Students' context-sensitive use of two kinds of conceptual resources for mechanical wave reflection

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In this paper, we refine and substantiate an initial observation that different styles of conceptual physics questions (i.e., questions that ask students to explain a phenomenon versus questions that ask students to predict an outcome and explain their reasoning) elicit different kinds of conceptual resources in students' responses. We analyze the responses that students from three universities gave to written questions about reflection of mechanical pulses. Some responses draw on rules, principles, or procedures; other responses use ideas about force, energy, and motion to reason about wave phenomena. In this preliminary study, we investigate the frequency of each kind of response. We find that a question which asks students to predict the outcome of an experiment regarding mechanical wave reflection more commonly elicits ideas about rules, principles, and procedures, while a question that describes the outcome of a wave propagation experiment and asks students to explain the phenomenon more commonly elicits ideas about forces, energy, and motion.

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I. INTRODUCTION

According to resources theory, explanations and concepts are constructed from pieces of knowledge (resources) that exist in the minds of individuals [1–5]. Resources are activated in-the-moment in context-sensitive ways as they are deemed relevant [4, 5]. One affordance of this theoretical framework is that it "naturally accommodates the observed context dependence of students' reasoning" [5]. Research has validated theoretical claims of context-sensitivity primarily through case studies that showcase a single student, or a few students, using different lines of reasoning in different situations [5, 6]. While theory suggests that certain features of the question or environment may trigger the activation of certain resources, few studies have investigated patterns in context-sensitivity that bear out across students, or whether some features of the context tend to elicit particular kinds of resources.

In this paper, we demonstrate that two physics questions on the same phenomenon (a mechanical wave reflecting at a fixed end) elicit responses that draw on different types of resources. In a larger investigation of students' conceptual resources for understanding mechanical waves, we asked physics questions that can be broadly characterized as two types: (a) questions that ask students to make a prediction about the outcome of an experiment and to 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). We initially observed that students gave strikingly different answers to "predict" and "explain" questions about mechanical wave propagation, superposition, and reflection, which led us to more closely examine - and seek to characterize - these differences. Through our initial observations, we formed 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). Here, we describe a study to refine and test this hypothesis. Our preliminary results affirm our hypothesis.

II. RESOURCES

The resources theoretical framework models student thinking in terms of context-sensitive activation of pieces of knowledge that exist in the minds of individuals. "Context," in this case, may include features of the question at hand and/or the social setting in which the question is asked [4, 5, 7, 8]. Thinking involves activating a variety of resources of different kinds (e.g., conceptual, epistemological, and procedural) and the activation of these resources is intertwined [6, 7, 9]. Thus, the activation of different epistemological resources may, for example, cue the activation of different conceptual resources.

Resources in themselves are not truth-determinate (they are not inherently correct or incorrect). Resources are derived from students' prior experience and learning, and they are sensible - i.e., students have good reason for using them as they do [1–3]. Resources theory proposes that learning involves increasing the degree of formality of resources, limiting or extending the context for activation of resources, or strengthening networks of connection between resources [5, 10]. That is, learning involves building from the resources that already exist in the student's mind. Thus, the resources framework suggests that even canonically incorrect ideas can be fruitful for learning.

In this paper, we draw on resources theory by attending to the pieces of students' knowledge that we, as physicists, deem appropriate or relevant for questions about reflection of mechanical pulses, even if incomplete or incorrect [8]. We assume that students' ideas are sensible and that they may be generative for physics learning. Further, we draw on resources theory in our expectation that students may activate different conceptual resources based on their prior experiences and learning, the question asked, and the setting the question is asked in. We do not assume that written responses 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.

III. QUESTION DESIGN AND ADMINISTRATION

In this study we analyze students' responses to two written questions about the reflection of a pulse at a fixed end of a string or spring. One question, the *cups* question, asked students to predict whether any of a row of paper cups, arranged on either side near the end of a spring, would be knocked over as a pulse reflects from the fixed end (Fig. 1). The question also asked students to explain their reasoning. This scenario is quite similar to a demonstration that students observe at the end of a Tutorial in Introductory Physics [11] on superposition and reflection. The second question, the *reflection mechanism* question, presented students with diagrams that illustrate a simple pulse reflecting at a fixed end of the string (Fig.2). The question asked students to explain the observed phenomenon: why would it make sense for the reflected pulse to be inverted at a fixed end?

These questions were given to a total of 629 students in introductory, calculus-based physics courses at three universities: University of Washington - Seattle, Baylor University, and California Polytechnic State University San Luis Obispo. In all courses, these questions were given after coverage of mechanical wave propagation and reflection in the course. The *cups* and *reflection mechanism* questions were given in different courses (i.e., to entirely different students) at each university. The course structure and content coverage varied across the courses in which they were administered at each university, and in most cases these courses were taught by different instructors. The questions were graded differently

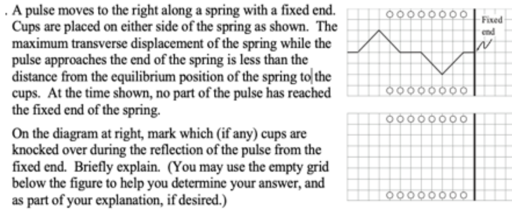

FIG. 1. The *cups question*.

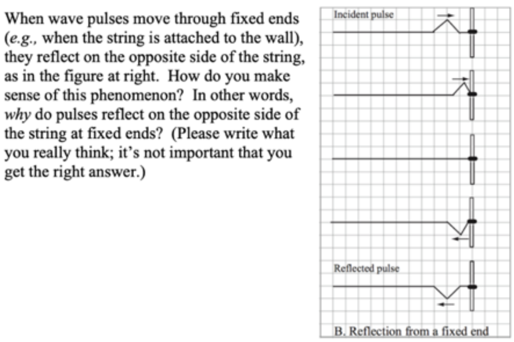

FIG. 2. The *reflection mechanism question*.

in different courses; in some, the questions were graded for completeness rather than correctness, and in other cases these questions were graded for correct answer and explanation. We address this variation in Section VI, and Table I provides additional details about the sample.

IV. METHODS

This investigation was motivated by our initial observation that the *reflection mechanism* question tended to elicit explanatory or mechanistic responses (e.g., many students gave narrative or multi-step responses that drew on a variety of physics concepts) and that the *cups* question tended to elicit rule-based or procedural responses (many students cited relevant principles and steps that supported their predictions about the outcome of the experiment). This observation provided an initial, rough coding scheme.

We then iteratively refined our scheme by applying it to small subsets of responses to each question and articulating the salient features of, and differences between, these two kinds of responses. This led us to a coding scheme with two codes: (1) resources about rules, principles, or procedures (RP) for superposition and reflection, and (2) resources about forces, energy, and motion (FEM). The first category (RP) encompassed statements of principles or models for reflection and procedures for making a prediction. The second category (FEM) encompassed ideas about force interactions between parts of the string or pulse and the boundary; about the motion or the string and/or boundary; or about energy conservation, transfers, or transformations during reflection. We did not code ideas that were either phrased as rules or procedures, or that used language of force, energy, or motion, but bore no clear connection to the reflection phenomenon. The two categories are illustrated in the following section.

Authors LMG and ADR independently coded student responses to each question using this scheme. A single response could receive no codes, one code, or both codes (the latter if a student issued separate lines of reasoning). We compared the codes separately assigned to each response, noting whether the two coders agreed or disagreed on each code. As a measure of agreement between the two coders, we took the normalized difference between the total number of codes possible and the total number of disagreements between the two coders, represented by:

$$1 - \frac{n_{\mathrm{totaldisagreements}}}{(n_{\mathrm{possiblecodes}})(n_{\mathrm{codedresponses}})}$$

For example, 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 fractional agreement of 0.50. Our fractional agreement for the entire data set was 0.93.

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

TABLE I. Question administration.

University	Question	Sample size	Fraction of course participating
CPSLO	Cups	24	65%
	Reflection Mechanism	69	96%
UW	Cups	140	78%
	Reflection Mechanism	128	72%
Baylor	Cups	99	79%
	Reflection Mechanism	169	80%

V. TWO CATEGORIES OF STUDENT RESOURCES

In this section, we illustrate the two categories of responses with examples from our data.

A. Rules, principles, and procedures

Responses in the RP category use resources that are (parts of) rules, principles, or procedures that are specific to situations involving reflection. These responses often take the form of "if-then" or "when x then y," statements. Or, they state principles, models, or problem-solving procedures as given. Examples include:

"[It is a] fixed end, so we can think of interference w/ another wave moving left that is upside-down and left-right reflected."

"The third cup from the right side is knocked down because the 1st pulse is inverted after a fixed end and has superposition with the 2nd pulse to do."

These responses both explain their prediction by citing the rule that at a fixed end, the reflected pulse is inverted. Other students answer the cups question by modeling reflection at a fixed end as the superposition of the incident pulse and an imaginary, inverted pulse moving toward the fixed end from the other side of the boundary. For example:

"...It is similar to having an inverse wave approaching the incident wave in the other direction w/ the same speed. We move both waves 5m and add the interaction."

"I drew an imaginary wave coming from the other side and had it propagate through. I then superimposed the two waves to get the final wave."

"Since the end is fixed, we can draw an imaginary pulse that is left-right reflected and up-down reflected. That way, by superposition, the fixed end never moves."

The first response references the imaginary pulse model, saying that the reflection at the fixed end is like the superposition of the incident pulse and its inverted mirror image. The second response also references an imaginary pulse and then describes how to use this model to determine the shape of the spring during reflection. The third response adds to the model by explaining that the inverted imaginary pulse means the boundary point is never displaced.

Other responses in the RP category explain how they determined the shape of the spring during reflection by describing a procedure, as in this example:

"From adding the blocks up (positive = + and negative = –, like 2+2=4 and -2+-2=-4 blocks)"

This response implies that the shape of the spring during reflection can be found by adding the displacements of the incident and reflected pulses (as measured by blocks or grid squares in the figure accompanying the question). The displacements above and below the horizontal equilibrium are treated as having opposite signs.

Common across these examples, and other responses in the RP category, is that they state rules, models, or procedures for reflection at a boundary. These responses rely on pieces of knowledge that are specifically relevant to superposition and reflection of pulses or waves.

B. Forces, energy, and motion

Responses in the FEM category discuss the forces acting on the pulse or the medium during reflection, the motion of the pulse or medium, or energy transfers and transformations that take place as the pulse is reflected at the boundary. Examples of force-type FEM answers include:

"Because the string is attached to the wall, it pushes on the wall once the wave reaches it. The wall pushes back on the string with an equal and opposite force, which causes the wave to be reflected on the other side..."

"As the incident pulse reaches the fixed end, the reaction forces at the anchor point exert forces in the exact same pattern and in the opposite direction as the forces that caused the incident pulse. The effect is a pulse that has the same shape but opposite direction."

These examples explain fixed-end reflection using forces ideas: the pulse pulls up on the fixed end, and the end exerts an opposing force, causing the pulse to be reflected on the other side of the spring. Other FEM responses explain fixed-end reflection using ideas about energy conservation or energy transfers and transformations:

"The pulse on a string with a fixed end transfers the energy from the pulse into the...fixed end. The energy that remains is sent through a reflected pulse on the opposite side (creates the potential for a standing wave)."

This response uses energy conservation and tracking to make sense of why a pulse is inverted when it reflects at a fixed end. Although this response is incorrect - no work is done by the string on the fixed endpoint, and thus no energy is transferred - this response nonetheless makes use of a foundational physics idea (energy) to construct an explanation for fixed-end reflection.

Other responses in the FEM category explain fixed-end reflection using ideas about the motion of the spring as the pulse propagates and reflects, as in this example:

"Any medium through which a [pulse] propagates...is always trying to return to the equilibrium position; as a pulse reaches a fixed end and tries to move the end in the direction of transverse displacement, there is a large acceleration in the opposite direction, initiating a pulse on the opposite side of the string."

This response is similar to responses using third-law-esque ideas, but it considers the motion of the medium rather than the forces on or by the endpoint.

Common to these responses and others in the FEM category is the fact that they apply foundational ideas about force, energy, and motion to explain reflection of mechanical pulses. We notice that many of the responses assigned this code give mechanistic explanations that chain together multiple causal steps or describe the relevant underlying structure of the medium and boundary to construct their explanations [12].

VI. FRACTION OF RESPONSES INSTANTIATING EACH CATEGORY

Fig. 3 shows the fraction of responses to each question that we assigned each resource code. The bar graphs substantiate our claim: in this study, the predict-type question (the *cups* question) elicited exclusively RP resources (dark shaded bars), while the explain-type question (the *reflection mechanism* question) elicited both FEM (light bars) and RP resources, with FEM resources being elicited at higher frequency. This pattern reproduces across all three universities. The courses we sampled from were taught by different instructors, using different texts and course structures and with different content emphases. The fact that similar patterns emerge despite variation in instruction suggests that the dif-

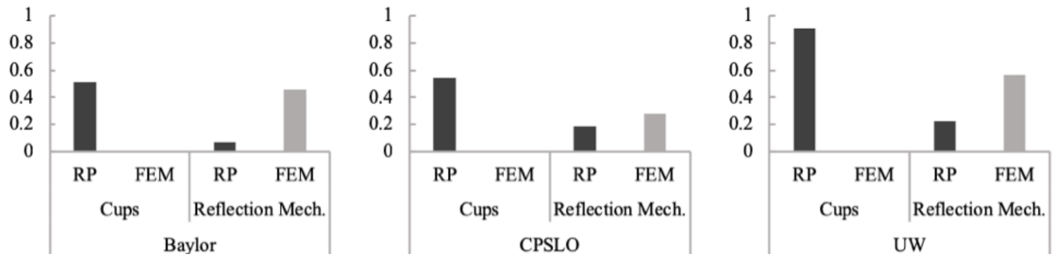

FIG. 3. Fraction of responses assigned each code in response to each question. From left: fractions at Baylor, CPSLO, and UW.

ferent patterns we see for the cups and reflection mechanism questions are explained, at least in part, by 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 [14]?

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. The two courses sampled at Baylor University were taught by the same experienced instructor, one year apart; they used the same text and followed the same instructional sequence, and the questions were graded according to the same standards. However, we see that the patterns in responses at Baylor resemble the patterns at the other institutions, where there was more variation in instruction and grading. Hence this counterargument does not fully explain the observed patterns.

This is not to say that we think the instruction students received had no impact on the use of RP and FEM resources. At UW, for example, students received both lecture and Tutorials instruction on reflection at fixed and free ends of strings, and they observed demonstrations similar to the *cups* question as they worked through a Tutorial that emphasized the "imaginary pulse" model for reflection at a boundary. This may explain why the fraction of students using RP resources, particularly in response to the *cups* question, is higher at UW than at the other universities.

VII. DISCUSSION AND CONCLUSIONS

One possible explanation for the patterns we observe - that "predict" questions tend to elicit RP resources and "explain" questions tend to elicit both RP and FEM resources, with the latter at higher frequency - is the epistemological framing of each question. 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 [2]. If the two questions communicate different things about what counts as an answer (i.e., communicate different epistemological framings and activate different epistemological resources), it makes sense that students will use different kinds of conceptual resources.

The analysis we present here showcases a recurring pattern in the kinds of resources students use, in the context of one "predict" and one "explain" question about mechanical pulse reflection. Whether similar patterns emerge in different content areas (e.g., electrostatics or thermodynamics) is a question to be explored in future work. However, our preliminary analyses of similar "predict" and "explain" questions about wave propagation and superposition suggest that similar patterns emerge for other wave mechanics topics. Thus, we have reason to think that these patterns are not specific to the two questions we have discussed in this paper.

Our results call attention to the impact that the style of question has on the kind of knowledge that students demonstrate in response. It is common in physics education and PER to use predict-style questions to assess student understanding. For example, conceptual inventories such as the FCI [13] or Waves Diagnostic Test [14] almost exclusively use predict-style questions. Our results demonstrate that such questions can prime students to apply principles and models to concrete physical scenarios; this highlights a way in which predict-style questions can be useful assessment tools. However, our results suggest that such assessments may overlook students' ability to use the fundamental physics ideas of force, energy, and motion to sense-make about complex physics questions. Physics education researchers have called for greater attention to students' mechanistic reasoning [15], which often consists of chaining together these fundamental concepts. Our results suggest that researchers and instructors who prioritize mechanistic reasoning might incorporate explain-style questions into their teaching or assessments.

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