They Still Remember What I Never Taught Them: Student Understanding of Entropy

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Abstract. As part of an ongoing project to examine student learning in upper-division courses in thermal and statistical physics, we have examined student reasoning about the approach of macroscopic objects to thermal equilibrium. We have examined reasoning in terms of heat transfer, entropy maximization, and statistical treatments of multiplicity and probability. In the current paper, we present student responses from a set of interviews completed 1-2 years after students had completed the thermal physics course. Students gave a variety of responses, but most students gave answers that did not correspond to the models that they had been taught in the course.

Keywords: research, student understanding, thermodynamics, statistical physics, upper division, entropy.
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INTRODUCTION

This research is part of a broader and ongoing project to investigate student learning and develop curricular materials for upper-division courses in thermal physics. Entropy is a fundamental concept in the physical sciences and a core idea of thermodynamics and statistical physics. We have investigated student learning of entropy and developed and tested curricular materials on entropy, engines, and the second law of thermodynamics.

BACKGROUND AND CONTEXT

Previous research suggests that entropy and the second law of thermodynamics are challenging concepts for students [1, 2, 3, 4]. Non-research based critiques have questioned the notion of entropy as a 'measure of disorder' as imprecise and potentially misleading [5, 6]. In recent years, a revised instructional approach, often described as 'thermal physics' in contrast to thermodynamics or statistical physics, builds the second law of thermodynamics as a consequence of the statistical behavior of matter [7, 8].

The current study proceeds from the assumption that students construct understanding of scientific phenomena, in some cases developing ideas that are in contrast with accepted scientific viewpoints. Broadly speaking, the work arises from a theoretical framework that might be described as investigating student difficulties [9]. However, student responses frequently did not suggest stable conceptual difficulties, suggesting the need for a knowledge in pieces perspective [10].

Context for Research

This work has taken place in the context of an upper-division thermal physics course at California State University Fullerton, a large public comprehensive university serving a diverse student population. This course is required for physics majors and follows the 'thermal physics' approach using a popular recent text [8]. It meets for two 75-minute blocks per week. The author has taught the course 12 times, with enrollments between 6 and 19, and typically spends a significant portion of class time on small-group tutorial exercises [11, 12].

Research Methods

We have sought to document student understanding of the target ideas using written conceptual questions and student interviews. In this portion of the study, we describe student responses from a set of interviews. We chose to study the responses of students a year or more after completion of the thermal physics course to probe the longer-term effects of the instructional approach and determine whether students would apply the statistical construct of entropy.

We interviewed individual volunteers, most of whom had completed the course 1-2 years prior to the interview. Students were compensated with a gift card. The sample of students was ethnically diverse and included 4 males and 4 females. All were physics majors, though several had a second major or minor in another discipline. The student grades in the course were 1 A, 3 B, 4 C. In quotes below, students are identified with pseudonyms.

In the interviews, students were given a sheet of written questions and asked to answer the questions while thinking aloud. The interviewer followed a protocol that included explicit follow-up questions asked of all students but provided latitude to probe student responses further.

The first set of tasks involved pairs of blocks (see Figure 1.) Students were given the temperatures of blocks in the initial and final states and asked to identify which of the situations were physically possible and explain why. The situations included only one physically possible process (part E in Figure 1). Others violated either the first or second law of thermodynamics: one did not conserve energy, one diverged from equilibrium (A), and one passed the equilibrium temperature (B). The interviewer prompted the students to give explanations but for the most part did not probe these explanations immediately. After students had explained their responses, they were directed to the back of the sheet, which included the 'general-context' problem from Christensen 2009 [3] shown in Figure 2.

After the students had answered the general context question, they were redirected to the front page, and the interviewer asked explicitly whether the students had thought about energy, entropy, and multiplicity / probability, and how those concepts would apply to the problems.

For each part below, two identical blocks are placed in thermal contact and isolated from the rest of the universe. The initial temperatures of the two blocks and proposed final temperatures are shown. For each pair of states, state whether the transition between initial and final states is possible, and explain why or why not.

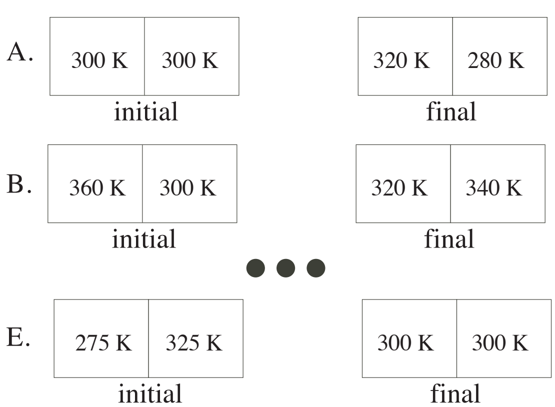

FIGURE 1. Pairs of blocks for interview task. Parts C and D are omitted for the sake of space, but included one situation that did not conserve energy and one that did not reach equilibrium.

For each of the following questions consider a system undergoing a naturally occurring ("s-pontaneous") process. The system can exchange energy with its surroundings.

a. During this process, does the entropy of the system [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 surroundings [$S_{surroundings}$] 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 2. Second page of the interview prompt, adopted from Christensen et al, 2009 [3]. A correct response is that the sum in part c increases, but that the changes for the system and surroundings could be of any sign.

STUDENT RESPONSES

After the interviews, student responses were transcribed and categorized by the interviewer. The analysis is ongoing, but several trends have emerged. The quotes below illustrate response patterns.

One of the more consistent results was that students used ideas that were not the ones they were taught. In the course, students were first taught statistical methods and the definition of entropy $k_B \ln \Omega$. They later covered a macroscopic treatment of entropy in terms of $dS \geq dQ/T$ and applied it to situations like those in Figure 1. However, these ideas were not invoked consistently in the responses to either part of the interview. Rather, student responses tended to rely upon several simpler ideas, including some that were not taught as part of the course.

Students used fairly simple reasoning in justifying their initial predictions for the block problems, which can be answered without reference to the second law of thermodynamics. Students noted that the blocks were identical, and stated that the final temperature would be halfway between the two initial temperatures. When prompted to reconsider the block problems, only two of the students used statistical interpretations as opposed to macroscopic entropy, despite the course emphasis on statistics. Student responses to follow up probing led to more involved discussion of entropy and student quotes below are drawn from responses to these later questions.

Conservation of Entropy

As has been reported in previous studies [3], several student responses were consistent with the idea that entropy is a conserved quantity. In some cases, students explicitly related entropy to energy. Pericles [pseudonym] stated that 'entropy is a form of energy' and went on to suggest that it was another one of the thermodynamic potentials (*F, G, H*) that are taught in the course. Another student was particularly explicit in making the connection to energy and invoking conservation:

> Calliope: You can't just, entropy … I can't really remember, but I want to say, it's like energy, like you can't create it or destroy it, it can't just come out of nowhere. […] Things have to be conserved. That's like the main thing they teach us, since like middle school or high school. Like, things just don't appear out of nowhere, they have to come from somewhere.

Equilibrium associated with order

Authors have criticized teaching entropy as a measure of disorder but research on the question is limited. Kesidou and Duit note that students use this notion readily but they claim that students have insufficient particulate understanding to fully understand it [1]. Bucy reinforces this conclusion and notes that students use the term in disparate ways [4]. Viard [13] reports students using disorder to make incorrect predictions for an adiabatic expansion.

In our study, there was evidence to suggest a previously unreported association with entropy. Four of the eight students in this sample gave responses suggesting an association of the equilibrium state of a system with greater *order* rather than disorder, and in some cases greater entropy.

One student seemed to reject the relationship of entropy to disorder based on the notion that an equilibrium state seemed more orderly:

> Jason: I think the system has to be increasing in entropy. The way I think about entropy is more the statistical sense, we always talked about a measure of disorder, but that's sort of inaccurate. It's more like it's more *orderly* in the sense that everything's fitting into its corresponding slot. Like the energy's being dispersed more evenly, and that would yield an increase in entropy.

He went on to confirm that he intended to say that the equilibrium state would be more 'orderly'

> Jason: I feel like it would be more orderly, if anything. And not just because you said that! Because, it feels like everything's moving to the most likely position because, that's just how it is.

This student seemed to have integrated this notion into a relatively correct understanding by rejecting the association of entropy with disorder. Other students did not resolve this confusion in the same way. When asked whether entropy would help to understand which two-block processes were possible, Jocasta said:

> It does help, seeing that it went from more entropy to less entropy… in a state of more equilibrium.

Note that an accepted explanation of the evolution of a system to thermal equilibrium is that the entropy is greater in the final state. This student seems to say otherwise, and a follow-up question both confirmed this and revealed confusion between entropy, order, and equilibrium.

> Jocasta: It's just weird because whenever I think of entropy I just think of more disorder, and so whenever I look at this, it's going from a state of disorder to order, to some sort of order, so that's why I would assume, there's some kind of order in equilibrium.

Another student brought up the idea of entropy and her messy room, but switched between the association of entropy with disorder and with order.

> Calliope: If entropy relates to *dis*order, then I guess a disordered… If we say that disorder goes with entropy, then my room would have more entropy, unless entropy comes with order. Hm.

These student responses seem to indicate that there is a conflict between the association of entropy and disorder and the association of the equilibrium state with higher disorder and/or entropy:

> Calliope: It doesn't sound right, it doesn't sound right, that [the blocks would] be at a high-entropy state, when they're in their natural state.

A fourth student stated that the initial state of two blocks with different temperatures would have more disorder than the state in which the blocks have reached thermal equilibrium:

> Gladius: I think this one has more disorder, the initial state. Because it's not happy, it's not where it wants to be. Whereas, the final state, you know, everything is equal, it's kind of like a, like a stable, environment.

Consistency of Student Responses

Although there were a few strong ideas that were used by multiple students, another striking feature of student responses was the lack of consistency. As the previous sections might indicate, students shifted between ideas, often within the same response. These ideas might best be described as *facets*, as they were not complete concepts but rather partial concepts that were more descriptive of aspects of a situation or problem [14]. Some of these resembled 'correct' physics ideas, ('entropy is a measure of disorder') but others did not ('entropy is a form of energy').

Calliope's responses were particularly striking, as her explanations featured several facets: conservation, entropy as disorder, equilibrium is ordered, and the idea that entropy opposes energy.

Another student, Gladius, displayed a similar shift between ideas. In response to the general context question she gave a response that seemed to be consistent with the second law of thermodynamics, though it may reflect system / universe confusion as described in Christensen 2009:

> If it's spontaneous, I think, for the first one, the entropy of the system, it's naturally occurring, I think [*faintly*]. I want to say it's increasing.

Later, when asked to discuss Part E of the two blocks question in terms of entropy, she shifted between three ideas. First she gave the quote from the previous section indicating that the different temperatures of the initial state corresponded to more disorder. Then she said the initial and final states have the same entropy, seemingly a conservation argument.

These two statements seem to be in conflict, but one refers to disorder and one to entropy, so it is not clear whether it represents a contradiction or a difficulty in relating entropy to order or disorder. Therefore, a few moments later, the interviewer probed for consistency, and Gladius changed again to relate entropy to disorder, saying 'I said this one would be more disordered, so this one should have more entropy. But I wouldn't know how to describe that.' She was unable to reconcile the confusion.

Even the students using a statistical basis seemed to struggle at times to reconcile it with macroscopic entropy, though the statistical model seemed a firmer anchor point. Hecate sketched a graph of multiplicity that was referred to frequently in class. She could not decide whether the approach to equilibrium meant an increase or decrease in entropy, but then resolved her confusion by referring to statistics:

> It will always move towards that central peak. Never away from it, as a natural spontaneous process. What I don't really remember is whether that corresponds to an increase in entropy or a decrease, just in terms of terminology. [...] I can actually find reasons that it's either one. Increase in that it has the most possible number of micro or macrostates. Yeah, that makes more sense now.

SUMMARY

Although this study includes a small sample of students, the findings have implications for future research and instruction. The results confirm some findings of Christensen 2009, but also expand upon them. While many students invoked arguments about entropy consistent with conservation, students readily shifted to and from these arguments, and often combined them with other ideas.

The association of equilibrium with order was a more prevalent idea than expected and has not previously been reported. For some students this connection seemed to undermine the relationship between the second law of thermodynamics (that entropy will increase for an irreversible process) and their understanding of entropy as a measure of disorder. The relationships between entropy, order, and equilibrium in these student responses are complex and shifting and we will explore these relationships further in future reports.

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