Using Students' Science Ideas to Drive Instruction:

How Responsive Teaching Shapes Learning Activity

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A thesis

submitted in partial fulfillment of the

requirements for the degree of

Master of Education

University of Washington

2014

Committee:

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Program Authorized to Offer Degree:

Curriculum & Instruction, College of Education

Abstract

Teaching in a way that is responsive to students' science ideas creates opportunities for meaningful, rigorous sense-making in a way that traditional science teaching does not. In this study, the researcher, as a visiting teacher, taught the same three-week circuits unit to one fourth grade class and two fifth grade classes from a responsive teaching stance. The teachers' attention to and incorporation of students' science ideas shifted unit trajectories and uniquely shaped the ongoing learning activity within whole-group discourse. A unit-level analysis of the frequency and category of science concepts present in whole-group discourse shows that all three classes discussed the same science concepts by the end of the unit; however, when these ideas presented themselves within whole group discourse differed across time, even though students were engaged in the same lessons. Tensions and dilemmas of responsive science teaching are discussed.

Introduction

Engaging students in rich, productive science talk is at the heart of recent science education reform (NRC, 2007; Harris, et al., 2011). This type of discourse plays a crucial role as a vehicle for student sense-making and learning (Chin, 2006; Mercer, 2008). Conversational interactions help students construct meaning (Roschelle, 1992; Bereiter, 1994) and engage in collaborative sense making about science concepts (van Zee et al., 2005). In order for students to engage in sense-making discourse, their ideas must be made public. Teachers typically do not have difficulty eliciting students' science ideas; however, helping students develop these ideas over time is a more challenging endeavor (Harris, et al., 2011). To engage students in collaborative sense making both teachers and students need to be responsive to the science ideas in play.

What does it mean to be responsive?

Being responsive requires an ongoing press by students and teachers for creating mutual understanding about ideas in play, but not necessarily acceptance of those ideas. Pierson (2008) characterized responsiveness as the ongoing "attempts to understand what another is thinking, displayed in how a conversational partner builds, questions, probes, clarifies, or takes up that which another has said'' (p. 25). In whole-group discourse, the teacher models what probing an idea sounds like. Students take up this language into their small group and pair interactions. The intensity of the intellectual work on the part of the responding actor is equal to that of the speaker. Ball, Lubienski, and Mewborn (2001) describe the complex nature of responding because it requires listening and interpreting what is said, probing to clarify if necessary, and then deciding to respond by posing a question, or making a connection to a prior contribution. Being responsive engages teachers and students in not only considering their own understanding and ideas about a

concept but attempting to understand how the others are reasoning in a particular way and how that reasoning might fit or not with their current way of thinking. This collaborative sense making is a social, interactive activity and the sense making happens uniquely in that space at that time.

Responsive Science Teaching

The driving principle of responsive science teaching is that students' science ideas are treated as leverageable intellectual resources rather than 'answers' to be evaluated. This first requires making students' thinking visible to others. The classroom space is a zone for idea construction rather than replication. This comes from an epistemological stance that science is a dynamic, sense-making endeavor rather than a static set of reproducible facts. By engaging students in rigorous sense-making discourse about observable evidence and their own hypotheses, students make progress together towards constructing causal explanations.

Furthermore, the treatment of questions and answers when teaching responsively differs from that of traditional science teaching. In traditional science teaching, the teacher responds to students' answers by judging them for correctness and students' questions are treated as requests for information, which the teacher typically provides, acting as the science authority. The teacher may be responding to students' but not being responsive to students.

Responsive science teaching positions students as equal and accountable contributors to classroom talk. To be accountable in conversations, students do not have to accept each other's ideas but must respond to them (Engle & Conant, 2002). Responsive discourse moves are not only the responsibility of the teacher but other students as well. Each student is an intellectual stakeholder as a member of a learning community, rather than an authority unto himself or herself (Engle & Conant, 2002). Through reflective discourse, the teacher engages students in a series of

exchanges around clarifying, developing, and understanding each other's thinking (vanZee and Minstrell, 1997). Responsive science teaching employs reflective moves, particularly in whole-class discourse, to model for students how to respond to a student's idea by asking for more information to clarify a word or phrase, adding onto the idea by agreeing, posing an alternative idea and disagreeing with reasoning, etc. This type of talk is appropriated by students who use it in small group and pair conversations.

The teacher intentionally designs and structures discourse opportunities as well as provides structured inscription tasks to help students build up and revise each other's ideas over the course of the unit. .

Research Questions

In a responsively taught science class, students are expected to play roles that help them co-construct making sense of science concepts. Students provide the intellectual resources (ideas) at the heart of the conversation then co-construct knowledge by holding each other accountable to not only explain their own ideas, but acknowledge how ideas relate to other ideas "in play". These types of interactions occur in-the-moment, at the level of turns-of-talk. But how do these individual moment-by-moment responsive discourse moves influence an entire unit of instruction? By comparing the same instructional unit across three classrooms, the following research questions aim to address some ways in which productively responsive teaching influences the unit as a whole:

1. How does a teacher's responsiveness to students' science ideas within classroom discourse shape the trajectory of developing ideas across the unit?
2. How does the teachers' attention to and incorporation of students' science ideas shift unit trajectories? How are trajectory shifts decided?

Methodology

Data Generation

Participants. Participants in this study were 27 students from one 4th grade classroom and two 5th grade classes (28 and 29 students), and their respective classroom teachers. The 4th grade class, taught by Ms. Preston, was part of a K-8 school which reported 7% free and reduced lunch, 80% white students, and 8% special education identified students (data from district website school reports, 2011-2012 school year). The two 5th grade classes were the morning and afternoon classes for the same math and science teacher, Mr. Lancaster, were part of a K-5 school which reported 40% free and reduced lunch, 57% white students, and 12% special education identified students (data from district website school reports, 2011-2012 school year).

Data Collection. The researcher acted in the role of a visiting guest teacher for the duration of a three-week circuits and pathways unit taught to three elementary classes and two different public schools. The units were planned and executed using the core practices of ambitious science teaching (Windschitl, et al., 2012). By teaching an entire unit, rather than one or two stand-alone lessons, the researcher cultivated relationships across time and gained a day-to-day working understanding of the development of students' science ideas over time. Understanding the overarching unit plan, classroom contexts, and interactions throughout the unit provided a crucial knowledge of context within which to analyze the sequence of discourse (Mercer, 2008). All lessons were video recorded with parental and student consent. As mentioned previously, this research was conducted by a researcher-as-teacher. Playing dual roles of both researcher and teacher within the classroom space was challenging particularly around ensuring complete data collection using video recording equipment. Prior to the lesson, cameras

were set to record; however, some lessons were not completely recorded because video equipment was minimally attended to while teaching was occurring.

Sources of Data and Measures

Coding by Category and Concept Video recordings of whole-group discourse for each lesson was transcribed and coded for science concepts (see Table 1). Students typically voiced these concepts by three means ideas within whole-group discourse: (1) spontaneously proposing an idea or hypothesis, (2) answering a question with evidence or reasoning, or (3) responding to another's idea by building onto it, typically by agreeing or disagreeing and then providing additional reasoning. Each idea represents a concept that is now "in play" (or remains "in play") in the whole group classroom-level space (as opposed to group-level, or individual-level).

The selected science concepts related directly to unit objectives, as provided by the district curriculum and state science standards, and also to the concepts students would need to understand in order to explain the anchoring phenomenon of a flashlight system ceasing to function after being left on for 30 days. The original selection of this phenomenon was directly influenced by the district's learning objectives and state standards such that the majority of concepts necessary to explain the phenomenon were covered within the grade band science standards (13 out of 20 concepts). These concepts were deconstructed from the teachers' full, gapless explanation of the phenomenon, written before the unit begins as part of unit planning. The teacher deconstructed her own explanation into component parts or conceptual pieces that can then be prioritized based on their utility in helping students understand the scientific phenomenon at hand and on how they address state and local grade level standards.

During the unit, students must be able to observe and collect evidence about each concept and then make sense of each in relation to other concepts, making connections and seeing

relationships that will ultimately allow them to stitch together their own evidence-based gapless explanation. Presenting lessons concept-by-concept and involving students in sense-making talk requires students to engage in the intellectual work of making connections between observations and concepts and then making connections between concepts. Thus, constructing an explanation over time as more information and reasoning is layered on, starting from what they think they know.

Table 1 Concepts Required to Compose a Gapless Explanation

Category	Concept
Matter (M)	M.1 Matter is composed of particles (atoms, particles, electrons). M.2 Particles have charges which makes some particles attracted to other particles. M.3 Particle arrangement in materials affects how electrons behave.
Conductors (C)	C.1* Some materials conduct (metals, minerals); while others are non-conductors or insulators of electrical energy (glass, plastic). C.2* Conductors are a pathway for electrical energy. C.3 Electron behavior affects the conductivity of a material. C.4 The bumping of electrons is the energy moving through matter.
Energy Source (B)	B.1* There is energy/power stored in a battery. B.2 There are particular materials (chemicals) inside that react. B.3* Batteries can "go out", be "used up", or "die" when chemicals inside the battery change. B.4* Energy leaves the battery over time when part of a circuit.
Energy Story (E)	E.1* There are different forms/kinds/types of energy (i.e. chemical, electrical, light, heat). E.2* Energy can be moved (transferred) through matter. E.3* Energy can be changed (transformed) by matter. E.4 Energy cannot be created or disappear, only transformed or transferred.
System (S)	S.1* Parts must be connected in a particular way. S.2* Parts must each be working properly. S.3* Parts each have a particular function. S.4* There can be more than one kind of part in the system (i.e. multiple batteries, bulbs). S.5* One part of the system can affect another (i.e. more batteries increases bulb brightness; dead battery affects bulb output)

* Denotes science standard and/or district grade level expectation

Observations are not coded as concepts. However, if students elaborated on patterns in data (i.e. all metals could be conductors since the penny, screw, and foil are) then that would count towards the concept. Observation-level contributions, though important for reasoning and sense-making, will not on their own allow students to make sense of science concepts, so observations were not coded as concepts.

Short excerpts from the transcript of Lesson 5 for Ms. Preston's class (IP4.L5) shows how these concepts and categories were coded in whole-group discourse. The following is a brief summary of the lesson contexts leading up to Lesson 5 which clarifies student's statements in the transcript excerpts. Lesson 5 is the third lesson where students are directly engaged with considering the battery as an energy source. They have been puzzling over what exactly happens inside a battery that we cannot directly observe. In Lesson 3, students created a voltaic pile using zinc, copper, and vinegar-soaked paper to light a small LED. Subsequently, several students proposed ideas that there must be some interaction between the metals and acids using evidence from their observations (i.e. their battery wouldn't work if the order stacking pattern was incorrect or if there was not enough metal or acid). In lesson 4, students compared cross-sections of different types of batteries by watching short video clips, comparing diagrams and photographs, and reading a few short paragraphs to create a list of generalizable similarities about battery structures. For lesson 5, the warm-up question directed students to revisit their original hypotheses about what they thought was going on inside a battery (from Lesson 2) in light of what they now understand. Here Emma proposes that they should combine the two of the hypotheses ("Chemicals/Acids inside" and "Energy inside") which shifted into a conversation about the origins of energy. The transcript excerpts below shows an example of how student utterances during whole-group discourse were coded by category and concept.

Figure 1 Transcript Excerpts to Illustrate Concept and Category Coding

Line	*Transcript Excerpts from Ms. Preston's class (Lesson 5)*	*Concept Code*
10	Emma: The reading says […] that chemical reactions happen in batteries and then can	B.2
11	transform into energy so both.	E.3
12	**Teacher: So, how is that both? I heard the energy part... what's the acid part?**	
13	Emma: Some acids combine and have a chemical reaction which gets formed into energy.	
14	**Teacher: Okay…anyone else have evidence for acids or energy… or if you agree with**	
15	**Emma? Disagree? …. Grady, do you want to share what you're thinking about?**	
16	Grady: Um I think the energy in batteries and I was thinking about how the cell phone battery	B.1
17	blew up and I think that there is energy in batteries. It's that there's acid and I don't think the	
18	acid would blow up but I think it's explosives [inaudible] and it's just gone.	
31	Justine: I agree with Emma that there's both. But that they put …the thing with Grady's is that if	B.1
32	it was just energy inside a battery then what would create that energy because you can't just	B.2
33	get energy, plain energy you have to have something that either reacts or makes energy.	E.3
34	**Teacher**: **So Grady I don't know if you heard her, but she said […] she said the energy**	
35	**can't just…**	
36	Justine (turning to look at Grady): appear.	
37	**Teacher: Appear. It has to come from someplace else.**	
38	Grady (shrugging): I plug my iPod into the wall.	

Most of the concepts during the entire whole-group discourse for Lesson 5 in Ms. Preston's class are about the energy source (7 out of 9). Since energy sources (like batteries) were the focus of the lesson, this is unsurprising. However, codes for "Energy Source" came up seven times during whole-group talk even though there are only four concepts under the category of "Energy Source" (see Table 1). This means that one or more of these concepts came up multiple times within the whole class discourse space. There are multiple uses of the same concept code (for example, B.1) because the concept is brought up at different points in time over the course of the lesson.

All the concept codes within a category count towards the frequency total of the category (i.e. all "B" codes count towards "Energy Source").

Coding for Teacher Responsiveness (TRBSI). In the interests of describing a relationship between responsive teaching moves and collaborative sense making, teacher utterances are marked as being *productively* responsive (TRBSI) only if the utterance results in students clarifying, elaborating, or connecting ideas based on their initial utterance. The discursive triad making it possible to identify a teacher's productive responsiveness to student's ideas would be: (1) student supplies an idea, or part of an idea (initial idea); (2) teacher decides on and delivers a responsive prompt (antecedent); and (3) student replies by doing something more with the idea (response). For the research questions in this study, the type of responsiveness is being responsive to students' intellectual work. When one student states a hypothesis, idea, or reasoning and the teacher is able to respond to a student's science idea in such a way to get any student to respond by doing something with the idea (i.e. unpack, clarify, elaborate connect, apply, rethink a prior idea in light of this new idea, etc.) then it counts as being productively responsive to students' intellectual work. One example in the previous transcript excerpt is the teacher's utterance in line 12. It was coded TRBSI because the teacher's response resulted in the student clarifying her idea from lines 10-11.

Findings

Teaching in a way that is responsive to students' science ideas requires flexibility on the part of the teacher to shift the order and type of lessons in the unit trajectory. These shifts create variations in number, frequency, and timing of when students surfaced targeted science concepts during whole group discourse. What follows are descriptive findings looking at each of the three classes, comparing units by category and concept.

Description of Unit Trajectories by Lesson. The order and type of lessons presented in each unit trajectory varied slightly between the three classes. Two major alterations to the unit trajectory occurred with Ms. Preston's class (IP4). The lessons appear in the order of 7, 9, 8 for IP4 on the unit trajectory (see Fig 3B). Working with Ms. Preston's class illustrated how responsive teaching can change the unit plan. The first shift happened as a result of lesson 8's warm-up question, which was intended to focus students on how conductors are energy pathways, but turned into a conversation about an energy transformation question, "What do you think causes energy to change?" Therefore, lesson 9 was substituted in-the-moment by the teacher to respond to students' current line of thinking instead on staying on plan and shifting the conversation back to organizing evidence for ideas we have about conductors. The second major alteration in trajectory was an addition of a "Current Debate" lesson (11.5) for Ms. Preston's class to allow students to explain their hypotheses, gather evidence, and debate the direction in which current flows in the circuit pathway. This instructional choice was made because two opposing hypotheses ("One way" versus " Two way" current flow) emerged at the end of lesson 11 when students were asked to trace the current pathway on a flashlight circuit diagram in their notebooks. How they traced the path differed, falling into two main "current direction" hypotheses. So at the beginning of lesson 11.5 teacher selected representative students from each side to come up and explain their hypothesis to the class, calling on other students to agree or disagree. At the end of lesson 11, Mr. Lancaster's classes claimed they agreed on the direction and pathway of current flow after several students traced the pathway during whole-group discourse; therefore, no lesson shift or addition was required. Mr. Lancaster's classes followed the same order and type of lessons; however, the number and type of concepts discussed varied across the unit and lesson by lesson.

Description of Unit by Science Category and Concepts. The following three representations characterize units by how often and when classes surfaced particular categories and science concepts: (1) looking at the total frequency and percentage of science concepts grouped by category for the unit, (2) looking at the distribution of categories over time, lesson by lesson and (3) looking at the distribution of concepts over time, lesson by lesson.

Each class addressed all five targeted categories of science concepts (see Table 1) through whole-group discourse during the unit. However, classes varied in the degree to which each of these categories were represented in whole-group discourse. To compare the variation in how classes addressed science categories differently, data were used from lessons 1-11, since all three classes engaged in these lessons.

Out of the total number of science concepts students referred to during whole-group discourse, Figure 2 shows the percentage of ideas from each category. The 'Matter' category is the least represented compared to the other categories across all classrooms. Ms. Preston's class (IP4) balanced their discourse across the remaining four categories, whereas, Mr. Lancaster's morning class (JLAM5) favored 'Energy Source' and his afternoon class (JLPM5) favored 'Energy Story.'

Figure 3 shows the total number of science ideas students addressed in whole-group discourse grouped by category. Though all classes addressed the five targeted categories, Ms. Preston's class referred to ideas in these categories 86 times, compared to Mr. Lancaster's morning and afternoon classes who mentioned or used ideas in these categories 54 and 50 times, respectively. This analysis provides a broad look at the content of student talk; however, looking more deeply into the particular science concepts reveals how specific concepts were addressed.

Figure 2

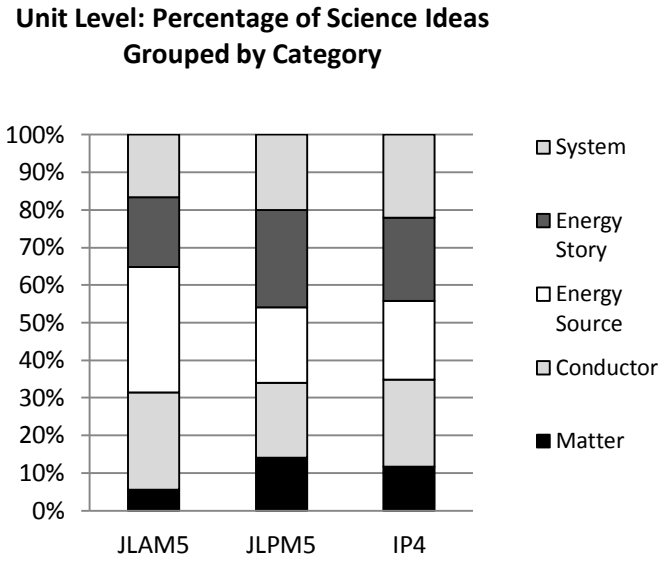
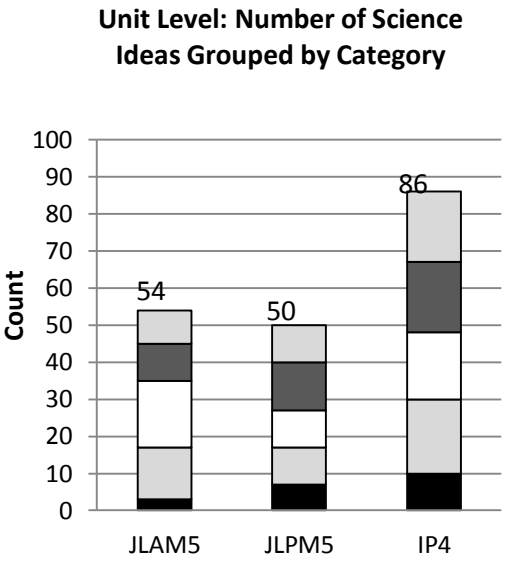


Figure 3



For all three classes, students engaged with nearly all of the concepts during whole-group discourse, some more often than others. Figure 4 shows the total number of times students voiced the 20 targeted science concepts during whole group discourse across the unit. Ms. Preston's class (IP4) and Mr. Lancaster's (JLPM5) afternoon class engaged with 90% of the total concepts and 85% and 92% of standard-related concepts, respectively; whereas, Mr. Lancaster's morning class (JLAM5) engaged with 75% of the total concepts but 92% of standard-related concepts. Figure 5 illustrates where and how often ideas within particular categories were addressed within lessons and across the unit. Overall, there is an observable shift towards the end of the unit, particularly around lessons 9 and 11, where there is an increase in the diversity of categories represented. Figure 6 deconstructs the categories into concepts addressed within whole-group discourse by students per lesson. It shows which of the 20 targeted science concepts were addressed in each lesson and the frequency they were used by students during whole-group talk.

Most importantly, figures 4, 5, and 6 together demonstrate that each lesson and unit has its own unique 'idea fingerprint.' Although each classroom was taught using the same lesson plans, all classes addressed all five categories and a majority of the 20 targeted science concepts in whole-group discourse within the 3-4 week unit at different points of time and different frequencies.

Figure 4. By Concept Total count of science concepts present in whole group discourse across the units.

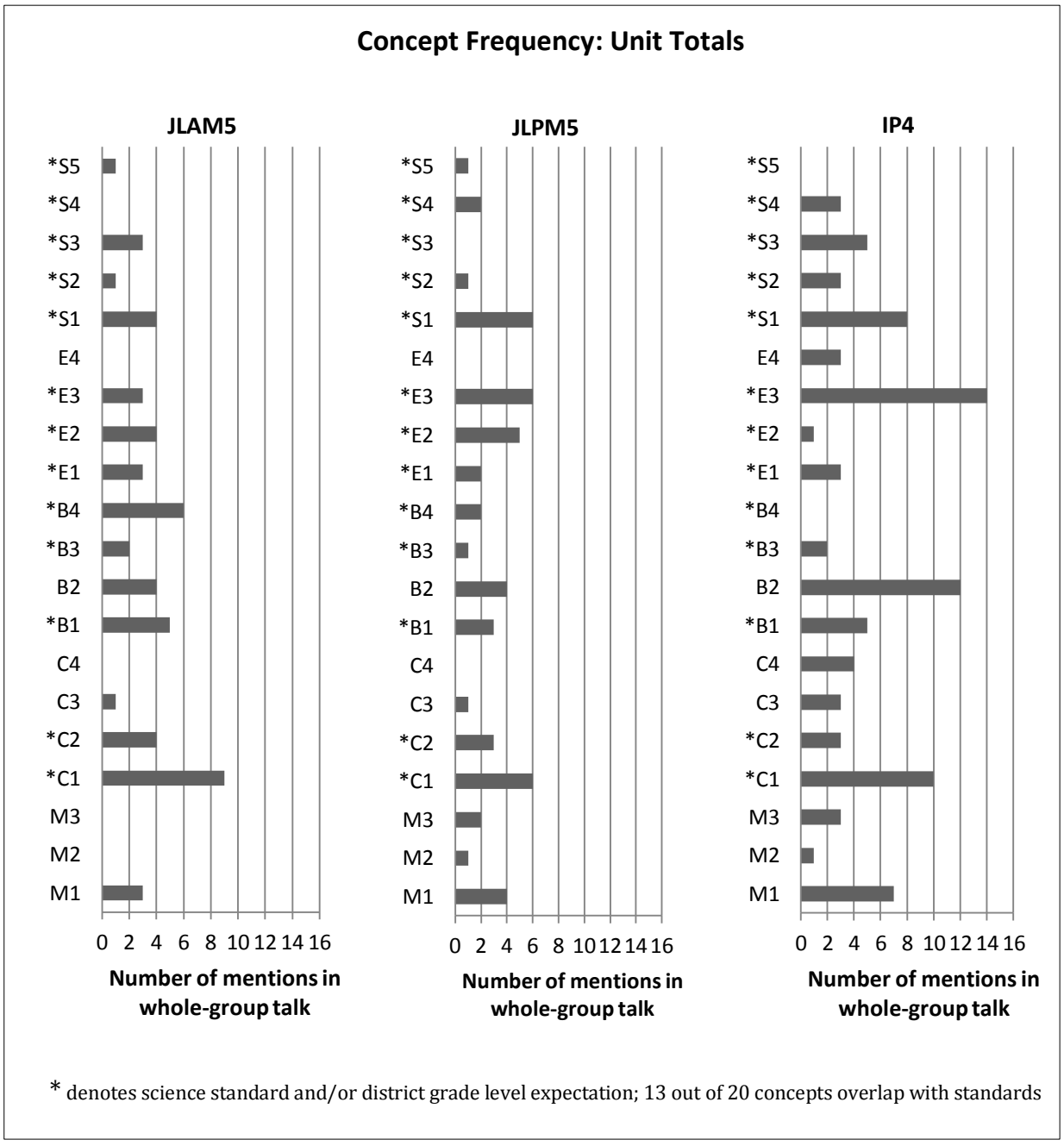


Figure 5. Categories by Lesson Comparison of frequency and category of science concepts present during whole group discourse by lesson and across units

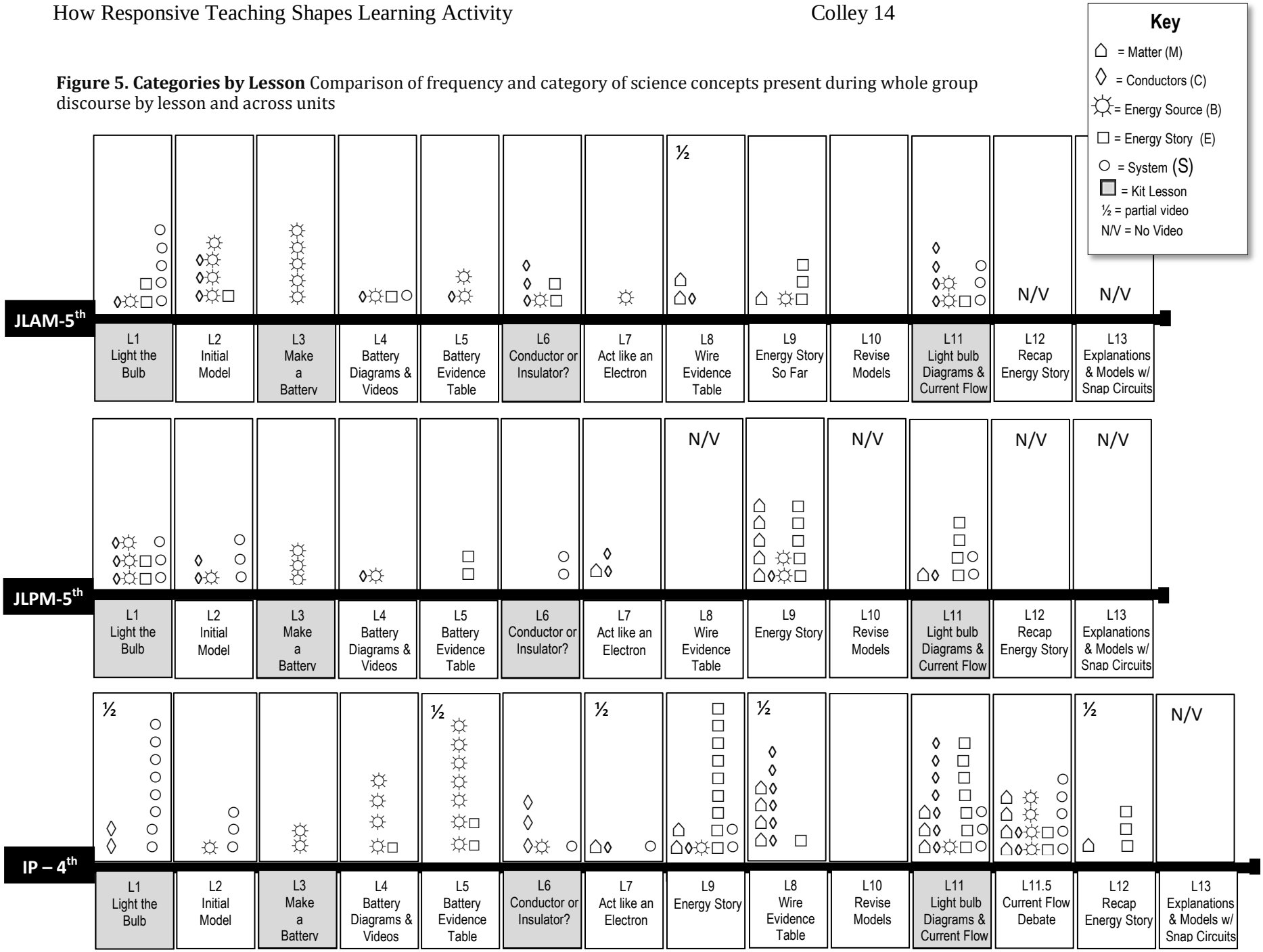
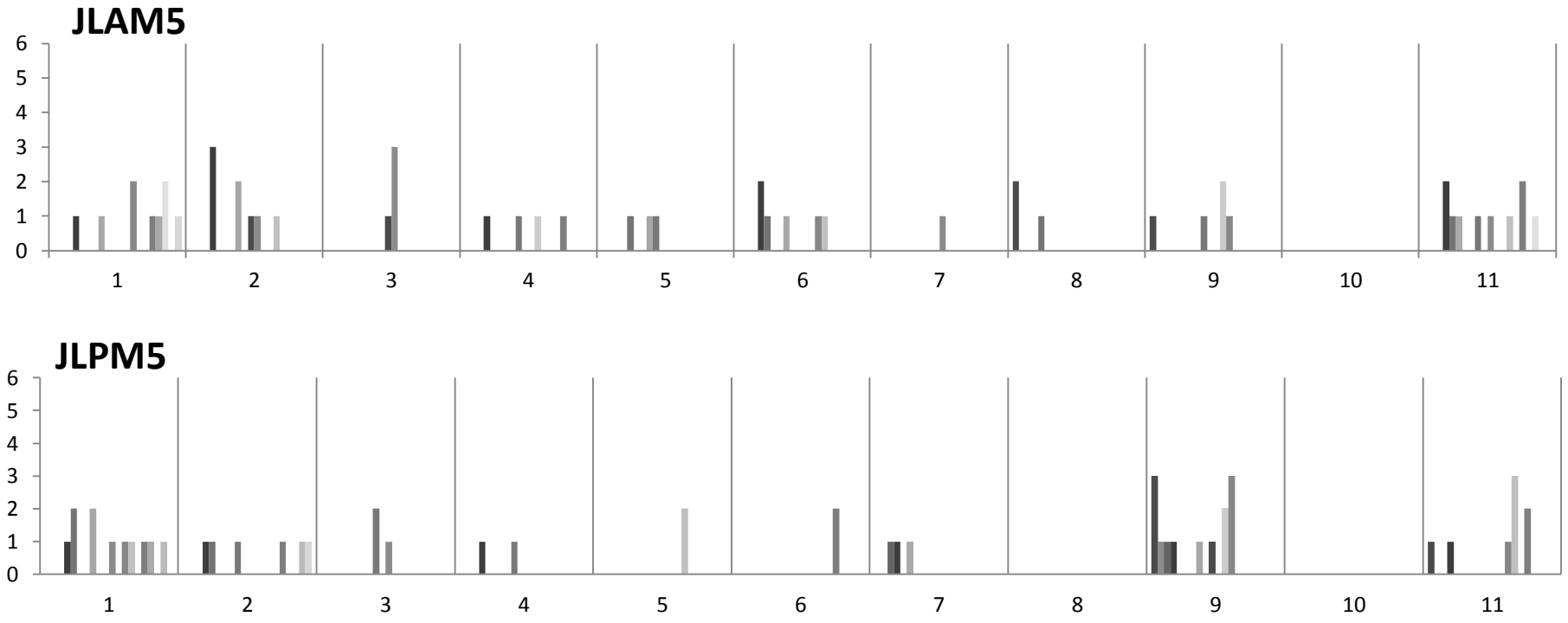
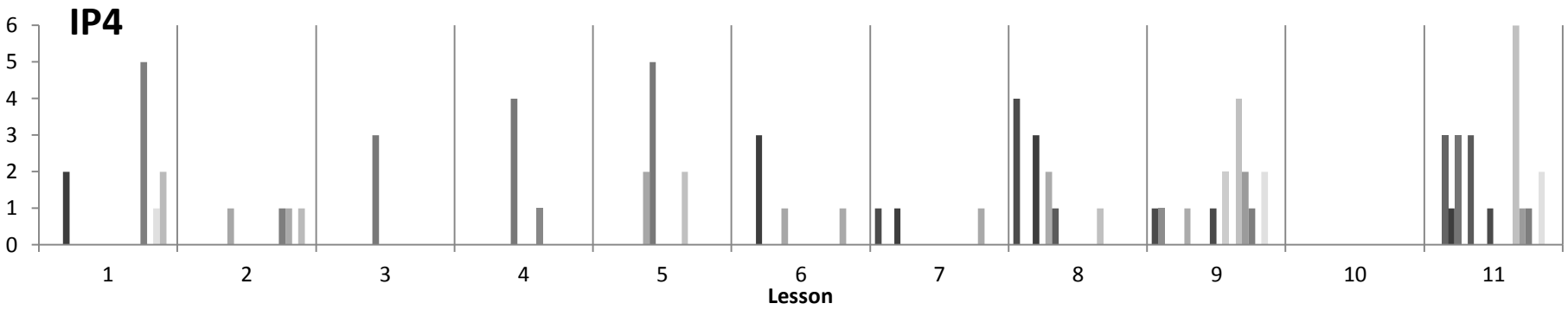


Figure 6. Concepts by lesson. This figure shows the frequency and diversity of science concepts represented per lesson. There are 20 frequency bars, one for each of the 20 targeted science concepts, in the order form M1 through S5 (left to right) within each lesson space.




IP4
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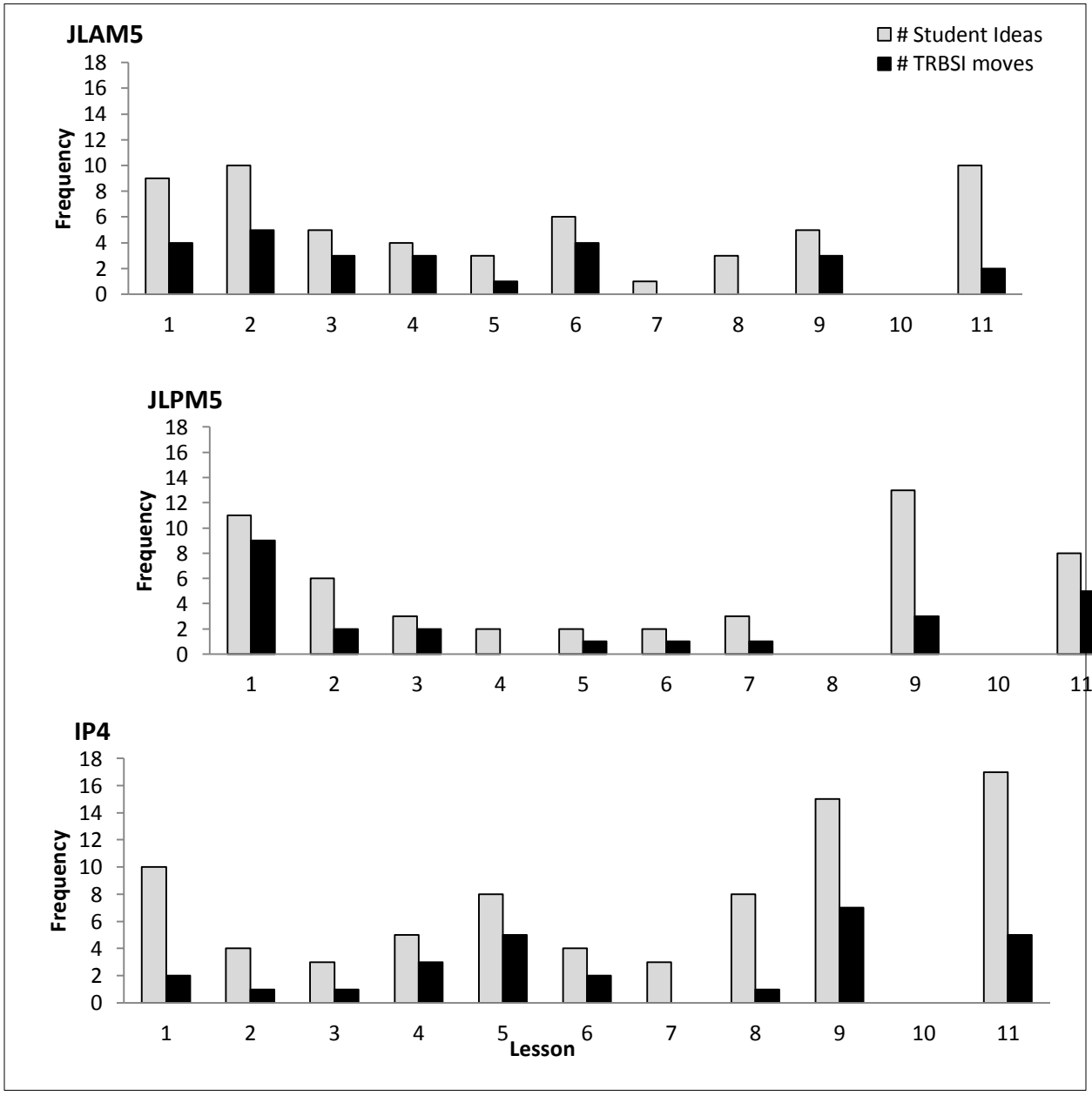
10
11
Lesson

Figure 7. Teacher Responsiveness to Student Ideas. This figure compares the frequency of student ideas and teacher's responsive utterances by lesson.



Description of the Unit by Teacher's Productive Responsiveness (TRBSI). The percentage of student's science ideas the teacher was able to productively engage (teacher antecedent caused a productive student response) over the course of the entire unit during whole-group discourse was 45% for Mr. Lancaster's morning class (JLAM5), 48% for the afternoon

class (JLPM5), and 35% for Ms. Preston's class (IP4). Figure 7 shows a comparison between the total number of student ideas and teacher's productively responsive moves decomposed by lesson. The number of productively responsive teacher utterances is always lower than the number of student ideas 'in play' in the whole-group discourse. The gap between number of student ideas and teacher's productively responsive prompts varies widely for particular lessons (i.e. Lesson 6 across three classrooms) and across the unit.

Discussion

Explaining Variability: Frequencies of Science Concepts and Categories. As figures 4, 5, and 6 indicate, there was a wide variety in the frequency of concepts appearing throughout whole-group discourse, across the unit and between classes. There are several possible reasons which would explain a low frequency of science concepts during whole group discourse. A low frequency may have occurred because (1) the activity influenced the kind of talk required of students, (2) the student talk was observation-centered regardless of the intent of the activity, or (3) these concepts were shared another way besides at the whole-group level during the lesson (i.e. small group level: pair-share, table group, or individual-level notebook inscriptions).

The difference in the intellectual demands of an activity might explain a difference in frequency. Consider Mr. Lancaster's afternoon class (JLPM) in lessons 3 and 9 using figure 5. Even though the average words per minute spoken by students during whole group discourse is similar (27 and 24 words per minute, respectively), the number of concepts "on the table" varies from 3 to 13. In this case, the purpose of the lesson likely influenced the type of talk students engaged in. Lesson 3 was focused on observations about the battery as an energy source. Students spent more utterances relating and confirming observational data than engaging in sense making. On the other hand, Lesson 9 had primarily an explanatory focus providing students the time to link

previously learned concepts together to make sense of how energy transfers and transforms in a flashlight circuit. An alternate explanation for a higher frequency and diversity of concepts in lesson 9 is merely because it is farther along in the unit. Students have had multiple prior experiences related to these concepts; therefore it is reasonable to observe an increase of ideas. However, looking at Lesson 7, a lesson also further along in the unit, there is a low frequency of science concepts. Lesson 7 was an interactive content injection about particles that make up matter. Talk mostly centered on observations of electron animations and observations of students acting like electrons, so very few concept ideas existed in the whole class space.

A low frequency of ideas present during whole group talk may also mean that these ideas were shared in another space, i.e. in a pair-share or table group conversation. The assumption cannot be made that a low frequency of concept in a whole group setting means that students were not considering these ideas; just they were not doing so as a whole group. For example, lesson 10 (Revising Models) stands out across all classrooms as appearing to have no science concepts present in whole-group discourse; however, whole group "talk" was not discourse per se but rather the teacher provided directions and offered students a chance to clarify activity expectations. Most intellectual work and concept use happened during the activity when students wrote feedback on sticky notes during a gallery walk looking at other small group's model revisions. This type of lesson positions students as sense-makers and as scientists (i.e. critiquing and communicating about ideas and evidence), but does not do so during whole group discourse; therefore, from a whole-group discourse analysis, the type of lesson does not present any science concepts.

Students may have also shared their thinking before or during whole-group discourse during a pair-share. In JL-PM Lesson 6, students did a pair-share after the activity to talk about

the trends and patterns about conductors and non-conductors. The teacher listened in on student pair-share to see what students understood about conductors or if there were lingering questions; however, since this talk was not part of the public whole group discourse, these ideas were not counted in the total. This partly explains why JL-PM Lesson 6 has no ideas about conductors and insulators in whole group discourse even though that was the primary focus of the lesson. Conductors and insulators were the topic of the pair-share. The pair-share was employed in JL-PM to respond to the fact that many students wanted to speak and there was limited time left in the science period. By pair-sharing, students were able to verbalize their thinking and also hear how the lesson sense to others in a timely manner. In JL-AM and IP for Lesson 6, they did not pair-share but had more time left in the period to do this thinking in whole group talk. This is likely why both JL-AM and IP had six science concepts arise during whole group talk, while JL-PM only had two.

A high frequency of ideas during whole group talk could either mean that multiple students share individual concept statements or that one student pulled one or more concepts together in their sense-making talk. A discourse-level analysis, rather than unit-level, is required. For example, lessons 1 and 2 have a higher frequency of ideas than in subsequent lessons. Lessons 1 and 2 were designed to give students hands-on observation of a simple circuit and provide a space and time to record their initial ideas and hypotheses. Lesson 1 had more time for whole group discourse than Lesson 2 where students used more class time to inscribe their ideas. Because the focus of lessons 1 and 2 was on eliciting students initial ideas, it is not surprising it has a higher frequency than some other lessons. Whole group discourse towards the end of the unit (lessons 9 and 11) was intended to allow time for students to pull ideas together.

Here it would be more likely to find one student using multiple science concepts together as part of an explanation.

A general trend shown by figures 4, 5, and 6 indicates an increase in either the frequency of particular concepts and categories or an increase in the diversity of concepts represented by students in whole group discourse as the unit progresses.

Explaining Variability in Teacher Responsiveness. Because of the way in which productive responsiveness is conceptualized in this paper (i.e. it only counts if any student responds to a teacher's prompt by building on the initial idea.), the teacher's ability to be productively responsive is contingent upon two factors: (1) students initially sharing their thinking to the whole group either spontaneously, by asking or answering a question, or by responding to another student's idea, and (2) the teacher's prompt succeeds in resulting in further discourse about the idea 'in play.' Both of these factors pose unique challenges while negotiating whole-group discourse. The teacher cannot pose a responsive prompt unless a student idea has been shared first.

In the following excerpt, there was an inverse relationship between the intellectual demand of teacher prompts and student contributions. The teacher's questioning trajectory begins at the explanation-level ("What made it change?") then shifts to an observational question ("Where does it change?") and finally a question that could be answered yes or no ("Have you seen that?"). Whereas the level of student utterance increased in sophistication from a one-word shout out, to a vague conceptual claim, to more specific observations, finally students proposed a partial causal hypothesis. Justine explicitly states she agrees with Josie's suggestion that the energy transformation happens in the filament but adds on her own reasoning as she coordinates

what she understands about the relationship of friction and heat energy to propose a causal reason about what's happening inside the filament that could cause the energy transformation.

Figure 8. Transcript excerpt from Ms. Preston's class (Lesson 9)

Line	*Transcript Excerpt from IP4.L9*
54	**Teacher: What made the energy transform?**
55	Zach: THE WIRE!
56	**Teacher: What wire? What made it transform?...In our flashlight system what makes the energy**
57	**change from inside the wire being electrical then it comes out as light and heat? What makes it**
58	**change? What do we think?...Annabelle?**
59	Annabelle: Well, there might be like something in the light bulb that once electricity comes in that it
60	changes or something to change the energy.
61	**Teacher: So then the question that I thought of when you said that, is at what point does it**
62	**change? Does it change to light energy here? here? here?** [pointing at different places in light bulb
63	diagram] **At what place does that change happen? Oliver?**
64	Oliver: In the filament.
65	**Teacher: In the filament, that's that squirrely piece of wire in the middle. It's the thin piece, the**
66	**curly Q piece of wire. He says that that's where it turns into light....How do you know that,**
67	**Oliver?**
68	Oliver: I just guessed.
69	**Teacher: Have you seen that part light up before?**
70	Oliver: Mm-hmmm… It generates it usually it just is two wires on either side. I could see there's two
71	wires and then the light is in the middle.
72	**Teacher: Okay. Josie, then Justine.**
73	Josie: So I think that I agree that it changes in the filament thing and I think that it changes there
74	because it's so curly Q'ed so tightly that the energy rubs against each other which makes a spark and
75	makes light.
91	Justine: I agree with both about how the heat, how it creates the heat but when it creates the light, not
92	creates, changes… in the filament … because [electrons] are so tightly packed but I think it's a
93	difference in metal which is why it changes when it goes from a battery to the wire it's because it's a
94	change… I mean we don't know that but it does change…

There are only two teacher prompts (lines 56-58 and line 69) that can be coded for as being productively responsive because they are responsive to a prior student comment and result in students' contributing to or building onto an idea (Annabelle, Josie, and Justine). The other teacher prompts (lines 61-62 and 65-66) may still be considered a responsive press but both attempts fail to further discourse and yield students building on a science ideas so they are not coded as being productive.

Furthermore, not every student idea was able to be pressed by the teacher or other students because of the nature of whole-group talk. Students frequently talk over each other, conversation is cut off because of time constraints, or the purpose of a section of whole-group talk is about idea generation than a press for sense making. Finer grained discourse analysis would provide information about the types of utterances both teachers and students employed and when.

Responsive Teaching Tensions and Dilemmas

Patterns of interaction are negotiated between teachers and students and cannot be determined by the teacher alone because of the unpredictable nature of discourse (Pierson, 2008). Given the unpredictable nature of discourse, one of the teacher's roles becomes that of negotiator between curriculum demands, science concepts, and students' science ideas. The teacher guides the discourse to keep it loosely within the bounds of what is required for students to understand in order to construct a causal explanation and meeting curriculum goals while also allowing flexibility in the discourse to follow through on in-the-moment student questions. The difference between guiding the discourse trajectory and following a fixed trajectory is that the teacher uses student utterances to negotiate the discourse trajectory. The overarching anchoring phenomenon helps bound and focus students' questions and ideas such that their 'tangential' comments would

not be as unrelated as student inquiries that would arise in a traditional classroom. Deciding when to let curriculum demands or student ideas lead the discourse trajectory is one of many dilemmas that arise as part of responsive teaching.

Tensions between curriculum demands and students' science ideas. When teaching responsively, students ask questions, tell stories, or pose hypotheses that go beyond the boundaries of the unit's curriculum goals. Therefore, the teacher needs to be able to negotiate the purpose of the discourse with students, in-the-moment, by listening to student thinking, comparing it to science concept targets, and deciding how much, if any, additional whole-group discourse should be devoted to pursuing this line of thinking. Two examples are provided to illustrate how such a tension arises in practice during whole-class discourse and how the teacher chose to manage the tension in a particular moment.

Example 1: Respectful Redirection. In this example, the teacher redirects the conversation to one student's question while respectfully not pursuing another students' question. In lesson 9 for Mr. Langston's afternoon class, students were fascinated by how batteries can be rechargeable. In the excerpt below, the teacher attempts redirection and finally respectfully redirects the conversation to a science idea (how batteries discharge) that is crucial for the causal explanation as well as being within the boundaries of the unit curriculum (with regards to types of energy and transformations of energy). Notice the negotiation between teacher and students as the teacher tries to refocus the conversation around the original question posed by a student about how does energy run out of the battery.

Figure 9. Transcript excerpt from Mr. Langston's afternoon class (Lesson 9)

1	Melissa: How does it run out?
2	**Teacher: That's the question, right?**
3	Doug: It's using too much energy.

Leah: Because it took the energy.
Greg: Because electrons have to go back into it and then transform the gel to the other electrons.
Mose: They're thieves, stealing energy.
Teacher: Okay… Juliana?
Juliana: I have a question
Teacher: Okay a question.
Juliana: They say that all the chemicals inside the battery are dead. How do we recharge batteries?
Geavonni: Oh yeah!
Teacher : There are different kinds of batteries. There are the batteries like in my cell phone, I don't throw my phone away every time my battery dies. I recharge it. So my guess is that those batteries are made of different chemicals. Rather than the Duracell, the batteries we've been using in class that once they die you can't recharge them. But my question back to you is, before we get to recharging, let's cover when a battery dies.
Student (mumble): What happens [inaudible: chemical used up]?
Teacher: When he says the chemicals get used up...
Student (mumble): Where does it go?
Teacher: What do you mean they get used up? …Do you, or is your question related to batteries dying?
Greg: Yeah
Teacher: Okay, go ahead.
Greg: When it dies, how does it…because you can, you can charge D-cells, you can buy a battery charger at the store and plug it into the wall and charge them.
Teacher: Let's hold the recharging thing, until we've mastered the dying thing. (Students laugh.) **Because first it has to die before you want to recharge it, if you even can. But let's get though the, "What do you mean chemicals run out?" first. I believe Mr. Langston showed you something last week that might help us with the conversation…yes?**
Greg: I think that in the battery there's like gel and it needs to like the electrons inside want to get to the electrons outside.

The teacher twice attempts to purposely and respectfully redirect the trajectory of the conversation (line 16; lines 26) to the original question posed by the student in line 1. As the discourse proceed from lines 30-31 onward, the discourse trajectory is redirected around how students think chemicals "are dissolved" and where the energy goes. The teacher had content

knowledge about the student's question and knew it would take students far beyond what they needed to know. Not that that alone should be a reason to curtail the inquiry; however, the space of whole-group discourse may not be the proper venue to continue the conversation.

Example 2: Leveraging an Experience. In this example, the teacher allows a shift in discourse trajectory because of a combination of student interest in a topic and its relationship to the concept energy transfer. Prior to Ms. Preston's science class, students were using glue guns for a project and some accidentally burned fingers on the hot glue before it cooled. They noticed it was soothing to touch metal which felt cool compared to touching other materials. This observation came up in whole-group discourse (lesson 8) which caused the majority of students to erupt in chatter about their personal experiences and observations. Employing a pair-share, the teacher allowed students to discuss thermal conductivity (though they did not use that term) in pairs. In whole-group discourse, post pair-share, plastic and metal were also discussed as insulators and conductors of heat energy as well as electrical energy. Then the teacher used the glue gun system later in the discourse to have students generalize about energy transformations. Though the curriculum expectations specify students understanding which materials demonstrate electrical conductivity, the idea of thermal conductivity is still within the boundaries of science concept of energy transfer.

Tensions between science ideas and student ideas: Being "wrong*".* Because a responsive teacher shares the authority in classroom discourse by positioning students as intellectual stakeholders, the dilemma arises about what to do (and when to do it) if the student says something that is incongruent with the current scientific understanding. What should a responsive teacher do if a student says a "wrong" idea? In lines 30-31 in Mr. Langston's excerpt above (Figure 9), Greg's statement that "electrons inside want to get to electrons

outside" is not technically correct; however, the general idea he's describing about attraction between particles is actually part of the explanation of what causes current to flow from a battery. When students' ideas are being used as intellectual resources in the classroom, it is unfair to judge them as correct or incorrect. But rather, teachers can employ a reconciling process (van Zee et al., 2005) whereby students are pressed to reconcile their idea with current evidence if relevant experiences have already been provided, or are provided with new experiences that require students to modify their claim. Reconciling can also happen for two divergent student ideas. For example, in Ms. Preston's class, lesson 11.5 was added to help students reconcile two opposing hypotheses, one of which was scientifically accurate and the other was not, through exposure to new experiences.

Tensions around Student Participation. In order to be responsive to students' science ideas, students must publicly share their ideas, putting them 'in play' for others to use as resources. Too much participation creates its own dilemmas as does too little.

At times student participation in the whole-group discourse was characterized by "short talk," one word utterances or short observational phases. Since responsive teaching needs ideas 'in play' it required more effort to elicit thinking beyond sharing observations. This does not mean that students do not have ideas, but it takes more probing to access student thinking. For example in lesson 3, Mr. Langston's students pair-shared after the make-a-battery activity to generate hypotheses about why a battery might die based on their experiences making one. The teacher engages in multiple attempts at revealing student thinking which finally results in one student idea (line 9) revealed in this excerpt. The students' initial statements are observations about what happened.

Figure 11. Transcript excerpt from Mr. Langston's morning class (Lesson 3)

1	**Teacher**: **Tierra, you and Melina were talking. What did you guys talk about?**
2	Tierra: Um we talked about uh the in our battery the vinegar dried out thing...
3	**Teacher: If the vinegar dried up, then what happened?**
4	Melina: It doesn't work.
5	Tierra: It just stopped.
6	**Teacher**: **[…] What do you think about that if we have a dead battery? Like we had…**
7	Jake: The acid's gone.
8	**Teacher**: **So the acid's gone, but where would it have gone?**
9	Jake : It would have gone into the energy and to the light.
10	**Teacher: Hmmm... so what did we learn about batteries? Could I put if the acid goes away or is**
11	**used up or the acid... how could I put that?**

During whole-class discourse, which students participate and for how long represents another tension. With an objective of engaging in progressive discourse to incrementally build meaning, connecting and merging ideas is essential. However, when the majority of students has their hands raised wanting to share, the dilemma is this: It will take too long to have each student share individually, not to mention the discourse would transform into a disjointed laundry list of ideas; however, by choosing to hear from some students and not others creates a problem of equity. In some of these situations, the teacher used a pair-share to allow all students to share their thinking with at least one other person. Then pairs were asked to volunteer to share whole group.

Another example of "too much" is having one student share for a long time without manipulating ideas. In lesson 9 in Ms. Preston's class, students were proposing hypotheses about how and where they thought the light bulb transformed electrical energy into light and heat energy. Two students built onto a developing hypothesis about they think the filament causes the transformation (see Figure 8 transcript excerpt). After Justine's contribution, another student

relays a camping experience with his dad and using a flint fire starter to create sparks, prefacing his story with "it's something about making heat energy." The teacher allowed one student to share for over a minute and a half of the sixteen minutes of whole group discourse during this lesson. Time is a constant pressure within a lesson. However, part of responsive teaching is allowing students to try out ideas, hypotheses, life stories that they think may be connected but aren't sure. He was also a student that normally does not demand a lot of "air-time" during whole-group discourse. So allowing him the time to talk, even though perhaps all the details he included in his description were not necessary for the energy transformation conversation at hand.

The final type of dilemma during whole-group discourse is how long the teacher should press one student about their idea while others are waiting to contribute. Again the transcript from figure 8 shows an example of the teacher's press on Oliver about his claim that the filament was where energy transformation happened. The teacher attempts multiple times to get Oliver to tell more about his claim that "the filament" was what changed the energy. Finally the teacher moves on to other students after Oliver gives a more detailed observation, though he did not offer a causal hypothesis which was the teachers' intention for the press.

Part of this dilemma would be alleviated if classroom climate and class norms reinforced student-student talk as part of what should happen during whole-class discourse. Instead of the teacher pressing or probing, students could engage in these talk moves with each other. This level of student-student responsive discourse only happened in Ms. Preston's class and only during lesson 11.5 which was the lesson added for students to debate current flow. Kevin and Alex presented their "One Way" current flow hypothesis to the class and are now taking questions about various parts of the current flow.

Figure 10. Transcript excerpt from Ms. Preston's class (Lesson 11.5)

1	Josie:	I agree with your guys' theory and I just thought that what you guys said wasn't super clear
2		about how the light, how the light energy is converted into...[…]…Well I was thinking about
3		that the, so when it goes up the support wire that's connected to the positive terminal, it, the
4		filament is a lot smaller than the support wires so the electrons are more squeezed, I guess?
5		So basically I think that they might go slower than they usually do, so that would cause um
6		some of the other electrons to bump more and then create friction which if you've ever rubbed
7		your hands together, rubbed them on the carpet or your jeans or whatever pants, it gets really
8		hot so if metal gets hot enough it will glow or friction can also make a spark so I think that
9		that's how the bulb lights up but I literally have not a clue about the bead.
10	Alex:	I sort of agree with you. I also think that it's a circuit so it probably isn't that it goes through
11		both wires. I think that when it comes up through the copper wire or the support wires I guess,
12		there of course is atoms in the support wires so it'll also bump with the atoms too to make it
13		glow. Yesterday I was watching the bright light bulbs and I could see the filament glowing.
14	Kevin:	Annabelle?
15	Annabelle	So I disagree I sort of, I'm not sure which one I totally agree with to where the [inaudible] but
16		the one I guess we're [inaudible] is if it goes back into the D-cell then when how would it...
17	Gina:	How would a D-cell ever run out?
18	Annabelle:	Then the D-cell would just keep getting the energy back, I guess?
19	Alex:	Well I think that something about the chemicals like there's chemicals inside it that ...okay
20		wait, let me think this through. ..
21	Kevin:	So um you know what's inside a battery right? A bunch of stuff, energy, acid, well the
22		electrons push it through causing the reaction to happen again and then it keeps pushing
23		through and then eventually the chemical reaction gets wasted or well not wasted but used
24		up, so when it pushes it nothing happens.
25	Annabelle:	That does make sense.

Revisiting Productive Responsiveness.

In order for teacher to respond to student ideas in a way that treats their ideas as intellectual resources, the teacher requires deep content understanding and ability to make connections or ask questions to help students engage in the intellectual work to make these

connections. The teacher engages in constant intellectual work to identify pieces of student ideas and decide if and when to reign in and refocus the ideas that are in play. Attending to the details of student's understanding is necessary but not sufficient for helping teachers decide how to respond (Jacobs et al, 2009). Teachers must know how to engage students in rigorous, intellectual work of connecting ideas, comparing hypotheses, and engaging in argumentation. The teacher chooses to foreground a particular student idea if it could potentially help students make sense of the science phenomena in question and may background tangential ideas, at least in the particular moment. This choice to either superficially acknowledge or truly engage with a students' idea is not based on scientific merits or "correctness" or the ideas but rather on the ability for the fundamentals of these ideas to be leveraged to help students make sense of material activities and also meet (or exceed) curricular learning goals. As the teacher listens to students' contributions she deconstructs the utterance, making note of the language the student uses, the partial and alternative ideas the student shares, as well as mentally mapping the pieces the student is offering onto the science concepts students need to understand in order to explain the larger science phenomenon. This work becomes challenging when a question or idea posed by the teacher results in short responses from students such as one-word or phrase answers.

By teaching in a way that is responsive to students' science ideas, lessons are not expected to go as planned. This happens because students, as equal intellectual participants, share unexpected but valuable experiences and ideas which the teacher or other students may choose to expound upon in-the-moment, shifting the planned trajectory of the lesson. Other actors must decide in the moment how to judge if the experiences or ideas have utility in helping understand a concept at hand. Some ideas may not persist publicly beyond those moments in a

longer conversation, but others evolve because of their utility in explaining the phenomena and the teacher and students continue to use and develop them.

Because of the unpredictable and negotiated nature of discourse, there are no guarantees that particular discourse moves will necessarily result in students engaging in progressive discourse. The transcript excerpt in figure 8 is one example of how the student contributions seemed to progress while the type of teacher question or prompt downshifted from causal question to observational level. Though particular ways of questioning may be more likely to elicit ideas or have students connect ideas. A finer-grained discourse analysis of each turn-of-talk would be required to make claims about the productive nature of particular antecedents.

Conclusion

Teaching in a way that is responsive to students' ideas requires flexibility. Lesson and unit trajectories will change as a result of responding to students' hypotheses and science ideas that are 'in play' for each class. The ideas present during whole-group discourse varied for each class by lesson; however, looking across the unit, all three classes addressed the majority of targeted science concepts, only at different times during the unit. Being responsive to students' science ideas, does not mean teachers abandon standards or chase tangential lines of inquiry that are of interest to students and have no bearing on curriculum. Productively responsive science teaching requires negotiating students' ideas, science ideas, and curriculum demands within a discourse space.

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