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Analyzing learning during Peer Instruction dialogues: A resource activation framework

Anna K. Wood,[1,*] Ross K. Galloway,[2] Judy Hardy,[2] and Christine M. Sinclair[1]

[1]*Moray House, School of Education, University of Edinburgh, Edinburgh EH8 8AQ, United Kingdom*
[2]*Physics Education Research Group, School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*

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Peer Instruction (PI) is an evidence based pedagogy commonly used in undergraduate physics instruction. When asked questions designed to test conceptual understanding, it has been observed that the proportion of students choosing the correct answer increases following peer discussion; however, relatively little is known about what takes place during these discussions or how they are beneficial to the processes of learning physics [M. C. James and S. Willoughby, *Am. J. Phys.* 79, 123 (2011)]. In this paper a framework for analyzing PI discussions developed through the lens of the “resources model” [D. Hammer, *Am. J. Phys.* 64, 1316 (1996); D. Hammer *et al.*, *Information Age Publishing* (2005)] is proposed. A central hypothesis for this framework is that the dialogue with peers plays a crucial role in activating appropriate cognitive resources, enabling the students to see the problem differently, and therefore to answer the questions correctly. This framework is used to gain greater insights into the PI discussions of first year undergraduate physics students at the University of Edinburgh, UK, which were recorded using Livescribe Smartpens. Analysis of the dialogues revealed three different types of resource activation corresponding to increasing cognitive grain size. These were activation of knowledge elements, activation of linkages between knowledge elements, and activation of control structures (epistemic games and epistemological frames). Three case studies are examined to illustrate the role that peer dialogue plays in the activation of these cognitive resources in a PI session. The implications for pedagogical practice are discussed.

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I. INTRODUCTION

Understanding how emerging technologies and associated pedagogies impact on student learning is a major goal of physics education research and is vital to ensure that they are implemented in a way which provides optimal benefit to students.

One technology increasingly common in undergraduate physics instruction is electronic voting systems (EVS) [1], which create the opportunity for interactive engagement during lectures, provide lecturers with instant feedback about the level of understanding of the students, and have been associated with large learning gains [2,3]. One pedagogy commonly used in conjunction with EVS is Peer Instruction (PI) developed by Mazur and Hilborn [4]. In PI students are presented with a multiple choice question designed to probe their conceptual understanding which they answer without discussion. If the results indicate a range of opinions, the students discuss the question in small groups, and are then asked to vote again, changing their answer if they wish. It has been shown that in PI sessions a higher proportion of students select the correct answer following the opportunity to discuss the question with their peers [5], suggesting that peer dialogue plays an important role in developing conceptual understanding. However, very little is known about what takes place during PI discussions and how they might influence learning.

In this research PI discussions between first year undergraduate physics students at the University of Edinburgh, UK, were recorded using Livescribe Smartpens that capture electronically both sound and written notes. By also recording the voting data through the technical capabilities of the EVS, we were able to study learning from two perspectives: probing the conceptual understanding of individual students through voting data, and studying the *process* of conceptual development during social interaction with peers, through recorded conversations.

The underlying hypothesis of this work is that thinking about the dialogue during a PI session in terms of the resources that have been activated can give some insights into how conceptual development takes place. A framework for understanding the dialogue, adapted from the resources model [6,7], was developed and then used to analyze recorded PI conversations.

*anna.k.wood@talktalk.net

II. BACKGROUND

A. Resources model

The resources model of learning, developed by Hammer and Redish [6–8], aims to provide a way to describe students' thinking and problem solving in the context of physics. A central idea is that units of knowledge (knowledge elements), which can be both declarative and procedural knowledge, link together to form larger "knowledge structures." These knowledge structures can be activated in response to inputs from the environment such as situational and contextual factors. Together, the knowledge elements, knowledge structures, and the control structures that determine when they are activated are known generally as "resources."

The associations between different units of knowledge and knowledge structures can vary in strength, and learning is conceptualized as a process of developing "patterns of association" [8], by which appropriate associations are strengthened, allowing the creation of higher level structures, while inappropriate associations are weakened.

A central tenet of the resource model is that when a student is struggling to solve a problem, it is often not that they do not know the relevant science, but rather that the cognitive resources that they need have not been activated. This contrasts sharply with the idea that students have misconceptions, an idea which has dominated much of physics education research in recent years. Rather than viewing an incorrect answer as a misconception, proponents of the resources model argue that the student is simply applying conceptions that are not appropriate for the given problem, but which may be useful in a different context.

Both Tuminaro and Redish [8] and Bing and Redish [9] have used the resources model to successfully analyze the strategies that students use and the difficulties that they have in solving physics problems. Two important ideas are developed in their research that are relevant here. The first is the idea of epistemic games (e-games) introduced by Tuminaro and Redish, which they define as "an activation of a pattern of resources that can be associated with a collection of resources" [8]. The second is the concept of epistemological frames, which is the student's judgement about what classes of tools are appropriate to use in a particular context [9].

B. Theoretical approach

Although approaches to science education have traditionally taken a purely cognitive view of learning, the importance of the social dimension is now being recognized. The resources model, focusing on the changes that take place in an individual student's head, is an example of the former. The model does, however, take into account the contextual and situational factors involved in learning and is therefore particularly suited to being integrated within a sociocultural perspective.

The aim of this research was to understand the learning that takes place during Peer Instruction (PI) dialogues. This involved gaining insights into the *processes* of conceptual development which take place during a PI session. The resources model, which focuses on analyzing students' thinking (as demonstrated by Tuminaro and Redish [8] and Bing and Redish [9] in the context of physics problem solving), was used as a starting point for the development of our framework. However, although group dialogues were used in the research by Tuminaro and Redish [8] and Bing and Redish [9], they used the dialogues as evidence of how a student was thinking at any moment in time. Here the aim was to take a more dynamic approach in which dialogue is viewed as an active agent in the cognitive changes that take place. The theoretical framework in this work therefore adapts the resources model by combining aspects of the cognitive approach with sociocultural theory.

This paper is organized as follows. First the theoretical framework that underpins this work will be discussed. This is followed by a description of the methodology for the research. Three case studies will then be used to illustrate the types of resource activation found in the dialogues, and, finally, the implications for physics learning and instruction will be discussed.

III. ACTIVATION FRAMEWORK

There are two main theoretical approaches found in the physics education research literature: the cognitivist approach, in which learning is considered to take place mostly in the head, and which focuses on the individual; and sociocultural theory, which focuses on the role that context, and social and cultural factors have in the processes of learning. In order to develop a framework for analyzing the complex process of learning during PI sessions it is necessary to bring these two approaches together.

Although it has been argued that these two perspectives are incommensurate [10] others believe that they can be made to work together to form a description of learning [11,12]. Indeed, Otero argues that the two perspectives "must be considered simultaneously as interacting features that define the process of learning science" [13]. It is this approach that will guide the theoretical perspective taken in this research. First, an overview of the key elements of each perspective as they relate to this research is given.

A. Cognitivist approach

The cognitivist approach is concerned with how an individual learns and therefore focuses on what is going on in their head during the process of learning. Although it is acknowledged that interactions with the world influence these mental processes, they are considered to be passive, in contrast to the brain, which is considered the "active agent" in learning [14]. The resources model therefore fits squarely into this perspective; although the influence of the context of the situation is important, the model focuses on the impact that it has at an individual, cognitive level.

The idea that students construct knowledge based on what they already know is the dominant paradigm in modern educational theory. In the cognitivist perspective, influenced particularly by the ideas of Piaget, knowledge construction results from learners' physical interactions with the world around them. Piaget proposed the existence of cognitive schemes which must adapt through processes of assimilation (when new knowledge is incorporated into existing schema), accommodation (where existing schema need to be rearranged to cope with new information), and equilibration (resolving of conflict produced when new experiences are different from prior beliefs) in order for intellectual growth to occur. Posner later brought together Piagetian concepts of accommodation and assimilation, with work by Ausubel (in Scott, Leach, and Asoko [15]) which recognized that prior knowledge influences learning, to develop conceptual change theory (Posner in Özdemir and Clark [16]).

Peer interactions within cognitive research tend to focus on using the dialogue as evidence of what a student is thinking at any given moment. If social interactions are considered, then they are interpreted through Piagetian ideas, such as the process of equilibration, which implies that learners need to encounter beliefs that differ from their existing ones. Although Piaget himself did not expand on this, others developed this idea into the concept of socio-cognitive conflict, which holds that learners benefit from coming into contact with people who hold conflicting views. This is particularly important in science education as cognitive conflict is thought to catalyze conceptual change [17].

B. Sociocultural theory

In contrast to cognitive theory, where if the world outside the head is considered at all, it is considered to be a passive influence on cognition, in sociocultural theory the context is seen as central and plays an active role in learning.

The Russian psychologist Lev Vygotsky is credited with providing the foundation stone for this view of learning. Vygotsky made explicit an association between communication and thinking—most notably asserting that higher-order thinking is mediated by signs and symbols (for example, language). In his view higher mental processes can only be formed through social interactions; in other words, it is through communication that ideas in the inter-psychological social plane are able to become part of the individual, intrapersonal plane [18]. This idea is often used when discussing how learning takes place through social interactions such as Peer Instruction.

Bakhtin also focused on the importance of social interaction and mediated learning, but took a slightly different approach from that of Vygotsky. Wegerif [19] describes Vygotsky's approach as essentially dialectic, in which the principal aim of the interaction is to arrive at a single agreed meaning, while Bakhtin's is dialogic, where meaning arises through the different perspectives of each voice.

Bakhtin's notions of the dialogic in which voices "interanimate" is particularly useful for describing how learning evolves during peer collaboration. Another key aspect of Bakhtin's dialogic approach is that it views the main mechanism for learning as taking the perspective of another [20]. A reanalysis of Mercer *et al.*'s experimental studies, in which students were taught to use "exploratory talk" when working in groups, came to the conclusion that the improvement in reasoning was due to the increased capacity to take the perspective of the others [20]. This idea is particularly relevant to the present research, which is investigating how the ideas expressed by one student are taken up by, and then result in, changes in the thinking of her fellow students.

C. The approach in this study

The approach taken here combines cognitive and sociocultural perspectives and follows from Otero [14], who argue that the context of a learning situation is not static, but transformed by and through cognitive changes that occur during the learning process. Otero found, for example, that changes in the students' conceptual framework result in changes in the social and material learning environment and vice versa.

This dynamic view of context is also described by Augier, Shariq, and Vendelø [21], who argues that the context itself changes during group problem solving. Drawing on the ideas of Polanyi they explore how context is a shared experience and yet interpreted differently by each individual, depending on their past knowledge and experience.

Applying these ideas to a resource activation perspective leads to the idea that the resources that have been activated in an individual at any particular time will be a constituent part of the social context of the situation. Indeed, Hammer hints at this idea when he proposes that the resources framework

> *"provides a mechanism by which elements of an individual's mind interact with elements of the social and physical environment to create knowledge that's situated or even distributed" [6].*

In this way the voices of the participants interanimate with each other, creating a shared social context, but one which is interpreted differently by each individual. The ideas expressed during the discussion (on the social plane) then in turn affect the resources that are activated within each individual (on the personal plane). The context is therefore dynamic, both changing and being changed by the resources that are activated, the group dialogue, and the interactions between the two.

IV. CONTEXT AND METHODOLOGY

A. Context

In this research undergraduate physics students' conversations during Peer Instruction at the University of Edinburgh, UK, were analyzed. The University of Edinburgh Physics course has a history of using research-supported, innovative pedagogy and has used EVS for a number of years [5]. It uses an inverted or "flipped" approach [22] in which course material is delivered to students in advance of the lectures through both electronic resources and text books. Lectures are then predominantly focused on problem solving and discussions through the use of Peer Instruction (PI). The course is calculus based and typical class sizes are 200–300 students, with a gender ratio of around 80:20 males to females. Approximately half the class are majors, intending to complete a physics degree, with the remaining students being nonmajors from predominantly (but not exclusively) other STEM disciplines. The class is taught as a single section with majors and nonmajors together. It should be noted, that, in terms of prior educational qualifications, the nonmajors are as well qualified as the majors: all members of the class must have satisfied the entrance requirements for the physics degree program.

B. Study design

This research took a case-study based approach. Data collection took place during a first year, semester two course, "The stuff of the Universe," which includes topics on matter as waves and particles, and an introduction to quantum mechanics. Approximately 200 students are enrolled in the course.

Students were asked to volunteer in small groups in order to help ensure that all the students who were being recorded had agreed to be part of the study. As participation was purely voluntary it was not possible to influence the demographics of the research group; however, the gender balance, approximately 20% female, 80% male, was similar to that of the class as a whole.

Data were collected using smartpens which capture electronically both sound and written notes. Three lectures held one week apart and containing a total of seven separate PI sessions were recorded. A total of 53 students were recorded over the three lectures. At each lecture approximately 7 groups were recorded, each consisting of between 2 and 4 students, giving a total of 20 distinct groups for the research as a whole.

In addition to the smartpen data, students' votes using the EVS were recorded. This meant that in many cases it was possible to match a given student conversation to how they voted in each question.

C. Smartpens

Smartpens were used to capture both students' written notes and their dialogues. Smartpens are normally promoted for their educational benefits, although their use in research similar to the present study has also been reported [23].

Using smartpens for this sort of research activities has a number of advantages over traditional microphones: they are portable, discreet and need no installation. In particular, they allowed us to record the written notes that students made (pencasts), which could then be viewed in real time as a video alongside the audio recording. This is a unique feature of the smartpens that allowed us to get additional insights into the processes taking place during PI, which would not be possible to capture using any other technologies. An example of this is discussed in case study 2.

It was also hoped that the smartpens' similarity to an everyday object would mean that students would quickly forget that they were being recorded, enabling us to obtain conversations that were as authentic and natural as possible. To a certain extent there is evidence that this was achieved; students, particularly later in the research, discussed a range of nonphysics related subjects (such as personal relationships) that they are unlikely to have done if they were conscious of being recorded.

D. Data analysis

Conversations were transcribed and coded as described below. Initially, conversations in which there was a change in how a student voted (from prediscussion to postdiscussion, as recorded with the EVS) were prioritized for transcription. However, during the course of the project we realized that the conversations in which there had been no change in the way that students voted were also rich sources of data. For example, resource activation was observed both in groups in which there was no change in vote because the students had already gotten the answer correct before the discussion and in groups where the students stayed with their incorrect answer, even after the discussion. For this reason, the final data set included conversations where students changed their vote, as well as discussions where students did not change their vote. In total, 25 complete conversations were transcribed. This provided enough data to be confident that the categories were representative of the PI conversations that took place.

It should be noted that it was not always possible to know how all the students in the group voted. This happened for a number of reasons; the groups were not fixed, even during a PI session, and it was common for students to join in conversations with nearby groups, or for students without smartpens to join a group of students being recorded. In addition, on a number of occasions the EVS system failed to record a vote, and occasionally students themselves forgot to place a vote. It was also difficult in some cases to accurately match the speaker to the smartpen and therefore to their voting data. However, as the discussion below shows, a major finding of the research was that how a student votes is not necessarily a good indicator either of what they know or of what learning has taken place. The connection between student votes and student conversations is therefore not a vital link for making sense of our findings.

Once the data had been transcribed they were coded for evidence of activation as detailed below. The codes used initially emerged from definitions in the literature previously observed in practice by the authors (described in Sect. V). Codes were then developed to categorize the different types of activation observed, and the transcripts were analyzed again using these codes, which were changed or updated as necessary. At each stage of the process we checked our understanding with one another and found that after discussion we were able to agree on how the codes should be allocated. This approach enabled the differing expertise and experiences of each member of the project team to contribute to the consensus, resulting in a richer interpretation about the meaning of the data than could be achieved by any one person working alone. The main researcher (AW) was a student in the School of Education with a background in physics. She undertook the first round of coding and this was then refined through discussions with the other three authors who were all equally and actively involved. RG and JH brought expertise in teaching physics and researching student learning from within the School of Physics. The contributions of RG, who was also the lecturer on the course in this study, brought a particularly useful teacher perspective to the analysis. In contrast, CS has expertise in broader areas of education, student learning, and dialogue analysis.

We used a grounded theory approach to analyze the conversations, based on Strauss and Corbin's later descriptions of the methodology [24]. The analysis of the dialogues was also influenced by various styles of discourse analysis, including the work of Barnes and Todd [25], Mercer [26], and Lemke [27], and was underpinned by the theoretical approaches of Vygotsky and Bakhtin.

Three case studies that are representative of the data and illustrate the different types of resource activation found were chosen for inclusion in this paper and are discussed below.

E. Unit of analysis

The initial inspiration for this work was the resources model developed by Hammer and Redish [6,7] and extended by others, for example, Tuminaro and Redish [8]. However, while Tuminaro's unit of analysis was the type and nature of resources (such as e-games) that students may use during problem solving at any given moment in time, the focus in the present work is on how and why those particular resources become activated, in other words the *process* of activation. There is a shift in emphasis here from something that is intrinsically static (a resource) to something that is dynamic (the process of activation).

One issue that arose during this research was, therefore, how to decide what did and what did not count as activation. The ideas found in Lotman's functional dualism, which describes the two basic functions of texts, helped to highlight the difficulties of this problem.

Lotman (1988 in Wertsch [28]), building on Vygotsky and Bakhtin's work, describes how texts can have two functions, the univocal, which is where the text simply aims to convey a meaning adequately, and the dialogic, where the aim of the text is to generate new meanings. This seems to describe the dichotomy of the dialogues quite well, in that sometimes what the students say can be interpreted as simply as them expressing their thoughts and sometimes as generating a change in understanding (in themselves and in others).

This led to the idea that key to the unit of analysis would be evidence of *change*. In most cases this was identified as an activating event followed by some evidence that a change in thinking had occurred. For example, from the thermodynamics dialogue, which will be discussed in more detail in case study 1:

> *Student 1: The work done on the gas, that means the work done by the gas is negative*

> *Student 2: I think you're probably right, ohh, yeah, I'm a fool. Yep*

In this case both the words and the tone of voice of student 2 indicate that a change in thinking has occurred. Student 1's statement is therefore classified as an activating event.

Initially, dialogue was the sole focus of the study, but as the research progressed it became evident that the wider context of the situation was important. The unit of analysis was therefore extended to encompass any event that could influence a student's thinking, such as the wording of the question. An example of this is discussed in case study 3.

V. RESOURCE ACTIVATION TYPES

In order to analyze the types of resource activation present in the dialogues, it is first necessary to define in more detail what is meant by resources. Tuminaro and Redish [8] present a detailed definition of resources as part of the resources model, which we used as the starting point for our analysis. Their description consists of three resource types: *knowledge elements* is used to describe knowledge held in long term memory, and includes both declarative and procedural knowledge; the linking patterns of association between these elements are known as *knowledge structures*; and the function that determines when these are activated are *control structures* [8].

This definition was used as a starting point for analyzing the PI data. The focus in this research is not on the resources themselves, but rather the interaction between types of resource and activation. The categories therefore represent the resources through which activation is observed. After an iterative process of data analysis three broad categories emerged from the data:

- Activation through knowledge elements
- Activation through linkages between resources
- Activation through control structures

Examples of activation occurred in approximately 50% of the dialogues transcribed. Sufficient recordings of each PI question were made and transcribed, such that there was at least one example of activation resulting from each question. A description of each category is developed below and each type of activation will be discussed in detail through the examples give in each of the three case studies.

It is noted that the three categories of resource activation correspond to increasing cognitive grain sizes. The smallest category is knowledge elements, the next largest are the links that form between these knowledge elements, and the largest cognitive structures are control structures that allow groups of resources to be activated together.

It is known that novices and experts organize and retrieve their knowledge differently; for example, the research of Chi, Feltovich, and Glaser [29] on problem categorization showed that novices and experts differ in the features of a problem that they pay attention to: experts see the problem in terms of the underlying physics, whereas novices focus on the surface features of a problem. Experts are also better able to see patterns, which enables them to "chunk" information together. This implies that larger bodies of resources can be activated as a whole. This idea fits with the finding that different categories of resource activation, corresponding to different cognitive grain size, are found in the PI data. The implication here is that different types of resource activation will be beneficial to a given student, depending on how advanced they are in that particular topic or concept. That is, where the student is on the novice-expert continuum (in a given topic) will affect what type of resources can become activated.

A. Category 1: Activation of knowledge elements

Knowledge elements is a general term, used here to refer to small cognitive structures that are stored in long term memory. Here, a knowledge element includes any piece of scientific information or a scientific relationship that students use in their discussions. The idea is highly influenced by the concept of facets, proposed by Minstrell and Stimpson, which they define as a "convenient unit of thought, a piece of knowledge or a strategy seemingly used by the student in addressing a particular situation" [30].

The analysis of the PI discussions found a number of examples of activation through knowledge elements, and an example will be discussed in case study 1.

B. Category 2: Activation of linkages between resources

The second category is activating links between these different knowledge elements. This category was highly influenced by the framework of "pedagogical link making" developed by Scott, Mortimer, and Ametller [31], which discusses the types of links that they believe need to be built for learning to be effective. These are links to (a) support knowledge building, (b) support continuity, and (c) encourage emotional engagement. The first category, links to support knowledge building, contains six different approaches to link making that are particularly useful for the present research. These are

(1) Making links between everyday and scientific ways of explaining.
(2) Making links between scientific concepts.
(3) Making links between scientific explanations and real world phenomena.
(4) Making links between modes of representation.
(5) Moving between different scales and levels of explanation.
(6) Analogical link making.

Two of Scott's links were found in the PI dialogues: links between scientific concepts and links between scientific and real world phenomena. In addition, a third type of link was found. This occurred when students refer to information outside the immediate situation, for example, a TV program that they have seen or a text book that they have all read. This category will be referred to as "links to common knowledge," based on Mercer's [26] observation of the importance of common knowledge in group dialogues. An example of activation of common knowledge is discussed in case study 3.

C. Category 3: Activation of control structures

The third level to be considered here is the activation of groups of resources through changing the overriding control structure. The two control structures that will be considered here are epistemic games (e-games) and epistemological frames. Both of these control structures have been studied in the context of the resource model [8,9]. Control structures are a slightly different category from the two categories above, as they are tacit, normally activated at a subconscious level. This means that the student is unaware that they are using a particular e-game or frame, or that their e-game or frame has changed. It can, however, often be deduced from the dialogue.

1. e-games

An e-game, as described by Tuminaro and Redish [8], is "an activation of a pattern of resources that can be associated with a collection of resources". Each game consists of its own set of rules or moves that are allowed. The six epistemic games that Tuminaro and Redish [8] found in their research are

(1) Mapping meaning to mathematics.
(2) Mapping mathematics to meaning.
(3) Physical mechanism game.
(4) Pictorial analysis.
(5) Recursive plug and chug.
(6) Transliteration to mathematics.

2. Epistemological frames

Epistemological frames are similar to e-games in that they are control structures that influence the activation of groups of resources. Frames play an important part in how students respond to questions; for example, during clinical interviews students' frames could be influenced by the way in which the interviewer set up and responded to the dialogue [32].

An epistemological frame is the student's judgement about what class of tools are appropriate to use in a particular context or situation. Bing and Redish [9] have identified four types of epistemological frames:

(1) Calculation.
(2) Physical mapping.
(3) Invoking authority.
(4) Math consistency.

In this research, it is not the presence of a particular e-game or frame that is of interest (as it was to Tuminaro and Redish [8] and Bing and Redish [9]), but instead, whether a change in frame or e-game can be identified.

The activation of the "physical mechanism" e-game and the "pictorial analysis" e-game is demonstrated in case study 2 and an example of a change in the epistemological frame (from "calculation" to "physical mapping") is discussed in case study 1.

VI. THREE CASE STUDIES

In this section three case studies will be presented which show how understanding the dialogues through examining the resources that have been activated can give insights into the processes of learning involved during PI sessions.

The first two case studies are examples of a "successful" PI episode, that is, the dialogues are productive, leading to both a change in how a student thinks *and* a change in how they vote (from an incorrect to a correct answer). In the first case, most of the students initially vote for the incorrect answer, but change to the correct answer following the discussion. In the second case study, two of the group of four students initially get the answer wrong while the other two chose the correct answer. Postdiscussion, all four students select the correct answer. It is particularly interesting to compare how the discussions evolve in these two examples, as it could be argued that PI works simply because students who know the correct answer "teach" the students who get the answer wrong. However, as the discussion below shows, the interactions are much more complicated than this: there is evidence, for example, of a change in understanding during the discussion for all of the students, including those who initially got the answer correct. This observation is supported by research which found that the most advanced students in a group may also gain from peer discussions [33].

The third case study, in contrast to the first two, is an example of an unproductive discussion in which no conceptual physics arguments are used in the dialogues. However, as all the students vote for the correct answer after the discussion, relying on voting statistics alone would lead to the conclusion that this was a successful PI episode. The implications for pedagogical practice of all these case studies are explored.

A. Case study 1

The question in this case study (Fig. 1) concerns the first law of thermodynamics ($\Delta U = Q - W$, where ΔU is the change in internal energy, Q is the heat transfer, and W is the work done by the system). The dialogue begins in a similar way to most PI dialogues, with each student revealing how they voted. In this dialogue most of the students initially picked answer C. This was the most popular, although incorrect, answer for the class as a whole with 53% voting for answer C before the discussion. Student 2 starts the discussion by partially explaining the thought process that he used to get to his answer. This is a promising start, providing a reasonable physical explanation for eliminating the answers B and D which both concern heat transfer "out of the gas." At this point he appears to get stuck and it is not clear why he chose C over A, which is the correct answer.

(1) *Student 1: What did you go for?*
(2) *Student 2: I went for C*
(3) *Student 4: I said C*
(4) *Student 3: I said C as well*
(5) *Student 1: I said C*
(6) *Student 2: Because, So first of all, the internal energy of the gas increases, there needs to be heat transferred into the gas, so that eliminates B and D yeah err, A and C…*
(7) *Student 1: The work done on the gas, that means the work done by the gas is negative*
(8) *Student 2: I think you're probably right, ohh, yeah, I'm a fool. Yep*
(9) *Student 3: oh yeah!*

Student 1 continues the discussion in line 7. It is interesting that his contribution does not directly follow from student 2's explanation but instead brings up the issue of work done, something that caused difficulty across many of the groups that we recorded. Students were particularly confused about whether the first law of thermodynamics

A cylinder of gas is compressed by a moveable piston. The work done on the gas by the piston is 2 J. If the internal energy of the gas increases by 10 J during the process, what is the heat transfer during the process?

A) 8 J into the gas

B) 8 J out of the gas

C) 12 J into the gas

D) 12 J out of the gas

FIG. 1. 1st law of thermodynamics question. Correct answer is A.

equation presented in the lecture referred to the work done *on* the gas, or the work done *by* the gas. It is interesting to note that student 1 was able to pick out the issue that was causing his fellow students difficulty. This ability of students to spot what might be causing their peers problems is something which we noticed regularly throughout the dialogues, and is perhaps one of the reasons that peer dialogue is so powerful in this type of situation. It is also interesting to note that all the groups we listened to relied on using the first law of thermodynamics equation directly to solve this problem, rather than trying to use physical reasoning, such as energy considerations (the first law of thermodynamics is essentially a statement about energy conservation in a gaseous system), to get to the answer.

Student 1's comment in line 7 is also the first activating statement in this dialogue. He correctly identifies that the information given in the question is the work done *on* the gas, whereas the W in the equation for the first law of thermodynamic refers to the work done *by* the gas. From student 2's reaction in line 8 and student 3's reaction in line 9, it is clear that this has resulted in a change in their thinking. We, therefore, interpret this as an activating event. This is evidence of the lowest level of resource activation, activation of a knowledge element. In this case the knowledge element activated is that the physical quantity represented by W in the first law of thermodynamics represents the work done by the gas. As the dialogue progresses it is clear that student 3, in particular, has understood the concept and is able to use his knowledge to contribute to the conversation.

In order to understand how the dialogue develops from this point it is helpful to analyze it in terms of the epistemological frames of the students, and how they change during the discussion. The interplay that is of particular interest occurs in the next section between student 3 and student 4. Bing and Redish [9] explain that an epistemological frame can be determined by the *warrants* that a student uses, that is the proof that they use to back up a claim. From line 10 it appears that student 4 has gotten to his answer using a calculation epistemological frame; he has stated that the answer is C, and for proof refers to the use of the equation:

(10) *Student 4: If you do it with the equation though it comes out as 12.*

(11) *Student 3: Yes but assuming that the work done on the gas by the piston, you want the work done by the gas*

(12) *Student 4: Ahh yes, so the work done by the gas would be, no that's the same thing isn't it*

(13) *Student 3: No*

(14) *Student 4: I refuse to be moved*

(15) *Student 3: Plus, that's why the work done was less, because the piston does work on the gas*

(16) *Student 4: Yeah, but that's the problem with decreasing, this is compressing the gas*

(17) *Student 3: I'm not being moved on this*

(18) *Student 4: Oh well that's fine, that PV diagram the arrow is going backwards, so the volume is getting less. Is it, no hang on, oh right yeah that is compression*

Student 3's thinking in this section was activated by student 1 as discussed above, and he continues to use this thinking throughout the dialogue. He initially repeats the argument that changed his own thinking, to student 4 (line 11); however, this approach appears not to work for student 4. Although it initially appears (line 12) that activation has taken place, student 4 then disagrees and it is clear that his thinking has not changed.

However, a key moment takes place in line 15. Student 3, building on his previous statement, thinks of a new way to persuade student 4 that the work done on the gas is different to the work done by the gas. He points out that the work done was less, and explains this by referring to the physical situation of the piston doing work on the gas. For this reason, this line can be interpreted as student 3 using the epistemological frame, physical mapping. Although it could be argued that student 3 is simply repeating the wording of the question, his use of that information coupled with his argument about the effect that the piston has on the work done on the gas (i.e., that it is less), implies that a physical mapping frame seems the most likely explanation for this thinking. This results in a light-bulb moment, in line 18. In the first half of this statement student 4 is trying to make sense of this question as it relates to a previous question presented in the lecture about the work done by a gas. But the key to his change of thinking comes when he realizes how compression of the gas fits into his thinking (although it is not clear whether this relates to the original problem or to the graphical representation in the PV diagram). The result, however, is that student 4 is then thinking about the physical situation of the compression of the gas, which implies that he has also changed his epistemological frame to physical mapping. This is then an example of activation of an *epistemological frame*. Key to this change was student 4 making a connection to a question about the work done by a gas, which the students studied earlier in the lecture. This is an example of activation of linkages, the second category of resource activation, which will be discussed in more detail in case study 3.

Although this dialogue is short it demonstrates many of the attributes that we found commonly throughout the discussions. The dialogue seems to work in different ways to change each student's thinking. For example, there is clear evidence that activation of a knowledge element has taken place, which alters student 3's thinking and, hence, the course of the discussion. Not all changes are instantaneous: the discussion between student 3 and student 4 takes a number of turns before student 4 changes his epistemological frame. By making a link to a previous question he is then able to change his understanding.

This dialogue demonstrates how activation of knowledge elements and activation of an epistemological frame can work together to change students' thinking. The result is the students who voted for the incorrect answer C change their answer to A postdiscussion, and, more importantly, they have all shown evidence in the discussion that their understanding of the underlying physics has developed.

B. Case study 2

The next two case studies are both taken from a lecture which covered Bragg diffraction. In this first example (Fig. 2) the question is about diffraction in a powdered crystal. Although the questions cover different aspects of the same topic, the resulting discussions are very different.

(1) *Student 8: It is either A or C*
(2) *Student 6: I think it is C*
(3) *Student 5: I went for C, because I fell apart*
(4) *Student 7: Well I thought, if it is* $2d\sin\theta$ *is equal to* $m\lambda$, $\sin\theta$ *is the same*
(5) *Student 8: No*
(6) *Student 7: 2 is the same*
(7) *Student 8: It doesn't matter,* θ *is the same*

This example consists of a group of four students, two of whom vote correctly before the discussion, and two vote incorrectly, but change their vote after the discussion, so

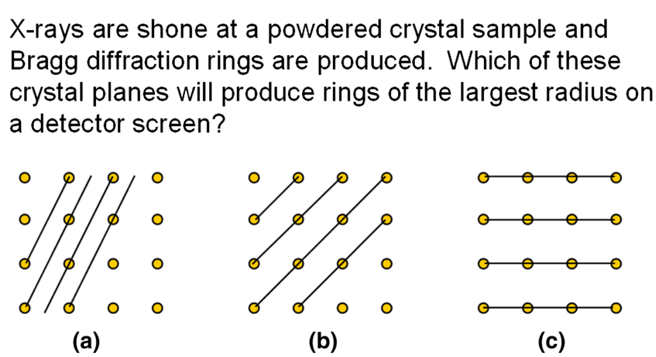

FIG. 2. Bragg diffraction question 1. Correct answer is A.

that all four students vote correctly in the final vote. This dialogue is classified as successful as all the students engage in a productive discussion about the physics that the question is designed to test. Although two of the students actually vote for the correct answer before the discussion, they do not demonstrate a clear understanding at the start of the dialogue, and benefit from it as much as the others.

What stands out particularly in this dialogue is that the discussion can be split into two sections, described by two different e-games.

(8) *Student 7: Theta is the same because you have one Bragg angle for that particular situation*
(9) *Student 8: Yep that's true*
(10) *Student 7: and Lambda is the same, because you have the same wavelength of light, which means d and m are the things that are changing in each one of them*
(11) *Student 7: If d gets smaller, if d gets bigger, m gets bigger*
(12) *Student 6: m is just the set of integers 1 2 3 4 5*
(13) *Student 7: But that's the middle maxima, next middle maxima, next middle maxim*
(14) *Student 5: These are different angles, they're all* $m = 1$, *but different angles*
(15) *Student 6: Are they?*
(16) *Student 7: If the spacing between those, the one the two the three the four*
(17) *Student 5: It's different angles*
(18) *Student 6: d is always the same here,*
(19) *Student 7: no the light*
(20) *Student 8: because d is just the distance between the planes*
(21) *Student 7: No no, distance between the planes of light is.. that's what's varying,*
(22) *Student 5: d and theta change*
(23) *Student 8: But in each situation the things are the same.*

The first major contribution to the discussion is from student 7 in line 4 where he proposes using the Bragg equation $2d\sin\theta = m\lambda$. The next few turns consist of students arguing about which quantities are fixed, and which are changing. However, from lines 4 to 11 there is very little evidence in the discussion that they know what physical quantities these variables represent. The one exception to this is student 7 who mentions the angle theta in line 8 and the wavelength of light in line 10. However, it still appears that the students do not fully understand what these quantities represent and which of them are the variables needed to solve the problem.

This leads to the conclusion that the students have activated an e-game which is in some ways similar to "recursive plug and chug" [8]. Tuminaro describes this game as when "students plug quantities into physics equations and churn out numeric answers, without conceptually understanding the physical implications of their calculations" [8]. A key rule in the game is that no thought can be given to the physical meaning of the quantities being used. However, in this case the students are not dealing with numbers or calculations, they are aware that they need to find the relation between two quantities. The problem seems to be that they do not know which two quantities are variables, or, indeed, what physical meaning the quantities in the equation represent. This dialogue therefore seems to show that the students are playing an e-game not previously mentioned by Tuminaro and Reddish [8] and which we name "recursive equation exploration." In this game students attempt to solve a physics problem in which there are no given numerical quantities, and which does not require a numerical answer, by trying to determine which of the quantities in the equation are variables and which are fixed. Just as when students play recursive plug and chug, they are less likely to activate resources concerning conceptual understanding [8]. For example in line 11 student 7 states "if d gets bigger, m gets bigger" without any indication that he knows what d and m represent, or how that helps him to answer the question. In this example it is unlikely that the students did not know what m and d represented, but by playing recursive equation exploration the students are unlikely to access the resources needed to make a link to this conceptual understanding.

As the discussion continues the students do slowly assign physical meaning to the quantities in the equation. A key turning point in the discussion occurs in line 20 when student 8 points out that d is the distance between the planes. Although he then claims, wrongly, that this quantity is the same for all three examples, this is an example of activating knowledge elements and it works to move the discussion forward.

Once most of the students have agreed that the variables are d and θ, they turn their attention to how θ relates to the Bragg angle (lines 24–27). Here, there seems to be a lack of understanding of how the Bragg angle is defined, and, in particular, whether it is the same for all three examples. This is particularly interesting as the previous question that the students had encountered in the lecture, which will be discussed in case study 3, was designed to test students' understanding of how the Bragg angle is determined. By using voting statistics alone, that question appeared to demonstrate a sound understanding of how to find and use the Bragg angle in a calculation, but evidence from this discussion implies either that this is misleading or that for some reason this knowledge was not activated in this situation.

(24) *Student 7: yeah, for each bit, but what we are changing is this d. I'm guessing we are hitting it at the same angle each time are we?*
(25) *Student 5: We are*
(26) *Student 8: No we are hitting it at an angle so that we get the Bragg diffraction which are different for each one*
(27) *Student 5: We are hitting it at the Bragg angle,*
(28) *Student 6: A (emphasis) Bragg angle, yeah, but it is different for each of those.*
(29) *muttering*
(30) *Student 6: Draw a diagram. You got like (draws lines) and you want this distance to be equal to lambda. And if they are closer together then it will take longer*
(31) *Student 7: I just think, small d, If d is small m is small.*
(32) *Student 8: If the wavelength is the same, then there will be more*
(33) *Student 5: yep it is A!*
(34) *Student 7: It is A!*
(35) *Student 5: because there is more distance*
(36) *Student 8: you have to turn in much further before the distance between them to get bigger*
(37) *Student 6: yep yep yep yep yep got it!*

The key section in this episode is lines 24–28. Led by student 8, the students realize that the angle required for Bragg diffraction is different in each scenario. This results in them visualizing the problem, prompting student 6 to draw a diagram (Fig. 3). Drawing a diagram of a physical situation is central to playing the "pictorial analysis" e-game [8], so this is strong evidence that the e-game of the students has changed. The diagram that he draws is one commonly found in textbooks when explaining Bragg diffraction, which implies that the shift in thinking has also enabled him to activate new resources. This example shows that a new e-game, pictorial analysis, has been activated. Combining the real-time video of the diagram being drawn with the audio recording of the students gave a clear indication of the impact that drawing the diagram had on the students' thinking.

In addition, this change in e-game results in a step change in understanding. Not only do the students realize that the correct answer is A, they understand conceptually why it must be A. Interestingly this light-bulb moment happens for three of the four students simultaneously, and it is clear from the dialogue, and their tone of voice that they are excited by their discovery. Only one of the students

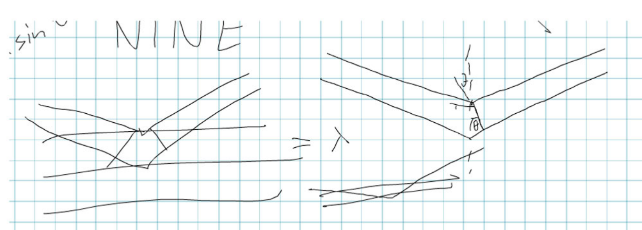

FIG. 3. Sketch by student 6 (powder diffraction).

does not seem to “get it” and still questions whether the Bragg angle is changing.

This is, therefore, an example of a successful dialogue; all the students engage in productive discussion with all but one showing clear progress in their understanding. The two students who initially voted incorrectly change their answer to the correct one.

C. Case study 3

This example is from the same lecture as the question in case study 2; however, it resulted in very different types of discussions. In this question (Fig. 4) the students are asked to use their understanding of the Bragg angle to find the spacing of the crystal planes. In all the transcripts a similar pattern was seen; students quickly identify the equation they want to use and then proceed to find suitable numbers to use in the equation. It is particularly notable that very little conceptual physics discussion takes place in any of the dialogues. Indeed, there is strong evidence that the students are playing the e-game, recursive plug and chug, discussed above. The dialogue below is representative of the types of discussion we observed.

(1) *Student 9: What did you put?*
(2) *Student 10: I thought it was B*
(3) *Student 10: Well the wavelength is* 10^{-10}
(4) *Student 9: and the Bragg angle is 30 I think*
(5) *Student 10: yeah*
(6) *Student 9: so sin 30 is* $\frac{1}{2}$*, so times 2 is 1, so you've got 1 divided by 1*
(7) *Student 10: Yeah, yeah you're right, B looks right*

The lecturer (RG), however, had a very different intention for this question. From his perspective this question was not really about the calculation, but was supposed to spawn some thinking about how the Bragg angle is defined and how to obtain it from the information given in the question. He felt that the actual calculation was secondary.

We also noticed that even in dialogues when the students did not know how to determine the Bragg angle, (the issue that the question was designed to tackle) they stayed within the “rules” of the e-game, which disallow conceptual physics considerations [8]. Examining voting statistics alone would imply that this was a successful question:

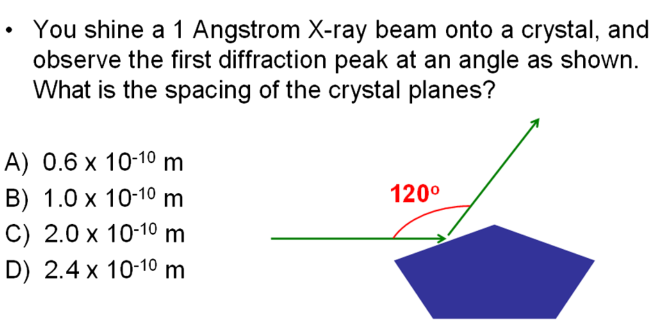

FIG. 4. Bragg diffraction question 2. Correct answer is B.

54% of students who voted got the answer correct before the discussion and 89% postdiscussion, yet it is clear from the dialogues that the question has not succeeded in stimulating the sort of thinking that was intended.

The first two case studies demonstrated how resources can be activated through dialogue. However, it has been shown [34] that the context in which the problem is presented also influences the way in which it is approached (and therefore the resources which are activated). A key element in the context of a problem is the wording of the question. Hinsley, Hayes, and Simon [35] have shown that students categorize algebra problems extremely quickly, often after reading only the first sentence. More recent work has shown that students given a Physics question that included a diagram performed less well than students who had to create the diagram for themselves [36]. This implies that how a question is worded is a critical aspect of its design, affecting the types of resources that are activated and, therefore, how the students approach the problem. This idea is supported by the finding of Chi, Feltovich, and Glaser [29] that novices and experts differ in the way that they categorize physics problems. In this example, it appears that the wording of the question, in particular, that the possible answers are numeric, has activated the e-game recursive plug and chug, which resulted in an understandable lack of conceptual physics discussion compared to other discussions in this topic area, such as the question in case study 2.

It should be pointed out that this observation is attributed entirely as a failure of the question rather than as any failing on the part of the students. Indeed, in order to have answered the question correctly the students must already have determined the Bragg angle, implying that this conceptual step takes place before any discussion happens. It may be that, as a result of studying the topic during the prelecture readings, or at school prior to university, during their A-level or Scottish Higher studies, students are so familiar with how the Bragg angle is determined that this is assumed to be common knowledge by the students. In almost all of the dialogues, this step is assumed, and not questioned by the students. It is not clear, however, why this question resulted in such a big gain for the class as a whole, or why only 53% got the answer right before the discussion. The discussions that we have recorded do not allow us to reach a definitive conclusion about this, although, one issue that we observed was that some of the students did not know the value of an Ångstrom. Indeed, this is something that the lecturer picks up while listening in to the discussions and addresses to the class as a whole before they vote for the second time.

(9) *Student 11 so c**p without a calculator*
(10) *Student 11 sin 30 is it?*
(11) *Student 12 root 3 over 2*
(12) *Student 11 oh*

(13) *Student 11: oh no it is a half I was right, no sin 30 is a half, I remember that from the Big Bang Theory when they were trying to push him up the stairs*

(14) *Student 12: oh yeah it was about half the work because it was 30 degrees*

Although most of the discussions of this question involved only the determination of numbers needed for the equation, in one example this resulted in a type of activation not yet mentioned. In this sequence the students are discussing the value of sin 30. Although this could be found using a calculator, students are normally encouraged to recall it from memory.

In order to make the point that sin 30 is $\frac{1}{2}$, student 1 makes a link to a scene that he remembers in a TV program called The Big Bang Theory [37]. Student 12 clearly also remembers this scene, as he goes further, relating the sine of the angle to the work done. The statement from student 11 therefore appears to activate resources in student 12 by making the link to the TV program.

This is an example of activating *linkages to common knowledge*. It shows how learning that takes place outside the classroom can be useful inside the classroom, and how important it is to help students to make links to this sort of knowledge. It was common to find examples of linkages to common knowledge in the dialogues, although the type of links that the students made were diverse. One student, for example, talked about his experiences of tuning a guitar in a question about beat frequencies, another referred to a passage in a text book about point masses when discussing a question about the ideal gas law. It is clear, however, that given the opportunity, students can integrate knowledge from other aspects of their lives in a way which helps them to learn physics.

VII. IMPLICATIONS

As shown through the case studies above, a powerful aspect of Peer Instruction is the peer dialogue that takes place between students. However PI also creates the opportunity for a dialogue between the students and the lecturer in a way which is not possible in standard format lectures. Indeed Beatty and Gerace [1] use the term "formative assessment" to describe EVS use, as it provides information to teachers about the level of students' understanding, which can then be used to adapt teaching practices to the needs of the students. Most commonly this happens by lecturers using information from voting statistics to gauge the level of student understanding and changing the lecture trajectory appropriately.

However, the detailed analysis of the dialogues presented here shows that the situation is much more nuanced than this: a correct vote does not automatically imply that the student has a comprehensive grasp of the physics behind the question, and an incorrect or absence of a vote may not mean that a student has absolutely no understanding.

Others have observed similar findings: James and Willoughby [38] found that in 26% of the conversations they observed, the voting data "misrepresented the nature of the existing student understanding." James and Willoughby noted two situations when votes do not tally with understanding demonstrated in discussions: "responding with another student's answer preference" (i.e., peer pressure) and "using extraneous cues to arrive at a response." Both of these situations were noted on occasions in the dialogues in this research. In addition, a number of other examples of dialogue-voting mismatch were found: students who did not know the answer but voted (often correctly) by guessing; students who got the answer correct but did not display any evidence of understanding, or displayed incorrect understanding to reach the correct answer; and students who voted incorrectly, but whose discussions reveal some change in their understanding (as discussed in case study 2).

In general, it is assumed in the literature that voting statistics can be used to gauge the level of student understanding; for instance, Beatty and Gerace state that "by seeing the histogram of answers entered, the instructor learns about students' understanding, and students learn about their classmates' thinking" [1]. However, one implication of the findings of this research is that voting data cannot necessarily be taken at face value; a correct vote does not automatically imply that the student has a comprehensive grasp of the physics behind the question, and an incorrect or absence of a vote may not mean that a student has absolutely no understanding. How a student votes certainly provides a starting point for understanding how they are thinking, but careful listening to and analyzing of conversations is essential in order to gain a more nuanced view.

Although it is clearly impossible for lecturers to record and listen to conversations during every lecture, being aware of the types of conversations that students are having and understanding them through a resource activation perspective may give a much more nuanced insight into the processes of student thinking and learning.

One reason this is important is that a key element of a PI session is the explanation that the lecturer gives after the final vote has taken place. The examples discussed above show that students may vote correctly but display little understanding of the physics in their discussions. In contrast, students may vote incorrectly, but for reasons which the lecturer has not foreseen. In both cases students would benefit from a post PI explanation which addresses the difficulties that they have encountered in the question. Students themselves recognize the importance of the lecturer's explanation. Research by Nicol and Boyle [39] found that 100% of students surveyed about various aspects of electronic voting system use felt that the teacher clearly explaining the right answer at the end of the session was important. This finding was backed up by interviews with students who felt that hearing the lecturer's explanation would clear up any confusion generated during the discussions. For this reason, it is important for lecturers to understand as much as possible about what their students are thinking as they answer the questions.

In addition, the analysis of the dialogues here has shown that students may benefit from the dialogue in a range of different ways regardless of how they voted either before or after the discussion. This means that lecturers should be aware that even when the PI gain (the normalized change in the number of correct votes from before to after the discussion) seems small, learning may still have taken place.

However, it is also important for lecturers to be aware that questions do not always result in the types of discussion that they had hoped for. In particular, the analysis of the dialogues in terms of resource activation has given insights into the effect that the wording of the question can have on peer conversations. The example in case study 3 in which all the students approached the questions using the e-game recursive plug and chug implies that avoiding numerical answers in the EVS options may encourage a more conceptually based physics discussion. In contrast, the question in case study 2, which covered a similar topic but which was presented in a different way, resulted in students having productive, conceptual physics based discussions. Understanding how a question is likely to impact on students' discussions is vital if lecturers are to design questions that contribute most effectively to the students' learning.

This finding supports the work of Ding *et al.* [40], who found that students often have different responses to physics questions compared to experts in physics, and understanding how and why this occurs can be helpful for designing effective EVS questions. Their research shows that using "student consultation" interviews is an effective way to pick up validity issues, and they developed a four stage response model which is able to uncover issues with the wording and/or representations that are used in EVS questions. This framework was successfully used to determine cognitive difficulties that students may encounter when answering questions, as well as to help design more effective questions. Our research shows that analyzing the conversations that students have in terms of the resources activated may also yield important information about the effectiveness of the question. More detailed work on the design of questions has been carried out by Beatty, Gerace, and Dufresne [41] who discuss how questions should have a threefold pedagogic objective consisting of a content goal, a cognitive goal, and a metacognitive goal. Again, their framework is useful for designing and evaluating effective questions. They make the further point that understanding the pedagogy and design logic behind a question is vitally important for it to work well, and for this reason care should be taken when using questions designed by other teachers.

VIII. IMPLICATIONS

It is important to note that the research presented in this paper is of a relatively small scale (consisting of 25 transcripts) and we are not seeking to make statistical claims, or to define trends (such as a link between type of activation and voting, or question type). Rather the aim of the research was to show that resource activations can be identified, that they can be categorized broadly into three types, and that thinking about dialogues in this way helps to understand how learning takes place.

One important finding of the research was that resource activation was observed both in the conversations where a change in vote was recorded and where no change was recorded. For this reason, no concrete link can be made between resource activation and voting statistics (although the latter may give some indication of a change in thinking).

It is possible that broader trends involving an even finer grained understanding of resource elements and linkages could be elucidated through further research on a much larger scale. The present study indicates the potential of such an inquiry. It also offers direct experience supporting those who have identified the importance of the use of EVS questions, but again serves more to justify further research than to create a conclusive picture at this stage. We hope that this paper leads other researchers and practitioners to use this as a general approach to thinking about their data rather than as a set methodology to follow, and believe that we have shown the potential of this approach by exploring it through the three case studies.

IX. CONCLUSIONS

In this paper a framework for analyzing student dialogues during PI, based on the resources model of cognition, has been developed. This framework focuses on the processes involved in the activation of resources, and incorporates aspects of cognitivist and sociocultural perspectives.

PI dialogues from first year undergraduate physics students at the University of Edinburgh, UK, were analyzed using this framework. The analysis revealed that changes in student thinking could be categorized into three different types of resource activation corresponding to increasing cognitive grain size. These were activation of knowledge elements, activation of linkages between resources and activation of control structures (e-games and epistemological frames). The examples presented here show that a resource activation analysis can be used to gain a deeper understanding of how PI dialogues contribute to learning. In particular, we have shown that the analysis can be used to understand what happens during a successful PI session, as well as what goes wrong in an unsuccessful PI session.

In addition, using a resource activation analysis to examine the dialogues in detail may prove to be a useful technique for highlighting mismatches between the aims of a question and the effect that a question has on students' discussions. Such an analysis could, therefore, point to other ways in which question design can be optimized to ensure that PI sessions are as productive as possible.

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