

“Which has more energy?” - An example of responsive teaching in university physics

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In responsive teaching, instructors seek to understand and pursue the substance of students' thinking by foregrounding connections between students' ideas and disciplinary understandings. Education research literature suggests that responsive teaching benefits student learning, yet is also difficult to implement in fast-paced science courses, including university physics courses. This may be one reason there are few examples of responsive teaching at the university level. We share an example of responsive teaching from a small group conversation about heat and temperature in an introductory, calculus-based university physics course. In this example, an instructor proposes a thought experiment that takes up and advances students' thinking about heat and temperature. This example illustrates that responsive teaching is possible in university-level courses, and suggests that one way university science instructors can bridge students' thinking and sophisticated content learning goals is by posing carefully-selected “thought experiments” that target the connections between students' thinking and scientific models.

I. INTRODUCTION

Responsive teaching is an instructional approach that is “grounded in an empirically and theoretically supported expectation that students’ intuitive thinking about science is productive and resourceful,” [1]. Science instructors enact responsive teaching by noticing the “seeds of science” in their students’ thinking [2] and then leveraging connections between student ideas and canonical science models to support the development of students’ understanding [3,4]. Therefore, the curriculum and learning goals emerge (at least to a certain extent) in real time, as students engage with the material an instructor presents to provide a basis for exploration [5]. Literature on responsive teaching suggests that this teaching approach has the potential to promote students’ growth as scientists more effectively than more traditional approaches. A number of studies have shown that responsive teaching practices improve students’ conceptual understanding, promote students’ agency in the classroom, and engage students in authentic scientific practices [1,2,6–10]. Here we present a short example of responsive teaching from a university physics class session. This comes from a classroom that used a worksheet that was specifically designed to be more open-ended than typical instructional materials for university-level physics. This worksheet – an ACORN Physics Tutorial on heat, temperature, and thermal energy [11] – provided an optimal context for enacting responsive teaching. This case study examines what responsive teaching strategies may look like amidst the inherent instructional challenges of an active, student-centered introductory physics course.

Though responsive teaching can promote students’ growth as scientists in multiple ways, there are very few examples of responsive teaching in university science classrooms [12]. Published examples of responsive teaching in STEM classrooms predominantly come from K-12 settings [1–3,13,14], which may suggest that responsive teaching is more appropriate for pre-college students. These examples depict teachers spending significant time clarifying and extending their understanding of students’ thinking, then adapting their instruction and curriculum to build on students’ fruitful ideas. In these examples, student ideas take up much of the “airtime” in discussions; science principles and correct answers take up less discursive space. Several of these examples articulate a tension between pursuing students’ science ideas and guiding students to the canonical result, model, or understanding [2,13,15]. While a commitment to responsive teaching does not mean that canonical scientific understandings are unimportant [16,17], it may mean that instruction follows a circuitous, dynamic

path, where some goals get more time than others, and a broader range of intellectual trajectories are planned for.

University physics courses are typically fast-paced and mathematically rigorous, and the content expectations for a university-level introductory physics course pose a particular challenge to responsive teaching. Knight’s calculus-based *Physics for Scientists and Engineers* text [18], the text used in the course studied here, includes approximately 30 chapters that are covered in three 10-week quarters or two 15-week semesters – there is little “wiggle room” in the course schedule. In other words, the inherent tensions of responsive teaching are likely to be particularly challenging in a university-level physics course. Yet, Robertson et al. give an example of responsive teaching in an introductory physics lecture course that suggests that it is possible, at least on short timescales [15].

In this paper, we add to the illustrative case given by Robertson et al., examining what we claim is a responsive teaching interaction in a calculus-based university physics course. Our example shows the emergent and dynamic interaction of responsive teaching in a new context – the physics topic and the course structure are both different from the example in [15]. In this example, a question posed by an instructor builds on students’ productive reasoning while also building towards the content goals of introductory physics. The instructor’s question closely relates to many of the ideas the students discussed earlier in the class session and explores those ideas further in a “thought experiment.” We argue that this case illustrates that responsive teaching is possible in university-level courses with rigorous content learning goals and is an example of how such responsive teaching interactions might look.

II. INSTRUCTIONAL CONTEXT

The case we share is from a small-group discussion that took place in a calculus-based introductory physics course at a small (<5000) liberal arts university in the Pacific Northwest United States. This course primarily serves students majoring in engineering, computer science, physics, chemistry, and biology. The racial and gender demographics of the population served by this course is as follows: 48% Female, 52% Male¹; 7% are international students; students who are residents of the U.S. are 44% white, 17.8% Asian, 8.3% Black or African American, 0.3% Hawaiian Native/Pacific Islander, 14.9% Hispanic of any race, 8.1% Two or more races; we do not know how the particular course studied may differ from this larger population. The class in which our data was collected was the second of a three-quarter introductory physics sequence, composed of approximately 30 students, taught by one experienced

¹ The university reports gender demographics as male/female; however, we do not assume this accurately represents the spectrum of identities held by students in this population.

faculty member and supported by two undergraduate Learning Assistants. Another faculty member was present in the classroom when video-recording occurred. A significant portion of class time was dedicated to small-group work scaffolded by worksheets, including *Tutorials in Introductory Physics* [19] and other materials. Students typically worked in table groups of 3-5.

Several student groups were video-recorded during two class sessions in which they worked through an **Attending to Conceptual Resources** iN (ACORN) Physics Tutorial on concepts of heat, temperature, and thermal energy [11]. The worksheet asked students to explain a set of experiments involving heat transfer by conduction. For example:

“Two identical metal blocks are sitting on a table. One is hot and one is cold. The blocks are placed in contact with one another and put into an insulated box. After several minutes, the blocks are the same temperature as one another. (1) Why does this happen? (2) Is the final temperature of the blocks halfway between their initial temperatures, between their initial temperatures but not necessarily halfway, or not necessarily between their initial temperatures?”

Then the worksheet directed students to articulate, apply, and refine their ideas about thermal phenomena, ultimately guiding students to generate a set of rules that predict and explain heat transfer by conduction. This process of addressing a scenario and constructing a set of rules is iterative and the students’ rules are expected to change and grow over the course of the worksheet. In our observations of the class using this worksheet, we notice that the goal of articulating rules about thermal phenomena guided the direction of students’ conversations and instructor moves more than the specific scenarios presented did. Students spent significant time articulating, refining, and making sense of rules; in doing so, conversations often diverged from the worksheet scenarios to other thermal phenomena.

III. THEORETICAL FRAMEWORK AND METHODS OF ANALYSIS

This paper presents a case study of a small-scale responsive teaching interaction in calculus-based university physics [20,21]. For this study we video recorded all groups for which we had consent from all students. We selected the focal episode of this paper from a larger corpus of video recordings that captured four groups of students for the entire class period on the day in which the ACORN Physics heat and temperature worksheet was used in the classroom described above. We began our analytic process with broad thematic questions about how instructor interactions support students’ progress through the ACORN Physics worksheet, and used an inductive approach to refine our research questions and claims [22]. This process led us to highlight the focal episode of this paper as an instance of rich, extended instructor-student interaction. We iteratively viewed and discussed the video of this conversation, discussing possible interpretations of and claims from this

episode [23]. Our interpretation was guided by the marks of responsive teaching articulated by Robertson, et al. [15]:

- a. Foregrounding the substance of students’ ideas;
- b. Recognizing the disciplinary connections within students’ ideas;
- c. Taking up and pursuing the substance of students’ thinking.

We applied principles (a) and (b) as a first filter, marking this as an interaction in which students’ science ideas were apparent to us, and in which an instructor responded to the disciplinary content of those ideas. After identifying this candidate episode, we analyzed the transcript closely, looking for evidence of instruction that took up, pursued further, or built on the physics content of students’ ideas that was apparent to us and that was taken up by the instructor. In the following section, we unpack how this episode fulfills these criteria to illustrate responsive teaching in a university-level physics classroom.

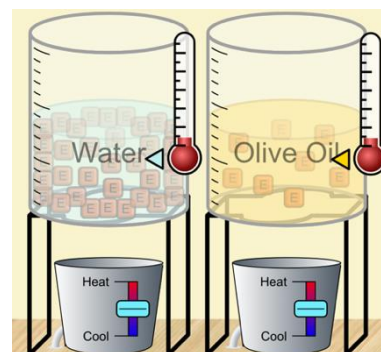


FIG 1: Image of the oil and water scenario from the Energy Forms and Changes Simulation by PhET Interactive Simulations, University of Colorado Boulder, licensed under CC-BY-4.0 (<https://phet.colorado.edu>).

IV. ANALYSIS

This analysis focuses on a conversation between three students, pseudonymed Sam, Stephanie, and Selena. At various points in the class period, the students discuss their thinking with Professor Pete. Although the focal episode begins during the middle of the activity, we believe it is important to describe what happened before the focal episode as it provides an important context.

The class session begins with a review of energy conservation, and Pete presents an energy conservation equation that includes a term for heat transfer. Pete introduces the heat transfer equation $Q = mc\Delta T$. He explains that Q is the heat transferred to a substance, which depends on its mass, change in temperature, and its specific heat capacity c . Pete shows a table of the specific heat capacity values for various materials. Then, Pete presents a scenario for the class to discuss in small groups: “If we add the same amount of heat to the water and oil, [so] Q is the same in both of them, will the temperature change be the same? If not, which one is a higher change of temperature?”

As he presents this question to the class, Pete shows the scenario in the PhET Energy Forms and Changes simulation (Fig. 1) [24], which the students used in a pre-class assignment. The simulation depicts energy units and thermometers that qualitatively show the change in energy and the change in temperature of water, oil, brick, or aluminum when they are heated or cooled.

Sam, Stephanie, and Selena begin to discuss the oil and water scenario. Initially, Sam predicts that “the oil heats up faster than the water.” Selena agrees, stating that “the oil needs less energy to be at that temperature.” The group discusses the equation $Q = mc\Delta t$ and how it applies to the oil and water scenario for several minutes. At the end of their discussion, Pete checks on the group and asks about their prediction: which liquid has a higher temperature, and which gains more heat? The group shares that the oil will have a higher temperature, but each liquid has the same heat added. Pete affirms their thinking and adds, “so heat and temperature are not the same.” We infer that distinguishing between heat and temperature is an important learning goal for Pete, which we see resurface later in our focal interaction.

Following this conversation, the class is instructed to begin the worksheet. After considering the first question in the worksheet (the question given in section II above), the group agrees that the final temperature of the two identical blocks must be halfway between the two initial temperatures, or the “average.” They explain that “the transfer of energy goes from high to low,” and write this down as a rule. They also express uncertainty that the final temperature would always be the “average.” Stephanie says, “That bothers me. Like there has to be one where it's not the average, but I guess that has to do with like energy, not staying in the system that causes that.” The group discusses the same ideas for a few more minutes without reaching a confident resolution.

Our focal episode begins just afterward, when Pete comes up to the table and asks about the group's progress:

Pete: Do you have any rules yet?

Sam: Oh. I haven't even gone back yet.

Selena: Uh, energy likes to go from high concentration to low concentration.

Here, Pete opens the conversation with a question about the group's progress toward the goal of the worksheet. We interpret this instructional move as *foregrounding students' ideas* because it is an open-ended question that invites the students to share a summary or important idea. While Selena's brief response does not convey all of the ideas that the group used in the preceding conversation, it does give Pete insight into their thinking that he uses to dig deeper into the group's understanding. Pete revoices Selena's rule, adding particular emphasis to the energy idea:

Pete: So the *energy*² goes from high concentration to low concentration?

Stephanie: Mhm.

Pete: Um, can I ask a question?

Stephanie: Yeah.

Pete: Oil, say at 30 °C, water at 10 °C. Which has more energy?

Revoicing students' ideas, as Pete does in the first line in the snippet of conversation above, is affirmed in the literature as a responsive instructional move [5,25,26]. We interpret this instructional move as both drawing the students' attention to the energy idea (particularly given Pete's emphasis), and solidifying Selena's meaning for the group, as Stephanie agrees in response. This instructional move thus is an instance in which Pete *attends to the disciplinary substance* of the group's thinking. We understand the energy idea that Selena voices as important and fruitful for modeling the scenarios the group considers in the class period; at the same time, Selena's rule is inaccurate in some situations. That is, energy can flow from objects with less energy to objects with more energy, if the object with less energy has a higher temperature. We note that Selena's rule was reasonable for the scenarios the group had considered in worksheet up to that point (which involved objects of the same material and similar size), though not broadly correct in every possible scenario (e.g., scenarios involving different masses and materials). It seems likely that Pete noticed this and thought it would be important to address this discrepancy. Pete then responds with a “thought experiment” that incorporates the group's ideas about energy flow and seems to be chosen to press the students' thinking further toward a key learning goal: differentiating between energy, temperature and heat transfer. We interpret the “thought experiment” Pete presents here as a key instructional move that *takes up and pursues* the disciplinary content of the students' thinking. We note that this question would be very challenging to answer in a canonically accurate and quantitative way. However, it calls back to the scenario discussed at the beginning of the class (Fig. 1), and we suspect that Pete anticipates they have (qualitative) ideas about this question from the previous discussion.

Sam is the first to respond to Pete's question:

Sam: The oil? Oh wait no, it's the water.

Pete: The water has more energy? Okay. Which has more temperature?

Stephanie: Oil.

Pete again revoices and affirms Sam's idea, then checks the group's thinking about the temperature of the two liquids. Since Pete gave specific temperatures for the oil and water in his question, we interpret this new question as a reminder intended to draw on ideas he knows the students have used, rather than a question to elicit their ideas. This exchange sets up a new question that connects their ideas:

Pete: Which way does the energy go?

Sam: Would the water be going to the oil? To even out?

Pete: So they would even out, according to your rule. Which way would it go?

There is a pause as the group thinks about the question.

² Italics indicate the speaker's emphasis.

Stephanie: It would go from oil to water.

Sam: But the oil doesn't have as much energy as the water.

Pete's repeated questions about the direction of energy flow, in conjunction with his affirmation of the rule that the temperature will "even out," takes up and coordinates the students' ideas that the oil has a higher temperature than the water, that the oil has less energy than the water, and that energy flows. This sequence of questions continues the conversation in a way that brings the group to a "vexation point," [27] or recognition of a gap in understanding that catalyzes sensemaking. This is evidenced by the pause in conversation before Stephanie responds and by Sam's comment, "but the oil doesn't have as much energy..." The conversation continues as Pete affirms what Sam points out:

Pete: that's the conundrum, right³?

Stephanie: But the temperature is higher, so the temperature has to even out. And that we *know*. I *know* that temperature goes from high to low. No matter what.

Selena: So it's not energy, but temperature that goes from high to low.

Pete: Does the *temperature* go?

Selena: Or not the temperature, the energy makes it so that the temperature –

Stephanie: The energy is transferred from like, from a, like a higher temperature to lower temperature. So if you wanna relate those two...

Selena: It moves, it moves, wait ... energy moves. Yeah. From an object that is higher to the lower temperature.

Pete: So from hot to cold.

Stephanie: Yeah.

Here Stephanie and Selena reformulate their statement, saying that instead of the energy moving from high to low concentration, the temperature moves towards equilibrium. Pete's question "does the *temperature* go?" seems to be chosen to push Selena's statement toward canonical correctness. Even though this question does not come across as open-ended, we see it as responsive to the ideas about energy flow and temperature change that the students have used throughout their conversation. Ultimately, this question helps Stephanie and Selena to connect their ideas: energy transfers from high to low temperature objects.

Following this interaction, the group concludes that water holds more energy than oil at the same temperature because it has a greater heat capacity. They return to the two-block scenario and clarify that the final temperature is halfway between the initial temperatures only because the blocks are identical. Stephanie says, "In this case, energy and temperature can be related and will be like a change in energy will have the same change in temperature for both." That Stephanie and Selena articulate a refined rule for heat

transfer suggests that the thought experiment was successful in connecting and extending their ideas. We also infer that their conversation with Pete ultimately supported the group to resolve the question that was "bothering" Stephanie earlier in the class period. Thus, Pete's instructional moves in this conversation (particularly the water and oil thought experiment) leveraged students' own ideas, advancing them toward an introductory physics learning goal.

V. DISCUSSION/CONCLUSION

In this example of responsive teaching, Pete asked a series of questions that first drew out then leveraged, connected, and refined students' thinking. Pete's instructional moves centered around his thought experiment about the energy and temperature of equal amounts of oil and water, building on a similar question he posed at the start of the class. This question successfully targets the students' thinking – we see that the question draws on ideas they have articulated previously and relied on throughout their discussion. It successfully connects several of these ideas, such that the group refines the rule they had previously articulated in a way that more closely approaches a canonical physics understanding. This process of understanding student ideas and teaching in a way that pursues student thinking is one of the hallmarks of responsive teaching.

This episode suggests that one way instructors may be able to implement responsive teaching practices in university science courses is to plan ahead questions and/or thought experiments, like the one Pete uses here, that can be flexibly deployed to respond to and build on students' thinking. These planned questions might anticipate common student ideas so that the instructor could respond to these ideas through a responsive teaching framework.

We note that the instructional materials used in the class were designed to provide open-ended scaffolding for student thinking, and Pete drew on that structure (asking for "rules") as he opened the conversation we analyzed. We hypothesize that the open-endedness of the worksheet and its design to elicit a range of common student ideas were important for this interaction. This structure may have supported Pete to plan for and use questions like the one used in this episode. Future work could explore whether materials that provide open-ended scaffolding, like ACORN Physics worksheets, are particularly supportive of responsive teaching practices.

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³ While Pete's questions up to this point bear some resemblance to an "elicit-confront-resolve" strategy [28], we do not see any evidence that Pete intentionally chose questions to draw out the incorrect idea that "energy goes from high concentration to low concentration." Instead, we

see Pete *responding* to the students' emergent idea with a series of questions that make visible some inconsistencies in their reasoning. The key distinction we see is that Pete's questions are guided by and build on students' in-the-moment thinking.

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