Characterizing and Leveraging Students' Conceptual Resources for Wave Mechanics

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2020

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Physics

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Abstract

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In its earliest days, a primary focus of physics education research was investigating common patterns of student reasoning about specific physics topics to inform instruction and curriculum development. This continues to be a fruitful research program with practical impacts on physics teaching. Such studies provide instructors with knowledge of ideas that their students are likely to use and informs the design of instructional materials and strategies to target common student ideas. To date, the bulk of PER studies that characterize student thinking about specific physics topics have focused on identifying the ways that student thinking is inconsistent with canonical physics concepts or principles. This kind of research promotes instruction that confronts and resolves students' incorrect thinking.

The work presented in this dissertation applies an alternative theoretical framework -- resources theory – to this influential paradigm in PER. Resources theory conceptualizes student thinking as the activation of context-sensitive pieces of knowledge that are fruitful for canonical physics concepts. This work implements resources theory by assuming that student thinking is sensible and can be the beginnings of scientific reasoning. This work also takes up resources theory in the assumption that student thinking is dynamic and affected by the context of the students' experiences, the learning environment, and the question at hand. This dissertation explores common conceptual resources for wave mechanics through both large-N investigations and an illustrative case study. Informed by these studies, this dissertation also presents preliminary instructional materials on wave propagation designed to elicit and build on students' common conceptual resources. These results extend the field's theoretical understanding of students' conceptual resources and support practical implementation of a resources perspective in physics instruction.

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ACKNOWLEDGEMENTS

There are many people who have supported this work – and who have supported *me* in the process – and I can only begin to acknowledge their contributions. I am extremely grateful to my advisors on the Conceptual Resources project: Paula Heron, Amy Robertson, and Rachel Scherr. It is a privilege to have been mentored by each of these researchers, in different capacities, throughout my graduate work. I have learned and benefitted from Paula's insight into various different research perspectives, Rachel's attention to metaphor and theoretical consistency, and Amy's sense of the structure of an argument. In particular, I am deeply grateful to Paula Heron for her guidance and encouragement throughout my graduate school experience. Paula, I am especially grateful for your openness to and encouragement of my crazy ideas and your flexibility as a graduate advisor. Your willingness to support me in pursing my ideas and goals has been one of the most meaningful examples of resources-oriented teaching to me, and your confidence in my capability has encouraged me through so many of the doubts I've faced as a student.

Amy Robertson's advice and guidance have shaped this work from its very beginning stages, before I began as a graduate student at UW. The words I write here cannot do justice to the time and effort she has spent mentoring me throughout this journey, which has encouraged my confidence and capability as a researcher in many ways. More importantly, collaborating with and being mentored by Amy has encouraged me to grow as a person: as a friend, sister, partner, colleague, and teacher. Amy, I am so immensely grateful for the care you have given me throughout this whole journey. I am a more compassionate and empowered person because of it.

This work has been supported by so many members of the PER people in Seattle and beyond. I am grateful for the support that the members of the UW Physics Education Group, past and present, have given me in planning, conducting, and presenting my work. Thank you especially to Suzanne Brahmia, who provided helpful feedback on drafts of this dissertation, and to Peter Shaffer, Donna Messina, Tong Wan, Alexis Olsho, Sheh Lit Chang, Bert Xue, Dean Bretland, Jared Canright, Anne Alesandrini, and Charlotte Zimmerman for your advice, collaborative support, and encouragement. Similarly, I am indebted to my collaborators on Conceptual Resources team: Lauren Bauman, Clausell Mathis, Brynna Hansen, Hung Tran, Cheyenne Broadfoot, Yohannes Abraham, Katie Marvin, and Raphael Mondesir. I want to particularly acknowledge my gratitude to Stamatis Vokos, without whom I would have never considered PER as possibility for my life, and who showed up to encourage me in many of the toughest moments. I am grateful to Hannah Sabo, who was my first research collaborator and a contributor to the intellectual foundations of this work, as well as a friend and support throughout graduate school. Thanks also to members of PERCoGS, particularly Gina Quan, Daryl McPadden, Danny Doucette, Brian Zamarripa Roman, and Constance Doty, who supported me in developing an identity as a PER person, helped me make connections in the field, and whose efforts and ideas have shaped my research perspectives and skills. I am also grateful to Lane Seeley, John Lindberg, and Kara Gray who have mentored as a physics teacher and supported me as an undergraduate and graduate student.

The support of my community beyond physics has been so important to me throughout the past five years. I'm incredibly grateful to my family: Mom, Dad, Joe, John, Mary, and Abby. Your encouragement and care have helped me persevere, reminded me of my capability, and pointed toward a greater good. To Savannah, Keely, Bryn and Matt, Maria, Jenny, and many others: thank you for laughing and crying with me and for reminding me that there is much more to life than academia. And, to the Dominican community in Seattle – especially Fr. Thomas Aquinas, Fr. Marcin, Fr. Jordan, and Fr. Lukasz – your support has enabled me to be a better Christian, scientist, teacher, friend, and colleague.

This material is based upon work supported by National Science Foundation Grants 1608510, 160822, 1914603, and 1914572, and by the National Science Foundation Graduate Research Fellowship Program under Grant No. 1256082. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation.

DEDICATION

To my family, who first fostered my excitement about learning

Chapter 1. INTRODUCTION

Science learners have intuitive knowledge about the natural world that affects their future learning. This tenet is at the center of constructivist learning theory. Learning involves an individual's "successful reorganization of his or her own experience," [1] rather than transmission of ideas from instructor to student. New knowledge is "actively built up by the learner," [2] beginning from the stores of ideas the learner already possesses [3]. The constructivist perspective emphasizes that an instructor's attention to students' existing ideas plays a significant role in effective teaching. The field of physics education research (PER) has contributed to constructivist science teaching by offering a wealth of research on the ideas that students commonly have about the physical world before, during, and after instruction. This kind of research has had a significant impact on physics teaching in recent decades because it contributes to an important part of instructors' professional expertise – knowledge of student ideas (KSI) [4] – that enables instructors to anticipate student thinking and target their teaching accordingly. Further, PER has provided research-based instructional strategies to support instructors in effectively responding to their students' ideas.

Research on students' ideas about specific physics concepts has predominantly focused on the ways student thinking is inconsistent with canonical physics concepts and presents an obstacle to be overcome by targeted instruction [3,5–9]. Numerous studies have investigated students' common misconceptions and difficulties[1] in content areas from kinematics to quantum mechanics (e.g., [9,10,19,11–18]). Research on student thinking about mechanical waves – the content focus of this dissertation – follows this trend [20–27]. These studies are intended to report on patterns of incorrect thinking that are common among physics students; their focus is not on explaining the nature or structure of student thinking through any particular theoretical framework [28]. However, student misconceptions and difficulties have typically been characterized in the

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[1] Researchers have called specific ideas that are inconsistent with canonical physics misconceptions, preconceptions, alternative conceptions, or difficulties. *Misconceptions, preconceptions, naïve conceptions* and *alternative conceptions* are more often used to describe specific ideas that are stable, coherent, and theory-like. Research on student *difficulties,* on the other hand, does not typically assume a particular structure of student thinking; the term "difficulties" can refer to patterns in student reasoning that are not necessarily concrete "things" that exist in a student's mind [28]. The important commonality across these terms is that they refer to reasoning that is inconsistent with canonical concepts. Because the term "difficulties" can encompass a broader range of misunderstandings, and because it is more commonly used in current research, I use the term difficulties to refer to incorrect student reasoning in this chapter.

literature as relatively robust and resistant to change, and sometimes as stable, coherent and theory-like [3,5–8]. Results of large-N studies of students' difficulties contribute to improved physics teaching because they enable instructors to anticipate where their students will struggle and target their instruction accordingly. These studies have also had a widespread impact on physics teaching through curricular materials (such as the University of Washington Physics Education Group's *Tutorials* [29], which have been cited in nearly 100 research articles since 2006 [30]) that have been developed to guide students to confront and resolve these difficulties. In this dissertation, I draw on the tools of this research tradition – characterizing common student ideas about specific physics topics and developing curricular materials based on the results of such investigations – using the *resources* theoretical framework, which orients toward the ways in which students' intuitive ideas can be part of the structure of expert thinking (e.g., [3,31–34]).

1.1 RESOURCES THEORY

Smith, diSessa, and Roschelle have argued that to be fully consistent with the central tenets of constructivism, research "must either reconsider the solely mistaken character of misconceptions or look for other ideas to serve as productive *resources* for student learning [3, emphasis added]." The resources theoretical framework models cognition in terms of pieces of knowledge – i.e., *resources* – that are activated in the moment in a context-sensitive way to construct arguments, theories, and concepts. Resources are the raw material out of which learners build understanding; this theoretical framework conceptualizes learning as activating, refining, and connecting resources and reorganizing the structure and conditions for their activation [3,31–35]. This may include increasing the degree of formality of individual resources, changing the role resources play, and/or changing the structure and connectedness of resources.

According to this view, the resources that novices activate as they seek to sense-make about the natural world are also part of the structure of expert physics thinking. This tenet of resources theory affords an instructional expectation that learners' existing understandings can be used to construct scientific explanations and concepts in the classroom and can be fruitful for science learning [3,31]. It also embeds an understanding that resources themselves are *continuous* with formal physics. Here, "continuous" means that student ideas, even those that are incorrect or incomplete, can be seen as "seeds" of sophisticated scientific concepts and practices [3,31,36]. In the Chapters 3, 4, and 5, I elaborate on the details of resources theory as it pertains to the research presented in each.

Researchers have argued that a resources perspective has several theoretical advantages. First, resources theory gives a more detailed account of the observed context-dependence and complex nature of student thinking (i.e., instructors observe that students do not necessarily apply the same idea across problems or in different situations, as a scientist would apply a scientific concept or theory) more naturally than a misconceptions or difficulties perspective does [31,35]. Second, as suggested by Smith *et al.,* a resources perspective is more immediately consistent with the constructivist assumption that new knowledge is built from pre-existing ideas, and thus intuitive knowledge is part of the structure of expert thinking [3,31].

In addition to these affordances of resources theory, some studies have suggested that instructional approaches consistent with a resources perspective have benefits over other research-informed approaches. In line with resources theory, instructional approaches of this kind aim to support students in articulating, refining, and building from their own ideas [31]. Examples of instructional approaches that are consistent with resources theory are characterized by: (a) instructors' emphasis on understanding the conceptual substance of student thinking (i.e., instructors seek to understand the meaning their students make of the physical world), (b) attention to the connections between students' thinking and disciplinary concepts, and (c) flexibility in pursuing student thinking in the moment [36–42]. Studies have shown that this kind of instruction may improve students' conceptual understanding beyond more traditional approaches and fosters student engagement in the practices of science [39,41–43]. Instruction that frames student thinking as the beginnings of sophisticated disciplinary understandings – and shifts the classroom focus toward students as constructors of knowledge – has the potential to support more equitable participation in science classrooms [44–47]. These proposed benefits have mostly been observed or hypothesized in the context of K-12 classrooms, where instructors bring different training and expertise (e.g. teacher certification) and are responsible to different learning goals and student expectations than instructors in typical university physics courses. The work presented in this dissertation aims to support resources-oriented instruction at the university level.

There are challenges to implementing resources-oriented instruction in typical university physics courses[2], which limit our understanding of the extent to which the potential benefits of resources-oriented instruction may be realized at the university level. For example, because resources theory highlights the dynamic, emergent, complex-systems-like nature of student thinking [35], instructional recommendations and curricular materials have to strike a balance between broad applicability and flexibility according to the particulars of the classroom. Resources-oriented teaching as defined above implies some degree of open-endedness and flexibility of learning goals so as to substantively build from students' own thinking. In this way, it is quite different than traditional lecture instruction or instruction using other research-based instructional strategies, particularly those informed by research on student difficulties (e.g., [29]). This dissertation addresses the practical implementation of resources-oriented instruction in the context of mechanical waves through three strands of research that answer questions about students' common conceptual resources and how they can be leveraged in curricular materials.

1.2 OUTLINE OF THIS DISSERTATION

The first strand of the work I present here (Chapter 3) addresses the question: what are the common conceptual resources that students use to reason about mechanical wave propagation? An analysis of ~ 900 written student responses to a set of similar questions about mechanical wave propagation highlights three common conceptual resources that recur across questions; it also demonstrates patterns in the context-sensitivity of these resources by showing which questions most commonly elicit specific conceptual resources. This research illustrates how researchers and instructors can view student thinking through a resources lens and contributes the kind of pragmatic knowledge of student ideas that can support a shift toward resource-oriented teaching practice. This analysis informs future research by demonstrating a methodology for exploring students' conceptual resources across physics content areas and supports preliminary curriculum development by demonstrating which questions reliably elicit particular resources. Chapter 3 has been published in *Physical Review Physics Education Research* [48] and is included here nearly verbatim, with the addition of demographic information about the research sample that we did not

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[2] Of course, there is variation in the structure, size, and content of university-level physics courses. By "typical," I refer to courses that are taught by physics faculty members or graduate teaching assistants who do not necessarily have expertise in specific research-based instructional strategies, are intended for physical science and engineering majors, and may have large enrollments.

have at the time of publication. Co-authors Amy D. Robertson, Paula R.L. Heron, and Rachel E Scherr contributed to the initial study design, gave advice on data analysis (Robertson was a second coder in this analysis), and provided feedback on the manuscript.

The second strand of this dissertation (Chapter 4) examines patterns in the sensitivity of resources to context. This investigation substantiates an observation that different kinds of questions on the same topic – questions that ask students to predict the outcome of an experiment (and explain their reasoning for the prediction) vs. questions that ask students to explain an observed result or phenomenon – tend to elicit different kinds of conceptual resources in different patterns. "Predict" questions tend to elicit rules, principles, and procedures, whereas "explain" questions elicit both rules, principles, and procedures *and* ideas about force, motion, and energy. In themselves, these results substantiate the prediction made by resources theory that the context – including features of the question or the epistemological framings cued by the question – influence what resources are activated for students. These results inform instruction in that they provide guidance on what kinds of questions may be most suitable given an instructor's goals. Additionally, this investigation raises new research questions about how these results generalize to new physics content areas and informs investigations of common conceptual resources in other physics areas. Chapter 4 has been submitted to *Physical Review Physics Education Research* and is included here verbatim. Co-authors Amy D. Robertson, Paula R.L. Heron, and Rachel E Scherr contributed to the initial study design, gave advice on the analysis (Robertson was a second coder in this analysis), and provided feedback on the manuscript.

In the third strand of my dissertation work (Chapters 5 and 6), I begin to explore questions about learning and instruction from a resources perspective through two case studies. The first case study (Chapter 5) examines the progress of one student's thinking over the course of a problem-solving interview, illustrating an example of refining and building from conceptual resources. This case study was published in the 2018 *Physics Education Research Conference Proceedings* [49] and is included here. Co-authors Amy D. Robertson, Paula R.L. Heron, and Rachel E Scherr contributed to the initial study design, gave advice on the analysis, and provided feedback on the manuscript. In the second case study (Chapter 6), I analyze an example of resources-oriented instruction in a calculus-based physics course at the University of Washington. This example comes from a preliminary implementation and test of an instructional worksheet on wave propagation that our team (Amy D. Robertson, Paula R.L. Heron, Rachel E. Scherr, and Lisa M.

Goodhew) developed based on the results of the first two strands of this dissertation, which I also describe in Chapter 6. This case study examines the knowledge, skills, and commitments that may support graduate TAs in implementing this kind of teaching, with the goal of guiding TA preparation. This case study has been accepted for publication the 2020 *Physics Education Research Conference Proceedings* and is included here. Co-authors Amy D. Robertson and Paula R.L. Heron gave advice on the analysis and provided feedback on the manuscript.

1.3 CONTEXT AND OVERVIEW OF RESEARCH METHODS

The data for chapters 3 and 4 come from students' written responses to conceptual physics questions about a range of wave propagation concepts, which were administered in introductory physics courses at a selection of U.S. universities and colleges between 2016 and 2020. All of these courses covered the physics of waves as part of the standard syllabus, and our questions were given to students after some instruction on waves as part of required coursework (though they were not always graded for content). However, these courses varied in structure and content emphases. Most used some research-based instructional strategies such as *Tutorials in Introductory Physics* [29], clicker questions or *Peer Instruction* [50], or *PHeT* simulations [51], although we do not know details of the curricula and instructional approaches used in the courses we sampled from.

We analyzed these data by constructing emergent coding schemes [52] based on a subset of student responses, and then applied this coding scheme to the whole set. This was done by two independent coders, and then the codes assigned by each were compared. We kept only the codes that both coders agreed upon in our final calculations of the fraction of students using each idea. The methods used to construct these emergent coding schemes, as well as the details of our codes and inter-rater agreement, are discussed in detail in Chapters 3 and 4.

In Chapter 5, I present two case studies which follow students and instructors in the third quarter of the University of Washington's calculus-based introductory physics course (PHY 123). The course is structured around three main components: lectures that meet three times a week for 80 minutes, a weekly 110-minute lab, and a weekly 50-minute small-group sessions in which students typically work through *Tutorials in Introductory Physics* [29]. The two cases come from different contexts. The first comes from a set of one-on-one research interviews with PHY 123 students that were not part of the course, while the second comes from an intervention in one of the weekly PHY 123 tutorial session in which students used a worksheet developed as part of this project. Each of these was video-recorded and later transcribed for analysis. In both case studies I use iterative, inductive methods [53,54] to tell a particular story of "what is going on here?" [55] that illustrates what learning may look like from a resources perspective. I discuss the particular theoretical constructs and methods relevant to each case study in Chapter 3.

1.4 SUMMARY

Each of the three strands of research presented here points to the overarching question of how the expectations of resources theory play out in real instructional situations. More specifically, chapters 3-5 address the questions: What are patterns in the conceptual resources used by introductory physics students as they reason about mechanical waves? In what ways can student thinking be fruitful for their science learning? What do learning and teaching look like, according to resources theory? What might support instructors in implementing resources-oriented instruction? Chapter 3 answers what resources instructors can anticipate and discusses how they may be the beginnings of scientific understandings, in order to support them is noticing these ideas in the moment and planning their teaching to build from student thinking. Chapter 4 supports instructors and researchers in predicting what kinds of resources will be elicited by the questions they ask. Chapter 5 illustrates how students' conceptual resources can be fruitful for learning and shows that particular kinds of knowledge may support instructors in seeing the fruitfulness of students' resources and building their instruction on students' own ideas.

In order to quantitatively test the effectiveness of the resources-oriented instructional approach described here, a more comprehensive body of materials is needed. Future work is needed to investigate the common conceptual resources that students use in other physics content areas, such that resources-based curricular materials can be developed for topics beyond wave mechanics. This dissertation provides a framework and test case for doing this kind of research and development. At the same time, it sparks new questions about what learning goals resources-oriented instruction best serves, and what instructors need in order to effectively implement resources-oriented instruction. These are important subjects of future research.

Chapter 2. OVERVIEW OF STUDENT IDEAS ABOUT MECHANICAL WAVES REPORTED IN THE LITERATURE

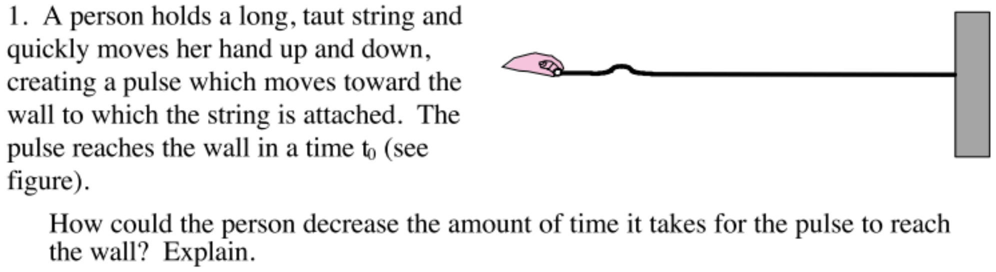
Studies contributing to instructors' knowledge of student ideas about mechanical waves have primarily focused on characterizing ideas that are incorrect or incomplete and may represent obstacles to learning, following a broader trend in PER. The literature reports a range of common misconceptions and difficulties [20–27,56], and researchers have developed conceptual surveys to diagnose some of these ideas (e.g., [20,57–59]) and curricular materials to improve students' conceptual reasoning about mechanical waves [20,29].

This chapter summarizes previous research on student thinking about wave mechanics, discussing specific ideas reported in the literature and the theoretical orientation toward student thinking taken by various studies. To match the physics concepts relevant to the work presented in subsequent chapters, this overview focuses on the literature that reports on student thinking about transverse pulses and waves in media (this chapter does not include the literature that discusses student ideas about sound waves, optics, and mathematical representations of waves, for example). The ideas reported in the literature can be characterized according to three content areas: ideas about pulse or wave speed, ideas about superposition, and ideas about reflection.

2.1 STUDENT IDEAS ABOUT PULSE OR WAVE SPEED

A pulse is canonically conceptualized as a propagating local disturbance of a medium, which transports energy but not matter. The speed of the pulse is determined by properties of the medium – in the case of a spring, its tension and mass density. The amplitude of the pulse is determined by the motion of the source, while the width is affected by both the motion of the source and the speed of the leading edge in the medium. Previous studies have found that students have difficulties or misunderstandings about what a pulse *is* and with how properties such as speed or width can be changed.

Several authors have found that students think that the speed of a pulse or wave depends on how it is generated when asked students questions like the one in Fig. 2.1 below, which is originally from Wittmann's Wave Diagnostic Test [20]. This question has been given in multiple choice, free response, and interview format [20,56,58].



1. A person holds a long, taut string and quickly moves her hand up and down, creating a pulse which moves toward the wall to which the string is attached. The pulse reaches the wall in a time t_0 (see figure).

How could the person decrease the amount of time it takes for the pulse to reach the wall? Explain.

Figure 2.1. Question on pulse speed from Wittmann's Waves Diagnostic Test

In the context of this question, Wittmann found that many students answer that flicking a string harder will generate a faster-moving pulse [20,60,61]. Other authors have asked the same question with similar results [26,27,56]. Caleon and Subramaniam report a slightly more nuanced version of this idea: that as frequency increases, wave speed also increases because more energy is being imparted to the particles of the medium [62]. In several studies, Wittmann and colleagues interpret this idea as treating a pulse like a Newtonian particle: just as throwing a ball harder makes it move faster, "throwing" a pulse on a string harder makes it move faster [20,60,63].

In subsequent papers, Wittman and colleagues re-interpreted these results [60,61,63] in terms of *resources* that are activated in inappropriate or unproductive contexts. For example, Wittmann, Steinberg, and Redish [5] propose two alternative ways of thinking about waves: waves as objects (like a ball being thrown) or waves as propagating events (like a domino chain). The first is unlikely to be a productive resource for thinking about wave phenomena, but the second is. In [60] and [63], Wittmann makes sense of the student response data from his dissertation [20] through different theoretical lenses (the "object coordination class" and conceptual blending).

Other studies have found that students have misunderstand the relationship between propagation speed, wavelength or pulse width, and frequency or duration of source motion. Based on the equation , students may think that wave speed depends on frequency (or vice versa) [22,26,56,62]. This idea may be associated with reasoning that a higher frequency means "more energy is imparted to the particles of the medium [62]," so the wave travels faster. Students may think that the transmitted wavelength or velocity depends on the incident wavelength or velocity when a wave crosses a boundary to a new medium. Kryjevskaia, Stetzer, and Heron [22] summarize this kind of idea as a difficulty understanding how the variables , , and can be manipulated experimentally – that wave speed is a property of the medium, frequency can be manipulated at the source, and wavelength is determined by the frequency and propagation speed in a given medium. Maurines reports that students tend to reason about wave propagation problems with only two variables at a time (implicitly holding the other constant). For example, when asked about how the width of a pulse changes when changes are made to the medium (given by the equation) students consider either the speed of the pulse *or* the time to create it [27]. Kryjevskaia et al. report that students may reason that a change in wavelength when a wave crosses a boundary is independent of any change in propagation speed [22]. The same authors also find that students may think of wavelength as an abstract quantity rather than as a length scale.

2.2 STUDENT IDEAS ABOUT SUPERPOSITION

A canonical application of the principle of superposition to wave mechanics involves first identifying pulses or waves as localized disturbances of a medium which can be co-located. When two or more pulses coincide, the resulting disturbance of the medium is determined by summing the individual vector displacements of each pulse at each point along the medium. Studies have found that students have difficulties with various steps in this procedure. The student ideas reported in this literature to fall into two broad categories: (a) misapplication or misunderstanding of the rules or mathematical procedures of superposition, and (b) alternative ways of thinking about superposition or thinking about waves physically.

Studies by Wittmann [20] and Sengören *et al.* [25] found that students may reason as if pulses only superpose when their peaks overlap. When the peaks do not overlap, students may draw partially overlapping pulses or say that the resultant pulse cannot be found. Both of these studies also found that students may reason that when two pulses meet, the amplitude of the resultant pulse is always given by the sum of their amplitudes (the maximum displacement from equilibrium) – even when the peaks of the pulses do not overlap. Relatedly, Kennedy & deBruyn reported that some students only add the amplitudes of the pulses, not their heights at every point [26]. Sengören et al. reported that students may think the superposition principle only applies to pulses on the same side of a string or spring. When two pulses are on opposite sides of the string, students using this line of reasoning draw two pulses at the same x-position on the string, one on each side [25]. The same study found that students may also reason as though superposition is always additive, even when pulses are on opposite sides of the string. Using this idea, students add the absolute value or magnitude of two pulses' amplitudes when pulses superpose.

The literature also reports a set of misunderstandings related to non-canonical ways of conceptualizing what a pulse is, or what superposition means. For example, Sengören et al. report that students may treat two pulses moving toward each other on the same side of a string like vectors, with the magnitude given by the amplitude of the pulse and direction given by the direction of motion. Since these "vectors" point in opposite directions, one amplitude is subtracted from the other to find the amplitude of the resultant pulse [25]. Some studies also report that students reason as though pulses can "bounce off of each other," [20] or, when two pulses meet, the resultant pulse continues in the direction of the larger pulse [25,60]. In the latter case, the resultant pulse may have a smaller amplitude or slower speed. Similarly, the study by Sengören et al. found that students treat superposition is a continuing effect, such that once two pulses meet (and superpose in some way) they continue their motion together in the direction of the larger pulse's motion. Students may think that the larger pulse encompasses the smaller when they meet, or that the amplitudes add in some way. Wittman also found that some students use the idea that if pulses cancel each other, they are not reformed at a later time [20]. Wittmann has interpreted students' reasoning as though pulses "bounce" or "stick together" as another manifestation of the "object coordination class," [60] or treating pulses as Newtonian particles. Using ideas about macroscopic objects to make sense of wave phenomena, students treat the meeting of two pulses like an elastic or inelastic collision, where the objects continue together in the direction of the more massive one at a smaller speed.

2.3 STUDENT IDEAS ABOUT REFLECTION

Physicists commonly model wave reflection at a boundary as the superposition of the incident pulse and an imaginary pulse of the same shape moving toward the boundary from the opposite side. The orientation of the imaginary pulse – whether it is upright or inverted – is determined by the boundary conditions. In the case of transverse pulses on springs, the imaginary pulse is upright when the end of the spring is free to move in the transverse direction in order to satisfy the condition that there are no transverse forces on the end of the spring. When the end of the spring is fixed, the imaginary pulse is inverted in order to satisfy the condition that the end point does not move. The shape of the spring during reflection is then determined by applying the procedures of superposition to the incident and imaginary (or reflected) pulse at each instant during the time that they coincide. Studies have found students have difficulty with the various steps in this procedure.

Some studies have found that students incorrectly predict the shape or orientation of the reflected (or imaginary) pulse. Specific findings include that students draw a pulse reflected from a fixed end of a string on the same side of the string as the incident pulse (whereas a correct answer would have the reflected pulse on the opposite side of the string) [21,24]. Or, students may believe that all pulses reflect on the opposite side of the spring, regardless of whether the end is fixed or free [24]. Some studies find that students may answer that there will be no reflected pulse at a free end [20,24]. Kryjevskaia et al. report that when asked to draw the shape of a pulse after it has reflected, students may use the wrong leading edge or orientation of the pulse [64]. After instruction, students may incorrectly generalize the results of experiments they have seen in class about reflection from fixed and free ends [21,64], using reasoning such as, "the maximum transverse displacement of a spring exceeds the amplitude of the incident pulse if the end is free, but not if the end is fixed [21]." Students may also have difficulty with or do not use the principle of superposition to determine the shape of a spring during reflection [21,64].

Chapter 3. STUDENT CONCEPTUAL RESOURCES FOR UNDERSTANDING MECHANICAL WAVE PROPAGATION

3.1 ABSTRACT

Much of the literature contributing to physics instructors' knowledge of student ideas (KSI) reports common patterns of reasoning that are framed as discontinuous with canonical concepts. Our work contributes new KSI about mechanical wave propagation from a *resources* perspective, framing student thinking in terms of context-sensitive pieces of knowledge that are continuous with canonical physics concepts. The intent of this work is to inform instruction on mechanical waves by identifying and illustrating some of the conceptual resources that instructors might expect their students to use. To support instructor predictions about student thinking, we identify resources that are common across multiple samples and questions. Our data include written responses to three versions of a conceptual question about mechanical pulse propagation. We use an emergent coding scheme to characterize a total of 862 written responses from 6 universities in the United States. Our analysis reveals three common conceptual resources: (1) *properties of the medium either impede or facilitate the motion of the pulse,* (2) *the speed or duration of transverse motion affects pulse speed* (3) *the speed of the pulse is affected by its kinetic energy.* We show how each of these resources can be viewed as continuous with formal understandings of pulse propagation.

3.2 INTRODUCTION

Knowledge of students' ideas is essential for effective teaching, according to conceptualizations of pedagogical content knowledge [4,65,66]. Most existing research that provides knowledge of student ideas (KSI) emphasizes ways in which student thinking is inconsistent with scientific understandings [67,68]. These research efforts have guided the development of instructional materials designed to target specific difficulties or misconceptions (e.g., [6,7] in the context of waves) and thereby improve students' conceptual understanding.

Investigations of common student difficulties or misconceptions and the curricula informed by them have had a widespread impact on physics education: the pragmatic, high-leverage KSI that they provide supports instructors in anticipating content areas where students may struggle and in designing instruction that considers students' existing ideas [5,6].

Physics education research focused on common student difficulties and misconceptions is grounded in constructivist learning theory [5,7,33], which assumes that "all individuals must construct their own concepts, and the knowledge they already have…significantly affects what they can learn" [5]. Also consistent with constructivism is the *resources* theory of knowledge, which sees student thinking as composed of inherently-sensible pieces of knowledge that are activated in the moment to construct concepts, arguments, or explanations [3,33,34,69,70]. Research that embodies a resources perspective tends to focus on student ideas that "serve as significant input to the process of conceptual growth" [3] rather than on ideas that represent obstacles to learning. In light of the significant impact that investigations of common incorrect patterns of student reasoning have had on physics education, authors have called for "complementary research to identify possible conceptual progenitors of expert understanding in students' intuitions" [35].

This "complementary research" is important for both pedagogical and theoretical reasons. From a pedagogical point of view, a resources approach to KSI motivates instruction to refine, extend, and build from existing knowledge [3,35,69], rather than to confront, remedy, or overcome incorrect ideas. From a theoretical point of view, resources theory makes claims that have not yet been empirically demonstrated for large numbers of students (e.g., that resources are context-dependent). Resources-oriented KSI research – particularly research into ideas that are common across many students – has the potential to support theoretical development and instructional practice.

Relatively few studies have investigated the common conceptual resources that students use to reason about specific physics topics. Most resources-oriented research has focused on developing theory or building a case for the pedagogical significance of resources theory, and most research documenting *common* patterns of student thinking has focused on misconceptions or difficulties. For example, research on student thinking about mechanical waves mainly attends to the ways in which student thinking is inconsistent with canonical physics concepts, and provides instructors with KSI in the form of common patterns of incorrect reasoning (e.g., [20,22,26,27,56,62]). A notable exception is [61], which identifies some possible conceptual resources that students might use to understand mechanical wave propagation. Our research extends such work both pedagogically and theoretically by empirically investigating some common conceptual resources that students use to reason about mechanical wave propagation.

Mechanical wave propagation is especially interesting to us because of its prominence as a foundational topic in both K-12 and introductory university physics [71], and thus its potential relevance and impact for physics instructors. The topic of mechanical wave propagation (a) often introduces a scientific understanding of what a wave *is,* (b) serves as a concrete and accessible foundation for understanding more abstract wave phenomena (namely electromagnetic waves) that are central to many areas of advanced physics study, and (c) is challenging for students, according to the literature [72].

In this paper, we address the research questions: *What are some of the common conceptual resources that introductory university physics students use to reason about mechanical wave propagation? How does student use of these resources vary across questions about mechanical wave propagation?* We report three common conceptual resources for mechanical wave propagation: (1) *properties of the medium either impede or facilitate the motion of the pulse;* (2) *the speed or duration of transverse motion affects pulse speed;* and (3) *the speed of the pulse is affected by its kinetic energy.* In section 3.7, we illustrate variation in how each of these resources was used by students in our study and we discuss how each of these resources may be productive for learning, even as they are not always fully correct. We also discuss some possibilities for leveraging each one instructionally. In section 3.8, we show that these resources are elicited at different frequencies for different wave propagation questions: that is, we demonstrate patterns in context-dependence of these resources that emerged in our analysis.

Our study contributes new, topic-specific KSI in the form of student *resources* for understanding mechanical wave propagation, and thereby serves the broader goal of supporting instructors in anticipating and building on student thinking about propagation in their classrooms. Further, our research illustrates what it might look like for an instructor to view their students' ideas as inherently sensible and potentially productive, which may be an entry point for a broader resources framing in instruction. Instructional approaches consistent with a broader resource-oriented framing have empirically-demonstrated benefits, including promoting students' conceptual understanding (beyond more traditional approaches) [43,73] and engagement in disciplinary practices [39,41,42], and supporting student agency in classrooms [41].

3.3 THEORETICAL BACKGROUND

This study draws on the resources theoretical framework, which models cognition in terms of pieces of knowledge – i.e., *resources* – that are activated in the moment in a context-sensitive way to construct arguments, theories, and concepts. Resources theory highlights the dynamic, emergent, complex-systems-like nature of student thinking [35] and emphasizes the continuity of student thinking with formal physics concepts. Our work draws on the resources theoretical framework as we identify patterns in student thinking about mechanical wave propagation, particularly by emphasizing the inherent sensibility and continuity of student thinking with formal physics.

Theoretical conceptualizations of the structure, deployment, role, and pedagogical significance of resources [3,33,34,69,70,74] have been developed by a number of researchers, and vary to some degree across different sources. Our work is most informed by the following tenets from resources theory:

- **Resources are sensible to the learner** [3,34,69,70,75]**.** Resources (for physics) are thought to be derived from a person's experiences of the physical world and prior learning and thus inherently sensible to the learner [3,34,69,70,75]. That is, learners have good reason for thinking in the ways that they do based on ideas that are useful for understanding many phenomena, even as these ways may be different than formal physics [40,70,75]. For example, diSessa [70] says that phenomenological primitives ("p-prims," which we consider to be a kind of resource) such as "closer means stronger" are best understood as "serv[ing] individuals well in dealing effectively with the physical world." From a resources lens, even canonically incorrect ideas are seen as arising from activation of resources that support the student in making sense of physical phenomena, and that may be correct in other contexts. In the resources perspective, instructors can expect that learners' ideas are fruitful for sense-making in some context(s), and that there is a way to "see the science" in learners' thinking [76].

- **Resources are activated in context-sensitive ways** [33–35,41,70]. Resources theory is a cognitivist perspective in that resources are understood to exist in the minds of individual students. They are "activated" as relevant in the moment to construct explanations, arguments, and concepts, and are not necessarily activated consistently across contexts. However, resources are generally considered stable in the sense that they can be reused and applied to multiple situations [77]. Resources are activated when they "make sense" or are deemed applicable by the student; activation of a particular resource is influenced by a constellation of conditions related to the learner, the environment, and the question at hand [33,34,74]. Thus, resources are not expected to be consistently activated across a set of physically similar problems. For example, instructors can expect that questions that seem conceptually similar to them may elicit very different resources from students, and they can expect that the same student may display one idea in one context and a very different idea (or set of ideas) in another [34,75].
- **Learning involves changing the structure or activation of resources, and thus resources are continuous with more sophisticated scientific understandings** [11–13,15,33,34]. Resources are depicted as the raw material out of which learners build understanding. For example, Smith *et al.*, define resources as "any feature of the learner's present cognitive state that can serve as significant input to the process of conceptual growth [3]." Learning involves refining resources and reorganizing the structure and conditions for their activation. This may include refining or increasing the degree of formality of individual resources, changing the role resources play, and/or changing the structure and connectedness of resources [3,34,70]. According to this view, the resources that novices activate as they seek to sense-make about the natural world are also part of the structure of expert physics thinking. This tenet of resources theory affords an instructional expectation that learners' existing understandings can be used to construct scientific explanations and concepts in the classroom [49,74]. It also embeds an understanding that resources themselves are *continuous* with formal physics: according to resources theory, resources have the potential to be fruitful for students science learning, and even ideas that are incorrect can be seen as "seeds" of sophisticated scientific concepts and practices [36,69,74,79–81]. That is, students' own thinking can develop toward canonical

physics understandings, support their engagement in rich disciplinary practices, or help to solve problems or create products that are meaningful to learners [74].

Our project takes up these three tenets: We identify resources that we see as sensible and we make an effort to make that sensibility visible to our readers. We also highlight an aspect of the context-sensitivity of these ideas by showcasing question-dependent patterns in resource activation that recur across instructors and universities. In our work here, we primarily attend to resources that we see as continuous with canonical understandings of mechanical wave propagation. That is, we identify resources that we see as "seeds of science," that resemble pieces of canonical models for wave propagation, or that represent scientific ways of thinking about wave phenomena [36]. In section IV, we articulate ways in which the resources we report are continuous with formal physics in such a sense. Finally, we suggest ways in which instructors support their students in refining and changing the structure and connectedness of these resources, toward a formal understanding of mechanical wave propagation.

The resources we report are phrased in terms of statements about mechanical pulse propagation – e.g., "the speed or duration of transverse motion affects pulse speed." Thus, the resources we report are smaller in grain size than scientific concepts (e.g., the concept of force), and concrete in description. This is consistent with depictions of resources in the literature, which vary in their grain size and in their degree of abstraction from particular physical phenomena. Specifically, resources are depicted as knowledge elements or ideas that are often of smaller grain size than scientific concepts (e.g., [70]), though they can also be more complex structures [77,82]). Examples of resource-like cognitive structures can be concrete, such as *the (less massive) car reacts twice as much (in a collision*) [14] or *active objects can exert forces* [83], and they can be abstract, such as *bouncing* or *force as mover* [70].

The resources we report are not the full set of student ideas in our data that are continuous with formal physics ideas. Our analysis focused on a subset of resources, informed by our goals of (1) contributing to KSI and (2) supporting instructors in noticing and building on students' potentially-productive thinking. To support instructional predictions, we investigate *commonly-activated* resources. We further focus on those resources that we judge to be most *instructionally relevant,* i.e., most likely to support shifts in instructional practice. For mechanical waves, we report students' ideas about physical mechanisms for wave phenomena and about the ontology of waves. We do not report students' resources for use of equations or discrete steps to solving a problem (although we have noticed such resources in our analysis).

3.4 THE PHYSICS OF MECHANICAL WAVE PROPAGATION

The motion of a single pulse that propagates without change in shape can described by a single, constant velocity v. If the leading edge (or any other point) of the disturbance is located at position x_0 at some instant t_0, the location of the disturbance at any later time can be described in the same way that the location of a Newtonian object could be described (i.e., $x_f = x_0 + vt$) [84]. Thus, we may treat the pulse as an abstract object-like entity whose speed is defined by the distance it travels in a given time interval [85]. In a string or spring, the speed of the disturbance can be demonstrated—either empirically or mathematically via more detailed modeling—to increase when tension applied to the medium is increased, and to decrease when the mass density of the medium is increased (e.g., [29]).

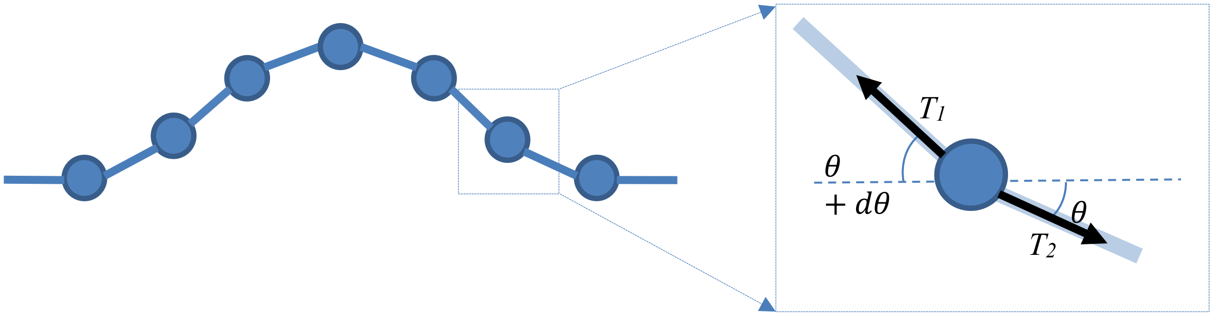


Figure 3.1. String-and-bead model for pulse propagation

To construct a more detailed mathematical depiction of transverse pulse propagation on a (non-dispersive) string (or spring), the string can be modeled as a number of small beads of mass dm connected by massless strings of length dx and equal tension T [48,49]. In the continuum limit, one can analogously consider a small segment of a massive string with uniform tension T, with length dx and mass $\mu\, dx$. According to this model a propagating pulse is described as the sequential, transverse disturbance and return to equilibrium of individual beads or segments of the medium. The wave equation for a disturbance on a string can be derived by considering the acceleration of a single bead or segment of string (we follow the derivations in [72,86]). According to Newton's second law

$$F_{net} = \mu \, dx \frac{\partial^2 y}{\partial t^2} \quad (1)$$

The nonzero net force acting on the bead is due to the small difference in the directions of the two tension forces acting on it [Fig. 1]. Assuming that tension is uniform throughout the system – i.e., the tension in all inextensible string segments is equal – the vertical and horizontal components of the net force are

$$F_{net,x} = T\cos(\theta + d\theta) - T\cos\theta \quad (2)$$

$$F_{net,y} = T\sin(\theta + d\theta) - T\sin\theta \quad (3)$$

Further assuming that all transverse displacements are small enough that the angle between any segment of string and the x-axis is small (i.e., θ and $d\theta$ are small), the horizontal force is negligible. Using the small angle approximation $\sin\theta \approx \theta,$ the vertical force is reduced to $F_{net,y} = T\, d\theta,$ and $d\theta$ can be written as $\frac{\partial\theta}{\partial x} dx$. Finally, θ is approximately equal to the slope of the string, $\frac{\partial y}{\partial x}$. Thus, the net force on the particle can be approximated as

$$F_{net} \cong T dx \frac{\partial^2 y}{\partial x^2} \quad (4)$$

Combining (1) and (4) yields

$$T\frac{d^2 y}{dx^2} dx = \mu \, dx \frac{d^2 y}{dt^2} \quad (5)$$

This is the wave equation $c^2 \frac{d^2 y}{dx^2} = \frac{d^2 y}{dt^2}$, where the speed of the propagating disturbance is

$$c = \sqrt{\frac{T}{\mu}} \quad (6)$$

In short, the pulse is modeled in terms of infinitesimal segments of a string that are displaced from equilibrium. The disturbance is shown to propagate in that it obeys the wave equation, and the motion of neighboring parts of the string is coupled by the tension force between them. Propagation is thus determined by properties of the medium that affect the transverse acceleration of small segments of the medium.

In the string-and-bead model, there is kinetic energy associated with each point mass, and the amount depends on its mass and transverse velocity [84]. The kinetic energy density is given by

$$\frac{dK}{dx} = \frac{1}{2}\mu\left(\frac{\partial y}{\partial t}\right)^2 \quad (7)$$

As the wave propagates, energy is transferred from one point mass or segment of the string to the next via the tension force interaction between them. The system also has potential energy associated with the slight stretching of its disturbed segments, which can be modeled by considering the connecting segments as massless springs that obey Hooke's law [84,87]. As point masses are displaced, the springs attached to them are stretched by a small amount $dl = \sqrt{dx^2 + dy^2}$. Since the tension in the string is assumed uniform, the potential energy gained by the segment is $dU = Tdl,$ or the work done in stretching the string. Assuming that the transverse displacement is small, the potential energy density can be approximated as

$$\frac{dU}{dx} = \frac{1}{2}T\left(\frac{\partial y}{\partial x}\right)^2 \quad (8)$$

Equations (7) and (8) show that a disturbance carries with it both kinetic and potential energy: $\frac{\partial y}{\partial t}$ and $\frac{\partial y}{\partial x}$ are only nonzero in regions where the medium is disturbed. Equations (7) and (8) also show that the amount of energy carried by the pulse is affected by the properties of the medium and by the shape of the pulse (which is determined by the motion of the source). It can be shown that for any traveling wave, (7) and (8) are equal, and therefore a pulse with greater kinetic energy must also have greater potential energy by the same amount. In Section 7, we will describe how three conceptual resources that were common in our analysis resemble aspects of this model for mechanical wave propagation.

3.5 PREVIOUS INVESTIGATIONS OF STUDENT UNDERSTANDING OF MECHANICAL WAVE PROPAGATION

Previous investigations of student understanding of transverse mechanical wave propagation report two clusters of student ideas: (1) the speed of a pulse or wave depends on or is determined by how it is generated, and (2) wave speed, wavelength, and frequency can all be manipulated (and held constant) experimentally.

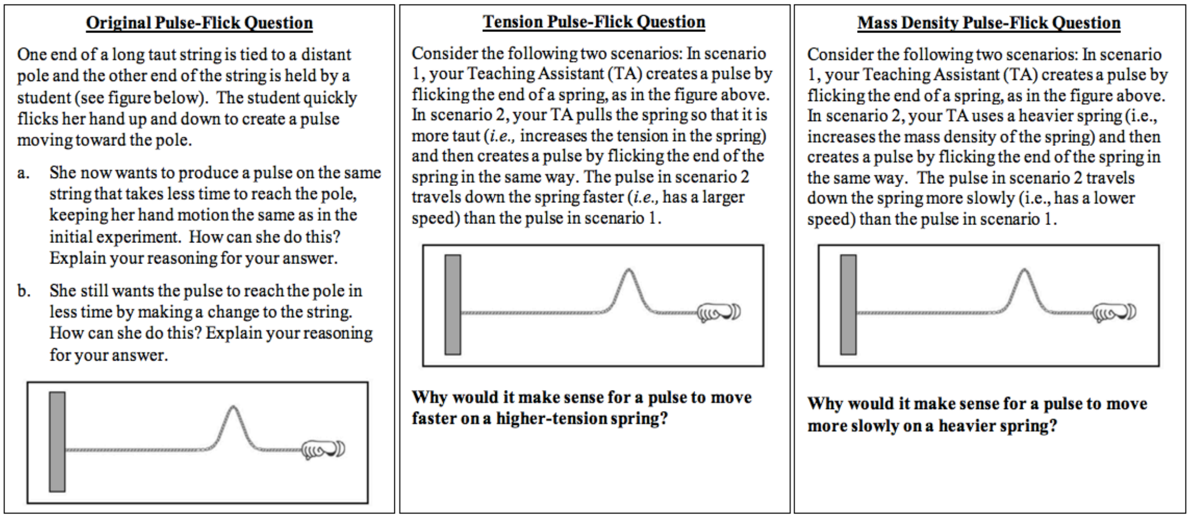
Several authors report that students commonly use the idea that the speed of a pulse or wave depends on how it is generated when answering the original pulse-flick question [20,57,58] (Figure 2). Many students answer that flicking a string harder will generate a faster-moving pulse [20,26,27,57,60,61,63,88]. Caleon and Subramaniam [62] report a slightly more nuanced version of this idea: that as frequency increases, wave speed also increases because more energy is being imparted to the particles of the medium. Wittmann [20,60,63] interprets this idea as treating a pulse like a Newtonian particle: just as throwing a ball harder makes it move faster, "throwing" a pulse on a string harder makes it move faster.

Multiple authors report that students rely on the equation $v = \lambda f$ to reason about the relationship between propagation speed, wavelength, and frequency. Based on this equation, students may think that wave speed depends on frequency (or vice versa) [22,26,56,62]. This idea may be associated with reasoning that a higher frequency means "more energy is imparted to the particles of the medium [62]," so the wave travels faster. Kryjevskaia, Stetzer, and Heron [22] summarize this kind of idea as a difficulty understanding how the variables and can be manipulated experimentally—that is, that wave speed is a property of the medium, frequency can be manipulated at the source, and wavelength is determined by the frequency and propagation speed in a given medium.

With a few exceptions [61,63] these studies of student thinking about mechanical waves have attended to the ways in which student thinking is inconsistent with canonical physics concepts and provide instructors with KSI in the form of common patterns of incorrect reasoning that are the result of the interaction between student thinking and the discipline.

3.6 DATA COLLECTION & METHODS OF ANALYSIS

We analyzed student responses to three versions of a conceptual question about pulse propagation on a string or spring (the "pulse-flick question"). The original question was drawn from Tongchai *et al.* [57] and is a modified version of a question from the Waves Diagnostic Test [6]. We chose this question as a starting point for our investigation because we expected the pulse flick phenomenon to be accessible to students with a range of prior experiences and because student difficulties in the context of this question have been well-documented [20,56,57,60,61], which affords the opportunity to compare students' resources and difficulties in the context of this question. Since we were interested in students' reasoning in addition to their answer choices, we



Original Pulse-Flick Question

One end of a long taut string is tied to a distant pole and the other end of the string is held by a student (see figure below). The student quickly flicks her hand up and down to create a pulse moving toward the pole.

a. She now wants to produce a pulse on the same string that takes less time to reach the pole, keeping her hand motion the same as in the initial experiment. How can she do this? Explain your reasoning for your answer.

b. She still wants the pulse to reach the pole in less time by making a change to the string. How can she do this? Explain your reasoning for your answer.

Tension Pulse-Flick Question

Consider the following two scenarios: In scenario 1, your Teaching Assistant (TA) creates a pulse by flicking the end of a spring, as in the figure above. In scenario 2, your TA pulls the spring so that it is more taut (*i.e.,* increases the tension in the spring) and then creates a pulse by flicking the end of the spring in the same way. The pulse in scenario 2 travels down the spring faster (*i.e.,* has a larger speed) than the pulse in scenario 1.

Why would it make sense for a pulse to move faster on a higher-tension spring?

Mass Density Pulse-Flick Question

Consider the following two scenarios: In scenario 1, your Teaching Assistant (TA) creates a pulse by flicking the end of a spring, as in the figure above. In scenario 2, your TA uses a heavier spring (i.e., increases the mass density of the spring) and then creates a pulse by flicking the end of the spring in the same way. The pulse in scenario 2 travels down the spring more slowly (i.e., has a lower speed) than the pulse in scenario 1.

Why would it make sense for a pulse to move more slowly on a heavier spring?

Figure 3.2. Three versions of the pulse-flick question. The original question is drawn from Tongchai *et al*. and is modified from Wittmann's Waves Diagnostic Test.

modified the original question to be free-response rather than multiple-choice. After receiving an initial set of student responses, we made several modifications to the question to elicit more about *why* students think that changing the tension or mass density – the two most common answers to the original pulse flick question – would change the pulse speed. This effort produced the tension pulse-flick question and the mass density pulse-flick question. All three versions of the pulse-flick question are shown in Figure 3.2.

In total, we analyzed 862 student responses across the three versions of the pulse-flick question. These questions were given in introductory physics courses at five U.S. Universities: the Baylor University, California Polytechnic State University - San Luis Obispo (CPSLO), Seattle Pacific University (SPU), University of Washington (UW), and Western Washington University (WWU). A typical introductory university-level physics course in the U.S. includes instruction on wave propagation, superposition, and reflection, as well as wave optics and interference. In all samples, our questions were given as a required part of the coursework (as homework or on an exam, not for extra credit) after some instruction on mechanical wave propagation. Participation in our study was at least 70% of students enrolled in each of these courses. In most cases, the questions were administered to students after some or all instruction. Table 3.1 provides additional details about the samples.

To analyze this data, two coders (L. M. Goodhew and A. D. Robertson) created an emergent coding scheme [52] that characterized the resources that students were using to reason about mechanical pulse propagation in the pulse flick question. To develop this coding scheme, LMG and ADR separately examined a subset of student responses from each version of the question and each participating institution, identifying preliminary resources – ideas that we deemed continuous with canonical wave propagation concepts – used by students in the subset. Our attention in this process was toward students' *conceptual* resources, rather than resources for mathematical procedures, problem-solving steps, or epistemological resources. In many cases, these early-analysis resources we identified were quite specific and concrete. For example, one early-analysis resource was "increasing tension means the pulse 'wants' to reach equilibrium faster." When we had completed our preliminary analyses for all three versions of the pulse-flick question, we looked for themes across questions – the *common* resources – by grouping early-analysis resources according to our sense of their productive substance. For example, the resources "higher tension means every particle moves faster," "pulse speed is related to how fast particles return to equilibrium," and "increasing tension means the pulse 'wants' to reach equilibrium faster" were grouped into the code *the speed or duration of transverse motion affects pulse speed*. The development of our final coding scheme was an iterative process; several versions of the scheme were proposed and tested on larger subsets of data to assess whether they accurately reflected students' ideas and appropriately captured the continuity of these ideas with formal physics. Ultimately, this process resulted in a coding scheme with five codes, three of which appeared frequently in our data set; these are the three discussed in Section 3.7.

Question	Institution & academic term	Number of students in sample
Original	CPSLO, Winter 2017	67
	UW, Autumn 2016	134
Tension	CPSLO, Spring 2017	159
	Baylor, Spring 2018	173
	WWU, Autumn 2017	103
Mass Density	CPSLO, Autumn 2017	35
	SPU, Spring 2018	42
	UW, Winter 2018	138

Table 3.1. Administration contexts and participation rates for three versions of the pulse-flick question. For all samples, participation was least 70% of students enrolled in the course.

Our interpretation of the resources we present here is shaped by our own understandings of wave propagation (as we describe in Section 3.4) and by the orientation toward student ideas that is embodied by resources theory (i.e., students' ideas can be fruitful for their learning). We expect that another researcher with different understandings and commitments would interpret these data differently. Our effort here has been to describe the categories of student thinking that we infer, expecting that others may be able to "f[i]nd or recogniz[e]" these categories "once [they] ha[ve] been described to them by the original researcher[s]" (us) [54]. It is not to suggest that "other researchers [would] find the same conceptions or categories if they were doing the study for the first time" [89]. Further, when we say students "use" a particular resource, we mean that their response is consistent with that resource – that is, we acknowledge that the existence of these resources is hypothetical, as is their use in these specific cases.

To be considered "common," a resource had to be used by at least 10% of students in at least one sample, and it had to be used by students in response to more than one question. Because these resources are used in many student responses across multiple sources of heterogeneity (i.e., instructor, institution, and version of the question) [90], we expect that these are resources that instructors of comparable courses might anticipate in propagation contexts. In this sense, our results contribute KSI that may support instructors in anticipating and leveraging these ideas in their classroom. Because much of our data comes from student responses after some instruction, it is appropriate to consider these resources that may be leveraged *during* instruction, after students have had some exposure to mechanical waves concepts.

In the final analysis for this paper, LMG and ADR independently coded each student's response according to the final scheme. A single response could be given more than one code when responses were seen as using more than one resource. We compared the codes LMG and ADR separately assigned to each response to establish a sense of percentage agreement.

Standard statistical measures of inter-rater agreement, such as Cohen's kappa, require that codes are independent or mutually exclusive [91]. Our coding scheme, in which it is possible for a single response to be assigned multiple (or no) resource codes, reflects our theoretical perspective that multiple resources can be activated to construct an idea. As our codes are not independent, and a single response can be assigned multiple resource codes, standard statistical measures are not appropriate for our data. As a measure of percentage agreement, we took the normalized difference between the total number of codes possible and the total number of disagreements between the two coders, represented by:

$$1 - \frac{(N\ disagreements\ in\ all\ coded\ responses)}{(N\ possible\ codes)(N\ coded\ responses)}$$

For example, for a scheme with two codes, if a student's response was assigned codes 1 and 2 by the first coder and code 1 by the second, there would be 1 disagreement for this data set of one response. Since there are two possible codes, this would represent a percentage agreement of 50%. The percentage agreement for our analysis of the data set for this paper was 91%.

In tabulating the fraction of responses that used each resource (reported in Sections VI and VII), we included only those codes that were in 100% agreement. That is, a response was included in these fractions only if both coders agreed that the response used the resource. However, the *percentage agreement* we report above (91%) was determined from our coding of the full data set, including all disagreements between coders.

3.7 DESCRIPTION OF COMMON CONCEPTUAL RESOURCES

Here, we report three resources for understanding mechanical wave propagation that were common across institutions and versions of the pulse-flick question. Students use the resources (1) *properties of the medium either impede or facilitate the motion of the pulse* (the *properties of the medium* resource), (2) *the speed or duration of transverse motion affects pulse speed* (the *transverse speed* resource), and (3) *the speed of the pulse is affected by its kinetic energy* (the *energy* resource). These three do not represent all of the resources that we identified in our data, or even all that may have been common. The resources we report are those that represent student thinking about physical mechanisms for wave phenomena and about the ontology of waves. We have focused on these because we judge them to be pedagogically significant.

In this section, we provide examples to illustrate the various ways in which these resources manifest in student responses. Our goal in doing so is to highlight diversity – that the same resource (e.g., *properties of the medium*) may show in quite different ways among different students and in response to different questions. It is not to make claims about the relative frequency of any one instantiation of a given resource. We also discuss here how these resources, while not necessarily complete or canonically correct, are continuous with the scientific understanding of mechanical wave propagation that we have described in Section 3.4.

3.7.1 *Properties of the medium either impede or facilitate the motion of the pulse.*

The *properties of the medium* resource was the most commonly-used resource across the three versions of the pulse-flick question: approximately 60-80% of students used it in response to the original question, ~10-15% in response to the tension question, and ~25-30% in response to the mass density question. This resource models pulses as unified entities whose motion is distinct from the motion of the medium and is described by a single velocity v; the pulse velocity is related to the properties of the medium that the pulse moves through (e.g., tension or mass density). This resource is continuous with the model for a pulse propagating on a string that we described in Section 3.4.

In response to the pulse-flick question, some students explain that making changes to the medium means pulses will move faster or slower through it, or that changing the medium makes it easier or harder for the pulse to move through it. Some responses describe a qualitative relationship between properties of the medium and pulse speed, such as:

"*If the string*[3] *is more taut, the wave wants to pass through faster.*" (tension question)

"*Decreas[ing] the tension in the string [increases pulse speed because] if the string is less tense, or not as stiff, the wave can travel faster*." (original question)

These responses and others like them state directly that the speed of the pulse depends on a property of the medium (in this case, the tension). Other responses use an equation to relate pulse speed to properties of the medium:

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[3] The original version of the pulse-flick question refers to a pulse on a *string,* while the mass-density and tension versions refer to a pulse on a *spring.* We do not notice any clear relationship between (a) the types of responses students offered and (b) whether the question refers to a spring or a string. Further, we notice that students do not consistently take up the wording in the question they were asked: some students refer to a *string* when the question refers to a *spring,* and vice versa. In the examples in this section, we have chosen to preserve the original language used by each student, and we view the words "string" and "spring" as interchangeable.

"*My intuition actually is from the equation* $v = \sqrt{\frac{T}{\mu}}$ *. So when* $\mu \uparrow$*, and* T *doesn't change, the* v $\downarrow$." (mass density question)

"*As we have witnessed by the equation* $v_{string} = \sqrt{\frac{T}{\mu}}, \left(\mu = \frac{m}{L}\right)$*, if she still wants the pulse to reach the pole in less time (wave speed) then she needs to find a string with a smaller* $\frac{m}{L}$ *ratio or smaller* μ*."* (original question)

"$v = \sqrt{\frac{T}{\mu}}$ *[so] the speed of propagation of the pulse is directly related to the square root of the tension."* (original question)

These examples, and others like them, describe the motion of the pulse by a single speed v, and they use a (correct) quantitative expression to show that pulse speed depends on the properties of the medium. In the first and second example, students use the equation $v = \sqrt{T/\mu}$ to support their arguments that higher pulse speed is associated with lower mass density. The third response interprets the same equation as demonstrating that tension directly affects pulse speed. Responses like these were especially common for the original pulse-flick question, where up to 90% of students cited an equation in their answers. However, simply stating the formula for pulse speed was not sufficient, on its own, to receive the *properties of the medium* code; such responses accompanied their use of the equation $v = \sqrt{T/\mu}$ with qualitative statements that relate pulse speed to properties of the string. For example, in all three responses above students use the equation $v = \sqrt{T/\mu}$ to support conceptual arguments that changing the mass density or tension in the string would change the speed of a pulse moving through it.

Some examples of this resource describe nascent mechanisms by which changing the tension or mass density will change the speed of the pulse:

"*The higher the tension of the spring, the more sensitive it is to movement so the pulse can travel faster*." (tension question)

"*Because tension is directly related to speed in waves, higher tension means that the pulse and speed can travel faster because higher tension makes a more linear path to travel.*" (tension question)

"*It makes sense for a pulse to move more slowly on a heavier spring because the velocity of the pulse depends on the string's medium. A heavier string moves more slowly because it takes longer for the pulse to move more mass.*" (mass density question)

These three examples treat the pulse as a distinct macroscopic entity moving on or through the medium and say that changing tension or mass density affects how the medium responds to the pulse. The first example explains that the speed of a pulse depends on the tension in the medium because increased tension means the medium can react more quickly to the pulse. The second example connects increased tension with increased pulse speed, implying that the pulse can move more efficiently through a tauter string. The mechanism implied in this response is incorrect: pulses are not like objects that move along curved paths that can be straightened by increasing tension. However, the essence of *properties of the medium* is still evident in this example; it appropriately associates tension with pulse speed. The third response argues that increasing mass density will decrease the pulse speed because it takes longer to displace something heavier, suggesting that the pulse is thought of as an entity that moves the medium out of the way. These examples only hint at mechanisms by which the medium affects pulse speed; details about the implied causal relationships are unstated. Nonetheless, nascent causal associations like these can be the beginnings of a more sophisticated mechanistic explanation of the relationship between pulse speed and properties of the medium, even if they are incorrect or incomplete [49].

Other examples of *the properties of the medium* resource make more formal mechanistic connections between properties of the medium and pulse speed, drawing on mechanics concepts such as energy, momentum, or Newton's Laws:

"*It takes more energy to move something of greater mass. The pulse also must travel through more particles per unit of distance therefore it makes sense intuitively that it would take longer.*" (mass density question)

"*Springs have inertia and heavier springs will have more inertia because inertia is proportional to mass. Since inertia is the tendency to resist change in motion, a heavier spring will oppose the motion of a pulse more.*" (mass density question)

Responses such as these include a sense of the physical mechanism by which a change to the medium affects pulse speed. The first example offers both macroscopic and microscopic arguments that mass density affects pulse speed because mass resists motion. The second example makes a clear distinction between the pulse and medium – the medium opposes the motion of the pulse – and explains that this is because mass or inertia resists motion. These, and other similar responses, not only state a relationship between the speed of a pulse and the properties of the medium it moves through, but also theorize a mechanism by which the medium affects the pulse.

The examples we provide in this section show that manifestations of this resource were quite varied, particularly with respect to the level of formality, quantification, or causality they embodied. As these examples illustrate, *properties of the medium* treats the medium and the pulse as distinct – though not independent – macroscopic entities. This resource bears some resemblance to the previously-reported difficulty *treating a pulse as a Newtonian object* because both treat pulses as distinct macroscopic entities. However, the resource focuses on propagation as an interaction between the pulse and medium – i.e., it focuses on *propagation* – rather than on what the pulse *is*. This resource is continuous with formal physics: it qualitatively – and in some cases, quantitatively – connects pulse speed to properties of the medium. In responses that use this resource, students correctly identify one or more of the factors that influence pulse speed, consistent with the commonly-taught model for the speed of a pulse on a spring or string ($v = \sqrt{T/\mu}$).

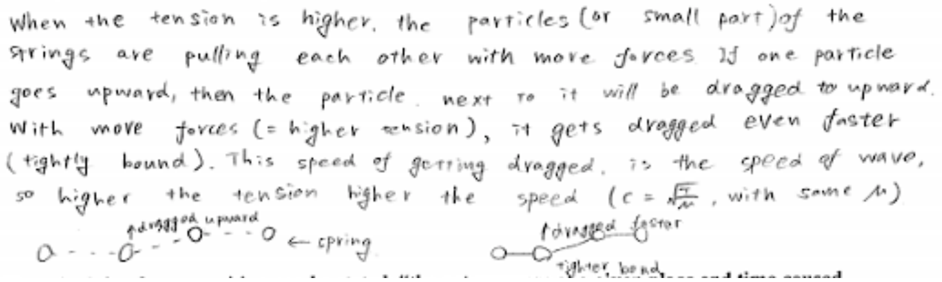
3.7.2 *The speed or duration of transverse motion affects pulse speed.*

Students also commonly used the *transverse speed* resource. Students used this resource in all three versions of the pulse flick question, though it was more common in the tension and mass density versions: between ~15 and ~25% used this resource in the tension question, and between ~10 and ~20% used it in the mass density question, but only 0-5% used it in the original question. This resource acknowledges that the pulse is a propagating disturbance of parts of the string and that propagation speed is linked to the transverse motion of the medium. The *transverse speed* resource represents a nascent mechanistic model for propagation: particles or segments of the medium are sequentially displaced and return to equilibrium at a rate that depends on parameters of the pulse and/or medium. According to a canonical understanding of pulse propagation, the transverse motion of a part of the medium is determined solely by the motion of the source. Therefore, assuming the same source motion, the velocity and acceleration of part of the medium are not affected when properties of the medium change. Even so, the *transverse speed* resource is continuous with mathematical models for propagation that arise from considering the dynamics of the system (e.g., [86]): the string-and-bead model described above begins by examining the transverse motion of a small segment of the medium, just as this resource does.

In some examples of this resource, faster or slower displacement is seen as being caused by the forces acting on, or acceleration of, a piece or particle of the medium. For example:

"In increasing the tension, the TA puts more force on the spring towards making it follow a straight line. This makes its acceleration towards the center greater, and thus, each individual point does 'the wave' more quickly. For the pulse to complete one length of the string, each point must complete the 'wave' motion. Therefore, since the points complete the wave more quickly, the pulse moves more quickly." (tension question)

"When the tension is higher, the particles (or small part[s]) of the springs are pulling each other with more forces. If one particle goes upward, then the particle next to it will be dragged upward. With more forces (= higher tension), it gets dragged even faster (tightly bound). This speed of getting dragged is the speed of the wave, so the higher the tension [the] higher the speed. $(c = \sqrt{T/\mu}, \text{with same } \mu.)$*"* (tension question)



When the tension is higher. the particles (or small part) of the strings are pulling each other with more forces If one particle goes upward, then the particle next to it will be dragged to upward. With more forces (= higher tension), it gets dragged even faster (tightly bound). This speed of getting dragged. is the speed of wave, so higher the tension higher the speed $(c = \sqrt{\frac{T}{\mu}}$, with same $\mu)$

"*It would make sense for the pulse to move more slowly on a heavier spring because you could represent each point of mass on the string with a free body diagram and the* F_{net} *on each point of mass is equal to mass times acceleration.* ($F_{net} = ma$) *Therefore, if the* F_{net} *on each spring is the* *same as scenario 1, when the mass increases in scenario 2, the acceleration must decrease to compensate. This means that each point on the spring will accelerate more slowly when moving away from the 'center line' of the spring, effectively resulting in the pulse moving more slowly."* (mass density question)

"If he used the same motion on the heavier string it would move slower because each part of the string is slower at moving up or down due to greater inertia which results in a slower wave propagation." (mass density question)

All of these examples focus on a "point," a "particle," or a "part" of the string or spring, and in doing so they imply a discretized model of the medium such as the string-and-bead model. The first and second responses above use the *transverse speed* resource as they argue that increasing tension makes each particle accelerate more quickly, increasing the wave speed. The second response supports such an argument with a diagram illustrating a spring as a series of point objects connected by strings. The third and fourth responses also use this resource to connect the dynamics of a particle in the medium to propagation speed, but in these examples an increased mass supposedly makes each part of the medium more resistant to movement.

Other examples of this resource explicitly describe the dynamics of the system in terms of the tendency of the medium to return to equilibrium or the magnitude of the restoring force, as in these responses:

"*The greater the tension in a wave, the higher the restoring force that returns it to equilibrium."* (tension question)

"If the tension is higher, the particles will move faster in the pulse because they want to return to equilibrium to have the lowest energy state. Whereas [with] loose rope the difference in energy of particles [at] rest and in a pulse isn't as big so they'll take longer to return to equilibrium." (tension question)

Both responses imply that increased restoring force, or tension in the medium, causes a higher wave speed because the medium responds more quickly to the disturbance and tends toward equilibrium more strongly. These and other responses like them center on the tendency of the medium toward equilibrium, which can be a way to investigate the tendency of the medium to "pass displacement along" [87].

Another illustration of this resource is the answer that decreasing the amplitude of the pulse means that the vertical motion of part of the medium takes less time, therefore the pulse moves faster. For example:

"The higher tension will decrease the amplitude if the same amount of force is used, which means each displacement is shorter, [and] tak[es] less time to do [therefore] moving faster." (original q.)

This example instantiates the *transverse speed* resource by explaining that when each displacement takes less time, the pulse moves faster. In canonical models, amplitude and duration of the displacement are both determined by the source rather that by properties of the medium; thus, taken as a whole, this statement is incorrect. However, we argue that this instantiation of the *transverse speed* resource is still continuous with formal physics because it expresses a (correct) connection between the transverse motion of the medium and the propagation of the pulse.

Taken together, these examples illustrate that the *transverse speed* resource is a mechanistic connection between transverse motion of the medium and longitudinal motion of the pulse. The *transverse speed* resource resembles previously-reported difficulties or misconceptions related to the idea that flicking a string up and down faster generates a faster-moving pulse in that a faster flick represents a faster displacement and return to equilibrium.[4] In our study, we characterize this idea as a resource: students are deploying this idea in a mechanistic way that is continuous with the way physicists model mechanical wave propagation. In particular, it models a mechanical pulse as sequential, local disturbances of a medium communicated via interactions between parts of the medium. In using the *transverse speed* resource, students attend to the dynamics of the transverse motion of particles or disturbed parts of the string, which is necessary for constructing a mathematical model of a wave on a string [72,86]. Further, this resource is appropriate for predicting the relationship between particle velocity and pulse speed when other parameters of the pulse (e.g., amplitude, width) have been held constant.

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[4] However, in our data set, students rarely focused on the speed of the flick.

3.7.3 *The speed of the pulse is affected by its energy.*

Finally, students used the *energy* resource in answering the three versions of the pulse flick question. Students deploying this resource use energy accounting (*i.e.,* considering how energy is increased, decreased, transferred, or transformed) to explain or predict changes in pulse speed. In order to receive this code, responses had to explicitly associate the amount of energy in the system with the speed of the pulse or a part of the medium. Some responses use the term "energy" to speak about the "ease" with which a pulse moves through a medium (e.g., "*It takes more energy to move something of greater mass…therefore it makes sense intuitively that it would take longer*"). This response and others like it focus on how the properties of the medium affect pulse speed, and thus are better represented by the *properties of the medium* resource. In contrast, responses coded as using the *energy* resource focus on how changing the and redistributing the energy in the system affects the speed of the pulse propagating through it. This resource applies a powerful physical model to wave propagation and is continuous with a scientific conception of waves as carriers of energy because it associates potential and/or kinetic energy with the pulse.

The *energy* resource was most commonly used in the mass density version of the question – ~10-20% of students used it there – but was also present in the other two versions: ~0-5% used this resource in the original question, and ~5-10% in the tension question. Though all of the responses that received this code connected changes in energy to changes in pulse speed, there were a variety of ways students used this resource in their responses.

Some responses imply that the energy added to the system is equal in the two experiments proposed in the pulse-flick question. These responses use the *energy* resource to reason about how changes to the medium affect the speed of the pulse:

"*There is kinetic energy being transferred into the spring when the professor creates the pulse. Since the mass of the second string is increased, it would make sense for the second spring to move slower because it has less velocity (if the amount of energy transferred is kept the same).*" (mass density q.)

"In a heavier spring, there is more mass in a given unit of length. It would take more energy to displace this mass than in a lighter spring. Since more energy is spent on actually displacing the

spring in a wave there will be less energy to drive the pulse's velocity, given that the same amount of energy was applied each time." (mass density q.)

"Having a tighter string means less energy gets represented as vertical displacement so that more energy goes into the pulse's forward movement, i.e. speed." (tension q.)

The first example correctly identifies that energy is added to the system by the source and relates the velocity of the medium to the kinetic energy of the system and its mass, consistent with the equation for kinetic energy density $\frac{dK}{dx} = \frac{1}{2}\mu\left(\frac{\partial y}{\partial t}\right)^2$. The second example similarly identifies that the kinetic energy of the system depends on the mass density and velocity, though in this response it is unclear whether the velocity mentioned is the (longitudinal) pulse speed or the (transverse) speed of the medium. In the third example, increased tension means that energy added to the system manifests differently. Though it is incorrect, the third response associates energy with the shape ("vertical displacement"), and associates the speed of the pulse with the tension in the medium.

Other responses using this resource describe how changes to the medium or pulse generation increase or decrease the amount of energy in the system and relate these changes to pulse speed:

"If the tension of the string is greater, the system would have more potential energy, then once the system is given a pulse, that potential energy is converted to kinetic energy which is a function of velocity. Therefore it would make sense for a pulse to move faster on a high-tension spring by the law of conservation of energy." (tension q.)

"*When you think about the energy in the spring, the higher the tension, the higher potential energy it would have. [Therefore] you would expect it to have a higher kinetic and in turn velocity*." (tension q.)

"[You can generate a faster-moving pulse] by adding an enormous amount of motion that gives the motion a small "T" period per wave cycle [because] the more energy you add, the faster the wave will travel." (original q.)

In the first two examples here, potential energy is appropriately associated with tension in the medium. Both examples relate the kinetic energy of the pulse to its potential energy and use this to explain how tension affects propagation speed. The third response argues that more energy in the system means that the wave will travel faster. While it is not true that pulses generated with more energy move faster (the energy will instead affect the shape of the pulse), this response still associates energy with the propagating pulse and reasons about speed using energy principles.

The examples we provide here do not illustrate all of the ways in which the *energy* resource was used by students, but they do represent some of the more common ways that we noticed students using this resource to answer versions of the pulse-flick question. Common to all of the responses we assigned this resource code is a sense that energy is associated with or carried by the pulse itself and that energy transfers and transformations play a role in the speed or motion of the pulse.

Students using this resource to answer the pulse-flick question apply a fundamental physical concept—energy—to explain wave propagation. Energy is a particularly powerful physical model for understanding waves because waves carry energy, but not matter. This idea has been emphasized as an important learning goal both because it expresses fundamental trait of waves and because of its important consequences for technological applications of wave phenomena [71]. Students' uses of this resource are consistent with energy models typically taught in mechanics (i.e., kinetic energy depends on mass and velocity, potential energy depends on how much a spring is stretched) and continuous with wave mechanics in some situations. Mathematical derivations of energy densities begin from considerations of mass, tension, and speed, which students enact when they use this resource to answer the pulse-flick question. This suggests to us that the *energy* resource is worth instructors' attention. Yet, the continuity between instantiations of this resource and scientific notions of mechanical wave propagation can be subtle—more so than for the first two resources we have discussed. Listening to and coming to understand the meaning students make when they use this resource is likely a prerequisite to building on it in instruction.

3.8 FREQUENCY OF COMMON CONCEPTUAL RESOURCES

Figures 3.3-3.5 show the fraction of student responses that used each resource for the three versions of the pulse-flick question, given at a total of six universities. (These fractions represent the percentages of student responses that both coders agreed instantiate each code.) Resources theory hypothesizes that resource activation is context-sensitive [33–35,69,74]. Our study supports this hypothesis: the frequency of resource codes appears sensitive to the version of the question students are asked, as shown in Figs 3.3-3.5. However, the frequencies of resource codes do not clearly depend on the university or course instructor – the bar charts are generally the same shape for each question. That is, for a given question, the frequency with which students use these resources is relatively consistent across universities. For example, in the original pulse flick question, students at both UW and CPSLO used *properties of the medium* at high frequency and *transverse speed* at low frequency (or not at all). However, the frequency with which students use these resources is qualitatively different across questions – the bar charts for the original question have very different shape than the ones for the tension question, and so on. For example, the original pulse-flick question appears to much more commonly elicit *properties of the medium* than any other question, and at much higher frequency than in other question contexts.

Instructors who want to plan instruction to elicit and build on particular resources may find it especially useful to observe the pairings of resources and questions indicated by this data. For example, instructors who wish to elicit and build on *properties of the medium* may wish to choose the original or mass density questions rather than the tension question. Instructors who wish to elicit a multiplicity of resources may wish to choose the tension or mass density questions. More research on the reproducibility of resource-question pairings may help to more firmly establish the relationship between context and resource activation.

The bar charts in Figs. 3.3-3.5 prompt questions as to why, for example, *properties of the medium* is more frequently elicited in the original question, or why a diversity of resources is more likely for the other two. Our hypothesis is that this is due at least in part to the question type. The original question asks students to *predict* what change to the experiment would produce a certain outcome, whereas the other two questions ask students to *explain* an outcome that is described to them. The interplay between the type of question asked and the diversity and frequency of resources is a phenomenon we hope to explore in future work.

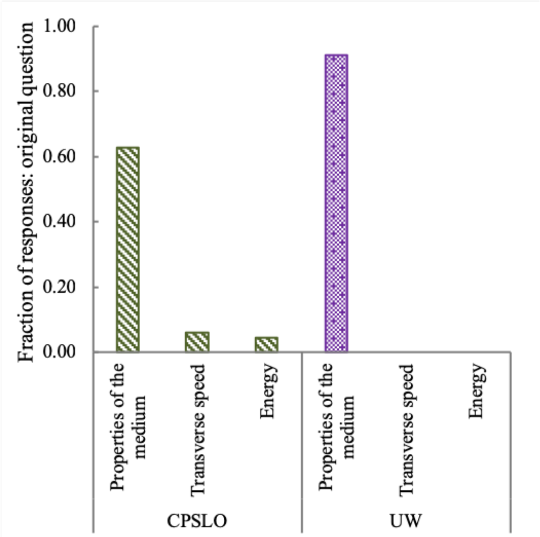


Figure 3.3. Fraction of responses using three common resources for the original pulse-flick question.

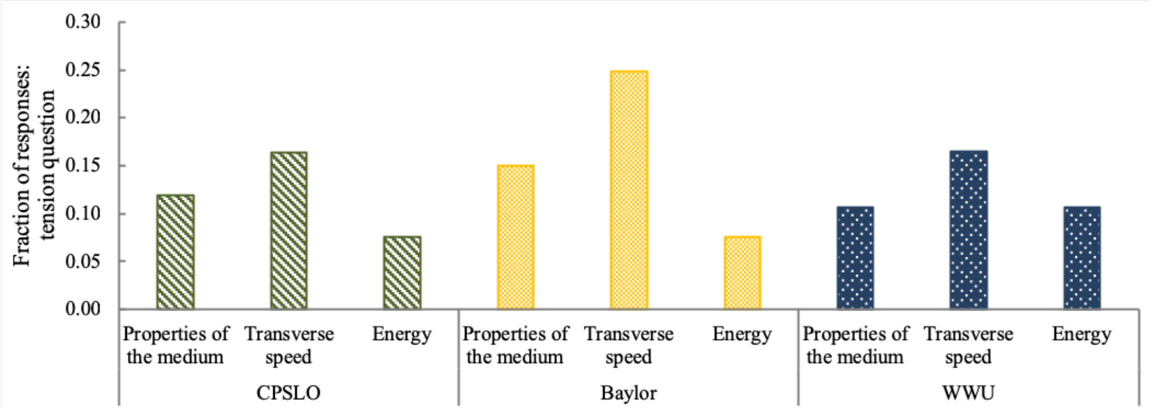


Figure 3.4. Fraction of responses using three common resources for the tension pulse-flick question.

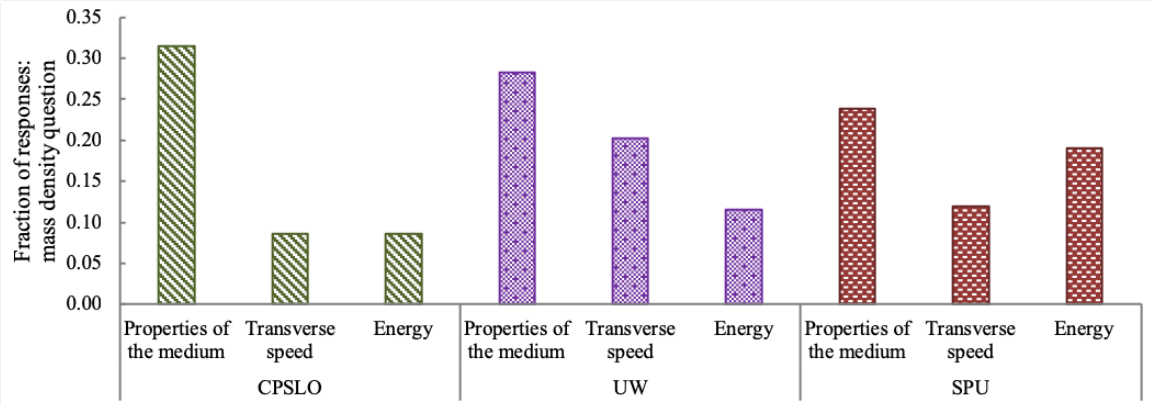


Figure 3.5. Fraction of responses using three common resources for the mass density pulse-flick question.

3.9 IMPLICATIONS FOR RESOURCES THEORY

We have described three common conceptual resources that students used to reason about mechanical wave propagation (the *properties of the medium, transverse speed,* and *energy* resources), contributing to instructors' repertoire of KSI. We have used classic tools of physics education research, looking at large numbers of student responses to written questions and coding student thinking according to common patterns. Yet, our contribution is new because we discuss common patterns of reasoning that can be viewed as continuous with canonical models for wave propagation. In doing so, this work takes up the tenets of resources theory described in Section 3.3: the resources we report are sensible and continuous with formal physics, context-sensitive, and may constitute the raw material for learning.

Our analysis suggests that in certain contexts, student ideas that have formerly been reported as difficulties can be viewed as continuous with formal physics. Wittmann reports that treating a pulse as a Newtonian particle can lead to difficulties in the context of pulse *generation* [20,60] – particularly the incorrect idea that flicking the string faster makes the pulse move faster, which has been reported by several authors [26,27,57,60]. This kind of thinking could be seen in terms of the *transverse speed* resource, which (as we showed in Section 3.7) can be viewed as continuous with a canonical understanding of pulse *propagation*.

Our study contributes to resources theory by demonstrating patterns of context-sensitivity for a large number of students. Previous resources-oriented physics education research has used case studies to illustrate the context-sensitivity of student thinking. These previous studies demonstrate a single student or small number of students using different ideas in different settings or when asked different questions (e.g., [34,92]). These studies do not demonstrate whether there are patterns in this context-sensitivity or identify patterns in resource-context pairings; *i.e.,* they do not answer questions about which resources are reliably elicited in which contexts. Our study illustrates how context-dependence plays out on a large scale and supports what has been previously shown in case studies.

An important limitation in the generalizability of this work is that we do not know the demographic data of the students in our sample. We have collected data from a number of different universities and instructors in an effort to sample across multiple sources of heterogeneity. At the same time, we know that our data set oversamples from selective, majority-white, four-year universities as compared to population of U.S. undergraduate students, as is the case with most PER studies [93]. Thus, it is most appropriate to say that the resources we report represent ideas that instructors of courses similar to those in our study might expect. In other words, these resources cannot be taken as useful KSI without careful attention to the ideas that students are bringing to bear in a particular classroom.

3.10 IMPLICATIONS FOR INSTRUCTION

The primary intent of this work is to inform instruction on mechanical waves by identifying and illustrating some of the conceptual resources that instructors might expect their students to use. Our study calls attention to the ways in which student thinking is continuous with physics concepts and suggests possibilities for eliciting and leveraging such ideas. Each of the resources we report can be seen as the beginnings of a scientific model for mechanical wave propagation. Students use *properties of the medium* to associate the speed of a pulse on a string with its tension and/or mass density; *transverse speed* models a pulse as a propagating local disturbance of the medium; and *energy* applies scientific energy concepts – kinetic energy, potential energy, and conservation – to propagation. None of these resources is entirely correct or complete. As our examples demonstrate, each is sometimes activated in ways that are limited or incorrect. For example, *transverse speed* is correct only when comparing pulses of the same shape on different media. Even so, these resources are sensible and continuous with formal physics: all three are central to students' sense-making about changes to the speed of a pulse, embody physics ideas such as force and energy, and connect to a scientific understanding of pulse propagation.

The context-dependence of these resources shows in the fact that they appear with different frequencies in response to different questions. The fact that the frequency pattern is fairly consistent across universities helps attribute the variation to the question asked, rather than to some other factor. We notice that different versions of the pulse-flick question elicit different resources most frequently, and some questions tend to elicit a diversity of resources whereas others elicit a single resource at high frequency. For instructors, this offers knowledge not only of the resources that may be likely to be used by their students, but also of which questions are more likely to elicit particular resources. Effective implementation of these question-resource pairings in instruction is an important direction for future work.

Resources theory describes learning in terms of reorganizing, refining, properly activating, increasing the degree of formality of, or changing the role of resources. Instructors might facilitate student learning about mechanical wave propagation, first, by listening to and sensemaking with students, given that the resources we report manifest in diverse ways and the connections to canonical physics may not be immediately recognizable. We notice that in many instantiations, these resources are causal or mechanistic in nature. Our attention to these conceptual resources also draws attention to rich mechanistic reasoning and model-building that students are doing in their answers to these questions. In many instantiations, these resources incorporate features of causal explanations and model-based reasoning. For instructors who have a goal of highlighting and building from their students' own thinking, our results may suggest an instructional focus on mechanisms for propagation – which are not common in introductory physics courses – and attention to more detailed explanatory models (not just an equation) for pulse speed.

For example, instructors might intentionally elicit the *properties of the medium* resource to support predictions about the behavior of waves in a variety of scenarios (standing waves on strings, for example). Likewise, *properties of the medium* might be generalized and extended through instruction to be useful for waves in media other than strings (such as water or air) and could even be generalized to situations when the "medium" is the vacuum with permittivity $\varepsilon$and permeability . Both *properties of the medium* and *transverse speed* may serve as starting points for students' construction of more detailed models of propagation (such as the string-and-bead model) [49]. For example, in using the *transverse speed* resource, students often model a pulse in terms of the motion of small parts of the medium and relate propagation speed to the dynamics of the transverse motion of the medium. The resemblance of this resource and the string-and-bead model suggests that eliciting the *transverse speed* resource may be a particularly fruitful starting point for instruction on wave mechanics. By eliciting students' own ideas about how propagation works, and then comparing and generalizing from them, instructors might leverage this resource to facilitate students' development of explanatory models for pulse propagation. Instructors might leverage the *energy* resource by eliciting it in the context of a more detailed exploration of the energy transfers and transformations that occur in the pulse-flick scenario. Finally, instruction might build on or refine the resources we identified by inviting students to consider parameters that affect the energy or speed of a pulse. For example, in many of the examples given in this paper, variables such as width, amplitude or the source motion have been implicitly held constant or unspecified. We are currently designing and testing instructional materials that elicit and build on student resources for understanding pulse propagation.

Chapter 4. STUDENTS' CONTEXT-SENSITIVE USE OF CONCEPTUAL RESOURCES: A PATTERN ACROSS DIFFERENT STYLES OF QUESTION ABOUT MECHANICAL WAVES

4.1 ABSTRACT

Resources theory assumes that resource activation is context-sensitive, and that an important dimension of this context is the question students are answering. The context dependence of resource activation has been demonstrated empirically by case studies that show students using different resources to answer questions that are similar in focus. In this paper, we further substantiate and add specificity to the field's understanding of the context-sensitivity of resource use by demonstrating a pattern in resource activation for questions about mechanical pulse propagation, superposition, and reflection. In particular, our analysis shows a pattern in the kinds of resources students use to answer different *styles* of question about the same physics topic. We find that questions asking students to make a prediction and explain their reasoning elicit ideas that are rule-based (i.e., involving statements of fact, principle, or problem-solving procedure specific to mechanical waves). Questions that ask students to explain a phenomenon elicit these *plus* ideas about force, energy, and motion. Our results call both researchers' and instructors' attention to the style of question that they ask and the impact it has on the resources commonly cued for students.

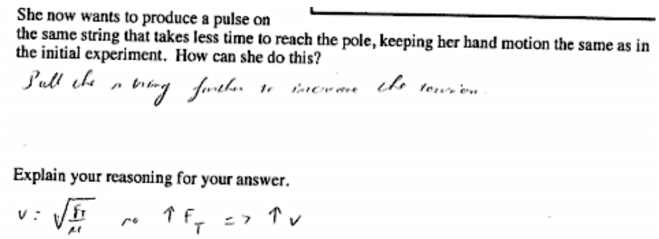
4.2 INTRODUCTION

The resources theoretical framework models cognition in terms of pieces of knowledge – i.e., *resources* – that are activated in the moment in a context-sensitive way to construct arguments, models, and concepts [3,32,33,69,75]. Other constructivist perspectives in physics education research, such as the alternative conceptions perspective (e.g. [5,7]), have historically conceptualized student thinking as stable and consistently-applied. Resources theory, on the other hand, predicts that students will *not* consistently apply the same line of reasoning to problems that a physicist would deem similar or even equivalent. Resources are instead thought to be activated in context-sensitive ways as learners deem them relevant [32–34,69]. In this paper, we demonstrate a recurrent pairing between the style of conceptual physics question asked and the kinds of resources that students used to answer it. Our results substantiate and add specificity to the assumptions of context sensitivity proposed in the literature. Our analysis shows that the *style* of question may affect the resources students use to answer, and more broadly demonstrates that the question a student is answering is an important aspect of the context for resource activation.

While resources theory suggests that certain features of the question or environment may trigger the activation of certain resources, few studies have explicitly investigated whether there are patterns in context-sensitivity that bear out across many students, or whether certain features of the context reliably elicit particular kinds of resources. Resources research has validated theoretical claims of context-sensitivity primarily through vignettes and case studies that showcase a single student using different lines of reasoning in different situations [33,34,92,94]. For example, Wagner [94] illustrates context sensitivity with the story of Kristin, an undergraduate student who uses two different lines of reasoning to answer two conceptually isomorphic probability questions, one about flipping a coin and another about dropping a ball through a vertical pinball machine.

In this paper, we demonstrate that different styles of physics questions about the same wave mechanics phenomena elicit responses that draw on different types of resources. Our data come from students' written responses to several conceptual physics questions asked as part of a larger study (e.g., [48]) of students' conceptual resources for understanding mechanical waves. In the broader study we asked conceptual questions that can be broadly characterized as two types: (a) questions that ask students to make a prediction about the outcome of an experiment or changes to an experiment, and then explain their reasoning for the prediction ("predict" questions), and (b) questions that describe the outcome of an experiment and ask students to explain why the outcome makes sense ("explain" questions). Here, we examine data from pairs of questions about three wave mechanics ideas: pulse propagation, superposition of pulses, and reflection of a pulse at a boundary.

We initially observed that students gave strikingly different answers to "predict" and "explain" questions, which led us to more closely examine – and then seek to characterize – these differences. For example, a "predict" question about propagation asked students to describe a change to a string that would result in a faster-moving pulse and to explain their answer, and an



She now wants to produce a pulse on the same string that takes less time to reach the pole, keeping her hand motion the same as in the initial experiment. How can she do this?

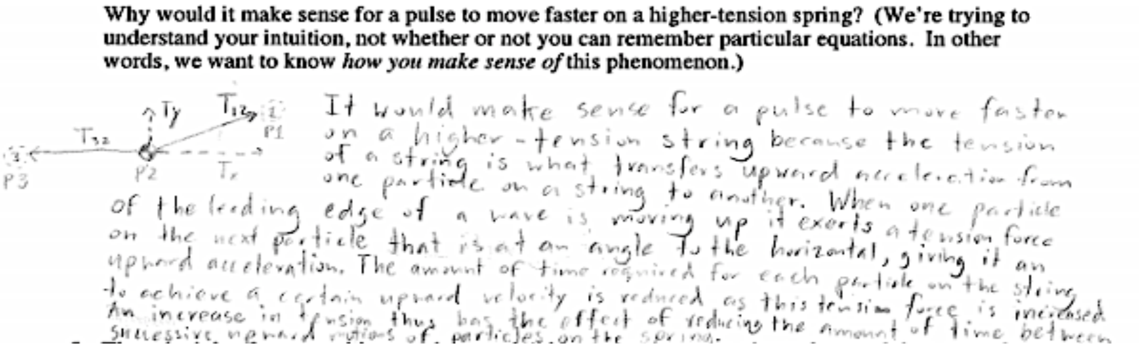
Pull the string further to increase the tension.

Explain your reasoning for your answer.

$v = \sqrt{\frac{F_T}{\mu}}$ so $\uparrow F_T \Rightarrow \uparrow v$

Figure 4.1. Example student response to a predict-style question. "[to make a pulse that takes less time to reach the pole, she should] pull the string further to increase the tension [because] v=√(T/μ) and ↑F_T→ ↑v."

explain-style question asked students to explain why it makes sense that increasing the tension in a spring results in a faster-moving pulse. The example in Fig. 4.1, which is a response to the predict-style question, states that increasing the tension in the spring will increase the speed of the pulse, and justifies this prediction using an equation for the speed of a pulse on a string. Since pulse speed depends on the square root of tension, increasing tension will increase pulse speed. In contrast, the example in Fig. 4.2 is a response to the "explain" question. This response describes the forces acting on a small part of a string as a pulse reaches it and constructs a mechanistic description of how increased tension affects the speed of the pulse. While both responses assert that pulse speed depends on tension, the reasoning used to explain this dependence



Why would it make sense for a pulse to move faster on a higher-tension spring? (We're trying to understand your intuition, not whether or not you can remember particular equations. In other words, we want to know *how you make sense of* this phenomenon.)

It would make sense for a pulse to move faster on a higher-tension string because the tension of a string is what transfers upward acceleration from one particle on a string to another. When one particle of the leading edge of a wave is moving up it exerts a tension force on the next particle that is at an angle to the horizontal, giving it an upward acceleration. The amount of time required for each particle on the string to achieve a certain upward velocity is reduced as this tension force is increased. An increase in tension thus has the effect of reducing the amount of time between successive upward motions of particles on the spring.

Figure 4.2. Example student response to an explain-style question. "It would make sense for a pulse to move faster on a higher-tension string because the tension of a string is what transfers upward acceleration from one particle on a string to another. When one particle of the leading edge of a wave is moving up it exerts a tension force on the next particle that is at an angle to the horizontal, giving it an upward acceleration. The amount of time required for each particle on the string to achieve a certain upward velocity is reduced as this tension force is increased. An increase in the tension thus has the effect of reducing the amount of time between successive upward motions of particles on the spring."

is quite different. The first response invokes an equation and says how it applies to the particular situation, while the second causally explains how tension causes an increase in the speed of the pulse.

Our initial observation was that contrasts like these recurred in our data, and this led us to form the preliminary hypothesis that "predict" questions tend to elicit ideas that are rule-based (i.e., involving statements of fact, principle, or problem-solving procedure), while "explain" questions elicit more mechanistic ideas (i.e., involving chaining ideas in a semi-causal manner). In this paper, we describe the process by which we sought to test this hypothesis: we developed a coding scheme that articulates the difference between these two types of responses, and applied it to a large number of responses to "predict" and "explain" questions in order to quantify our initial observations. Our results both affirm and add nuance to our initial hypothesis.

4.3 RESOURCES THEORETICAL FRAMEWORK

Resources theory highlights the complex, dynamic, and emergent nature of student thinking [35] and emphasizes the continuity of that thinking with formal physics concepts. Our work draws on the resources theoretical framework to identify patterns in student thinking about mechanical waves, particularly by emphasizing the context sensitivity of student thinking.

Resources theory is a cognitivist theory in that resources are understood to exist in the minds of individual students. Resources are thought to be derived from students' prior experience and learning, such that they are fundamentally sensible – i.e., students have good reason for using them as they do [34,69,70,75,95]. Resources theory takes the view that student thinking is potentially fruitful or productive [69,74,79], rather than inconsistent with scientific thinking. In resources theory, learning physics involves increasing the degree of formality of resources, limiting or extending the context for activation of resources, or strengthening networks of connection between resources [33,69,70,95,96]. Learning, therefore, involves activating and building from the resources that already exist in the student's mind, and can involve resources that are canonically incorrect or incomplete.

Resources are activated when they "make sense" or are deemed applicable by the student; activation of a particular resource is influenced by the lived experience of the learner, the social setting in which the question is asked, and the question at hand [33,34,74]. Thus, resources theory does not view student thinking as stable, coherent, and consistently applied; instead it assumes that specifics of the context in which a question is asked will influence the resources activated in a student's mind [33,34,69,77,96]. Based on this theoretical perspective, instructors can expect that questions that seem conceptually similar to them may elicit very different resources from students, and they can expect that the same student may display one idea in one context and a very different idea (or set of ideas) in another [34,96].

A particular form of context-sensitivity discussed in the literature is that activation of one resource may in turn stimulate or suppress activation of other resources [33,34,97]. Researchers have identified and named different kinds of resources (e.g., conceptual [48], epistemological [96], or procedural [98]), and the activation of these resources is thought to be intertwined [33,34,92]. For example, if two different contexts cue different epistemological resources, this may in turn cue different conceptual resources that are appropriate within or linked to the cued epistemological frame[5]. A question on a worksheet in a physics classroom may either cue epistemological frames of "making common sense" or of "applying formal knowledge" for different students [33]. The "making common sense" frame in turn may cue conceptual resources related to everyday experiences that are appropriate for sense-making, while the "applying formal knowledge" frame may cue technical vocabulary and principles communicated by authorities such as the instructor or textbook. The connection between epistemological resources or frames and conceptual resources has been particularly emphasized in the literature. Several case studies demonstrate that the epistemological framing activated by a particular instructional activity, such as a group discussion or an exam, may be an important factor in determining when certain conceptual resources are, or are not, activated [82,92]. However, studies have not demonstrated that there are patterns in the contexts that elicit particular epistemological and conceptual resources.

In this paper, we draw on resources theory by attending to (some of) the pieces of students' knowledge that we deem sensible and relevant for questions about propagation, superposition, and reflection of mechanical pulses, even if incomplete or incorrect. We assume that students have good reason for using these ideas, and that these ideas can be fruitful for physics learning in ways that extend beyond what we can infer solely from written responses to our questions [74]. Most prominently, we draw on *context-dependence* in our expectation that students may activate different conceptual resources in different situations, based on their prior experiences and learning,

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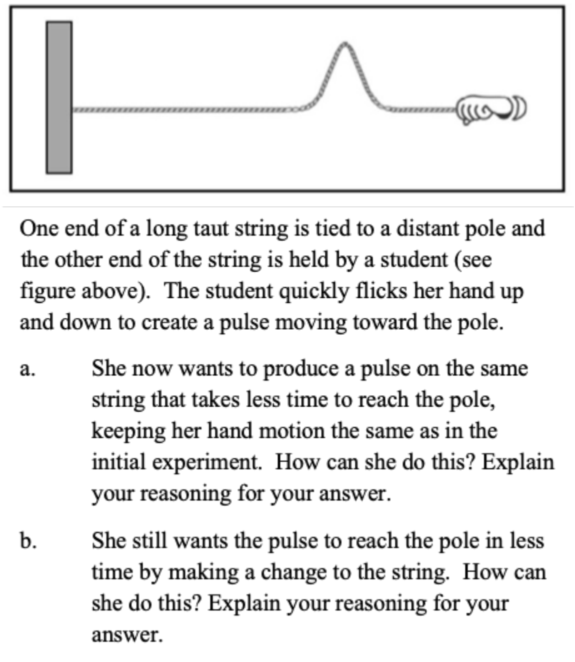
[5] An epistemological frame is the set of epistemological resources activated for a particular situation, and answers the question "What is it that's going on here?" [33].

the question asked, and the setting in which it is asked. We specifically attend to the question type as a dimension of context in this paper. In our analysis we do not assume that the written responses we analyze reflect all of the resources activated by or available to the student; rather we assume that students' written responses demonstrate a subset of resources that students (consciously or unconsciously) deemed appropriate for answering the question.

4.4 QUESTION ADMINISTRATION

In this study, we analyzed students' responses to conceptual questions about three mechanical wave phenomena: propagation, superposition, and reflection. For each of these topics, we analyzed one "predict" question and one "explain" question (as shown in Figs 4.3-4.8). These questions were asked as part of a broader study investigating students' conceptual resources for wave mechanics, where we began with predict-style questions that had been previously been used in research and instruction and then modified these questions as "explain" questions to probe students' ideas more deeply.

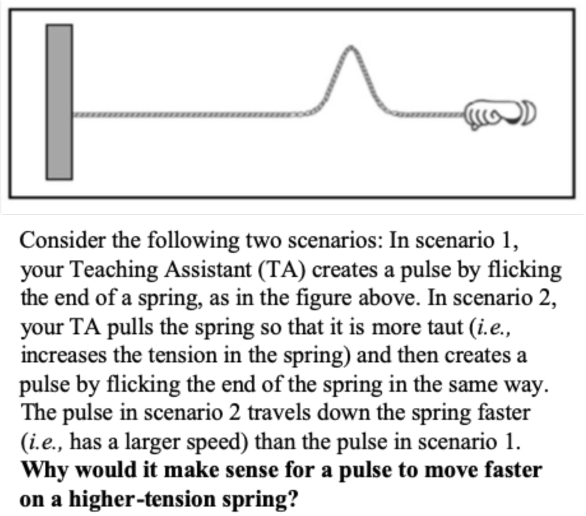


One end of a long taut string is tied to a distant pole and the other end of the string is held by a student (see figure above). The student quickly flicks her hand up and down to create a pulse moving toward the pole.

a. She now wants to produce a pulse on the same string that takes less time to reach the pole, keeping her hand motion the same as in the initial experiment. How can she do this? Explain your reasoning for your answer.

b. She still wants the pulse to reach the pole in less time by making a change to the string. How can she do this? Explain your reasoning for your answer.

Figure 4.4. The predict-style question on pulse propagation (the original pulse-flick question). This question is modified from Wittmann [22].

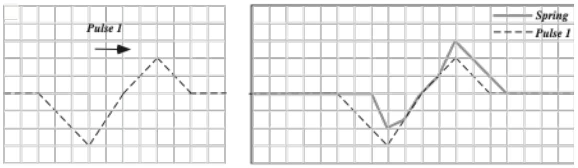


Consider the following two scenarios: In scenario 1, your Teaching Assistant (TA) creates a pulse by flicking the end of a spring, as in the figure above. In scenario 2, your TA pulls the spring so that it is more taut (*i.e.,* increases the tension in the spring) and then creates a pulse by flicking the end of the spring in the same way. The pulse in scenario 2 travels down the spring faster (*i.e.,* has a larger speed) than the pulse in scenario 1. **Why would it make sense for a pulse to move faster on a higher-tension spring?**

Figure 4.3. The explain-style question on pulse propagation (the tension pulse-flick question).

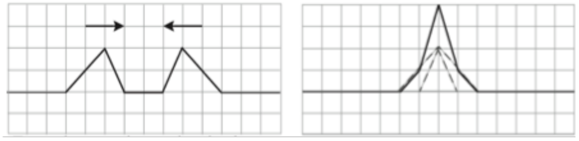
The propagation "predict" question was modified from Wittmann's Waves Diagnostic Test [20]. This question asked students to determine a change, either to the same string or by using a different string, that would make the pulse reach the end of the string faster (the *original pulse-flick* question – Fig 4.3). The propagation "explain" question asked students why it would make sense that a pulse moves faster on a higher-tension spring (the *tension pulse-flick* question – Fig. 4.4). For both of these questions, a correct answer would indicate that pulse speed is determined by the tension and mass density of the string or spring. That is, pulse speed increases with increased tension and decreases with increased mass density. Answers to these questions can be justified in a variety of ways that are consistent with canonical physics thinking. For example: a statement that the speed of pulses and waves is determined by the properties of the medium they move through, an equation that quantifies the relationship between speed and properties of the medium, or a mechanistic description of how changing tension or mass density affects the motion of small parts of the medium and thus affects the speed of propagation. Section 4.6 includes student responses that illustrate these various types of explanations.

The superposition "predict" question (the *pulse subtraction* question – Fig. 4.5) presented students with a figure showing both (i) the shape of a spring at an instant when two pulses overlap and (ii) the shape of one of the pulses at that instant. This question asked students to draw the shape of the second pulse at that instant, and to explain why their answer makes sense. We modified this question from Kryjevskaia, Stetzer, and Heron's previous study of student ideas on



Pulse 1 moves to the right along a spring, as shown in figure (a) above. Another pulse (pulse 2, not shown) moves in the opposite direction along the same spring. Figure (b) above shows the location of **pulse 1** (dashed line) and the **shape of the spring** (solid line) at an instant while the two pulses meet.
On Figure (b), draw the shape and location of **pulse 2** at the instant shown. Say why your answer makes sense to you in the space below.

Figure 4.5. The predict-style question on superposition (the pulse subtraction question). This question is modified from Kryjevskaia, Stetzer, and Heron [23].

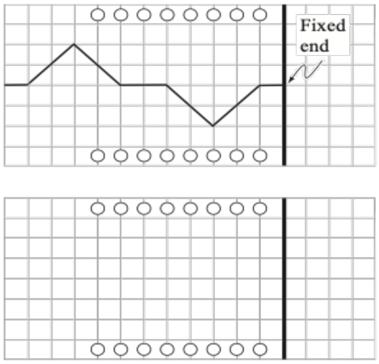


When two wave pulses on the same side of a spring meet, they add, as in the figure at right. This is an example of superposition.
How do you make sense of this phenomenon? In other words, why do pulses add when they're on the same side of the spring/why does the superposition principle work the way it does?

Figure 4.6. The explain-style question on superposition of two pulses (the *why superposition* question).

mechanical pulse superposition and reflection [21]. The superposition "explain" question asked students to explain why pulses add when they meet (the *why superposition* question – Fig. 4.6). For the *pulse subtraction* question, the correct shape of pulse 2 can be obtained by subtracting the displacement of pulse 1 from the displacement of the spring at each location along the spring. Analogously, the shape of the spring shown in the right diagram for the *why superposition* question is the sum of the displacements of the two pulses at each location along the spring. For both of these questions, there are a variety of ways to explain the shape of the spring that are consistent with canonical physics. These include: a description of the procedure used to apply the principle of superposition to two pulses on a spring, a statement that pulses or waves do not behave like objects but instead are superposed when they coincide, or a mechanistic description of the additive effects of each disturbance on the part of the spring where they meet. Student responses that illustrate these lines of reasoning are given in Section 4.6.

The reflection "predict" question asked students to predict which of several paper cups, arranged on either side of a spring near its fixed end, will be knocked over when the depicted pulse reflects at the endpoint (the *cups* question – Fig. 4.7). We modified this question was modified from Kryjevskaia, Stetzer, and Heron's previous study of student ideas on mechanical pulse superposition and reflection [19]. The reflection "explain" question asked students to explain why a pulse reflects on the opposite side of a spring at its fixed end (the why reflection question – Fig. 4.8). For the cups question, the shape of the spring can be determined by modeling the boundary as a point that is equidistant from the leading edge of the incident pulse and the leading edge of another pulse, traveling in the opposite direction toward the boundary, that is the same shape as the incident pulse but reflected across the x and y axes (which we refer to as the "ghost pulse"). The displacements of the two pulses add according to the principle of superposition during the time interval that they overlap. When displacement of the spring (on the left side of the boundary) meets or exceeds the location of the cups, it is knocked over. For the situation in Fig. 4.7, only the second cup from right, above the spring, is knocked over. The same procedure can be used to determine the shape of a spring at several instants during the reflection of a single pulse as shown in the figure of the why reflection question (Fig. 4.8). For both questions there are a variety of ways to explain the shape of the spring during reflection that are consistent with canonical physics, such as describing the model used for reflection at a fixed end, explaining the procedure used to determine the shape of the pulse as it reflects, or by articulating a mechanism that causes the pulse to reflect at the fixed end. Examples of responses using each of these lines of reasoning are illustrated in Section 4.6.



A pulse moves to the right along a spring with a fixed end. Cups are placed on either side of the spring as shown. The maximum transverse displacement of the spring while the pulse approaches the end of the spring is less than the distance from the equilibrium position of the spring to the cups. At the time shown, no part of the pulse has reached the fixed end of the spring.

On the diagram at right, mark which (if any) cups are knocked over during the reflection of the pulse from the fixed end. Briefly explain.

Figure 4.7.The predict-style question for reflection (the cups question). This question was modified from Kryjevskaia, Stetzer, and Heron [23].

When wave pulses move through fixed ends (*e.g.*, when the string is attached to the wall), they reflect on the opposite side of the string, as in the figure at right. How do you make sense of this phenomenon? In other words, *why* do pulses reflect on the opposite side of the string at fixed ends?

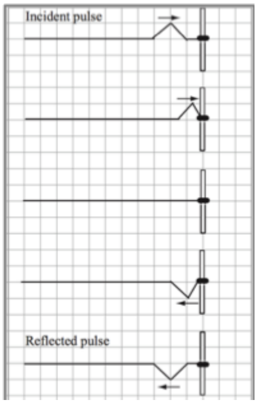


Figure 4.8. The explain-style question for reflection (the why reflection question).

In total, our data for this investigation includes 2,102 student responses spanning a total of 17 courses from 5 universities in the US: Baylor University, California State University – San Luis Obispo, Seattle Pacific University, the University of Washington, and Western Washington University. For each question described above, we analyzed student responses from 2-3 universities. All of these courses were introductory, calculus-based physics courses that covered wave mechanics,[6] though the specific topics and depth of coverage varied from course to course. In all cases these questions were given after coverage of wave mechanics and were included on homework (extra credit in one case), quizzes, or exams. In some courses, these questions were graded for correctness, in some they were graded for correctness and correct explanation, and in

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[6] A typical introductory university-level physics course in the US includes instruction on wave propagation, superposition, and reflection, as well as wave optics and interference.

some they were graded for participation. We expect that specific grading practices and expectations varied across the courses in which we asked these questions, but we do not know exactly what they were. Table 4.1 gives additional details about the administration of these questions.

The racial/ethnic demographics and parental income statistics for the universities in our study (blue bars) versus all college students/universities (orange bars, line) are approximated in Figures 4.9 and 4.10.[7] Orange bars in Fig. 4.9 were constructed from percentages cited in Kanim and Cid [93]; blue bars in Fig. 4.9 were constructed from publicly-accessible university-level demographic data [99–102], weighted by sample size. Blue bars in Fig. 4.10 were constructed from university-level data reported by the Equality of Opportunity Project [103]; the orange line represents the average of all median parental incomes reported there. Both figures indicate that our

Question Administered	University	N	Fraction of course participating
propagation "predict"	CPSLO	70	0.97
	UW	134	0.76
propagation "explain"	CPSLO	163	0.91
	WWU	105	~ 0.7
	UW	162	0.7
superposition "predict"	Baylor	175	0.91
	CPSLO	153	0.85
	SPU	65	0.94
superposition "explain"	CPSLO	76	0.9
	Baylor	170	0.89
	UW	200	0.87
reflection "predict"	Baylor	99	0.79
	CPSLO	24	0.64
	UW	140	0.78
reflection "explain"	Baylor	169	0.8
	CPSLO	69	0.96
	UW	128	0.73

Table 4.1. Details of the samples used in this study. At CPSLO, our questions were given in multiple independent sections of the course taught by different instructors. Multiple questions were given in a course at Baylor and in some courses at CPSLO.

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[7] We say "approximated" because although we accessed university-level demographic data within a year of collecting data from each university, the data that was available to us at the time of our search does not necessarily reflect the university-level demographics for the specific quarter or year we collected data.

research samples from universities that disproportionately serve white, wealthy students; this is aligned with a general trend in PER, as highlighted by Kanim and Cid. One limitation of Figures 4.9 and 4.10 is that they are based on (approximations of) university-level data, rather than data at the level of our sample (which we do not have); this assumes that our samples are demographically representative of the university. We are skeptical of this assumption and have made this a subject of future work.

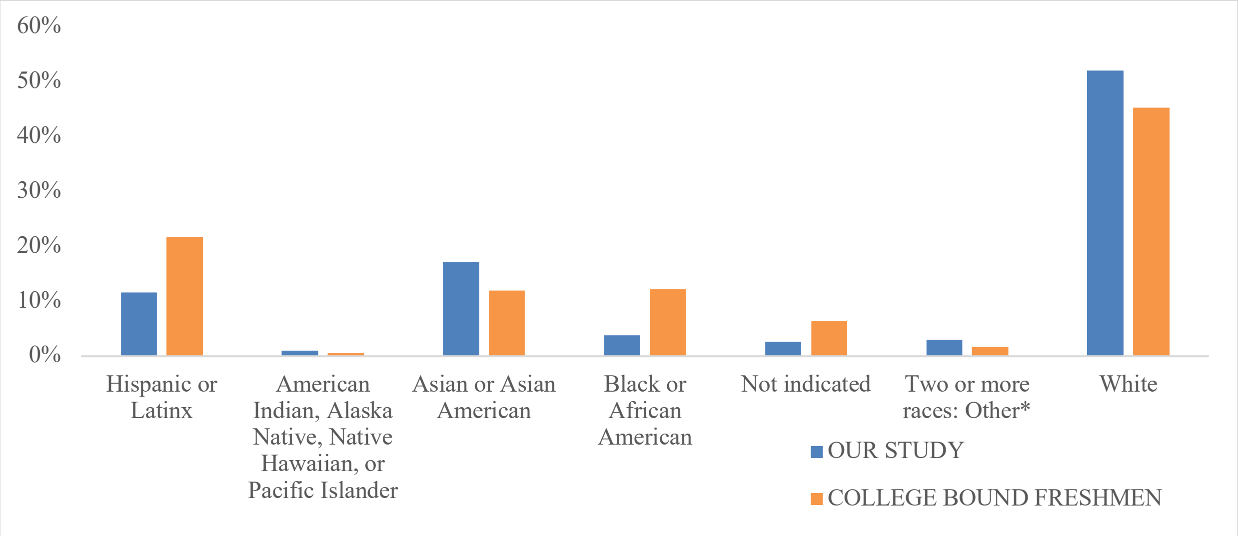


Figure 4.9. Racial demographics of our sample versus college-bound freshmen.

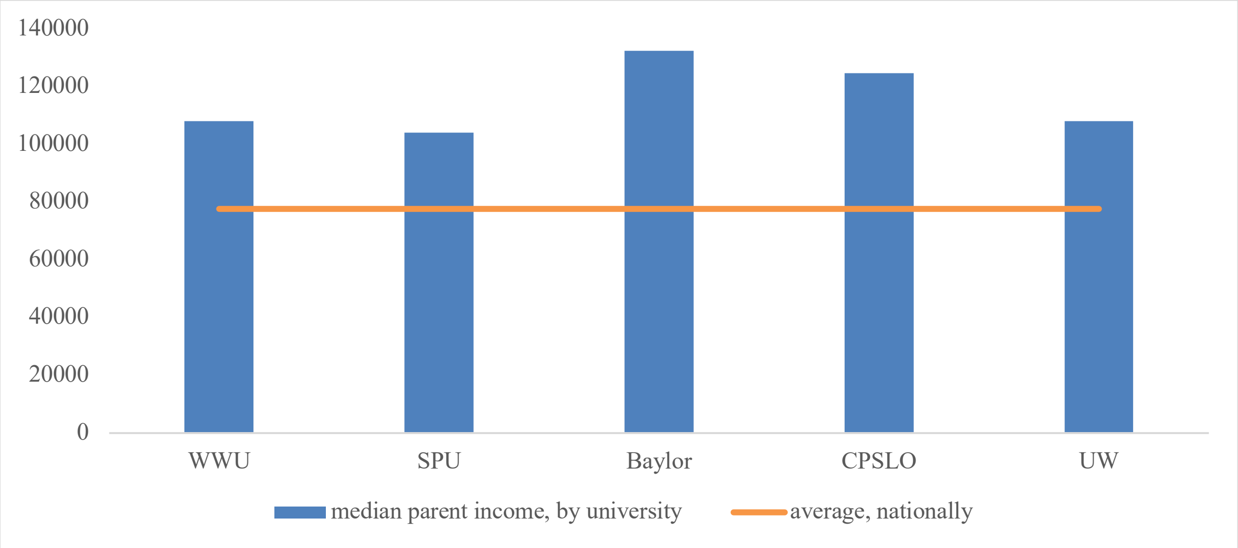


Figure 4.10. Wealth demographics of our sample versus national average. Median parent income is in U.S. dollars.

4.5 METHODS

This investigation was motivated by our initial observation that “explain” questions seemed to elicit explanatory or mechanistic responses, whereas “predict” questions seemed to elicit rule-based or procedural responses. We began to construct a coding scheme to refine this observation by articulating in detail what we meant by the two categories and roughly characterizing the kinds of responses that fit in each. We examined the commonalities and differences among narrative or multi-step responses that drew on a variety of physics concepts (those we had roughly called “mechanistic”), and the commonalities and differences among the responses that cited relevant principles and steps that supported a predictions about the outcome of the experiment (those we had roughly called “rules”). As we articulated the features of these two categories, we found that there were a variety of rule- and procedure-based responses: students drew on physical models and narrowly-applicable principles, equations, and mathematical procedures. We also found that students’ explanatory and mechanistic responses were frequently based on ideas of force, motion, and energy. We used these observations to further refine the two codes in our scheme.

We iteratively refined our coding scheme by applying it to small subsets of student responses to each question and discussing the salient features of, and differences between, these two kinds of responses. This led us to a coding scheme with two codes: (1) resources related to forces, motion, and energy (FME), and (2) resources related to principles and models, rules, or procedures (RP) for propagation, superposition and reflection. The first category (FME) encompassed resources that described force interactions between parts of the string, pulse, or boundary; that described details of the motion or the string and/or boundary; or that described energy conservation, transfers, or transformations in the system. The second category (RP) encompassed resources related to physical or mathematical models or rules for propagation, superposition, or reflection, and resources regarding procedures for making a prediction about these questions. The two categories are illustrated in detail in the following section.

In order to clarify the bounds of each of these codes, we chose to only code RP or FME resources that we, as physicists, recognize as relevant (even if incomplete or incorrect) for wave mechanics questions. For example, we did not code the response, “pulses are reflected because ‘every action has an equal and opposite reaction,’” because this rule is not (to us) clearly connected to pulse reflection; that is, it is not clear to us whether the action in this case is the pulse itself, or a force exerted on the spring that makes it move in a particular way, or something else entirely. Our coding scheme captures resources that are *disciplinarily* productive ("a physicist would deem [them] appropriate," – and we interpret "appropriate" somewhat generously [74]), but not resources that may *situatedly* productive (productive as they support a student or group of students' progress toward an emergent conceptual goal) [74]. This is primarily a practical choice: in static written data, we cannot see how the ideas expressed contribute to a student's own unfolding sensemaking process or self-defined questions, but we can see how these ideas are relevant for the physics questions at hand. This means that there are likely rules or procedures (or force/motion/energy ideas) that are not captured by this coding scheme because our perspective as physicists limits our ability to recognize how they are relevant for students' own emerging understandings of wave mechanics. We do not expect that our categories capture all of the resources that students bring to bear in answering these questions, and they are not meant to indicate that these are the only types of thinking that researchers or instructors should attend to. However, as we will show in the next sections, these two categories of resources are relatively common (at least in some questions), represent rich physics thinking, and answer to our original purpose of testing our hypothesis.

Two researchers (Lisa M. Goodhew and Amy D. Robertson) independently coded student responses to each question using the refined scheme. A single response could receive no codes, one code, or both codes (the latter if students issued separate lines of reasoning). After independent coding, we compared the codes separately assigned to each response, noting whether the two coders agreed or disagreed. We used Cohen's kappa as a measure of the inter-rater reliability of our codes [104]. This statistic improves upon simple measures of percentage agreement by taking into account chance agreement between the two coders. Our kappa values were 0.84 for the RP codes and 0.86 for FME codes; kappa values in this range are typically understood as "strong" or "excellent" agreement [105,106].

In reporting the percentages of student responses that used each type of resource (Section 4.6), we kept only codes that were assigned by both coders. The final codes assigned to a single response reflect complete agreement between coders.

4.6 TWO CATEGORIES OF CONCEPTUAL RESOURCES

In the following sections, we give examples that show the variety of resources and responses encompassed by each of our categories (RP and FME), and we describe the bounds of these codes.

4.6.1 *Rules & procedures category*

Across questions, students invoked rules and procedures to explain or justify their answers. The rules and procedures included in our scheme are specific to mechanical wave superposition, propagation, and reflection (e.g., pulses reflect on the opposite side at a fixed end), including principles and predictive models for the behavior of waves, equations for wave mechanics, and procedures for determining the outcome of experiments.

4.6.1.1 Rules

"Rules" responses often take the form of "if-then" or "when *x* then *y*," statements. These responses may connect specific salient features of the given situation to specific outcomes or behaviors, or they may state a principle or models as given. Some responses apply a physical model to the specific question being asked, as in these responses:

"A fixed end can be modelled by a reflected, inverted pulse approaching from the opposite side of the boundary. I superimposed the incident wave shifted 5m right and the imaginary wave shifted 5m left." (cups question)

"Inversion occurs when the transmitted pulse moves towards a medium with a greater mass density. The fixed end always has a greater mass density than the medium through which the transmitted pulse travels so inversion will occur." (reflection mechanism question)

"The speed the pulse is moving at is a property of the spring. This means that if you were to change something about the spring, then the velocity will change. If we assume the frequency is going to remain the same, then the pulse is going to need to travel at a faster speed so it can cover a lager distance in the same amount of time as the shorter distance." (tension pulse-flick question)

The first response highlights that a salient feature of the situation is the fixed end of the spring, and describes the model that applies in fixed-end situations (that the reflection is like a superposition of the incident pulse, and a matching "ghost pulse" is coming from the opposite side of the boundary and on the other side of the spring). The response then describes how the model is applied to the particular situation using superposition, which instantiates another facet of the RP category which we discuss below. The second response above states a different rule—that pulses invert when they reflect at a boundary with a denser medium—and applies the rule to the "why reflection" question. The third response above states as a rule that pulse speed is a property of the medium it travels through and describes how this rule applies to the situation in the tension pulse-flick question.

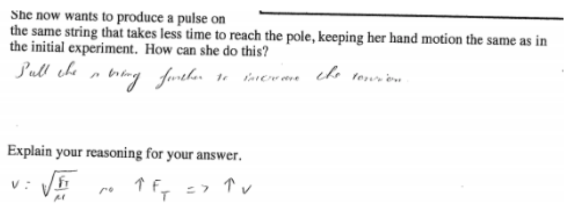
We included in our coding rules that were relevant for the question, even if they were not canonical principles or models for the situation, or if the model was applied incorrectly. For example:

"*I think this happens because…as the wave moves into a fix[ed] end it is like any other object hitting a wall that would be reflected in the same angle but opposite side.*" (why reflection question)

The rule that objects reflect at an equal and opposite angle to the incident is relevant for reflection, which was the topic of the question. Thus, we assigned this response the RP code even though the mechanics of a Newtonian object reflecting at a barrier are different than the mechanics of a string as a pulse reflects at its fixed end.

4.6.1.2 Equations

Particularly in the propagation questions, some responses stated an equation as a justification or explanation, such as these examples:



She now wants to produce a pulse on the same string that takes less time to reach the pole, keeping her hand motion the same as in the initial experiment. How can she do this?

Pull the string further to increase the tension

Explain your reasoning for your answer.

$v = \sqrt{\frac{F_T}{\mu}}$ so $\uparrow F_T \Rightarrow \uparrow v$

"*[to make a pulse that takes less time to reach the pole, she should] pull the string further to increase the tension [because]* $v = \sqrt{T/\mu}$ *and* $\uparrow F_T \rightarrow \uparrow v$*."*(original pulse-flick question)

"[The pulse] moves faster [on a tauter spring] because $v = \sqrt{T/\mu}$ *; if the linear density of the string is lower, then v will be higher. Pulling the string tighter lowers the linear density."* (tension pulse-flick question)

"If she moves her hand in the same motion as she did originally but just flicks it faster it will take less time to reach the pole, [because] $v = \lambda f$ *so when she flicks her hand quicker frequency is higher than before so velocity is faster."* (original pulse-flick question)

Each of these responses states an equation that applies to pulses or waves on a string/spring and explains how the equation applies to the particular situation (e.g., pulling the string tighter increases T or decreases μ) and what the equation predicts (e.g. pulse speed increases). Responses like these use a model in a particular way– by explicitly stating an equation – to justify a prediction or answer. Like responses that use other forms of models or rules, these responses tend to state the rule as given or as a premise of the student's argument.

4.6.1.3 Procedures

Some responses in this category describe the steps used to make a prediction or the mathematical procedure used to determine an answer.

"By the principle of superposition, wave_result = wave_1 + wave_2, or wave_2 = wave_result – wave_1. This subtraction is done at each point along the line." (pulse subtraction question)

"I went point by point to make the second pulse add or cancel out with pulse 1 so the spring is the result of the two." (pulse subtraction question)

"I got my results by drawing my diagram as if it could keep continuing through space but anything after the fixed end was reflected on the other side. I then added the amplitudes to any areas that intersect and got my result." (cups question)

The first two responses describe a procedure for applying the principle of superposition to the "pulse subtraction" question – the amplitude of the given pulse is subtracted from the shape of the spring shown at each point along the line. Similarly, the third response describes the mathematical procedure (adding amplitudes of the parts of the pulse that overlap as it reflects) that is used in conjunction with the "ghost pulse" model to answer the "cups" reflection question. Common to all three responses is that they describe the steps that the student used to determine the answer to the question.

Other responses referenced a mathematical procedure for determining the answer without describing the steps, such as these examples:

"By superposition, the amplitudes will add." (cups question)

"This was very hard to visualize, but, it seems that the spring position would just be the average of the two waves' positions." (pulse subtraction question)

The first response references the principle of superposition to justify that the amplitudes of two pulses (which we assume are the incident and reflected parts of a pulse reaching the fixed end of the string in the cups question) add together. It also references a procedure (addition) for determining the answer. The ideas expressed in this response could be called either a "rule" or a "procedure;" our aim is to show the variety within the RP category, rather than to emphasize distinctions between various kinds of responses within the category. The second response cites a mathematical procedure – averaging – to justify an answer. Though averaging is not the correct mathematical procedure for the pulse subtraction question, it is a sensible mathematical procedure for this situation, and thus we include it in the RP category.

In summary, we grouped these Rules, Equations, and Procedures into one category because they represent succinct, specific ideas, that can be used to make predictions about wave propagation experiments.

4.6.2 *Force, motion, and energy category*

Particularly for the "explain" questions, many responses mapped fundamental mechanics ideas onto wave phenomena. Responses in this category described forces on the pulse or medium or between parts of the pulse or medium, described motion of parts of the pulse or medium, or used energy conservation or tracking to make sense of wave phenomena.

4.6.2.1 Forces

In some responses, students explained or predicted a phenomenon by describing the forces acting on or between parts of the system, as illustrated in the following examples:

"Every action has an equal and opposite reaction. So as the wave propagates towards the wall, and hits the wall, there is a force upwards on the wall. This means the wall exerts a force downwards on the string. Because $F = m\left(\frac{dv}{dt}\right)$ *and the wall does not accelerate, the string accelerates downwards, effectively inverting the wave. Also maybe something to do with energy, I D[on't] K[now]."* (why reflection question)

"The principle of superposition can be explained by looking at the forces acting on individual particles of the spring. Looking at a single particle, the forces acting on it will be from the adjacent particles right next to it. The net forces will be from the adjacent particles right next to it. The net forces will vary depending on where the particle is on the spring. Once two wave pulses meet that are on the same side, the net force will be the sum of both waves causing a higher magnitude of force, therefore a higher displacement." (why superposition question)

"By increasing the tension, we increase the contact forces between particles of the string, thus they do not have to displace far to transmit the motion. It takes less time for each particle to transmit [the] pulse." (tension pulse-flick question)

Each of these responses describes how forces acting on or between parts of the medium cause the observed behavior of the string or pulse. The first response applies Newton's second and third laws to the part of the string near the boundary (the wall): the pulse is inverted because the string pulls up on the boundary, and the boundary pulls down with an equal and opposite force, which causes the string to accelerate and move past the equilibrium point. The second and third responses describe how force interactions between small parts of the medium cause the undisturbed parts of the medium to be displaced, and the magnitude of the force determines how high (in the second response) or how quickly (in the third response) the medium is displaced from equilibrium.

As illustrated by the examples above, many of the responses we assigned this code were quite detailed, but the level of detail was not a criteria we used to determine which responses to assign the FME code. Other examples, like this one, more briefly referenced forces in the medium in their answers:

"It makes sense because the forces in the pulses that cause the displacement, just like with basic vector math." (pulse subtraction question)

This response implies that when two pulses are co-located, the forces associated with each pulse add as vectors to cause the observed displacement of the medium. This response is not specific as to whether the forces act on the pulse as a whole or on parts of the pulse. However, like other force examples in the FME category, the basis of its argument is that forces "in" the pulse cause the observed phenomenon (superposition of two pulses, in this case).

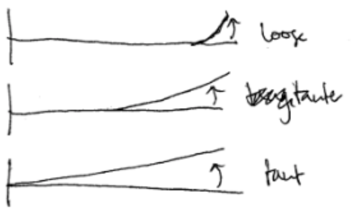
4.6.2.2 Motion

Other responses in the FME category examined *motion* of parts of the medium or parts of the pulse to construct an explanation, as the following examples show:

"For each wave pulse, the pulses have vertical velocities which have the same direction, when they meet each other, the vertical velocities combine and give a larger vertical velocity." (why superposition question)

"I just think of it as a wave on top of a wave. A wave displaces a medium. If that medium is already displaced, the wave will still act the same way." (why superposition question)

"... I think this happens because it is a fixed end and because the pulse is not allowed to drift upwards to meet its highest peak at the boundary point, it is pulled down and continues with this motion of downward motion when reflected and will then stay on that side because nothing is pushing it back up to the origin." (reflection mechanism question)



"[A] tauter string means a greater length is affected at once by the movement (longer λ)." [accompanied by the diagram at left] (tension pulse-flick question)

The first and second examples here explain that two pulses add when they are co-located because each pulse makes the medium move away from its equilibrium position, and the effects on the motion of the medium from each pulse combine or add. The third response describes the transverse motion "of the pulse" during reflection in order to explain why a pulse is reflected on the opposite side at a fixed end. The fourth response above explains that when tension in a string is higher, more of the string is disturbed "at once" (i.e., as the source itself moves), and therefore the pulse is wider and must move faster. Though it is quite different from other examples of this category, this response still describes the motion of the medium and relates it to the motion of the pulse.

Other responses seem to describe a relationship between the motion of the pulse and the motion of the medium, or the transverse and longitudinal motions associated with the pulse:

"Repeat the same motion, but more quickly [because] the time it takes for the pulse to pass a certain point, leading edge to trailing edge (relates to velocity), is the same as the creation time of the pulse. By repeating the same motion (flick up and down) faster, the pulse will be faster." (original pulse-flick question)

"With more tension in the spring, there would be less of an amplitude, meaning the wave will travel less in the "up and down" motion and more in the "left to right" motion. Less tension will result in waves that have a greater amplitude (speed??)." (tension pulse-flick question)

The first response explains that a pulse that passes over each point on the string in less time will have a higher speed. While this is incorrect, because it does not account for the width of the pulse (or how many other particles of the medium are moving during the time a pulse passes a particular point), it appropriately describes pulse propagation as sequential transverse movements of parts of the medium. The second response above explains that if transverse displacement associated with the pulse is limited by tension, then there can be more longitudinal motion. Again, though this explanation is incorrect – transverse motion and longitudinal motion associated with the pulse are not the same kind of thing – we recognize it as explaining propagation in terms of motion of parts of the pulse and medium.

4.6.2.3 Energy

Some responses in the FME category explain or justify an answer using ideas about energy conservation or tracking, like these examples:

"…I believe that the reason it reflects to the other side is due to conservation of energy. Because the wave constantly wants to displace upwards, however [it is] unable to b/c of [the] fixed end. The only way it can go to maintain its energy is to deflect downward. Furthermore, energy has no direction, nor does it care about direction, therefore reflecting downwards does not change energy state." (why reflection question)

"Pulses reflect on the opposite side at fixed ends, because energy is lost during contact with the wall, causing the reflected wave to have less potential energy." (why reflection question)

"Pulses add because each wave/ pulse is energy being carried across the spring (or other medium). When the 2 pulses cross each other, the resultant is the sum of their amplitudes because both energies are present at the same point at the same time." (why superposition question)

"Each part of the spring is pulling harder (in better contact) with the part next to it, so the energy transfers better/faster and the wave travels faster." (tension pulse-flick question)

The first response explains that there must be a reflected pulse to conserve energy in the system. This response does not say *why* the fixed end means that the pulse must be inverted in order for energy to be conserved; this is stated as given. The second response explains that a pulse must invert when it reflects at a fixed end because energy is lost during the reflection. We infer that the student sees the inverted pulse as a lower energy state, perhaps because the reflected pulse in the figure in this question is on the "bottom" of the string, and thus can be thought of as lower or having less gravitational energy. Although this is not a canonical explanation for the inversion of a pulse at a fixed boundary, this response instantiates the force-motion-energy category because it uses energy conservation to explain the phenomenon. The third response above explains that pulses carry energy across the medium, and thus when two pulses meet, the energy associated with each pulse is in the same location. This response implies that greater displacement from equilibrium indicates more energy at that location, and thus when the two pulses are co-located the medium is displaced more. The fourth response focuses on the energy transfers between parts of the medium as the pulse propagates. It identifies tension as a mechanism of energy transfer (i.e., the tension between parts of the spring) and associates the transfer of energy across the medium with the motion of the pulse itself, and uses these ideas to explain the observation that increasing tension in a spring increases the speed of a pulse moving on it.

We coded energy tracking/conservation ideas, but not statements that describe the pulse *as* energy. When students say "the energy of the pulse moves faster" we did not code it because this is not an explanation based on energy tracking or conservation. We grouped responses that involve force, energy, and motion ideas together into one code because they share an explanatory nature: these describe the physical entities and actions that are relevant in various wave propagation phenomena. In this sense, many of these responses share characteristics of mechanistic reasoning [107,108]. However, "mechanistic reasoning" was not the primary criterion for this code; there were causal statements in our data set that we did not assign the FME code because they did not clearly demonstrate force, energy, or motion resources. For example, the response: *"In the second scenario, the spring is higher in tension, so it's less dense. And since it's less dense, the pulse can move along the string easier, therefore faster,"* (tension pulse-flick question) causally connects the density of the spring to the speed of the pulse, but does not discuss forces, energy, or motion of the medium. This criterion represents a refinement of our initial sense that this category was based on mechanistic or "explanatory" resources.

In summary, the FME category encompasses resources for broadly-applicable physics concepts that have been applied to wave mechanics questions, whereas the RP category encompasses resources that relate to the rule-like application of particular models, principles, and equations for wave mechanics. The example responses presented in this section illustrate two categories of conceptual resources which are, at least in the context of wave mechanics[8], distinct.

4.7 PATTERNS IN FREQUENCY

Figures 4.11-4.16 represent our coding of student responses to each question; each figure shows the fraction of responses from each university that we assigned rule-procedure or force-energy-motion codes for each question. Since a single response could be assigned no codes, one code, or both codes, the fractions for a single university and question do not necessarily add up to 1. These fractions include only the responses assigned a particular code by both coders. Across the six bar graphs, we notice a consistent trend: that ‘predict’ questions elicit primarily rule-procedure resources, while ‘explain’ questions elicit *both* rule-procedure and force-motion-energy resources. These results add nuance to our initial hypothesis that “explain” questions commonly elicit one kind of resource, while “predict” questions commonly elicit another.

More specifically, for each of our “predict” questions (Figures 4.11-4.13), at least 50% of responses used rule-procedure resources, and, with the exception of the sample from CPSLO given the original pulse-flick question, fewer than 2% of responses used force-energy-motion resources to answer ‘predict’ questions. Across all samples given the ‘explain’ questions (Figures 4.14-4.16), both rules-motion resources and force-energy-motion resources are relatively common. Each resource was used by more than 20% of students in at least one sample given each question, and more than 5% of responses from every sample used each kind of resource. We note that that overall, FME resources were more common than RP resources in these questions: FME resources were used in 28% -73% of responses to ‘explain’ questions, whereas RP resources were used in 7% - 47% of responses[9].

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[8] We suspect that for kinematics and dynamics questions (i.e., questions about force, energy, and motion) these two categories may not be distinct, or there may be corresponding categories appropriate for the topic.

[9] Of the three explain questions, the “why superposition” question most commonly elicited RP resources. This may be because the mathematical procedure of addition is particularly salient for understanding and explaining superposition.

These patterns reproduce across universities and questions, with the exception of the original pulse-flick question at CPSLO. The courses we sampled from were taught by different instructors, using a range of texts and course structures, and with varying content emphases. The fact that similar patterns emerge despite the variation in instruction suggests that the different patterns we see for the "predict" and "explain" questions can be made sense of, at least in part, by

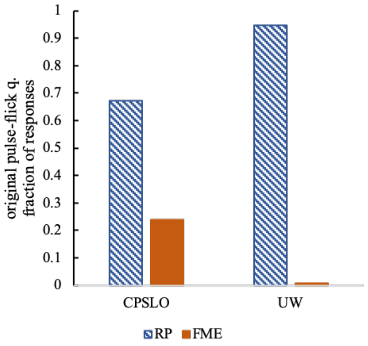

Figure 4.11. Fraction of responses assigned the RP (striped blue bars) or FME (solid orange bars) codes for the predict-style question on propagation (the original pulse-flick question).

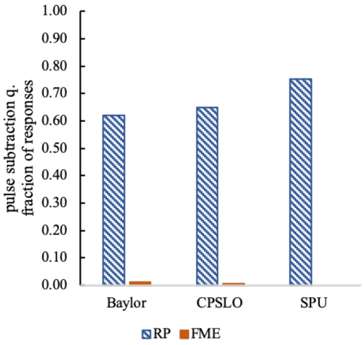

Figure 4.12. Fraction of responses assigned the RP or FME codes for the predict-style question on superposition (the pulse subtraction question).

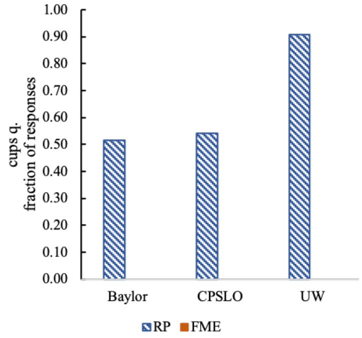

Figure 4.13. Fraction of responses assigned the RP or FME codes for the predict-style question on reflection (the cups question).

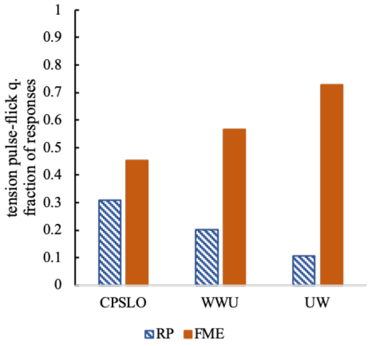

Figure 4.14. Fraction of responses assigned the RP or FME codes for the explain-style question on propagation (the tension pulse-flick question).

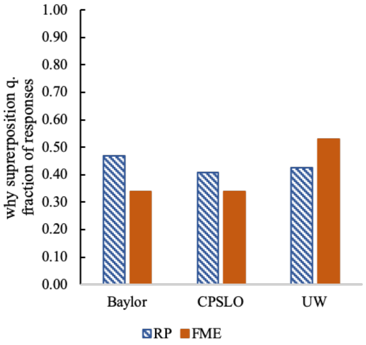

Figure 4.15. Fraction of responses assigned the RP or FME codes for the explain-style question on superposition (the why superposition question).

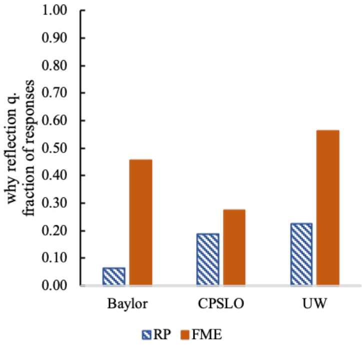

Figure 4.16. Fraction of responses assigned the RP or FME codes for the explain-style question on reflection (the why reflection question).

differences in the questions themselves. This latter claim draws on a model of generalizability that looks for patterns that reproduce across multiple sources of heterogeneity; that is, in the absence of a controlled experiment, the "operative question" becomes "can the same…relationship be observed" across contexts [90]? If the differences in resource activation and use were primarily due to differences in instruction or grading, rather than the question, we would expect that in courses where instruction was most similar, the two questions would elicit similar patterns in responses. For example, at Baylor University, four questions were administered in three courses (the two superposition questions were given in the same course, and the reflection questions were given in two other courses) taught by the same experienced instructor, in the span of one year. All three courses used the same text and followed the same instructional sequence. However, we see that the patterns in responses at Baylor resemble the patterns at the other institutions, where there was more variation in instruction. Hence this counterargument does not fully explain the observed patterns.

4.8 THEORETICAL SIGNIFICANCE & DISCUSSION OF FUTURE WORK

While the context sensitivity of resources has been demonstrated in smaller samples through case studies, to our knowledge patterns in context-sensitivity have not been overtly explored on a large scale. Our results contribute to the empirical validation of context-sensitivity using a large-N study, and add specificity to theoretical notions of *what* features of the context matter for resource activation. In particular, this study suggests that the *style* of a question affects what kind of resources students use to answer it. The categories we articulate in Section 4.6 show that this pattern is more than students giving explanatory answers to explain-style questions, and using models to make predictions. We see that there are specific ideas – force, motion, energy – that students commonly draw on to explain physics phenomena. We also see that students are drawing on rules, principles, and procedures relatively frequently, even as they explain physical phenomena.

One explanation for the patterns of context-sensitivity we observe is that "predict" and "explain" questions cue different epistemological resources or framings, which in turn cue different kinds of conceptual resources for mechanical waves. As we stated earlier, resources theory proposes that activation of epistemological and conceptual resources are linked, such that epistemological framing is expected to influence the activation of conceptual resources. If the two questions communicate different things about what counts as an answer, it makes sense that students will use different kinds of conceptual resources.

Our current study is specific to “predict” and “explain” questions about wave mechanics. Whether similar patterns emerge in different content areas (e.g., electrostatics or thermodynamics) is a question we are exploring in emerging work. We hypothesize that the categories we have articulated in the context of wave mechanics are specific instances of more general categories corresponding to the “predict” and “explain” structure of questions across physics content areas. Extending this work to new physics content areas may clarify whether there are nuances to the question structure or features of the physics content itself that contribute to the patterns of responses we see in this study.

Our results open up questions about the extent to which these patterns would be impacted by small changes to the instruction that students receive before answering our questions or to the wording of our questions. For example, at UW, a Tutorial [109] that students completed in-class prior to answering our superposition questions emphasizes a predictive model and procedures for determining the shape of a spring or string during reflection. In a course at Seattle Pacific University taught by LMG (not included in this data) that more explicitly discussed mechanisms for reflection (in addition to procedural tutorials), we saw that a higher fraction of students used FME resources to answer a question like the cups question – though students still used RP resources more frequently. However, these results may also be explained by small changes in the wording of the question: for example, these students were asked to predict (and draw) the shape of a spring at several instants during a fixed end, and then to “explain why their drawings make sense.” It is possible that this wording cued framings like those cued by “explain” questions for some students, and thus a higher fraction of students used FME resources (either instead of, or in addition to, RP resources) to answer the question.

As we have discussed in Section 4.4, our study samples from universities that disproportionately serve white and wealthy students as compared to the U.S. college-age population. Though this imbalance is consistent with a broader trend in physics education research [93], it represents an important limitation to the generalizability of our results. The broader trend leads to a skewed accrual of the benefits of PER to white, wealthy students. Our knowledge of the demographics and representativeness of our sample is limited by the fact that we do not know the demographic information of the courses in which we administered our questions, so we rely on the tenuous assumption that the demographics of these physics courses match the overall demographics of the university. In future work we intend to collect data from a more representative sample by over-sampling from minority-serving institutions and two-year colleges. We also intend to collect demographic data for the courses we sample from, rather than use university-level data to estimate the demographics of our sample.

4.9 INSTRUCTIONAL IMPLICATIONS

Both RP and FME resources represent types of physics reasoning that have been emphasized in physics education literature. Identifying and mapping appropriate physics and math concepts to a particular problem or translating qualitative problem statements into more quantitative or mathematical forms, as students are doing in RP answers, is an important step in physics problem solving (e.g., [110]). Identifying relevant entities and activities for the mechanisms of wave mechanics, and chaining them together to construct causal or mechanistic explanations, as students do in FME responses, are important features of mechanistic reasoning [108]. The RP and FME categories, then, call instructors' attention to categories of reasoning that represent "wonderful ideas" [40].

The bar graphs in Figs 4.11-4.16 show that "explain" questions about wave mechanics tend to elicit a more diverse set of resources than "predict" questions do. This finding contributes useful pedagogical content knowledge that instructors can use to guide their choice of in-class or assessment questions that match their goals. "Predict" questions offer the advantage of commonly cuing resources that are appropriate for making specific predictions and are closely tied to the content of the question. Such questions may be useful for assessing students' knowledge of specific mathematical or conceptual models. "Explain" questions commonly elicit a broad variety of resources and responses, which would be appropriate for goals of debating ideas, broadening and connecting resources, and sensemaking and mechanistic reasoning. Though these results are limited to the content area of wave propagation, we hypothesize that "predict" and "explain" questions in other content areas may also elicit different kinds of thinking in the classroom.

It is common in physics teaching and PER to use predict-style questions to assess student understanding. For example, conceptual inventories such as the FCI [111] or Waves Diagnostic Test [20] almost exclusively use predict-style questions. Our results demonstrate that such assessments may be limited in their capacity to assess students' ability to use the fundamental physics ideas of force, energy, and motion to sense-make about complex physics questions. Our results suggest that incorporating “explain” questions into assessments could expand the scope of physics thinking that is valued through classroom discussions or assessment.

Chapter 5. EXAMINING THE PRODUCTIVENESS OF STUDENT RESOURCES IN A PROBLEM-SOLVING INTERVIEW

5.1 ABSTRACT

It is central to the resources theoretical framework that the knowledge elements that comprise thinking – *i.e.*, resources – are sensible, based on experience, and continuous with formal physics. While many authors agree that students' conceptual resources can be framed as continuous with formal physics, few have discussed how and in what ways specific resources are productive for learning. We closely examine the progression of one introductory physics student's thinking during an exploratory problem-solving interview, attending to the role that specific conceptual resources play in the evolution of her ideas over short time-scales. Two commonly activated resources for wave propagation (treating a pulse as an object moving through a medium and treating a pulse as a propagating disturbance) are integral to the conceptual progress she makes during this episode, and therefore can be considered productive for this situation.

5.2 INTRODUCTION

While the literature that develops the resources theory of knowledge is multi-faceted, and thus does not offer a single synoptic definition of a resource, there are several points of consensus regarding what resources are. Resources are described as knowledge elements or ideas at a smaller grain size than scientific concepts, which are activated in the moment to construct explanations, arguments, and concepts [32,34,69]. Activation of a particular resource is context-sensitive, influenced by the learner themselves, the environment, and the question at hand [33]. Across the literature, resources are depicted as neither inherently correct nor incorrect; instead, they may be appropriately or inappropriately activated for a particular question. Though resources are neither correct nor incorrect, they are described as inherently sensible (reasonable to the learner) and continuous with formal physics ideas, such that there exists a trajectory over which a "raw" resource can become a scientific concept [3,32,69].

In previous work we identified two common conceptual resources for wave propagation from student responses to the "pulse-flick question" (Fig. 5.1), a conceptual question about wave propagation used in previous studies [6]. These resources are: (A) treating a pulse as a macroscopic object moving in medium whose properties affect the pulse's speed (*object-in-medium*), and (B) treating a pulse as a propagating local disturbance in a medium (*propagating-disturbance*)[10] [81]. Each of these resources is continuous with formal physics concepts about mechanical wave propagation: *object-in-medium* may represent the beginnings of understanding that wave speed is determined by properties of the medium. *Propagating-disturbance* appropriately describes the nature of pulses and may represent the beginnings of a canonical model for propagation.

Some authors who report particular conceptual resources describe how they are continuous with canonical physics or *might* be productive for students, but authors have less commonly illustrated how these resources *are* productive in context. This paper presents an illustrative case of the productiveness of the resources *object-in-medium* and *propagating-disturbance*, and thereby demonstrates how theoretical notions of productiveness may be realized in context. We analyze a short (approximately 20-minute) excerpt from an exploratory problem-solving interview with one introductory physics student, pseudonymed Sophie. We identify instantiations of these two conceptual resources and give evidence that these resources are both (i) appropriately activated for the question at hand and (ii) contribute to the development of Sophie's thinking. We claim that because these two resources are appropriately activated and contribute to Sophie's thinking, they are *productive* for her.

5.3 PRODUCTIVENESS OF RESOURCES

While resources are thought of as inherently continuous with formal physics, assessing their productiveness – the extent to which a resource is appropriately activated or plays a role in progress – requires examining the context in which they are activated. To do this, we draw on the work of Harrer [74], who defines two types of productiveness: *disciplinary productiveness* and *situated productiveness*.

5.3.1 *Disciplinary productiveness*

Harrer defines disciplinary productiveness as "appropriate activation [of a resource] in a particular context, as judged by the community of physicists via the instructor or researcher" [74].

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[10] These two resources are nearly equivalent to the "properties of the medium" and "transverse speed" resources that are articulated in chapter 3. This case study was conducted at an earlier stage of our analysis of students' conceptual resources and I have retained the resources as they were conceptualized at the time of this analysis.

Thus, disciplinary productiveness is not an attribute of the resource itself, but of the resource-in-context. For example, the resource *closer means stronger* [31] is productive for explaining why the air is warmer closer to a fire, but not for explaining why it is warmer on Earth during the summer. While disciplinary productiveness is evaluated in light of a resource's consistency with relevant canonical concepts, we do not interpret this to mean that the student must be “almost there” [38,74] for a resource to be considered productive in this sense. In this paper, we use disciplinary productiveness to assess the appropriateness of these two resources for reasoning about pulse propagation.

5.3.2 *Situated productiveness*

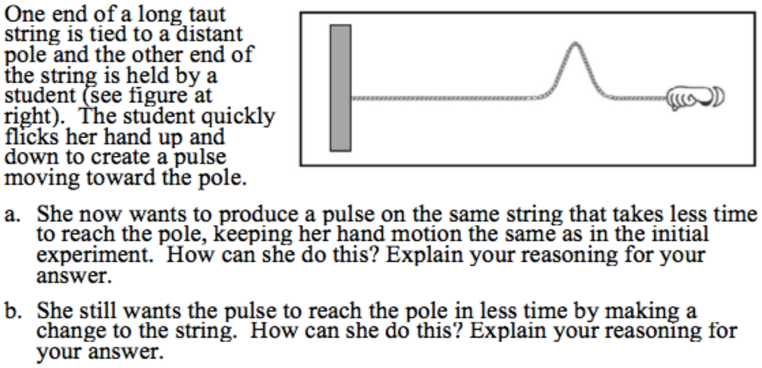
Harrer defines situated productiveness of resources as a contribution to intellectual progress toward an (often emergent) goal that is implicitly or explicitly defined by students themselves [74]. Situated productiveness is discussed in Harrer’s work in the context of group interactions: “If a resource allows the group to make significant progress toward an emergent, shared goal…it can be considered productive for the situation at hand” [74]. In other words, situated productiveness is evaluated in light of the role a resource plays in a student's or group's evolving thinking. Thus, it is appropriate to use this construct in situations where students’ unfolding thinking is on display, whether this occurs in group interactions or in instances where students verbalize their thought processes individually. In this paper, we use the construct of situated productiveness to assess two conceptual resources’ contribution to a student’s progress toward answering an emergent question.

5.4 METHODOLOGY & EXCERPT SELECTION

In this paper, we use interview excerpts to (1) demonstrate disciplinary and situated productiveness in the context of mechanical wave propagation and in doing so (2) provide proof-of-concept of the productiveness of two resources for understanding mechanical waves. Thus, the objective of this work is to illustrate theoretical notions of productiveness by examining a case of productiveness of two particular conceptual resources. The transcript we analyze for this case-study comes from one of five exploratory problem-solving interviews conducted with students enrolled in a third quarter, calculus-based introductory physics course at the University of Washington. Interviews were unrelated to the coursework or grades, and student volunteers were selected on a first-come basis. The interview with Sophie took place after she had received some instruction on wave mechanics. In the interview, Sophie was given two conceptual questions about mechanical waves and asked to "think aloud" about her answers. The interview was video-recorded and lasted about 40 minutes. The excerpts presented here come from Sophie's response to the second of two questions she was given in her interview (Shown in Fig. 5.1). We chose these particular excerpts because in them Sophie articulates (and then resolves) an emergent question, and she uses the two common resources we have reported. Since Sophie uses these two resources in the context of wave propagation, these excerpts have the potential to demonstrate the disciplinary productiveness of the resources. Since Sophie uses these two resources to articulate and resolve an emergent question, these excerpts have the potential to demonstrate the situated productiveness of these resources.

To analyze the disciplinary productiveness of the two resources, we examine their specific instantiations against a disciplinary understanding of pulse propagation: the pulse can be modeled as transverse displacement of sequential parts of the medium governed by the laws of mechanics, such that pulse speed is determined by properties of the medium.

To analyze the situated productiveness of these resources, we examine the ways in which they contribute to the progression of Sophie's thinking during her interview. We draw on Odden and Russ's notion of a "vexation point" to understand a tension Sophie articulates as the beginning of a process of sense-making and knowledge construction. The vexation point is defined as the "critical moment...when [she] attend[s] to and articulate[s] an inconsistency or gap in [her] understanding" which signals a shift from recalling previously learned knowledge to constructing new knowledge [112]. Therefore, in our analysis we attend to the role these resources play in Sophie's knowledge-building following a vexation point in her interview.



One end of a long taut string is tied to a distant pole and the other end of the string is held by a student (see figure at right). The student quickly flicks her hand up and down to create a pulse moving toward the pole.

a. She now wants to produce a pulse on the same string that takes less time to reach the pole, keeping her hand motion the same as in the initial experiment. How can she do this? Explain your reasoning for your answer.

b. She still wants the pulse to reach the pole in less time by making a change to the string. How can she do this? Explain your reasoning for your answer.

Figure 5.1. A conceptual question on pulse propagation, modified from [57].

5.5 ANALYSIS

In the following excerpts Sophie discusses the pulse-flick question (Figure 5.1) with author LMG. After reading the question, Sophie says:

> Sophie: *Instinctually we wanna say, flick it harder, um, because you think that you can affect the speed by adding more force into something, but you already kind of know that speed is, only depends on the medium. So trying to make the pulse faster wouldn't really do anything.*

Sophie's idea that flicking harder will make the pulse move faster can be interpreted as treating the pulse as a Newtonian object, which moves faster when thrown with greater force [61]. She articulates a dissonance between her intuitive thinking and her learned response that only the medium affects pulse speed. This is the vexation point: she articulates something that does not "make sense," and (in what follows) begins to sense-make about why tension should affect pulse speed but the motion of the source of the pulse should not. After some discussion, Sophie sighs and says, "The answer is increase the tension." Then she starts to explain her thinking about tension:

> Sophie: *Oh! I can answer this! With music...I really like instruments. Um, in order to make the pitch for a string higher, you need to tune it by tightening it. So you're adding tension by tightening the string. The frequency...it's related to the speed. So, if you wanted to make it go faster, going at a higher frequency, you've gotta make the string tighter.*

Sophie expands on her ideas about instruments, but seems dissatisfied because she says,

> *Now to try and explain that without any, without music, because music seems to be a really easy answer, how that works, um...okay! Let's use roads.*

Sophie continues, saying:

> *Yeah. Um, an un-tense road is kind of wavy. You're gonna slow down at the turns. If you add tension, the road becomes straighter and you can just zoom through it...without having to decelerate at any of the turns.*

In this statement, Sophie treats the slack as a property or part of the medium that impedes the pulse moving through it, using the resource *object-in-medium*. While a pulse is ontologically unlike a car on a road (*i.e.*, pulses are not Newtonian objects), Sophie uses this analogy to associate the tension of the string with the speed of the pulse in a causal manner. For this reason, we consider this resource appropriately activated and disciplinarily productive. The resource *object-in-medium* also helps Sophie to connect her initial ideas, which treat pulses like objects, to ideas about the effect of the medium on pulse speed. In what follows, Sophie uses a second resource, *propagating-disturbance*, to expand on this idea, suggesting that her use of the second resource was in fact stimulated by the first. The interview continues with the following exchange:

> LMG: *So you're thinking then, tell me if this sounds like what you're thinking…if I make a tighter string, then the pulse…has less…there's less points that make it slow down.*
>
> Sophie: *Yeah. Kind of. Um, there's, there's, if we look at everything really, really, small, like we zoom in, uh —*
>
> LMG: *On the string?*
>
> Sophie: *On the string. A string that is not completely tense will have points where it's just kind of floating there, and it will take more energy to move those than something that's kind of ready to move.*

Here, Sophie begins to attend to the movement of "points" on the string – an instantiation of the resource *propagating-disturbance*. This resource helps Sophie elaborate on her ideas about how tension affects the speed of the pulse: tension tells her something about how "ready" the points in the medium are to move. Consideration of the dynamics of component parts of the medium is an important part of a canonical model for pulse propagation, so from a disciplinary perspective, this resource is productive here. Following this statement, Sophie continues:

> LMG: *Okay. So it takes more —*
>
> Sophie: *It's kind of like when you're doing "The Wave," and you've got people not paying attention.*
>
> LMG: *Okay, so there's less, like, there's less of whatever thing it is that makes each point of the string go up and down.*
>
> Sophie: *Yeah. So it just proceeds a bit slower.*
>
> LMG: *Okay!*
>
> Sophie: *It's like, if the string were a bunch of humans, because we're doing a Wave in a stadium, um, if none of the people are ready to do the Wave, they're sort of relaxed, there's a time it takes to communicate the idea that, 'Hey guys we're doing a Wave now,' so it kind of goes slowly. But if everyone's like, 'Yeah! We're gonna do the Wave! Guys, guys, Wave, woo!'*

Here, Sophie builds on her thinking about the motion of particles in the medium by constructing an analogy between people participating in "The Wave" in a stadium (where successive groups of spectators briefly stand, yell, and raise their arms) and propagation of a pulse on a string. Using this analogy, Sophie implies that tension determines how quickly a disturbance of the string propagates, just as visual or verbal communication between people determines how quickly "The Wave" propagates. Although this analogy is limited—"The Wave" does not propagate through physical interaction but through the choice of audience members to participate—it instantiates the resource *propagating-disturbance* in a way that is disciplinarily productive because it supports Sophie in thinking about a pulse as sequential, transverse disturbances of parts of a medium [61]. Next, Sophie extends her analogy:

> Sophie: *I guess, another example…if you're doing a Wave while holding hands with a bunch of people, um, you don't know they're pulling on your hand until they're actually doing their side of the Wave, and then you realize, 'Oh wait!' Unless you guys are all stretched out and you can clearly feel every time a person moves just a bit, because you've got nothing else, nowhere else to go, but move with them.*

In this statement Sophie continues to use the resource *propagating-disturbance*, extending her analogy between a pulse on a string and "The Wave" in a stadium. Her extension introduces a physical interaction between discrete parts of the medium, more accurately modeling the forces between particles of the medium. This accuracy indicates the continued disciplinary productiveness of this resource.

At this point in the interview, Sophie has articulated a model for pulse propagation: discrete parts of the medium are disturbed perpendicularly to the direction of motion of the pulse, and that disturbance is communicated by physical interactions between those discrete parts. After this excerpt, Sophie reconciles her initial intuition about flicking the string harder with her answer that the tension affects the speed. She says,

> Sophie: *I guess, okay, instinctively, because for some reason our brain already knows what to do, by adding more force we're actually increasing the tension in the string because we're pulling it back some more before we go. So kind of like how when you crack a whip, you don't just go like that (pulls her hand back and makes and up-and-down flicking motion). You pull it back before you go...except here it's attached, so when you pull it back,*

> *you're increasing the tension and then that makes it actually go faster...okay. I have an answer.*

This statement suggests that Sophie has resolved her initial question. Whereas initially she expressed dissonance between her intuition that flicking the string harder generates a faster pulse and her recollection that only changing the medium changes the speed, here she explains how her intuition could be consistent with canonical physics. Although Sophie's thinking is not entirely complete or true in all cases ("flicking harder" does not necessarily mean increasing tension) it *is* consistent with both her initial intuition and with the equation $v = \sqrt{T/\mu}$.

Looking at the course of Sophie's thinking, we see evidence of the situated productiveness of both resources she uses: both contribute to her conceptual progress. *Object-in-medium* supports Sophie in connecting her ideas about the pulse as an object to ideas about the effect of the medium, which then stimulates her use of *propagating-disturbance*. Specifically, her ideas about the motion of small pieces of the string come from her analogy between a winding road and a slack string. Ideas about motion of parts of the medium then lead to Sophie's use of *propagating-disturbance* in her "Wave" analogy. Sophie uses this second resource to construct a model of a pulse as a transverse displacement of sequential parts of the medium propagated via physical interactions. Ultimately, this progression of ideas allows Sophie to answer *why* tension affects propagation speed, resolving the dissonance she expressed at the vexation point.

5.6 DISCUSSION

In these excerpts, we see Sophie activating two resources for mechanical wave propagation that we have reported elsewhere. Our analysis illustrates both (1) the notions of disciplinary and situated productiveness that have been described in the literature [74] and (2) the productiveness of these two resources specifically. We suspect that Sophie's interview is unique in the specific way her thinking unfolds as she discusses the pulse-flick question with the interviewer. Thus this case is not necessarily representative of a common pattern of reasoning for introductory physics students. This does not limit the theoretical significance of Sophie's interview as a case of the productiveness of these resources; Sophie's case offers an existence proof that these resources – including the canonically incorrect notion of pulses as objects – can support conceptual and situated progress. Further, we do not view Sophie's thinking as idiosyncratic: many students from several introductory physics courses use the same two conceptual resources to correctly answer several versions of the pulse-flick question in written form [81].

The analysis of interview excerpts, where we can follow a student's unfolding thinking, calls particular attention to the situated productiveness of conceptual resources. Many authors have described resources in general as productive when appropriately activated for certain physics concepts or questions (e.g., [34,69]), and some have illustrated how specific resources are disciplinarily productive for students in context [38,61,69,74]. Our illustrations of disciplinary productiveness add to this literature by giving specific examples in the context of wave propagation. However, fewer authors have illustrated situated productiveness. Harrer gives some examples of situated productiveness in the context of group work. We build upon this by illustrating how two specific conceptual resources are situatedly productive for a single student in the context of a one-on-one interview.

Our case study illustrates how the theoretical construct of situated productiveness calls attention to ways that students' ideas can be fruitful that do not necessarily correspond to disciplinary appropriateness. In this case, resources that are activated inappropriately can still move students' thinking forward, and thus are productive despite being incorrect. For example, some have argued that *propagating-disturbance* should be elicited in instruction to circumvent difficulties that may arise when students treat pulses as Newtonian objects [61]. In contrast, our analysis demonstrates that both *object-in-medium* and *propagating-disturbance* are (situatedly) productive for Sophie; both contribute to her development of an appropriate model for pulse propagation. Thinking in terms of both disciplinary and situated productiveness may enable researchers and instructors to see student thinking as productive (or potentially so) in a broader sense.

Chapter 6. A CASE OF RESOURCES-ORIENTED INSTRUCTION IN CALCULUS-BASED INTRODUCTORY PHYSICS

6.1 ABSTRACT

Many research-based instructional materials in physics have been informed by investigations of common student difficulties – thinking that is inconsistent with canonical understandings. Our research team is beginning to develop instructional materials that elicit and build on common conceptual *resources* – ideas that may be continuous with formal physics. These materials are open-ended and emphasize on building from students' thinking, in contrast with other research-based materials that aim to address specific difficulties or scaffold toward well-specified conceptual understandings. We expect that resources-oriented materials like ours place different demands on instructors, and that the instructional behaviors that are effective in this context may differ from other research-based approaches. In this paper, we use classroom video from preliminary resource-oriented instructional materials on pulse propagation to analyze a *case* of resources-oriented instruction in introductory physics, to explore what knowledge, skills, and/or dispositions may support instructors in implementing this kind of instruction.

6.2 DESCRIPTION OF CONTEXT

One goal of the work presented in this dissertation is to provide instructors with high-leverage, pragmatic information that supports them in implementing a resources perspective of learning and teaching in their classrooms. One way of accomplishing this goal is to provide research-based instructional materials that scaffold conversations to elicit and build from students' own conceptual resources for specific physics topics. The results of the studies presented in Chapters 3-5 informed the development of a resources-oriented instructional worksheet entitled *Representing Pulse Propagation* (included in Appendix A), which serves as a pilot for development of a suite of resources-oriented instructional materials. This chapter presents a case study that examines an episode of resources-oriented teaching in the context of this worksheet. This case study has been accepted for publication in the proceedings of the 2020 Physics Education Research Conference under the title "A case of resources-oriented instruction in calculus-based introductory physics," and is included verbatim in sections 6.1 (the abstract) and 6.3-6.8. In this section (6.2) I contextualize the case study by discussing the development and revision of the *Representing Pulse Propagation* worksheet.

The learning objective for this worksheet was informed by our previous research on common conceptual resources for mechanical wave propagation. Across the resources we report in Chapter 3, we noticed that students were articulating what pulse propagation *is,* or describing nascent models for pulse propagation. The interview with Sophie discussed in Chapter 5 further illustrates that these resources represent the beginnings of models for propagation. Our goal was to design curricular materials that built from what we observed students to be naturally doing – constructing models for pulse propagation – so we developed a worksheet to further scaffold that work. Thus, the learning objective we chose for this worksheet was for students to construct a model for mechanical pulse propagation that could accurately predict and explain the outcome of new wave propagation experiments. Our previous work showed that the "tension pulse-flick question" and the "mass density pulse-flick question" (see Fig. 6.1) tended to elicit a range of conceptual resources for pulse propagation, and thus we used these questions to elicit students' ideas early on in the activity. The design of this worksheet was further guided by our assumption that there are multiple valid ways to approach these questions. Thus, the learning objective for this worksheet focused on engagement in the scientific practice of refining a physical model rather than on constructing a particular canonical model for wave propagation.

Our first iteration of this worksheet guided students to answer the mass density and tension questions and then to articulate an analogy or model for propagation that was consistent with their explanations. The worksheet told students to compare their answers with other students' explanations and analogies to refine their thinking. Finally, the worksheet guided students to test their models by using them to predict the outcome of a new pulse propagation experiment. The

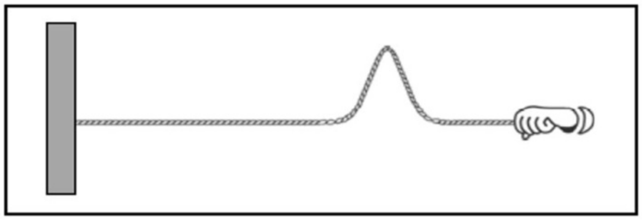


Figure 6.1. The tension pulse-flick question asks why a pulse like the one shown above moves faster on a higher-tension spring. The mass density pulse-flick question asks why a pulse like the one shown above moves more slowly on a heavier spring.

sequence of this worksheet is similar in structure to the Interactive Science Learning Environment (ISLE) learning approach [113–116] in that it asks students to observe a phenomenon, generate various explanations, and then design experiments to test their explanations. Like ISLE, our worksheet emphasizes participation in the process of science (particularly constructing and testing explanations). Our wave propagation worksheet is distinct in that it leverages research-validated resources associated with student models for pulse propagation to more explicitly scaffold the construction of an explanation before experimentation. We chose this particular scaffolding for our worksheet because our previous research showed that students common conceptual resources for wave propagation tended to resemble models for propagation or what a pulse *is*. Our preliminary worksheet is included in Appendix A.

We tested this worksheet in the calculus-based introductory physics sequence at Seattle Pacific University (SPU) in the Spring 2019 term (taught by the author), in the algebra-based introductory physics sequence at the University of Washington-Bothell in the Summer 2019 term, and in the calculus-based introductory physics sequence at the University of Washington (UW-Seattle) in the Autumn 2019 term. In both instances, the worksheets were used in normal class sessions where students typically worked in small groups to complete an activity from *Tutorials in Introductory Physics* [29]. In all courses, we video-and audio-recorded groups of students as they used the worksheet.

Our research team watched and content-logged approximately 10 hours of video from these pilot tests. We observed that students were able to construct appropriate analogies or models for propagation based on their own ideas about the tension and mass density questions. These analogies were complex, imaginative, and mapped well onto certain aspects of pulse propagation (e.g., a pulse on a spring is like a kangaroo jumping on a treadmill: it is successive vertical motion that occurs in a location that moves in the transverse direction). We noticed rich sensemaking in many of the groups that we observed. However, students frequently articulated frustration and uncertainty about several aspects of their experience with the activity, such as:

- how to engage with the worksheet activity (e.g., What does this question mean? What are the goals of the worksheet? What does "analogy" mean in this context?),
- their answers to the questions in the worksheet (e.g., Am I doing this right? How do I check my solutions?)

- the value of the worksheet (e.g., How will this be graded? Why am I doing this during tutorial?).

An interaction between four students (pseudonymed Paige, Garrett, Jian, and Wendy) at UW-Seattle in Autumn 2019 illustrated the coexistence of fruitful sensemaking and frustration particularly well to us. This group used a chain of dominoes as an analogy for pulse propagation: sending a pulse on a more massive spring is analogous to using heavier dominoes, and increasing tension is either like spacing the dominoes closer together, so one impacts the next more quickly, or like increasing a magnetic or spring force between each domino. After constructing the analogy, the group debated it for most of the class period, signaling to us that they were uncertain about whether it was correct or useful:

> Paige*: I'm gonna stick with my dominos, even though they don't really work. At all. I'm gonna say, the distance represents tension because it increases the impact each domino has on the next domino which is the same "thing" as tension where you increase the impact.*
>
> Garrett: *With greater tension, that means that the pulse itself will be lesser displacement with wider (inaudible)... the amplitude will be lesser. So... let's see... less movement and equal energy... Ah this is so hard... The particles aren't moving horizontally at all. They're only moving up and down. If they're moving less so up and down with the same amount of energy then they must be doing so faster… In order to conserve energy.*

This dialogue gives us insight into important pieces of Paige and Garrett's model for a pulse propagating on a spring. Paige articulates that tension is the kind of thing that increases the impact that the motion of one particle has on the next. Garrett points out that, unlike dominoes in a line, the particles in a spring only move in the transverse direction ("up and down"). Garrett voices his idea that increasing tension decreases the amplitude of the pulse, which means that the up-and-down disturbance has to propagate faster in order to conserve energy.

To us, it appeared that the domino analogy was supporting these students in thinking about pulse propagation – e.g., what the role of tension is and how the particles in the string move as the pulse propagates – and it supported Garret's further sensemaking about why a pulse moves faster in a higher-tension spring. However, as the conversation continued, the group continued to express uncertainty about their model and did not resolve the questions that came up for them. As they were packing up to leave, the students expressed frustration that they were leaving with more questions than they started with, and that they were not sure if they were doing the right kind of thing in class:

> Jian: *That was… very laid back and stressful at the same time.*
> Wendy: *Yeah.*
> Jian: *Like I just gotta know—*
> Wendy: *Yeah, that's how tutorial will be!*
> Paige: *I don't do well with not having clear answers about things. I just need to know.*
> Jian: *I'm like come on tell me! Or at least help me understand.*
> Paige*: I think we were supposed to be made more comfortable with uncertainty — which I am not happy about!*

Conversations like these illustrated to us that students were not necessarily noticing the productiveness in their own conversations that we noticed as researchers. This motivated us to revise the worksheet so that it would (a) more clearly frame the worksheet activity as constructing a scientific model, and (b) give students more opportunities to evaluate their models and receive affirmation of their thinking.

To accomplish these goals, we revised the worksheet to guide students to construct a mechanism for pulse propagation, rather than an analogy, and we changed the sequence of the worksheet so that students were asked to make predictions based on their mechanisms earlier on in the worksheet. The revised version of this worksheet begins with the tension question because we noticed that students often changed their initial models, constructed in response to the mass density question, when they reached the tension question in the preliminary version. The worksheet then guides students to consider other group members' explanations and to articulate a *mechanism* for pulse propagation based on each explanation. This version scaffolds the process of testing the explanation by guiding students to make a prediction about the mass density question based on the mechanism they constructed for the tension question. Finally, the worksheet asks students to revise their mechanism(s) and design a new experiment to further test or refine them. The revised version is included in Appendix B. We tested the revised version during the Winter 2020 term in the introductory calculus-based sequence at the University of Washington. Again, we video- and audio-recoded groups of students as they worked through the activity. Our team again watched and content-logged approximately 10 hours of video from this round of testing. With this version of the worksheet, we observed that students were less often confused about what the worksheet was asking them to do, although some groups (like the one in the case study that follows) asked questions about what a physical mechanism is. However, we observed that students were still suspicious of the open-ended nature of the worksheet. Students expressed frustration and uncertainty about how they could know their answers were correct ("I wish they would just tell us the right answer") and how they would be graded on the associated homework.

In both iterations of our testing, we noticed that instructors' guidance was significant for the progress of students' thinking over the course of this worksheet. There were multiple instances in which an instructor's intervention helped students to navigate their uncertainty in productive ways or supported students in answering their own questions in ways that refined and extended their understandings. In other instances, instructors' guidance either confused students further or affirmed notions that there was no real merit to the activity. These observations led us to posit that effective instructor preparation is important for successful implementation of our open-ended, resources-oriented instructional materials. In the following sections, we look at one aspect of what is important for successful implementation of this worksheet: the preparation and skills that may support graduate TAs in effectively responding to students' ideas and questions. In situ exploration of what is happening in class sessions where students use our worksheet affords a close look at teaching practices in real time, and so we chose a case study.

6.3 INTRODUCTION

Resources theory conceptualizes knowledge use as context-sensitive, in-the-moment activation of *resources:* cognitive units that can be of smaller grain size than a scientific concept, theory, or skill. *Learning,* in resources theory, is a cognitive process in which resources are activated, refined, and connected. Learning, then, "requires the engagement and transformation of prior productive resources" [3], which may involve reusing them in new contexts, connecting resources to one another, or changing the conditions for activation [3,31,34]. Resources theory directs instructional attention to the ways in which student thinking is sensible and fruitful in some contexts [3,31,32]. This perspective contrasts with instructional strategies that aim to address common difficulties or misconceptions [6,7], which have had a pronounced impact on university physics education in recent decades.

Examples of instructional approaches that are consistent with a resources perspective on learning are characterized by: (a) an emphasis on understanding the substance of student thinking, (b) attention to the connections between students thinking and disciplinary concepts, and (c) flexibility in pursuing student thinking in the moment [36–41]. In line with resources theory, instructional approaches of this kind aim to support students in articulating, refining, and building from their own ideas [31].

We are in the early stages of developing and testing instructional worksheets that are designed to elicit and refine common conceptual resources. These materials do not aim for a single, predetermined conceptual outcome; the goal is to facilitate the refinement of students' own thinking through metacognition and experimentation (Section 6.6 includes a more detailed description of an example). The materials are designed to be implemented in small-group sessions in university physics courses, which are often led by graduate or upper-division undergraduate teaching assistants (TAs). As we iteratively test and refine these materials, we are beginning to ask what preparation may support TAs in effectively implementing them. The answer to this question is not obvious because (i) instruction using these materials is likely different than the kind of instruction TAs have experienced [117], (ii) TAs have different preparation than the experienced K-12 teachers who are the subject of literature on resources-oriented instructional approaches, and (iii) most existing TA studies have been done in the context of materials that motivate different instructional action (e.g., Socratic questioning to address specific misunderstandings). In this paper, we present a case study to explore the question: *What knowledge, skills, or dispositions might support instructors in effectively implementing resources-oriented instruction in a university physics course?* Our aim is to inform recommendations for TA preparation in resources-oriented contexts, and to explore the extent to which the knowledge, skills, and dispositions posed by existing literature generalize to this context.

6.4 OVERVIEW OF LITERATURE

Literature on teacher professional development suggests that certain kinds of preparation support teachers in effectively implementing instructional approaches consistent with resources theory. These suggestions include: practice in noticing and responding to the substance of students' ideas [118,119], a commitment to listening to and understanding student thinking [41,120], or content knowledge that helps to see the connections between student thinking and disciplinary concepts [36,121]. However, the bulk of these suggestions have been primarily developed through the study of instructors in K-12 classrooms, who bring different expertise and training (*e.g.*, teacher certification) and respond to different sets of student expectations and content goals than typical instructors in a large university physics course.

Other literature focuses on recommendations for instructors preparing to teach with existing research-based instructional materials or approaches for university-level physics (*e.g.*, [29]). This literature emphasizes a need for both content knowledge and pedagogical content knowledge [4], which includes awareness of students' common misconceptions or difficulties, knowledge of effective pedagogical practices, and familiarity with research-based instructional materials and strategies [6,122,123]. Some research highlights the importance of instructor buy-in and appropriate epistemological framing of activities [124], or emphasizes attention to instructors' beliefs and goals [124,125]. Literature on the ISLE approach, which our worksheet resembles in its structure, emphasizes that instructors should be prepared to support students in designing experiments to test their own explanations should be committed to reserve evaluation or correction of student explanations until after students have tested their own thinking [114–116,126,127]. Because our instructional materials are informed by a different research basis or have different learning goals that other research-based materials, we anticipate that this kind of resources-oriented instruction may place different demands on instructors than other research-based instructional strategies.

The differences between (a) TAs and K-12 teachers, (b) university and K-12 instruction, and (c) existing research-based instructional materials and our resources-oriented worksheets raise questions about the degree to which existing recommendations are appropriate for resources-oriented university physics contexts with open-ended content goals. This study begins to explore what knowledge, skills, and/or dispositions university TAs need to implement resources-oriented instruction, by looking at a *case* of such instruction in our local context.

6.5 METHODOLOGY & EXCERPT SELECTION

The video data for this study was collected at the University of Washington. The university's Office of the Registrar reports that during the term in which we collected this data, the overall student population was: 54.5% female, 45.5% male; 40.6% Caucasian, 25.7% Asian, 16.8% International, 8.1% Hispanic/Latinx, 4.0% African-American, 1.1% American Indian, 0.9% Hawaiian/Pacific Islander, and 2.6% did not indicate ethnicity. The episode we selected for this study comes from a set of video-recorded small-group sessions in the calculus-based introductory physics course, which primarily serves engineering and physical science majors. These weekly, 50-minute sessions are a required part of the introductory physics course, and typically groups of students work through one worksheet from *Tutorials in Introductory Physics* [29].

In the video for this study, students worked on a preliminary worksheet developed by our team, which was designed to elicit and build on some common conceptual resources for mechanical pulse propagation that had been identified in our earlier work [48]. As we watched the video, we looked for *cases of* resources-oriented instruction [55]. Our criteria for calling an episode "resources-oriented instruction" was that it loosely satisfied the three characteristics we articulate in the Introduction.

For this analysis, we chose a 16-minute conversation between a group of three **s**tudents – **S**am, **S**arah, and **S**eung (pseudonyms) – and a graduate **t**eaching assistant – **T**homas – in which they discuss a mechanism for pulse propagation. We originally selected this clip to share in a group meeting because it was a sustained interaction between the students and instructor in which they are engaged with the physics content of this worksheet. We went on to analyze the clip more carefully because it contained clear instances in which the TA used elements of resources-oriented instruction, and because we saw the students making conceptual progress over the course of the conversation (i.e., students were learning in the context of resources-oriented instruction).

We used an inductive approach [54] that drew on elements of interaction analysis [53] to identify some of the knowledge, skills, and dispositions that Thomas brought to bear in this interaction. The analysis involved an iterative process of watching and discussing this clip in our research team, each time refining our focus toward particular interactions and characteristics [53,54]. This process led us to highlight instances where we inferred that Thomas was drawing on his knowledge of physics content and practices and where he made instructional moves consistent with particular commitments or dispositions. In Section IV, we seek to make visible the meaning we make of the interactions between Sam, Sarah, Seung, and Thomas [55].

The purpose of our analysis is to articulate some of the knowledge, skills, and dispositions that are integral to real-time deployment of instruction that is consistent with resources theory. Our aim is *hypothesis generation,* in service of local decision-making and contributions to scholarship about TA preparation. For these purposes, a case study is appropriate [55].

6.6 RESOURCES-BASED WORKSHEET

Our team developed a preliminary worksheet intended to elicit and build from common resources for mechanical pulse propagation. The worksheet is designed to be open-ended to accommodate a breadth of context-sensitive resources that students may use for making sense of propagation. The goal of the worksheet is the articulation and refinement of these resources through experimentation and metacognition, not a particular content outcome.

At the beginning of the worksheet, students observe a demonstration of a pulse generated by flicking the end of a spring up and down (experiment 1). Then, the tension is increased, and a pulse is generated using the same hand motion (experiment 2). Students are asked to explain why a pulse moves faster on a higher-tension spring, and then to find someone who has a different explanation and record both. Next, the worksheet presses students to describe the mechanism for pulse propagation that is implied by each of their explanations. Finally, students generate hypotheses based on these mechanisms for new pulse propagation experiments. The learning goal of this worksheet is that students should construct a physical mechanism from their own ideas. This mechanism should address causal questions about propagation experiments ("*why* does this happen?") by identifying the relevant physical entities and activities [107] and should support predictions about new propagation experiments. The worksheet does not guide students toward a specific, correct mechanism.

6.7 ANALYSIS

Leading up to the episode we selected, Sam, Sarah, and Seung discussed two different explanations for why increasing the tension increases the speed of a pulse on a spring. Their first explanation was based on something they recalled from lecture and focused on forces: with more tension in a spring, there is less force in the transverse direction and more force the longitudinal direction, making the pulse move faster.[11] The second explanation focused on energy and was

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[11] An explanation based on the width of the pulse and the relative magnitudes of the transverse and longitudinal components of the tension force at the leading edge of the pulse is described in the course text ([28] - see Ch. 16) and was discussed in the lecture section of the course.

suggested to the group in an earlier conversation with another TA. Specifically, the group agreed that when there is higher tension in the spring, there is more potential energy, which is then available to be converted into kinetic energy associated with the pulse's motion.

Just before the excerpt we chose, Thomas joined the group and Sarah asked what is meant when the worksheet asks for a "mechanism" for pulse propagation. Thomas responded with an example of a mechanism for why the capacitance of a parallel-plate capacitor changes as area changes. He recapped his example by saying that *the explanation for a particular outcome builds off of the underlying mechanism.* We analyze the conversation between Thomas and the students that follows as they work to articulate a specific mechanism based on their understandings of pulse propagation. In this excerpt, most of the conversation is between Thomas and Sarah, who summarizes the group's previous conversation and contributes new ideas.

6.7.1 *Seeking to understand student thinking*

In the video, Thomas appears to cut his capacitor example short before finishing, perhaps because he perceives that the example is not satisfying Sarah's question. He shifts course and asks the students what their explanations for the tension question are. This shift seems to signal a commitment to understanding and building on student thinking, because it refocuses the conversation on the students' own ideas. It is also responsive to the question the worksheet is asking – "What is the underlying mechanism implied by *your* explanation?"

Sarah answers Thomas' question by drawing on the energy explanation they discussed earlier, saying that when the spring is tauter, there is more potential energy in the system, which means there must also be more kinetic energy in the system. In response, Thomas first re-voices Sarah's idea and affirms the explanation, then he presses it further:

(1)[12] Thomas: *Okay, so you're saying as I increase the tension then that increases the potential energy, which in turn increases the kinetic energy...Okay, um, so, I think that this*

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[12] The parenthetical numbers denote line numbers in the transcript of this conversation. In the transcript excerpts included in the main body, dashes
(—) indicate pauses in dialogue. Ellipses (…) indicate the authors' editing of the transcript to remove unimportant (um, uh) or repeated utterances. Words in square brackets are the authors' inferences about inaudible parts of the video.

explanation has a lot of good stuff going for it. There's some assumptions that are in here. So why does the kinetic increase if the potential energy increases?

Thomas notices and validates Sarah's resourceful ideas about how energy affects pulse speed (which are similar to documented resources for pulse propagation [48]). His question presses into Sarah's thinking by inviting students to articulate the assumptions that their explanation makes; he is asking them to "say more," of a particular kind of thing. This move suggests a commitment[13] to understanding and building from student thinking. Thomas' question does not clearly address the question of what is meant by a mechanism for pulse propagation. However, as the conversation continues, Thomas asks questions – building on the one in line 1 – that both press into Sarah's understanding and point toward a mechanistic description of propagation:

(2) Sarah: *Because it's a closed system, so all the kinetic energy comes from the—potential energy?*
(3) Thomas: *So, but why doesn't the increased potential energy just stay as potential energy? Why does it have to become kinetic energy?*
(4) Sarah: *Because then there's no energy [moving]?*
(5) Sam: *Because it moves?*
(6) Thomas: *Because it moves. Okay we've got a question mark here but somehow, somehow potential becomes kinetic energy. Alright, um—Okay, so I think this is a good explanation, I think that the mechanism um…that you wanna explain is um, how does U get converted to K. Right, and how does T connect, or T change U.*

In this exchange, Sarah begins by stating an assumption that their energy explanation makes – the idea that potential energy turns into kinetic energy relies on the system being closed (or the energy being conserved). In response, Thomas asks *why* potential energy must become *kinetic* energy. This clarifies his question in line 1 (why does kinetic increase if potential does?) in a way that points toward a mechanistic explanation. That Thomas intends his questions to point students toward a mechanism becomes clearer in line 6: he acknowledges that the group has a good

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[13] Consistent with resources theory, we assume Thomas' knowledge, skills, and commitments may be constructed in the moment of the conversation. We do not expect that these are stable and consistently applied.

explanation that they can build from, *and* that there is room for clarification that will support a mechanistic description. These instructional moves continue to enact a commitment to understanding and building from students' own thinking.

In line 6 above, Thomas suggests that the group consider a specific mechanism that builds from the ideas Sarah has already articulated: one that explains how potential energy (U) is converted to kinetic energy (K), and how changing tension (T) changes potential energy. The connection between tension and potential energy is Thomas' addition to the conversation and suggests that he sees it as an important part of a mechanism for propagation. From this we infer that Thomas draws on knowledge that tension and potential energy depend on a shared variable. In the conversation that follows, Thomas more overtly draws on his knowledge of the forces involved in propagation as he responds to the group.

6.7.2 *Guiding toward a mechanism*

Sarah answers Thomas' suggestion to consider how tension is connected to potential energy (line 6) by saying that there's an equation that includes the spring constant (k) and displacement of the spring (Δx). Thomas names the equation for potential energy in terms of these variables ($U = \frac{1}{2} k\Delta x^2$). Then, Sarah asks:

(11) Sarah: *Is that enough, to say that, like, because the tension relies on delta x, and delta x goes up, the potential goes up, is that a mechanism?*

(12) Thomas: *yeah, so that's a mechanism for how increasing tension would increase potential energy.*

Here, we see Thomas responding directly to Sarah's question about mechanism by clarifying *what* her response is a *mechanism for,* linking back to the group's original question. This move is consistent with instructional goals of answering Sarah's questions and supporting her in refining her thinking.

Following this dialogue, Sarah double-checks that the group needs a second mechanism to answer the worksheet's question. Thomas affirms this and offers his own ideas about the mechanism for pulse propagation:

(14) Thomas: *Yeah exactly—I think it's kinda like, that next level down—So there's…this energy way of thinking about it, and then you can also approach it from like a forces standpoint, where you can think about breaking your spring down into a series of points, and looking at… the force on the individual points as the wave propagates. So you initiate the wave by pulling up on one here, and then looking at the impact that that has on the neighbors as you go down. So this is…your energy, and this is …the forces buildup…this one feels more fundamental to me.*

In this move, Thomas draws on his understanding of a mechanism for propagation as he guides the conversation: the wave is initiated by pulling up on one particle which impacts the adjacent pieces of the spring and so on. For him, a mechanism based on the forces acting on and between particles of the spring in more fundamental; it is a deeper explanation, "one level down." Importantly, the specific mechanism he articulates extends a particular concept – tension – within the mechanism that Sarah began to articulate previously ("*because the tension relies on delta x, and delta x goes up, the potential goes up"*).

Following line 14, conversation between Thomas and the students continues for three and a half more minutes as Sarah explains that the group's first explanation had to do with forces on the spring. Thomas encourages the group to come up with a mechanism for propagation based on whichever explanation they prefer, and he reiterates what a forces-based mechanism could look like. This prompts Sarah to say that she doesn't understand how to explain *why* increasing tension means there is more force in the horizontal direction and less in the vertical direction (referring to the group's original forces-based explanation for the tension question). Thomas asks for clarification about this explanation. After some discussion with Sam about the group's force-based explanation, Thomas again suggests the group think about a mechanism based on the connections between small parts of the spring. He suggests that they use this mechanism to make a prediction about the next experiment in the worksheet and says he will return to discuss the prediction.

6.8 DISCUSSION & CONCLUSIONS

In this case study we explore the question: *what knowledge, skills, or dispositions might support instructors in effectively implementing resources-oriented instruction in a university physics course?* Our analysis suggests to us that resources-oriented instruction is supported by a commitment to understanding and building from student thinking and by flexibly deployed knowledge of scientific concepts and practices. In particular, the structure and sequencing of the guidance that Thomas offers throughout the episode we analyzed is consistent with a commitment to understanding and building from students' own thinking. He gives more specific guidance toward a mechanism only after understanding and pressing into Sarah and Sam's ideas. Thomas' enactment of this kind of instruction appears to be supported by knowledge of physics content – about energy and the mechanics of pulse propagation – and practices –particularly knowledge of how mechanistic explanations are used in scientific discourse. Importantly, Thomas guides Sarah to understand what a mechanism is in a way that simultaneously presses student thinking forward and inserts elements of the scientific process.

The findings from this case study affirm suggestions from the literature that a commitment to noticing, understanding, and making disciplinary connections to and building from students' own ideas [12,17] – which has not been emphasized as much for other research-based strategies – is important for resources-oriented teaching. Our findings also affirm suggestions that relevant content knowledge is important for both resources-oriented teaching and other research-based instructional strategies [6,41,121,122]. Our analysis specifically suggests that instructors should be prepared with a breadth of content knowledge such that they can adapt this knowledge as they respond to student thinking in the moment. This case study also places emphasis on instructors' knowledge of disciplinary practices (e.g., Thomas' understanding of physical mechanisms), especially those latent in the instructional materials used.

These findings may guide decisions about how to prepare instructors to use resources-oriented instructional materials like those we are developing. In particular, this case study suggests that resources-oriented instruction may be supported by TA preparation in which TAs discuss multiple ways to think about the physics content covered in the worksheet, and what scientific practices might be used to carry student thinking forward. Investigating the most effective way to prepare instructors (including graduate TAs) to use materials like those we are developing is the subject of future work.

Chapter 7. DISCUSSION & OUTLOOK

In this dissertation I apply the tenets of resources theory to a well-established paradigm of physics education research, in which investigations of common patterns in student thinking about specific physics topics inform instructional interventions and curriculum development. First, I investigate the common, potentially-productive patterns of reasoning that introductory physics students use for mechanical wave mechanics. I also investigate how student thinking about wave propagation is sensitive to the context, particularly the framing of the physics question at hand. I begin to apply these results to classroom practice by examining how these resources may be productive for students in real time and by examining what knowledge, skills, and dispositions support instructors in enacting resources-oriented instruction. The work presented here contributes to learning theory by extending resources theory to large-N studies of patterns of student thinking; it contributes to physics instruction by illustrating a resources orientation toward student thinking, and by providing instructors with concrete information about the potentially-productive ideas that their students may use during introductory physics courses. In this chapter, I summarize the results presented in this dissertation, and I synthesize across these studies to discuss the implications of this work for research and for physics teaching. Finally, I discuss some possibilities for future research.

7.1 SUMMARY

Chapter 3 uses resources theory to frame a large-N study of student thinking about mechanical pulse propagation. We found that students in our sample commonly used three conceptual resources to reason about mechanical pulse propagation: (1) *properties of the medium either impede or facilitate the motion of the pulse;* (2) *the speed or duration of transverse motion affects pulse speed;* and (3) *the speed of the pulse is affected by its kinetic energy*. In describing these resources, we provide instructors with knowledge of some of the common, fruitful ideas that their students may use for wave propagation. More broadly, our discussion of the student responses that instantiate these three resources illustrates what it looks like to view student thinking through the lens of resources theory. We also report the frequency of students' use of each resource in the context of three different versions of a wave propagation task, providing instructors with information about physics questions that are more likely to elicit specific resources or a range of resources. These findings contribute knowledge of student ideas [4] that may support physics instructors in planning their teaching to elicit and build on students' conceptual resources and in noticing and capitalizing on students' conceptual resources in real time.

Chapter 4 formalizes and substantiates an observation that questions asking students to *explain* rather than to *predict* a mechanical waves phenomenon elicited markedly different kinds of thinking about wave phenomena. Our analysis shows that predict-style questions tend to elicit resources that resemble content-specific rules and procedures, whereas explain-style questions tend to elicit resources that resemble rules and principles *and* resources about forces, motion, and energy. This result empirically validates the assumption of resource theory that resource activation is influenced by the context, and suggests that the style of the question may be an important feature of the context for conceptual resource activation for many students. This finding has important implications for instructional design and assessment, because it (a) suggests that the style of question impacts the kinds of reasoning that instructors or researchers can expect to observe in response, and (b) informs choices about what kinds of questions may be most effective for accomplishing different instructional goals or answering different research questions. The patterns reported in this chapter suggest that predict- and explain-style questions may serve different learning goals: predict-style questions are more likely suited for goals of mastery of formal models and principles of wave mechanics, while explain-style questions are more likely to serve goals of mechanistic reasoning and engaging in discussion and debate across different scientific ideas.

Chapters 3 and 4 argue that students' conceptual resources *can be* productive for learning, and I have proposed that instruction can elicit and build from these resources. However, showing that students have ideas that may be fruitful for physics learning does not necessarily provide instructors with the support they need to shift instructional practice. To this end, Chapters 5 and 6 includes two case studies that begin to explore practical aspects of learning and teaching from a resources perspective. The first case study (Chapter 5) illustrates a concrete example of a student's conceptual resources being employed in fruitful sensemaking. The second case study (Chapter 6) examines what knowledge and commitments may support instructors in supporting students in their sensemaking process.

Chapter 5 follows the progress of one student's (Sophie's) thinking over the course of a problem-solving research interview: we analyze how Sophie's conceptual resources are productive for her in constructing a satisfying answer to a question about pulse propagation. Examining how resources can be productive for students' reasoning is an important first step in examining the process of *learning* from a resources perspective. Sophie's reasoning illustrates an example of learning as "the gradual recrafting of existing knowledge that, despite many intermediate difficulties, is eventually successful [95]." This case study suggests to us that some markers of learning in real time may include increasing sophistication of conceptual resources already activated and activation of new, more productive resources. Further, the interview with Sophie supports our notions that the conceptual resources reported in Chapter 3 are productive for constructing mechanistic models for wave propagation, and that one way to leverage these resources in instruction is to scaffold students' construction of a model for wave propagation.

Chapter 6 describes the development and preliminary testing of a worksheet on mechanical wave propagation. The worksheet described in section 6.2 is one way that the findings of Chapters 3-5 can be coordinated to support instructors in implementing resources-oriented instruction. The bulk of Chapter 6 examines a case of resources-oriented instruction in the context of this worksheet, which begins the work of assessing what makes resources-oreinted teaching effective. The case study presented in sections 6.3-6.8 suggests that an instructor's knowledge of physics content and scientific practices, along with a commitment to noticing and understanding students' ideas, may support instructors in implementing the kind of instruction we aim to encourage and support through the work presented in this dissertation.

7.2 OUTLOOK & FUTURE DIRECTIONS

This dissertation builds on very preliminary research on students conceptual resources [79] (in the context of questions about energy) that Hannah Sabo, Amy D. Robertson, and I conducted before I began my Ph.D. work. In this dissertation, I refine a methodology for characterizing the conceptual resources that students use in written responses to physics questions. This dissertation extends our previous preliminary work by looking deeper into resources' context sensitivity, by examining the fruitful nature of students' conceptual resources more closely, and by establishing an example of curriculum informed by research on common resources. In doing so, this body of work advances a framework for resources-oriented research and curriculum development that can be implemented across physics topics.

The research I present in this dissertation is aimed to support a shift in research and teaching practice toward a perspective in which student thinking is viewed as sensible and fruitful for constructing sophisticated scientific understandings. This work has the potential to support such a shift by illustrating what it looks like to apply such a perspective to students' responses to wave mechanics questions by illustrating what it may look like for resources to be used productively by students, and by suggesting an activity that builds on students' ideas. However, I do not anticipate that research in a single physics content area – wave mechanics – is enough to support a meaningful shift in introductory physics instruction. Further work characterizing students' common conceptual resources across physics topics, and curriculum development based on those studies, would enable researchers to test of the effectiveness of resources-oriented instruction on a more meaningful scale (i.e., at the level of a unit or course, rather than a single instructional activity). Quantitative demonstration of the effectiveness of resources-oriented instruction would further support its take-up in classrooms and enhance the impact of this kind of work. In this dissertation, I present theoretical groundwork and a test case for broader-scale research and development of resources-oriented curricular materials.

The results I present here open up new theoretical and practical questions about what may cue the activation of particular conceptual resources. The results of Chapters 3 and 4 both suggest that some of the wave mechanics questions that we administered to students are more likely to elicit a range of mechanistic or model-like resources, while other questions we administered are more likely to elicit rule-like or principle-like resources. This raises the theoretical question of *what* about the question context cues these different kinds of resources: for example, is it that different styles of questions cue different epistemological framings for students? Preliminary investigations by collaborators of student responses to predict-style and explain-style questions about other physics topics (e.g., circuits) suggest that the same pattern bears out in some parings, but not others. Further research could explore the nuances of what it takes for an "explain" question to cue students' mechanistic thinking or investigate whether there is a more general pattern of resource use across a broader spectrum of predict-style and explain-style questions. This kind of research would support instruction, assessment and curriculum development by informing choices about what questions are most appropriate for particular learning goals.

The research I present here, particularly in Ch. 6, also raises new questions about what instructors need in order to effectively implement resources-oriented instruction. We know that it is much more than knowledge of common resources and resource-oriented curricula that matter for instructors. While static curricular materials can provide a scaffolding for resources-oriented instruction, they do not in themselves respond to the complex, dynamic, and context-sensitive nature of student thinking. In order for this kind of research to comprehensively support adoption of resource-oriented instructional practices, it is important to understand what preparation, knowledge, and commitments support instructors in effectively implementing resource-oriented instruction. Fruitful questions for future research include: To what extent are the learning goals supported by resources-oriented instruction consistent with or complementary to common learning goals for introductory university physics? Do faculty see resources-oriented instruction as a viable option for their courses? What kinds of preparation best supports instructors in implementing resource-oriented instruction? What are high-leverage instructional practices that facilitate students' building upon, refining, and generalizing their conceptual resources? Explorations of these questions would enhance the contribution of this work by providing further insight into what effective resources-oriented teaching looks like in practice and by informing professional development for instructors who implement teaching practices based on this work.

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APPENDIX A

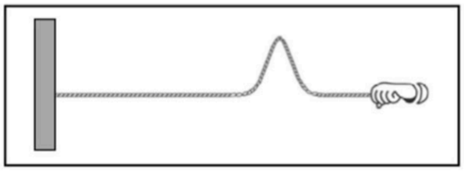
Representing Pulse Propagation Worksheet – Version 1

REPRESENTING PULSE PROPAGATION

Name:____________________________
Section:

Waves
1

The purpose of this worksheet is to help you to articulate what a pulse *is,* and what this implies about the way pulses move along springs, in a way that makes sense to you. We will begin by thinking about how changes to a spring affect the way a pulse moves, because thinking about changes to an experiment or system is a strategy that scientists often use to better understand a phenomenon.



I. Consider the following two scenarios:

Scenario 1: Your instructor creates a pulse on a spring by flicking the end of the spring, as in the figure above.

Scenario 2: Your instructor uses a heavier spring (i.e., a spring with a higher mass density) and then creates a pulse by flicking the end of the spring in the same way.

It is observed that the pulse in scenario 2 travels down the spring more slowly (i.e., has a lower speed) than the pulse in scenario 1.

(*Note that several springs are available in the classroom for you to use, if experimenting with them would help you to make sense of this phenomenon.*)

a. **Why would it make sense to you for a pulse to move more slowly on a heavier spring?** Be as thorough as possible in your explanation.

b. There are a number of different well-justified explanations for why this happens. Find someone at your table whose explanation makes sense to you, but is different than yours, and summarize their explanation here.

Often, physicists use "images" – descriptive metaphors, analogies, or representations – to describe physical phenomena. For example, a professor might use the image of a handshake to explain what a force is, because like forces, handshakes are interactions between two things that can have different "strengths," and they only exist in interaction and are experienced by both. There are usually parts of the image that don't map well onto the phenomenon itself, like the social norms that may dictate the strength or duration of the handshake.

c. What is another example of an image for a physical phenomenon or system that you have come across in physics?

d. With the person you found in (b), construct an image for pulse propagation that matches each of your explanations, and record them here.
Note that it is possible that the same image supports both explanations, or it may be that a different image best supports each explanation.

What in your image represents mass density, in particular? What represents the pulse? Why are these appropriate or analogies for mass density and the pulse?

II. In **scenario 3**, your instructor pulls the spring so that it is more taut than in scenario 1 (*i.e.,* increases the tension in the spring used in scenario 1) and then creates a pulse by flicking the end of the spring in the same way as in scenario 1. The pulse in scenario 3 travels down the spring faster (*i.e.,* has a greater speed) than the pulse in scenario 1.

a. **Why would it make sense for a pulse to move faster on a higher-tension spring?** Be as thorough as possible in your explanation.

b. Could your explanation above use the same the image for pulse propagation as your explanation in **I.a**? If it does not, articulate a new image that works for your answer in **II.a**.

c. What in the image you described above (part b) represents tension (or changes to the tension) in the spring? Why is it appropriate or helpful to represent tension in this way?

III. At this point in your thinking, you and your partner have come across between one and four images for a propagating pulse on a spring. (One if the two of you used the same image as each other, and the same image for scenarios 2 and 3. Four if you used different images from each other, and different images for scenarios 2 and 3.)

NOW, with your partner, negotiate either:

- a consensus image that you both agree on, or
- a set of images with guidelines that describe when each is useful.

Describe your image(s) in the space below. Your description should:

- clearly communicate your image(s) to other students
- say how your image represents important aspects of the pulse and the medium (for example, the tension of the string or the width of the pulse) and *why* these are appropriate representations for the aspects you think are important
- help you to predict how making a change to the hand motion, the string, or the pulse in scenario 1 will affect the speed of the pulse's propagation.

IV. With your partner, choose a change you will make to the spring or to the hand motion that generates the pulse, and use your image(s) from the previous question to predict how that change will affect the propagation speed of the pulse. Describe the change you will make and your prediction in the space below.

V. Test your prediction by doing the experiment you came up with. Do the results of your experiment agree or disagree with your prediction?

If your experiment does not work out the way you expected, consider whether this is because of a limitation of the image you used to make your prediction, or because something is happening with the equipment that limits your ability to test that prediction.

VI. Based on the results of your experiment, find at least one way to modify or refine your image for propagation. Describe your final image for pulse propagation here.

APPENDIX B

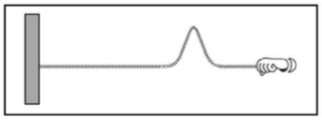
Representing Pulse Propagation Worksheet – Version 2

REPRESENTING PULSE PROPAGATION

Name:____________________________
Section:

In this worksheet, you will use what you know from your everyday life and past science classes to construct an explanation for how a pulse propagates on a spring or string. The goal is to be able to predict how, and explain why, changes to the spring or to the generation of the pulse will affect the pulse's shape and/or speed.

I. Consider the following two experiments:



Experiment 1: Your instructor creates a pulse on a spring by flicking the end of the spring, as in the figure at right.

Experiment 2: Your instructor pulls the spring so that it is more taut than in scenario 1 (*i.e.,* increases the tension in the spring) and then creates a pulse using the same hand motion as in scenario 1.

The pulse in experiment 2 travels down the spring faster (*i.e.,* has a greater speed) than the pulse in experiment 1.

(*Note that several springs are available in the classroom for you to use, if experimenting with them would help you to make sense of this phenomenon.*)

a. **Why does it make sense for a pulse to move faster on a higher-tension spring?** Be as thorough as possible in your explanation. You may find it helpful to use pictures or diagrams to communicate your explanation.

b. There are a number of different well-justified explanations for why this happens. Find someone else whose explanation makes sense to you, but is different than yours, and summarize it here.

c. Each of these explanations implies (or overtly states) a mechanism for pulse propagation – *i.e.,* how or why the pulse moves down the spring. For both of these explanations, write down what that mechanism is in the space below.

II. In Part I, you constructed an explanation for why a pulse propagates faster on a higher-tension spring, and you used your explanation to articulate a *mechanism* for pulse propagation. One goal of physics is to articulate mechanisms that can explain many different phenomena. The process for doing so is like what you will do in this worksheet: coming up with a mechanism in one experiment (Part I), and then applying and refining it in additional experiments. You'll do that next.

In a new experiment (experiment 3), you will generate a pulse using the same hand motion as experiment 1 (i.e. same speed, height, and duration of motion) on a *heavier* spring with the same tension as experiment 1.

a. What does each mechanism you described in I.c tell you will happen to the speed and/or shape of the pulse in experiment 3, as compared to experiment 1? For each prediction, use the associated mechanism to explain *why* you think this will happen. Your answer should take the form of something like, "If I think of pulse propagation as _______, then increasing the mass of the spring will mean the pulse is ______ in experiment 3, because _______."

Explain your prediction(s) to an instructor, who will help you set up experiment 3.

b. Now, conduct experiment 3. Record the details of what happens in this experiment below.

c. If the results of experiment 3 are not what you predicted in part a, how can you explain your observations? If warranted, revise your mechanism for pulse propagation so that it can account for the results of both experiments 2 and 3.

III. The goal of your next experiment is to help you improve, extend, or add detail to your mechanism for propagation.

One possibility for such an experiment would be to change something about the hand motion used to generate the pulse, keeping the tension and mass density of the spring the same as in experiment 1. (For example, what happens to the speed and shape of the pulse if the hand moves up and down twice as fast?)

Alternately, you could choose a new experiment that will help you answer a question about pulse propagation that has emerged in the course of your discussion of this worksheet.

a. With your partner or group, choose a new pulse propagation experiment to conduct.

  i. Briefly explain why you chose this experiment.

  ii. What does the mechanism you described in parts I (c) and/or II (c) predict about what will happen in this experiment and why?

Explain your prediction(s) to an instructor, who will help you set up your experiment.

b. Test your prediction by conducting this experiment. Do the results of your experiment agree or disagree with your prediction? Explain.

c. If the results of experiment 3 are not what you predicted in part a, how can you explain your observations?

d. Based on the results of your experiment, find at least one way to modify or add specificity to your mechanism for pulse propagation from parts I and II.

VITA

Lisa Goodhew was born and raised in Boulder, Colorado, whose interest in physics was sparked by how physics explained the intuitions about motion that she developed as a gymnast. Lisa graduated from Seattle Pacific University with a B.S. in Physics in 2014. She chose to return to Seattle to pursue her doctoral degree in Physics at the University of Washington, where she joined the Physics Education Group at UW. Lisa was awarded a National Science Foundation Graduate Research Fellowship to support her research on students' conceptual resources in 2016. As a graduate student Lisa taught introductory physics at Seattle Pacific University for two years, an experience which shaped the research and curriculum development that she presents here.