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Centering Student Ideas in Introductory Physics Instruction

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2025

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Physics

University of Washington

Abstract

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Using a constructivist framework for learning, which proposes that students actively build new understandings from their existing ideas and experiences, this dissertation examines multiple sites of intersection between student ideas and introductory physics instruction. First, this work begins by identifying potentially productive ideas students use when answering physics questions. This includes identifying conceptual ideas about physics that students use in their written answers to physics questions, such as the resources students have for thinking microscopically about heat and temperature. This also includes identifying ideas about the form and purpose of conceptual explanations in physics that students use when responding to the common prompt 'explain your reasoning'. Next, this work continues with how student ideas are taken up in physics instruction. This includes a study of how students feel about their ideas in the context of instruction with materials that were either designed primarily to build on student ideas or to address student difficulties. This also includes identifying the pedagogical ideas that student learning assistants have that can be resources for understanding instruction as centering student

ideas. Together, the pieces of this dissertation offer an expansive view of students' ideas, experiences, and perspectives as potential assets for instruction.

Table of Contents

1 Introduction

6 Chapter 1:

Identifying student resources for reasoning microscopically about heat and temperature

6 1.1 Introduction

7 1.2 Theoretical Framework: Resources

8 1.3 Methods

13 1.4 Results and Discussion

13 1.4.1 Prevalence of microscopic reasoning

14 1.4.2 Microscopic heat and temperature resources

18 1.5 Conclusion

19 Chapter 2:

Identifying student conceptual resources for understanding physics: a guided activity for researchers

19 Step 1: Collect students' written responses to open-ended conceptual questions

19 Step 2: Identify student conceptual resources specific to individual questions

30 Step 3: Reduce the preliminary set of candidate resources into a smaller set of common conceptual resources

35 Step 4: Test and refine preliminary coding scheme

37 Final Steps

38 Chapter 3:

Types of explanations students use to explain answers to conceptual physics questions

38 3.1 Introduction

40 3.2 Context and Methods

42 3.3 Preliminary Results

46 3.4 Discussion and Future Research

49 Chapter 4:

Modes of explanation students use when explaining answers to conceptual physics questions

49 4.1 Introduction

50 4.2 Context and Methods

50 4.2.1 Interviews

52 4.2.2 Phenomenographic analysis

53 4.3 Results

53 4.3.1 Modes of explanation

58 4.3.2 Using explanation modes in combination

59 4.4 Discussion and Future Research

62 Chapter 5:

Instructional material design and students' feelings about their ideas

62 5.1 Introduction

66 5.2 Background

70 5.3 Literature Review

73 5.4 Methods

74 5.4.1 Research setting

74 5.4.2 Survey considerations

76 5.4.3 Survey development and validation
82 5.4.4 Survey administration
86 5.4.5 Data analysis
88 5.5 Findings and Discussion
89 5.5.1 Student experiences of ACORN Physics Tutorials and Tutorials in Introductory Physics
93 5.5.2 Student experiences of correcting their ideas
96 5.5.3 The multiplicity of students' feelings
98 5.5.4 The role of peers and instructors
100 5.5.5 Limitations
102 5.6 Summary
104 Chapter 6:
Learning Assistants' resources for understanding instruction as centering student ideas
104 6.1 Introduction
106 6.2 Theoretical Framework: Resources
108 6.3 Methods
109 6.3.1 Research context and participants
114 6.3.2 Data analysis
118 6.4 Results
119 6.4.1 Beliefs about learning
126 6.4.2 Knowledge of instructional strategies
133 6.4.3 Values related to students
140 6.5 Implications for LA Development

143 6.6 Conclusions

145 Conclusion

151 Acknowledgements

153 References

166 Appendices

Dedication

To our students,

may we never stop learning from you

Introduction

This dissertation takes as a starting point that in university physics courses, learning begins with the ideas that students bring with them into the classroom: ideas about physics concepts and the way the physical world works, ideas about what physics is and what types of reasoning are desirable in physics spaces, even ideas about how physics instruction can and should look. During instruction, these ideas can be nurtured and challenged and developed and revised. This view of learning aligns with constructivism, in which students actively construct new knowledge and understandings, building from what they already think and know [1, 2]. It follows that physics instruction can be improved when it more effectively interfaces with student ideas. Research can inform this improvement by making more apparent the ideas that students have - both to inform the development of instructional materials and to contribute to instructors' knowledge of student ideas - and by examining how student ideas are taken up by instruction - both to better understand the impact of different instructional approaches to student ideas and to support instructors in effectively leveraging student ideas.

The research presented in this dissertation centers student ideas and the ways they are taken up by instruction in a crosscutting manner, examining different key elements that come into play during physics instruction. First, it begins with identifying student ideas about physics concepts (Chapters 1 and 2). Then it moves outward to student ideas about explanations to conceptual physics questions - the written forms in which their conceptual physics ideas are embedded (Chapters 3 and 4). Then it moves outward again to examine the instructional materials presenting the conceptual physics questions and how students feel about their ideas when different materials are used (Chapter 5). Finally, it considers the role of instructors in the

classroom and what ideas novice instructors have about teaching and learning that can potentially develop into deeper understandings of instruction as centering student ideas (Chapter 6). In the work of this dissertation, I have aimed to enact research as a practice of listening to students with scientific rigor and to honor the complexity of physics instruction and its many interacting elements (students, instructors, teaching materials, and physics itself). Prior research, methods, theoretical frameworks, etc. are included within their relevant chapters.

Overview

To most directly (or typically) use research to attend to student ideas in physics, we can look at the conceptual ideas that students have about physics content. Physics Education Research has a long tradition of collecting common student ideas and building effective curriculum around them. The first two chapters in this dissertation are a part of that enterprise. Chapter 1 presents a study on common student ideas that can be meaningfully connected to canonical physics ideas (i.e., student conceptual resources) in the context of reasoning microscopically about heat and temperature. The study identifies three conceptual resources found in a sample of 624 written responses to three different heat and temperature questions administered to introductory physics students at four different colleges and universities. The reporting of these conceptual resources can inform curriculum developers and assist instructors in noticing, appreciating, and building on student ideas during introductory thermal physics instruction. This chapter has been published in the Physics Education Research Conference Proceedings [3]. Coauthors Trà Huỳnh, Lauren Bauman, and Amy Robertson contributed to the initial study design and data collection, assisted with analysis, and provided feedback on the manuscript. Chapter 2 is a guided activity that illustrates the methodology of conceptual resource

identification used in Chapter 1's study and other studies like it. It provides a starting place for researchers interested in using the method themselves in new contexts. The guided activity has been published as an appendix to a methodology paper in Physical Review - Physics Education Research [4]. The first author of the paper, Amy Robertson, provided feedback on a draft of the guided activity.

When looking for common conceptual ideas that students have in physics, studies typically analyze samples of students' written responses to physics questions. It is worth noting, then, that these samples are not direct captures of the thinking that students do, but rather the thinking that is embedded in what students choose to write down when explaining their reasoning. Part of what physics instruction teaches, implicitly or explicitly, is what we as instructors and/or physicists find relevant and compelling in conceptual physics explanations. A second way, then, of using research to attend to student ideas in physics is to look more closely at the ideas students have about explanations. Chapter 3 presents a study on the types of explanations students use when explaining their answers to conceptual physics questions. It identifies and provides examples of six different explanation types found in the written work of students in introductory physics that illustrate the breadth of forms that student explanations take. A version of chapter 3 has been published in the Physics Education Research Conference Proceedings [5]. Coauthor Paula Heron advised on all stages of the project. Chapter 4 extends the study in Chapter 3 by moving from an analysis of written explanations themselves to examining students' process of writing explanations. The study in Chapter 4 presents four modes that students use while writing explanations to conceptual physics problems as found in a set of student interviews. These modes capture differences in what students report as the aims of their explanations, who they picture themselves addressing their writing to, and how the reasoning

students used in solving conceptual physics problems relates to what they included in their final written explanations as captured in a set of student interviews. The studies in Chapters 3 and 4 together can inform instruction aimed at the development of student explanation and argumentation skills in ways that leverage and are responsive to students' initial understandings of explanations.

So far we have considered student ideas (in the form of conceptual physics ideas and ideas about what constitutes conceptual physics explanations) as things that can be collected and examined as input for instruction. We now turn to examining how student ideas are taken up by instruction.

Different curricula take up student ideas in different ways that may or may not have different impacts on student experiences of instruction and their relationships to their ideas. As instructors and developers of instructional materials, we would like instruction to be a positive experience for students of building on the ideas they already have and revising their thinking as necessary. Chapter 5 presents a study on how students feel about their ideas (confused, confident, frustrated, etc.) and how they perceive their ideas being impacted (corrected, confirmed, cleared up, etc.) in the context of instruction with materials that were either designed primarily to build on student ideas (ACORN Physics Tutorials) or to address student difficulties (Tutorials in Introductory Physics). The study describes the creation and administration of a survey instrument to allow students to self-report their experiences. The survey results are then used in an exploratory analysis of what students reported feeling during sessions of instruction and potential differences in feeling when differently designed materials were used. The findings have implications for how impactful instructional material design appears to be in shaping students' feelings about their ideas during instruction. A version of chapter 5 will be submitted to Physical

Review - Physics Education Research. Coauthors Paula Heron, Amy Robertson, Jon Owen, and Clausell Mathis advised on the study design, assisted in analysis, and gave feedback on the manuscript.

Finally, we move from how instructional materials interface with student ideas to an instructor's role in centering student ideas. Chapter 6 is a study on instructors' development in understanding instruction that centers student ideas. It identifies nine potentially productive ideas (i.e., resources) that novice instructors express in the categories of beliefs about learning, knowledge of instructional strategies, and values related to students. The novice instructors in this study are undergraduate Learning Assistants (LAs), students who join the teaching teams of courses they have (typically) previously taken while concurrently being students in a pedagogy course. The study analyzes LA assignment submissions from pedagogy courses at four universities and presents the pedagogical resources we find in this sample with their approximate prevalences. It highlights those resources' connections to the literature on responsiveness and constructivism and how they can be seen as productive starting places towards centering student ideas during instruction. A version of chapter 6 will be submitted to the International Journal of STEM Education. Coauthors Sam Engblom, Rachel Scherr, and Lisa Goodhew advised on the study design, assisted in data collection and analysis, and gave feedback on the manuscript.

Chapter 1.

Identifying student resources for reasoning microscopically about heat and temperature

1.1 Introduction

One way in which Physics Education Research (PER) has served instructors is through systematic investigations of student ideas about physics topics. By identifying common student ideas about heat and temperature, for example, researchers provide instructors with Knowledge of Student Ideas (KSI), which, along with physics content knowledge and knowledge of instructional strategies, supports an instructor in facilitating student learning [1-3].

Extensive work has been done investigating student ideas about heat and temperature in introductory physics [4-20]. In investigations that included microscopic models for understanding heat and temperature concepts, researchers found that students mistakenly associate volume with number of particles, assume collisions between particles lead to heat production or changes in internal energy, and fail to correctly interpret or apply particle flux in thinking about pressure [11-18]. While previous research primarily focused on identifying student difficulties or misconceptions, a few studies have taken a resources lens, seeking to identify "seeds of science" in student ideas, which rather than needing to be replaced, may be nurtured by instruction and grown into canonically correct physics concepts [19-21]. These studies have identified students' conceptual resources about heat and temperature, including that heat transfer is directional, that temperature is associated with energy, and that systems naturally move 'toward' equilibrium [22-25]. Our study combines the focus on *microscopic* reasoning of some previous difficulties-oriented heat and temperature research and the *resources* approach of

more recent studies by identifying the promising ideas present in students' microscopic thinking about heat and temperature.

We explore the question: *What conceptual resources are common in student responses to heat and temperature questions when microscopic thinking is used?* To answer this, we analyzed 624 written student responses to three heat and temperature questions administered at four different colleges and universities. We identified three resources for reasoning microscopically about heat and temperature: 1) *differences will eventually even out*, 2) *macroscopic changes connect to microscopic collisions*, and 3) *when something is hotter (colder), its molecules are moving faster (slower)*. By defining and offering examples of these resources, including their connections to canonically correct physics concepts, we aim to add to instructor KSI and therefore aid instructors in anticipating and building on student ideas during heat and temperature instruction.

1.2 Theoretical Framework: Resources

In resources theory, a resource is a piece of knowledge that is activated in context-sensitive ways, sometimes in concert with other resources, to form an idea, explanation, argument, or theory [19, 21, 26-32]. Researchers have theorized extensively about the development, structure, and role of resources, and have used resources theory to highlight the dynamic, emergent, complex-systems-like nature of student thinking [27].

Our work draws extensively from resource theory's orientation toward student thinking as fundamentally sensible and continuous with formal physics [19, 21, 27-29, 31, 32], seeking to make visible the continuities between students' thinking and formal physics, even and especially

when that thinking does not use the language of formal physics or is incorrect. Our work also builds from resource theory's definition of learning, which involves changing the structure or activation of resources, by reorganizing, refining, or increasing the degree of formality of resources [19, 21, 26, 28, 31, 32]. Our primary aim in identifying resources is to provide instructors with knowledge that they can use to build from student ideas in instruction.

1.3 Methods

The resources we report in this paper were identified in written student responses to three questions about thermal phenomena: the *hot to cold* question, the *piston* question, and the *cold tire* question (Figure 1.1). All three were constructed for the purposes of this project, with different conceptual targets in mind. The *hot to cold* question was meant to target mechanisms for energy transfer in thermal phenomena; the *piston* question, microscopic reasoning about the first law of thermodynamics; and the *cold tire* question, microscopic explanations for changes in (macroscopic) thermal quantities. We chose these questions from among our data set because student responses frequently relied on microscopic reasoning, which was the focus of our analysis.

Hot to cold question:
You may have heard that "heat" or "thermal energy" transfers from hot to cold objects, and not the other way around. Why is this the case? How do you make sense of this phenomenon?

Piston question:
An ideal gas is in a container that is closed on the top by a movable piston. The gas is now heated, so that the temperature goes up. As this happens, the piston moves up. Use ideas about microscopic gas particles and interactions to explain why this happens.

Cold tire question:
It became suddenly very cold last night. You start your car in the morning to go to work and get a warning light indicating that your tire pressure is low. You check the tires carefully, and there is no sign of any puncture. You remember from class that the ideal gas law (PV=nRT) says that temperature and pressure are related, so you hypothesize that because there was a sudden decrease in temperature, there must also have been a decrease in pressure.

U1 version ending:
What is another way (using something other than the ideal gas law) to make sense of what happened with your tire?

U3 version ending:
You also remember a class discussion about a gas being made of many small particles. How can you use this particle picture of a gas to make sense of what happened to your tire?

FIG. 1.1 Questions used in our study

In the *hot to cold* question, hot objects have higher temperatures, which corresponds to particles with higher kinetic energy. When two objects come into contact, one hot and one cold, the interactions between the higher- and lower-energy particles transfer some of the energy to the colder object. In the *piston* question, as the temperature goes up, the speed of the particles of the gas increases, and they collide with the piston with greater "oomph" as they move upward. This means that the force exerted by the gas on the piston increases; the gravitational force on the piston by the Earth remains the same, so there is a net upward force on the piston, and it moves up. For the *cold tire* question, "tire pressure" is the pressure of the gas on the tire. Microscopically, pressure is the force of the collisions of the gas particles with the wall of the tire, per unit area. When the temperature decreases, the speed of the particles decreases, and the force that particles exert as they collide with the wall also decreases.

We analyzed a total of 624 written responses from introductory physics courses at four US colleges and universities. U1 and U2 are large public institutions, U1 in the Pacific

Northwest US and U2 in the Midwest. U3 is a mid-sized public community college in the Western US. U4 is a small private institution in the Pacific Northwest. Students answered the questions on homework and quizzes, before and after instruction on heat and temperature. The course response rates (i.e. number of responses divided by the number of students enrolled in the course) were 73%-86% for questions asked at U1; 33% for U2; 78-89% for U3; and 90% for U4. Ranges indicate that students from more than one course or quarter answered questions. The low response rate for U2 reflects that students turned in responses as part of a group assignment at that institution, with one response given per group, rather than one response given per individual.

The racial and/or ethnic demographics for the colleges/ universities in our study versus all college/university students are shown in Figure 1.2. Figure 1.2 suggests that the institutions in our study are not racially and/or ethnically representative of the population of college-bound freshmen in the US. By this measure, the universities in our study serve more Asian and Asian American students, more multiracial students, fewer Hispanic or Latinx students, fewer Black or African American students, and fewer white students than are in the general population of college students. The median parental income of the students at colleges/universities in our study is also higher than the national average. This sampling limits the generalizability of our results; though the resources we identified are common among the students in our sample, we cannot speak to their commonality in the population of introductory physics students writ large.

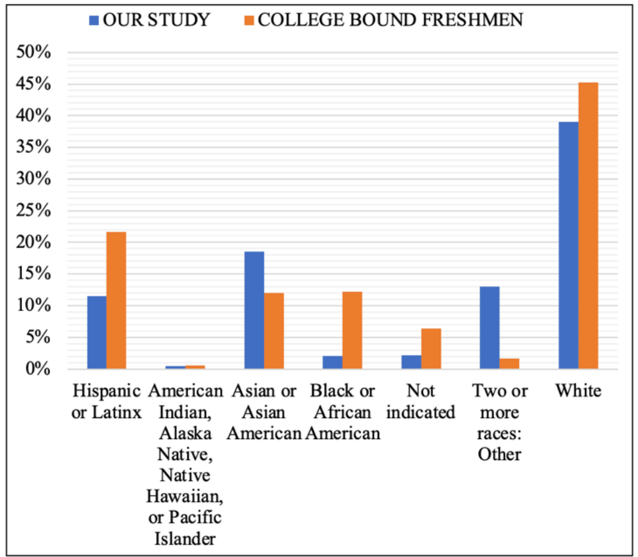


FIG. 1.2. Racial and/or ethnic demographics of institutions in our sample (blue) versus all college-bound freshmen (orange). Blue bars were constructed using demographic data provided by offices of institutional research or institutional websites, weighted by sample size. Orange bars were constructed using data from Kanim and Cid [33]. As explained by activist Kat Lazo [34], neither Hispanic nor Latinx are racial groups, and these two identities are not the same. "Hispanic" is a descriptor for people of Spanish-speaking origins, and "Latinx" is a descriptor for people with origins in Latin America. The former focuses on language, the latter on geographic location.

We used responses to the questions in Figure 1.1 to create an emergent coding scheme [35] that captured some common resources that the students in our sample used to reason microscopically about thermal phenomena. Author AA, in consultation with author TH, conducted preliminary analyses of student responses to each question, looking for ideas that they considered to be continuous with relevant formal physics concepts, even if not stated in formal terms. They then identified patterns across questions, producing a coding scheme of three resources. This pattern-seeking approach foregrounds a model of generalizability that emphasizes recurrence across multiple sources of heterogeneity [36].

Authors AA and LB then independently coded student responses to the three questions. As a first step, they independently coded whether each response did or did not contain

microscopic thinking. The agreement was near perfect (Cohen's kappa = 0.99). Responses that did contain microscopic thinking were then coded for the use of each of the three resources. Resources can be and often are activated in concert; thus, a single response could receive no code, one code, or many codes. As a measure of inter-rater agreement, we took the normalized difference between the total number of possible codes and the total number of disagreements between the two coders. We used percentage agreement rather than a standard statistical measure of agreement (e.g., Cohen's kappa) because our codes are not independent or mutually exclusive [37, 38]. The percentage agreement on resource codes for the full data set was 96%. Disagreements were not resolved through discussion; instead, the percentages reported in Tables 1.1 and 1.2 represent the fraction of responses for which both authors were in agreement.

TABLE 1.1. Prevalence of microscopic reasoning by question and institution

	Hot to Cold			**Piston**		**Cold Tire**	
	U1	**U2**	**U3**	**U1**	**U4**	**U1**	**U3**
Total N	258	18	39	89	37	159	24
Micro N	88	10	26	74	26	81	23
Micro %	34%	56%	67%	83%	70%	51%	96%

TABLE 1.2. Percentage of microscopic responses containing each resource by question and institution

	Hot to Cold			**Piston**		**Cold Tire**	
	U1	**U2**	**U3**	**U1**	**U4**	**U1**	**U3**
Resource 1	36%	10%	23%	7%	12%	4%	0%
Resource 2	42%	80%	65%	80%	42%	36%	74%
Resource 3	65%	90%	92%	77%	96%	68%	91%

1.4 Results and Discussion

1.4.1 Prevalence of microscopic reasoning

We considered a student response to contain microscopic reasoning if it used atoms, molecules, or other particulate descriptions of an object or substance, either in drawings or in words. Responses that mention microstates or basic states but do not otherwise contain particulate descriptions (e.g. "A system tends to move toward having the most basic states, or the greatest entropy.") were *not* categorized as microscopic thinking, as it was often unclear if students understood these terms as referring to particle configurations or microscopic descriptions. The prevalence of microscopic reasoning varied across questions and institutions, as seen in Table 1.2. We believe several factors are at play here. First, the three questions used in our research prompt microscopic thinking to differing degrees. Some of our questions ask explicitly for students to use microscopic ideas and others do not, and we see the prevalence of microscopic thinking varying in a way that appears consistent with these constraints. Second, we expect variability due to the nature of resources: resources are activated in context sensitive ways [19, 20, 31]. For example, the likelihood of particular resources to be activated may depend on the scenario in the question prompt, the physics topics a student has most recently engaged with during instruction, the thinking elicited by other questions given at the same time as our research questions, etc. Finally, different student populations who have experienced different instruction may also vary in the prevalence or accessibility of a particular resource or way of thinking. By sampling from different institutions, we expect to witness variation.

1.4.2 Microscopic heat and temperature resources

Within student responses that used microscopic reasoning, we identified three common resources. The prevalence of each resource, by question and institution, is given in Table 1.2. As with the variation in prevalence of microscopic reasoning, we expect variation in the prevalence of these three resources due to the contextual nature of resources and the heterogeneity of our sampling. To be considered common, a resource needed to be present in student responses to multiple questions and in at least 10% of responses that included microscopic thinking for at least one question. We will next describe each of these resources, with examples of how they are used in both correct and incorrect responses. We will also discuss their connections to formal physics ideas and relationships to prior research.

1. Differences will eventually even out

Student responses commonly included the idea that objects or systems tend toward uniform distributions of quantities such as pressure, temperature, energy, force, density, molecular speed, and molecular flux. This resource, *differences will eventually even out*, does not always involve microscopic modeling in and of itself; it is included in our findings here because it was often used in conjunction with microscopic reasoning. It can describe a quantity inside a system coming to balance with a quantity outside the system (e.g. "The average thermal energy of the tire changes to match the average thermal energy of the surrounding environment."). It can also describe a quantity that varies within a system becoming more uniform (e.g. "The equilibrium state will be reached when each atom has the same thermal energy and it will even out.").

The resource *differences will eventually even out* is used in support of ideas that are both consistent and inconsistent with formal physics. Using the examples above: we *do* think of systems as coming into thermal equilibrium with their environments, as is implied by the first example, but we *do not* think of each atom as having equal energy when equilibrium is reached, as described in the second example. What is shared by both examples is the abstract resource that systems tend toward uniformity. This resource is continuous with formal physics ideas of systems tending toward equilibrium configurations. At the macroscopic level, that might be internal and external pressure balancing as a piston moves; at the microscopic level, that might be the particle speed distributions of ideal gases converging to the Maxwell-Boltzmann distribution.

The *differences will eventually even out* resource also has connections to student resources identified in other studies. Loverude identified the resource s*ystems naturally move 'toward' equilibrium rather than away* in the thinking of upper division thermal physics students, which may be a more specific or formal version of *differences will eventually even out* [24]. Abraham et al. identified the resource *heat transfer is directional* in the thinking of introductory physics students, which includes reasoning that the direction in question is towards an equilibrium [22]. At a higher level of abstraction, diSessa discusses the intuitive idea of *equilibration*, used by high school students in reasoning about heat and temperature topics, which includes the tendency to return to balanced configurations [25]. We believe *differences will eventually even out* may be tapping in to this more basic idea.

2. Macroscopic changes connect to microscopic collisions

Many student responses drew connections between changes at the macroscopic level—such as changes in temperature, pressure, volume, and heat flow—and collisions at the microscopic level. In some cases those collisions were happening between particles within a substance, and in other cases those collisions were happening as particles struck the container walls or the particles of neighboring substances. The connections were often, but not always, explicitly causal. In all these cases we considered students to be using the second resource we identified: *macroscopic changes connect to microscopic collisions*. For example, in response to the *piston* question, one student wrote, "When the gas is heated, this gives the particles more energy and they move with more speed and collide with each other with more force. Not only do they collide with each other with more force, but also the walls of the container and the piston. This is what causes the piston to rise." Here, the student describes particles colliding with the piston with more force as causing the macroscopic movement of the piston. In response to the *cold tire* question, one student writes, "As temperature lowers, gaseous molecules move slower. Therefore, they hit the tire less frequently causing pressure to lower." Here, the student describes a decrease in macroscopic pressure as being caused by less frequent microscopic collisions between the gas molecules and the tire.

Neither example above gives a *complete* picture of how we model microscopic collisions as causing changes in volume or pressure in physics; we would want to consider changes to both frequency of collisions as well as impulse per collision when molecules are moving faster or slower. Nonetheless, the resource *macroscopic changes connect to microscopic collisions* is continuous with the kinetic theory of gases, as students are looking to microscopic collisions to explain changes in macroscopic properties.

This resource relates to some of the common student difficulties identified in previous research. Several studies report that students mistakenly connect collisions between particles to an increase in internal energy [14, 16-18]. While Robertson & Shaffer note that some students attribute pressure of an ideal gas to particle-wall collisions [12], which we see as an appropriate use of the resource *macroscopic changes connect to microscopic collisions*, Kautz et al. describe many ways that students fail to completely and correctly use this microscopic model of pressure [17]. We believe the resource we have identified and these related difficulties identified by others *complement* each other in the space of Knowledge of Student Ideas (KSI). It is potentially helpful for an instructor to see *both* the resourcefulness in students' making connections between microscopic collisions and macroscopic changes in order to build on those ideas *and also* the potential pitfalls that students can be guided around or through in the application of those models [39].

3. When something is hotter (colder), its molecules are moving faster (slower)

The final, and most common, resource we identified was that *when something is hotter, its molecules are moving faster*, or its opposite, *when something is colder, its molecules are moving slower*. "Something is hotter (colder)" included both descriptions of substances being hotter/colder and having higher/lower temperatures or thermal energies, and "its molecules are moving faster (slower)" included descriptions of particles moving faster/slower and having higher/lower speeds, velocities or kinetic energies. For example, one student writes, "...an increase in temperature is caused by the gas particles speeding up." Another student writes, "…the atoms of a hot object have a higher kinetic energy than that of a cold object." This

resource is continuous with the formal physics conception of temperature as a measure of the average kinetic energy of the particles in a substance.

We believe this resource is closely related to the resource *hotter objects have more energy*, identified by Abraham et al. [22]. Young & Meredith also identified that students connect temperature with kinetic energy [23], and Leinonen et al. identify that thermal energy is associated with the motion of particles [14]. Our study supports their findings and adds to the literature on these student ideas by reporting the prevalence of this resource in larger samples and at multiple institutions.

1.5 Conclusion

In this study, we identified three resources introductory physics students use when they reason microscopically about heat and temperature: 1) *differences will eventually even out*, 2) *macroscopic changes connect to microscopic collisions*, and 3) *when something is hotter (colder), its molecules are moving faster (slower)*. These resources were common in student written responses to three different heat and temperature questions given at four different colleges and universities. These findings support, complement, and expand previous work on student conceptions about heat and temperature topics. Instructors may benefit from this research by increasing their Knowledge of Student Ideas (KSI), therefore better positioning themselves to anticipate and notice these resources in the thinking of their students, and then build on these resources in their instruction.

Chapter 2.

Identifying student conceptual resources for understanding physics:

a guided activity for researchers

This activity offers an opportunity to try out our method for identifying *resources*, i.e., *ideas that are expressed by students that can be framed as continuous with formal physics,* in students' written responses to questions about heat and temperature, following the steps outlined in the corresponding paper [1].

You may work through this activity alone or with one or more collaborators.

Step 1: Collect students' written responses to open-ended conceptual questions

We asked open-ended heat and temperature questions to introductory physics students at multiple universities and collected their written responses. Beginning in Step 2, you'll analyze a small subset of these responses. In this activity we've chosen to focus on student responses that can be interpreted as including microscopic reasoning, where students often refer to particles, molecules, atoms, etc.

Step 2: Identify student conceptual resources specific to individual questions

Here you'll look at a small number of responses to identify the ideas students appear to be using in them. By the end of this step you'll have a preliminary list of question-specific resources that you'll go on to synthesize in Step 3.

2.A. Here's the first question prompt you'll look at responses to:

Tire Question:

It became suddenly very cold last night. You start your car in the morning to go to work and get a warning light indicating that your tire pressure is low. You check the tires carefully, and there is no sign of any puncture.

You remember from class that the ideal gas law (PV=nRT) says that temperature and pressure are related, so you hypothesize that because there was a sudden decrease in temperature, there must also have been a decrease in pressure.

What is another way (using something other than the ideal gas law) to make sense of what happened with your tire?

You'll start with just one student response:

Student A:

"As the temperature goes down, the gas molecules inside the tire will slow down in speed, so less hitting the side of the tire, thus pressure goes down."

What ideas do you notice in this student's response? Make a list for yourself. Keep in mind that at this point you do not need to attend to whether these ideas are correct or incorrect (or anything in between).

Your list of student ideas:

Here are some of the ideas we noticed in Student A’s response:

- Gas molecules slow down as temperature goes down.
- Slower molecules hit the sides of the tire less often.
- When molecules hit the sides of the tire less often, the pressure goes down.

You may have noticed some of the same ideas we did. You may also have noticed different ideas, or you may have focused on different aspects of the ideas listed here. We chose to focus in our list on ideas that involve thinking at the microscopic scale, which you may or may not also have done. Our expectation is not that the ideas we all are identifying should be the same, but that we are all (i) trying to make sense of what students are saying and (ii) keeping the level of specificity of the ideas we name “close” to the level of specificity in the student’s response at this point.

2.B. Now you’ll continue your list by looking at more student responses.

What ideas do you notice in the student responses below? Make a list of these ideas, and for each one, include one or more examples of student responses where that idea appears, in order to share what you’re noticing with collaborators.

Note: Even with only 5 responses, a list of every idea that you notice in these responses could be very long. Our eventual goal is to have a list of resources, that is, *ideas that can be framed as continuous with formal physics*. As such, attend particularly to ideas that you are able to connect to learning goals an instructor might have for the topic of heat and temperature. This doesn't mean the ideas need to be 'correct', only that you can trace a path between the idea and a learning goal.

You also may start to notice the same ideas – or very similar ones – in multiple responses, in which case you need not write the idea down multiple times. As you include more and more student responses in your set, you may start to tweak the way you describe an idea in your list so as to capture multiple students' thinking. As you do that, you'll want to stay attentive to keeping your descriptions as close to the ideas that students are articulating as possible.

> Student B:
>
> *"Since particles of gas have no potential energy and are all kinetic, the pressure they exert stems from the speed of their collisions. Since the particles become colder, their kinetic energy lowers, making those collisions less powerful, thus lowering the pressure."*

> Student C:
>
> *"The decrease in temperature causes the volume of the gas to decrease due to less movement (less kinetic energy). Less movement means less collisions with the walls of the tire, meaning that not all of the space will be occupied in a single instantaneous moment of time. So this will create a decrease in pressure."*

Student D:

"Because it's colder, the particles become more tightly packed so it's not pushing on the inner surface of the tires as much."

Student E:

"As the temperature decreases outside, the thermal energy of the gas particles will also decrease. As this thermal energy decreases, the speed of the gas particles will slow down, causing less force during collisions with other particles and with the walls of the tire. Less force $\propto$ lower pressure, since $P=F/A$"

Student F:

"The molecules of air are moving slower so they collide with the walls of the tire with less force"

Your list of student ideas (with examples):

Here's a list of some of the student ideas we noticed at this point:

- Particles move less as temperature decreases.
    - Example: "*As the temperature goes down, the gas molecules inside the tire will slow down in speed*" (Student A)
    - Example: *"The decrease in temperature causes the volume of the gas to decrease due to less movement (less kinetic energy)"* (Student C)
- Particles have less energy when the temperature is lower.
    - Example: *"As the temperature decreases outside, the thermal energy of the gas particles will also decrease."* (Student E)

    - Example: "*Since the particles become colder, their kinetic energy lowers*" (Student B)
- Slower particles collide with less force.
    - Example: *"The molecules of air are moving slower so they collide with the walls of the tire with less force"* (Student F)
- Slower particles collide less often.
    - Example: "*As the temperature goes down, the gas molecules inside the tire will slow down in speed, so less hitting the side of the tire*" (Student A)
- Particles take up less space when the temperature is lower.
    - Example: "*Because it's colder, the particles become more tightly packed*" (Student D)
- Pressure decreases when particle collisions are less powerful.
    - Example: "*Since the particles become colder, their kinetic energy lowers, making those collisions less powerful, thus lowering the pressure.*" (Student B)
    - Example: "*As this thermal energy decreases, the speed of the gas particles will slow down, causing less force during collisions with other particles and with the walls of the tire. Less force* $\propto$ *lower pressure, since P=F/A*" (Student E)

Again, your list probably has both commonalities and differences with our list, and our expectation is not that the ideas we all are identifying should be the same. In fact, one benefit of having collaborators for this research is to share and discuss the different ideas that we each notice. There is no need to reach any sort of consensus at this point, although it is helpful to be able to justify your interpretation of a student response to collaborators.

While you only looked at six student responses here, we'd typically look at 10% of the responses in a complete data set, which is often far more (perhaps 15-30 responses). With a larger number of responses, it's more likely that you would start to develop a sense for which ideas are coming up again and again.

2.C. Next you'll repeat this process with a set of student responses to a different question prompt.

Once again, make a list of the ideas you notice in the following student responses and include examples of each idea you note, focusing primarily on those ideas which you see as continuous with formal physics. You might approach this as making a new list from scratch, or as adding to the list you made with the Tire Question responses. Either way, the goal at this step is still to stay close to the ideas that students are articulating with a minimal level of abstraction. Because resources are context-sensitive, it is possible that the ideas you notice here will be quite different from the ones you noticed in the Tire Question responses.

> Piston Question:
> *An ideal gas is in a container that is closed on the top by a movable piston. The gas is now heated, so that the temperature goes up. As this happens, the piston moves up. Use ideas about microscopic gas particles and interactions to explain why this happens.*

Student Q:

“When gas is heated, the gas molecules gain energy. When molecules gain energy, they move faster & have more collisions.This in turn, moves the piston up since they collide with the piston more often. So basically when it is heated, gas will expand to move the piston up.”

Student R:

“The gas molecules are colliding more violently with the piston in an upward direction, moving the piston up and decreasing pressure so it is not pushing up as hard.”

Student S:

“As you heat the gas, the particles of the gas begin to move faster. As they move faster, more and more particles collide with the piston, imparting momentum to the piston. As this continues, eventually the particles move fast enough and collide often enough with the piston that they begin to move it.”

Student T:

“Since the piston moved up when temperature got hotter that means the pressure inside the container increased. The gas particles gained more thermal and kinetic energy, making them move faster.”

Student U:

”At the microscopic level, gas particles move around and bump into the walls of the container and also bounce off of each other. When the gas is heated, the gas particles

have more kinetic energy, so they will collide with things with more force. Since they collide into things with more force, that force will have more of an effect on the piston and will push it higher."

Student V:

"When the microscopic gas particles are heated the particles will gain energy. Therefore the particles become more active and will want to expand. As a result, the gas will push the movable piston to increase volume.

Your list of student ideas (with examples):

Here's a list of some of the student ideas we noticed at this point:

- Heating the gas causes the particles to gain energy.
    - Example: *"When the microscopic gas particles are heated the particles will gain energy."* (Student V)
- Heating the gas causes the particles to speed up.
    - Example: *"As you heat the gas, the particles of the gas begin to move faster."* (Student S)
- Faster particles collide more frequently.

    - Example: "*When molecules gain energy, they move faster & have more collisions"* (Student Q)
- Particles with more energy collide with more force.
    - Example: "*When the gas is heated, the gas particles have more kinetic energy, so they will collide with things with more force."* (Student U)
- Particles with more energy want to expand.
    - Example: "*When the microscopic gas particles are heated the particles will gain energy. Therefore the particles become more active and will want to expand. "* (Student V)
- Increased particle collisions with the piston move the piston upward.
    - Example: "*As this continues, eventually the particles move fast enough and collide often enough with the piston that they begin to move it."* (Student S)
    - Example: *"The gas molecules are colliding more violently with the piston in an upward direction, moving the piston up and decreasing pressure so it is not pushing up as hard."* (Student R)

Once again, our expectation is not that your list will be identical to this one. Our list is meant to serve as a helpful comparison to the list you produced.

Step 3: Reduce the preliminary set of (specific, often fine-grained) candidate resources into a smaller set of (often coarser-grained) common conceptual resources for understanding heat and temperature

Now you are ready to take the full preliminary set of finer-grained, question-specific resources that you've made in Step 2 and collapse them into a smaller number of coarser-grained resources which will become your set of resources for coding.

The goal is to identify a limited number of resources (5 or less) that (i) you expect to be common in the student responses of the data set based on what you've seen so far, that (ii) are stated abstractly enough to appear in the responses to multiple question prompts, and that (iii) you believe instructors might be able to recognize and use as helpful starting places for building toward introductory physics learning targets.

3.A. Look back over the student ideas you identified in Step 2 from the two different question prompts. Which of those ideas might be meaningfully grouped together into a single resource, despite coming from different question prompts? For example, are there some essential qualities that some of the ideas share? Are there ways of grouping some of these ideas that might help others see their resourcefulness or continuity with particular conceptual learning goals?
Note: The goal is not to fit each idea from your previous lists into a new grouping. Instead, you're allowing yourself a new level of abstraction, if necessary, to highlight the possible commonalities and resourcefulness of some of those ideas in a way that may be slightly less context-dependent.

Your groupings of student ideas:

3.B. Take a look at each grouping you've made. For each one, consider:

- What is the fundamental idea that this group shares, and in what way do you see that idea as continuous with formal physics? For example, our focus was on microscopic reasoning in heat and temperature, so we aimed for resources that we believe can connect to formal physics ideas in the kinetic theory of gases and/or statistical physics.

- What are the boundaries of what is included in this grouping? The clearer the boundaries are articulated, the easier finding agreement in coding this resource during Step 4 will be.

For example, what sort of student language would you accept as evidence that this resource is present in a student response? What related ideas do you consider to be separate from this resource?

- What phrase might you use to articulate this resource and label this grouping? The goal is to aim for language that can both (i) mimic what a student might say or agree with, if they heard their own thinking rearticulated in that form, and also (ii) resemble the formal physics being taught in introductory physics courses.

Step 3 typically involves iteration and collaboration as you discuss what you think the final resources should be and the reasons for and ramifications of those choices.

Here are two resources that we settled on:

1) When something is hotter (colder), its molecules are moving faster (slower).
2) Macroscopic changes connect to microscopic collisions.

The first resource groups together the idea that 'Particles move less as temperature decreases' from the Tire Question and the idea that 'Heating the gas causes the particles to speed up' from the Piston Question. We chose to include within this resource reasoning where students describe something as heating up (or cooling down), even if they don't explicitly mention temperature. We also chose to include 'Heating the gas causes the particles to gain energy' and 'Particles have less energy when the temperature is lower' in this category *if* they specifically reference kinetic energy, as we believe the students in our sample typically connect kinetic energy to movement. We might have chosen to focus on energy rather than movement with this resource, but we felt that movement might be more central to the microscopic picture we're hoping to promote. A similar resource that does focus on energy ("Hotter objects have more energy") was also previously identified in another paper [2].

The second resource groups together the idea that 'Pressure decreases when particle collisions are less powerful' from the Tire Question and the idea that 'Increased particle collisions with the piston move the piston upward' from the Piston Question. We also chose to include in this grouping multi-step reasoning where a change in temperature leads to changes in particle motion or energy which then leads to a change in the frequency or force of collisions. This resource reflects that students are frequently using collisions to draw connections between what is

happening to particles at a microscopic level and the changes that are happening at the macroscopic level given in the question prompts.

While there is no ‘correct’ set of resources that everyone should have identified at this point, it is during this step that you and your collaborators come to consensus about what set of resources *you* will be using as you move forward together into coding. In order to keep coding manageable, limit yourself to a set of 5 resources or less.

Your final set of resource(s):

Step 4: Test and refine preliminary coding scheme

In this step, you'll be coding a subset of the data with the resources you and your collaborators decided on in Step 3. This step of coding is to check whether you and your coding partner have a shared understanding of what does or does not fall into each resource code and to negotiate that understanding in places where you find you don't yet have consensus.

4.A. If you haven't already, pick a final resource or set of resources that you'd like to use for coding. If you have a coding partner, you may choose a set of resources or a single resource that you came up with, the set that we came up with above, or a combination of both. If you are doing this as an individual, you may use the two resources we give in Step 3 so that you can compare your thinking with us.

4.B. Go back through each of the 12 student responses shared in Step 2. Decide and record whether each response contains sufficient evidence for each of the resources in your coding scheme. *Do this step independently from your coding partner.* Consider making notes for yourself on the decisions you make, particularly if you feel unsure. Look back at descriptions of the resources and what they include and do not include from Step 3 as often as you wish.

	CODER 1				CODER 2			
	Resource 1	Resource 2	Resource 3	Notes:	Resource 1	Resource 2	Resource 3	Notes:
Student A								
Student B								
Student C								
Student D								
Student E								
Student F								
Student Q								
Student R								
Student S								
Student T								
Student U								
Student V								

4.C. Once you've made your own independent judgements for each of the student responses, compare with your coding partner. Take note of how often you agreed for each resource that you coded. Discuss and resolve any inconsistencies. Make notes about how your understandings of the resources have changed as a result of these discussions.

If you are using the two resources we give in Step 3, you can compare your judgements with ours in the table below:

Resource 1: When something is hotter (colder), its molecules are moving faster (slower)

Resource 2: Macroscopic changes connect to microscopic collisions

	CODER 1			CODER 2		
	Resource 1	**Resource 2**	**Notes:**	**Resource 1**	**Resource 2**	**Notes:**
Student A	1	1				
Student B	1	1				
Student C	1	1				
Student D	0	0	Student says 'it's not pushing on the inner surface of the tires as much' which might be a reference to the push from collisions, but might be something else. Decided Resource 2 was absent			
Student E	1	1				
Student F	1	1				
Student Q	1	1				
Student R	0	1				
Student S	1	1				
Student T	1	0				
Student U	1	1				
Student V	0	0	'active' might mean more motion, but it might mean something else. Decided Resource 1 was absent. 'the gas will push the moveable piston' might be in the form of particle collisions, but might not. Decided Resource 2 was absent.			

4.D. Once you are confident that you and your collaborator will have high levels of agreement (percentage agreement > 85%), you would continue on to the final steps of coding. Remember, while you coded all of the responses given in this activity, those 12 responses are meant to represent a small subset (<10%) of the total student responses in a larger data set. The coding of a complete set of data would not come until the final steps.

Final Steps

From here, assuming that you'd come to a high level of agreement in Step 4, you and your collaborator would go on to independently code the full set of data and calculate your percentage agreement using the formula in our full paper.

Your final resources, including their descriptions and examples, their prevalence in your data set as determined by your coding, and the percentage agreement of that coding, would then be ready to report to the research community.

The question prompts, student responses, and resources used in this activity come from Alesandrini et al. 2022 [2]. You can find more information about our final resources, their prevalences, and our percentage agreement there.

Chapter 3.

Types of explanations students use to explain answers to conceptual physics questions

3.1 Introduction

When answering conceptual questions in physics, students are often asked for explanations to go with their answers. They are asked to "explain their reasoning," or more simply, to "explain." We as instructors and/or researchers may have a clear idea of what we are asking of them, but it is not clear that they understand the task in the same way that we do. For example, in the context of an exam or homework assignment, we may intend for introductory physics students to justify why the answers they have given are correct using physics principles, and we may score their explanations according to how well they accomplish this task. Some students offer responses that are well matched to this expectation, even if they are only partially successful in it, but others appear to be attempting something else entirely. In this research, we examine written explanations students give to support their answers to conceptual physics questions on homework and exams in the introductory physics classes at the University of Washington. We are interested not in the correctness of the content they offer, but in the variation that exists in the ways that students explain. In this paper, we will focus on different types of explaining that we find students do when asked to explain their reasoning.

We set out to investigate the ways that students explain their reasoning in order to gain insights that may prove helpful in improving instruction aimed at helping students explain their answers in ways that more closely match our expectations. We want our students to be able to use physics to create logical chains of reasoning that justify their answers. By knowing more

about the explanations that our students give, we may be able to better tailor instruction to bridge the gap between where they are initially and where we would like them to be. This is somewhat analogous to the logic behind investigating students' prior conceptions of a particular physics topic; instruction that addresses the thinking our students are already doing can improve instructional outcomes [1, 2]. Furthermore, if we consider student explanations that are submitted for grading to be a reasonable approximation of what they consider to be 'good reasoning,' or at least the most worthy of sharing of the reasoning they are doing on a given problem, our findings may provide insight into what students find satisfying in explanations or what they consider to be sufficient reasoning to reach, or accept, an answer.

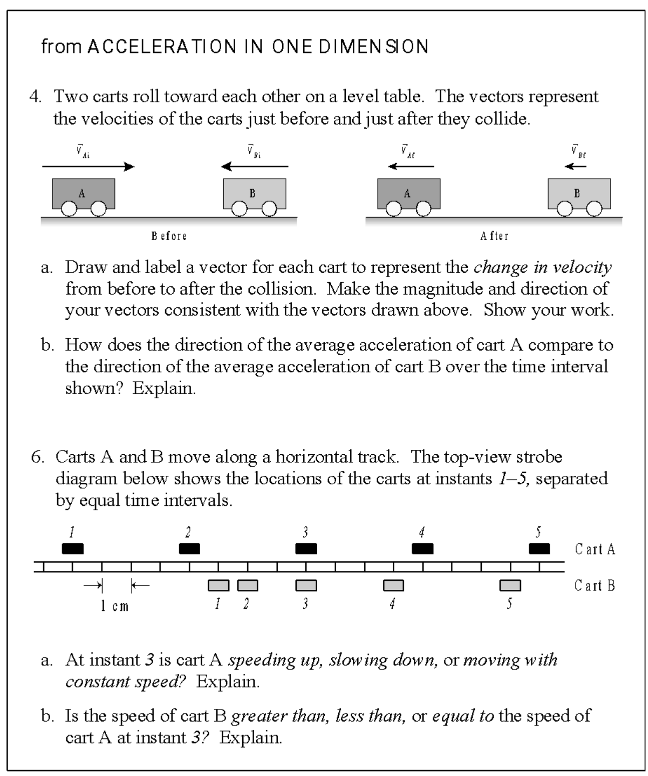
Previous research has been done on the scientific explanations students construct to make sense of physical phenomena. For example, Yeo and Gilbert [3, 4] present a multidimensional framework that categorizes scientific explanations in terms of function, form, and level, which they apply in interview settings where high school students are asked to explain a specific physical phenomenon. Touger et al. [5] offer three categories for written student explanations to open-ended "what if..." questions: formula- driven, intuitive, and hierarchical. Formula-driven explanations proceed with algebraic manipulation from formulas; intuitive explanations use real-world terminology and are typically qualitative; hierarchical explanations use governing concepts and often involve multiple representations. The questions students are asked in such research are more broad and open-ended in scope than in our work, with the variable(s) to be analyzed largely unspecified. Instead of asking students to explain a phenomenon, our students are asked to answer a specific question and then explain that answer (see Fig. 3.1 for example questions).

Other research has been done on how students use argument in the science classroom using Toulmin's model of argumentation [6], where arguments are labeled and analyzed in terms of claims, warrants, grounds, quantifiers, rebuttals and backing. Arguments can then be fruitfully compared by attending to which of these features are present and what plays the role of each included or implied feature. While some of the explanations that students give in our research could very effectively be compared under such an argumentation framework, others are interesting precisely because they appear to be doing something other than making an argument. At this point we are more interested in the nature of students' own explanations than in the degree to which they diverge from those of "experts," or from some expected form.

3.2 Context and Methods

In this work, we examined the written explanations students gave in response to conceptual physics questions on homework and exams, post relevant instruction, in introductory physics classes at the University of Washington (UW). Questions were chosen in which no calculations were necessary and a minimal number of reasoning steps were required to reach the answers. The first set of explanations analyzed were from the first tutorial homework of the first quarter of the calculus- based introductory physics sequence on the topic of acceleration in one dimension [7]. Tutorial homework assignments are associated with the weekly tutorial sessions at UW, which supplement lecture instruction and allow smaller sections of students to develop conceptual understanding of physics topics in small groups. A sample of 93 student submissions of this first tutorial homework was collected from 5 tutorial sections chosen at random out of the total 26 sections taught that quarter. Examples of student explanations used in this paper are

taken from this homework, and the relevant questions from this homework are included as Fig. 3.1. Students had received very minimal instruction and no formal feedback on what is expected for written explanations before completing this homework. We chose this as a starting place because we expected to see variation in explanations more plainly at this stage than in successive assessments.



from ACCELERATION IN ONE DIMENSION

4. Two carts roll toward each other on a level table. The vectors represent the velocities of the carts just before and just after they collide.

a. Draw and label a vector for each cart to represent the *change in velocity* from before to after the collision. Make the magnitude and direction of your vectors consistent with the vectors drawn above. Show your work.

b. How does the direction of the average acceleration of cart A compare to the direction of the average acceleration of cart B over the time interval shown? Explain.

6. Carts A and B move along a horizontal track. The top-view strobe diagram below shows the locations of the carts at instants *1–5,* separated by equal time intervals.

a. At instant *3* is cart A *speeding up, slowing down,* or *moving with constant speed?* Explain.

b. Is the speed of cart B *greater than, less than,* or *equal to* the speed of cart A at instant *3?* Explain.

FIG. 3.1 Questions from the homework. Note: When responding to question 4b, students will have already determined change-in-velocity vectors for both carts.

As our aim is to capture the variation that exists in student explaining, a phenomenographic approach was taken [8]. In the analysis, more attention was paid to ways in which student explanations varied from each other than to ways in which they varied from what an "expert" might offer in the form of a solution. The initial emergent coding identified variation in the *forms* the explanations took (e.g., words, diagrams, equations), the *features* present in the explanations (e.g., specialized vocabulary, narrative elements, references to the physical situation

of the problem or its representation), and the *types* of explaining present. Here we focus on the variation in *types* of explaining: the different ways in which an explanation supports an answer or connects that answer to other ideas. The next round of emergent coding, then, was used to group different *types* of explaining. These categories were revised after analyzing other homework and exam questions in different introductory physics courses at the University of Washington and in different physics contexts (primarily mechanics) in order to reflect categories that exist across different student populations and physics topics. The first author made the initial categorizations, and the second author was able to corroborate proposed categories on sample data before the categories reached this stage of finalization.

In line with a phenomenographic approach, the intention is not to categorize students by means of their explanations, but rather to categorize the *ways of explaining* that are evidenced in the pool of student explanations as a whole. Thus, individual students may do more than one type of explaining within a single homework or within a single explanation. We are also not, at this point, interested in the relative frequency of these types, but rather a depiction of the variation that is present.

3.3 Preliminary Results

What follows is a list of types of explaining that we find students are doing in their written explanations. These types reoccur, demonstrate the breadth that exists within type, and may inform future research and instruction. More than one type of explaining is often present in a single explanation. All explanation types may be used in support of either a correct or incorrect answer. (Please refer back to Fig. 3.1 for the questions used in the examples.)

(1) "You might think" explanations - These center around features of the question that might tempt someone else to come to a different conclusion than the responder has. Rather than staying limited to why a chosen answer is correct, these may explore why a different answer is incorrect. *Example 1, in response to homework question 6b:* "Less than because even though they are in the same position at the same time, cart B started at a different position than cart A and cart A is still increasing its displacement faster than cart B." Here, the student is pointing out that the carts "are in the same position at the same time," not because their own answer depends on it, but to acknowledge its irrelevance to their answer. They answer as they do "even though" this feature is present, that is, in spite of whatever competing answer this feature might suggest.

(2) Process explanations - These describe the steps taken, often in abstract form, to arrive at an answer. They do less to justify the answer directly than to offer the reader a process by which the answer can be found. *Example 2, in response to homework question 6b:* "Less than. If you draw a line from instant two to instant three for both cart A and B, then the line would be longer for A." Here, the student is instructing us what we need to do ("draw a line from instant two to instant three for both cart A and B") in order to determine the answer as they have.

(3) Contextualizing explanations - These take an approach beyond the physics topic at hand. They might describe what causes the answer to be true, relate the outcome to a potentially analogous 'real world' situation, or use previously learned physics concepts. In doing so, they bring in a broader context that justifies or corroborates the answer. (Note: The following example responses came before any instruction of forces had occurred in this course or its prerequisites.) *Example 3A, in response to homework question 4b:* "They go in opposite directions, as the collision pushed them apart." This student tells us what causes their answer to be true ("the collision pushed them apart"), rather than explaining in terms of kinematics. The degree to which

this student's notions of pushes impacting motion is based on formal dynamics instruction from a previous physics course or from intuition from real-life experience is unclear. *Example 3B, in response to homework question 4b:* "The acceleration directions are opposite because a force coming from the opposite direction caused them to slow down/ go the other way." Here, the student sees the accelerations of the carts as caused by forces, which they likely learned about in a previous physics course. Their answer, then, is related to a larger context that goes beyond the instruction they have so far received in class.

(4) "Expert" explanations - These include statements of what physics principles were used to arrive at an answer, how those physics principles are relevant to the situation presented in the question, and therefore what the answer must be. For the purposes of this research, an explanation is considered this type if it is structured in this way, whether or not a correct answer has been reached. An explanation offered as a full-credit solution by the instructor would likely be of this type. *Example 4A, in response to homework question 4b:* "Since average acceleration is the change in velocity divided by the time interval, carts A & B have an opposite direction of change in velocity, therefore the direction [of] their average acceleration is opposite as well." This student states a relevant definition for the quantity they are asked about ("average acceleration is the change in velocity divided by the time interval") and connects it to the problem at hand ("carts A & B have an opposite direction of change in velocity") to justify their answer. *Example 4B, in response to homework question 6a:* "Cart A moves with constant speed. Cart A is consistently 4 cm apart for each time interval. Δposition/Δtime is the same, so velocity, and subsequently speed, is constant." This student identifies a feature of the scenario ("Cart A is consistently 4 cm apart for each time interval"), then relates it to the quantity being asked about ("Δposition/Δtime" and so velocity and speed) in order to justify their answer.

(5) Salient features explanations - These identify features of the scenario (e.g., types of motion, events, comparisons between variables) that are offered in support of the answer. While many explanations include features of the scenario as part of a larger explanation, and therefore could be said to contain this kind of explaining, some explanations are remarkable because they include nothing else. For example, these explanations may be like "expert" explanations that fail to mention the underlying reasons why these features connect to the answer given. *Example 5A, in response to homework question 4b:* "The [directions of the average accelerations are] opposite since cart A changed direction but cart B didn't change direction." Here, the student has identified whether each of the carts has changed directions or not, which is relatively easy to see from the question prompt, as the feature that leads to their answer. No more justification is given. *Example 5B, in response to homework question 4b:* "The Ave acceleration of A cart should be [in the] same direction as cart B cuz they move in same direction after [the] collision." This student identifies the final direction of motion of the two carts, which is given in the diagram, as the feature that leads to their answer. No more justification is given. *Example 5C, in response to homework question 6a:* "Constant speed, the strobe carts are evenly spaced." This student points out the spacing of the images of the cart apparent in the question diagram. The relevance of this feature is left unexplained.

(6) Description explanations - These tell more about the answer, perhaps giving other details about a variable in question or about what happens next, focused on taking us beyond the answer more than how the answer was determined or why it makes sense. *Example 6, in response to homework question 4b:* "A's average acceleration is negative, B's is also negative but smaller." Rather than simply state their conclusion that the average accelerations are both in the same direction, this student supplies additional information about those accelerations, namely,

that both are negative and that one is smaller than the other. This provides more details about the variable in question without describing how any of this is known.

3.4 Discussion and Future Research

There is considerable breadth in the types of explaining students include in their written explanations. The mode of explanation we as instructors typically aim for, that of connecting physics principles to the particulars of a question prompt and demonstrating how they lead to a particular answer, is one type out of many.

We assume that all students did more thinking than what they wrote down in their explanations, and our analysis is purposefully limited to what was written explicitly. That is, we envision the thinking that a student does when determining an answer and the explaining that a student does when writing an explanation as two distinct, although interrelated, processes. As such, there are likely interesting complexities in student reasoning hiding within individual explanation types. In particular, those students who gave salient features explanations are likely to have used different types of reasoning to connect the features they mention to the answers they give. What they have in common is their choice not to put that part of their reasoning down in writing. A next stage of research will be conducting student interviews to investigate how students are reasoning as they make an answer choice compared to what they chose to write down. We also hope to gain insight into the degree to which they are actively considering their instructor audience as they write an explanation as well as what students value or find lacking in particular explanations.

As instructors, we see value in many of the student explanation types, even as we hope that students who provide explanations of these types can additionally give us "expert" explanations. For example, "You might think" explanations are powerful in refuting what might be a tempting intuitive choice; being able to talk oneself out of those answers, or explain to a classmate why the seemly obvious choice is not correct, is also something we would like our students to be able to do. Process explanations reflect important knowledge about the mechanics of completing a problem that we often offer to our students at some point during instruction and that students might find useful in offering to each other. Contextualizing explanations are ones we might hope that our students use to predict an answer or to double check an answer that has been justified with an "expert" explanation. In this way, contextualizing explanations can help our students incorporate knowledge from one physics topic into a larger framework that spans other parts of physics as well as life outside of the classroom. Our purpose need not be, then, to eliminate these types of explaining from our students' repertoires. Instead, similar to the approach of a resources framework for conceptual understanding [9], we may consider the types of explaining that our students are already doing as something that we as instructors can build upon. Our instructional goals might then be to contextualize when and where these different forms of explanations might be advantageous and where they may fall short of what is required. Simultaneously, we might also aim to make clear how powerful we find "expert" explanations to be and make the case for why we consider an "expert" explanation the best choice in the contexts that we require it (or grade based on it) in our courses. Further investigation of the utility of this approach is possible.

An additional argument for addressing these different types of explaining more explicitly in classroom instruction comes from the work being done using dual process theories of

reasoning [10-13]. According to this framework, a heuristic process is always our starting place in approaching a problem, and necessarily, our intuitions influence the outcomes of our thought processes. A second, analytic process only comes into play to the degree that it seems necessary to justify, check, or override our initial intuitive response. Helping students to know, then, when the reasoning they have done is sufficient to give them well-earned confidence in their answers is a worthy goal. For example, a salient features explanation might be enough to justify an answer with high confidence in a topic area where a person has developed expert intuition (that is, where their heuristic process is likely to be correct). However, a student might be clued in to a need to do additional thinking in order to be sure of an answer if they find they are only able to supply a salient features explanation in a topic area where they do not have such expertise (that is, where their heuristic process is just as likely to be incorrect). Additionally, acknowledging the role that other non-“expert” explanations might play in all of our thought processes and making space for them in our classroom conversations might positively impact student metacognition in terms of awareness of the strengths and pitfalls present in their own thought processes.

Further investigation could also center around the generalizability and prevalence of different types of explaining over time, across different student populations, physics topics, and/or question types. This might look like coding for student explanation types and comparing frequencies in different samples as well as looking for additional types that were not detected in our sample. We will also be investigating how instructors and graders explain their own reasoning, including the extent to which the explanations produced by these “experts” fall into the category which we have preliminarily called “expert” explanations. Additionally, we will investigate their views of student explanations.

Chapter 4.

Modes of explanation students use when explaining answers to conceptual physics questions

4.1 Introduction

Students are often asked to explain their reasoning in introductory physics courses, and being able to use physics principles and logical reasoning steps to solve conceptual physics problems is a common, if not explicit, learning goal. When we (as researchers or instructors) ask students to provide written explanations for their answers to conceptual physics problems, we may envision this as a small additional step - students are simply capturing in writing the thinking they have already done. Not all students experience it this way. For example, during an interview with an introductory physics student, Sarah[1], solved a conceptual physics problem and gave a concise, complete, and correct oral explanation to her answer. When Sarah was next prompted to provide a written explanation, she remarked, “That’s the hard part!”

In this study, we aim to better understand how and why students write the explanations they do. Initially in our analysis, we considered what qualities students said they liked or disliked in written explanations. While students in our interviews named several features they look for, different students often valued opposite extremes of the same dimensions (e.g., concise vs thorough, simple language vs technical terms, more words vs more diagrams or equations). Students who expressed the same likes also disagreed on how they should be enacted (e.g., brevity might be the goal, but there are different opinions about what can be left out). Our study therefore focuses on how students operationalize the task of making written explanations, which motivates why a more concise or thorough explanation might be preferred, for example, or which

[1] We use pseudonyms when referring to individual students in this study.

pieces are considered essential. We consider the aims that students have for their explanations, the audiences they imagine writing their explanations for, and the correspondence between the thinking they do in arriving at their answers and what they write down. In order to capture the variation present, we use phenomenography as our method of study.

This work follows a previous study in which we examined the written explanations to conceptual physics problems submitted by students in introductory physics classes. In that study, we attended to the variation present in the ways explanations support an answer or connect that answer to other ideas [1]. We identified six different types of explanations: “you may think,” process, contextualizing, “expert,” salient features, and description explanations. The analysis in this prior work was on the final product of student explanation making, the written explanation itself, whereas the study presented here considers the process and aims of students in their explanation writing.

4.2 Context and Methods

In order to map the variation present in how introductory physics students approach the task of writing explanations, we conducted interviews and phenomenographic analysis as described below.

4.2.1 Interviews

We conducted interviews with 23 students during weeks two or three of the first quarter of the calculus-based introductory physics sequence at the University of Washington (UW). At this point, students had very minimal guidance on how to write explanations in this course and

had not yet received feedback on the first homework they had submitted that contained written explanations. All students enrolled in the course were given an opportunity to volunteer for the interviews, and all volunteers who were able to schedule interviews during the targeted window of time were included in the study.

The semi-structured interviews were approximately 30 to 45 minutes in length. In the first part of the interview, the student completed a conceptual physics problem (identifying the direction of acceleration for a block connected to a spring with a given strobe diagram - see Appendix A) that included an ask to “explain your reasoning.” The students were prompted by the interviewer to think aloud as much as possible while solving the problem and then were prompted to give a written response to “explain your reasoning” if they did not do so unprompted. All of the 23 students interviewed were able to reach the correct answer (the acceleration points to the left) with varying levels of ease, and all students provided a written explanation with varying levels of detail. If necessary, the interviewer clarified which parts of what the student had written would be included as an explanation if the problem were submitted as a homework assignment. The interviewer then asked open ended questions about how the student wrote their explanation (e.g., What thinking goes into what you write down for your explanation? How do you go about writing an explanation? Are there particular things you are aiming for?).

In the second part of the interview, students were given five sample responses to the physics problem they had just solved and were asked what they liked or did not like about each of them (also included in Appendix A). The sample responses all had the correct answer but varied in the type of explanation presented [1]. The interviewer then asked open-ended questions

about what the student looks for in explanations in general, and what the student thinks physics instructors are looking for in explanations.

In the final part of the interview, students were given a list of nine different prompts that might be used in the place of "explain" (e.g., *Justify your answer*, *Why does your answer make sense?*, *How did you arrive at your answer?*- see Appendix A). Students were asked if they considered any of them to be equivalent or if they would respond differently to them.

4.2.2 Phenomenographic Analysis

Phenomenography is used to describe the collective experience or understanding of a phenomenon, drawing on the breadth and variation in individual experiences to create an expansive picture of the thing being studied [2]. In this study, we use individual interviews to map the variation present in our sample in order to describe the phenomenon of writing explanations to conceptual problems in introductory physics.

Our phenomenographic analysis began by gaining familiarity with the interview data and compiling significant statements from the interviews about students' conceptions of explanations. We identified multiple dimensions of variation: the *aims* students have for their explanations, the imagined *audiences* they describe writing their explanations for, and the relationship between their final written explanations and the *processes* they initially used to determine their answers. Once the many elements present in these dimensions of variation were mapped out, we recombined them to create a limited number of coherent and discrete descriptions of what we see students doing when they create written explanations. This output of

the analysis (called "categories of description" in phenomenography) are the modes of explanation we describe as our findings.

While these modes of explanation are meant to span the space of what we see students doing and thinking in our sample, they are not meant to map neatly to individual students; a single student may switch between multiple modes of explanation while solving a single physics problem. Which mode or modes were used by a student is also not necessarily clear from the final written explanation produced. These modes are abstracted forms of what students *do* in their explanation making *collectively*. While we might wish to quantify the usage of different modes in the future, that is beyond the scope of this study.

In phenomenography, categories of description are also meant to logically relate to one another. Often this logical relationship takes the form of a linear hierarchy. In our case, the four modes we identify are ranked along two dimensions: how central physics concepts are to their purposes, and how central a clear reasoning pathway is to their purposes. By reasoning pathway, we mean a series of connected reasoning steps that link the problem givens with the problem solution. We describe these relationships further in our findings.

4.3 Results

4.3.1 Modes of Explanations

We find four modes of explanation present in our sample, summarized in Figure 4.1 and described in detail below.

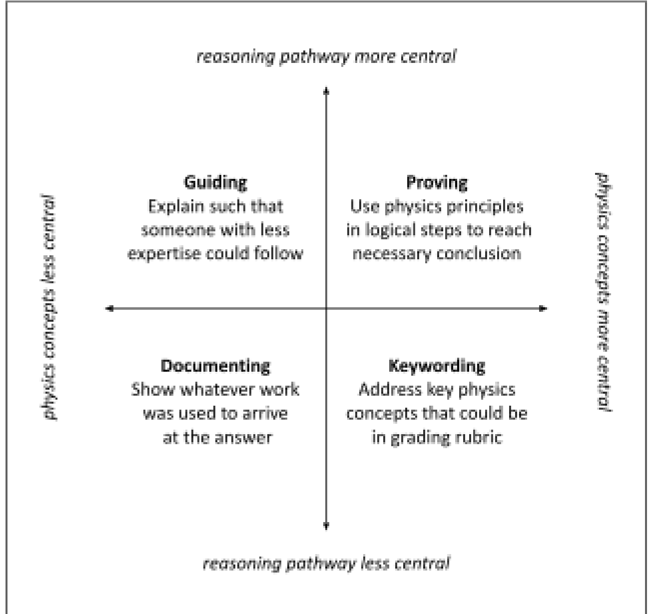


FIG. 4.1. Four modes of explanation, *documenting*, *guiding*, *keywording*, and *proving*, arranged by the degree to which physics formality and reasoning pathways are central to their purposes.

1. Documenting

When using this mode in writing an explanation, students are primarily concerned with documenting the thinking that they do when figuring out the answer. The pathway they take may be circuitous, and there is little or no attempt to edit or curate what goes into the final written explanation. In this way, the process students use to arrive at the answer is well represented by the final explanation given. The changes that are made in the written explanation after the answer has been found are often adding labels or otherwise making what is already there more legible to an outsider; they are cosmetic rather than substantive.

An imagined external audience is less central to this mode, and being authentic to oneself may matter more. One student, Chelsea, described explaining your reasoning as something that is personal to *you*, and Shaye emphasized how her explanation was about how it made sense to *her* to get the answer she did. William does bring up graders as a potential audience while

documenting in that making your reasoning transparent to graders allows them to more easily catch and correct your mistakes. Thoroughness is valued over conciseness (there is no need to keep things brief or to the point), but only steps that the student is aware of or finds value in will be included: what goes without saying in the students' thinking will also go without being written down in the explanation. Physics concepts, diagrams, and relationships are likely used as helpful tools in these explanations, but the primary goal is not to showcase them. The degree to which the explanation uses technical terms, equations, and diagrams is a reflection of how helpful the student finds them rather than a sense that they are more or less virtuous than common language or intuitive understandings.

2. Guiding

In this mode, the goal is to provide an explanation to the answer that could be followed by someone whose expertise is less than or equal to the expertise of the student. The reasoning pathway is intended to be clear enough for an external audience to follow and understand. When using this mode, a student is likely to work out their answer first and then write down what reasoning they consider to be essential; the pathway the student takes to arrive at their answer may be distinct from their written explanation.

There is a strong sense of an imagined audience in this mode, and many of the students we interviewed brought up what audience they envisioned unprompted. During his interview, Ethan described this mode as being able to explain your answer to a fifth grader. When explaining, Mehdi will try to "do it in a way that would make sense to anyone." William brought up explaining to someone who was new to physics. Andrew considers if he were helping friends, what does it take for them to understand. Rebecca considers, "for a person who didn't actually

learn this, they need to understand…" in order to decide what to write down. For this audience, there is virtue in being both thorough and concise: including enough that a novice audience can follow and not overwhelming them with details or tangents. Everyday language is valued over technical terms. Diagrams that help the reader visualize what is going on might be helpful, but words are likely preferred over more mathematical work.

3. Keywording

When *keywording*, students aim to demonstrate that they understand or have used key physics concepts with their explanations. Like in *documenting*, there is less concern with providing a clear and direct reasoning pathway that arrives at the answer. Instead, students using this mode are concerned with hitting whichever physics ideas seem central to the problem, often explicitly considering what a grader would be looking for or what the instructor or problem-writer intended to address with the problem. Students using this mode may sketch out an initial explanation as they work out the answer and then go back and edit or add in any big ideas, key equations or relationships that they think might be relevant that they had previously missed.

Audience is central to this mode of explanation, and students are picturing themselves as performing for graders or instructors. They are 'doing school' as much as they are doing physics. Sarah talks about making sure to address whatever has been talked about in lecture. Mario mentions the goal of making your explanation as easy for graders as possible, and Jonathan mentions that graders are looking for key words and ideas. Patrick aims to identify what the question is looking for and what is going to get a lot of points. Conciseness might be nice but is less important than making sure to say the right things. Andrew advises to keep writing to cover

all your bases until you think you will get a good score. Several students mention paying attention to how much space you are given in determining how much to write. Others mentioned how context mattered in both how much and what they would include in their written explanations (test vs homework, physics vs other classes, one instructor vs another) as the expectations of their audience shifts in different settings. Using formal physics terminology and representations are central to this mode of explanation, as demonstrating proficiency with them is the primary goal.

4. Proving

This mode of explaining may be most aligned with what instructors *hope* their students will do when writing an explanation to an answer in physics. The aim is to construct a logical pathway from the problem's givens to the final answer by applying physics ideas. Students in this mode may first figure out the answer and then separately write the explanation as a distinct step in which they more carefully 'prove' that answer correct, often catching mistakes and missed steps in their initial thinking as they write. In some cases, they may pick an entirely different approach to the problem in writing than in initially determining the answer.

The imagined audience in this mode may be less explicit and more abstract. It can be as though students are aiming to satisfy the discipline of physics itself. In his interview, Lawrence describes explanations as 'like geometric proofs' and argues about what should be included based on what is important in physics, as he sees it (e.g., general laws that can describe all situations). Debussy refers to what is more 'serious,' and Pinecone refers to what is more 'scientific' in the approaches they choose to take or the representations they choose to use in

their explanations. There is a preference for the precision of physics terms, graphs, and equations in this mode. These explanations are meant to be both complete and concise.

It is important to note that while students using this mode may intend to be adopting the values and practices of the discipline of physics, these are introductory students who are not yet experts in the field. What they view as important, obvious, or correct in their approaches may not always match more expert thinking. For example, both Debussy and Pinecone were able to articulate two ways of determining the direction of the acceleration of a block in the problem they were given during the interview, one involving analyzing the forces on the block and one involving analyzing the motion of the block as seen in a strobe diagram. Debussy considered using forces to be the more ‘serious’ and therefore appropriate approach, and Pinecone considered using the strobe diagram as more ‘scientific’ and therefore preferable. Both approaches are canonically correct in physics and either can be employed seriously and scientifically. Students are using their conceptions of best physics practices, even as they learn them.

4.3.2 Using explanation modes in combination

As the four modes of explanation presented here are abstracted categories of description, individual students may move between modes while writing a single explanation to a conceptual physics problem. In this section, we give an example of a student, Marcus, who uses both *documenting* and *keywording* during his interview.

Marcus began by *documenting* as he solved the physics problem given during the interview. He made sketches and wrote words as he determined his answer. When asked about

what he chose to include in his written explanation, he gave a quick oral summary of his thought process in solving the problem and stated that he does not include in the written explanation the parts that he thinks can be taken for granted. He said, “Generally, just, I think, if I can understand it, if I come back to it later, and I can understand what’s going on, that’s pretty good for me.” He is his own primary audience, and he is aiming to capture his thinking as he goes.

When his explanation was read back to him, he then decided to add an additional piece of explanation (about how he knew the velocity of the block to be decreasing). When asked about it later, it became clear that Marcus had switched into *keywording* mode. He described that addition as something he would include on a test but not his homework. He said, “I usually, on tests, I’ll try to like, rewrite things in a variety of ways, so that one of them will get the point, or just over explain it sometimes.” He had switched his audience from himself to an imagined grader, and he aimed to include enough in his explanation to score well.

4.4 Discussion and Future Research

While different modes of explanation might be more appropriate for different goals or in different contexts, all four have value and can be built upon. *Documenting* involves recording one’s process, which when done systematically and with precision is an important scientific practice, particularly in laboratory and experimental settings [3]. It can allow others to see a more complete thought process, which can help both with the catching of mistakes as well as normalizing the circuitous routes that we often take while figuring something out [4]. Instructors and researchers may both benefit most from this mode of explaining when the goal is to learn about how students think in all of its messiness. Instructors may also support students in more

purposefully using this mode to develop higher levels of self-awareness of their own thought processes [5, 6].

Guiding is a mode of explaining we commonly practice as instructors and that students can helpfully use with each other. Being able to clearly communicate science knowledge to audiences that do not share your level of expertise is a prized skill in many contexts [3]. This mode of explanation may also relate more closely to the outcomes of student sensemaking, where students have integrated their answer to a problem into a broader understanding of the world [7].

Keywording involves connecting a specific problem to relevant physics content, looking deeper than the surface features present in problems, which is a skill students need to practice and develop [8]. *Keywording* is also a reasonable and practical response to the incentives present in learning within graded course contexts and can remind us that students are responsive to what instructors assign points to. Instructors can be upfront with students about how their work will be graded and make sure that grading rubrics reflect their learning goals in order to better align this mode of explaining with the physics reasoning they aim for students to practice.

Proving is most similar to the intended explanation mode of the physics instructors teaching the students in our sample. Instructors may be able to assist more students in using this mode by explicitly differentiating it from other possible modes of explaining (e.g., “Rather than showing your work, form an argument using physics principles for why your answer must be true.”). As students are drawing on their perceptions of what is valued or considered appropriate in physics when they use this mode, instructors may also more explicitly discuss with students the kinds of reasoning and logic that we aim for when we practice physics.

The mode of explanation that students use impacts what they do or do not include in their final written explanations, but it is not always clear from a written explanation which mode (or modes) of explaining went into its making. Future research could more carefully connect different modes of explanation with different types of written explanations and their different levels of completeness and correctness [1]. For example, all of the students in our interviews were able to arrive at the correct answer to the conceptual physics question they were given. There were students who used *guiding* or *proving* that caught mistakes that they made in originally determining their answer when they set out to more carefully explain it. Perhaps these two modes might therefore be more regularly associated with correct answers. The "you might think" type of explanation, where students explore why a tempting alternate answer is incorrect, may more commonly be present when students use a *guiding* mode of explaining, aiming to help their audience with less expertise avoid a tempting mistake. "Expert" type explanations may or may not be more common when the *proving* vs *keywording* mode is used. These sorts of potential connections could be explored further.

While the focus of this study was on how students *write* explanations of their own, future work could also focus on how students *evaluate* explanations. We saw in our interviews that students have varying skill levels in evaluating the explanations given by both themselves and others, even when their criteria of evaluation was self determined. Being able to assess whether an explanation meets particular standards may be especially important in courses that use alternative grading practices where students are more involved in their own evaluations. Additionally, as students more commonly use ChatGPT and other AI services as a learning resource to generate explanations, being able to effectively evaluate the merits of different explanations may be crucial to students being thoughtful technology users.

Chapter 5.

Instructional material design and students' feelings about their ideas

5.1 Introduction

We know that student ideas impact how learning unfolds during physics instruction [1, 2, 3]. Student intuitions, previous knowledge, and experiences from the 'real world' can shape the approaches students take and the challenges they face in learning physics. This finding has shaped instruction and research in a variety of ways. Among them are two orientations towards student thinking which we will refer to as the 'seeds' approach and the 'obstacles' approach.

Theoretically, one can see in student ideas the 'seeds' of normative physics ideas, which can be cultivated and 'grown' into more complete or sophisticated canonical understandings [see for example, 3, 4]. Instructionally, a corresponding primary goal might then be to elicit, guide, and refine these ideas [5]. In a second orientation, often presented as dichotomous to the 'seeds' approach, one can see the gaps between the reasoning approaches commonly taken by students and the normative approaches we hope to teach [see for example, 6, 7, 8]. Instruction can then be aimed at aiding students through these 'obstacles' or spots of difficulty, unsettling incorrect conceptions and demonstrating the utility of canonical approaches [9].

The 'seeds' approach to student ideas is sometimes associated with the instructional learning goal of helping students see their ideas and experiences as relevant to physics and productive in classroom settings [10]. This sometimes comes with the assumption that a 'seeds' approach will be affirming in a way that will help students feel more positively towards their ideas. The 'obstacles' approach is often associated with instructional strategies that involve

direct confrontation of student ideas: student ideas may be found to be incompatible with observations or physics principles and will therefore need to be corrected [11]. There is also sometimes an assumption that students will feel more negatively when their ideas are contested in this way.

Among the co-authors of this paper are researchers and instructors who have taken both approaches, including sometimes switching back and forth between the two. In all cases, it is our hope that when students think back on the instruction that they have received (and that we have designed), they will recall feeling positively, both as a desired outcome in itself and also because previous research has tied student affect to persistence, motivation, and belonging [12, 13]. We are curious about the feelings students have about their ideas (e.g., *frustration*, *confidence*, etc.) when using instructional materials designed with different theoretical orientations towards student ideas. As student experiences of instruction are not always the same as those intended by curriculum designers, we also want to consider how students characterize the ways their ideas are impacted by instruction (e.g., they *corrected* their thinking, they *clarified* their thinking, etc.), and how instruction described by those different characterizations relate to the feelings students report.

In this study, we designed a survey instrument for students to self report the feelings they had about their ideas when they think back on particular instances of instruction in small group settings (see Figure 5.1.1). The survey also asks students to characterize what happened to their ideas when they think back on those instances of instruction (see Figure 5.1.2). We administered this instrument to students after nine different sessions of instruction in introductory physics courses at two different universities. These nine sessions included instruction using materials

designed with an 'obstacles' aligned orientation (Tutorials in Introductory Physics) and materials designed with a 'seeds' aligned orientation (ACORN Physics Tutorials).

For each statement below, choose how strongly you agree or disagree on the following scale:

1 means strongly disagree,
2 means disagree,
3 means neither agree nor disagree,
4 means agree,
5 means strongly agree

At some point during tutorial this week, I felt ____ about some, any, or all of my ideas.

- ***confused***
- ***encouraged***
- ***confident***
- ***frustrated***
- ***embarrassed***
- like my ideas ***mattered***

Please elaborate on the statement(s) you most strongly agreed with.

FIG. 5.1.1. Survey instrument questions related to student feelings about their ideas, given in summary form. The full instrument can be found in Appendix A.

For each statement below, choose how strongly you agree or disagree on the following scale:

1 means strongly disagree,
2 means disagree,
3 means neither agree nor disagree,
4 means agree,
5 means strongly agree

During tutorial this week, I_________.

- ***corrected*** something that I had been thinking.
- ***confirmed*** something I already knew
- ***learned more*** about something I already knew about
- ***became unsure*** about something I had been thinking
- ***cleared up*** some of my uncertain ideas and thoughts about a topic

Please elaborate on the statement(s) you most strongly agreed with.

FIG. 5.1.2. Survey instrument questions related to student characterizations of what happened to their ideas, given in summary form. The full instrument can be found in Appendix A.

In analyzing the survey results, we take an exploratory look at the feelings students report having about their ideas. We consider if instruction using Tutorials in Introductory Physics appears to be associated with more negative feelings (e.g., lower levels of *confidence* or higher levels of *embarrassment*) and if instruction using ACORN Physics Tutorials appears to be associated with more positive feelings. We also consider if instruction in which students report *correcting* their ideas appears to be associated with more negative feelings. Our findings have implications for how impactful instructional material design appears to be in shaping student

experiences of instruction, as well as what level of generalization is appropriate when considering how an individual session of instruction impacts student affect.

5.2 Background

This study took place as part of a larger research collaboration aimed, in part, at the development of ACORN Physics Tutorials, instructional materials designed to elicit and build on student conceptual resources [14]. In resources theory, resources are pieces of knowledge in learners' minds that are activated in context-sensitive ways [15, 16]. Learning takes place when resources are restructured, synthesized, elicited with different frequency or in different contexts, or formalized. This theory highlights the ways in which student thinking is sensible and student ideas can be seen as generative for formal physics understandings [4, 17]. ACORN Physics Tutorials are therefore an example of materials designed using a 'seeds' approach to student ideas.

ACORN Physics Tutorial materials provide opportunities for students to bring up their conceptual resources about specific physics topics. The materials then aim to support students in developing more sophisticated models, concepts, or mechanisms that include or build from those resources. Students work in small groups to answer conceptual questions and construct models based on their own ideas. One common form of conceptual question used in these materials describes a physical system (e.g., a particular arrangement of bulbs and batteries in a circuit). Students are told what outcome is observed (e.g., how the brightness of the bulbs compare) and asked to explain why that outcome occurs without first being instructed to make a prediction.

By treating the ideas that students have as relevant building blocks for instruction, there is a hope that students will see themselves as bringing fruitful ideas to their physics learning and that they will feel good about their ideas when using these materials. The aims of the ACORN Physics Tutorials, then, are in part affective: that students will have particular experiences of instruction and feel particular ways about their ideas. In evaluating the effectiveness of the materials, we would like to examine the potential affective impacts of instruction in addition to whatever conceptual learning gains may be taking place.

ACORN Physics Tutorials were tested in classrooms that typically use Tutorials in Introductory Physics. Tutorials in Introductory Physics were designed using an 'obstacles' approach to student ideas [18]. They are based on research that identifies common lines of reasoning that can lead students to incorrectly answer conceptual physics questions. The materials target these specific obstacles, often asking students to resolve differences between their observation and predictions they have made or to identify errors in fictional student statements that incorporate common incorrect student reasoning. These and other strategies in the tutorials are sometimes categorized as instances of *elicit-confront-resolve*, an instructional approach that aims to elicit incorrect student thinking that is assumed to be relatively stable in nature; confront the ways that thinking is inconsistent with observation, givens, or other productive lines of thought; and then guide students to resolve those inconsistencies as they build more canonical understanding [11].

Tutorials in Introductory Physics have been shown to be effective in improving student conceptual understanding [e.g., 9, 19, 20]. There have, however, been questions raised about whether instruction using strategies that confront student ideas might lead to negative student outcomes in terms of student affect, epistemology, or relationship to physics. Outside of formal

research, these potential negative impacts appear as a frequent concern. For example, on the PhysPort website, from which different research-based physics materials can be accessed and compared, the following statement is made: “Tutorials confront students' naive intuitions, which may give them a sense that their intuition is always wrong, reducing their confidence and enjoyment of physics [21].” Instructors, including some coauthors, can recall episodes of students feeling negatively after discovering that something that had made sense to them was incorrect during an instructional session using Tutorials in Introductory Physics.

The question is more broad than a specific curriculum or flavor of ‘obstacles’ approach. Authors Smith, et al. argue that in addition to confrontation of student ideas being problematic as a way to conceptualize how student learning happens, “confrontation is also problematic as an instructional model,” in part because it “essentially denies the validity of students’ ideas. It communicates to students that their specific conceptions and their general efforts to understand are fundamentally flawed [3].” They argue instead for the adoption of a ‘knowledge in pieces’ framework that highlights the continuity between novice and expert thinking and for instructional strategies aligned with this view. That is, they argue for the comparative benefit of taking a ‘seeds’ orientation towards student ideas. Warren et al. also raise the possibility of harm in treating student sense-making practices and scientific sense-making practices as discontinuous, voicing concern that students’ sense of themselves as learners and thinkers might be diminished if their ideas are portrayed as incompatible with science [22]. Both the works of Smith, et al. and Warren, et al. are proposing frameworks to aid in analysis of (and appreciation for) student thinking and sense-making; neither presents empirical evidence of negative affective outcomes tied to particular instructional practices.

There are also examples of instructors highlighting the affective or epistemological goals that motivate them to take 'seeds' oriented approaches in their teaching and instructional design. Hammer described how taking a 'seeds' perspective (in this case, p-prims) on student knowledge rather than an 'obstacles' perspective (misconceptions) allows him to coordinate multiple agendas he has in his teaching, including promoting appropriate student epistemologies and students' confidence in themselves as scientists. He writes, "Often, these other agendas provide reasons for caution with respect to confrontation as an instructional strategy. To contest students' reasoning, for example, may dissuade them from participating or from believing that their ideas and experiences are relevant [10]." In a paper with Elby, Boudreaux considers the advantages of taking up a 'seeds' orientation (in this case, conceptual resources) to improve a draft of a physics tutorial [23]. He mentions the potential benefit to allowing students to refine their ideas, rather than just identify them as incorrect, as it might boost students' confidence in their own thinking as productive.

Following this logic, one could imagine that students experiencing instruction with ACORN Physics Tutorials might feel more confident and encouraged about their ideas and that they might feel more like their ideas matter. In contrast, students experiencing instruction with Tutorials in Introductory Physics might feel more corrected in their thinking as well as more embarrassed or frustrated about their ideas. In this study, we set out to see if we observe effects such as these.

To be clear, we do not attempt to capture differences or similarities in student outcomes that would generalize to all instruction coming from 'seeds' or 'obstacles' orientations. We also do not take on potential impacts to student epistemologies or physics identity. We limit ourselves to an exploratory look at how a sample of students feel about their ideas when thinking back on

instruction they experienced using materials designed with a 'seeds' approach (ACORN Physics Tutorials) and materials designed with an 'obstacles' approach (Tutorials in Introductory Physics). This study then serves as a test case of sorts for how instructional design and student feelings about ideas may interact in measurable ways, and it may serve to inform further empirical investigations.

5.3 Literature Review

This study investigates the feelings students report having and the characterizations students offer about their ideas in introductory-level university physics instruction. Previous research has been conducted on student epistemologies in physics settings, which are relevant to how students view the relationship between instruction and their ideas [27]. Work has also been done considering epistemic affect, which includes how students feel while their ideas are being challenged or transformed [28]. Other STEM (Science, Technology, Engineering, and Math) fields also have research related to students' reception of new types of instruction and how students perceive the instruction they experience [24-6].

For example, DeMonbrun, et al. developed the StRIP (Student Response To Instructional Practices) survey to measure student satisfaction and resistance to different teaching techniques in STEM courses [24]. The survey asks students to characterize a course as interactive, constructive, active, and/or passive, and it has them evaluate their instruction in terms of effectiveness, enjoyment, and their level of participation. The StRIP has been used to distinguish between different types of active learning (group vs individual) in engineering courses and to measure how resistant to active learning, on average, students in particular courses are [25].

Meant to capture students' reception to shifting from traditional to active learning strategies, it is used at the level of a course rather than a class session. It has a single scale for positivity but does not consider individual feelings.

Further work has been done where students characterize the instruction they receive and the factors involved in those characterizations. In the context of chemistry, Barger, et al. gave students a 10 item survey on the extent to which they perceived a course as constructivist [26]. The authors found that students' initial epistemic beliefs were predictive of their perceptions of how constructivist a classroom environment was. They additionally found that an instructors' practices do not always align with students' experiences of those practices. This points to the importance of asking students directly for their experience of instruction, rather than assuming it from instructional design alone.

In physics, the CLASS (Colorado Learning Attitudes about Science Survey) is commonly used as an assessment of student beliefs about physics and about learning physics [27]. Its items probe student epistemic beliefs with questions that are relevant to the relationship between a student's ideas and instruction (e.g., "To understand physics, sometimes I think about my personal experiences and relate them to the topic being analyzed" and "I cannot learn physics if the teacher does not explain things well in class"). The CLASS does not ask for students' impressions or feelings around a particular course or instance of instruction. Instead, it aims at the generalizations students make about physics and physics learning, and can be used to measure how those generalizations shift in response to instruction, usually on the timescale of a course or course sequence.

There is plenty of education research that points to the importance of student feelings in educational settings, including the relationship between feelings and motivation, persistence,

belonging, etc. [12, 13]. More specific to science education and to student ideas, Jaber and Hammer claim that affect is inherent to the disciplinary practice of science and present case studies that show some of the ways in which student feelings are bound up in scientific inquiry in elementary school classrooms [28]. For example, scientists feel joy, frustration, curiosity, confusion, etc. as we make observations, develop models, and seek understanding in our disciplines. Part of what students are experiencing, and gaining familiarity with, in a science classroom are the affective elements that come hand-in-hand with scientific practices. This work points towards the importance of attending to *epistemic affect* in the classroom and the possibility of guiding its development in particular ways. For example, science learning can include becoming familiar with the feeling of having one's ideas challenged and getting comfortable presenting unpopular ideas.

Sawtelle and Turpen use a case study to illustrate the interactions between student affect, epistemology, and identity in a student's developing relationship to physics [29]. A student's understanding of what kinds of knowing or learning 'count' within a discipline both shapes and is shaped by the ways a student feels in or about a discipline. The 'kind' of person a student describes themself to be in relation to a discipline also both reflects and impacts their affective responses in that discipline. Sawtelle and Turpen's research takes place in the context of a physics for life science course with a biologist-identifying student, and they highlight the role educators and curriculum designers can play in creating interdisciplinary learning environments that support students in positively transforming their relationships to physics. This includes finding ways to build on students' existing knowledge and expertise and giving accolades to students for success and progress. They also call on future researchers to attend to the identities and affective orientations students bring into these spaces.

Our study takes from these previous works the importance of attending to student affect and the need to ask students for their own perceptions of the instruction they receive. We extend this research by focusing on student perceptions of individual class sessions, rather than entire courses, and looking specifically at the interaction between student ideas and instruction.

5.4 Methods

We began this study by asking two questions about students' perceptions of the impact of instruction on their ideas:

1. What feelings do students report having about their ideas when they think back on particular instances of instruction in small group settings?
2. How do students characterize what happened to their ideas when they think back on particular instances of instruction in small group settings?

The first stage of this research was to find what students give as common answers to these questions, and then to develop a multiple-choice type survey instrument using those common answers in order to ask these questions to a large number of students post-instruction.

The second stage of this research was an exploratory look through a large number of survey responses, as well as classroom video data, in order to better understand students' feelings and characterizations of the impacts of instruction on their ideas.

In this section, we discuss the institutional and instructional contexts for our research, the development and validation of the survey instrument, the collection of survey data and supplemental video data, and the analysis of those data.

5.4.1 Research setting

This study examines university level introductory physics instruction where students are working in small groups. Our research was conducted primarily at University A, a small private university in the western United States, and University B, a large public research-intensive university in the western United States. University C, a mid-size public university in the western United States, also served as a site for administering a draft of the survey.

5.4.2 Survey considerations

We chose to ask students directly about what happened to their ideas and how they felt about their ideas during instruction as our primary means of assessing impact rather than using researcher inferences based on classroom video, for example. This reflects our interest in the student experience of instruction, which can be distinct from the perspective of an outside observer. When assessing something like conceptual learning gains, one might be primarily interested in external measures (e.g., are students more able to rank the current flow through different elements of a circuit after instruction) independent of students' perceptions of how much they learned. In this case, however, it is the meaning that students make of instruction and their feelings that we are examining. We did review classroom video alongside students' self-reports as a means of better understanding, from the perspective of an outside observer, the context in which they had the experiences they self-described.

Emotions are multi-component, coordinated processes with affective, cognitive, motivational, expressive, and peripheral physiological aspects [30]. In our study, we do not try to capture the complexity of emotions or specify what qualifies as which feeling for each student.

Instead, we limit ourselves to the student self-report of feeling. Students may not be fully aware of all the emotions they are experiencing, including those that influence their behavior and outlook. By having students self-report their feelings, we may have an incomplete view of the emotions at play during instruction. What we are best capturing are the feelings that students remember themselves experiencing.

We chose to construct a survey to use as our primary means of data collection in order to include a larger number of student voices in our study. This allowed us to have a broader sense of what is typical and possible than we would from a more limited number of interviews, for example. It does, however, limit the depth to which we understand the experience of any individual student.

We chose to administer our survey after the relevant session of instruction (i.e., one tutorial lesson) was complete, but before a week had passed. We are not trying to capture the in-the-moment feelings students have while taking part in instruction, but rather what feelings are memorable or present for students when instruction is over and they reflect back on their experiences. In the Control-Value Theory of achievement emotions, a distinction is made between activity emotions, which one experiences during an academic or goal-driven activity, and outcome emotions, which one experiences either in anticipation of or when reflecting back on an activity or outcome [30]. We are interested in the latter. We also want to capture the feelings students have that are still tied to specific moments of instruction for which the details have not yet been forgotten, so the connections between the specifics of instruction and the emotions are still relatively clear.

5.4.3 Survey development and validation

We developed our survey for the context of group instruction in introductory university level physics courses in order to describe student experiences of instruction, both in general and when different instructional materials are used. We do not assume our survey can be meaningfully used outside of this context, for different purposes, or with student populations that do not well match the student populations of the universities in our data set. We describe the development of the survey and present validity evidence in order to aid in the interpretation of survey results - that is, to help in the understanding of what the survey is measuring, where there is ambiguity, and what can be meaningfully asserted using the survey results. The categories for validity evidence used below are taken from Standards for education and psychological testing [31]. A final version of the survey instrument is included in Appendix A.

1. Content validity evidence (alignment of items and content they intend to measure):

Our intention is to capture students' perceptions of what happened to their ideas, and how they felt about their ideas. We therefore want our survey prompts and answer choices to be grounded in the ways students describe their experiences of this instruction. We thus began with student interviews. Eight students from University A were asked about how their ideas were impacted by instruction that used Tutorials in Introductory Physics, referencing the most recent of students' sessions of tutorial instruction. The interviews were semi-structured and approximately half an hour in length. Two researchers, CM and AA, identified themes around idea change from these interviews (e.g., students were *adding to / building from* an

understanding, *replacing / rejecting* a previous way of thinking, *becoming confused* about something that had once seemed clear, etc.).

The themes from the interviews became the basis for a first draft of a written survey with multiple-select questions (e.g., "*I came into the tutorial thinking a thing, and I built something new out of that thing*" and "*I came into the tutorial thinking one thing, and the tutorial challenged that way of thinking*") and short answer explanations (e.g., "*For each of these that you selected, say what the thing you thought originally was (if anything), say what you think now, and then say what affirmed, challenged, or added to that thing*"). The first survey draft was then administered online at University A and B after instances of small group instruction.

Next, we broadened our survey questions, drawing on the content of students' short answer responses to the first survey draft, theoretical work on emotions [30], and our own senses of what other options might more completely span the space of possibilities, to create an updated draft of the survey. For example, '*encouraged*' was added to the feeling options after it was expressed by students. "*I came into the tutorial thinking a thing, and the tutorial challenged that way of thinking*" was split into "*During the tutorial, I replaced an idea that I had with a new one*" and "*During the tutorial, I became unsure about something that I had been thinking*" to better differentiate between the experience of having an idea become unsettled and the possible resolution of changing one's way of thinking. This second draft was then administered at University A, B and C, again with a multiple-select and short answer format, after instances of small group instruction.

We then created a final draft of the survey to more closely resemble student language in its prompts and answer choices, based on students' short answer responses to the previous draft (e.g., '*affirmed*' became '*confirmed*,' '*replaced*' became '*corrected*,' '*added to an understanding*

that I had' became '*learned more about something I already knew about*,' etc.). This final draft was administered at University B. Through this iterative process of asking students questions about their experiences and then modifying our questions based on their responses, we believe our final survey matches well to what we hope to measure, namely students' perceptions of what happened to their ideas and how they felt about their ideas during small group instruction.

2. Response process validity evidence (how respondents interact with items):

In order to better understand how students interact with our survey, we conducted a second set of student interviews. This time we had nine students from University B respond aloud to the questions of our final draft survey and tell us about how they interpreted the questions and why they answered the way they did. We analyzed these interviews to identify places where students diverged in the ways they engaged with or interpreted the survey, which could lead to ambiguity in how we should interpret student survey responses. For example, we found that with the multiple-select format, some students would select every option that they experienced to any degree, while others would only select the ones that felt the most important. This led to us changing our questions from multiple-select (where students are limited to selecting or not selecting each option) to Likert scale (where students choose a level of agreement for each option) in the final survey. We also looked for any hesitation with or disconnect from the constructivist framing of our questions, i.e., checking that students were comfortable seeing themselves as coming to class with ideas that were then impacted by instruction. We did not observe any evidence of trouble with this framing. We also gave students the opportunity during the interview to call out if there were ways their ideas were impacted by instruction that were not

well reflected in the answer choices provided. This served as another check that our provided answer choices reasonably span the space of experiences for the students in our sample.

In addition to the student interviews, students' responses to the short answer questions in the final survey also provide evidence that students are interacting with our survey in ways that are consistent with our expectations. For example, we have reviewed these short answer responses to aid our interpretations of student Likert scale responses, helping us better understand what students mean by the options they choose.

3. Internal structure validity evidence (how items relate to each other):

Our survey is designed to be short, without multiple items to probe the same construct. Descriptive statistics are therefore more appropriate than quantitative analysis of the survey results. This is sufficient to address the exploratory research questions we aim to answer in this study. While a longer survey could be designed for more inferential claims, for which a formal factor analysis would be appropriate, that is beyond the scope of this current work. Nonetheless, there are potential correlations between the survey items that we can look for as a check on whether survey items relate to each other as expected. For example, we would expect that in a situation where one's ideas were confirmed, one might also be more likely to feel confident about one's ideas, and that in a situation where one became unsure of their ideas, one might also be more likely to feel confused about their ideas. Reassuringly, 'confirmed' most highly correlates with 'confident' (Spearman's rho = 0.46) in our data, and 'unsure' most highly correlates with 'confused' (Spearman's rho = 0.41). A table of correlations for all items can be found in Appendix B.

4. Relations to other variables (how items relate to outside variables):

We also have expectations of relationships between our survey results and outside variables that we can use to check if our survey is functioning as expected. Our intention was to develop a survey that is sensitive to differences in instruction; student survey responses should therefore have the potential to vary depending on the type of instruction students receive. We therefore compare survey responses after two broadly different types of small group instruction: laboratory instruction and tutorial instruction. For example, Figure 5.4.1 shows survey results for two instances of instruction during the same week at University B (see section 5.4.5 Data Analysis for more about interpolated medians). The same students during the same week give different responses to the survey items for the laboratory session than the tutorial session. The interpolated medians for multiple items differed by nearly 1 (i.e., *corrected* and *cleared up*), while other items (i.e., *unsure* and *confident*) differed little. The range of answers we get with the same sample of students provides evidence that our survey is sensitive to differences in instruction.

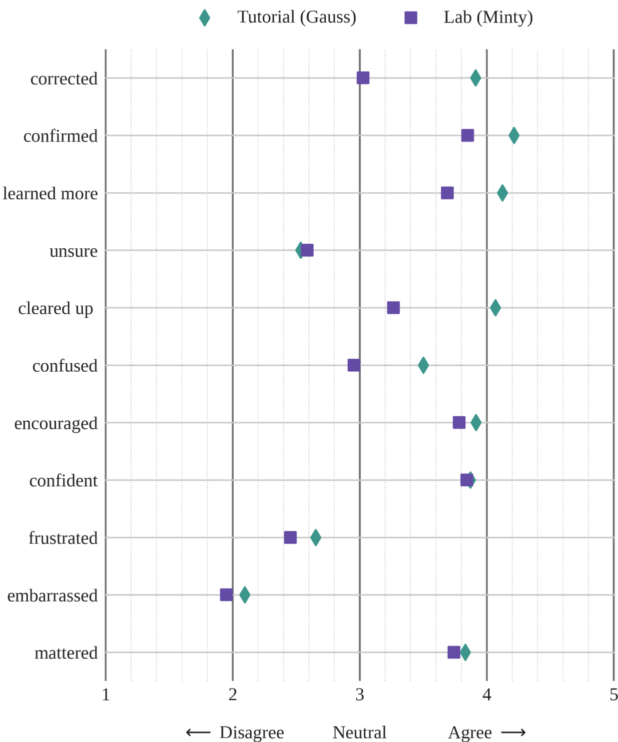


FIG. 5.4.1. Interpolated medians for student survey responses after a tutorial session and lab session given in the same week at University B

Relatedly, we assumed that the feelings and idea changes that students report will vary from session to session rather than being stable for a given individual across different sessions of instruction. Appendix C includes plots of survey responses for five sessions of instruction for each of the 50 students at University B who completed all five administrations of our survey. Individual students did in fact typically respond with different levels of agreement to the survey questions for different sessions of instruction. Over the five surveys given, individual students typically varied their answers across 3 responses for each survey item given (e.g., from 2 Disagree to 4 Agree or from 3 Neither Agree nor Disagree to 5 Strongly Agree). This provides

evidence that our survey is sensitive to individual students' different experiences with different sessions of instruction.

Finally, we were able to do video analysis in support of our survey analysis. There were eight students at University B for whom we have both survey responses and classroom video recording for a session of instruction using an ACORN Physics tutorial. By watching the video for these students, we can compare the students' speech, gestures, and interactions with what appears in their survey responses. While these students very rarely spoke directly about their feelings or what was happening to their ideas in the video, we see behavior that we might expect to correlate with particular survey responses. For example, we see students who reported their ideas being *corrected* revising their thinking and erasing and rewriting answers. We see students who reported feeling *confident* about their ideas being outspoken within their group or with their instructors.

5.4.4 Survey Administration

The final survey was administered after four different sessions of instruction at University A and after five different sessions of instruction at University B.

1. University A

The final survey was administered during the first and second quarter of a calculus-based introductory physics course sequence in the 2022-2023 academic year. Classes occurred for an hour and twenty minutes three times a week and for an additional hour and fifty minutes once a week. These courses were taught in a studio style, with active learning, including laboratory and

tutorial activities, integrated throughout the courses with students working in small groups for the majority of class time. Each session was taught by a professor with the support of two undergraduate Learning Assistants who had previously taken the course. The courses enrolled 41 and 42 students.

All students in the courses were encouraged to take the surveys directly after the targeted episodes of instruction and were separately given the opportunity to consent to the research study. Approximately half of the students enrolled in the courses participated as research participants in taking the surveys. Surveys were administered after the following:

- Quarter 1 (N23, TiIP):
  "Newton's second and third laws" from Tutorials in Introductory Physics
- Quarter 1 (Energy, other):
  "Energy" from unpublished University A small group activity
- Quarter 2 (Momentum, ACORN):
  "Force and momentum in collisions" from ACORN Physics Tutorials
- Quarter 2 (Pressure, TiIP):
  "Pressure in a liquid" from Tutorials in Introductory Physics

The number of surveys taken after each session of instruction in our sample is given in Table 5.4.1.

At University A, demographic information was taken from a questionnaire students filled out in the final quarter of the course sequence. According to this data, our sample underrepresents students who chose "Not of Hispanic/Latinx/Spanish origin" for ethnicity (64% of students in our study vs 80% of students in course), and students who selected "Yes" to having a parent with a 4 year degree (36% of students in our study vs 54% of students in the course).

Our sample slightly underrepresents students who chose "Man" as their gender (44% of students in our study vs 51% of students in course), and students who chose "White" alone as a racial category (44% of students in our study vs 51% of students in the course). Our sample also slightly overrepresents students who selected "No" to having a parent with a 4 year degree (36% of students in our study vs 29% of students in course). It is worth noting, however, that a higher percentage of students in our sample did not respond to demographic questions than for the course overall (20% no response from students in our study vs 10% no response from students in the course). All other differences in sample vs course percentages for Gender, Ethnicity, Race, and First Gen Status were <5%.

Table. 5.4.1. Number of surveys taken after each session of instruction at University A and University B

University A		University B	
N23 (TiIP)	N=26	Gauss (TiIP)	N=108
Energy (other)	N=20	Minty (lab)	N=106
Momentum (ACORN)	N=25	EPC (TiIP)	N=88
Pressure (TiIP)	N=20	Circuits (ACORN)	N=74
		RC (lab)	N=70
Total University A	N=91	Total University B	N=446
Total University A and B			N=537

2. University B

The survey was administered during the second quarter of a calculus-based introductory physics course on electromagnetism in Autumn of 2022. Students in the course had an interactive lecture for 50 minutes three times a week, small group tutorial sessions for 50 minutes

once a week, and laboratory sessions for 110 minutes once a week. There were two different lecture sections that quarter, each with a different lecturer. The laboratory and tutorial sections of both of these sections, however, were overseen together by a third party. In the tutorial and lab sessions, students typically worked in groups of four students, with two Teaching Assistants (TAs) managing a classroom of no more than 32 students. In both lab and tutorial, students typically maintained the same groups and had the same TAs throughout the quarter. The TAs were most often physics graduate students, although some sections had undergraduate TAs.

All students in the course, a total of 467 students, were given an opportunity to enroll in the study, and 140 students enrolled. Students were given a $15 gift card to participate. 123 students completed at least one survey and 50 students completed all five. Surveys were administered online during weeks 4, 6, and 10 of an 11 week quarter. Students were emailed a link to each survey after they had completed the corresponding instructional session: one for tutorial and one for lab in week 4, one for tutorial in week 6, and one for tutorial and one for lab in week 10. The surveys became inactive at the end of the week. Students received one reminder email to complete the survey, if necessary, during that time. The instructional sessions surveyed were as follows:

- Week 4 (Gauss, TiIP):

  "Gauss's law" from Tutorials in Introductory Physics
- Week 4 (Minty, lab):

  "Minty particles empirical modeling" from Novel Observations in Mixed Reality
- Week 6 (EPC, TiIP):

  "Electric properties of conductors" from Tutorials in Introductory Physics

- Week 10 (Circuits, ACORN):

  “Circuits” from ACORN Physics Tutorials

- Week 10 (RC, lab):

  “RC circuit model” from an unpublished University B reformed lab curriculum

The number of surveys taken after each session of instruction in our sample is given in Table 5.4.1.

We took all volunteers for our study rather than selecting a representative sample. The final course scores of students who participated in the study from University B were nearly comparable to the larger set of students in the course (Mean 78.1 SD 9.2 for participants vs Mean 76.0 SD 12.1 for students in the course who did not participate, t-test $p = 0.0783$). Our sample was less representative in terms of demographics. There are a larger percentage of students who mark the ‘F’ box for gender in our sample than for the course as a whole (49.6% F, 50.4% M vs 37.4% F, 62.6% M). There are a smaller percentage of students who are classified as ‘Underrepresented Minority (URM)’ or as ‘International (Int)’ by University B’s Office of of the Registrar in our sample than for the course as a whole (10.5% URM, 1.6% Int, 87.9% not URM vs 12.7% URM, 9.0% Int, 78.2% not URM) [32]. We therefore consider our sample to be a reasonable approximation to the course as a whole in terms of student academic success in the course, but the voices of students categorized as ‘International’ and ‘M’ in particular are underrepresented compared to their prevalence in the course.

5.4.5 Data Analysis

1. Survey Analysis of Likert Scale Questions

We aim to describe how students respond to the survey questions in a given condition (e.g., having received instruction using ACORN Physics Tutorials or reporting that they *corrected* their ideas during instruction). We use stacked bar charts to represent the distributions of survey responses and interpolated medians to represent the central tendency of the responses. The interpolated median [M_i = median + (# of responses above median - # of responses below median)/(2 x # of responses at the median)] is a measure used for ordinal data like ours to show the extent to which the data is more heavily weighted above or below the median. For example, an interpolated median of 2.7 would correspond to a median of 3 (Neither Agree nor Disagree) with a higher number of 1 or 2 responses (Disagree or Strongly Disagree) than of 4 or 5 responses (Agree or Strongly Agree).

When more carefully scrutinizing differences between groups, like between survey responses where students have expressed agreement vs disagreement with *corrected*, we use the common language effect size of 'risk difference'. This describes how much higher the 'risk' of a particular outcome is for participants in one group (the 'exposed' group) compared to another (the 'control' group). 'Risk' is defined as the proportion of participants who report the outcome in question. In our study, when making such a comparison, we consider binary categories of survey responses that either express agreement (i.e., selected 4 Agree or 5 Strongly Agree) or disagreement (i.e., selected 2 Disagree or 1 Strongly Disagree), leaving out students who were neutral (i.e., selected 3 Neither Agree nor Disagree). This may serve to emphasize differences present in the data compared to an analysis that includes those who were non-committal about their experiences.

2. Supplemental Video and Survey Short Answer Analysis

In order to better understand and illustrate the experiences of students reported in the Likert scale survey questions, we reviewed student responses to the short answer survey questions and classroom video data. Analysis of the short answer survey questions included categorizing and coding for what factors students mention when describing the feelings they had (e.g., the physics topics in the lessons, interactions with their peers, interactions with the TA, etc.). Two researchers discussed and came to consensus about these emergent categories and what word markers would be considered sufficient evidence for their presence.

Classroom video data consisted of eight different students for whom we had survey responses working with their respective groups to complete the ACORN Physics tutorial at University B. Two researchers watched the videos both before and after reading the student survey responses, logging what they noticed in student actions, speech, body language, and interactions that might point to how the students in question might be feeling or might characterize what was happening to their ideas. The researchers discussed their observations and possible interpretations, challenging and expanding each other's perspectives as much as looking for consensus. While we defer to students as experts of their own experiences, we were able to supply plausible interpretations for when and in what context students might be having the experiences reported in the survey, and to constrain our assumptions about what a particular student experience might look like.

5.5 Findings and Discussion

Here, we present an exploratory look at the feelings students report having about their ideas when thinking back on instruction. First, we do not find that the Tutorials in Introductory Physics (developed within the ‘obstacles’ paradigm) correspond to more negative affective outcomes than the ACORN Physics tutorials (developed within the “seeds” paradigm) in our sample. Second, instruction in which students agreed that they *corrected* their ideas does not appear to be associated with more negative affective outcomes in our sample than instruction in which students disagreed that they *corrected* their ideas. We also find that students typically report agreement to many feelings during one session of instruction, often including both positively-valenced and negatively-valenced feelings, and that students often bring up their peers and instructors when elaborating on when or why they felt the ways they did.

5.5.1 Student experiences of ACORN Physics Tutorials and Tutorials in Introductory Physics

Students at both universities in our sample reported higher levels of agreement to positively-valenced feelings than negatively-valenced feelings when thinking back on sessions of instruction using both ACORN Physics Tutorials and Tutorials in Introductory Physics. Figure 5.5.1 below shows the interpolated medians for the survey items about student feelings. Students generally reported agreement to having felt *encouraged*, *confident*, and that their ideas *matter*. They generally reported disagreement to having felt *embarrassed* about their ideas. Students at University B were slightly more likely to report disagreement to having felt *frustrated* about their ideas, and students at University A were slightly more likely to report agreement. Students at both universities generally reported agreement to having felt *confused* about their ideas. Stacked

bar charts showing the complete distributions of student responses for each of the items can be found in Appendix D.

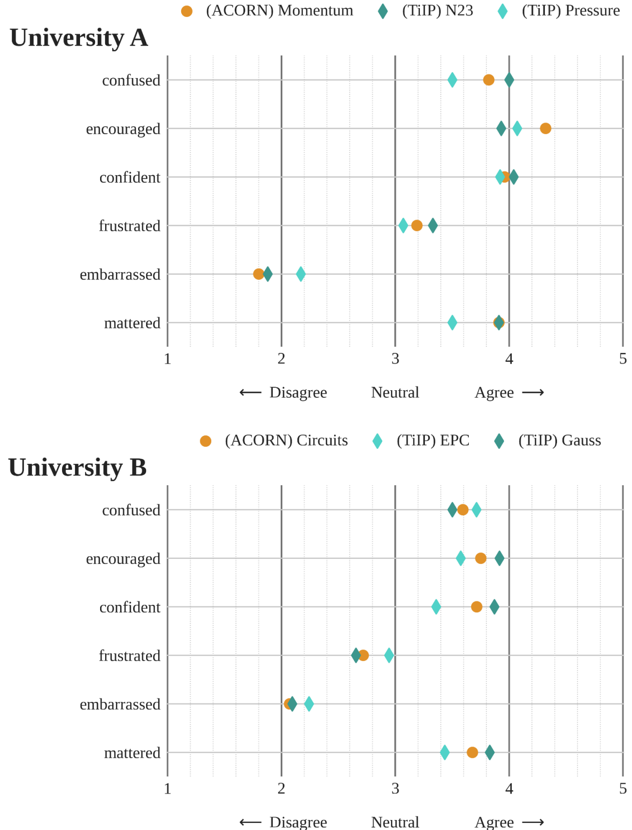


FIG. 5.5.1. Interpolated medians for student survey responses to feelings items after two sessions of Tutorials in Introductory Physics (light and dark green diamonds) and one session of ACORN Physics Tutorials (orange circles) at University A and at University B. Complete distributions of student responses can be found in Appendix D.

Instruction using Tutorials in Introductory Physics does not appear to be associated with more negative feelings and instruction using ACORN Physics Tutorials does not appear to be associated with more positive feelings. As the Tutorials in Introductory Physics were designed to address areas of student difficulty, they may have more centrally set students up to notice places where their thinking was inconsistent with canonical physics understanding. We might then

imagine that this could lead students to feel more *frustration*, more *embarrassment*, less *confidence*, less *encouraged*, and less like their ideas *mattered*. As the ACORN Physics Tutorials were designed to build on student ideas, they may have more centrally set students up to recognize and use their ideas productively towards more sophisticated or robust physics understandings. We might then imagine that this could lead students to feel the opposite (less *frustration* and *embarrassment*, more *confidence*, *encouragement*, like their ideas *mattered*). These do not appear to be dominant effects in our data. The levels of agreement and disagreement with the feelings items in our survey are comparable between the ACORN Physics Tutorials and the Tutorials in Introductory Physics.

We might also imagine that students would report higher levels of agreement to having *corrected* their ideas with Tutorials in Introductory Physics as compared to ACORN Physics Tutorials. This also is not the case in our sample. The levels of agreement to *corrected* are comparable between the two types of tutorials at University B. At University A, there were in fact higher levels of agreement to *corrected* for the ACORN Physics Tutorial than for the Tutorials in Introductory Physics. Figure 5.5.2 below shows the interpolated medians for *corrected* at both universities, and a stacked bar bar chart showing the complete distributions can be found in Appendix D.

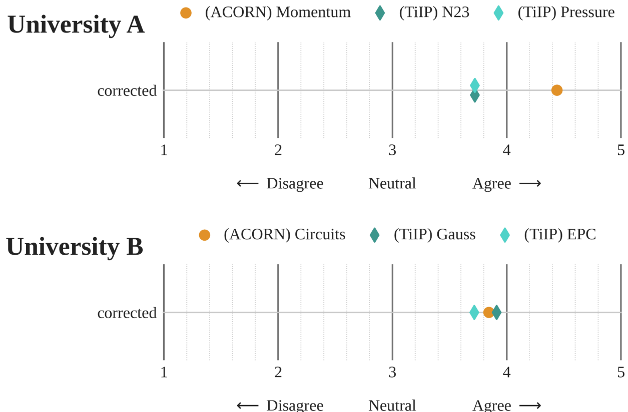


FIG. 5.5.2. Interpolated medians for student survey responses to *corrected* item after two sessions of Tutorials in Introductory Physics (light and dark green diamonds) and one session of ACORN Physics Tutorials (orange circles) at University A and University B. Complete distributions of student responses can be found in Appendix D.

That we do not observe large or consistent differences in survey responses after the two instances of ACORN Physics Tutorials use compared to the four instances of Tutorials in Introductory Physics use does not necessarily mean that material design did not have an impact on student feelings. In addition to the different tutorial designs, instruction varied in what physics topics were being addressed and when in the academic term the instruction was taking place. Student groups and instructors were not necessarily identical session to session. Any of these factors or their combination and interactions could have masked smaller differences that were due to the 'seeds' and 'obstacles' designs of the tutorials. Our findings do suggest that the design of the materials might have a smaller impact than other factors, and perhaps a smaller impact than some might have expected.

While the theoretical orientation towards student ideas differ between the ACORN Physics Tutorial and Tutorials in Introductory Physics designs, these tutorials also have a lot in common in terms of structure that might be shaping student experiences in similar ways. Both

ACORN Physics Tutorials and Tutorials in Introductory Physics step groups of students through conceptual sense-making with periodic check-ins from instructors. In the ACORN Physics Tutorials, students are often asked to revisit and refine the models that they are building in response to new observations. While the ACORN Physics Tutorials' framings may not explicitly be those of confrontation, replacement, or correction, there are opportunities for students (and instructors) to adopt those framings themselves when reconciling previous understandings with new information. This may be why students expressed high levels of agreement with *corrected* at University A for the ACORN Physics Tutorial, for example.

5.5.2 Student experiences of correcting their ideas

As we did not find the experience of *correcting* one's ideas to be well aligned with one form of tutorial design compared to the other, we also analyzed how students' feelings about their ideas compared when they agreed vs disagreed to having *corrected* their ideas, independent of the type of instruction they received. We did this by grouping survey responses in which the student **agreed** that they *corrected* their ideas (by selecting either Agree or Strongly Agree to that survey item) and grouping survey responses in which the student **disagreed** that they *corrected* their ideas (by selecting Disagree or Strongly Disagree). We then compared the feelings that these two groups reported in the other survey items (e.g., *confused*, *encouraged*, *confident*, etc.). Our analysis here is limited to University B as the number of students that reported disagreement with *corrected* at University A was too small (N=5) to allow for meaningful comparisons within that institution's sample.

Students reported higher levels of agreement to positively-valenced feelings than negatively-valenced feelings when thinking back on sessions of instruction whether they reported agreement or disagreement to having *corrected* their ideas. Students generally reported agreement with feeling *encouraged*, *confident*, and like their ideas *mattered*. They generally reported disagreement with feeling *embarrassed* and *frustrated* about their ideas. Figure 5.5.3 below shows the interpolated medians for the survey items about feelings for these two groups. Stacked bar charts showing the complete distributions of student responses can be found in Appendix E.

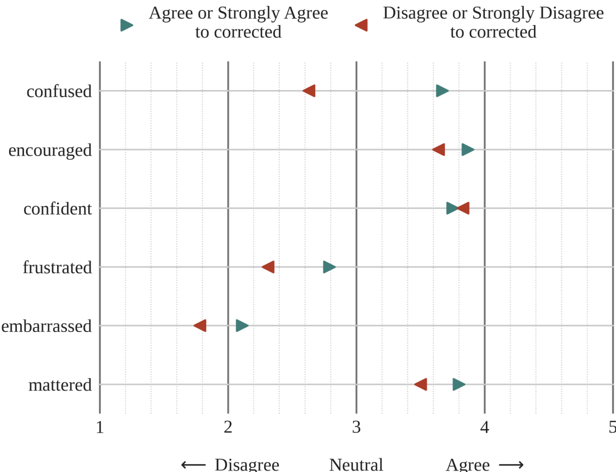


FIG. 5.5.3. Interpolated medians for student survey responses to feelings items divided by surveys reporting agreement with *corrected* (green triangle pointing right) and disagreement with *corrected* (red triangle pointing left) at University B. Complete distributions of student responses can be found in Appendix E.

To compare the experience of *correcting* one's ideas to not *correcting* one's ideas in our sample, we also found how much higher the 'risk' of each feeling is for the *corrected* group than for the not-*corrected* group. Figure 5.5.4 below shows these 'risk differences' with their confidence intervals.

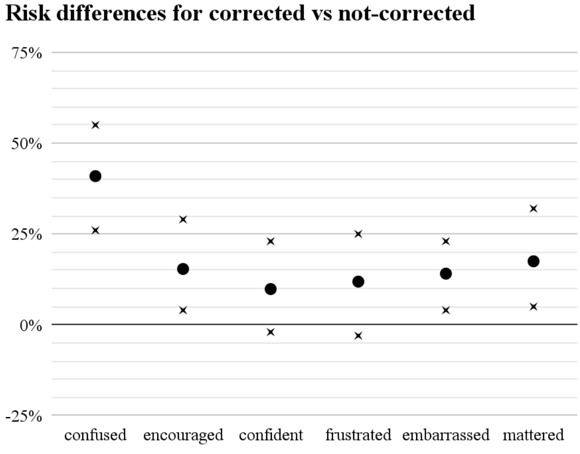


FIG. 5.5.4. Risk differences ('risk' of feeling in the corrected group minus 'risk' of feeling in the not-*corrected* group). For each feeling item, a dot marks the risk difference and x's mark the edges of the confidence interval. For example, the percentage of students who agreed that they felt *confident* about their ideas was 9.8% higher for those that agreed that they had *corrected* their ideas compared to those that disagreed that they had *corrected* their ideas. The confidence interval for *confident* includes 0% in its range, a point which would indicate no difference in percentage agreement with *confident* between those who agreed and disagreed with *corrected*.

Students in our sample are significantly more likely to have felt *confused* on occasions when they have *corrected* their ideas: the percentage of students who reported feeling *confused* is 41% higher for those who agreed with *corrected* than those who disagreed with *corrected*. This is perhaps unsurprising, as being *confused* would be a logical precursor to deciding to change one's way of thinking. One might have imagined that being *corrected* would be associated with higher levels of agreement with the negatively-valenced feelings (i.e., *embarrassed* and

frustrated) and with higher levels of disagreement with positively-valenced feelings (i.e., *confident*, *encouraged*, like their ideas *mattered*). This is not the case in our sample. Students in our sample were more likely to report agreement to both negatively- and positively-valenced feeling items (*encouraged*, *confident*, *mattered*, as well as *embarrassed* and *frustrated*), when they reported agreement to having *corrected* their ideas, although less significantly so. Whatever increased 'risk' there was in feeling *embarrassed*, for example, while *correcting* one's ideas, it was comparable to the increased 'risk' of feeling *encouraged* as well.

5.5.3 The multiplicity of students' feelings

To better understand the experiences of students who reported both positively-valenced and negatively-valenced feelings during instruction in which they *corrected* their ideas, we looked to video data and students' short answer responses. One way these seemingly contradictory feelings appear to coincide in a single session of instruction is when students feel things like *confusion* and *frustration* while their ideas become unsettled, but then this resolves, and they feel things like *confident* and *encouraged* after they have *corrected* their thinking. For example, one student who Strongly Agreed with *corrected*, *confused*, and *frustrated* as well as *confident* and *encouraged* said, "There were of course times where I made mistakes so I was pretty confused which ultimately led to me being frustrated but confident once I figured it out." Some students did report agreement only to more positively valenced or negatively valenced feelings. For example, one student who chose Agree to *corrected* and *frustrated* and Strongly Agree to *embarrassed* said, "I felt goofy talking about my ideas of the easiest path of resistance it was so embarrassing," and a student who chose Strongly Agree for *corrected* and *mattered* and

Agree for *confused*, *encouraged*, and *confident* said, “I have established a great group for tutorials who never judges me and we all help each other out. It was good to explain my ideas to others to make sure they are correct and I fully understand them.”

One possibly unique student reported, “I loved doing this lab due to the joyful frustration.” While we may not imagine that most students feel joyful in their frustration, it does highlight that how students relate to their feelings in the context of physics can differ. Experiences of *correcting* our ideas, feeling *confused*, and perhaps even feeling *frustrated* for some can be something we come to expect and even welcome in our learning and physics practices. Perhaps many students in our sample have developed some level of epistemic affect along these lines.

Beyond students’ experiences of *corrected*, individual students commonly report having multiple feelings about their ideas and characterize their experiences of instruction in multiple ways for even single episodes of instruction. A majority of student surveys express agreement to 3 or more characterizations (79% at University 1 and 60% at University 2) and to 3 or more feelings (80% at University 1 and 59% at University 2) for a single session of instruction. Student survey responses commonly include seemingly contradictory feelings and characterizations. For example, of students who Agreed or Strongly Agreed to feeling *embarrassed* about their ideas, more than half (57%) simultaneously reported feeling *confident* about their ideas. Students’ experiences of even a single session of instruction are often complex, and having one feeling does not preclude students from having other contrasting feelings. It may not be true, for example, that minimizing negatively-valenced feelings will maximize positively-valenced feelings, or vice versa. Interventions aimed at student feelings might need to be more targeted. If researchers are interested in resolving a more singular experience of

instruction (e.g., have individual students report a single feeling) without artificially limiting students' options, it might be more likely when looking at a smaller time interval (e.g., one moment during instruction) or from a different point of reflection (e.g., after more than a week has passed post-instruction).

5.5.4 The role of peers and instructors

Students' short-answer survey question responses offer insight into other factors beyond curriculum design that may be impacting their feelings about their ideas. We were struck by how often students bring up their peers and instructors when elaborating on their feelings, although the prompt references neither. Nearly half of the short answer responses include references to groupmates, instructors, or collaboration/discussion. Students often relate the feelings they had with how their group or instructor interactions went. People played both a positive and negative role in how students felt. Examples of student statements can be found in Table 5.5.1 below.

Table 5.5.1. Examples of short answer responses that reference group mates, instructors, or collaboration/discussion. The table includes the tutorial session and highest feeling item response(s) for the survey from which each example was taken. Examples are grouped into those responses that imply a positive impact and those that imply a negative impact.

Tutorial	**Feeling item(s) with highest level of agreement**	**Please elaborate on the statement(s) you most strongly agreed with. For example, in what specific context did you feel that way about your ideas, and what ideas did you feel that way about?**
positive impacts		
Pressure (TiIP)	confused, frustrated, mattered	*I feel like my thoughts are always heard, and people always try to help me understand when I am confused*
Gauss (TiIP)	confused, encouraged, confident, mattered	*I felt validated when others had the same thoughts as me and they were wrong.*
Momentum (ACORN)	encouraged	*I felt like group helps a lot if your peers are also willing to open up and talk as well. There was ideas I was hesitant but I wasn't able to word them yet, but with the people around me, I was able to get support to have a clear understanding!*
Circuits (ACORN)	confused, mattered	*My TAs do a great job of explaining concepts without fully giving the answers and building off of the answers already written, so I feel comfortable asking them questions and overall don't feel strongly negatively about my ideas.*
negative impacts		
Gauss (TiIP)	confused, frustrated, embarrassed	*I just didn't think my answers made sense to my partners*
Momentum (ACORN)	confused, frustrated, embarrassed	*Because it was a new concept I am not sure if what I said was correct and didn't have the courage to speak up*

It is not new to conceptualize instructional outcomes as influenced by this triad of elements (students, teachers, and instructional materials) and the complex interactions between them [33]. In our study, the students and instructors were accustomed to using Tutorials in Introductory Physics, but not ACORN Physics Tutorials. The latter were implemented without larger (intentional) changes to groupwork procedures or the established classroom culture. It is possible that the ways students share and discuss their ideas or build group consensus might differ in classrooms that exclusively used ACORN Physics Tutorials, or that TAs and instructors whose training came primarily from implementing ACORN Physics Tutorials might interact differently with students and their ideas. These differences might lead to more noticeable impacts on student feelings than single implementations of different materials alone. More research could investigate the ways instructional material design shapes group and/or instructor interactions and their impacts on student affect. For example, Bagdovitz, Allen, and others have investigated how student groups navigate confusion in the context of elicit-confront-resolve activities [34, 35]. One could also imagine studying the questions instructors ask their students or the ways they interact with student ideas in the context of ACORN Physics Tutorials and the potential impact on student confidence in their ideas.

5.5.5 Limitations

Our study does not address whether the impact of confrontation with students' ideas might be felt differently by different groups. Students from identity groups that have historically been excluded from science or are farther from educational justice might feel greater negative impacts from instruction that highlights discontinuities between student approaches and formal science [22]. Our study is not designed to adequately respond to this question. Within our

sample, we are not able to resolve differences in student responses between those who select 'F' vs 'M' boxes for gender or between those who are categorized by their university as 'URM' (Underrepresented Minority) vs 'non-URM' [32].

In our study, the ACORN Physics Tutorials were administered in contexts with established use of Tutorials in Introductory Physics, which may have impacted the ways in which students and instructors interacted with them. The interviews we conducted and the administrations of draft versions of our survey also took place in contexts primarily using Tutorials in Introductory Physics. We assume that the language used and the answer choices available in the survey are shaped by student experiences of Tutorials in Introductory Physics, and it is possible that a survey designed in the context of a 'seeds' based curriculum might highlight or capture different aspects of student experiences. This is a form of 'construct underrepresentation' our survey is vulnerable to.

Our study does not focus specifically on how students feel about their intuitions or their 'real world' understandings within physics instruction. When we ask students how they felt about *their ideas* during instruction, we have not specified *which* ideas we are referring to. During validation interviews at University B, we asked students which of the following they used or considered during tutorial:

a. things I've learned from this physics class
b. things I've learned from other classes
c. things I've observed or experienced in the physical world outside of classes
d. my intuition
e. my own ideas about how things work
f. ideas that I generated during the tutorial

g. other:

Six of the nine students interviewed said that they used all of the options a-f, and typically gave examples of each when prompted. Three of the nine students interviewed expressed some level of disagreement to having used some combination of choices c, d, and e, with the shared sentiment that they are accustomed to that type of input being wrong or unhelpful. The answers these three students gave about how they felt about their ideas varied. This suggests to us that there is variation in students' epistemological stances on how relevant intuition and 'real world' understandings are to physics within our sample, and that the feelings students report having about their ideas should be interpreted as some combination of thinking derived primarily from formal instruction and more general sense-making about the physical world.

5.6 Summary

In this study, we developed a survey instrument for students to self-report their feelings about their ideas (i.e., *confused*, *encouraged*, *confident*, *frustrated*, *embarrassed*, like their ideas *mattered*) and how they perceived their ideas being impacted (i.e., *corrected*, *confirmed*, *learned more*, *became unsure*, *cleared up*) when they thought back on sessions of small group instruction in introductory physics. We administered surveys to students at two universities after sessions of instruction using ACORN Physics Tutorials and Tutorials in Introductory Physics. Though these instructional materials were designed using different orientations towards student ideas (the former taking a 'seeds' approach meant to build upon common student resources; the latter taking an 'obstacles' approach meant to address common student difficulties), we did not find measurable differences in the feelings students reported about their ideas in our sample

attributable to the differences in these two material designs. Students in our sample also did not report higher levels of having *corrected* their ideas when using the ‘obstacles’ based tutorials.

It also does not appear to be the case that students who corrected their ideas are reporting a more negative affective experience of instruction in our sample. Students who reported agreement with having *corrected* their ideas during instruction also reported feeling *confused* about their ideas at higher levels than those who reported disagreement with having *corrected* their ideas. Whatever increased levels of agreement they reported towards other feelings were smaller in magnitude and common across feelings with both positive and negative valences (i.e., *confident* and *encouraged* as well as *embarrassed* and *frustrated*).

In general, students typically reported agreement to multiple feelings for a single session of instruction, often including both positively and negatively valenced feelings. Students commonly brought up interactions with their group members and instructors when elaborating on how they felt about their ideas, suggesting that peers and instructors may play an important role in shaping students’ affective experiences, perhaps more directly than instructional material design.

Chapter 6.

Learning Assistants' resources for understanding instruction that centers student ideas

6.1 Introduction

Throughout STEM education there is a push toward student-centered instruction, in which students are actively engaged in knowledge construction [1, 2]. A common concern surrounding the implementation of these forms of instruction is the need for increased instructional support [3]. One solution to this increasing need is to use Learning Assistants as members of instructional teams [4]. Learning Assistants (LAs) are undergraduates who support student engagement in active learning environments, and studies have found LAs to be effective in supporting student-centered instruction in STEM contexts [5, 6]. As part of the LA experience, LAs are enrolled in a pedagogy course that develops LAs' pedagogical knowledge and brings that knowledge into dialogue with their instructional practices.

Instruction that supports students' active engagement in knowledge construction is aligned with a *constructivist* view of learning, in which learners construct knowledge for themselves by building on what they already think or know. A primary role for instructors in this view of learning is to elicit student ideas and assist students in building from them towards the instructional learning goals. In this spirit, we look towards the ideas about teaching and learning that LAs bring to their pedagogy courses from their own experiences as students and learners. We find that LAs have a rich collection of ideas and intuitions about instruction that can be elicited and refined within pedagogy courses as LAs develop in their understanding of how

learning works, the potential roles instructors play in learning, and the goals instructors have for their students.

In this study, we identify potentially helpful ideas that LAs have about instruction, focusing specifically on ideas that may contribute toward understanding instruction that centers student ideas. We characterize these ideas as *resources for teaching*. In this paper, we present nine such resources for teaching; three are about how learning works (*multiple paths, active learning,* and *prior knowledge*), three are about strategies for teaching (*attend to ideas, support engagement,* and *be responsive*), and three are about larger goals for instruction (*inclusion, affect,* and *skills*).

To identify these resources, we looked at LA submissions to pedagogy course assignments, asking ourselves what kinds of things we see LAs saying that pedagogy course instructors might find useful to foreground and build upon during discussions of student-centered teaching. We identified LA resources that were evidenced across multiple forms of heterogeneity (across different individual LAs, institutions, and assignment prompts) in order to increase the likelihood of our findings generalizing outside of our sample. We additionally structured these resources in order to make more apparent the ways they are connected to the pedagogical and instructional goals we have for our LAs..

This work contributes to the literature on the pedagogical development of LAs and expands the resources framework common in physics education research into the context of how teaching and learning are understood by students. By naming and categorizing LA resources for teaching, this work may also aid pedagogy course instructors in noticing, eliciting, and building on the potentially productive ideas that LAs bring to their courses. Highlighting the helpful ideas

of LAs can also serve to foreground the potential expertise LAs bring into teaching spaces and the possible benefits of LA programs towards positive student outcomes.

Our study was conducted in introductory physics contexts across four universities, and our findings are relevant and potentially useful for LA programs and similar peer instructional models across other STEM disciplines. While LAs are the subject of this study, these resources are likely to bear relevance to novice instructors in any active learning environment in which there is a desire to incorporate student thinking into instruction.

6.2 Theoretical Framework: Resources

Across educational contexts, the term 'resources' can take on several different meanings. In the context of studying teaching, resources have been defined broadly as anything that is utilized by a teacher for instruction [7]. In Cohen's framework, resources fall into three distinct categories: *conventional* (e.g., funding, facilities, or course materials), *personal* (e.g., a teacher's knowledge, affect, or goals), and *social* (e.g., student buy-in or support from colleagues). Work has already been done that considers the ways in which these varied types of resources can be used by teachers when attending to student ideas in STEM classrooms [8].

In this paper, our use of the term 'resource' refers to something more specific, a type of *personal* resource (in Cohen's sense) that is cognitive in nature. In the resources framework often used in physics education research, a resource is defined as a component of human cognitive structure, where resources are pieces of prior knowledge that can be contextually activated for building new knowledge and making sense of new situations [9]. These resources exist at various grain sizes and can relate to many types of knowledge. Considering the domain of physics as an example case, conceptual resources relate directly to ideas about concepts in physics—forces,

motion, and the like [10]—while epistemological resources contain ideas on how knowledge of physics is structured and obtained [11]. The process of learning is then the activation and connection of multiple resources to create new knowledge [9, 12]. An instructional principle that follows from this framework is that learners' ideas should be treated with more nuance than simply whether they are correct or incorrect; a wrong answer can contain resources that serve as 'seeds' of understanding. Goertzen et al. offer the following example of looking to the pedagogical ideas and practices of Teaching Assistants (TAs) with this sort of nuance: some TAs ask questions that may be inappropriately broad (e.g., "How does circular motion occur?"), which may not be helpful to students in the moment [13]. This instructional move may still reflect seeds of expertise. Broad questions can stem from a TA's intention to allow students to develop their own line of reasoning, an instructional goal they would encourage and support TAs in achieving more effectively. In a case study of TA teaching practices, Goertzen et al. argue for an asset-based approach to the pedagogical ideas and practices of TAs, using conceptual and pedagogical resources as part of their analytical framework. We view our identification of LA pedagogical resources as aligned with this approach, aiming to treat LA thinking as containing 'seeds' of understanding that are useful for grounding or making sense of pedagogical knowledge.

We apply the cognitive resources framework in our conceptions of what resources are and in the methods by which they are identified in student work. The goal of our work is to identify pedagogical ideas espoused by LAs that could be viewed as 'seeds' for further developing their knowledge and skills for understanding and responding to student thinking. Our search to identify cognitive pedagogical resources benefited from Cohen's broader resources framework by cuing us to attend to the many forms that internal resources might take, including affective

stances and goals. In the end, we see the resources we identified as fitting within the cognitive resources framework, as well as being a narrow type of personal resources within Cohen's framework.

There are several affordances in applying the cognitive resource framework to the teaching practices of LAs (or, more broadly, to any new teachers). Viewing LA teaching knowledge through the lens of resources gives us a framework by which to identify the 'seeds' of expert-like conceptions of teaching, even when the LAs themselves are still in a relatively novice space. Additionally, the resources framework is well-suited to cognitive structures in which there is not always a coherent structure to the knowledge one possesses about a topic. Prior studies connecting teachers' beliefs about learning to their in-class teaching have found instances of both alignment and misalignment between beliefs and practice [14, 15]. A resource framing of teacher knowledge offers a possible explanation for seemingly contradictory results like these: varying emergent contexts of teaching may activate many different sets of resources, some of which may seemingly contradict one another. Finally, since each of us authors work within programs that aim to prepare LAs to notice and build upon the productive resources of their students, we model this behavior in our training and instruction of our LA students as a form of practicing what we preach.

6.3 Methods

This study identifies and codes for the presence of multiple LA resources at multiple institutions. The context of the study, process of thematic analysis for resource identification, and method of resource coding are described below.

6.3.1 Research context and participants

Data for this study were taken from four universities with undergraduate LA programs in physics. Pseudonyms are used for each university. While the LA programs differed in program scale and teaching contexts, several common features exist across all four university contexts. The LAs studied here all taught in in-person classrooms in contexts that included small group collaborative activities. All LAs in this study were enrolled in an LA pedagogy course concurrently with their teaching responsibilities, though the curricula of these pedagogy courses differed. LAs at each university consented to having their work used in this study via an informed consent process overseen by each university's institutional review board. Across all four universities, a total of 42 LAs had their work included in our dataset.

All data for this study were taken in the form of LA pedagogy class assignments at the four participating universities. The types of assignments collected varied by university, but included LA field notes, comments on readings, and both written and video reflections. Examples of assignment prompts can be found in Appendix A. All of these assignments were completed as a regular part of the pedagogy course curriculum during a single quarter or semester of instruction and were graded for completion.

1. Western State University (WSU)

Western State University 1 is a research university in the western United States with around 50,000 students. LAs at Western State University co-teach with graduate teaching assistants (TAs) in the laboratory and discussion sections that complement large lectures for the introductory calculus-based physics sequence. Lab and discussion sections typically have 20-30 students working in small groups and two instructors (either two TAs or one LA and one TA) per

section. LAs answer questions and assist students in completing lab and small group active learning activities.

Data for this study of LAs at Western State University were taken from 16 LAs enrolled in an LA pedagogy course; all LAs in the course opted to participate in the study. Students were informed of an opportunity to be an LA through a mass emailing or through academic advising. Students were selected as LAs based on a written application describing why they were interested in the role and their course grades, with occasional other input from academic advising. All LAs had previously taken the introductory physics courses they would teach. The pedagogy course met for one hour weekly in addition to LAs' instructional load and class preparation time. The course aimed to enable LAs to teach their students "with an awareness of best pedagogical practices," and included topics such as the Socratic method, student-TA interactions, think-pair-share, learning objectives, observations of active classrooms, and grading rubrics.

For this study, we used the homework assignments that the LAs submitted in the form of a weekly online discussion forum post to a given prompt. The prompts included asking students to reflect on particular aspects of their experiences as students, to report on parts of their experiences with students as LAs, and to read and respond to given articles. There was also a single 'pretest' given at the beginning of the course that asked students about their thoughts on teaching that was included in the data set.

2. University of Central Plains (UCP)

University of Central Plains is a Midwestern university with around 45,000 students. Introductory physics courses at University of Central Plains are large enrollment classes with

LAs positioned as course assistants and co-teachers in the labs and discussion sections alongside at least one graduate teaching assistant. Both LAs and TAs are present during labs and discussion sections and make themselves available to answer questions and give feedback.

Data for this study of LAs at University of Central Plains were taken from 15 participating LAs teaching discussions sections in an introductory physics class designed to prepare incoming students to take calculus-based mechanics. All LAs participating in this study were first-time LAs and former students of the course, recruited via an email to all former students. Students interested in becoming LAs submit an application in order to join the LA program. All first-time LAs are required to enroll in a LA pedagogy course that meets once a week for 80 minutes. The pedagogy course goals center LAs learning the pedagogical content presented in the course, connecting their own experiences to the pedagogical theories they learn, critically evaluating new teaching methods through the lens of their experiences as teachers and students, and reflection on the efficacy of their teaching approach.

In this study, we looked at the 10 weekly field note assignments given in the pedagogy class. Field note assignments consisted of an open-ended prompt asking the LAs to record observations about their discussion section that week, sometimes through the lens of a recent pedagogy topic (e.g., a reading about asking open-ended questions to students would be paired with a field note assignment asking them to write down a few observations of how students responded to different types of questions).

3. University of Brackett (UB)

University of Brackett is a private four-year university with around 3,000 students. Introductory physics classes at University of Brackett have less than 40 students per class and

involve collaborative group activities and whole class discussions. LAs help small groups and facilitate active learning activities. The LAs are all former students in the courses they help teach, and are selected through an application process.

Data for this study from University of Brackett was collected from the five LAs enrolled in one term of the LA pedagogy course; all five opted to participate in this study. The pedagogy course met for one hour weekly, and the theme for the quarter was detecting and interpreting student ideas. Class sessions typically included sharing LAs teaching experiences from during the week and class discussions of assigned readings.

In this study, we used two types of weekly homework assignments from the course. The first were weekly reflection assignments that were submitted as short videos (1-2 minutes) posted in a collective online space for other LAs to see and comment on. The reflections were responses to specific weekly prompts that had LAs consider their own experiences both as LAs as well as students. The second weekly assignment type was reading responses which took the form of comments annotating assigned readings from the course. Again, these were visible to fellow classmates.

4. Cedarburg College

Cedarburg College is a regional public comprehensive four-year university serving about 6,000 students. Introductory physics classes at the Cedarburg College are 40-100 students and are taught in a studio format, in which two-hour blocks of class time and flexible seating arrangements give instructors the ability to transition smoothly between lectures and small group collaborative active learning activities. LAs help facilitate small group activities. All course sessions are taught by faculty; there are no graduate TAs. There are no discussion sections and

labs are taught as a separate course. Students were informed of the opportunity to be an LA through a mass emailing or by instructors recruiting them directly. Students were selected as LAs based on a written application and interview focused on their interest in the role and their teaching philosophy. All LAs had previously taken the introductory physics courses they would help teach.

Data for this study from Cedarburg College came from six LAs enrolled in the LA pedagogy course, representing all the students in the course that term. The LA pedagogy course met for 90 minutes weekly in addition to LAs' instructional load and class preparation time. The pedagogy sessions typically focused on instructional support and discussion of theories of learning and their applications. The assignment types and prompts for Cedarburg College were largely the same as those for University of Brackett, as the two courses were planned in part together.

While this study aimed to identify resources across multiple forms of heterogeneity, including different LAs and different institutions, there are limits to which our sample represents a broad spectrum of LAs or LA programs. While the four institutions from which we sampled are different in many ways (e.g., in their sizes, locations, racial and ethnic demographics, competitiveness of admissions, private vs public, etc.), they do not represent the diversity of institutions that host LA programs across the country, let alone internationally. For example, none are Historically Black Colleges and Universities or Hispanic serving institutions. All four of the LA pedagogy courses in our sample, and therefore all of the LAs, were hosted within physics departments and focused on the teaching of physics. While we imagine many of our

findings may generalize to LA programs beyond our sample, that is more tenuous the more unlike our sample the LA programs in question are.

6.3.2 Data analysis

In analyzing the LA submissions to pedagogy course assignments for the presence of resources, we first identified resources through an iterative process and then did independent coding to determine the approximate prevalences of the identified resources in our sample, as outlined below.

1. Identifying Resources

We began with a single researcher (AA) reviewing the assignment submissions of LAs from a single university (Cedarburg College) and highlighting each instance where an LA mentioned an asset (defined as broadly as possible) that students bring to instruction and/or the role of the instructor in teaching (either in the abstract or in practice). They then identified preliminary themes within these mentionings, attending particularly to those with possible connections to student-centered instruction. These themes were then brought back to the larger research team for discussion and critique as 'candidate resources' [16]. This process was then repeated with the assignment submissions from a second university (University of Brackett), with additional attention paid to which themes were common to both data sets. The larger research team agreed on a preliminary set of five resources that were present in both data sets, connected to instruction that centers student ideas, and plausibly captured important aspects of LA thinking as seen from the researchers' personal experiences working with LAs.

Next, two more universities (Western State University and University of Central Plains) were added to the data set and an additional researcher (SE) joined for coding. The preliminary set of resources went through a final iteration at this point, which adjusted the grain-size of the resources so that they might be more consistently identified by each coder, and also to organize the resources into categories that might make their connections to the literature on teaching more visible. At the end of this process, we settled on nine resources (described in detail in the Results section) within three categories (beliefs about learning, knowledge of instructional strategies, and values related to students). These resources were therefore identified primarily through a 'bottom-up' process, with themes from the data playing the central role, and then 'top-down' connections to literature played a secondary role in how the resources were structured.

2. Coding for Resources

361 student responses were coded for the presence of the final set of nine resources in order to get a general sense of their prevalences. Each LA response to an assignment prompt (which could be a 1-2 minute reflection video, a single 'field notes' entry, an online discussion post, etc.) was coded as a single unit for the presence or absence of each of the nine resources. Each resource was considered independently, so a single coded unit could be marked as containing all nine resources, no resources, or anywhere in between. As there was large variation in the assignment prompts, from LAs describing their observations within a classroom to commenting on academic theory of learning papers, there was also variation in how the nine resources presented themselves in student responses and the level of inference required to code a resource as present. This made for a challenging coding situation, which we undertook as follows.

Two researchers independently coded the full data set. Each coder marked each resource as being ‘present (1),’ ‘absent (0),’ or ‘implied (i),’ where ‘implied’ meant that the resource was either implicitly present or that the resource was consistent with one possible interpretation of the LA statement, but other plausible interpretations were apparent to the researcher. During a first round of coding a small subset of the data (approximately 10% of the data that spanned the different institutions, LAs, and assignment types), the two coders (AA and SE) met with a third researcher (LG) to discuss any differences between coding, and conflicts were resolved through consensus. This allowed the team a final calibration in what would be considered acceptable evidence for each resource. The full data set was then coded independently by the two coders. For the final count, a resource was considered present if both researchers coded ‘present’ (11) or one researcher coded ‘present’ and the other coded ‘implied’ (1i). A resource was considered absent if either coded ‘absent’ (01, 0i, 00) or if both coded implied (ii).

All of the routine weekly assignments at the four universities were included in our data set by default. A small number of assignments were removed before coding as follows. One assignment was removed from Western State University which had LAs identify the learning objectives (in the form of physics concepts) for a set of physics problems. Two teaching reflections were removed from University of Brackett and Cedarburg College; the first asked LAs to come up with as many ways as they could to answer a specific physics problem, and the second asked for an example of a type of expertise that is not demonstrated through a test and how such expertise can ‘show’. These assignments prompted very little direct discussion of teaching and learning or classroom activities, and so were not considered relevant enough to merit coding. In total, 32 distinct assignments were coded across the four universities.

The two coders were in total agreement in their codes (11, ii, 00) 80% of the time and in at least partial agreement (11, ii, 00, 1i, i0) 93% of the time. Cohen's Kappa, linearly weighted to account for partial agreement, primarily fell into a range of moderate agreement (0.4 - 0.5) with the exception of resource S3 (0.2) and V2 (0.7). While this level of agreement is sufficient for our purposes of determining if each of the resources is rare or common in general terms, it is insufficient to make careful quantitative comparisons in prevalence. We also consider the results from our coding to likely be an undercount of what resources are present in LA thought for multiple reasons. First, while we coded a resource as present if one coder marked 'present' and the other marked 'implied' (1i), we coded the resource as absent when both coders marked 'implied' (ii). This helped set a boundary for what level of inference was accepted in attributing a resource to a statement, but it seems likely that if LAs were given the opportunity to answer follow up questions, many of these statements could have been confirmed to have been rooted in a particular resource. Additionally, our data captures the routine assignment submissions of courses operating independently of this research: if instead we designed targeted prompts to specifically capture the activation of these resources, we might more efficiently elicit these resources and get higher counts. As it is, our data better reflects how these resources 'naturally' show up in pedagogy course activities rather than what is maximally possible with targeted intervention. Lastly and most fundamentally, resources are cognitive elements that are activated in the minds of individuals: a resource can be activated and used to shape a response or make an observation without it ever translating into what is written or submitted in an assignment, and thus remain outside of our count.

6.4 Results

We find that LAs have resources for understanding teaching that centers student ideas. Similar resources are evidenced in the responses of many different LAs, at different institutions, and in response to varied prompts. In this section we describe and give examples of the nine resources we found evidenced in the pedagogy course assignment submissions of 42 LAs at four different universities. We have arranged them into three categories (beliefs about learning, knowledge of instructional strategies, and values related to students), as shown in Table 6.4.1 below. Within each resource description we include how we see each resource as 'resourceful,' both in its continuities with understanding teaching that centers student ideas and also in the directions we hope that it can grow. We also include whether each resource was common in our sample. A more in depth look at the prevalences of each resource can be found in Appendix B.

Table 6.4.1. The nine resources identified by this study, sorted into three categories.

Beliefs about learning	Knowledge of instructional strategies	Values related to students
B1. *Multiple paths* There's more than one way to understand things.	S1. *Attend to ideas* Pay attention to student thinking.	V1. *Inclusion* We want all of our students to be included in learning.
B2. *Active learning* Learning is an active process.	S2. *Support engagement* Support students' active engagement.	V2. *Affect* We want our students to feel good about sharing their thinking.
B3. *Prior knowledge* What you know impacts what you learn.	S3. *Be responsive* Be guided by student ideas.	V3. *Skills* We want our students to build skills and understandings beyond getting the answer correct.

6.4.1 Beliefs about learning

The first category of resources is ‘beliefs about learning’. These resources are about how LAs conceptualize the process of learning, and the focus is on the learner. They are about how learning works and what learners do. These resources are conceptual in nature, similar to conceptual resources for physics [10] in that they relate directly to modeling the way in which something works (where that something might be a physical phenomenon, or in our case, learning). The resources in this category all can be seen as ‘seeds’ for developing a constructivist model of learning, where students learn through a process of active construction using their own ideas as building blocks.

B1. Multiple paths

LAs often talk about the multiple pathways that can be used to arrive at an answer or to think through a scientific concept. These are cases of LAs using the resource *multiple paths* that asserts ‘there’s more than one way to understand things.’ This includes noting that multiple representations, models, or problems solving strategies are possible for a given scenario. It also includes that the approaches students take to reach understanding or solve a problem can differ student to student, or that what is easy, interesting, or intuitive for one student will not necessarily be what is easy, interesting, or intuitive for another student. *Multiple paths* is also expressed by LAs as the examples, representations, or questions that are most helpful to one student will not necessarily be the ones that are most helpful to another student. Table 6.4.2 includes quotes from LA responses that evidence *multiple paths*.

The belief that ‘there’s more than one way to understand things’ is resourceful towards LAs developing an understanding of teaching that centers student ideas and has connections to

research on effective learning in STEM. The literature on responsive teaching contains many examples of unexpected or unique student thinking that can be effectively leveraged towards student learning [17, 18]. Research has shown that student success in problem solving can vary depending on which representations are used and that becoming fluent in multiple representations benefits students [19-21]. Students also have varied cultures and daily experiences relevant to learning that teachers may or may not recognize and use as cultural capital in the classroom [22, 23]. In the classroom experiences of LAs, recognizing that 'there's more than one way to understand things' may provide a reason for an LA (or any instructor) to turn towards student thinking: if there are many different ways to understand something, an instructor should not assume they already know what a student is thinking, or that if a student's thinking is different from what is most familiar to the instructor that it cannot be worthwhile [e.g., 24]. It also can provide motivation for an instructor to adjust instruction to the student(s) in front of them: what worked best for the instructor (or a previous student) might not work best for every student, and what students find to be most challenging or exciting will vary. This does not mean, however, that LAs who express this resource are expert-like in the ways they turn towards student ideas or are responsive to the students in front of them. For example, the LAs in our sample sometimes remark on different approaches students are using to solve a problem (using *multiple paths*) and also express a preference towards a single path forward or a 'right' approach (for example, discouraging students from using a guess-and-check method to find a quantity or suggesting that all students use a single type of diagram to support an answer). It is our hope that these LAs grow in their ability to see disciplinary connections between multiple student approaches and disciplinary practices rather than stopping at judgments of correctness [25]. Similarly, we see the potential in LAs noticing and calling out the multiple approaches students

take, even if they are not yet able to consistently find what can be productively built upon in all of those approaches.

Multiple paths was commonly evidenced in the LA assignment submissions in our data set, widespread throughout the different assignment prompts and across the different LAs in our sample. Most LAs voiced this resource in their assignment submissions at least once, and many LAs voiced this resource routinely. Most assignment prompts elicited this resource from at least one LA, and many of the assignment prompts elicited this resource from many of the LAs. LAs in our sample bring up *multiple paths* most frequently in contexts where they are speaking to the advantages of working in groups or discussing ideas, to the ways students have different experiences or learning styles, to the usefulness of diagrams, visual tools and hands on activities, or when sharing new ways that they as LAs have been exposed to new ways of thinking through a problem or understanding a concept.

B2. Active learning

In reflecting about the processes involved with both learning and teaching, LAs will occasionally make statements or observations about how learning seems to happen for their students or themselves. When these observations portray learning as an active process that benefits from—or outright requires—student engagement, LAs are drawing upon the resource *active learning*. Included within this resource are statements about the necessity of engaging with or struggling with material in order to learn it deeply. Also included are LAs placing emphasis on the learning benefits associated with sensemaking about material individually or collaboratively, or any descriptions of the process of learning that characterize it as being an internal or social process enacted by students themselves. Mentions of the benefits of active learning techniques in

teaching are also included in this resource. Example quotes for this resource are provided in Table 6.4.2.

Active learning ties directly to a set of instructional active learning practices that are well established as beneficial to student learning [26, 27]. Believing that learning is active can shift an instructor's focus from what the instructor is teaching to what the student is learning. Most directly for the LAs in our sample, it can provide a reason to make space for students to do the work of learning without trying to 'rescue' them from struggle or uncertainty too soon. While LAs expressed this belief, this sometimes happened in the abstract without an apparently clear understanding of the ramifications this might have for their own interactions with students or known strategies for following through in supporting students' active engagement. As such, this resource provides LAs a place from which to grow.

For many LAs, a formal introduction to the active-ness of learning is presented early on in their pedagogy class and making use of this formal knowledge can fall under this resource. "Naive" student theories and observations about learning emphasizing the need for putting in effort and making sense of the material are also included in this resource. These types of personal theories and beliefs about learning often arise in reflections where LAs are asked to reflect on their own learning process.

Active learning appeared frequently across both LAs and assignment types within our dataset. Over half of the LA sample voiced this resource at least once, and many LAs voiced it regularly across all assignments. Across the sample of assignments, approximately half of the prompts saw *active learning* occur at least once and a few assignments saw it occur frequently across LAs.

B3. Prior knowledge

LAs make observations about the ways that students' prior knowledge, experiences, and intuitions about the physical world impact their learning in the classroom. They comment on the ways that 'misconceptions' can hold students back and the ways that knowledge from past experiences can ease students along. These are uses of the resource *prior knowledge* that asserts 'what you know impacts what you learn.' This resource also includes rejections of seeing students as 'blank slates' or 'empty vessels' ready to take in new knowledge without interaction with currently held mental models, or noting how learning can be more difficult when one lacks sufficient prior knowledge or experience in a given topic. See Table 6.4.2 for quotes from LA responses that evidence *prior knowledge*.

Prior knowledge is connected to understanding instruction that centers student ideas as it takes the current knowledge and thinking of students to be relevant inputs to learning. That students' ideas are influential in science instruction has long been recognized in research, and instructor knowledge of student ideas is often considered an important part of pedagogical expertise for this reason [28-31]. Believing that what you know impacts what you learn can provide motivation for instructors to attend to student thinking throughout the learning process. While our goal is for LAs to be able to see disciplinary connections in their students' thinking and be able to take up student ideas in positive ways, *prior knowledge* also includes LAs seeing student ideas as barriers to easier learning. LAs in our sample talk about how students' experiences, intuitions, or ideas can get in the way of their learning, including describing students as having troublesome 'misconceptions.' While there are ways this may be misaligned with a constructivist model for learning [32], it still represents an understanding that student ideas are involved in the learning process and a counter-model to seeing learning as a simple

transfer of knowledge from someone who knows (actively giving) to someone who does not know (passively receiving). These examples therefore can still be resourceful towards developing and strengthening a constructivist understanding of the learning process in ways that grow into seeing the resourcefulness in student thinking.

Prior knowledge was moderately common in our sample. Most LAs voiced this resource at least once and many voiced it routinely. Similarly, a majority of the assignment prompts elicited *prior knowledge* from at least one LA, and many prompts elicited this resource from many of the LAs. *Prior knowledge* came up most frequently when LAs discussed how formal science connects to 'real world' experiences, what makes some disciplinary topics more challenging than others, and when responding to theoretical takes on learning.

Table 6.4.2. The three resources in the *beliefs about learning* category with example quotes taken from LA pedagogy assignment submissions

Beliefs about learning	
Resource	Example Quotes (italics added)
B1. *Multiple paths* There's more than one way to understand things. Includes: ● There are multiple possible strategies, models, or representations used for thinking something through in STEM. ● The "paths" students take to reach understanding may differ student to student. ● What is easy, interesting, or intuitive for one student will not necessarily be the thing that is easy, interesting, or intuitive for another student.	● "In my experience of helping students in the past two weeks, I found that *students have different views and ideas about a problem*. The mutual discussion between students encourages them to say their ideas, and at the same time encourages them to listen to different ideas, which will make them think more and more carefully." ● "This discussion was their introduction to freefall. They also got the chance to *graphically answer AND answer the question also using equations and analytical thinking*. It was interesting to see *how some students understood the graph very clearly but had trouble with the equations, how other students understood the equation but not the graph as much, and how others understood both equally*." ● "One of the main differences in this week's discussion is that *every student approached the discussion questions in a different way.* Some had only calc 1 background and would use more trig and Pythagorean theorem to solve while others have taken calc 3 and could use vectors. This make my job of

● The examples, representations, or questions that are most helpful to one student will not necessarily be the ones that are most helpful to another student.	explaining some problems difficult because *one explanation wouldn't necessarily make sense for all of the students*." ● "Being an LA has helped me learn *how to express an idea in a variety of ways* and to figure out what a student is trying to communicate. I have also learned to be patient when my first try at getting an idea across doesn't work, and I think I'm getting faster at regrouping and *coming up with an alternate explanation*. It's helped me to better understand and respect different ways of taking in information."
B2. *Active learning* Learning is an active process. Includes: ● The necessity of deeply engaging with the material one is learning ● The importance of thinking through something on one's own (or actively with others) ● Learning being an internal (or social) process enacted by students ● The benefits of active learning techniques	● "*Allowing me to come to an answer on my own* (while still recognizing when I was getting frustrated) *did actually help me quite a bit. Getting moments of being able to correct myself when I figured out what I was doing wrong on my own, and then finally figuring out something for myself with guidance, was often very satisfying and made me want to continue even when I had struggles in the future*." ● "This point is very true, because *learning is multifaceted and takes more than just something like listening to a lecture in class. Rather, it combines many things like understanding concepts in different situations and being able to make connections*." ● "Active learning is much more challenging. *From experience as a student I'd say active learning made me think, struggle, and research on my own which was much better in the long run for my education.* In my opinion although it's much tougher on the student, with the right support system it can be much better than traditional systems."
B3. *Prior knowledge* What you know impacts what you learn. Includes: ● In learning, one makes use of one's prior knowledge, past experiences, and/or intuitions. ● Students can be held up by misconceptions. ● Students are not blank slates. ● The absence of experience or prior knowledge can make learning more difficult	● "*Thinking about the real world and how you experience Newton's laws can help you build a better relationship with concepts and connect them mathematically to the physics of what's going on*." ● "To this day, I find myself struggling in class when some new concept does not work the way I expected it to. *The old experiences, or knowledge, or methods are rooted in our minds that it blocks us from understanding new ones*." ● "I could see this in class as some students didn't grasp vector addition in 1D, so *doing an exercise which required knowing vector addition in 2D was incredibly challenging as the previous groundwork wasn't set*." ● "*In order to make deeper connections, students are encouraged to think about their current mental models and how it compares to what physics is telling them*. I think this beneficial in the learning process for students of all ages."

	• "In my experience with school, teachers would throw out any wrong ideas and work their hardest to steer us away from the wrong answer. I wonder *how much easier it would have been to learn the topic if our "wrong" ideas were used in a way to understand the concept*. Additionally, many people shut down when told they're wrong. Students may be more responsive if you use their ideas instead of dismissing them."

6.4.2 Knowledge of instructional strategies

The second category is knowledge of instructional strategies. These resources are about how LAs see the role of the instructor. They are about how teaching works and what instructors do. Note that these are still cognitive resources; they do not represent evidence of LAs enacting these strategies (although that sometimes happens). Rather, these resources are evidenced when LAs discuss these strategies in the abstract or frame instruction they have witnessed or enacted in these terms. While these resources sometimes appear more conceptual in nature (as knowledge about a thing - that thing being a teaching strategy), they also can reflect how an activity is framed or approached (i.e., what is teaching 'about'). In this way, these resources are more analogous to epistemological resources [11], although they consider the nature of teaching rather than the nature of knowledge.

The three resources in this category all describe skills for centering student ideas in instruction. They are also potential seeds for understanding responsive teaching practices. In the context of STEM education, responsiveness is a practice that aims to elicit and harness student thinking in science learning [18, 33-4]. It involves foregrounding the substance of student ideas, recognizing disciplinary connections within those ideas, and taking up and pursuing the substance of student thinking [18]. It can allow instructors to meaningfully engage with student

resources, facilitate more authentic science experiences, and promote more equitable learning outcomes [33, 35-7].

S1. Attend to ideas

When the LAs in our sample describe what they do, or hope to do, in the classroom, listening to their students came up again and again. More specifically, the LAs discussed instances of trying to figure out what their students were thinking, what background knowledge students already had, or what students already understood. The LAs emphasized the importance of instructors taking student ideas seriously. When LAs describe their teaching as paying attention to student thinking in these ways, or discuss the use of this teaching strategy in the abstract, the resource *attend to ideas* is present. Table 6.4.3 includes quotes from LA responses that evidence this resource.

Relatedly, LAs often described asking their students questions, observing their students, and waiting to intervene. When it was clear that the intention or outcome of these moves was that the LA learned about what a student was thinking, the resource *attend to ideas* is also evidenced. This particular resource was not necessarily evidenced if instead these moves served the purpose of leading student thinking in a given direction or giving students space to figure things out themselves.

Attending to student thinking is fundamental to responsive teaching, and the resource *attend to ideas* is central to understanding teaching that centers student ideas. This is the precursor to seeking disciplinary connections in student thinking, to pivoting instruction to better align with where students are in their thinking, and to seeing students as the producers of knowledge and skilled sense-makers. Developing the skill of careful attention to student thinking

within classroom contexts has been studied in math education as *teacher noticing* [38-9], and researchers identify noticing as an important precursor to teaching responsively [40]. The act of thoughtful listening to student thinking can also feed instructor recognition of the differences in student perspectives and ideas as well as the ways in which a students' current thinking shapes future learning. An LA does not have to be thinking of student ideas as cognitive resources or as positive input for instruction in order for us to recognize the use of this resource; an LA identifying a 'misconception' that they see a student as having also is demonstrating that they are attending to student thinking, even if they have not turned towards finding meaningful disciplinary connections in that thinking. Identifying a place where a student is stuck without attending to what ideas the student has or the thinking the student already has done would not on its own be enough to demonstrate use of this resource.

There are many ways that *attend to ideas* can be built upon and further integrated into LAs' understanding of instruction. While the importance of listening to student thinking was commonly discussed in our data, LAs often also mentioned the difficulty of figuring out next steps in the moment after they came to understand a particular student's thinking. As such, LAs may benefit from knowing (and practicing) more strategies for following up with students based on their thinking. When LAs are tuning in to student thinking, we also might aim to move them farther away from primarily viewing it through the lens of what is right or wrong and towards what can be built upon by looking for the potential connections between student ideas and the disciplines we are teaching.

Attend to ideas was commonly evidenced in the LA assignment submissions in our data set across the different assignment prompts and different LAs in our sample. Most LAs voiced this resource in their assignment submissions at least once, and many LAs voiced this resource

routinely. Approximately half of the assignment prompts elicited *attend to ideas* from at least one LA, and many of the assignment prompts elicited this resource from many of the LAs. LAs brought up *attend to ideas* most frequently in contexts where they were reflecting on what they did in the classroom with their students or in conversations about what they are aiming for or think is important when instructors interact with students.

S2. Support engagement

A key component of enacting any active learning practice in classrooms is providing instructor support for the learning activities in which students participate. When LAs indicate a preference for, or discuss enacting, strategies to engage students with the process of learning in the classroom, they are drawing upon the resource *support engagement*. Many strategies can be considered to fit within this resource so long as they center the work, sensemaking, and engagement of students. Asking questions to prompt student discussion is a common way in which *support engagement* occurs. Giving students opportunities to voice their ideas, providing guidance for students to figure out something for themselves, and waiting to intervene when they perceive the students are making progress are other examples of how this resource may manifest in the strategies LAs discuss using. LAs may also make broad claims in which *support engagement* is present if their claim places an emphasis on engaging with students, even if it does not name a specific strategy (e.g., "It is important for me as a LA to help guide student thinking so that the students can come to their own conclusions"). Additional quotes that evidence *support engagement* can be found in Table 6.4.3.

Similarly to S1 *attend to ideas*, intention and outcome are important to consider in looking for evidence of the resource *support engagement*. If an LA described enacting a strategy

that could be used to support student engagement, but then made it clear in describing its implementation that the LA's goal was something other than student engagement, it was not coded as *support engagement.* Similarly, any strategy described by an LA that focuses more on the LA doing the work of making the students understand rather than leaving the students some room to make sense of things for themselves is not an occurrence of this resource.

By shifting the focus away from instructors and towards students, *support engagement* is resourceful towards instruction that centers student ideas. As the benefits of active learning have been recognized, there has been much research on student engagement levels and strategies for promoting active engagement [e.g., 41-4]. We find LAs sometimes begin their time as LAs thinking that their primary job is to be able to explain things, mini-lecture style, to their students. The resource *support engagement* acknowledges a different role for LAs, aligned with a constructivist view of learning, where the 'doing' of learning takes place with the student. It can also help reframe where knowledge comes from in a science classroom - away from being given by authority figures and towards being generated by learners. In the descriptions LAs give of trying to enact the practice of supporting students' active engagement, we see differing amounts of success, and differing levels of understanding of why such practices are desirable. Both of these are dimensions in which LAs may continue to grow from this resource.

Support engagement was the most commonly occurring resource out of the nine identified resources. Nearly all of the participating LAs voiced this resource at least once across all their assignments, and most of these LAs voiced it routinely across multiple assignments. This resource was also identified as occurring at least once across most of the assignments surveyed within the study, and was commonplace within approximately half of the assignments we coded. *Support engagement* most frequently appeared in contexts where LAs were sharing

moments of what went well while teaching or discussing an LA's role as an active listener or how to begin conversations with students.

S3. Be responsive

When LAs describe ways that they (or other instructors) build on student thinking, incorporate student experiences into instruction, or modify their instructional actions in response to student ideas or questions, the resource *be responsive* is evidenced. This resource is about framing the instructor's role in teaching as not just taking in or making space for student ideas, but finding ways to let those ideas be drivers of what an instructor enacts in the classroom. While LAs commonly described guiding students in learning, letting student ideas guide them in instruction was much more rare. This resource is closely tied to an understanding of responsive teaching, as the strategy involves taking up and pursuing the substance of student thinking. Table 6.4.3 includes quotes from LA responses that evidence *be responsive*.

When coding for this resource, we noted many places where the actions of LAs *may* have been guided by their students' ideas. For example, whenever an LA discussed figuring out what a student was thinking about a particular physics scenario, or an LA reported asking a student a series of questions, it seems as likely as not that their next actions with the student were shaped by that discovery. For us to code an LA response as evidencing the resource *be responsive*, we wanted the LA themself to note a causal connection between student thinking and their actions, or for us as researchers to believe that their actions only made sense in the context of their knowledge of specific student thinking. As such, we considered this resource evidenced when LAs showed a high level of awareness of how student ideas impacted their actions and/or when student ideas had more substantive impacts on LA actions.

At this level of scrutiny, *be responsive* was the most rare of all the resources we coded for. Very few LAs voiced this resource in their assignment submissions at all, and no LAs voiced this resource routinely. Few assignment prompts elicited this resource from at least one LA, and no assignment prompt elicited this resource from many of the LAs. When *be responsive* was elicited, it was while LAs were discussing what went well during their classroom experiences.

Table 6.4.3. The three resources in the *knowledge of instructional strategies* category with example quotes taken from LA pedagogy assignment submissions

Knowledge of instructional strategies	
Resource	Example Quotes (italics added)
S1. *Attend to ideas* Pay attention to student thinking. Includes: ● Listening to students ● Figuring out what a student thinks or already knows ● Not dismissing student ideas	● "It's important to *invest time in figuring out the lens from which students are viewing the content* and understand that *our students are already smart and rational thinkers, and so usually have some explanation for why they are thinking about a situation the way they are* even if it's wrong." ● "*I enjoy listening to each student's unique thought*; sometimes they even give me a brand new perspective of looking at the problem." ● "I tried my best to ask questions more and talk less so that they have a chance to think rather than just listen to someone else speak. *I think listening is also really important as an LA because it lets you understand the student's knowledge of a topic* so you can gauge how to explain/help them with their problem." ● "I like that *you handed the student the pen to draw with to get a better sense of their ideas* of velocity, speed, and acceleration!"
S2. *Support engagement* Support students' active engagement. Includes: ● Asking students questions ● Making space for students to figure things out for themselves	● "*Sometimes when a student is just verbally explaining their thought processes to me, they are able to self correct or notice a problem with their explanation*. I think that just by being an active listener, we have the potential to help students out." ● "*Making students explain their thought process is helpful for me and for the student*. The question most helpful for students was 'How did you get the equation for distance?' *through that question many students figured out the issue or non-issue if they were right, on their own*."

● Prompting students to talk, draw, or otherwise take action	● "I tried my best to *ask questions more and talk less so that they have a chance to think* rather than just listen to someone else speak." ● "*I liked how you made sure they drew all the parts of the drawing to understand the concept*, and it wasn't until they looked back on some of their notes was when they realized their misconception. I also had a similar *method of asking them questions on what they thought* before going into more depth on the new concept, that way *they can practice thinking for themselves* and working with others." - one LA commenting on another LA's reflection
S3. *Be responsive* Be guided by student ideas. Includes: ● Building on student thinking ● Incorporating student experiences into instruction ● Modifying activities or sequencing in response to student ideas or questions	● "I really liked how *you were listening to students mental models to decide how to explain the concep*t! By hearing a lot of connections with the motion of a car from students, you decided to relate physics to the student's personal experience with cars to build a stronger connection with the concept." - one LA commenting on another LA's reflection ● "I feel like now I've got a lot better at asking questions to figure out how students are approaching a problem. What they're thinking about and what they're bringing like to the situation like that and giving up to like the bottom line of the assumptions that they're making when solving a problem, and *ways that I can use what they're thinking and also correct their thinking to get them to the right answer and not just jumping in for like what works for me, or like how I think about it*."

6.4.3 Values related to students

The final category is values related to students. These resources are about the larger motivations LAs have that may shape their decision making in the classroom. They are about the goals and commitments LAs have in their teaching and the things they want for their students. They connect to ethical and motivational aspects of teaching, such as Campbell's ethical knowledge in teaching [45], which is described as teachers "mak[ing] conceptual and practical links" between "values such as honesty, compassion, fairness, and respect for others and their own daily choices and actions" [46]. In our data, we see these resources as grounding principles

that LAs use in their reasoning about teaching, potentially motivating and enabling teaching that centers student ideas.

V1. Inclusion

One of the values that our LAs bring to the classroom is a desire for all students to be welcomed into participation in learning. We see this in LAs acting to include more students in instruction (or noticing when other instructors take such actions), in voicing a desire that *all* students have what they need to participate and be successful, and in making (or seeing the need for) moves to create equitable opportunities for student engagement. These are all expressions of the resource *inclusion*. Table 6.4.4 includes quotes from LA responses that evidence this resource.

A desire for more equitable learning outcomes is often one of the motivations for using active learning and student-centered instructional modes [47-8]. Equity is featured in frameworks of pedagogical knowledge [e.g., 22, 49], and extensive work has been done in developing strategies for inclusion at many levels [e.g., 50-1]. Caring about who is learning, and who is left out, can also motivate shifts to more responsive or active modes of instruction that treat diverse student reasoning and conceptions as valid and continuous with scientific knowledge [37]. This value pushes back against the temptation to move on when the boldest or quickest students seem to understand, even when there are still conflicting ideas or confusion present more broadly. It also motivates attending to the ideas of individual students, whether or not they are commonly held. In all these ways, we see the resource *inclusion* as being connected to teaching that centers student ideas.

Inclusion was less commonly evidenced in the LA assignment submissions in our data set. While many LAs voiced this resource in their assignment submissions at least once, few LAs voiced this resource routinely. Many assignment prompts elicited *inclusion* from at least one LA, but few of the assignment prompts elicited this resource from many of the LAs. In our sample, LAs bring up *inclusion* most frequently in contexts where they are discussing group dynamics, reflecting on what they did in the classroom with their students and how successful it was, and speaking to the broader hopes they have for education.

V2. Affect

In addition to valuing inclusion, the LAs in our sample often bring up the confidence, comfort, and voice of their students. We see examples of LAs paying attention to whether their students feel comfortable enough to voice ideas and questions, caring about the growth of their students' confidence as learners, and wanting students to view making mistakes as a normal part of the learning process. These are LA uses of the resource *affect* that asserts 'we want our students to feel good about sharing their thinking.' Table 6.4.4 includes quotes from LA responses that evidence *affect*.

The resource *affect* has areas of potential overlap with the resource *inclusion*, and some LA assignment responses evidence both together. *Affect* is about how we want individual students to feel, which can impact whether all students have what they need to fully participate, which is what *inclusion* is about. In other words, one way to promote all students being included in learning (the goal of *inclusion*) is to ensure that students feel good about sharing their thinking (the goal of *affect*).

Wanting students to feel good about sharing their thinking is resourceful for understanding teaching that centers student thinking in that it recognizes the need to create learning environments where students are able to freely share their ideas, without which those ideas could not become an integral part of the learning process. Ideally, to the extent that it is applied to all or most students, it also pushes to make space for a diversity of ideas and perspectives, including those that challenge each other and/or those most comfortable to the LA, potentially making for richer, more authentic, and more responsive discussions. Research related to the resource *affect* includes instructor strategies and frameworks for putting students more at ease and motivating participation in idea sharing [41, 52-5]. LAs may also grow in their ability to seek out disciplinary connections in the content of student ideas as one strategy for affirming what students feel comfortable sharing.

The resource *affect* was very commonly evidenced in the LA assignment submissions in our sample. A large majority of LAs voiced this resource in their assignment submissions at least once, and many LAs voiced this resource routinely. Most assignment prompts elicited this resource from at least one LA, and many of the assignment prompts elicited this resource from many of the LAs. LAs evidence *affect* most frequently in conversations about getting things wrong, reflecting on personal experiences of positive learning environments, discussing the benefits and risks of working in groups, and observing who participates most or least.

V3. Skills

The LAs in our sample were typically motivated to help students correctly answer questions and complete classwork. There are also many instances where LAs bring up the other goals they have for students' learning. In addition to (and sometimes even more than) getting

answers correct, they often place value on students' processes, explanations, and understandings. They frequently express a desire for their students to gain deep understandings of disciplinary concepts and scientific practices, to develop critical thinking and problem solving skills, to be able to clearly explain the how and why of their thinking, etc., which all take students beyond what will get the 'right' answer in the moment and towards knowledge or skills that will continue to serve them in the future. These are all ways of expressing the resource *skills*. Table 6.4.4 includes quotes from LA responses that evidence this resource.

This value is resourceful towards instruction that centers student ideas. For example, it can provide motivation to put time and effort towards rich learning for students in the face of constraints - sometimes short term incentives, like finishing classwork on time or getting a good grade on an assignment, can compete with longer term goals, like gaining deep understanding. Teaching techniques like active learning and responsiveness often do not feel efficient towards the goal of getting students short-term right answers, but LAs using *skills* may see the potential for greater payoffs with these practices. Engaging students in sense-making, thinking like a physicist, building skills for career readiness, and connecting learning across disciplines are examples of goals that *skills* may be connected to [e.g., 56-9].

When coding for *skills*, we constrained ourselves to places where wanting students to build skills and understandings beyond getting the answer correct seemed to be the central idea, typically where a deeper or more desired type of learning was explicitly contrasted with 'right answers' or a more surface level learning. There were many more places where LAs mention learning outcomes they want for their students (e.g., improved reasoning, understanding, problem solving, critical thinking, intuition building, etc.) that we also see as exciting and related to this resource, even if we did not attribute *skills* to them.

At that threshold of attribution, *skills* was common in the LA assignment submissions in our sample. Most LAs voiced this resource in their assignment submissions at least once, and many LAs voiced this resource routinely. Most assignment prompts elicited this resource from at least one LA, and many of the assignment prompts elicited this resource from many of the LAs. *Skills* is evidenced most frequently when LAs are discussing ways that STEM classes or learning can benefit students outside of class and in diverse careers, what student interactions LAs find satisfying or productive, and when sharing the larger goals LAs have for their students.

Table 6.4.4. The three resources in the *values related to students* category with example quotes taken from LA pedagogy assignment submissions

Values related to students	
Resource	Example Quotes (italics added)
V1. *Inclusion* *We want* all *of our students to be included in learning.* Includes: ● Taking action to include more students in instruction ● Voicing desire that all students have what they need to participate and/or be successful ● Creating equitable opportunities for student engagement	● "I would like to explain things to the lowest common denominator, meaning teach to the lowest person in the classroom, *I feel like a ton of teachers/TAs teach to only the smartest students in the classroom, leaving the other students behind. So, I would rather assume the students know less, and build from simple ideas to the harder concepts*." ● "I would *observe who is being ignored by their classmates and give them more opportunity and respect to express their opinions*, but not stressing or putting too much pressure. Sometimes they have creative and correct ideas but they are just afraid of cutting in their classmates speech." ● "I feel like *everyone in the groups were involved, not a single person seemed to be uninterested* - There was a lot more talk about their individual thought processes and *they would all share and evaluate the best approach*." ● "Yes, some of my best collaborative groups have been open to open and mutual agreement. This is important because *this creates a space where all are welcome to learn, no matter where others Ed backgrounds lie*."
V2. *Affect* *We want our students to feel good about sharing their thinking.*	● "It is true that there will always be students who are afraid to put out their ideas in group discussions even if the class is packed with open questions. *We need to encourage these students and let them know that their ideas and thoughts are*

Includes: ● Caring that students feel comfortable voicing their ideas and questions ● Wanting students to grow in their confidence as learners ● Wanting students to view making mistakes as a normal part of the learning process	*accepted and welcome*. And honestly, I'm still trying to figure out how to do that effectively.” ● “I have a small discussion so I felt like I was a bit too overbearing on the groups. I was surprised that me listening in did not stop any discussion because I always get nervous when a teacher walks over. I approached every group being super nice and steering them towards the correct path when they fell off of it a bit. I think this worked out great b/c a student stayed after class to ask me a question. *I’m so happy I made that student comfortable enough to ask questions* b/c I know that some people have trouble with that.” ● “I really like working through conceptual questions with the people around me. I find thinking out loud also helps me to single out my own misconceptions or gaps in knowledge. *Working in groups also allows for a more approachable environment to bring up wrong answers*. Especially for long lectures, having group discussions helps break up the time and allows for deepening understanding. In tutorial, I really enjoyed being able to talk through all of the problems with my groups mates. Over the quarter, *we were able to get really comfortable in our pod and had great, insightful discussions. I want to help students get to that same level of openness in their groups because it makes such a huge difference in understanding and academic confidence*.“ ● “I think *a welcomed and positive talking environment helped me learn the most. I would feel more comfortable if my classmates are patient and willing to listen to my opinions or ideas instead of just talking to whom are smarter*. So I would learn the most if the class were asking students to work in groups and students have to take turns to answer the question.”
V3. *Skills* *We want our students to build skills and understandings beyond getting the answer correct.* Includes: ● Valuing students’ processes, explanations, and understandings in addition to (or more than) a correct answer or completion of an assignment ● Thinking beyond what will get students correct answers in the moment and towards knowledge or skills that will	● “*Interpreting and understanding are just as important as being able to come up with the correct answer*.” ● “*I think ‘understanding thought process to get the correct answer’ is way more important than just knowing the correct answer*.” ● “I have also experienced inconsistent grading as a student. Especially in the intro courses, I remember talking to my peers about which TAs would grade more critically than others. It was frustrating at the time, but those who graded my work more critically also often gave more constructive feedback about conceptual gaps I needed to fill. *Even when I had correct answers, it was helpful to have the push to think in depth about why I answered that way, and that my reasoning could still be flawed*.” ● “I've also noticed that students want to be done with a problem once they have found the right answer. However, *sometimes a*

continue to serve them in the future	*problem is useful for asking questions, comparing and contrasting, finding other ways of solving it, and much more*. It can be hard to motivate students to go beyond the right answer." ● "This is one of the features that really drew me to physics in the first place! *I really enjoyed the fact that it focused on building analytical skills and a new way to think through situations and reason rather than memorize*. I really hope to provide my students with a similar outlook on physics by the end of the course."

6.5 Implications for LA development

One of the goals of identifying these resources is to provide them as an aid for instructors in LA pedagogy courses who aim to train their LAs to look for and take up student ideas in the classroom. At the most basic level, they are ideas to look for, affirm, and nurture in pedagogy course discussions and assignments. While identical resources may not show up in all pedagogy courses outside of our sample, they can also serve as examples of the *kinds* of ideas that can be celebrated and built upon as LAs grow in their expertise.

Growth in the use of these resources may look like increases in the frequency or consistency of their activation or the appropriateness of the contexts in which they are activated. They also may grow in complexity, more closely aligning with best teaching practices. They can also be co-activated in ways that promote increased engagement with student thinking. In this section, we provide suggestions on how the resources presented in this paper might be built upon in the context of a LA pedagogy course.

As an example of how strengthening connections between resources can serve as a way to build these resources toward more student-centered teaching action, LAs using the resource *active learning* can be encouraged to recognize how this resource connects to *support*

engagement. This connection may already be clear to some LAs, but for others each of these resources may exist separately. An LA may describe past experiences consistent with *active learning* in their reflections, but may lack knowledge of teaching strategies to operationalize their experiences. Likewise, an LA may implement teaching strategies consistent with *support engagement* because they have been instructed to do so or because they have modeled their teaching approach after a former TA or teacher, but may not consider what makes the approach effective, leading to inflexibility or misapplication of the approach. To build upon this connection and operationalize it for the classroom, it may be helpful to have LAs reflect on prior experiences in which they experienced the process of learning actively, and to consider how they can support students in carrying out their own active learning in light of their prior experiences. Offering LAs questions to ask or teaching moves to make that support students in voicing their ideas [41] is also likely to be helpful in building upon *support engagement*. For some LAs, the *skills* resource may also make a meaningful connection with *active learning* and *support engagement* when LAs view the skills and understandings they wish for students to develop as only attainable via engaged practice and experience, thus serving to connect *skills* and *active learning*.

We see the *inclusion* and *affect* resources as helpful in creating learning environments in which all students are able to contribute their ideas and be listened to by others, including their instructors. In building upon these values, it may be helpful to remind LAs that students may differ in what makes them feel included and comfortable, and help LAs build an awareness of the range of ways in which they can be helpful to students. Pedagogy course instruction seeking to build on these resources can help LAs build understandings of the barriers to participation and sources of discomfort, both individual and systemic, that students may face in the classroom.

Affect may also present an avenue to motivate LAs to attend to the disciplinary substance of student thinking, as helping students find these connections may serve as a means to build student confidence in sharing their thoughts even when they may be incomplete or not entirely correct. The reverse can also be true, in that students may be more motivated toward *inclusion* and *affect* if they understand them as necessary toward supporting students' active engagement.

We do not see any of the resources we have identified as being exclusive or unique to LAs; many of the same resources are likely present in the thinking of other novice instructors including graduate Teaching Assistants. TA training programs may also find it helpful to draw on these or similar resources. We can also theorize that LAs are well-positioned to operationalize resources about student learning. As near-peer instructors, LAs are well-acquainted with the experiences of being a student, often in the same class in which they find themselves teaching. This proximity can serve to engender feelings of empathy toward their students, as LAs may recognize and connect with the experiences and feelings their students are having [60]. These proximal prior experiences and feelings of empathy may then result in LAs readily evidencing some of the resources we have identified. For instance, LAs in our data frequently brought up their own experiences of having to engage with their coursework deeply and actively in order to learn the concepts well. Experiences such as this can lead to LAs more readily seeing resources such as *active learning*, *support engagement*, and *skills* as important contributing elements of their teaching practices. Similarly, being acquainted with negative affective student-side experiences that are sometimes associated with the class they teach, such as feelings of discomfort, confusion, or fear of sharing a wrong idea, may lead LAs to enact practices aligned with the *inclusion* and *affect* values that aim to reduce these negative feelings. Future work could

explore whether similar resources are commonly evidenced in other populations of novice instructors who have differing degrees of proximity.

6.6 Conclusions

In this study, we identified nine cognitive resources that LAs have for understanding instruction that centers student ideas. These include three resources that are beliefs about learning (*multiple paths, active learning,* and *prior knowledge*), three resources that are knowledge of instructional strategies (*attend to ideas, support engagement,* and *be responsive*), and three resources that are values related to students (*inclusion, affect,* and *skills*). These resources were identified in the weekly coursework of LA pedagogy courses and found to be present across multiple forms of heterogeneity (i.e., present in the responses of multiple LAs to multiple assignment prompts at multiple universities).

We view this work as a call to see LAs as resourceful agents for attending to student ideas—and, more broadly, for carrying out constructivism-aligned teaching. As LAs have been shown to positively impact student learning across many contexts, the utility of LAs in classroom settings is not in question [5, 61-4]. We argue that identifying LA resources for taking up student ideas plays a valuable role in illuminating the mechanisms by which LAs are effective as instructors, while also serving as evidence of the expertise many LAs possess in teaching.

Just as we aim to elicit and build upon students' existing ideas in science courses, we see these resources for teaching as ideas that can be elicited and built upon in the context of LA pedagogy courses. Studies of the fleeting nature of novice teacher responsiveness have suggested that teacher resources impact the ways in which teachers frame moment-to-moment interactions in the classroom [65], and that moving these instructors toward responsiveness could be

accomplished by getting teachers to more consistently frame their instruction as attending to student thinking [66]. We argue that the eliciting and building upon of LA resources such as those we have described here could serve to stabilize LA framings of student ideas as useful for instruction, which in turn would lead to LAs centering student ideas in their instructional practices more frequently. We additionally see these resources as being useful as a framework for future research on the beliefs, values, and teaching practices of LAs.

While our study took place in the context of LAs who teach in physics classrooms, these findings are relevant to other types of novice instructors in other STEM disciplines where there is a desire to increase engagement in instructional teaching practices that attend to and build on student ideas; further research could examine how cognitive resources for teaching differ across instructor populations and disciplinary contexts.

Conclusion

This dissertation takes a crosscutting look at student ideas in physics instruction. It begins by examining the ideas that students have about physics, both physics concepts and physics explanations. It then investigates how different orientations towards student ideas in instructional material design impacts how students feel about their ideas during instruction. It finally identifies ideas students who are also novice instructors have about instruction, particularly those ideas that can be built upon to better understand instruction that centers student ideas. Together, these pieces explore student ideas and their interactions with key elements of the complex space that is physics learning, including teaching materials, instructors, and physics itself. In this work I have also aimed to practice what I preach, turning with attention and curiosity to the thoughts, feelings, and practices of students as sources of helpful input towards improving physics instruction.

Summary

Chapter 1 identifies three conceptual resources, i.e., potentially productive student ideas, that introductory physics students in our sample commonly use when reasoning microscopically about thermal physics topics: 1) *differences will eventually even out*, 2) *macroscopic changes connect to microscopic collisions*, and 3) *when something is hotter (colder), its molecules are moving faster (slower).* We report the prevalence of these resources, as well as the prevalence of microscopic thinking, in 624 written responses to three different heat and temperature questions administered to introductory physics students at four different colleges and universities. This work complements past research identifying common student *difficulties* in using microscopic models for heat and temperature, and it adds to the small but growing body of literature that

focuses on student *resources* for heat and temperature, identifying ideas in student thinking that are sensible and continuous with formal physics. By reporting common student resources, we aim to assist instructors in noticing, appreciating, and building on student ideas during introductory thermal physics instruction.

Chapter 2 gives an inside look at the methodology used in Chapter 1 and offers an opportunity for researchers to try out this method for identifying conceptual resources in students' written responses to questions. It leads interested researchers through identifying student conceptual resources specific to individual questions, reducing that preliminary set of (specific, often fine-grained) candidate resources into a smaller set of (often coarser-grained) common conceptual resources, testing and refining the preliminary coding scheme made from that smaller set of resources, and then coding with a finalized set of resources. This scaffolded activity uses students' written responses to open-ended heat and temperature questions as its context. It may help researchers who are curious about conceptual resource identification to join into that research enterprise.

The kinds of written responses collected for research like that presented in Chapters 1 and 2 are the subject of Chapter 3. In order to investigate student ability to use and communicate correct and complete reasoning, we examine written explanations from students in introductory university physics courses who have been prompted to answer a conceptual physics question and to "explain." Rather than focusing on context-specific reasoning difficulties, we examine the variation in what, to students, may constitute satisfying explanations, paying attention to what is present beyond what might score points on an instructor's rubric. We present six different types of explanations that capture the breath of student responses: 1) *"you might think" explanations*, 2) *process explanations*, 3) *contextualizing explanations*, 4) *"expert" explanations*, 5) *salient*

features explanations, and 6) *description explanations*. We include illustrative examples of each type. This broad view of student explanations has the potential to guide instruction aimed at the development of student explanation and argumentation skills in ways that leverage and are responsive to how students initially explain their reasoning.

In Chapter 4 we extend this work on student explanations by considering students' processes of explanation writing. Better understanding how introductory physics students approach explaining their reasoning can help us better interpret the explanations they give and better support students in writing the kinds of physics explanations we seek. In this study, we investigate what students *do* when they are asked to explain their reasoning. We consider how students conceptualize the task of explaining, what audience(s) they picture themselves explaining to, and how their process of arriving at an answer compares to what they write down in their explanations. We conducted interviews with 23 students at the beginning of their university introductory physics coursework. Through a phenomenographic analysis of these interviews, we find four 'categories of description' for how students explain their reasoning: 1) *documenting*, 2) *guiding*, 3) *keywording*, and 4) *proving*. These four modes of explaining vary in how central both physics formalism and reasoning pathways are to their purposes. Together, these modes of explanation describe breadth and variation present in students' writing of explanations in introductory physics.

Chapter 5 turns to the instructional materials in which conceptual physics questions, and the explanations we ask students to write, are often embedded. Rather than investigating student ideas, we consider how students *feel* about their ideas during instruction. Introductory physics instruction has the potential to impact how students feel about themselves, their ideas, and the field of physics. Furthermore, student affect is thought to be intertwined with student

engagement, persistence, and the very doing of science. In assessing instructional outcomes, we therefore want to look not only toward physics content learning, but also toward how students experience instruction. In this study, we examine what feelings students report having when using instructional materials designed with two different orientations towards student ideas. The materials are ACORN Physics Tutorials, which were designed, in part, to build on common student ideas (i.e., resources), and Tutorials in Introductory Physics, which were designed, in part, to address common student difficulties. One might imagine that these different design orientations towards student ideas might have measurably different impacts on the feelings students have about their own ideas. We began by developing a survey instrument to allow large numbers of students to self-report their feelings. We then administered the survey after multiple sessions of tutorial instruction at two universities. We find that students in our sample report higher levels of agreement with positively-valenced feelings (e.g., confident, encouraged) than negatively-valenced feelings (e.g., frustrated, embarrassed) when thinking back on instruction with both types of tutorials, and that the levels of agreement and disagreement with the feelings items in our survey are comparable between the ACORN Physics Tutorials and Tutorials in Introductory Physics. We also discuss students' feelings when they report having 'corrected' their ideas, other factors beyond instructional design that students report affecting their feelings, and what students may have in mind when referring to 'their ideas'. Our findings have implications for instructional design that considers affective outcomes and for future research on the role of affective elements in physics learning.

Finally, in Chapter 6 we take up one of the factors beyond instructional design that appears to be centrally relevant to how students feel about their ideas during instruction: the instructor. In this study, we consider Learning Assistants (LAs), undergraduate students who

support student learning as part of the instructional team in active learning classrooms. Our focus is on the ideas that LAs have about physics instruction that may be helpful in building an understanding of instruction that centers student ideas. We examine LA submissions to pedagogy course assignments, looking for those ideas (i.e., cognitive resources) that are evidenced in the responses of multiple LAs to multiple assignment prompts at multiple universities. We identify nine resources: three are beliefs about learning (*multiple paths*, *active learning*, *prior knowledge*), three are knowledge of instructional strategies (*attend to ideas*, *support engagement*, *be responsive*), and three are values related to students (*inclusion*, *affect*, *skills*). These resources for teaching are ideas that can be elicited and built upon in the context of LA pedagogy courses, and they can be used in future research on LA pedagogical development.

Implications

The studies in this dissertation each have their own implications for future research. From Chapters 3 and 4, for example, further investigation of physics explanations from student perspectives appears promising. How do students evaluate their own explanations or the explanations of others? How do shifts in context (e.g., physics topics, forms of evaluation, or modes of delivery) affect the explanations students give? How do student explanations compare to those modeled by their instructors? What interventions promote student development of expertise in explanation writing in physics? The study presented in Chapter 5 also raises as many questions as it answers.

Nonetheless, the findings in this work can be of use. This research has identified resources for thinking microscopically about thermal physics and resources for teaching that centers student ideas in physics. It has described types of written explanations and modes of

explanation writing to conceptual physics problems. These research outputs can be used by future researchers in tracking student development, in comparing student outcomes, or in close qualitative analysis of student thinking. They can be used by curriculum developers in producing materials that build on student thinking. They can also be used by instructors who can seek out these particular ways of thinking in the students of their classes, plan lessons using these student ideas, or find new aspects of physics instruction in which they can center student ideas.

Acknowledgements

It has been a privilege to complete this work with so many people and communities offering me support, mentorship, inspiration, and interest along the way. I feel such gratitude for the experience. My thanks goes first to Paula Heron, who is the reason I found Physics Education Research in the first place. It has been a pleasure to learn from you and explore with you.

I have had wonderful collaborators in all of my work. Thank you to Amy Robertson, who has taught me as much about working thoughtfully with others as about research, and who is also a dear friend. Thank you to Rachel Scherr, who always asks the most interesting questions, and Sam Engblom, who made me believe my work was helpful. To Lisa Goodhew, Clausell Mathis, Tra Huynh, and Lauren Bauman, I have loved working alongside you all. To Ava Aflatooni, Jon Owen, Brynna Hansen, and Olin Sorby, what an honor to have crossed paths with you; I am excited to see where each of you go. To the rest of the Conceptual Resources team, what a dream it was to feel supported by you, especially coming out of the pandemic. To Sam McKagan and Adrian Madsen, I hope I get to work more with you in years to come

I am deeply grateful to the Physics Education Group, past and present members, who have been my professional home for so many years. Thank you to Mackenzie Stetzer and Mila Kryjevskaia, who got me started and whom I still look up to. Thank you to Peter Shaffer, Donna Messina, and the whole Physics by Inquiry and Summer Institute crew; I learned to love teaching through you. To Suzanne White Brahmia and her grapefruit and to David Smith and his devotion to students, what a pleasure to be in community with you. To Jared Canright, Charlotte Zimmerman, Alexis Olsho, Dean Bretland, Tong Wan, Jon Goldak, Kristin Kellar, and Cam Flynn, where did the time go? I would like to share space with you all forever.

To Al Snow and Abby Daane, thank you for keeping me grounded in the things I care about while I do my work. To Shannon Houghton, thank you for your unwavering support and enthusiasm. To Lori Durko Fisher, thank you for being alongside me in juggling small children and graduate school. To the rest of my family, especially my parents, Patrick, and Ame, thanks for always showing up for me. And to Kate, with whom anything is possible, I am so lucky to have you.

Finally, my gratitude goes to the students and instructors who made this research possible. This work was also supported in part by National Science Foundation grants DUE-1914603, 1914572, and 1821123.

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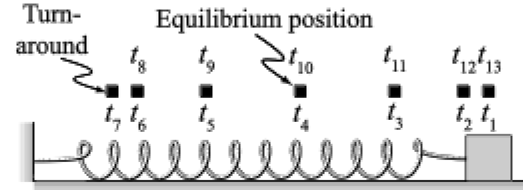
APPENDICES

Chapter 4 - Appendix A

Interview handout content

Part 1: Conceptual physics problem (Block and Spring) for student to solve

A block on a frictionless surface is attached to a spring. The block is pulled to the right and released from rest at time t_1. The motion of the center of the block is shown by the dots in the strobe diagram. (The time intervals are equal.) The block turned around at time t_7 and returned to its stretched position at t_{13}.



Draw a vector indicating the direction of $\vec{a}_{11}$, the instantaneous acceleration of the block at time t_{11}. If $\vec{a}_{11}$ is zero, state so explicitly. Explain your reasoning.

Direction of $\vec{a}_{11}$

Part 2: Sample responses to physics problem (Block and Spring) for students to critique[2]

← The acceleration is to the left at t_{11}. The acceleration is zero at the equilibrium and then gets larger as the block approaches the turnaround point.

← The acceleration at t_{11}. is to the left. It is slowing down.

← The spring is trying to pull the block back toward equilibrium, so the acceleration is to the left.

← Even though the velocity is to the right because it is moving to the right, the change in velocity is in the opposite direction. So the acceleration is to the left.

---

[2] These sample responses were written by the first author to represent succinct versions of different types of written explanations [1]. They were based on actual student exam responses to the Block and Spring problem (see Part 1 above) from the first quarter of the introductory calculus-based physics course at the University of Washington. This study's participants were drawn from a different enrollment of the same course during a different academic term.

← Draw the velocity vector for before and after t_{11}. Then when you subtract the initial velocity from the final velocity, the resultant vector will point in the direction of the acceleration.

Part 3: Prompts for students to compare

Explain.

- Explain your reasoning.
- Tell me about your answer.
- Why does your answer make sense?
- How do you know that your answer is true?
- How might you convince someone else of your answer?
- Justify your answer.
- How did you arrive at your answer?
- What caused this outcome?
- What else do you know about this answer?

Chapter 5 - Appendix A

Survey instrument

What did you experience in **TUTORIAL** *this week*?

For each statement below, choose how strongly you agree or disagree on the following scale:
1 means strongly disagree,
2 means disagree,
3 means neither agree nor disagree,
4 means agree,
5 means strongly agree

During tutorial this week, I corrected something that I had been thinking.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

During tutorial this week, I confirmed something I already knew.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

During tutorial this week, I learned more about something I already knew about.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

During tutorial this week, I became unsure about something that I had been thinking.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

During tutorial this week, I cleared up some of my uncertain ideas and thoughts about a topic.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Please elaborate on the statement(s) you most strongly *agreed* with.

For example, describe what you had been thinking, what happened in tutorial that interacted with that thinking, and what you are thinking now.
[If you did not agree with any of the statements, please write a statement that *does* describe how/if your ideas were impacted by instruction.]

How did you feel about your ideas in **TUTORIAL** *this week*?

For each statement below, choose how strongly you agree or disagree on the following scale:
1 means strongly disagree,
2 means disagree,
3 means neither agree nor disagree,
4 means agree,
5 means strongly agree

At some point during tutorial this week, I felt confused about some, any, or all of my ideas.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

At some point during tutorial this week, I felt encouraged about some, any, or all of my ideas.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

At some point during tutorial this week, I felt confident about some, any, or all of my ideas.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

At some point during tutorial this week, I felt frustrated about some, any, or all of my ideas.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

At some point during tutorial this week, I felt embarrassed about some, any, or all of my ideas.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

At some point during tutorial this week, I felt like some, any, or all of my ideas mattered.

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Please elaborate on the statement(s) you most strongly agreed with.

For example, in what specific context did you feel that way about your ideas, and what ideas did you feel that way about?
[If you did not agree with any of the statements, please describe the feelings, if any, you did have about your ideas.]

Chapter 5 - Appendix B

Correlations survey instrument

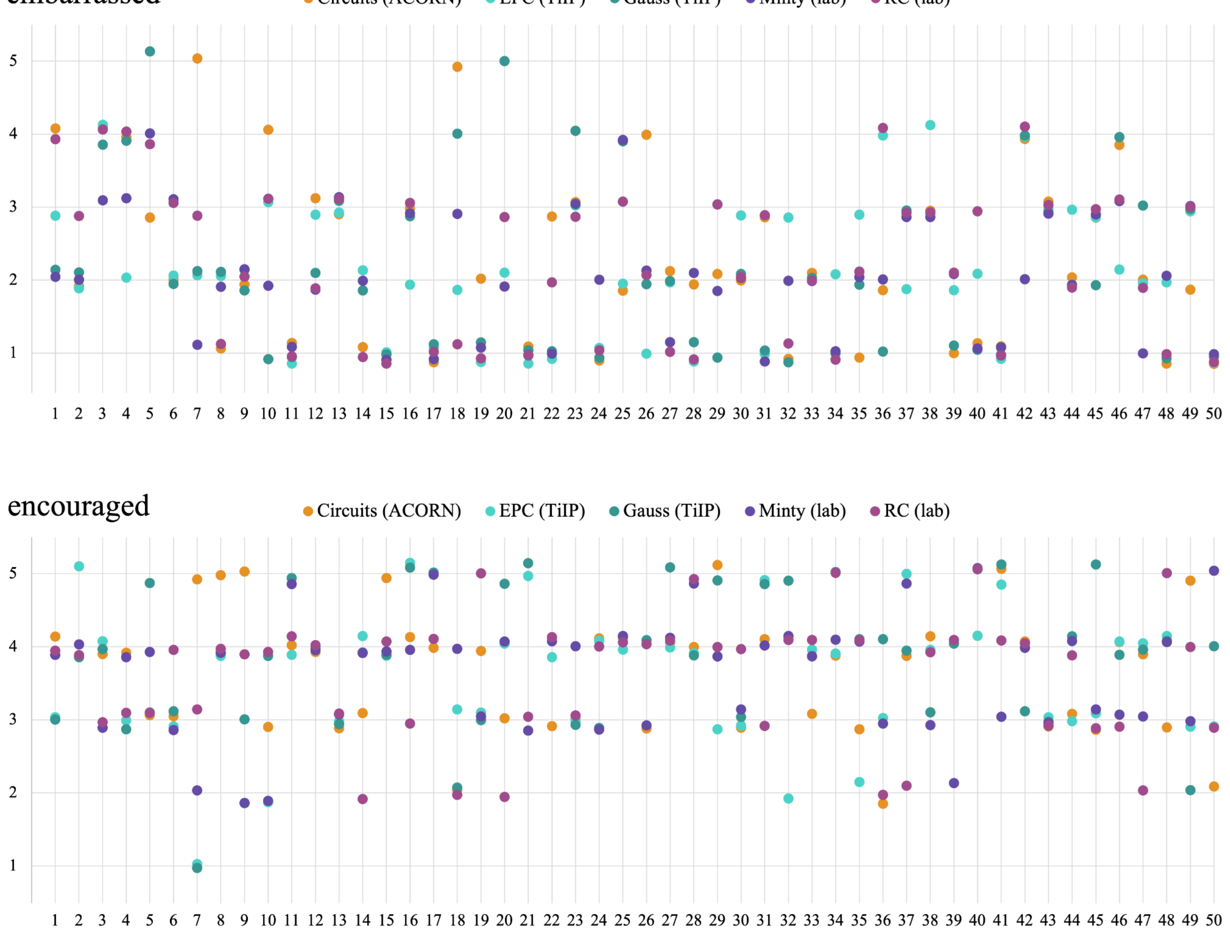
Spearman's rho for correlation of ordinal data: 0 means no monotonic relationship, +/-1 perfect positive or negative monotonic relationship

	corrected	confirmed	learned more	unsure	cleared up
confused	0.30	-0.16	0.07	0.41	0.15
encouraged	0.18	0.41	0.30	-0.13	0.29
confident	0.05	0.46	0.25	-0.20	0.19
frustrated	0.10	-0.20	-0.03	0.32	0.05
embarrassed	0.08	-0.14	0.00	0.26	0.04
mattered	0.18	0.29	0.29	-0.11	0.31

Chapter 5 - Appendix C

Variation in individual student survey responses

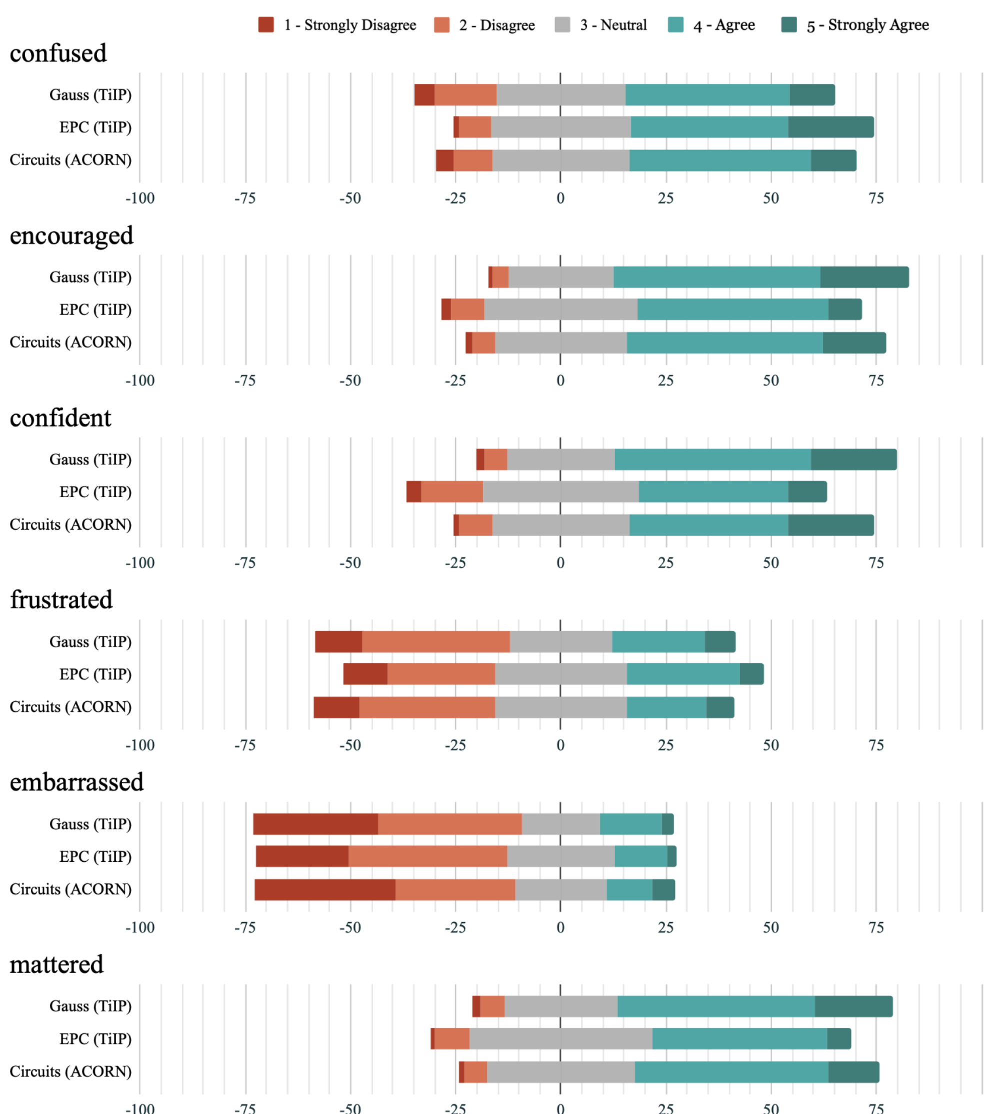
Each number along the horizontal axes represents an individual student from University B who completed all 5 surveys. Each dot represents a survey response. The dots are 'jittered' for easier visibility in the case of overlap. Survey items *embarrassed* and *encouraged* were chosen to include as examples of the larger set of survey items, as the former represents the smallest median range and the latter represents the largest median range in individual student response



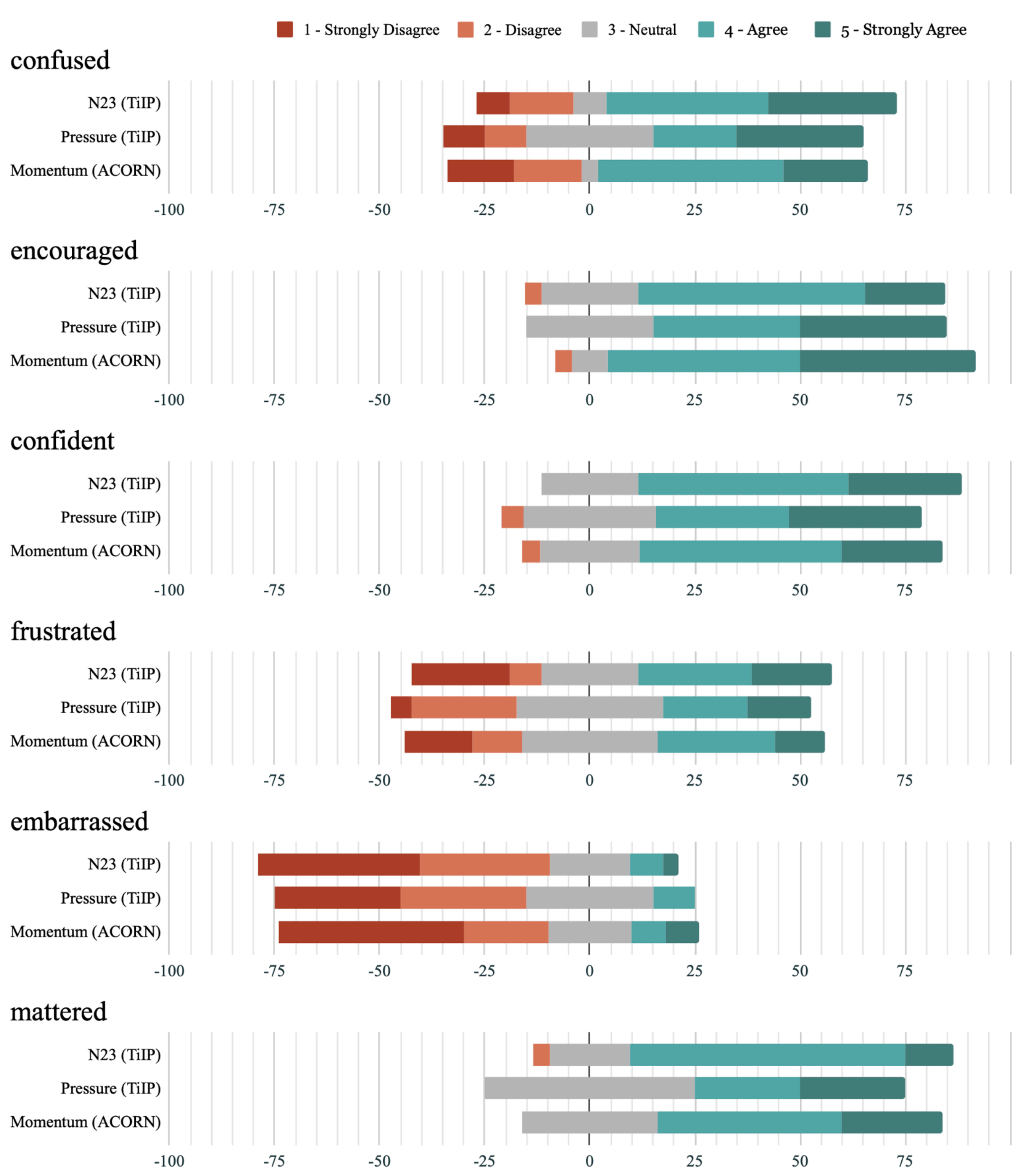
Chapter 5 - Appendix D

Full distribution of survey responses

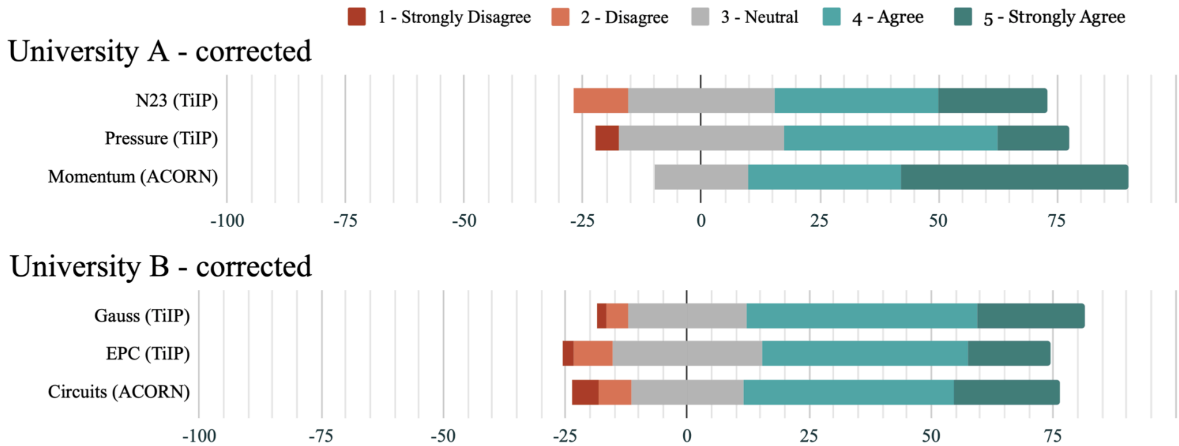
University B: Percentages of each Likert response to each feeling item for two sessions of instruction with Tutorials in Introductory Physics (TiIP) and one session of instruction with an ACORN Physics Tutorial (ACORN)



University A: Percentages of each Likert response to each feeling item for two sessions of instruction with Tutorials in Introductory Physics (TiIP) and one session of instruction with an ACORN Physics Tutorial (ACORN)



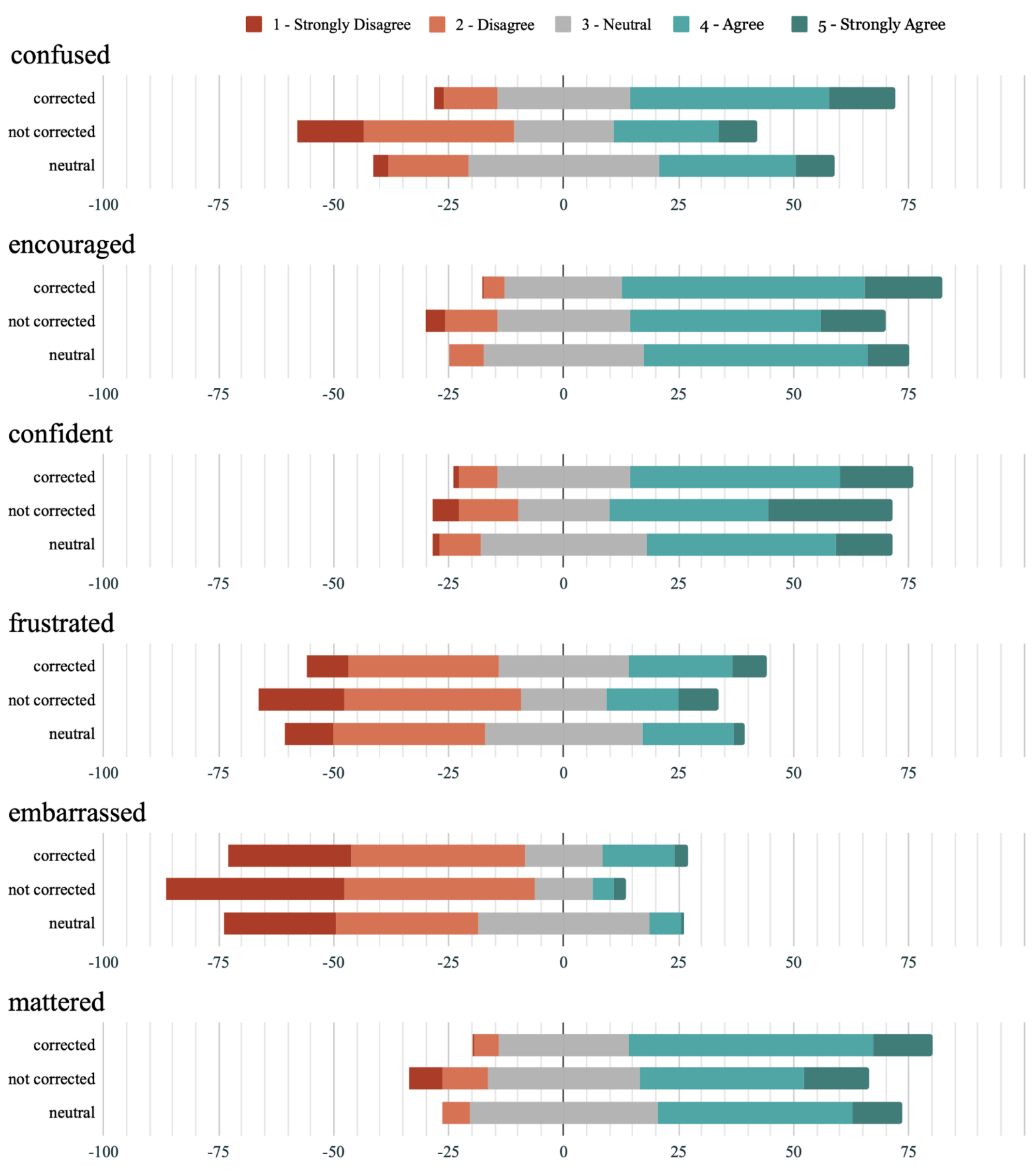
Corrected: Percentages of each Likert response to *corrected* for two sessions of instruction with Tutorials in Introductory Physics (TiIP) and one session of instruction with an ACORN Physics Tutorial (ACORN) at University A and University B



Chapter 5 - Appendix E

Corrected vs not corrected

Percentages of each Likert response to each feeling item for surveys in which students reported agreement, disagreement, or neither to *corrected* at University A



Chapter 6 - Appendix A

Examples of assignment prompts at each university

University	Prompt type	Example
Western State University	Field notes	Reflect on interactions that you had with your students or that you observed in your sections recently. Comment on what went well or what you would do differently in retrospect.
	Reflection	Post an entry on an experience you have had with grading of homework or exams *etc.,* either as feedback you received as a student or issues that came up as a grader, if applicable.
	Reading response	Read the following three papers [1-3], and in this discussion post comment on student-TA interactions by ● Asking a question that you have about the reading. ● Answering a question already posted. ● Writing about the topic, such as an opinion, a link to other relevant information, or your previous experiences related to the reading, either as a student or teacher.
University of Central Plains	Field notes	This week, alongside any notes of your own, document some of the techniques you are practicing during your teaching. There are many ways to teach effectively, and hopefully you've had a chance to find some teaching habits and practices that are effective for you. Don't feel like you need to provide an answer that will impress your instructor; instead, try to use this as an opportunity to reflect on how your own personal approach to teaching is developing. What techniques from the pedagogy class did you implement in your class today? Have you developed and used any approaches of your own? If so, be sure to document those as well!
University of Brackett	Field notes	Reflect on a time in your teaching where you noticed a student had a misconception or wrong idea. How did you respond? How did the student's idea change (if you noticed this)? Could that idea have been fruitful in another situation?

	Reflection	How can students/ instructors cultivate a classroom learning community where everyone gets to show their expertise, and where their resources are welcome contributions?
	Reading response	Read Hammer, "Student resources for learning introductory physics" [4] on Perusall. Respond with at least three questions or comments.
Cedarburg College	Field notes	Describe a student interaction that gave you insight into the student's mental model and/or prior knowledge about a physics concept.
	Reflection	Reflect on your teaching interactions now as compared to the start of the quarter. What have you gotten better at over the past several weeks?
	Reading response	Read and respond to Redish, "Implications of cognitive studies for teaching physics" [5]. Access this assignment in Perusall. The assignment is to read the article and annotate it with at least three questions or comments.

[1] Koenig, K. M., & Endorf, R. J. (2004, September). Study of TA's ability to implement the Tutorials in Introductory Physics and student conceptual understanding. In AIP Conference Proceedings (Vol. 720, No. 1, pp. 161-164). American Institute of Physics.

[2] Plato. (1994). The classic Socratic method. The Physics Teacher, 32(3), 138-141.

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[5] Redish, E. F. (1994). Implications of cognitive studies for teaching physics. American Journal of Physics, 62(9), 796-803.

Chapter 6 - Appendix B

Prevalence of resources

One of our goals for this research was to identify resources that were evidenced by many different LAs, at different institutions, and in response to many different prompts. In this section, we report which resources were present or absent, common or uncommon, across these dimensions. While there are limitations to how widely we can assume findings from our sample will generalize, resources that are present across these different types of heterogeneity in our sample may also be more likely to be elicitable in LAs more broadly. We selected the nine resources detailed above for coding due to their connections to teaching that centers student ideas and to their potential to be widespread within our data set. First we consider their presences in the responses of different LAs, then we consider their presences in the responses to different assignment prompts.

In looking at these nine resources, all but resources S3 and V1 are present in the responses of many LAs at all four institutions. Resources B1, B2, B3, S1, S2, V2, and V3 were all evidenced in at least one response by more than half of the LAs across all universities in our sample and by many of the LAs at each of the four institutions in our sample. As such, we consider these seven resources to be widespread across LAs in our sample, including at different institutions, and more likely to be elicitable from LAs more broadly. Figure B.1 shows the prevalence of LAs at each institution who evidenced each of the resources in at least one assignment response, and Figure B.2 shows the prevalence of LAs who commonly evidenced each of the resources (>20% of their assignment prompts).

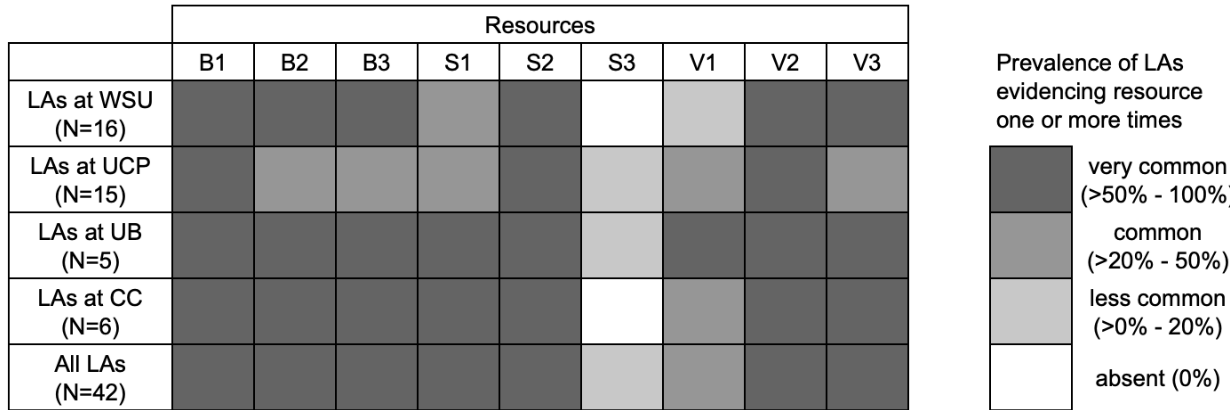

Fig. B.1 Prevalence of LAs with each resource present in at least one of their responses at each institution. For example, it was very common for the LAs at Western State University to have expressed resource B1 in at least one of their responses (13 of the 16 LAs); it was less common for the LAs at Western State University to have expressed V1 in at least one of their responses (2 of the 16 LAs).

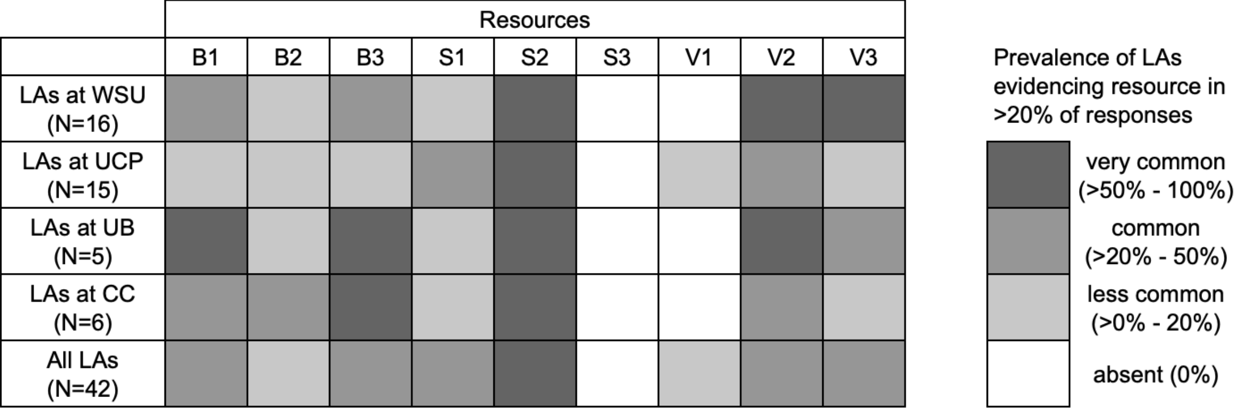

Fig. B.2 Prevalence of LAs with each resource present in many (>20%) of their responses at each institution. For example, it was very common (12 of the 16 LAs) for the LAs at Western State University to have expressed resource S2 in many (>20%) of their responses; it was less common (2 of the 16 LAs) for the LAs at Western State University to have expressed B2 in many (>20%) of their responses.

In looking across different prompts, all but resource S3 and V1 are present in the responses to many assignments at all four institutions. Resources B1, B2, B3, S1, S2, V2, and V3 were all evidenced in the responses to more than half of the assignment prompts by at least one

LA across all universities in our sample. We therefore consider these seven resources to be elicitable in the context of a wide variety of assignment prompts within our sample and more likely to be elicitable without carefully targeted questions more broadly. Figure B.3 shows the prevalence of assignment prompts at each institution that evidenced each of the resources in at least one LA response, and Figure B.4 shows the prevalence of assignment prompts that evidenced each of the resources in many LA responses (>20%).

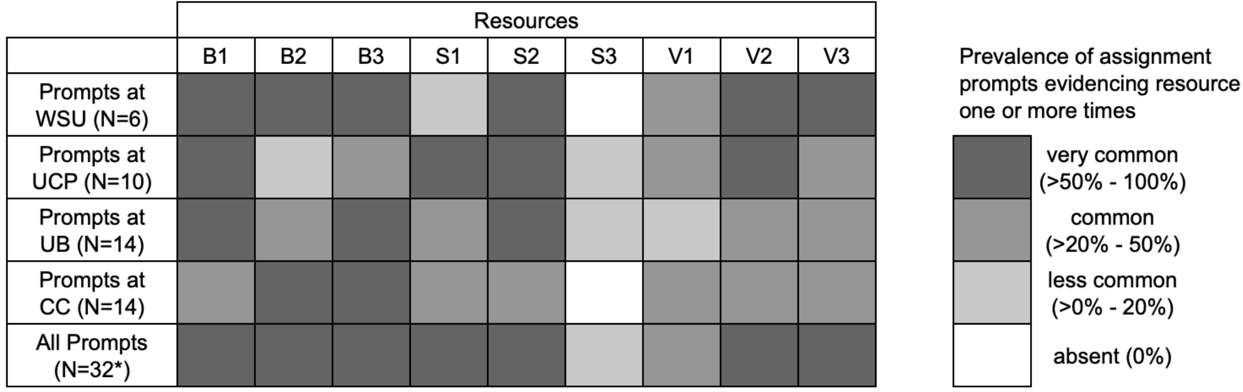

Fig. B.3 Prevalence of assignment prompts with each resource present in at least one LA response at each institution. For example, it was very common for the assignment prompts at Western State University to have elicited resource B1 in the response of at least one LA (5 of the 6 prompts); it was less common for the assignment prompts at Western State University to have elicited S1 in the response of at least one LA (1 of the 6 prompts). *Some assignment prompts between University of Brackett and Cedarburg College were shared, giving less total prompts across all universities than the sum of the prompts at each of the four universities.

	Resources								
	B1	B2	B3	S1	S2	S3	V1	V2	V3
Prompts at WSU (N=6)									
Prompts at UCP (N=10)									
Prompts at UB (N=14)									
Prompts at CC (N=14)									
All Prompts (N=32*)									

Prevalence of assignment prompts evidencing resource in >20% of responses

very common (>50% - 100%)

common (>20% - 50%)

less common (>0% - 20%)

absent (0%)

Fig. B.4 Prevalence of assignment prompts with each resource present in many (>20%) LA responses at each institution. For example, it was very common (4 of the 6 prompts) for the assignment prompts at Western State University to have elicited resource S2 in >20% of LA responses; it was less common (1 of the 6 prompts) for the assignment prompts at Western State University to have elicited B2 in >20% of LA responses. *Some assignment prompts between University of Brackett and Cedarburg College were shared, giving less total prompts across all universities than the sum of the prompts at each of the four universities.

Resources S3 and V1 were more rare in our sample. Resource S3, *be responsive*, is perhaps the most complex of the three *knowledge of instructional strategies* resources and the closest to fully fledged responsive teaching. As such, it is unsurprising that it is the least frequent in the knowledge of instructional strategies category. Additionally, LAs are typically the members of an instructional team with the least amount of power to make in the moment changes to what students are expected to do or learn. This might limit how much or in what ways they can let student ideas steer their teaching or see this form of responsiveness as relevant to instruction. If it is not too lofty a goal to have LAs view *be responsive* as a normalized and desirable teaching practice, we have more work to do to get them there.

Resource V1, *inclusion*, was also more rarely evidenced in our data set. This resource is about equity in participation, and it is important beyond the ways it underpins student access to learning that centers their ideas. It is possible that this value is not widespread among LAs. We

suspect that instead, the pedagogy class assignments in our sample are not sufficiently cueing LAs to consider and discuss issues of equity within their readings, reflections, and observations of teaching and learning. This may be because LAs lack the language or comfort to bring up such issues, that the classroom cultures of the pedagogy classes subtly discourage such discussion, that LAs lack the nuance to see how equity plays into the topics more directly addressed in class, etc. None of the assignment prompts in our sample seem designed specifically to address equity in the classroom, and in that absence, we do not see evidence of LAs activating and communicating that resource much on their own. Again, if we want LAs to be explicitly aiming for all students to be included in learning, we have more work to do.

Further study could examine how the prevalences of resources vary over time. If these resources were originating from instruction within the pedagogy courses, we might expect to see few (or zero) instances of a resource initially followed by either a stark increase when a resource was introduced through instruction or a gradual increase as a resource became more accessible or utilized by LAs through their continued learning. As the pedagogy courses progressed, the prevalences of the resources did not grow convincingly over time in our sample, as seen in Figure B.5. This does not support the idea that these resources are coming primarily from learning taking place during the LA courses, and it is possible that instead the LAs are bringing these resources into their pedagogy courses after acquiring them as students or in their other experiences of teaching and learning. It is also possible that as assignment prompts varied over the academic term, they influenced which resources were and were not elicited enough to mask any trends that reflect increased resource usage more broadly. Future research could use more targeted prompts to track specific resource prevalence over time, and more limited prompts could also allow for more concretized coding parameters to enable more precise quantitative

comparisons. Future research could also examine what prompts, or types of prompts, most consistently elicit particular resources.

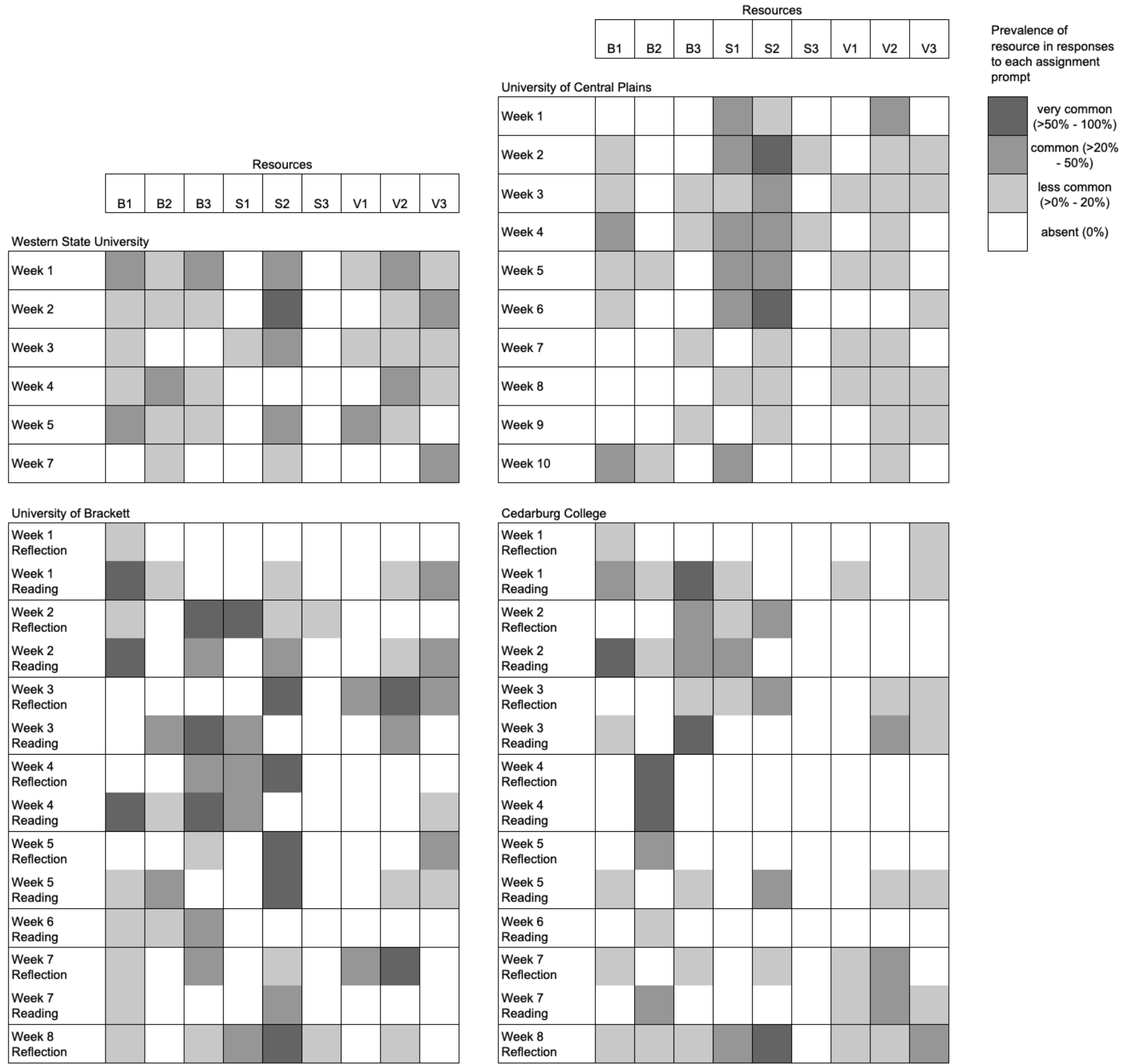

Fig. B.5 Prevalence of each resource in assignment responses at each university, arranged chronologically. The prevalences of the resources, as seen by their shading, do not convincingly increase as time progresses downward.