the same (which is incorrect). The other two students argued that both the entropy of the

low-temperature cube and the total entropy would remain the same during the process.
The later both cite the lack of a measurable temperature change as evidence that there had
been no change in entropy.

SB5 "…the entropy of the system remains the same… so the entropy of
the two blocks together remains the same… conserved: entropy and energy"

SB6 "for the low temperature cube, the entropy would increase, because
when you give something energy you increase how much things are in chaos…
total: the system will stay the same, because one is increasing and one is
decreasing so they sort of cancel each other out…"

SB7 "Entropy of a system can never decrease, and it said it would take a
long time for the temperature to change so I'm saying that it'll remain the same.
Total [entropy]: for the same reason as (a) it'll remain the same… conserved?
Energy is always conserved. I guess since entropy remains the same, I guess it
could be considered a quantity since it has a numerical value so it could be
conserved too."

**Spring 2006, Post-Instruction (performed Entropy Spontaneous-Process
Worksheet), General-Context Question:**

Only three of the twenty students we interviewed in the spring of 2006
answered that the total entropy remained the same. The remarkably low
percentage of "total entropy remains the same" responses is consistent with free-

response and multiple-choice data we collected post-instruction in spring 2006,

and is further discussed in section 5.7.4.2.

SD15 "I know ΔS of the universe equals S of the system plus S of the

surroundings, so I have two things in the universe, my system is possibly losing

order and increasing in entropy but overall S in the universe will stay the same

because I think it's the 3rd law of thermodynamics… the ΔS of the universe

equals zero."

5.6.3 "System" and "surroundings" are not arbitrary distinctions

5.6.3.1 Pre-Instruction Analysis

In the general-context question, the most common answer was that the changes in

entropy of the system (42%) and of the surroundings (42%) during the process were not

determinable with the given information. (see Table 5.6.5) For the concrete-context

question, a similar proportion of students responded that the changes in entropy of the

object (50%) and of the air in the room (49%) were not determinable.

If we look at those responses where students made a specific directional choice,

we find that in the general context, students' preferred answer was that the entropy of the

system would increase (26%), rather than decrease (19%) or remain the same (10%).

Similarly more students expected the entropy of the surroundings to increase (28%) than

to decrease (14%) or remain the same (11%). This preferential response is statistically

significant over our sample of four semesters of data. In contrast, for the concrete-context

question, we do not see the same preferential response regarding changes in the entropy of the object (17% increases, 19% decreases). However students do show a preference regarding the entropy of the air in the room, with responses that entropy would increase (27%) nearly triple those that stated entropy would decrease (9%). At the outset of our study we expected students would disproportionately expect entropy to increase rather than decrease, calling to mind the common phrase "entropy never decreases." Our findings have shown that while this may be true in a variety of circumstances, there are contexts that will move students away from this belief.

According to a two-sample t-test for the "entropy of the system" question, the "increases" response is more common than the "decreases" response ($p < 0.05$). Similarly, the response that entropy of the surroundings *increases* is more popular than the response that entropy of the surroundings *decreases* ($p < 0.002$), and a similar preference is expressed for the entropy of the air in the room ("increases" preferred over "decreases," $p < 0.01$).

**Table 5.6.5 Pre-instruction Responses Related to "System" and "Surroundings,"
General- and Concrete-Context Questions, Cumulative data**

Entropy of…	Pre-Instruction General-Context Cumulative Results	Pre-Instruction Concrete-Context Cumulative Results
	N = 1084	N = 609
Entropy of…	*System…*	*Object…*
Increases	26 ± 3%	17 ± 2%
Decreases	19 ± 4%	19 ± 3%
Remains the same	10 ± 4%	6 ± 7%
is not determinable	42 ± 6%	50 ± 5%
Entropy of…	*Surroundings…*	*Air in room…*
Increases	28 ± 2%	27 ± 2%
Decreases	14 ± 2%	9 ± 1%
Remains the same	11 ± 1%	6 ± 3%
is not determinable	42 ± 4%	49 ± 1%

Table 5.6.5 Pre-instruction responses on "system" and "surroundings" questions, cumulative data
Response rates for "entropy of system" and "entropy of surroundings" questions (general-process question, Fig 5.4.1), and "entropy of object" and "entropy of air in the room" questions (concrete-context question, Fig 5.4.2). The data show that before instruction, students show highly consistent response patterns. Uncertainties reflect the 95% confidence interval based on response rates and standard deviations observed in four different courses for the general-context question, and three different courses for the concrete-context question; see Appendices 5.1 and 5.2 for detailed data tables.

5.6.3.2 Post-instruction and interview data

Free-response Questions

The matched-data sample from the Spring 2005 course shows consistent responses before and after instruction (see Table 5.6.6). Students have a distinct preference for the "entropy increases" responses (compared to "decreases" or "remains the same"), but this preference seems to be altered when dealing with an object in a concrete context. The same pattern of student preference for entropy increasing rather than decreasing persists after instruction is complete.

According to a test for binomial proportions for the "entropy of the system" question, the "increases" response is more common than the "decreases" response ($p <$ 0.001). Similarly, the response that entropy of the surroundings *increases* is more popular than the response that entropy of the surroundings *decreases* ($p < 0.01$), and a similar preference is expressed for the entropy of the air in the room ("increases" preferred over "decreases," $p < 1 \times 10^{-5}$). Both before and after instruction students show a statistically significant preference for entropy to increase except in the case of the object in our concrete-context question.

Table 5.6.6 Pre- and Post-Instruction Responses Related to "System" and "Surroundings," General- and Concrete-Context Questions (Matched Sample, Spring 2005)

	Pre-Instruction General-Context Spring 2005	Post-Instruction General-Context Spring 2005	Pre-Instruction Concrete-Context Spring 2005	Post-Instruction Concrete-Context Spring 2005
	$N = 153$	$N = 153$	$N = 131$	$N = 131$
Entropy of…	*System…*	*System…*	*Object…*	*Object…*
Increases	27%	35%[†]	21%	17%[†]
Decreases	14%	18%	17%	23%
Remains the same	3%*	9%*[†]	2%	3%[†]
is not determinable	50%*	37%*[†]	54%	56%[†]
Entropy of…	*Surroundings…*	*Surroundings…*	*Air in room…*	*Air in room…*
Increases	27%	31%	26%	30%
Decreases	11%	17%[†]	10%	7%[†]
Remains the same	8%	10%	7%	6%
is not determinable	46%	40%[†]	50%	56%[†]

Table 5.6.6 Pre- and Post-instruction responses on "system" and "surroundings" questions, cumulative data
*Significant difference (p < 0.05) between *pre-* and *post*-instruction rates on general-context question, based on binomial proportions test.
† Significant difference (p < 0.05) between *concrete*-context and *general*-context rates on post-instruction questions, based on binomial proportions test.

Pre- and post-Instruction responses given by students to the general-context (Fig. 5.4.1) and concrete-context (Fig. 5.4.2) questions in Spring 2005. The same group of students (the "matched

sample") responded to the questions both pre-instruction and post-instruction. The data show small or negative gains over the course of instruction. See detailed data in Appendix 5.7.

Interview Data

Spring 2005, Post-instruction (performed Entropy State-Function Worksheet), General-Context Question:

Our interview sample included seven of eighteen students who used some type of "entropy of the system can never decrease" argument. It's particularly interesting since, prior to our study, we thought students might be attracted to the general notion that "entropy increases" and over-apply it. And in fact, this "entropy increases" answer *was* a popular response when dealing with "the system"; the seven students in this sub-sample had the specific idea that the system entropy must increase. However, their answers for entropy of the surroundings varied among "not determinable" (four), "remains the same" (two), or "increases" (one). All seven students stated that the entropy of the system plus that of the surroundings would increase.

SC2 "Entropy of the system will increase because it's irreversible and you have to have an increase in entropy if it's irreversible… second one I wasn't sure of… entropy must either stay the same or increase…Because you can't achieve order from disorder, but it can go the other way around."

SC14 "It maybe increases because there is a transfer of heat energy and whenever you transfer heat energy the molecules become more unordered so entropy increases."

I: Does the direction of heat transfer matter?

SC14 "In the direction the heat is being transferred those molecules would be more unordered. 'Surroundings' I said remain equal or increase, and that depends on whether the heat is transferred to the system."

I: Could it decrease?

SC14 "It would always remain the same or increase. Remain the same because the universe can't possibly become more ordered… it's one of the laws of thermodynamics."

Fall 2005, Post-Instruction, Traditional Instruction, Entropy Spontaneous-Process Worksheet Elicit Question:

Two of the nine students in our Fall 2005 interview sample gave explanations consistent with entropy never decreasing.

SB2 "Entropy never decreases, I'm guessing it will increase because heat transfer is happening so there is an energy change... even though it's really small there is still a change. I believe [the total] would increase because the low temperature cube is increasing… hmm… I think both of the cubes are increasing because they both have a rate of energy change so they both have an entropy increase. The temperature doesn't measurably change so it's conserved."

5.6.4 Entropy change depends on "size"

5.6.4.1 Pre-instruction data and Post-instruction data

About 5% of the responses to part (d) of the concrete-context question (i.e., the "entropy of the universe" question) suggested that students might be arguing that, during some random process, the entropy of the universe would be unaffected "because it's too big." These responses accounted for less than 10% of all explanations for the "entropy of the universe remains the same" answers. A higher proportion of students claimed that the entropy of the universe is "unaffected" by the process, or that the universe is "isolated" from the process. It's unclear how many of these students employed the "unaffected because it's too big" argument, and how many mistakenly perceived "the universe" to *exclude* the object, air, and the room.

5.6.4.2 Interview data

Our free response data suggested that a small number of students considered size to be a crucial factor in their determination of whether entropy changes occur during a naturally occurring process. We wanted to probe this idea further in an attempt to clarify our understanding of student thinking. In parallel, we also wanted to devise a question with a completely concrete ("real-world") context; this would allow us to further assess our finding that student answers remained consistent across context, at least in the case of the general-context and concrete-context questions.

We developed the "metal in the ocean" question which, we felt, could effectively address both issues. The problem describes a 1 cm^3 block of hot metal being thrown into

an ocean. (It was noted that the hot metal was initially at a higher temperature than the ocean.) The students are asked to consider the entropy change of the metal, the ocean, and the ocean plus the metal, after several hours have elapsed. Out of twenty post-instruction interviews in spring 2006, all interview subjects correctly stated that the entropy of the metal will decrease during the process. Seventeen of the twenty stated that the entropy of ocean would increase, and all but one of those seventeen students correctly stated that the total entropy of metal plus ocean would increase. The one remaining student stated that the entropy of the metal would decrease and the entropy of the ocean would increase, but that the total would not be determinable because it could either increase or stay the same.

Three out of the twenty students stated that although the metal would decrease in entropy, the entropy of the ocean would remain the same. Their explanation hinged on some type of size argument, and led to their conclusion that the total entropy of metal plus ocean would decrease. Excerpts from interviews with two of these three students are given below.

Spring 2006, Post-Instruction (Performed Entropy Spontaneous-Process Worksheet), Metal in the Ocean Question:

SD4 "…entropy of the metal is going to decrease because it's losing heat, once it reaches equilibrium it will have lost entropy because it's also lost heat; the entropy of the surroundings I think means the ocean, then the ocean remains the same, it's a law or it's a frame of reference… a very small change in

entropy into a very large surroundings isn't going to result in any measurable change in entropy in the surroundings because of the size difference between the two… it's a theory we learned about in recitation where we did a similar problem like this, even though you change the immediate surroundings since you have to go through all the surroundings of the ocean its too minute a change to have any measurable change. [The change in entropy of the metal cube plus the surroundings] would decrease, the entropy in the ocean is going to remain the same but the entropy of the very hot piece of metal will decrease drastically to come in equilibrium with the ocean…"

I: How does this compare with your answer to the object plus the air in the room? [The student had said that the entropy changes of the object and of the air in the room were not determinable, and that the total entropy of the object plus the air in the room remained the same.] Is there something different?

SD4 "In the object in the room the object was large enough to create a change in entropy in the room then there would be enough to determine if it's the same. In *this* problem there wasn't a noticeable change in entropy of the ocean but there was in the metal."

SD15 "The entropy of the metal decreases because the temperature is going to be cooling down, the internal energy is going to be decreasing. Since the ocean is in contact with the air and the air is the rest of the universe, the entropy is going to remain the same. That size of the metal is not enough to increase the ocean by the slightest amount… the relationship between how much energy that piece of metal is going to give the ocean isn't substantial. [Total]

entropy would decrease because the temperature of the metal is decreasing; it's

going to be exchanging heat with the ocean and the air."

5.6.5 Entropy is a process-dependent quantity

We administered our cyclic-process question (Figure 5.4.3) before instruction in

the Fall 2004 and the Spring 2005 (see Table 5.6.7) courses. It was administered pre- and

post-instruction in Spring 2005, but pre-instruction only in Fall 2004. This question

describes a gas that is taken on a completely general cyclic process (no details of the

process provided), and asks students to consider whether the four thermodynamic

quantities listed are always equal to zero or not always equal to zero (see Table 5.6.7.).

Note that this question explicitly tells students that the initial and final

temperatures are the same, and yet only 81% of students correctly stated that the change

in temperature was equal to zero. Student performance on questions about the change in

entropy and the heat transfer during the cyclic process are consistent between semesters

pre-instruction, and showed little or no improvement after instruction was complete. (In

Spring 2005, this instruction included our Entropy State-Function Worksheet.)

Table 5.6.7 Pre-Instruction (2004 and 2005) and Post-Instruction (2005) Responses on Cyclic-Process Question

	Cyclic-Process Question Pre-Instruction Fall 2004	Cyclic-Process Question Pre-Instruction Spring 2005	Cyclic-Process Question Post-Instruction Spring 2005
Correct Answers	$N = 123$	$N = 233$	$N = 233$
Change in Temperature = 0	81%	82%	88%
Change in Internal Energy = 0	67%	84%*	72%*
Change in Entropy = 0	65%	56%	53%
Heat Transfer ≠ 0	56%	50%	60%

Table 5.6.7 Proportion of correct responses on the cyclic process question (Fig 5.4.3)
*Statistically significant difference ($p < 0.01$) between pre- and post-instruction responses in Spring 2005 course.

Pre- and post-instruction responses show few differences except on the Internal-Energy question.

We administered our *PV*-Diagram State Function Question, Version *A* (Spring 2005), and Version *B* (Spring 2006) after all-instruction in an attempt to probe student thinking on the state function property of entropy. Version *A* has only one choice that is consistent with entropy being a state function, and this was the most common answer among students (67%). Version *B* has two choices that are consistent with entropy being a state function: (1) the correct answer, that entropy is a state function and entropy change is not equal to zero for the processes given (65%), (2) an incorrect answer, that entropy is a state function and that entropy change is equal to zero for the processes given (16%). It's difficult to make reasonable comparisons between these two questions as Version *B* requires an additional understanding compared to Version *A*.

Table 5.6.8, Post-Instruction, PV-Diagram State Function Question, Spring 2005 and Spring 2006

	Spring 2005 Course *With* Entropy State-Function Worksheet Version *A*	Spring 2006 Course *With* Entropy Spontaneous-Process Worksheet Version *B*
	N = 341	*N* = 311
Consistent with greater area under curve implies greater change in entropy	23%	11%
Consistent with entropy is a state function	67%	81%
... and not equal to zero [correct]	--	*65%*
... and equal to zero	--	*16%*
Other Responses	**10%**	**8%**

Table 5.6.8 Post-instruction responses on *PV*-diagram state-function question
Students who responded to Version *A* (Spring 2005) had performed the Entropy State-Function Worksheet, and students who responded to Version *B*, (Spring 2006) had performed the Entropy Spontaneous-Process Worksheet.

5.6.6 Section Summary

We documented specific student difficulties regarding the behavior of entropy in a spontaneous process. Both before and after instruction, most students fail to recognize the correct answers on questions regarding the change in entropy during a naturally-occurring process. These questions deal with entropy changes in a system and its surroundings, and with the total entropy change of the system plus its surroundings. The most common responses suggest belief in a conservation principle that requires total entropy to remain the same. Among those students who assert a direction for entropy change even when none can be specified (e.g., stating that the system entropy increases and the surroundings' entropy decreases), a significantly higher proportion of students

claim that entropy will increase rather than decrease. The exception to this occurs on a question involving the entropy change of a specific object, for which students show no preference for believing in either increasing or decreasing entropy.

Among the other student ideas that we discussed in this section, one involves a belief that entropy change depends on system "size" in some poorly defined manner. Although this issue was only identified for one question, it's possible that this notion may be leading students along incorrect lines of reasoning on other questions as well. Another line of student thinking corresponds to responses which imply that the state-function property of entropy varies slightly depending on the context. In particular, students show a tendency to associate entropy change with area under the curve of a *PV*-diagram.

5.7 Development and testing of research-based materials

In this section we discuss the two worksheets we produced in spring of 2005 and spring of 2006 which were based on our preliminary research findings.

5.7.1 Testing methodology and motivation

The testing of curricular materials for their effect on student understanding in a real class has many difficulties. The ideal experiment for testing materials that are to be used during recitation periods in a large-enrollment course is to administer the worksheet to a randomly selected subset of the entire class. This treatment group would be given the newly developed curriculum whereas the control group would receive the "traditional" instruction that would ordinarily be used in the class. The calculus-based courses in which we conducted our study did not allow for this experimental design.

The courses in which we collected data were taught by two different instructors (one in the fall courses, and the other in the spring courses). The fall instructor is an experienced instructor and tenured faculty member who employs purely traditional instruction methods: passive lectures and lecture demonstrations, quantitative, end-of-the-chapter homework assignments, and standard university laboratories. Recitation periods occur once per week and are spent with TAs working problems at the board with no structured student-student or TA-student interactions. The instructor did not want worksheets used during recitation as, he said, "That time is crucial for students to have an opportunity to ask questions about the homework."

The spring instructor is also an experienced instructor and tenured faculty member who used a multitude of research-based pedagogical techniques such as highly interactive lectures and demonstrations via a personal response system or "clickers." These methods were used to promote student-student interactions and provide rapid feedback to both the students and the instructor. Recitation periods occurred once per week and featured either complex group work with a focus on improving problem-solving strategies, or on research-based tutorials. This instructor wanted all students to utilize the research-based curricular materials we developed, and believed that the materials could aid students' learning.

Lacking a course environment in which we could create standard intervention and control groups, we had to rely on comparisons made across different semesters, and on pre- and post-instruction testing in a given semester. The reliability of our pre-instruction data (see Appendix 5.1 & 5.2) makes these comparisons justifiable, although lack of comparative post-instruction data is certainly a shortcoming of this work.

5.7.2 Entropy State-Function Worksheet

(The tutorial, along with a solution sheet, can be seen in its entirety in Appendix 2.3 & 2.4.)

We developed a tutorial based on a so-called "three-process" question that was designed by John Thompson and his collaborators at the University of Maine, to probe student thinking on the state-function property of entropy and the principle of increasing entropy. The question requires students to have some knowledge of the first law of thermodynamics in order to determine the direction of heat flow during an isothermal expansion. We developed a longer version of this question (see Appendix 5.11) to probe for students' first-law difficulties that might be impeding their second-law understanding. During interviews in which this question was presented, students had substantial difficulties recognizing key ideas regarding the three processes (isothermal, adiabatic, and free-expansion), such as the fact that an "isothermal expansion" is a process that occurs at constant temperature. We also found significant student difficulties in correctly applying concepts of work and heat transfer. (So substantial were these difficulties that analysis of student data for this question was essentially impossible as so many poorly conceived and inconsistent threads of logic were utilized by students.) Because this question employed many first-law ideas before addressing second-law notions, we felt it might be effective to build a tutorial-style worksheet that guided students to recognize how these first-law concepts could be used as a basis for thinking about second-law concepts.

The Entropy State-Function Worksheet was based on the three-process question, accompanied by a large number of additional questions to provide guidance for students' thinking. Through follow-up interviews, we determined that students required a great deal of assistance in answering fundamental questions regarding pressure and temperature, before they could consider issues regarding work, heat transfer, and entropy. The worksheet guides students to realize that relative changes in thermodynamic quantities in isothermal and adiabatic ideal-gas expansions can be analyzed by using *PV* diagrams. It also guides students to compare the properties that define a particular state on a *PV* diagram, and asks them to compare the initial and final states of a system that undergoes isothermal-expansion and free-expansion processes.

Following this, the worksheet examines effects on the surroundings during each particular process, and develops this into a discussion about the universe being composed of a system and its surroundings. The results of the worksheet are then summarized by the students in a table where they are asked to generalize their findings.

The Entropy State-Function Worksheet was administered to students in the Spring 2005 course at Iowa State.

5.7.3 Entropy Spontaneous-Process Worksheet

(The tutorial and a solution sheet can be seen in their entirety in Appendix 2.5 & 2.6.)

We developed a tutorial based on a set of two large, insulated metal blocks, connected only by a thin metal rod. The two blocks are initially at different temperatures, and students are asked to consider net changes in energy and entropy of the two blocks

during the heat-transfer process. Dimensions of the blocks and rod are specified, and temperature changes of the blocks are shown to be so small as to be negligible during the time interval under consideration. The relationship $\Delta S \equiv \int_{Initial\ State}^{Final\ State} \frac{\delta Q_{rev}}{T}$ simplifies, for the constant-temperature blocks (which act as thermal reservoirs), to $\Delta S = \frac{Q}{T}$, where Q is the heat transfer to the block and T is the temperature of that block. (Heat transfers to the thin rod are stated to be negligibly small.)

At the very beginning of the tutorial, students are asked questions concerning the change in entropy of the low-temperature cube, and the net change in entropy of both cubes together. Students are asked whether there are any conserved quantities for this process, and whether energy and/or entropy are conserved. As our data show that most students tend to apply an inappropriate conservation argument to questions of this type, we wanted to elicit these difficulties at the beginning so that students could address and resolve them over the course of the tutorial.

Students are asked to consider the magnitudes and signs of heat transfers to the two blocks; they are led to recognize that these heat transfers are equal in magnitude and opposite in sign, and that net energy doesn't change. Students are then asked to consider the relative magnitudes and signs for the entropy changes of the two blocks, as well as the change in net entropy. Students are guided to realize that the entropy increase of the cooler block is larger in magnitude than the entropy decrease of the warmer block, and so the change in *net* entropy is positive.

The tutorial continues by strengthening students' understanding of the relationship among system, surroundings, and universe. Students are guided to realize that regardless of how the "system" and "surroundings" are defined—e.g., which block is taken to be the "system" and which the "surroundings"—the total entropy of system *plus* surroundings will always increase during this process.

Students proceed to consider the net entropy change in an imaginary process where heat transfer occurs spontaneously from the low temperature block *to* the high temperature block. Nearly all students come to recognize that, although this process would result in a net entropy decrease, it cannot actually occur. Finally, students are asked to consider a limiting case for entropy change as the temperatures of the two cubes approach each other arbitrarily closely. Students are guided to realize that in this situation, net entropy change becomes infinitesimally small; this is stated to be an approximation to an ideal "reversible" process.

The Entropy Spontaneous-Process Worksheet was administered to students in the Spring 2006 course at Iowa State. In addition, we were able to administer this worksheet to students in a course at the University of Washington during Winter 2006.

5.7.4 Student Performance after Worksheet Instruction

We were able to administer questions on entropy after all instruction was complete in the spring of 2005 and the spring of 2006, the two courses in which we were able to carry out instruction based on our worksheets. The details of the post-instruction

data in Spring 2005 were covered in Sec 5.6. All of these data related to the calculus-based course.

In Section 5.7.4.1 below, we describe an intervention/control study that we were able to conduct in an algebra-based introductory course using the Entropy State-Function Worksheet. In this study, we utilized both an experimental group and a control group to assess the effectiveness of instruction using the research-based worksheet. In Section 5.7.4.2, we will examine some of the effects of the Entropy Spontaneous-Process Worksheet that we administered in the calculus-based course in Spring 2006, focusing on the general- and concrete-context questions. In Section 5.7.4.3 we continue this analysis of the effects of the Entropy Spontaneous-Process Worksheet by examining pre- and post-instruction data in the calculus-based course related to the "universe = system + surroundings" concept. In Section 5.7.4.4 we assess the net effect of instruction on students' ability to answer questions involving free expansions. Finally, in Section 5.7.4.5, we address some implementation issues regarding use of the worksheet.

5.7.4.1 Student Performance in Algebra-Based Course With and Without Instruction Using Entropy State-Function Worksheet

The Entropy State-Function Worksheet was administered to both the algebra-based and calculus-based courses in the spring of 2005. Throughout Section 5.6 we examined student responses to our various diagnostic questions in the calculus-based course. In Section 5.6.5 we briefly discussed calculus-based students' responses to the *PV*-diagram state-function questions (Section 5.4.5). This present section will focus on

student responses in the algebra-based course to the *PV*-diagram state-function question. The *PV*-diagram state-function question was the diagnostic question most directly relevant to the major objectives of the Entropy State-Function Worksheet. We will also include a brief discussion of student responses in the algebra-based course to the spontaneous-process question (Version *B*), and we will reproduce data from the calculus-based course for purposes of comparison.

5.7.4.1.1 PV-Diagram State-Function Question

Four sections (N_{total} = 83) of an introductory algebra-based physics course were originally designated the "intervention group"; that is, they served as an experimental group, while the remaining seven sections (N_{total} = 154) were originally designated as the control group. (The sections for the intervention group were randomly selected using a random number generator.) The experimental variable was the type of recitation instruction during the hour covering entropy and related second-law concepts. The control group received traditional instruction which consisted of faculty and graduate-student TAs answering questions and working problems from the previous week's homework assignment, while the intervention group completed or attempted to complete a specially designed tutorial on the same material that was administered by one member the ISU PER group per each section. Our objective was to test whether students' understanding, as reflected in their responses to questions on the final exam, would be better for students who had completed the tutorial in comparison to those who had received traditional recitation. Ultimately, the number of students in the pre-assigned

groups who were actually present in class for instruction was $N = 60$ for the intervention group, and $N = 110$ for the control group. These numbers are reflected in the statistics below, and henceforth when we refer to the intervention and control groups we will be referring to these groups of 60 and 110 students, respectively.

The most significant result obtained was on our *PV*-diagram state-function question, Version *A*, which addressed the concept of entropy as a state function. This question was administered on the final exam after all instruction in the course was complete. A statistically greater proportion of students in the intervention group (who had been present for the modified instruction) answered correctly (78%, $N = 60$), than among members of the control group (61%, $N = 110$); p < 0.03 using a test for binomial proportions. (We do not have pre/post or intervention/control comparative data in the calculus-based course for the same question; the post-instruction data we do have from Spring 2005 can be seen in Appendix 5.8)

Table 5.7.1 Responses on *PV*-Diagram State-Function Question, Version *A*, Algebra-based Course, Spring 2005

	Algebra-based Course *Without* Entropy State-Function Worksheet	Algebra-based Course *With* Entropy State-Function Worksheet
	$N = 110$	$N = 60$
Consistent with greater area under curve implies greater change in entropy	21%	12%
Consistent with entropy is a state function	61%*	78%*
Other Responses	17%	10%

Table 5.7.1 Responses on *PV*-Diagram State-Function Question, Version *A*, Algebra-based Course, Spring 2005
* Statistically significant difference using a test of binomial proportions, *p* < 0.03

The category *"Consistent with greater area under curve implies greater change in entropy"* corresponds to answer *B* that ranked the change in entropy according to the area under the curve in the *PV*-diagram for each process. The category *"consistent with entropy is a state function"* corresponds to answer *D* which stated that all processes between the same initial and final states

have the same change in entropy, i.e., that $\Delta S_1 = \Delta S_2 = \Delta S_3$. The category *"Other responses"* corresponds to answers that fall into neither of these two groups; they are further explored in Appendix 5.8)

5.7.4.1.2 Spontaneous-Process Question

In addition to questions on the state-function property of entropy, we administered the spontaneous-process question (Version *B*) after all instruction was complete to assess student understanding that entropy of the system plus surroundings must increase during a spontaneous process. In the algebra-based course, a small number of students in the intervention group answered the question correctly (20%, $N = 60$) which is nearly identical with the correct-response rate among members of the control group (21%, $N = 110$). The calculus-based course that preformed the Entropy State-Function Worksheet in the spring of 2005 did not have a statistically higher correct response rate (27%, $N = 341$) on the Spontaneous-Process question than did the algebra-based course. The data for the calculus-based course were shown in Table 5.6.4, and we show the same data here in Table 5.7.2 for purposes of comparison.

Table 5.7.2 Post-Instruction, Spontaneous-Process Question, Version *B*, Calculus-based Spring 2005, Algebra-based Spring 2005: Intervention and Control groups

	Algebra-based Spring 2005 Post-Instruction *With* Entropy State-Function Worksheet	Algebra-based Spring 2005 Post-Instruction *Without* Entropy State-Function Worksheet	Calculus-based Spring 2005 Post-Instruction *With* Entropy State-Function Worksheet
	$N = 60$	$N = 110$	$N = 341$
A. Total entropy remains the same	57%	50%	36%
B. Total entropy increases and system entropy increases	3%	5%	12%
C. Total entropy decreases and system entropy increases	0%	6%	2%
D. Total entropy increases and system entropy can increase *or* decrease *[correct]*	20%*	21%*	27%[†]
E. Total entropy increases *or* remains the same	20%	17%	23%

Table 5.7.2 Post-instruction responses on Version *B* of the Spontaneous-Process question
* Statistically identical response for intervention and control group based on binomial proportions test, $p = 0.88$
† Statistically identical response for calculus-based course compared to the algebra-based course based on binomial proportions test, $p = 0.21$

Column 1 descriptions are characterizations of the actual numerical response options in the original question; see Section 5.4.4 for the actual response options.

5.7.4.2 Student Performance on General- and Concrete-Context Questions Before and After Worksheet Instruction

In the Spring of 2006 we administered our Entropy Spontaneous-Process Worksheet (see Appendix 2.5) to all students who attended recitation during the week entropy was covered in class. Post-instruction testing took place on the mid-term exam which covered all thermodynamics topics (using multiple-choice questions), and also during one week of laboratories conducted two weeks after the mid-term was complete (using free-response questions). As seen in Table 5.7.3 and 5.7.4, student performance gains (pretest to posttest) on the general-context question and concrete-context question

are much better in the Spring 2006 course, on each sub-part, when compared to the

matched sample in the Spring 2005 course. The most substantial gains are in correct

answers for system + surroundings and the corresponding object + air in the room

questions; there is also a very large increase in the proportion of students who answered

all parts correctly.

Table 5.7.3, Correct Responses, Pre- and Post-Instruction, on the General-Context Question (Spring 2005, Spring 2006)

	Pre-Instruction General-Context Spring 2005 Matched Sample	Post-Instruction with Entropy State-Function Worksheet General-Context Spring 2005 Matched Sample	Pre-Instruction General-Context Spring 2006	Post-Instruction with Entropy Spontaneous-Process Worksheet General-Context Spring 2006
	$N = 153$	$N = 153$	$N = 247$	$N = 237$
A. Entropy change of system not determinable	50%	37%*	43%	75%*
B. Entropy change of surroundings not determinable	46%	40%*	42%	76%*
C. Entropy of system + surroundings increases	24%	35%*	19%	68%*
All Correct	4%	8%*	5%	53%*

Table 5.7.3 Correct responses, pre- and post-instruction, on the general-context question: Spring 2005, Spring 2006
*Statistically significant difference between instruction using Entropy *State-Function* (2005) and Entropy *Spontaneous-Process* (2006) Worksheets, p < 1 x 10^{-9} using a test of binomial proportions.

The Spring 2005 class performed the Entropy State-Function Worksheet, while the Spring 2006 class performed the Entropy Spontaneous-Process Worksheet

Table 5.7.4 Correct Responses, Pre- and Post-Instruction, on the Concrete-Context Question (Spring 2005, Spring 2006)

	Pre-Instruction Concrete-Context Spring 2005 Matched Sample	Post-Instruction with Entropy State-Function Worksheet Concrete-Context Spring 2005 Matched Sample	Pre-Instruction Concrete-Context Spring 2006	Post-Instruction with Entropy Spontaneous-Process Worksheet Concrete-Context Spring 2006
	$N = 131$	$N = 131$	$N = 223$	$N = 231$
A. Entropy change of object not determinable	54%	56%*	52%	74%*
B. Entropy change of air in the room not determinable	50%	56%*	50%	74%*
C. Entropy of object + air in the room increases	20%	23%[†]	15%	68%[†]
D. Entropy of universe increases	27%	26%*	14%	44%*
A, B, and C Correct	7%	13%[†]	5%	56%[†]

Table 5.7.4 Correct responses, pre- and post-instruction, on the concrete-context question
* Statistically significant difference between instruction using Entropy *State-Function* (2005) and Entropy *Spontaneous-Process* (2006) Worksheets, p < 0.001, using a test of binomial proportions.
† Statistically significant difference between instruction using Entropy *State-Function* (2005) and Entropy *Spontaneous-Process* (2006) Worksheets, p < 1 x 10^{-14} using a test of binomial proportions.

The Spring 2005 class performed the Entropy State-Function Worksheet, while the Spring 2006 class performed the Entropy Spontaneous-Process Worksheet

Table 5.7.4.1 Post-Instruction Responses on Spontaneous-Process Question

	222 Fall 2004 Post-Instruction (Version *A*)	222 Spring 2005 Post-Instruction (Version *B*)
	$N = 539$	$N = 341$
A. Total entropy remains the same	54%	36%
B. Total entropy increases and system entropy increases	5%	12%
C. Total entropy decreases and system entropy increases	7%	2%
D. Answers B & C	4%	--
E. Total entropy increases and system entropy can increase *or* decrease *[correct]*	30%	27%
E.* Total entropy increases *or* remains the same	--	23%

Table 5.6.4 Post-instruction responses on Versions *A* and *B* of the spontaneous-process question
Only Version *B* contains the option of total entropy either increasing *or* remaining the same.
Column 1 descriptions are characterizations of the actual numerical response options in the original question; see Section 5.4.4 for the actual response options.

We've had limited opportunity to distribute our curricular materials to other universities due to complications involving school restrictions and communication problems. We were able to use our Entropy Spontaneous-Process Worksheet in a sophomore-level physics course at the University of Washington that covers a wide-range of topics on thermal physics. (This course was taught by David Meltzer in Winter 2006.) As discussed in Chapter 1 of this thesis, the students in this course are primarily physics majors, all of whom have completed UW's introductory calculus-based courses. However, this thermal physics course is, for most of them, their first exposure to thermodynamics in the context of university-level physics. Table 5.7.5 shows that the proportion of correct responses on the general-context question in the UW class was significantly higher than in the Spring 2005 course at ISU (in which the Entropy Spontaneous-Process Worksheet had been used). Similar results were obtained on the Concrete-context question (Table 5.7.4.c).

Table 5.7.5 Correct Responses, Pre- and Post-Instruction, General-Context Question, ISU 2005 and University of Washington 2006

	Iowa State University Introductory Course		University of Washington Sophomore Course	
	Pre-Instruction General-Context, Spring 2005 Matched Sample	Post-Instruction with Entropy State-Function Worksheet General-Context, Spring 2005 Matched Sample	Pre-Instruction General-Context, Winter 2007 Matched Sample	Post-Instruction with Entropy Spontaneous-Process Worksheet General-Context Winter 2007 Matched Sample
	$N = 153$	$N = 153$	$N = 32$	$N = 32$
A. Entropy change of system not determinable	50%	37%	50%	84%
B. Entropy change of surroundings not determinable	46%	40%	53%	84%
C. Entropy of system + surroundings increases	24%	35%	34%	72%
All Correct	4%	8%	13%	63%

Table 5.7.5 Correct Responses, Pre- and Post-Instruction, General-Context Question, ISU 2005 and University of Washington 2006

Table 5.7.6 Correct Responses, Pre- and Post-Instruction, Concrete-Context Question, ISU 2005 and University of Washington 2006

	Iowa State University Introductory Course		University of Washington Sophomore Course	
	Pre-Instruction Concrete-Context, Spring 2005 Matched Sample	Post-Instruction with Entropy State-Function Worksheet Concrete-Context, Spring 2005 Matched Sample	Pre-Instruction Concrete-Context, Winter 2007 Matched Sample	Post-Instruction with Entropy Spontaneous-Process Worksheet Concrete-Context Winter 2007 Matched Sample
	$N = 153$	$N = 153$	$N = 32$	$N = 32$
A. Entropy change of object not determinable	54%	56%	47%	88%
B. Entropy change of air in the room not determinable	50%	56%	47%	88%
C. Entropy of object + air in the room increases	20%	23%	34%	78%
A, B, and C Correct	7%	13%	19%	69%

Table 5.7.6 Correct Responses, Pre- and Post-Instruction, Concrete-Context Question, ISU 2005 and University of Washington 2006

Discussion

Our investigation has shown (see Section 5.6) that students' pre-instruction responses for our general-context and concrete-context questions are highly consistent across four semesters, two instructors, and more than 1000 students (600 students in the case of the concrete-context question). We've also highlighted multiple findings of the minimal impact that instruction has on student performance (see Section 5.6.2-5) We therefore believe that, while there are still many unanswered questions (see below), the use of our Entropy Spontaneous-Process Worksheet during the Spring 2006 semester assisted in improving students' understanding as assessed by these questions.

One of the remaining questions relates to the effect of student attendance in recitation on student performance. We were unable to obtain complete attendance data for the recitation date when we administered the tutorial in the Spring 2006 course. For those sections where attendance was recorded, we found that students performed at high

levels whether or not they attended the recitation in which the tutorial worksheet had been done.

Instruction in the spring of 2006 was modified in two ways from the instruction in spring 2005: (1) we administered the Entropy Spontaneous-Process Worksheet during recitation in place of the Entropy State-Function Worksheet and (2) the lecture content was changed dramatically by the instructor. An awareness of student difficulties with the entropy-increase principle led the instructor to modify his existing lecture in order to more directly challenge students' known misconceptions. The instructor gave examples and posed questions to students, getting feedback during lecture via electronic clickers; these examples and questions included some that were extremely similar to those used in the Entropy Spontaneous-Process Worksheet. The overall improvement in students' correct answers was dramatic as compared to spring 2005, but evidence is inconclusive as to whether attending the tutorial, or the lecture, or both were significant causes of the increase in student understanding. Based on the incomplete attendance data available to us, no one single factor could be identified as being associated with a significant difference in student performance, relative to the other factors.

It is discomforting that students seemed to do well regardless of whether or not they received our worksheet instruction in recitation; however, we don't have information on the motivation or previous knowledge of those who were attending compared to those who were not attending recitation. Therefore we will need to further test this observation in future data runs.

Description of Lecture Instruction: Here we provide additional details of the differences in lecture instruction between the Spring 2005 and Spring 2006 courses. The mode of instruction was nearly identical in that the lecturer used PowerPoint presentations which focused on conceptual explanations and qualitative calculations, and included two or three interactive "clicker" questions to which all students responded. However, the content covered in the introductory entropy lecture was strikingly different from one year to the next.

The Spring 2005 lecture began with examples of order-to-disorder processes. Students were then presented with the idea that entropy is a measure of the disorder and that the second law of thermodynamics says that "disorder" increases. A brief discussion of reversible versus irreversible processes led to a calculation of entropy change during an isothermal expansion, and comparison to the entropy change in a free-expansion process with identical initial and final states. A clicker question was posed to illustrate that entropy of a system can decrease, depending on how the system is defined. Finally, students were told that the entropy of the system plus the entropy of the environment remains constant for reversible processes and increases for irreversible processes.

The Spring 2006 lecture, in sharp contrast, did not mention disorder at all. The concept of increasing entropy was built by starting from the observation that heat transfers only occur naturally from high-temperature objects toward low-temperature objects, and never in the opposite direction. Students were told that entropy of the system plus the entropy of the environment always increases for real processes. An example of cold water (the "system") in a hot room (the "environment") was used to show that $dS_{system} > 0$, $dS_{environment} < 0$, and the total $dS_{total} > 0$. The instructor used a bar chart to show that the increase in entropy is greater than the decrease in entropy. Students were asked to respond to a clicker question regarding a hot brick (the system) put into a cold bath, in order to demonstrate that entropy of a system can decrease. Students were also asked whether the change in entropy can be determined for the system and the

environment undergoing a naturally occurring process, in the absence of more detailed information.

5.7.4.3 Student Performance Before and After Worksheet Instruction on Questions Related to "Universe = System + Surroundings" Concept

We attempted to assess student understanding of the idea that an arbitrarily defined system and that system's surroundings define "the universe." Our concrete-context question shed light on student thinking on this concept by asking for the change in entropy inside the insulated room as well as the change in entropy of the universe. The question does not explicitly ask about a "system" or its "surroundings," but students had received instruction through the Entropy Spontaneous-Process Worksheet on the above concept, and therefore might be expected to give consistent answers. The proportion of responses for each possible answer of the "entropy of the object + air in the room" question and the "entropy of the universe" question are statistically equivalent both before and after instruction with the Entropy State-Function Tutorial Worksheet (see Appendices 5.2 and 5.6 for complete breakdown).

However, after instruction with the Entropy Spontaneous-Process Worksheet, student responses were statistically different when comparing answers to the "entropy of the object + air in the room" question and "entropy of the universe" question (see Table 5.7.5). Student explanations that justified the "entropy of the universe remains the same" response often incorrectly describe the universe as being isolated from the room. Despite a substantial improvement in overall understanding as measured by our free-response and

multiple-choice questions (see Table 5.7.3 and 5.7.4), it seems that use of our Entropy

Spontaneous-Process Worksheet actually increased student difficulties in interpreting the

meaning of "universe" in the context used here.

Table 5.7.5 Pre- and Post-Instruction, Concrete-Context Question, Entropy of object + air in the room vs. Entropy of the Universe Responses, Spring 2005 performed Entropy State-Function Worksheet, Spring 2006 performed Entropy Spontaneous-Process Worksheet

	Pre-Instruction Concrete-Context Spring 2005 Matched Sample		Post-Instruction with Entropy State-Function Worksheet Concrete-Context Spring 2005 Matched Sample		Pre-Instruction Concrete-Context Spring 2006		Post-Instruction with Entropy Spontaneous-Process Worksheet Concrete-Context Spring 2006	
	N = 131		*N* = 131		*N* = 223		*N* = 231	
	Entropy of the object + air	Entropy of Universe	Entropy of the object + air	Entropy of Universe	Entropy of the object + air	Entropy of Universe	Entropy of the object + air	Entropy of Universe
Increases	20%	27%	23%	26%	15%	14%	68%*,	44%*·†
Decreases	0%	1%	1%	1%	4%	0%	2%	0%
Stays the same	69%	62%	70%	66%	74%	72%	24%*	53%*†
Not determinable	4%	5%	6%	5%	3%	8%	5%	0%

Table 5.7.5 Responses on parts (c) and (d) of the concrete-context question, pre- and post-instruction, 2005 and 2006
* Statistically significant difference compared to *pre*-instruction response on same item ($p <$ 0.0001)
† Statistically significant difference compared to "object + air" response on same question ($p < 10^{-6}$)

Instruction in 2005 utilized the Entropy State-Function Worksheet, while in 2006 the Entropy Spontaneous-Process Worksheet was utilized instead. Post-instruction responses in 2005 were consistent with pre-instruction responses, but in 2006 post-instruction responses were significantly different than pre-instruction responses. Responses on the "universe" question were consistent with those on the "object + air" question in 2005 (both pre- and post-instruction), and in 2006 on the pre-instruction test. However, after instruction in 2006 there were significant differences in responses between the "universe" and the "object + air" questions.

5.7.4.4 Student Performance on Free-Expansion Questions After Worksheet Instruction

After all instruction in spring of 2006 we administered our free-expansion

question (Fig 5.4.7) along with our other post-instruction questions. As noted in Section

5.4, students could use their understanding that the entropy of the universe must increase for any spontaneous process to reason that the gas must increase in entropy because the entropy of everything outside the insulation would remain the same as it is isolated from the container.

Our data (Table 5.7.6) show that nearly all students were able to correctly respond that the entropy of "everything outside the container" due to the free-expansion would remain the same (90%). (Recall that the actual question does not use the language of "due to the free-expansion", but there is no evidence that this affected student responses in any way.) The proportion of correct responses for the entropy of the freely expanding gas (36% class, 45% interview sample), and the entropy of everything outside plus the gas (38% class, 45% interview sample) are much lower. The most popular response was that the entropy of the gas and the total entropy would remain the same (49% class, 45% interview sample). Approximately half of those students who believed the entropy of the gas would remain the same justified their answer with an explanation that cited the temperature of the gas remaining constant (9% of total), the fact that there was no heat transferred (12% of total), that there was no work done (2% of total), or some combination of these explanations (5% of total).

Table 5.7.6 Responses on the Free-Expansion Question, Post-Instruction, Full Class and Interview Samples (Spring 2006)

	Spring 2006 Post-Instruction	Spring 2006 Post-Instruction Interviews
	N = 239	*N* = 20
Entropy of everything outside…		
Increases	6%	0%
Decreases	1%	0%
Stays the same [*correct*]	90%	100%
is not determinable	2%	0%
Entropy of gas…		
Increases [*correct*]	36%	45%
Decreases	11%	10%
Stays the same	49%	45%
is not determinable	2%	0%
Entropy of everything outside + gas…		
Increases [*correct*]	38%	45%
Decreases	8%	0%
Same	49%	50%
not determinable	4%	5%

Table 5.7.6 Responses on the free-expansion question, post-instruction, full class and interview samples, Spring 2006
The Entropy Spontaneous-Process Worksheet was performed in this class. Both the full-class and the interview sample show persistent confusion about the change in entropy during a spontaneous process.

Interview Data

All twenty students in our interview sample (Spring 2006) recognized that anything outside the insulation would not receive any heat transfer and would therefore not change in entropy. When asked about the change in entropy of the gas, however, student answers varied among three common responses. Some representative quotes are given in this section, while all relevant quotes can be found in Appendix 5.10.

Nine of the twenty interviewees correctly stated that the entropy of the gas would increase. However, only three made clear statements that the process was irreversible and

that therefore the entropy of the gas must increase, since the entropy of everything else remains the same.

SD1 "Entropy of the gas increases, because it's going to be in a greater volume. The formula would calculate out to be zero, but I remember it was supposed to be increasing because it was irreversible."

Six of the nine students used some argument about increasing volume leading to an increase in randomness to explain their answers:

SD10 "Entropy inside does increase because there is more volume, the molecules are more random; bounce around more, more chaotic. I guess the total entropy does increase. The definition of entropy is more changing, more random, more volume."

Eight of the twenty students stated that the entropy of the gas would remain the same, and every one of the eight cited some combination of temperature remaining constant (7 of 8), and no heat transferred or work done during the process (6 of 8):

SD3 "B remains the same, there is no heat transfer, no work is done by the gas, final temperature is the same as the initial temperature, and for C total entropy would remain the same, because the outside and inside don't change so the total wouldn't either."

Two of the eight even justified a "no net change in entropy" response by arguing

that entropy changes due to the increasing volume would be compensated by entropy

changes due to the decreasing pressure:

SD17 "Temperature is staying the same, the volume is increasing but the

pressure is going down, so I guess there is no real change. The other factors are

making up for the change in volume. It would remain the same. By the rule of

system plus surroundings it would have to increase which would mean the gas

would increase, but I don't see how it would, so I'll say remain the same for all

three."

5.7.4.5 Implementation Questions: How Much of the Worksheet Did Students Actually Use?

Online Histogram

Approximately one third of recitation sections in Spring 2006 worked on the

tutorial via computer interface. The online monitoring system provides us with a

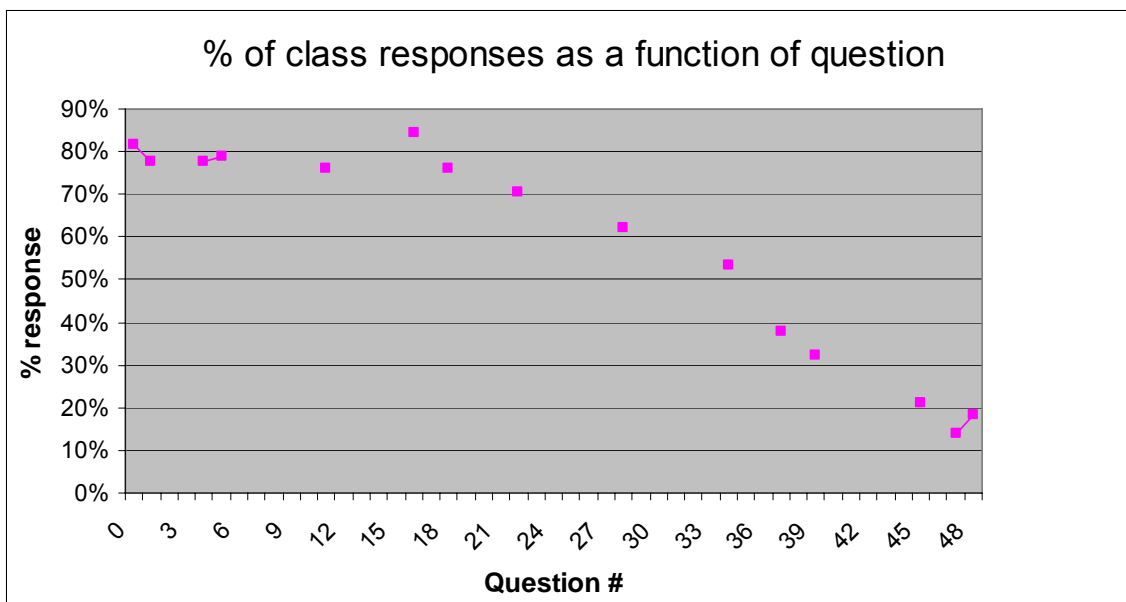histogram that describes the extent to which students were able to complete the tutorial.

Figure 5.11 The points on this graph represent the proportion of students that gave a written answer to each free-response question on the online-format version of the Entropy Spontaneous-Process Worksheet.

Only about half of the students who started the tutorial were still giving responses on page 6 (out of 8) of the tutorial. One quarter of the students who started the tutorial provided answers for the last question.

5.7.5 Section Summary

We designed and implemented two research-based tutorials to address known difficulties with student understanding of entropy.

Our Entropy State-Function Worksheet was administered to calculus- and algebra-based students during the Spring of 2005. We conducted an intervention/control-group study with the algebra-based course in which we randomly selected four sections to receive special instruction, while the remaining sections performed traditional instruction. The students who employed worksheet instruction performed better on post-

instruction testing involving a *PV*-Diagram question that was related to the state function property of entropy.

Our Entropy Spontaneous-Process Worksheet was administered during the Spring 2006 calculus-based course to all students who were present on that day of recitation. Student performance on post-instruction free-response and multiple-choice questions were significantly better than on the same questions after instruction in the spring of 2005 and the fall of 2004.

5.8 Discussion

5.8.1 Early exposure to entropy concepts (revisited)

When our results on entropy were first presented at an AAPT conference, textbook author Randall Knight questioned whether our pre-instruction data were valid, saying he didn't believe these students "really knew anything about entropy at all." As I stated at the time and as we can now substantiate with data, student responses follow consistent patterns and reflect well-defined ideas about entropy. Our results from testing before all instruction are highly consistent and follow distinct patterns, e.g., arguments that total entropy is conserved are consistently popular (see Table 5.6.1). These same ideas can persist in spite of direct and focused instruction on the relevant material (see Table 5.6.2). That's not to say that students with these ideas have well-developed conceptual knowledge of entropy, but the fact that consistent response patterns exist necessitates that we address these ideas during instruction, especially when those incorrect ideas tend to persist even after instruction.

5.8.2 Potential confusion related to word meanings

If a student has never heard the word "entropy," it must sound a lot like "energy." It is conceivable that some students may be confusing the words *entropy* and *energy* when answering the general- and concrete-context questions. Many students explicitly cite energy conservation when stating that entropy remains the same. However, if there had been an explicit confusion between the two words *entropy* and *energy*, it seems highly likely that our interviews would have revealed this error in some way. Numerous students claimed that entropy and energy are related, and many asserted that total entropy could not change, but not a single student in more than 30 interviews claimed that entropy and energy were the same thing. It is also extremely significant that our Spring 2005 matched-sample data show highly consistent response patterns both before *and* after instruction. If there had been any confusion between the words "energy" and "entropy" before instruction in that course, there was surely ample opportunity for it to have been resolved over the course of the semester.

These data suggest that whatever the details of students' thinking regarding distinctions between entropy and energy, their response patterns were consistent before instruction across semesters and *remained* consistent after instruction, despite the instructor's repeated discussion of the differences between entropy and energy. If students are in fact failing to make the distinction between the two words, then that distinction becomes part of the concepts we need to emphasize through tutorials and other means of instruction.

After all instruction on entropy was completed in the fall of 2005, student volunteers were asked questions involving the change in entropy between two massive

blocks at different temperatures that were allowed to exchange energy with one another through a conducting rod. One student clearly remarked *"So the entropy of the low temperature cube increases because it's gaining heat from the high temperature cube over the extended period of time."* But this student went on to say, *"The entropy of the system remains the same, so the entropy of the two blocks together remains the same, not considering the insulating rod."* A follow-up question asked what, if any, quantities were conserved, to which this student replied: *"Entropy is conserved, so energy is conserved."* This and similar responses suggest that, although confusion with energy conservation plays a significant role in students' mistaken notions concerning entropy changes, the confusion is not simply one in which the words themselves are taken to refer to the same entity.

5.8.3 Implications for Instruction

We've discussed the development and testing of two research-based tutorial worksheets that were designed to improve student understanding of entropy in the context of spontaneous processes. Many students have a strong belief that total entropy for a spontaneous process remains the same, and an inclination to believe that entropy must increase, rather than decrease, in the case of any entity that is referred to either as the "system" or as the "surroundings." These notions were observed in both general and concrete contexts, and often persisted despite focused instruction on the topic.

We've demonstrated the successful implementation of our Entropy Spontaneous-Process Worksheet, which guides students to compare changes in energy and entropy for a heat-transfer process involving two thermal reservoirs. Use of this worksheet, along

with revised lecture instruction, seems to have improved student performance on questions related to the entropy-increase principle, in comparison to courses in which this worksheet was not used.

We've also demonstrated limited success in the implementation of our Entropy State-Function Worksheet, as assessed with an intervention/control group study in the introductory algebra-based course via use of a *PV*-Diagram state-function question.

Various statements of the second law (e.g., Clausius, Kelvin-Planck, etc.) in physics typically provide only a piece of the most general applications and ideas of the second law of thermodynamics. In his Ph.D. dissertation Matt Cochran argued that the entropy inequality $\Delta S > \int \frac{\delta Q}{T}$ was the most general and useful statement for attaining a functional understanding of the implications and applications of the second law (Cochran 2005). However even in this "best" form there is no explicit discussion of entropy changes in the system and surroundings due to heat transfer and irreversibilities.

Chemistry emphasizes the use of Gibbs free energy $\Delta G = \Delta H - T\Delta S$ which is simply a formulation from the principle of increasing entropy for processes that occur at constant pressure and temperature. The change in enthalpy term and the change in entropy term are related to changes in entropy of the surroundings and the system, respectively, and thus in some sense bring the idea of "total" entropy change out in the open.

The tradition in engineering thermodynamics textbooks includes definitions of quantities and statements of relationships (e.g., "entropy balance") that explicitly require students to consider entropy changes due *both* to heat transfers to the system *and* to

irreversibilities of the process undergone by the system. Since entropy changes due to heat transfer are linked to the entropy change in the surroundings, this formulation puts the definition of "total" entropy change on a more explicit basis. It's possible that explicitly bringing to light these various entropy changes allows students to learn more effectively and to apply those concepts we are trying to address in our work. However, there does not yet seem to be any published research examining this possible learning effect.

5.9 Conclusions

We conducted an extensive analysis of student thinking regarding the principle of increasing entropy, and of the state function property of entropy. Analysis of data from four semesters of classes demonstrated that students have well-defined and consistent lines of thinking and reasoning. Results from matched samples of students assessed through pre- and post-instruction testing show that some student difficulties can persist despite deliberate and focused attempts at overcoming those difficulties. We developed a research-based worksheet that explicitly addressed known student difficulties. Early indications are that instruction using this worksheet is effective in improving students' correct-response rate on questions regarding the principle of entropy increase in spontaneous processes, at least in processes that involve heat transfer. Difficulties regarding processes that do not involve heat transfer (e.g. the free expansion of a gas) persist to some extent. Other preconceived notions persist despite instruction, and this topic is thus well-suited for future investigations.

Notes for Chapter 5

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Chapter 6 Future Work

6.1 Investigating the interaction between students' understanding of the first law, and their understanding of the second law

Research shows that it is difficult to form robust understanding of first-law ideas. (Loverude 2002, Meltzer 2004) If we hope to improve understanding of second-law concepts, many of which depend crucially on first-law notions, we need to be aware of the potential interplay between these two ideas. For instance, how does the learning and teaching of the first law impact the understanding and instruction of the second law? How does the learning and teaching of the second law impact student understanding of the first law? This section will be a discussion of how a study might be designed so that it could probe these types of "interaction" effects.

6.1.1 Challenges

Human thought is an ever-evolving process. Student thinking about physics may not be rapidly changing at all times, but we expect there to be periods during which students' thoughts do change significantly, as they are presented with new ideas and confront new problems. It is these changes in student thinking that we want to assess. Carrying out such assessment is made more difficult by the structure of students' knowledge, which is less well organized and less tightly connected than is expert's knowledge (Van Huevelen 1991; Reif 1995). This means that many assessments must be done at many different times in order to yield an accurate picture of student thinking.

Expert thinking seamlessly interweaves the ideas of the first and second laws into a cohesive framework of knowledge. Given the difficulties reported by Loverude (2002), Meltzer (2004), Cochran (2006), and this thesis, it seems unlikely that a large proportion of students in introductory courses are developing this same deep understanding. It's very possible that the addition of new knowledge for students may affect the ways in which they understand (or perhaps misunderstand) previously learned concepts. However, testing the connections between new knowledge and previously learned ideas is difficult to do in a manner that provides valid and accurate results. Numerous observations are needed in a variety of different contexts and at a number of different times.

6.1.2 Outline of Possible Study Scenario

Initially we would need to develop several diagnostic instruments, i.e., sets of problems and questions, to assess student thinking on first- and second-law concepts. The instruments would be tested for reliability (reproducibility of results) as well as interchangeability (similar results from each instrument). Having three to four different questions that can be used to assess the same concept would allow us to probe student thinking at multiple points during instruction, without students simply remembering answers from having seen the same question many times. For instance, we could probe student thinking on first- and second-law topics before instruction, then after instruction on the first law but before instruction on the second law, and then finally after all instruction on thermodynamics is complete.

An ideal experiment would allow us to probe student thinking at many points: during lecture, during tutorials, before and after homework, etc. All of these data could then be matched, analyzed, and correlated on a student-by-student basis. By dissecting how individual student thinking evolves, we could map out a student's learning "trajectory," that is, how a student's understanding changes over time. (Meltzer 2005, Thornton 1997)

6.1.3 Further Discussion

Besides the development of adequate questions, there are other substantial challenges for this type of study: 1) there needs to be some consideration given to the amount of testing students are subjected to in a short time period, and 2) it becomes quite difficult to correlate and track a large sample of students over many measurements.

The first challenge is substantial. Given that most introductory courses cover the first and second law in the span of no more than two weeks, it's difficult to find the necessary time to probe student thinking in a thorough, reliable and accurate way. The use of Personal Response Systems (or "clickers") before and after lecture with some developed and tested questions may help alleviate some of the burden on the students, but such response data would inherently be devoid of student explanations. One might consider the use of online testing, but it's difficult to determine the validity of such data since we have little control over the environment in which the questions as answered. It is likely that, to gather the type of data we would need, the instructor would have to sacrifice some lecture time to administer free-response questions whenever discussions

pertaining to first-law topics were complete. These data would provide the strongest link between the "before all instruction" data point and the "after all instruction" data point; they could be supplemented by use of multiple-choice questions given during lecture.

The second difficulty could reasonably be addressed by testing a large number of students and then randomly selecting twenty students out of the entire class. These twenty students could be more effectively and efficiently analyzed than a group of 300 or more, and one could calculate statistics for this sample and proceed with more detailed analysis afterwards. Another possible method is the importing of all student data into a database that could be programmed to look across various cells and tables to identify and label particular correlations. It's difficult to assess in advance the difficulty of such a task, but it seems potentially workable.

Another completely different investigation that might address some of these same ideas would be to acquire 2-3 students who could serve as a case study for student thinking on thermodynamics. These students would meet with the researcher for individual interviews after each lecture or set of lectures, and after any worked assignment for the course related to thermodynamics. This case-study approach might yield insights that could be used later in a large-scale study.

6.2 Further testing and development of research–based tutorials

This section contains an outline of how we plan to continue gathering data and testing our materials.

6.2.1 Further Testing at Iowa State University

We have conducted a thorough study on student thinking regarding entropy change in spontaneous processes, in a calculus-based introductory physics course. We have had free access to students before instruction, and therefore we have significant sample sizes for several of our questions. Our opportunities to measure learning gains via both traditional and research-based curricula have been somewhat limited. In order to make scientifically justifiable claims about our students' knowledge state, we need more opportunities to administer our tutorials and measure their effect on student learning. Through collaborations with cooperating faculty, we hope to collect additional data on entropy questions over the course of the next few years.

6.2.2 Off-site testing

Our study would be helped by using additional testing sites for measuring student learning gains via traditional instruction, as well as with our research-based tutorials. Our group attempted to gather data from other universities, but we ran into a multitude of problems including interference from the Institutional Review Boards (which give approval for testing on human subjects), difficulties with communication, and difficulties in coordinating timing and logistics. It was particularly disappointing that these off-site testing efforts were not productive. Additional testing of our questions and our curricular materials could serve to support and deepen our initial findings on student thinking about the learning of entropy.

6.2.3 Chemistry testing

As we discussed in Section 5.1.1, students encounter nearly identical statements of the "principle of increasing entropy" in many introductory and advanced chemistry courses. Two thirds of the students in the Iowa State University physics course reported having studied entropy previously in a chemistry course at ISU. Information about the extent to which students have the misconceptions we have outlined (in Sections 5.6 and 5.7) both before and after instruction in chemistry could shed light on the obstacles we are facing in teaching related topics in physics courses.

Notes for Chapter 6

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Chapter 7 Conclusions

This investigation sought to answer some key questions concerning student understanding and learning of concepts related to calorimetry and entropy. We utilized pre- and post-instruction testing via multiple-choice and free-response questions, along with numerous one-on-one student interviews, to assess what difficulties students were typically facing when attempting to learn these topics. We found students have consistent and reliable pre-instruction notions about both calorimetry and entropy concepts, including many incorrect ideas which persist despite focused instruction on the topic.

Calorimetry

Calorimetry is a fairly straightforward topic for most students in an introductory calculus-based physics course. In order to probe student thinking in this area we developed a variety of questions which were non-quantitative and thus unlike most traditional calorimetry problems. We found that the majority of students could give correct answers for these problems, but a significant minority had substantial difficulties. Most striking was the proportion of students that gave inconsistent responses on very similar questions which utilized the same calorimetric concepts, although posed in different contexts or representations.

The first goal in our investigation (see Chap. 1) was to determine:

"1) How…students' understanding of thermodynamic concepts evolve[s] during their studies in the introductory general-physics course…Specifically, what are students' initial, pre-instruction ideas regarding:

a) the conservation of energy and the role of specific heat in heat transfer processes involving two substances at different initial temperatures…and what is the nature of students' thinking after instruction has been completed?"

We found that on these topics, students' pre-instruction thinking did not differ very significantly from their post-instruction thinking, so we will answer this question in the context of a response to our second question, which was as follows:

"2) What are the primary conceptual and reasoning difficulties that students encounter when studying calorimetry…in an introductory general-physics course?"

We found that students' correct explanations generally involved very basic stripped-down "rules-of-thumb," rather than detailed elaborate arguments. Many students employed algebraic calculations to justify their answers, although students didn't seem to show an overwhelming preference for the algebraic method. Instead, many simply employed a straightforward qualitative argument involving rather perfunctory rule-based reasoning.

It was clear that many students had been misled by mistaken rules-of-thumb such as "equilibrium means equal temperature change" or "rate of temperature change is directly proportional to specific heat." Students' ideas about what *should* happen appeared to lead them to form conclusions to fit their expectations.

Entropy and the Second Law of Thermodynamics

We conducted an extensive analysis of student thinking regarding the principle of increasing entropy and of the state-function property of entropy. Analysis of data from four semesters of classes demonstrated that students have well-defined and consistent lines of thinking and reasoning. Matched samples of students observed with pre- and post-instruction testing show student difficulties tend to persist despite deliberate and focused attempts at overcoming those difficulties. We developed a research-based worksheet that explicitly addressed known student difficulties. Early indications are that instruction using this worksheet along with modified lecture instruction is effective in improving students' correct-response rate on questions regarding the principle of entropy increase in spontaneous processes, at least in processes that involve heat transfer. Difficulties regarding processes that do not involve heat transfer (e.g. the free expansion of a gas) persist to some extent. Other preconceived notions persist despite instruction, and this topic is thus well-suited for future investigations.

Our first goal in the investigation on this topic was to determine:

"1) How…students' understanding of thermodynamic concepts evolve(s) during their studies in the introductory general-physics course…Specifically, what are students' initial, pre-instruction ideas regarding…:

b) entropy and second-law concepts, including those involved with spontaneous processes and the state function property of entropy, and what is the nature of students' thinking after instruction has been completed?"

We found that before instruction, student responses on questions posed in different contexts were highly consistent and varied very little from one year to the next. All indications from our data were that difficulties and confusion persisted after traditional instruction and, in some case, even after focused research-based instruction. Since the ideas associated with these student difficulties persisted throughout instruction, the substance of these ideas is discussed immediately below.

Our second goal was to determine:

"2) What are the primary conceptual and reasoning difficulties that students encounter when studying…entropy, and second-law concepts in an introductory general-physics course?"

We documented specific student difficulties regarding the behavior of entropy in a spontaneous process. Both before and after instruction, most students fail to recognize the correct answers on questions regarding the change in entropy during a naturally occurring process. These questions deal with entropy changes in a system and its surroundings, and with the total entropy change (that of the system plus its surroundings). The most common responses suggest belief in a conservation principle that requires total entropy to remain the same. Among those students who assert a direction for entropy change even when none can be specified (e.g., stating that the system entropy increases and the surroundings' entropy decreases), a significantly higher proportion of students claim that entropy will increase rather than decrease. The exception to this occurs on a question involving the entropy change of a specific object, for which students show no preference for believing in either increasing or decreasing entropy.

Our third goal for this project can be considered independently for the calorimetry and entropy components, respectively, of our research:

"3) How can these difficulties be addressed more effectively to help improve student learning of these topics?"

Calorimetry

An intervention/control group study employing a research-based Calorimetry Worksheet in the intervention group showed no statistically significant between-group differences in performance on our post-instruction free-response question, although some differences on multiple-choice data were noted. The implication of these results is uncertain, but they suggest that in the time allotted, our Calorimetry Worksheet had no significant effect on student learning as far as we could determine.

Focusing on developing and refining students' rule-based reasoning, and giving students more practice at using it correctly, might be an efficient way to promote improved problem solving with calorimetry. In addition, problems should be developed that confront students with the failure of incorrect ideas, so that they can be aware of their imperfect understanding and thereby be more apt to modify their thinking.

Entropy and the Second Law of Thermodynamics

We designed and implemented two research-based tutorials to address known difficulties with student understanding of entropy.

Our Entropy State-Function Worksheet was administered to calculus- and algebra-based students during the Spring of 2005. An intervention/control-group study

with the algebra-based course showed those randomly selected students that used the worksheet during recitation instruction performed better than those that received traditional instruction on post-instruction testing involving a question that was related to the state-function property of entropy.

Our Entropy Spontaneous-Process Worksheet was administered during the Spring 2006 calculus-based course. In addition, changes were made to the lecture instruction in this course that were consistent with the ideas presented in the worksheet. We found that student performance on post-instruction free-response and multiple-choice questions was significantly better than on the same and/or similar questions after instruction in the spring of 2005 and the fall of 2004.

Final Comments

This research investigation as a whole posed many difficulties. For example, we experienced substantial logistical difficulties in collecting needed data and gaining access to students at necessary times. In spite of these challenges we are able to collect a great deal of data using diverse diagnostic questions, and we were able to make some useful discoveries about students' thinking regarding entropy and the second law of thermodynamics. We also found useful results and identified new points of interest for potential future investigations through our study of students' reasoning in calorimetry.

Appendix 1: Data Inventory from Chapter 5

This appendix consists of the full inventory of data collected and additional interview quotes from our study on student thinking of entropy from Chapter 5. For clarity, all tables and charts are titled with 5.# to match with the numbering system in Chapter 5.

Appendix 5.1 Itemized Response Data, General Context Question, Pre-instruction, All semesters

	Fall 2004 Pre-Instruction General Context	Spring 2005 Pre-Instruction General Context	Fall 2005 Pre-Instruction General Context	Spring 2006 Pre-Instruction General Context	Pre-Instruction General Context Cumulative Results
	$N = 406$	$N = 171$	$N = 360$	$N = 247$	$N = 1184$
Entropy of system…					
Increases	30%	26%	24%	24%	26 ± 4%
Decreases	19%	14%	25%	18%	19 ± 7%
Stays the same	9%	5%	13%	13%	10 ± 6%
is not determinable [*correct*]	39%	50%	35%	43%	42 ± 10%
Entropy of surroundings…					
Increases	26%	26%	31%	28%	28 ± 4%
Decreases	16%	11%	14%	14%	14 ± 4%
Stays the same	12%	9%	11%	11%	11 ± 2%
is not determinable [*correct*]	42%	47%	38%	42%	42 ± 6%
Entropy of the system + surroundings…					
Increases [*correct*]	19%	23%	16%	19%	19 ± 5%
Decreases	2%	1%	3%	2%	2 ± 1%
Same	67%	60%	69%	71%	67 ± 8%
not determinable	8%	12%	7%	4%	8 ± 5%
All Correct	**5%**	**4%**	**4%**	**5%**	**4 ± 1%**

Appendix 5.2 Itemized Response Data, Concrete Context Question, Pre-instruction, All semesters

	Spring 2005 Pre-Instruction Concrete Context	Fall 2005 Pre-Instruction Concrete Context	Spring 2006 Pre-Instruction Concrete Context	Pre-Instruction Concrete Context Cumulative Results
	$N = 155$	$N = 207$	$N = 237$	$N = 609$
Entropy of object…				
Increases	19%	15%	17%	$17 \pm 5\%$
Decreases	16%	20%	21%	$19 \pm 6\%$
Stays the same	3%	14%	3%	$6 \pm 16\%$
is not determinable [*correct*]	54%	45%	52%	$50 \pm 11\%$
Entropy of air in the room…				
Increases	25%	27%	28%	$27 \pm 3\%$
Decreases	8%	10%	10%	$9 \pm 2\%$
Stays the same	7%	9%	3%	$6 \pm 8\%$
is not determinable [*correct*]	48%	48%	50%	$49 \pm 3\%$
Entropy of the object + air in the room…				
Increases [*correct*]	17%	11%	15%	$14 \pm 9\%$
Decreases	1%	5%	4%	$3 \pm 6\%$
Same	68%	71%	74%	$71 \pm 7\%$
not determinable	5%	4%	3%	$4 \pm 2\%$
Entropy of the universe…				
Increases [*correct*]	23%	9%	14%	$15 \pm 18\%$
Decreases	1%	2%	0%	$1 \pm 2\%$
Same	61%	73%	72%	$69 \pm 17\%$
not determinable	6%	7%	8%	$7 \pm 3\%$
A, B, C correct	**6%**	**3%**	**5%**	**$5 \pm 3\%$**

Appendix 5.3 Total Entropy Remains the Same Response Data, General Context Question, Pre-instruction, All semesters

	Fall 2004 Pre-Inst General Context	Spring 2005 Pre-Inst General Context	Fall 2005 Pre-Inst General Context	Spring 2006 Pre-Inst General Context	Pre-Inst General Context Cumulative Results
	$N = 406$	$N = 171$	$N = 360$	$N = 247$	$N = 1184$
Total entropy *[of (system + surroundings / (object + air in the room)]* remains the same	67%	60%	69%	71%	67 ± 8%
A. Entropy of (system *and* surroundings)/ (object *and* air) not determinable, but total entropy remains the same	27%	33%	16%	29%	26 ± 12%
B. Entropy of (system/object) increases [decreases] and entropy of (surroundings/air) decreases [increases], but total entropy remains the same	30%	16%	31%	25%	25 ± 10%
C. Students with one of these notions of entropy conservation (sum of A and B above)	57%	49%	46%	53%	51 ± 7%

Appendix 5.4 Total Entropy Remains the Same Response Data, Concrete Context Question, Pre-instruction, all semesters

	Spring 2005 Pre-Instruction Concrete Context	Fall 2005 Pre-Instruction Concrete Context	Spring 2006 Pre-Instruction Concrete Context	Pre-Instruction Context Cumulative
	$N = 155$	$N = 207$	$N = 237$	$N = 609$
Total entropy *[of (system + surroundings)/ (object + air in the room)]* remains the same	68%	71%	74%	71 ± 7%
A. Entropy of (system *and* surroundings)/ (object *and* air) not determinable, but total entropy remains the same	37%	35%	41%	38 ± 8%
B. Entropy of (system/object) increases [decreases] and entropy of (surroundings/air) decreases [increases], but total entropy remains the same	19%	22%	24%	22 ± 6%
C. Students with one of these notions of entropy conservation (sum of A and B above)	56%	57%	65%	60 ± 13%

Appendix 5.5 Itemized Response Data, General Context Question, Post-instruction, All semesters

	Spring 2005 Post-Instruction General Context	Spring 2006 Post-Instruction General Context	Pre-Instruction General Context Cumulative Results
	$N = 255$	$N = 237$	$N = 1184$
Entropy of system…			
Increases	34%	12%	26 ± 4%
Decreases	18%	11%	19 ± 7%
Stays the same	7%	10%	10 ± 6%
is not determinable [*correct*]	40%	75%	42 ± 10%
Entropy of surroundings…			
Increases	29%	16%	28 ± 4%
Decreases	19%	5%	14 ± 4%
Stays the same	10%	3%	11 ± 2%
is not determinable [*correct*]	39%	76%	42 ± 6%
Entropy of the system + surroundings…			
Increases [*correct*]	30%	68%	19 ± 5%
Decreases	2%	2%	2 ± 1%
Same	56%	23%	67 ± 8%
not determinable	4%	7%	8 ± 5%
All Correct	**7%**	**53%**	**4 ± 1%**

Appendix 5.6 Itemized Response Data, Concrete Context Question, Post-instruction, All semesters

	Spring 2005 Post-Instruction Concrete Context	Spring 2006 Post-Instruction Concrete Context	Pre-Instruction Concrete Context Cumulative Results
	$N = 155$	$N = 231$	$N = 609$
Entropy of object…			
Increases	21%	13%	$17 \pm 5\%$
Decreases	20%	11%	$19 \pm 6\%$
Stays the same	4%	0%	$6 \pm 16\%$
is not determinable [*correct*]	54%	74%	$50 \pm 11\%$
Entropy of air in the room…			
Increases	28%	15%	$27 \pm 3\%$
Decreases	9%	8%	$9 \pm 2\%$
Stays the same	9%	1%	$6 \pm 8\%$
is not determinable [*correct*]	54%	74%	$49 \pm 3\%$
Entropy of the object + air in the room…			
Increases [*correct*]	24%	68%	$14 \pm 9\%$
Decreases	2%	2%	$3 \pm 6\%$
Same	69%	24%	$71 \pm 7\%$
not determinable	6%	5%	$4 \pm 2\%$
Entropy of the universe…			
Increases [*correct*]	24%	44%	$15 \pm 18\%$
Decreases	2%	0%	$1 \pm 2\%$
Same	69%	53%	$69 \pm 17\%$
not determinable	5%	0%	$7 \pm 3\%$
A, B, C correct	**13%**	**56%**	**$5 \pm 3\%$**

Appendix 5.7 Itemized Response Data, General Context Question, Pre- and Post-Instruction, Spring 2005 Matched Sample

	Spring 2005 Pre-Instruction General Context Matched Sample	Spring 2005 Post-Instruction General Context Matched Sample	Spring 2005 Pre-Instruction Concrete Context Matched Sample	Spring 2005 Post-Instruction Concrete Context Matched Sample
	$N = 153$	$N = 153$	$N = 131$	$N = 131$
Entropy of…	*System…*	*System…*	*Object…*	*Object…*
Increases	27%	35%	21%	17%
Decreases	14%	18%	17%	23%
Stays the same	4%	9%	2%	3%
is not determinable [*correct*]	50%	37%	54%	56%
Entropy of…	*Surroundings…*	*Surroundings…*	*Air in the Room…*	*Air in the Room…*
Increases	27%	31%	26%	30%
Decreases	11%	17%	10%	7%
Stays the same	8%	10%	7%	6%
is not determinable [*correct*]	46%	40%	50%	56%
Entropy of the…	*System + Surroundings…*	*System + Surroundings…*	*Object + Air in the Room…*	*Object + Air in the Room…*
Increases [*correct*]	24%	35%	20%	23%
Decreases	1%	3%	0%	1%
Same	60%	50%	69%	70%
not determinable	12%	10%	5%	6%
Entropy of the…	--	--	*Universe…*	*Universe…*
Increases [*correct*]	--	--	27%	26%
Decreases	--	--	1%	1%
Same	--	--	62%	66%
not determinable	--	--	5%	5%
A, B, C Correct	**4%**	**8%**	**7%**	**13%**

Appendix 5.8 PV-Diagram State-Function Question Version *A* Itemized response

	Algebra-based Course without Entropy State Function Worksheet	Algebra-based Course with Entropy State Function Worksheet	Calculus-based Course with Entropy State Function Worksheet
	$N = 110$	$N = 60$	$N = 341$
A. Consistent with less area under the curve implies greater change in entropy	7%	5%	5%
B. Consistent with greater area under curve implies greater change in entropy	21%	12%	23%
C. Two processes with smallest area have an equal change in entropy and the process with the largest area has a greater change in entropy	7%	3%	2%
D. Consistent with entropy is a state function	61%	78%	67%
E. Not enough information	3%	2%	3%

Appendix 5.10 Compilation of relevant interview quotes

5.10.1 Total entropy remains the same Interview data

Spring 2004, Post-instruction (performed traditional instruction), General-Context Question:

Two out of eight students answered that the entropy of the system plus the surroundings would remain the same. We found that both students had an understanding that was consistent with our groupings of "conservation ideas".

SA2 - "I knew that the entropy of everything has to be at equilibrium, so that'd be remain the same [for part c]. I kinda guessed that [system] was decreasing, if it's at equilibrium the surroundings would have to increase. It could be increases [for system] and decreases [for surroundings], but irreversible gives it away... at first I thought it was

not determinable, but then I thought there were different processes, like irreversible and
reversible."

I: What do you mean by *everything*?

SA2: "I want to say the entire system; the system that is undergoing the
irreversible process and the surroundings is everything around it."

I: What if this were a reversible process, how would that change your answers?

SA2: "If it was a reversible I would put not determinable because it could go one
way or the other."

SA7: "We need to know more about the process to determine what the change in
entropy was, it depends on whether it is endo- or exothermic. The total entropy would
remain the same. Because one [of system or surroundings] is increasing and one is
decreasing."

**Spring 2005, Post-instruction, performed Entropy State Function Worksheet,
General Context Question:**

Seven out of eighteen students responded to part (c) by stating that the total
entropy remained the same. By examining their answers to parts (a) and (b), we were
able to determine that all seven students fell into one of our two defined conservation
categorizations.

SC3 "I think for the irreversible process… I actually started with step
(c)… I was thinking that the entropy of the system plus surroundings equals zero.
So it would remain the same… I know these two would be opposite of each

other… I wasn't 100% sure, but I was thinking the system would decrease… and the surroundings would increase"

SC5 "I was leaning toward ND, but since it's interacting with the environment it's losing something to the environment and since it's irreversible it couldn't get it back. The surroundings is acting on the system; it has to be getting something from the system. When you add them together, negative plus positive or whatever I figured it would be even."

SC6 "… Since $Q = mc\Delta T$ we don't know if the system heats up or cools down, we don't know if the T is getting smaller or larger. If it goes up the entropy increases, if it goes down it decreases… what happens to one has the happen to the other so they will have the same ΔT… so entropy will remain the same."

I - Is heat transfer the same as entropy?

SC6 - "I can't remember, but I'll go with that."

SC11 "… [c] it remains the same because the surroundings and system is like the universe and entropy of the universe is constant"

SC13 "… For (c) I was going to guess it would stay the same, something reminded me that the entire universe, the entire system would remain the same. When you work out to all matter and energy in the universe…"

I – Would the change in entropy for parts (a) and (b) have a preference to increase or decrease?

SC13 "I think your more common thing is to have a increase in entropy… I had some thing in HS that nature will always gravitate toward a higher entropy."

SC18 "I thought I remembered entropy was proportional to energy... so if energy is lost then entropy decreases. …[(c) total entropy remains the same] The system would lose the same amount of energy as the surroundings gains so the system loses energy and the surroundings gain energy.

Fall 2005, Post-Instruction, Traditional Instruction, Entropy Spontaneous-Process Worksheet Elicit Question:

Four of nine students gave explanations consistent with the total entropy remaining the same. Of the four students, two argued that the low-temperature block would increase in entropy (which is correct) and that the total entropy would remain the same (which is incorrect). The other two students argued that both the entropy of the low-temperature cube and the total entropy would remain the same during the process. The later both cite the lack of a measurable temperature change as evidence that there was no change in entropy.

SB5 "…the entropy of the system remains the same.. so the entropy of the two blocks together remains the same… conserved: entropy and energy"

SB6 "for the low temperature cube, the entropy would increase, because when you give something energy you increase how much things are in chaos…

total: the system will stay the same, because one is increasing and one is

decreasing so they sort of cancel each other out; energy would be conserved"

SB7 "Entropy of a system can never decrease, and it said it would take a

long time for the temperature to change so I'm saying that it'll remain the same.

Total [entropy]: for the same reason as (a) it'll remain the same… conserved?

Energy is always conserved. I guess since entropy remains the same, I guess it

could be considered a quantity since it has a numerical value so it could be

conserved too."

SB8 "It would be remain the same. If there is no measured temperature

change, the total would remain the same for the same reason as the above; energy

is always conserved."

Spring 2006, Post-Instruction, performed Entropy Spontaneous-Process
Worksheet, General Context Question:

Only three of the twenty students we interviewed in the spring of 2006

answered that the total entropy remained the same. The remarkably low

percentage of "total entropy remains the same" responses is consistent with free

response and multiple-choice data we collected post-instruction in spring 2006,

and is further discussed in section 5.7.4.2.

SD15 – "I know ΔS of the universe equals S of the system plus S of the

surroundings, so I have two things in the universe, my system is possibly losing

order and increasing in entropy but overall S in the universe will stay the same

because I think it's the 3rd law of thermodynamics… the ΔS of the universe

equals zero.

SD4 – "… in part (c) during the process, the S of the system plus the S of

the surroundings would remain the same… any change in entropy in the system

would result in a negative change of entropy for the surroundings, because

energy could not be created or lost just exchanged.

I - How are energy and entropy related?

SD4 – They are directly proportional.

SD10 – "…(c) would remain the same because if one increases, the entropy of

the entire universe would be the same. If one increases the other one would

decrease."

5.10.2 System vs. Surroundings Interview data

Spring 2005, Post-instruction, performed Entropy State-Function Worksheet,

General Context Question:

Our interview sample showed some students that use some type of "entropy of the

system can never decrease" argument. It's particularly interesting since prior to our

study, we thought students might pick up on the general notion that "entropy increases"

and over-apply it. Seven of eighteen students specifically had the idea that the system

entropy must increase, while their answers for entropy of the surroundings varied among

not determinable (four), remains the same (two), or increases (one). All seven students claimed that the entropy of the system plus surroundings would increase.

SC2 "Entropy of the system will increase because it's irreversible and you have to have an increase in entropy if it's irreversible… second one I wasn't sure of… entropy must either stay the same or increase… the third one… based on my previous two answers it would have to increase or remain the same. Because you can't achieve order from disorder, but it can go the other way around."

SC7 "As soon as I say entropy I started thinking randomness and I remembered that a process will only occur spontaneously if entropy increases. The surroundings I thought of the situation where you are mixing two chemicals… If you add heat to the surroundings you are increasing molecular speed which increases the entropy."

SC9 "It's irreversible for all irreversible processes we know the entropy increases, [surroundings] remains the same, because entropy is the amount of disorder in a system and the surroundings won't be in greater disorder, S universe increases, you can't return it to its original state and entropy can never decrease."

SC14 "It maybe increases because there is a transfer of heat energy and whenever you transfer heat energy the molecules become more unordered so entropy increases.

I "Does the direction of heat transfer matter?"

SC14 "In the direction the heat is being transferred those molecules would be more unordered. Surroundings I said remain equal or increase and that depends on whether the heat is transferred to the system."

I "Could it decrease?"

SC14 "It would always remain the same or increase.   Remain the same because the universe can't possible become more ordered… it's one of the laws of thermodynamics."

SC15 "Entropy of system increases because for an irreversible process it can't be reversed because the disorder of the system increases. Entropy of the surroundings, you couldn't tell, because the system could affect the surroundings or it could not. Overall entropy increases for an irreversible, because that's the tendency for the universe to go toward more disorder in an irreversible process."

Fall 2005, Post-Instruction, Traditional Instruction, Entropy Spontaneous-Process Worksheet Elicit Question:

Two of the nine students in our Fall 2005 interview sample gave explanations consistent with entropy never decreasing.

SB2 "entropy never decreases, I'm guessing it will increase because heat transfer is happening so there is an energy change... even though it's really small there is still a change. I believe [the total] would increase because the low temperature cube is increasing… hmm… I think both of the cubes are increasing because they both have a rate of energy change so they both have an entropy increase. The temperature doesn't measurably change so it's conserved."

SB4 "It will increase in temperature, entropy is always positive."

5.10.4 Metal in the Ocean Interview quotes

Three of the twenty students stated the metal would decrease in entropy, the ocean would remain the same due to some type of size argument, and the total entropy would therefore decrease.

Spring 2006, Post-Instruction, Performed Entropy Spontaneous-Process Worksheet, Metal in the Ocean Question:

SD4 - "entropy of the metal is going to decrease because its losing heat, once it reaches equilibrium it will have lost entropy because it's also lost heat, the entropy of the surroundings I think means the ocean, then the ocean remains the same, it's a law or it's a frame of reference… a very small change in entropy into a very large surroundings isn't going to result in any measurable change in entropy in the surroundings because of the size difference between the two… it's a theory we learned about in recitation where we did a similar problem like this, even though you change the immediate surroundings since you have to go through all the surroundings of the ocean its too minute a change to have any measurable change. [The change in entropy of the metal cube plus the surroundings] would decrease, the entropy in the ocean is going to remain the same but the entropy of the very hot piece of metal will decrease drastically to come in equilibrium with the ocean…"

I – how does this compare with your answer to the object plus the air in the room? (Object: Not Determinable, Air in the Room: Not Determinable, Object plus Air in the Room: Same) Is there something different?

SD4 - "In the object in the room the object was large enough to create a change in entropy in the room then there would be enough to determine if it's the same. In *this* problem there wasn't a noticeable change in entropy of the ocean but there was in the metal."

SD14 - "first one I put decrease, because it's losing heat, it's a hot piece of metal thrown in the ocean so it's going to lose it's heat so I'm saying it's a decrease in entropy.

The ocean being so huge in volume compared to this small object, so its entropy change would remain zero."

I – "If the metal loses heat does that go to the ocean?"

SD14 - "Yeah, it goes to the ocean, but the heat is able to spread out through such a large volume its change in entropy is virtually nothing due to the large volume. Entropy of the metal plus entropy of the ocean would decrease because I said the first one decrease and this one stays the same."

SD15 – "The entropy of the metal decreases because the temperature is going to be cooling down, the internal energy is going to be decreasing. Since the ocean is contact with the air and the air is the rest of the universe, the entropy is going to remain the same. That size of the metal is not enough to increase the ocean by the slightest amount… the relationship between how much energy that piece of metal is going to give the ocean isn't substantial. [Total] entropy would decrease because the temperature of the metal is decreasing; it's going to be exchanging heat with the ocean and the air."

5.10.3 Free-expansion Interview quotes

Nine of the twenty correctly stated that the entropy of the gas would increase however only three made strong statements about the process being irreversible and therefore requiring that the entropy of the gas increases because everything else remains the same. SD1 – "entropy of the gas increases, because its going to be in a greater volume, I'm trying to remember how entropy works… it's hard to get a hold of (a physical feel for) because it's not like a physical principle… entropy is kind of arbitrary. I'm going to say the entropy increases because it's the same temperature it's going to have an increase in volume and decrease in pressure. I'm not sure how that will affect it… I think the

pressure will make a difference, but I think the increase in volume will outweigh that. c) added system plus surroundings to say total increases… I'm trying to remember there was a test question or homework question… a gas expanding into a vacuum. The formula would calculate out to be zero, but I remember it was supposed to be increasing because it was irreversible."

SD2 – "there was no change in temperature and Q… I don't know about Q, it wasn't transferred to any new molecules (the outside or the other half of the container) it just changed the pressure and the volume. It must be isothermal because it's still the same temperature; I'm trying to remember… Entropy increases because it would be pretty hard to get it back into a vacuum, therefore it's irreversible.

I – When you say to get back into a vacuum?

SD2 – "To get back to it's original state. Total entropy would probably increase in well, because the outside never decreased, so you only have an increase on the gas."

SD6 – "This is irreversible process, only when we can have an entropy change of zero process was when it was reversible, (goes on to accurately describe a reversible process). You can never get it back. So entropy has to increase in this case. The outside remains the same, the inside increases, so the total increases by just adding them up."

Six of the nine students used some argument about increasing volume leading to an increase in randomness to explain their answers.

SD9 – "because entropy is degree of randomness and we're increasing the volume, so there is more randomness of the moles of gas, they can do more things inside the container. "

SD10 – "entropy inside does increase because there is more volume, the molecules are more random; bounce around more, more chaotic. I guess the total entropy does increase. The definition of Entropy is more changing, more random, more volume."

SD15 – "it's becoming more random, because I'm teaching the same temperature so it's an isothermal process. So (drawing) PV, so my volume is increasing, my pressure is decreasing… The only thing I know about S is that it is Q over T, so Q equals my Work, and work is area underneath this curve. In isothermal system there is no delta U = Q – W, and in isothermal, delta U equals zero. Just because there is no temperature change doesn't mean there is no heat transfer… [hits the wall] the entropy increases because the randomness increases… pressure decreases, volume is going to increase, so my entropy is going to increase. c) same plus increases equals increases"

SD18 – "there isn't a temp change but I think it would increase because there is more volume for it to move within. If there isn't a temperature there may not be any entropy change. Doesn't entropy just describe the randomness of everything?"

Eight of the twenty students stated that the entropy of the gas would remain the same, and every single one cited some combination of temperature remaining constant (7 of 8), and no heat transferred or work done during the process (6 of 8).

SD3 – "b) remains the same, there is no heat transfer, no work is done by the gas, final temperature is the same as the initial temperature, and for c) total entropy would remain the same, because the outside and inside don't change so the total wouldn't either."

SD7 – "b) remains the same because final temperature was the same so there wasn't any heat transfer, c) same, because the other two remained the same"

I – "Does there have to be a temperature change?"

SD7 – "There has to be a heat exchange for there to be an entropy change."

I – "In order to have a temperature change does there has to be a heat exchange?"

SD7 – "No… but I'm getting confused now."

SD11 – "entropy of the gas remains the same because it doesn't experience heat transfer it stays the same temperature all it does is expand in volume and decrease in pressure. C) remains the same, because everything outside stays the same and the gas stays the same"

SD12 – "for b it stays the same because there is no temperature change and no work is done so no energy is transferred or changed, I suppose there could be heat transfer from one side of the container to the other… no, it remains the same. Occupies a bigger space and the pressure changes. For c), most cases it always increases, but since I said neither one of these change at all, it wouldn't change in c either."

SD14 – "There is no change in temperature, so the entropy of the gas stays the same too. The first two don't change, them two added together don't change."

SD16 – "it's at the same temperature and there is no heat exchange so it should be at the same entropy. The total entropy of everything is going to stay the same too. If the outside didn't change and the inside doesn't change… there is also no heat transfer. This isn't naturally occurring... in a real system it would cool down a little bit."

Two of the eight even justified that entropy changes due to the increasing volume would be compensated by entropy changes due to the decreasing pressure so that there was no net change in entropy.

SD4 – "You double the volume and half the pressure… actually I'm saying it remains the same. The change in pressure would be negated by the change in volume. c) total remains the same since there is no exchange… it's an isothermal process"

SD17 – "Temperature is staying the same, the volume is increasing but the pressure is going down, so I guess there is no real change. The other factors are making up for the change in volume. It would remain the same… but rule of system plus surroundings it would have to increase which would mean the gas would increase, but I don't see how it would, so I'll say remain the same for all three."

5.11 Isothermal and Free-Expansion Question

A system consisting of one mole of a monatomic *ideal gas* is confined in a cylinder with a moveable piston. The system goes through the two different processes as shown below. The initial values of volume (V_i), pressure (P_i), and temperature (T_i) are the same for each process. Also note that the final volume (V_f) is the same for each process. In Process #2, the adiabatic expansion, the cylinder is thermally insulated.

Process #1: *Expansion at constant temperature*   Process #2: *Adiabatic Expansion*

Initial
State:

Final
State:

For each of the thermodynamic quantities listed below, specify

     i. whether the quantity is *positive, negative,* or *zero* for each of the two processes and

     ii. rank whether the quantity for Process #1 is greater than, less than or equal to that quantity for Process #2

Explicitly justify your reasoning.

   a) ΔU, the change in internal energy of the system

   b) W, the work done by the system

   c) Q, the heat transfer to the system

   d) ΔS_{sys}, the change in entropy of the system

   e) ΔS_{surr}, the change in entropy of the surroundings

   f) ΔS_{univ}, the change in entropy of the universe

Appendix 2: Worksheets

This section is comprised of our original research-based worksheets. We have used slightly modified versions of these depending on the time and location, but the essence of each is clearly represented here.

Appendix 2.1 Calorimetry Worksheet, authored by Ngoc-Loan Nguyen

Calorimetry Worksheet

> *When energy is transferred to an object of mass* m *in the form of heat transfer* Q, *the magnitude of the object's temperature change* ΔT *depends on its specific heat* c, *a quantity that is characteristic of the material:* $\Delta T = \dfrac{Q}{mc}$. *If heat transfer is positive* (Q > 0), *the object's temperature increases* (ΔT > 0).

3. Suppose we have two samples, *A* and *B*, of the same material placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample *A* has the same mass as sample *B*. Energy but no material can pass through the conducting partition. The gas inside the container has negligible mass; it allows energy transfer but absorbs no energy. (Assume specific heat is independent of temperature.)

a. A long time after time zero, what ratio do you expect for the temperatures of the two samples?

$\dfrac{T_A}{T_B} =$ _____? Explain your answer.

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.

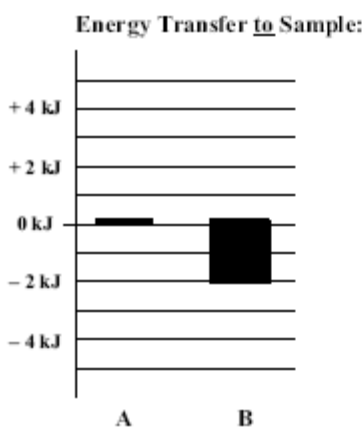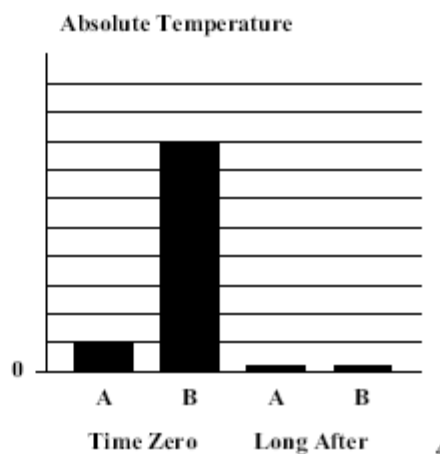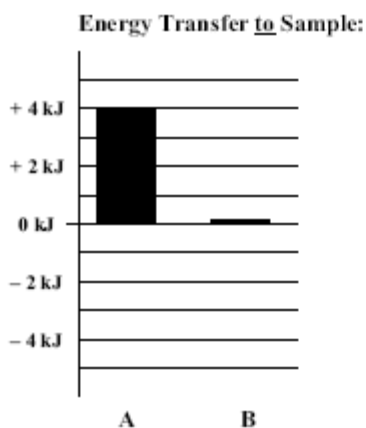Energy Transfer <u>to</u> Sample:

Absolute Temperature

1

Calorimetry Worksheet (p. 2)

Calorimetry Worksheet

4. Suppose we have two samples, A and B, of the **same** material placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has **three times** the mass of sample B. Energy but no material can pass through the conducting partition. The gas inside the container has negligible mass; it allows energy transfer but absorbs no energy. (Assume specific heat is independent of temperature.)

a. If the internal energy of sample A changes by an amount $|\Delta U_0|$ (absolute value), what is the amount of internal energy change (absolute value) of sample B?

b. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in the temperature of sample B? $\Delta T_B = $ _____? (Check that the sign of your answer is correct.)

c. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.
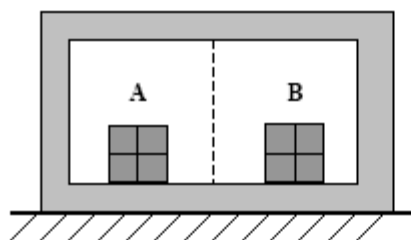

Energy Transfer to Sample:

Absolute Temperature

2

Calorimetry Worksheet (p. 3)

Calorimetry Worksheet

5. Suppose we have two samples, A and B, of **different** materials, placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has the **same** mass as sample B. Energy but no material can pass through the conducting partition. The gas inside the container has negligible mass; it allows energy transfer but absorbs no energy. (Assume specific heat is independent of temperature.) **The specific heat of material A is twice that of material B.**

a. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in the temperature of sample B? $\Delta T_B =$ _____? Explain your answer.

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.

Energy Transfer to Sample:

Absolute Temperature

Time Zero   Long After

3

Calorimetry Worksheet (p. 4)

Calorimetry Worksheet

6. Suppose we have two samples, A and B, of **different** materials, placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample **A** has **1.5 times the mass** of sample B. Energy but no material can pass through the conducting partition. The gas inside the container has negligible mass; it allows energy transfer but absorbs no energy. (Assume specific heat is independent of temperature.) **The specific heat of material B is twice that of material A.**

a. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in sample B? $\Delta T_B = $ _____? Explain your answer.

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.


Energy Transfer to Sample:

Absolute Temperature

Time Zero   Long After

4

Appendix 2.2 Calorimetry Worksheet Solution

Calorimetry Worksheet

When energy is transferred to an object of mass m in the form of heat transfer Q, the magnitude of the object's temperature change ΔT depends on its specific heat c, a quantity that is characteristic of the material: $\Delta T = \dfrac{Q}{mc}$. *If heat transfer is positive (Q > 0), the object's temperature increases (ΔT > 0).*

3. Suppose we have two samples, A and B, of the same material placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has the same mass as sample B. Energy but no material can pass through the conducting partition. (Assume specific heat is independent of temperature.)

a. A long time after time zero, what ratio do you expect for the temperatures of the two samples?

$\dfrac{T_A}{T_B} =$ _____? Explain your answer. $\dfrac{T_A}{T_B} = 1$, as they attain thermal equilibrium

$$Q_B = -Q_A \quad \Rightarrow \quad m_B c_B \Delta T_B = -\left(m_A c_A \Delta T_A\right)$$

$$\Delta T_B = -\left(\frac{m_A c_A}{m_B c_B}\right)\Delta T_A$$

$$m_B = m_A \quad \text{and} \quad c_B = c_A \quad \Rightarrow \quad \Delta T_B = -\Delta T_A$$

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.
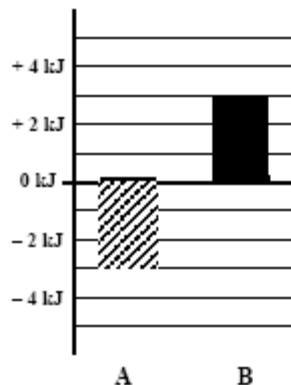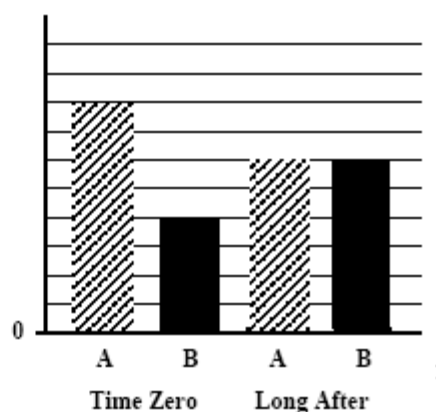
Calorimetry Worksheet Solution (p. 2)

Calorimetry Worksheet

4. Suppose we have two samples, A and B, of the same material placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has **three times** the mass of sample B. Energy but no material can pass through the conducting partition. (Assume specific heat is independent of temperature.)
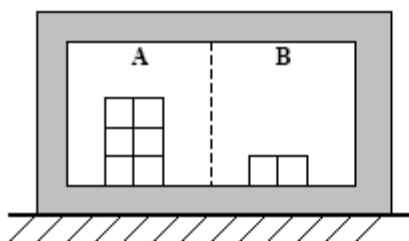

a. If the internal energy of sample A changes by an amount $|\Delta U_0|$ (absolute value), what is the amount of internal energy change (absolute value) of sample B? $|\Delta U_0|$ since $Q_B = -Q_A$

b. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in the temperature of sample B? $\Delta T_B = -3\,\Delta T_A$ (Check that the sign of your answer is correct.)

c. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.

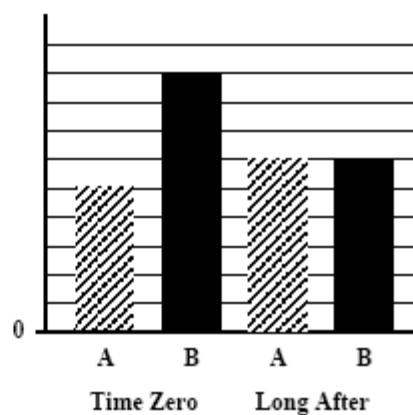$$Q_B = -Q_A \quad \Rightarrow \quad m_B c_B \Delta T_B = -(m_A c_A \Delta T_A)$$

$$\Delta T_B = -\left(\frac{m_A c_A}{m_B c_B}\right)\Delta T_A$$

$$m_A = 3m_B \quad and \quad c_B = c_A \quad \Rightarrow \quad \Delta T_B = -3\Delta T_A$$
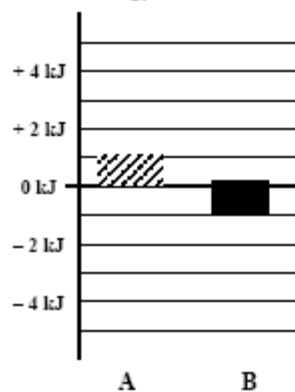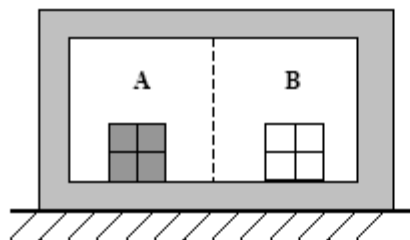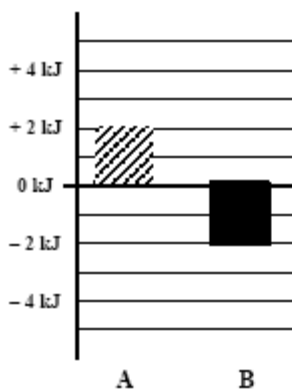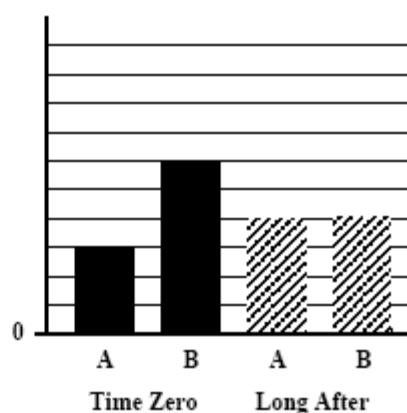
Calorimetry Worksheet Solution (p. 3)

Calorimetry Worksheet

5. Suppose we have two samples, A and B, of **different** materials, placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has the **same** mass as sample B. Energy but no material can pass through the conducting partition. (Assume specific heat is independent of temperature.) **The specific heat of material A is twice that of material B.**

a. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in the temperature of sample B? $\Delta T_B = -2\,\Delta T_A$ Explain your answer.

$$Q_B = -Q_A \quad \Rightarrow \quad m_B c_B \Delta T_B = -\left(m_A c_A \Delta T_A\right)$$

$$\Delta T_B = -\left(\frac{m_A c_A}{m_B c_B}\right)\Delta T_A$$

$$m_B = m_A \quad \text{and} \quad c_A = 2c_B \quad \Rightarrow \quad \Delta T_B = -2\Delta T_A$$

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.
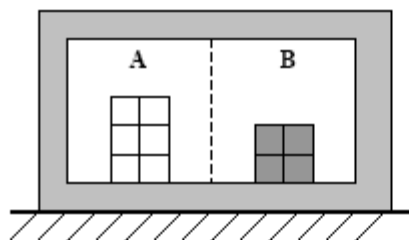

Energy Transfer <u>to</u> Sample:

Absolute Temperature

Time Zero   Long After   3

Calorimetry Worksheet Solution (p. 4)

Calorimetry Worksheet

6. Suppose we have two samples, A and B, of different materials, placed in a partitioned insulated container which neither absorbs energy nor allows it to pass in or out. Sample A has **1.5 times the mass** of sample B. Energy but no material can pass through the conducting partition. (Assume specific heat is independent of temperature.) **The specific heat of material B is twice that of material A.**

a. If the temperature of sample A changes by ΔT_A, what would be the corresponding change in sample B? $\Delta T_B = -(3/4)\,\Delta T_A$ Explain your answer.

$$Q_B = -Q_A \quad \Rightarrow \quad m_B c_B \Delta T_B = -(m_A c_A \Delta T_A)$$
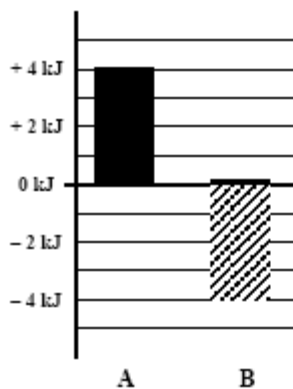
$$\Delta T_B = -\left(\frac{m_A c_A}{m_B c_B}\right)\Delta T_A \quad and \quad m_A = \frac{3}{2} m_B \quad while \quad c_B = 2c_A$$

$$\Rightarrow \quad \Delta T_B = -\frac{3}{2} \times \frac{1}{2}\Delta T_A \quad \Rightarrow \quad \Delta T_B = -\frac{3}{4}\Delta T_A$$

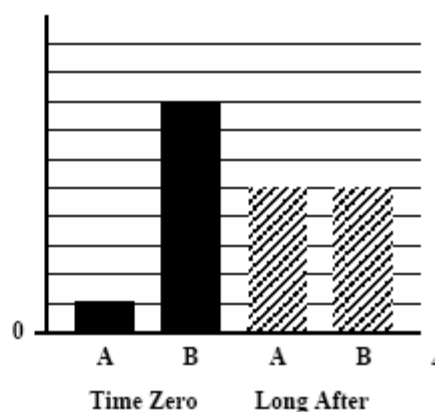$$if \quad \Delta T_A = 4 \quad then \quad \Delta T_B = -3$$

b. Complete the bar charts below for temperature and energy transfer. If any quantity is zero, label that quantity as zero on the bar chart. Explain your reasoning below.

Energy Transfer **to** Sample:

Absolute Temperature

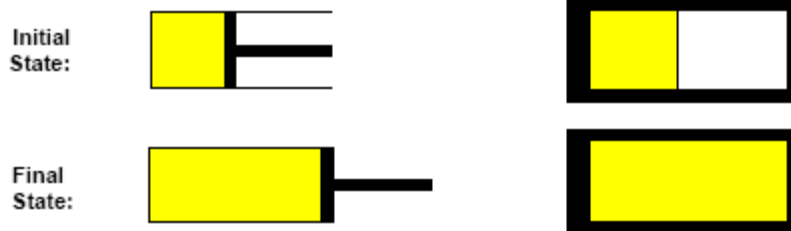## *Appendix 2.3 Entropy State-Function Worksheet*

Entropy Worksheet

A system consisting of one mole of a monatomic *ideal gas* goes through two different processes as shown below. The initial values of volume (V_i), pressure (P_i), and temperature (T_i) are the same for each process. Also note that the final volume (V_f) is the same for each process.

Process #1 occurs very slowly so that it is always at the same temperature as the surroundings, and the pressure applied to the piston may vary. Note that the piston for Process #1 slides without friction. (Processes #1 is reversible.)

The system is thermally insulated from its surroundings in Process #2. In Process #2, the gas is initially trapped in one half of the container by a thin partition; the other half of the container contains vacuum. The partition is suddenly removed, and the gas quickly fills the rest of the volume.

#1: *Reversible Isothermal Expansion*   #2: *Free Expansion into a Vacuum*
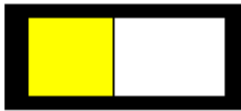
Initial State:

Final State:

1.1 Consider Process #1: Explain the meaning of "isothermal."

1.2 During this process, state whether the following quantities *increase, decrease,* or *remain the same*:
   a. temperature

   b. volume

   c. pressure

1.3 For an ideal gas, internal energy is directly dependent on temperature by the equation $U = 3/2\ nRT$. Does the internal energy of the system in Process #1 (the system consists of the gas only) *increase, decrease,* or *remain the same*? Explain.

1.4 In Process #1, the gas molecules exert a force on the piston by colliding with it while the piston is moving. Does this mean work done by the system on the surroundings is *positive, negative,* or *zero*?

1.5 According to the first law of thermodynamics, is the heat transfer to the system from the surroundings in Process #1 *positive, negative,* or *zero*? Explain.

Check that you and your group members have the same answers and consistent explanations for the questions above. If not, reconcile the responses and enter the group explanation.

1

Entropy State-Function Worksheet (pg 2)

Entropy Worksheet

#1: *Reversible Isothermal Expansion*   #2: *Free Expansion into a Vacuum*

Initial State:

Final State:

2.1 Consider Process #2: According to the information, the system in Process #2 is thermally insulated. Explain what "thermally insulated" means.

2.2 In Process #2, is the heat transfer to the system from the surroundings *positive*, *negative*, or *zero*?

2.3 In Process #2, the gas is expanding but there is nothing for the molecules to collide against therefore there is no force exerted during the expansion. Is the work done by the system on the surroundings *positive*, *negative*, or *zero*? Explain.

2.4 According to the first law of thermodynamics, does the internal energy of the system in Process #2 *increase*, *decrease*, or *remain the same*? Explain.

2.5 During this process, state whether the following quantities *increase*, *decrease*, or *remain the same*:
   a.   temperature

   b.   volume

   c.   pressure

2.6 Is the final volume of the system in Process #2 *greater than*, *less than*, or *equal to* the final volume of the system in Process #1? Answer the same question for the initial volumes. *HINT: Check the information at the top of page 1.*

2.7 Is the final temperature of the system in Process #2 *greater than*, *less than* or *equal to* the final temperature of the system in Process #1? Explain.

2.8 Is the final pressure of the system in Process #2 *greater than*, *less than* or *equal to* the final pressure of the system in Process #1? Explain.

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Entropy State-Function Worksheet (pg 3)

Entropy Worksheet

3. Draw points to represent the initial and final states of the two processes on the same P-V diagram; label each state 1_i, 1_f, 2_i, and 2_f, respectively. (e.g. 1_i is the initial state of Process #1, etc.)

P

V
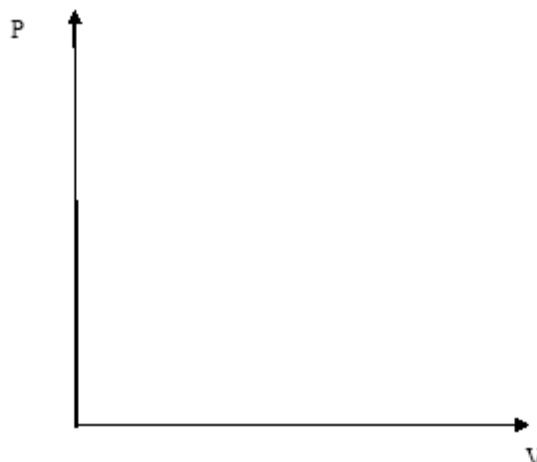
Note: Check that the final volumes of both processes are the same.

Is your diagram consistent with your answer to Questions 2.6, 2.7, and 2.8 on the previous page?

4. Which process has the greatest magnitude of heat transfer to the system? If the two are equal, indicate with an "=" symbol.

5. Is $S_{1(\text{initial state})}$, the initial entropy of the system in Process #1, *greater than*, *equal to*, or *less than* $S_{2(\text{initial state})}$, the initial entropy of the system in Process #2?

The change in the entropy of a system that begins in initial state i and ends in final state f can be expressed as $\Delta S = \frac{Q_{reversible}}{T}$. Here, $Q_{reversible}$ represents the heat transfer to the system *only* during a process from i to f that is reversible; the T in this equation is related to the average temperature of the system during the process.

6. Does the entropy of the system *increase*, *decrease*, or *remain the same* for Process #1?

Is your answer to Question #6 consistent with $\Delta S = \frac{Q_{reversible}}{T}$? Explain.

Do NOT continue until you check your answers with the recitation instructor.

3

Entropy State-Function Worksheet (pg 4)

Entropy Worksheet

7. Consider ΔS_2 and ΔS_1, the *changes* in the entropy of the system during Process #2 and Process #1, respectively; $\Delta S \equiv S_{(final\ state)} - S_{(initial\ state)}$. Three students are discussing whether ΔS_2 is *greater than*, *equal to*, or *less than* ΔS_1. Read through the discussion and follow the directions below.

Student A: *"I think that the entropy for Process #2 is going to stay the same. The system is thermally insulated so if there is no heat transfer to the system from the surroundings there is no change in the entropy of the system because $\Delta S = \dfrac{Q_{reversible}}{T}$."*

Student B: *"That makes sense from the ΔS equation we were given, but that is only correct for a reversible process. We must remember that entropy is a state function. Process #2 has the exact same final pressure, volume, and temperature as Process #1, so I think that the entropy in Process #2 will increase the same amount that entropy in Process #1 increases."*

Student C: *"I think you are on the right track, but Process #2 can't go back to its initial state like Process #1; that means that it's not reversible. So even though it has the same final state as Process #1, I think the change in entropy for Process #2 will be different from that in Process #1."*

Student B responds to Student C: *"I agree that #2 is irreversible, but we already determined that the initial entropy for both processes was the same in Question #5. The change in entropy is $\Delta S \equiv S_{(final\ state)} - S_{(initial\ state)}$, so if the initial AND final states of Process #2 and Process #1 are the same the change in entropy in Process #2 has to be the same as Process #1 regardless of whether it's reversible or irreversible."*

Re-read each student's statement and comment on the parts with which you agree, and identify the statements that you believe are incorrect. Explain your reasoning.

Discuss your reasoning and that of your group with the recitation instructor before continuing.

Entropy State-Function Worksheet (pg 5)

Entropy Worksheet

8. Is $\Delta S_{system\,1}$, the change in entropy of the **system** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{system\,2}$, the change in entropy of the system for Process #2? *Explain.*

9. Is $\Delta S_{surroudings\,1}$, the change in entropy of the **surroundings** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{surroundings\,2}$, the change in entropy of the **surroundings** for Process #2? *Explain. Hint:* $Q_{system} = - Q_{surroundings}$

10. Using your answers from Questions 8 and 9, is the magnitude of $|\Delta S_{system\,1}|$ *greater than, equal to,* or *less than* the magnitude of $|\Delta S_{surroundings\,1}|$? *Hint:* $Q_{system} = - Q_{surroundings}$ & $\Delta S = \dfrac{Q_{reversible}}{T}$

11. Is $\Delta S_{universe\,1}$, the change in entropy of the **universe** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{universe\,2}$, the change in entropy of the **universe** for Process #2? Explain your answers. (Note that $\Delta S_{universe} \equiv \Delta S_{system} + \Delta S_{surroundings}$)

12. Use the results from the worksheet to fill out the Table below

	Process #1	Process #2
Reversible or Irreversible?		
$Q_{to\ system} > 0$, $Q_{to\ system} < 0$, or $Q_{to\ system} = 0$?		
$\Delta S_{system} > 0$, $\Delta S_{system} < 0$, or $\Delta S_{system} = 0$?		
$Q_{to\ surr} > 0$, $Q_{to\ surr} < 0$, or $Q_{to\ surr} = 0$?		
$\Delta S_{surr} > 0$, $\Delta S_{surr} < 0$, or $\Delta S_{surr} = 0$?		
$\Delta S_{universe} > 0$, $\Delta S_{universe} < 0$, or $\Delta S_{universe} = 0$?		

In any real (or irreversible) process, does the entropy of the **universe** *increase, decrease, remain the same,* or is this *not determinable* without additional information?
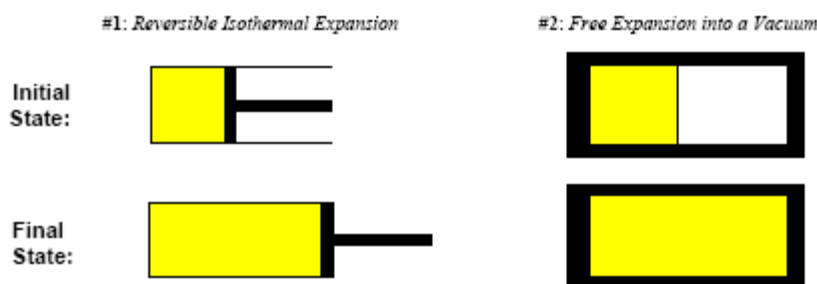
5

Appendix 2.4 Entropy State-Function Worksheet Solution

Entropy Worksheet

A system consisting of one mole of a monatomic *ideal gas* goes through two different processes as shown below. The initial values of volume (V_i), pressure (P_i), and temperature (T_i) are the same for each process. Also note that the final volume (V_f) is the same for each process.

Process #1 occurs very slowly so that it is always at the same temperature as the surroundings, and the pressure applied to the piston may vary. Note that the piston for Process #1 slides without friction. (Processes #1 is reversible.)

The system is thermally insulated from its surroundings in Process #2. In Process #2, the gas is initially trapped in one half of the container by a thin partition; the other half of the container contains vacuum. The partition is suddenly removed, and the gas quickly fills the rest of the volume.

#1: *Reversible Isothermal Expansion*   #2: *Free Expansion into a Vacuum*

Initial State:

Final State:

1.1 Consider Process #1: Explain the meaning of "isothermal."

Isothermal means "same temperature"; an isothermal process occurs at a constant temperature.

1.2 During this process, state whether the following quantities *increase*, *decrease*, or *remain the same*:

 a. temperature

 Remains the same; by definition, an isothermal process takes place at constant temperature.

 b. volume

 Increases; we can see this in the diagram and it is stated in the paragraph above.

 c. pressure

 Decreases, pV=nRT. T is constant, V increases, and therefore p decreases.

1.3 For an ideal gas, internal *[thermal]* energy is directly dependent on temperature by the equation $E_{th} = 3/2\ nRT$. Does the internal energy of the system in Process #1 (the system consists of the gas only) *increase*, *decrease*, or *remain the same*? Explain.

 Remains the same; since n and T are constant, the internal [thermal] energy will be constant as well.

1.4 In Process #1, the gas molecules exert a force on the piston by colliding with it while the piston is moving. Does this mean work done by the system on the surroundings is *positive*, *negative*, or *zero*?

 The force applied is in the same direction as the motion of the piston, therefore positive work W_s is done.

1.5 According to the first law of thermodynamics, is the heat transfer to the system from the surroundings in Process #1 *positive*, *negative*, or *zero*? Explain.

 The first law states that when $\Delta E_{th} = 0$, $Q = W_s$. Therefore the heat transfer to the system is positive.

Check that you and your group members have the same answers and consistent explanations for the questions above. If not, reconcile the responses and enter the group explanation.

1

Entropy State-Function Worksheet Solution (pg 2)

Entropy Worksheet

#1: *Reversible Isothermal Expansion*   #2: *Free Expansion into a Vacuum*

Initial State:

Final State:

2.1 Consider Process #2: According to the information, the system in Process #2 is thermally insulated. Explain what "thermally insulated" means.

"Thermally insulated" means there is no heat transfer between the system and its surroundings.

2.2 In Process #2, is the heat transfer to the system from the surroundings *positive*, *negative*, or *zero*?

$Q = 0$, because the piston is thermally insulated.

2.3 In Process #2, the gas is expanding but there is nothing for the molecules to collide against therefore there is no force exerted during the expansion. Is the work done by the system on the surroundings *positive*, *negative*, or *zero*? Explain.

$W \equiv \int \vec{F} \cdot d\vec{s}$ but $F = 0$, therefore $W = 0$.

2.4 According to the first law of thermodynamics, does the internal energy of the system in Process #2 *increase*, *decrease*, or *remain the same*? Explain.

$\Delta E_{th} = Q - W_s; Q = 0, W_s = 0$, therefore $\Delta E_{th} = 0$.

2.5 During this process, state whether the following quantities *increase*, *decrease*, or *remain the same*:

a. temperature

Remains the same, since E_{th} is constant and $E_{th} = 3/2nRT$.

b. volume

Increases, as we can see from the diagram.

c. pressure

Decreases, $pV = nRT$. If V increases and T is constant, then p must decrease.

2.6 Is the final volume of the system in Process #2 *greater than*, *less than*, or *equal to* the final volume of the system in Process #1? Answer the same question for the initial volumes. *HINT: Check the information at the top of page 1.*   *The final volumes for Process #1 and Process #2 are stated to be the same.*

2.7 Is the final temperature of the system in Process #2 *greater than*, *less than* or *equal to* the final temperature of the system in Process #1? Explain.

In both processes, the temperature remained constant, therefore the final temperatures are equal.

2.8 Is the final pressure of the system in Process #2 *greater than*, *less than* or *equal to* the final pressure of the system in Process #1? Explain.

Since the final volumes and temperatures are the same, the ideal gas law implies that the final pressures also are equal.

2

Entropy State-Function Worksheet Solution (pg 3)

Entropy Worksheet

Check that you and your group members have the same answers and consistent explanations for the questions above. If not, reconcile the responses and enter the group explanation.

3. Draw points to represent the initial and final states of the two processes on the same P-V diagram; label each state 1_i, 1_f, 2_i, and 2_f, respectively. (e.g. 1_i is the initial state of Process #1, etc.)
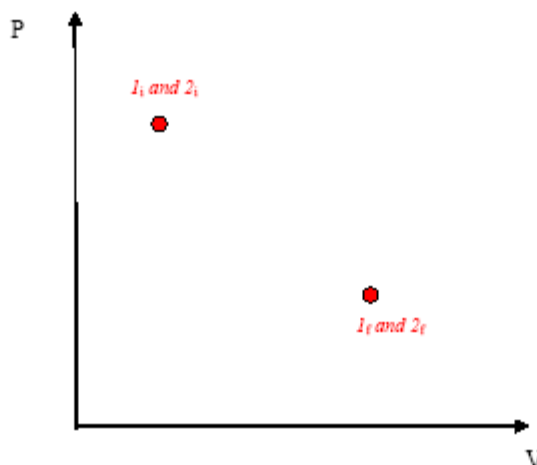
Note: Check that the final volumes of both processes are the same.

Is your diagram consistent with your answer to Questions 2.6, 2.7, and 2.8 on the previous page?

4. Which process has the greatest magnitude of heat transfer to the system? If the two are equal, indicate with an "=" symbol.

    $Q_1 > Q_2 = 0$

5. Is $S_{1(initial\ state)}$, the initial entropy of the system in Process #1, *greater than*, *equal to*, or *less than* $S_{2(initial\ state)}$, the initial entropy of the system in Process #2?

    Equal to; the two systems are in the same state initially, and since entropy is a state function they have the same entropy.

The change in the entropy of a system that begins in initial state i and ends in final state f can be expressed as $\Delta S = \dfrac{Q_{reversible}}{T}$. Here, $Q_{reversible}$ represents the heat transfer to the system *only* during a process from i to f that is reversible; the T in this equation is related to the average temperature of the system during the process.

6. Does the entropy of the system *increase*, *decrease*, or *remain the same* for Process #1?

    Increases; it is a reversible process so we can use the above equation. $Q_{to\ system}$ is positive and temperature is constant.

Is your answer to Question #6 consistent with $\Delta S = \dfrac{Q_{reversible}}{T}$? Explain.

3

Entropy State-Function Worksheet Solution (pg 4)

Entropy Worksheet

Do NOT continue until you check your answers with the recitation instructor.

7. Consider ΔS_2 and ΔS_1, the *changes* in the entropy of the system during Process #2 and Process #1, respectively; $\Delta S \equiv S_{(\text{final state})} - S_{(\text{initial state})}$. Three students are discussing whether ΔS_2 is *greater than*, *equal to*, or *less than* ΔS_1. Read through the discussion and follow the directions below.

Student A: *"I think that the entropy for Process #2 is going to stay the same. The system is thermally insulated so if there is no heat transfer to the system from the surroundings there is no change in the entropy of the system because $\Delta S = \dfrac{Q_{reversible}}{T}$."*

Student B: *"That makes sense from the ΔS equation we were given, but that is only correct for a reversible process. We must remember that entropy is a state function. Process #2 has the exact same final pressure, volume, and temperature as Process #1, so I think that the entropy in Process #2 will increase the same amount that entropy in Process #1 increases."*

Student C: *"I think you are on the right track, but Process #2 can't go back to its initial state like Process #1; that means that it's not reversible. So even though it has the same final state as Process #1, I think the change in entropy for Process #2 will be different from that in Process #1."*

Student B responds to Student C: *"I agree that #2 is irreversible, but we already determined that the initial entropy for both processes was the same in Question #5. The change in entropy is $\Delta S \equiv S_{(\text{final state})} - S_{(\text{initial state})}$, so if the initial AND final states of Process #2 and Process #1 are the same the change in entropy in Process #2 has to be the same as Process #1 regardless of whether it's reversible or irreversible."*

Re-read each student's statement and comment on the parts with which you agree, and identify the statements that you believe are incorrect. Explain your reasoning.

Discuss your reasoning and that of your group with the recitation instructor before continuing.

Student A's argument is incorrect because the free expansion is an irreversible process and so we can't calculate the change in entropy directly using the equation $\Delta S = \dfrac{Q_{reversible}}{T}$.

Student B is correct.

Student C claims that the irreversible process must have a greater entropy change than the reversible process; however, since the initial and final states are the same for both processes, this is not correct.

Student B is explicitly correct here.

Entropy State-Function Worksheet Solution (pg 5)

Entropy Worksheet

8. Is $\Delta S_{system\ 1}$, the change in entropy of the **system** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{system\ 2}$, the change in entropy of the system for Process #2? *Explain.*

    $\Delta S_{system\ 1} = \Delta S_{system\ 2}$; entropy is a state function and both the initial and final states are the same.

9. Is $\Delta S_{surroudings\ 1}$, the change in entropy of the **surroundings** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{surroundings\ 2}$, the change in entropy of the **surroundings** for Process #2? *Explain. Hint:* $Q_{system} = - Q_{surroundings}$

    $\Delta S_{surroundings\ 1} < \Delta S_{surroundings\ 2}$. There is no heat transfer to/from the surroundings, or <u>any</u> change in the surroundings, in Process #2 so $\Delta S_{surroundings\ 2} = 0$. In Process #1 the heat transfer to the surroundings is negative so $\Delta S_{surroundings\ 1} < 0$.

10. Using your answers from Questions 8 and 9, is the magnitude of $|\Delta S_{system\ 1}|$ *greater than, equal to,* or *less than* the magnitude of $|\Delta S_{surroundings\ 1}|$? *Hint:* $Q_{system} = - Q_{surroundings}$ & $\Delta S = \frac{Q_{reversible}}{T}$

    $|\Delta S_{system\ 1}| = |\Delta S_{surroundings\ 1}|$; the heat transfers are equal and opposite and the temperatures are the same.

11. Is $\Delta S_{universe\ 1}$, the change in entropy of the **universe** for Process #1, *greater than, equal to,* or *less than* $\Delta S_{universe\ 2}$, the change in entropy of the **universe** for Process #2? Explain your answers. (Note that $\Delta S_{universe} \equiv \Delta S_{system} + \Delta S_{surroundings}$)

    $\Delta S_{universe\ 2} > \Delta S_{universe\ 1} = 0$. In #10 we found ΔS for system and surroundings to be equal and opposite so the net change in the entropy of the universe is zero for Process #1, while Process #2 had a net increase.

12. Use the results from the worksheet to fill out the Table below

	Process #1	Process #2
Reversible or Irreversible?	*Reversible*	*Irreversible*
$Q_{to\ system} > 0$, $Q_{to\ system} < 0$, or $Q_{to\ system} = 0$?	*$Q_{to\ system} > 0$*	*$Q_{to\ system} = 0$*
$\Delta S_{system} > 0$, $\Delta S_{system} < 0$, or $\Delta S_{system} = 0$?	*$\Delta S_{system} > 0$*	*$\Delta S_{system} > 0$*
$Q_{to\ surr} > 0$, $Q_{to\ surr} < 0$, or $Q_{to\ surr} = 0$?	*$Q_{to\ surr} < 0$*	*$Q_{to\ surr} = 0$*
$\Delta S_{surr} > 0$, $\Delta S_{surr} < 0$, or $\Delta S_{surr} = 0$?	*$\Delta S_{surr} < 0$*	*$\Delta S_{surr} = 0$*
$\Delta S_{universe} > 0$, $\Delta S_{universe} < 0$, or $\Delta S_{universe} = 0$?	*$\Delta S_{universe} = 0$*	*$\Delta S_{universe} > 0$*

In any real (or irreversible) process, does the entropy of the **universe** *increase, decrease, remain the same,* or is this *not determinable* without additional information?
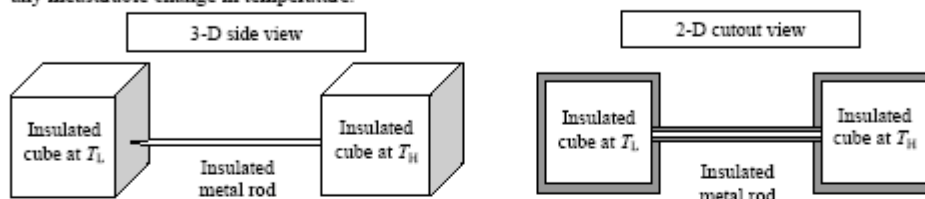
Increase, according to the second law of thermodynamics.

5

Appendix 2.5 Entropy Spontaneous-Process Worksheet

Entropy Tutorial – Phys 224, March 10, 2006

I. Energy Reservoir

A metal cube, one meter on each side, is enclosed in a thermally insulating jacket. Another metal cube of the same size is enclosed in its own insulating jacket. The temperature of this second cube is higher than the temperature of the first cube. We'll refer to the high-temperature cube as "H," and the other as "L," and their temperatures as T_H and T_L, respectively. The only connection between the cubes is through a narrow metal rod that has a very small mass. Heat transfer to or from the cubes can take place only through this narrow metal rod. We will assume that when heat transfer does take place, the rate of energy change is so small that neither of the metal cubes undergoes any measurable change in temperature.

Is it reasonable to assume the temperature of the two cubes will remain constant?
A quantitative argument: Suppose we have two different copper blocks each with volume of 1 m³; assume that the temperature difference between the blocks is 50 K and that they are connected by a copper rod 20 cm long, with diameter 1 cm. There would be 8 joules of energy transferred each second through heat conduction. However, given the mass of the blocks (each weighs roughly 10 tons), it would take almost 12 days before the temperature of the blocks changed even by *one* kelvin.

Definition: The term used for a system so massive that it does not change temperature even when heat transfer takes place is "energy reservoir" or "thermal reservoir."

Does the high-temperature cube fit the definition of an energy reservoir? Why or why not?

Does the low-temperature cube fit the definition? Why or why not?

The following questions refer to the process that takes place when the cubes are connected by the metal rod; consider a process with duration of one minute.

II. What do you expect will happen? *(These questions are meant to get you thinking about the problem, don't be concerned if you are unsure of your answers.)*

a) Consider the system consisting *only* of the low-temperature cube. While the two cubes are connected with the rod, does the entropy of this system *increase, decrease,* or *remain the same?*

b) During the same process, does the total entropy of the high- and low-temperature cubes <u>together</u> *increase, decrease,* or *remain the same?* Explain your reasoning.

c) State whether the following quantities are conserved during this process: (i) energy; (ii) entropy.

→ On the diagram above, draw an arrow to indicate the direction of *positive* heat transfer.

1

Entropy Spontaneous-Process Worksheet (pg 2)

Entropy Tutorial – Phys 224, March 10, 2006

III. Heat transfer and entropy

1. During a process with duration of one minute, consider Q_H and Q_L, the heat transfers *to* the high-temperature and low-temperature cubes, respectively.

    a) Is Q_H, the heat transfer *to* the high-temperature cube, *positive*, *negative*, or *zero*?

    b) Is Q_L, the heat transfer *to* the low-temperature cube, *positive*, *negative*, or *zero*?

    c) Compare the magnitudes (absolute values) of Q_H and Q_L; is one larger than the other? If so, which one?

    d) Is the sum $[Q_H + Q_L]$ positive, negative, or zero?

    e) For this process, is energy a conserved quantity? Explain.

The entropy change in a reversible process is given by $\Delta S = \int_{initial}^{final} \frac{dQ_{reversible}}{T}$. For any process involving heat transfer to an energy reservoir at constant temperature T, this expression can be rewritten as $\Delta S_{reservoir} = \frac{Q_{to\ reservoir}}{T_{reservoir}}$, where $Q_{to\ reservoir}$ is the heat transfer to the reservoir during the process and $T_{reservoir}$ is the temperature of the reservoir.

2. During the heat transfer process, consider ΔS_H and ΔS_L, the change in entropy of the high-temperature cube and low-temperature cube, respectively.

    a) Is ΔS_H, the change in entropy of the high-temperature cube, *positive*, *negative*, or *zero*?

        Does this mean the entropy of the high-temperature cube *increases*, *decreases*, or *remains the same*?

    b) Is ΔS_L, the change in entropy of the low-temperature cube, *positive*, *negative*, or *zero*?

        Does this mean the entropy of the low-temperature cube *increases*, *decreases*, or *remains the same*?

    c) Consider the magnitudes (absolute values) of ΔS_H and ΔS_L. Is the absolute value of one larger than the other? If so, which one? Explain.

    d) If we consider the actual values, is the sum $[\Delta S_H + \Delta S_L]$ *positive*, *negative*, or *zero*?

    e) For this process, is entropy a conserved quantity? Justify your answer. Explain any differences between this answer and your answer to 1(e) above.

Entropy Spontaneous-Process Worksheet (pg 3)

Entropy Tutorial

IV. Outside the Insulation…

3. In Question #2, we determined the change in entropy of everything inside the insulating jackets, (i.e. the cubes). We must now consider the change in entropy of *everything else* apart from the cubes and the rod.

If you were to physically describe "everything else," what are some things that would be considered to be part of "everything else?" Discuss this with your group (and don't be afraid to think big).

 a) If we assume the jackets that surround the cubes and the rod are perfectly insulating, is there any heat transfer to the outside world from the metal cubes or rod? Why or why not?

 b) Calculate the change in entropy of everything outside the insulation due to heat transfer from the metal cubes and rod. $\Delta S_{EVERYTHING\ ELSE}$ = _____

 c) Based on your answer to (b), does the entropy of everything else due to heat transfer from the cubes and rod *increase, decrease* or *remain the same*?

V. System and surroundings

4. For now, let us refer to the high-temperature cube *alone* as the thermodynamic "system." We will define "surroundings" (same as "surrounding environment") as *everything that is <u>not</u> the system*.

 a) If we define the high-temperature cube as the system, describe what would be considered the "surroundings." Would the surroundings include the low-temperature cube? *Hint:* What criteria are we using to determine whether or not something should be considered as part of the surroundings?

 b) With this definition of system and surroundings, and considering the same one-minute time interval,

 i) does the entropy of the system *increase, decrease,* or *remain the same*?

 ii) does the entropy of the surroundings *increase, decrease,* or *remain the same*?

 Be sure to explicitly address the change in entropy of everything that is <u>not</u> the system.

3

Entropy Spontaneous-Process Worksheet (pg 4)

Entropy Tutorial

V. System and surroundings (cont.)

5. Now, let us refer to the *low*-temperature cube alone as the "system."

   a) Using our previously stated definition, describe what would be considered the "surroundings," or "surrounding environment." Would the surroundings include the high-temperature cube?

   b) With this new definition of system and surroundings,

      i) does the entropy of the system *increase, decrease,* or *remain the same*?

      ii) does the entropy of the surroundings *increase, decrease,* or *remain the same*?

6. Given our definition of system and surroundings in Question #4, can one determine the sign of entropy change of the [system + surroundings]? If no, why not? Answer the same question for the case of Question #5.

   If you can determine the sign in both cases, is the sign the same in both, or different? Explain.

   Summarize the results from Question #4 and Question #5 in the following table.

	Question #4	Question #5
System consists of…		
Surroundings consist of…		
Entropy of system *increases, decreases,* or *remains the same*?		
Entropy of surroundings *increases, decreases,* or *remains the same*?		
Entropy of system + surroundings *increases, decreases,* or *remains the same*?		

Discuss the results with your group. What can you say about the entropy of the system + surroundings for these two processes?

4

Entropy Spontaneous-Process Worksheet (pg 5)

Entropy Tutorial

V. System and surroundings (cont.)

7. You overhear a group of students discussing the above problem. Carefully read what each student is saying.

> *Student A:* Well, the second law says that the entropy of the system is always increasing. Entropy always increases no matter what.

> *Student B:* But how do you know which one is the system? Couldn't we just pick whatever we want to be the system and count everything else as the surroundings?

> *Student C:* I don't think it matters which we call the system or the surroundings, and because of that we can't say that the system always increases. The second law states that the entropy of the system plus the surroundings will always increase.

Analyze each statement and discuss with your group the extent to which it is correct or incorrect. How do the students' ideas compare with your own discussion about the table on the previous page?

8. For both Questions #4 and #5, we made a specific designation for the "system" and considered the "surroundings" to include *everything* that was <u>not</u> the system.

> a) If we wanted to describe the "system," and the "surroundings" with one word—where surroundings refers to everything outside the system—what word could we use?
> *Hint:* Remember to think big!
>
> Write this word in the box in part (c) below.

> b) Review your answers from Question #6: did you determine that the S_{system} + $S_{surroundings}$ *increases*, *decreases*, or *remains the same*, for the case in Question #4? What about for the case in Question #5?
>
> Would these answers change whether or not we included objects outside the insulation in "the surroundings?" Why or why not?

> c) Complete this sentence: During any real process, the entropy of the [ ]
> ...increases. ...decreases. ...remains the same.

Entropy Spontaneous-Process Worksheet (pg 6)

Entropy Tutorial

VI. Heat flow from low to high?

9. Suppose for a moment that heat transfer occurred spontaneously from low-temperature objects to high-temperature objects; draw an arrow to indicate the direction of *positive* heat transfer in this case.
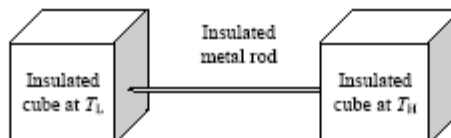
a) Could such a situation actually occur "spontaneously" (that is, without any outside intervention)?

If it did occur, how would it affect your answers to Question #2? Explain in detail for each part a-d.

b) In real processes where high- and low-temperature objects are in thermal contact, is there ever actually *zero* heat transfer?

Suppose heat transfer between the high- and low-temperature cubes *were* zero; how would that affect your answers to Question 2?
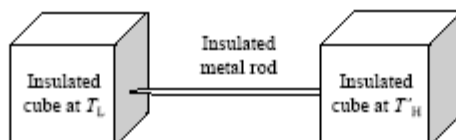
c) Based on your answers to (a) and (b), can you make any specific statements regarding the change in $[S_{system} + S_{surroundings}]$ that could occur in any *real* process? (For example, could that total change be negative or zero?) Explain.

6

Entropy Spontaneous-Process Worksheet (pg 7)

Entropy Tutorial

VII. Reversible Processes

10. Let's now consider a situation that is similar to our original problem. The temperature of the L cube is the same as it was before, but the temperature of the H cube is *lower* than its previous value and is designated by T'_H. Although the H cube now has a lower temperature, it is still higher than that of the L cube.

We'll designate the heat transfers to the high- and low-temperature cubes in this case as Q'_H and Q'_L, respectively. Consider that the heat transfer process, that originally lasted one minute, now lasts sufficiently long to ensure that the heat transfer to the higher-temperature cube is exactly the same as it was before, that is, $Q'_H = Q_H$.

  a) Is Q'_L, *greater than, less than,* or *equal to* Q_L?

  b) Consider the magnitudes (absolute values) of the entropy changes in the high-temperature cube, $|\Delta S'_H|$, and the low temperature cube, $|\Delta S'_L|$, and compare them to the values in the original case $|\Delta S_H|$ and $|\Delta S_L|$ (see Question #2):

  i) is $|\Delta S'_H|$ *greater than, less than,* or *equal to* $|\Delta S_H|$?

  ii) is $|\Delta S'_L|$ *greater than, less than,* or *equal to* $|\Delta S_L|$?

  c) Is the total entropy change in this present case $[\Delta S'_H + \Delta S'_L]$ *greater than, less than,* or *equal to* the total entropy change in the original case $[\Delta S_H + \Delta S_L]$ (when the temperature difference between the cubes was larger)?

7

Entropy Spontaneous-Process Worksheet (pg 8)

Entropy Tutorial

VII. Reversible Processes (Cont.)

Suppose the temperature of the L cube remains the same, and the H cube drops to a temperature that is still higher, but infinitesimally close to the temperature of the L cube.

   d) For this case, what will happen to the *total entropy change* of the two cubes during the process, assuming that the heat transfers continue to remain the same as before? What can you say about the time required for this new process, compared to those before?

   e) As the temperatures of the cubes come closer together, what happens to the total entropy change of the universe, compared to that in the previous cases?

   f) In *reversible* heat transfer processes, all temperature differences are infinitesimally small (and there is no frictional dissipation). Such processes are idealizations of real processes; no real process is completely reversible.

      i) Based on your answers to the questions above, what would be the entropy change of the universe in a completely reversible process?

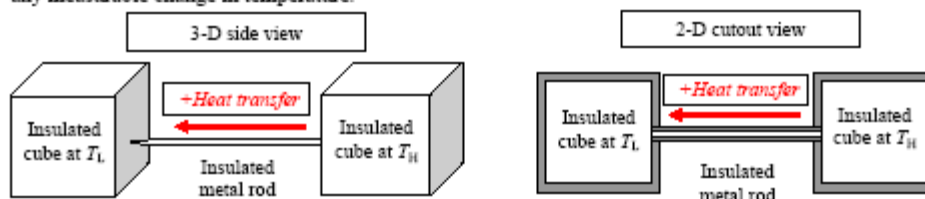   ii) Could this be the entropy change of any real process? Why or why not?

Check that your answer is consistent with your statements in Question #9, part c.

Appendix 2.6 Entropy Spontaneous-Process Worksheet Solution

Entropy Tutorial – Phys 224, March 10, 2006

I. Energy Reservoir

A metal cube, one meter on each side, is enclosed in a thermally insulating jacket. Another metal cube of the same size is enclosed in its own insulating jacket. The temperature of this second cube is higher than the temperature of the first cube. We'll refer to the high-temperature cube as "H," and the other as "L," and their temperatures as T_H and T_L, respectively. The only connection between the cubes is through a narrow metal rod that has a very small mass. Heat transfer to or from the cubes can take place only through this narrow metal rod. We will assume that when heat transfer does take place, the rate of energy change is so small that neither of the metal cubes undergoes any measurable change in temperature.

Is it reasonable to assume the temperature of the two cubes will remain constant?
A quantitative argument: Suppose we have two different copper blocks each with volume of 1 m³; assume that the temperature difference between the blocks is 50 K and that they are connected by a copper rod 20 cm long, with diameter 1 cm. There would be 8 joules of energy transferred each second through heat conduction. However, given the mass of the blocks (each weighs roughly 10 tons), it would take almost 12 days before the temperature of the blocks changed even by *one* kelvin.

Definition: The term used for a system so massive that it does not change temperature even when heat transfer takes place is "energy reservoir" or "thermal reservoir."

Does the high-temperature cube fit the definition of an energy reservoir? Why or why not?

Yes, there is energy transfer that takes place, but the temperature (essentially) does not change.

Does the low-temperature cube fit the definition? Why or why not?

Yes, similarly, there is energy transfer that takes place, but the temperature (essentially) does not change.

The following questions refer to the process that takes place when the cubes are connected by the metal rod; consider a process with duration of one minute.

II. What do you expect will happen? *(These questions are meant to get you thinking about the problem, don't be concerned if you are unsure of your answers.)*

a) Consider the system consisting *only* of the low-temperature cube. While the two cubes are connected with the rod, does the entropy of this system *increase, decrease,* or *remain the same*?

These questions are answered later in the tutorial.

b) During the same process, does the total entropy of the high- and low-temperature cubes together *increase, decrease,* or *remain the same*? Explain your reasoning.

c) State whether the following quantities are conserved during this process: (i) energy; (ii) entropy.

→ On the diagram above, draw an arrow to indicate the direction of *positive* heat transfer.

1

Entropy Spontaneous-Process Worksheet Solution (pg 2)

Entropy Tutorial – Phys 224, March 10, 2006

III. Heat transfer and entropy

1. During a process with duration of one minute, consider Q_H and Q_L, the heat transfers *to* the high-temperature and low-temperature cubes, respectively.

    a) Is Q_H, the heat transfer *to* the high-temperature cube, *positive*, *negative*, or *zero*?

Negative, there is positive heat transfer to the low-temp cube.

    b) Is Q_L, the heat transfer *to* the low-temperature cube, *positive*, *negative*, or *zero*?

Positive, heat flows from high- to low-temperature.

    c) Compare the magnitudes (absolute values) of Q_H and Q_L; is one larger than the other? If so, which one?

They have equal magnitudes. We know this because energy is conserved during the process.

    d) Is the sum $[Q_H + Q_L]$ positive, negative, or zero?

The sum is zero, because the two values are equal in magnitude (1d) but have opposite signs (1a, 1b).

    e) For this process, is energy a conserved quantity? Explain.

Yes, the cubes and the rod are insulated, and energy is not transferred in any way.

The entropy change in a reversible process is given by $\Delta S = \int_{initial}^{final} \dfrac{dQ_{reversible}}{T}$. For any process involving heat transfer to an energy reservoir at constant temperature T, this expression can be rewritten as $\Delta S_{reservoir} = \dfrac{Q_{to\ reservoir}}{T_{reservoir}}$, where $Q_{to\ reservoir}$ is the heat transfer to the reservoir during the process and $T_{reservoir}$ is the temperature of the reservoir.

2. During the heat transfer process, consider ΔS_H and ΔS_L, the change in entropy of the high-temperature cube and low-temperature cube, respectively.

    a) Is ΔS_H, the change in entropy of the high-temperature cube, *positive*, *negative*, or *zero*?

Negative. Heat transfer to the high-temperature block is negative, and temperature is positive.

        Does this mean the entropy of the high-temperature cube *increases*, *decreases*, or *remains the same*?

Decreases. A negative change in a quantity means that the final value is less than the initial value.

    b) Is ΔS_L, the change in entropy of the low-temperature cube, *positive*, *negative*, or *zero*?

Positive. Heat transfer to the low-temperature block is positive, and temperature is positive.

        Does this mean the entropy of the low-temperature cube *increases*, *decreases*, or *remains the same*?

Increases. A positive change in a quantity means that the final value is greater than the initial value.

    c) Consider the magnitudes (absolute values) of ΔS_H and ΔS_L. Is the absolute value of one larger than the other? If so, which one? Explain.

$\Delta S_H = \dfrac{Q_H}{T_H}$ $\Delta S_L = \dfrac{Q_L}{T_L}$; *The heat transfers are equal in magnitude (1c), but the temperature of the low-temperature reservoir is less than the high-temperature reservoir. Thus the magnitude of ΔS_H is less than ΔS_L.*

    d) If we consider the actual values, is the sum $[\Delta S_H + \Delta S_L]$ *positive*, *negative*, or *zero*?

ΔS_H is less than ΔS_L, and ΔS_H is negative, ΔS_L is positive, therefore the sum is positive.

    e) For this process, is entropy a conserved quantity? Justify your answer. Explain any differences between this answer and your answer to 1(e) above.

No, there is more entropy after the process is complete than there was when it started.

Entropy Spontaneous-Process Worksheet Solution (pg 3)

Entropy Tutorial – Phys 224, March 10, 2006

IV. Outside the Insulation…

3. In Question #2, we determined the change in entropy of everything inside the insulating jackets, (i.e. the cubes). We must now consider the change in entropy of *everything else* apart from the cubes and the rod.

If you were to physically describe "everything else," what are some things that would be considered to be part of "everything else?" Discuss this with your group (and don't be afraid to think big).

   a) If we assume the jackets that surround the cubes and the rod are perfectly insulating, is there any heat transfer to the outside world from the metal cubes or rod? Why or why not?

   No, assuming perfect insulation, there can be no heat transfer through the insulation.

   b) Calculate the change in entropy of everything outside the insulation due to heat transfer from the metal cubes and rod. $\Delta S_{\text{EVERYTHING ELSE}} = $ _____

   There may be other processes occurring outside the insulation, but the change in entropy of everything else due to the heat transfer between the cubes is zero.

   c) Based on your answer to (b), does the entropy of everything else due to heat transfer from the cubes and rod *increase, decrease* or *remain the same*?

   It remains the same. If there is no change then the quantity stays the same.

V. System and surroundings

4. For now, let us refer to the high-temperature cube *alone* as the thermodynamic "system." We will define "surroundings" (same as "surrounding environment") as *everything that is not the system*.

   a) If we define the high-temperature cube as the system, describe what would be considered the "surroundings." Would the surroundings include the low-temperature cube? *Hint:* What criteria are we using to determine whether or not something should be considered as part of the surroundings?

   The low-temperature cube, the rod, the insulation, and everything outside the insulation; everything in the universe that isn't the high-temperature cube is considered the surroundings.

   b) With this definition of system and surroundings, and considering the same one-minute time interval,

      i) does the entropy of the system *increase, decrease,* or *remain the same*?

   The system is defined as the high-temperature cube, which we calculated to be decreasing in entropy; therefore, the entropy of the system is decreasing in this case.

      ii) does the entropy of the surroundings *increase, decrease,* or *remain the same*?

   The system is defined as everything that isn't the high-temperature cube. There is no heat transferred to anything in the surroundings except the low-temperature reservoir. It has an increase in entropy, while everything else in the surroundings has no change in entropy. Therefore, the entropy of the surroundings increases.

   Be sure to explicitly address the change in entropy of everything that is not the system.

3

Entropy Spontaneous-Process Worksheet Solution (pg 4)

Entropy Tutorial – Phys 224, March 10, 2006

V. System and surroundings (cont.)

5. Now, let us refer to the *low*-temperature cube alone as the "system."

a) Using our previously stated definition, describe what would be considered the "surroundings," or "surrounding environment." Would the surroundings include the high-temperature cube?

> *The high-temperature cube, the rod, the insulation, and everything outside the insulation; everything in the universe that isn't the low-temperature cube is considered the surroundings.*

b) With this new definition of system and surroundings,

i) does the entropy of the system *increase*, *decrease*, or *remain the same*?

> *The system is defined as the low-temperature cube, which we previously calculated to be increasing in entropy; therefore, the entropy of the system is increasing in this case.*

ii) does the entropy of the surroundings *increase*, *decrease*, or *remain the same*?

> *The system is defined as everything that isn't the low-temperature cube. There is no heat transferred to anything in the surroundings except[away from] the high-temperature reservoir. It has a decrease in entropy, while everything else in the surroundings has no change in entropy. Therefore, the entropy of the surroundings decreases.*

6. Given our definition of system and surroundings in Question #4, can one determine the sign of entropy change of the [system + surroundings]? If no, why not? Answer the same question for the case of Question #5.

> *Yes, we can determine the sign of the change in entropy of the system plus surroundings in both cases. We can use our previous calculations about the change in entropy of the high- and low-temperature cubes.*

If you can determine the sign in both cases, is the sign the same in both, or different? Explain.

> *They would be the same sign, since in both Questions 4 and 5, you are adding the same values.*

Summarize the results from Question #4 and Question #5 in the following table.

	Question #4	Question #5
System consists of…	*High-temperature cube*	*Low-temperature cube*
Surroundings consist of…	*Low-temperature cube, rod, insulation, everything outside*	*High-temperature cube, rod, insulation, everything outside*
Entropy of system *increases, decreases,* or *remains the same*?	*Decreases*	*Increases*
Entropy of surroundings *increases, decreases,* or *remains the same*?	*Increases*	*Decreases*
Entropy of system + surroundings *increases, decreases,* or *remains the same*?	*Increases*	*Increases*

Discuss the results with your group. What can you say about the entropy of the system + surroundings for these two processes?

4

Entropy Spontaneous-Process Worksheet Solution (pg 5)

Entropy Tutorial – Phys 224, March 10, 2006

V. System and surroundings (cont.)

7. You overhear a group of students discussing the above problem. Carefully read what each student is saying.

> *Student A:* Well, the second law says that the entropy of the system is always increasing. Entropy always increases no matter what.

> *Student B:* But how do you know which one is the system? Couldn't we just pick whatever we want to be the system and count everything else as the surroundings?

> *Student C:* I don't think it matters which we call the system or the surroundings, and because of that we can't say that the system always increases. The second law states that the entropy of the system plus the surroundings will always increase.

Analyze each statement and discuss with your group the extent to which it is correct or incorrect. How do the students' ideas compare with your own discussion about the table on the previous page?

Student A is being careless with the language here. The entropy of the system + surroundings must increase, but the system entropy by itself is not constrained to increase. Entropy does not always increase, it can decrease locally. Student B is correct in addressing the designation of a system and what consists of the surroundings. Student C's statement is correct.

8. For both Questions #4 and #5, we made a specific designation for the "system" and considered the "surroundings" to include *everything* that was not the system.

> a) If we wanted to describe the "system," and the "surroundings" with one word—where surroundings refers to everything outside the system—what word could we use?
> *Hint:* Remember to think big!

UNIVERSE

> Write this word in the box in part (c) below.

> b) Review your answers from Question #6: did you determine that the $S_{system} + S_{surroundings}$ *increases*, *decreases*, or *remains the same*, for the case in Question #4? What about for the case in Question #5?

Increases for both

> Would these answers change whether or not we included objects outside the insulation in "the surroundings?" Why or why not?

No, as mentioned in Question 3b the entropy of "everything else" does not change due to the process.

> c) Complete this sentence: During any real process, the entropy of the | *UNIVERSE* |
> …increases. …decreases. …remains the same.

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Entropy Spontaneous-Process Worksheet Solution (pg 6)

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VI. Heat flow from low to high?

9. Suppose for a moment that heat transfer occurred spontaneously from low-temperature objects to high-temperature objects; draw an arrow to indicate the direction of *positive* heat transfer in this case.
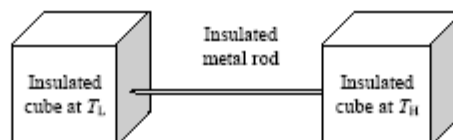
a) Could such a situation actually occur "spontaneously" (that is, without any outside intervention)?

No, heat only transfers from high to low temperatures unless there is some influence (e.g., work) by an outside system.

If it did occur, how would it affect your answers to Question #2? Explain in detail for each part a-d.

The values for the change in entropy of the high-temperature cube and low-temperature cube would change sign, but the magnitudes are the same. Therefore the net change in entropy is negative.

b) In real processes where high- and low-temperature objects are in thermal contact, is there ever actually *zero* heat transfer?

No, heat transfer will be positive flowing from the high-temperature object to the low-temperature object.

Suppose heat transfer between the high- and low-temperature cubes *were* zero; how would that affect your answers to Question 2?

If the heat transfer between the two cubes was zero, then the net change in entropy would equal zero.

c) Based on your answers to (a) and (b), can you make any specific statements regarding the change in $[S_{system} + S_{surroundings}]$ that could occur in any *real* process? (For example, could that total change be negative or zero?) Explain.
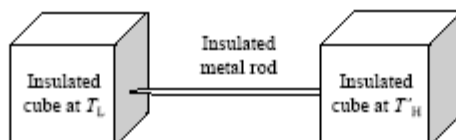
For any real process the entropy of the system plus the entropy of the surroundings (the net entropy) must increase.

Entropy Spontaneous-Process Worksheet Solution (pg 7)

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VII. Reversible Processes

10. Let's now consider a situation that is similar to our original problem. The temperature of the L cube is the same as it was before, but the temperature of the H cube is *lower* than its previous value and is designated by T'_H. Although the H cube now has a lower temperature, it is still higher than that of the L cube.

We'll designate the heat transfers to the high- and low-temperature cubes in this case as Q'_H and Q'_L, respectively. Consider that the heat transfer process, that originally lasted one minute, now lasts sufficiently long to ensure that the heat transfer to the higher-temperature cube is exactly the same as it was before, that is, $Q'_H = Q_H$.

a) Is Q'_L, *greater than, less than,* or *equal to* Q_L?

Q'_L is equal to Q_L since the heat transfer is equal in magnitude to the previous case.

b) Consider the magnitudes (absolute values) of the entropy changes in the high-temperature cube, $|\Delta S'_H|$, and the low temperature cube, $|\Delta S'_L|$, and compare them to the values in the original case $|\Delta S_H|$ and $|\Delta S_L|$ (see Question #2):

i) is $|\Delta S'_H|$ *greater than, less than,* or *equal to* $|\Delta S_H|$?

$|\Delta S'_H|$ is greater than $|\Delta S_H|$ because the heat transfer is the same, but the temperature is lower than in the original case.

ii) is $|\Delta S'_L|$ *greater than, less than,* or *equal to* $|\Delta S_L|$?

$|\Delta S'_L|$ is equal to $|\Delta S_L|$ because the heat transfer is the same, and the temperature is the same as in the original case.

c) Is the total entropy change in this present case $[\Delta S'_H + \Delta S'_L]$ *greater than, less than,* or *equal to* the total entropy change in the original case $[\Delta S_H + \Delta S_L]$ (when the temperature difference between the cubes was larger)?

The total entropy change is less than the original case, since the magnitude of the positive number is the same, and the magnitude of the negative number is greater, so the sum is still positive, but less than in the original case.

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Entropy Spontaneous-Process Worksheet Solution (pg 8)

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VII. Reversible Processes (Cont.)

Suppose the temperature of the L cube remains the same, and the H cube drops to a temperature that is still higher, but infinitesimally close to the temperature of the L cube.

    d) For this case, what will happen to the *total entropy change* of the two cubes during the process, assuming that the heat transfers continue to remain the same as before? What can you say about the time required for this new process, compared to those before?

The total entropy change will be an infinitesimally small positive value, essentially zero. This process will take an infinite amount of time to allow the same amount of heat transfer between the blocks.

    e) As the temperatures of the cubes come closer together, what happens to the total entropy change of the universe, compared to that in the previous cases?

The total entropy change of the universe is essentially zero.

    f) In *reversible* heat transfer processes, all temperature differences are infinitesimally small (and there is no frictional dissipation). Such processes are idealizations of real processes; no real process is completely reversible.

        i) Based on your answers to the questions above, what would be the entropy change of the universe in a completely reversible process?

For a completely reversible process, the entropy change would be equal to zero.

        ii) Could this be the entropy change of any real process? Why or why not?

No, because in any real heat-transfer process the temperature change can not be equal to zero; therefore the entropy change for any real process is greater than zero, and no real process can be completely reversible.

Check that your answer is consistent with your statements in Question #9, part c.

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