RESPONSIVE TEACHING IN
SCIENCE AND MATHEMATICS

Answering calls in recent reform documents to shape instruction in response to students’ ideas while integrating key concepts and scientific and/or mathematical practices, this text presents the concept of responsive teaching, synthesizes existing research, and examines implications for both research and teaching. Case studies across the curriculum, from elementary school through adult education, illustrate the variety of forms this approach to instruction and learning can take, what is common among them, and how teachers and students experience them. The cases include intellectual products of students’ work in responsive classrooms and address assessment methods and issues. Many of the cases are supplemented with online resources (www.studentsthinking.org/rtsm), including classroom video and extensive transcripts, providing readers with additional opportunities to immerse themselves in responsive classrooms and to see for themselves what these environments look and feel like.

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RESPONSIVE TEACHING IN SCIENCE AND MATHEMATICS

Edited by Amy D. Robertson
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Responsive teaching, at heart, celebrates the “having of wonderful ideas” (Duckworth, 2006). It stems from several foundational assumptions: that students come to classrooms with a wealth of productive knowledge and experience; that this wealth is too rich and diverse for teachers and curricula to know it in advance; and that students should learn to be the agents of their own learning. From these assumptions comes the stance that teaching begins with watching and listening. Responsive instruction foregrounds the substance of students’ ideas, seeks out disciplinary connections within students’ ideas, and adapts or builds instruction on the basis of students’ ideas. Hammer, Goldberg, and Fargason (2012) write:

A responsive approach . . . is to adapt and discover instructional objectives responsively to student thinking. The first part of a lesson elicits students’ generative engagement around some provocative task or situation (or, perhaps, by discovering its spontaneous emergence). From there, the teacher’s role is to support that engagement and attend to it—watch and listen to the students’ thinking, form a sense of what they are doing, and in this way identify productive beginnings of scientific thinking. In this way, the teacher may select and pursue a more specific target, in a way that recognizes and builds on what students have begun.

(p. 55)

Responsive teaching is increasingly the focus of teacher education and research. It responds to calls in recent science and mathematics reform documents (National Committee on Science Education Standards and Assessment, 1996; National Council of Teachers of Mathematics, 2000; National Research Council, 2012; Next Generation Science Standards, 2013) that instruction (i) integrate key
concepts and scientific and/or mathematical practices and (ii) shape instruction on the basis of students’ ideas. Ball (1993) describes this approach as both responsive to students and responsible to the discipline. Responsiveness

- enhances students’ conceptual understanding (Carpenter, Fennema, Peterson, Chiang, & Loef, 1989; Empson & Jacobs, 2008; Fennema et al., 1996; Fennema, Franke, Carpenter, & Carey, 1993; Goldberg, 2012; Hiebert & Wearne, 1993; Kersting, Givvin, Sotelo, & Stigler, 2010; Pierson, 2008; Saxe, Gearhart, & Seltzer, 1999);
- promotes student agency and voice (Coffey, Hammer, Levin, & Grant, 2011; Gallas, 1995; Lemke, 1990; Levin, 2008); and
- promotes equitable participation by seeking to understand the ideas that all students—including those from culturally, linguistically, and socioeconomically diverse communities—bring to the classroom (Empson, 2003; Gallas, 1995; Hudicourt-Barnes, 2003; Michaels, 2005; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001; Warren, Ogonowski, & Pothier, 2005).

For these reasons and others, the recent shift in attention toward practices of teaching—rather than skills—includes “attending and responding to student thinking” among “high leverage” or “ambitious” practices (Ball & Forzani, 2009; Lampert, Beasley, Ghousseini, Kazemi, & Franke, 2010; Lampert et al., 2013; Thompson, Windschitl, & Braaten, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012).

This book is for readers interested in the current state of research, including some of the pressing questions that future research may pursue. It grew out of our sense that responsive teaching is a key emerging area in science education, and that a number of researchers are beginning to make progress in documenting and understanding its instructional power. We began with a small conference held at Seattle Pacific University in 2013, with the goals of clarifying what our disciplines have to say about responsive teaching, envisioning future research directions and fostering inter-institutional collaborations. The conference involved presentations and video analysis sessions designed to bring out participants’ diverse assumptions, as well as areas of consensus. Many of the participants traced their inspiration to similar sources, including classic studies by Ball (1993) and Goodwin (1994) and more contemporary work by Hammer and colleagues (Hammer, 1997; Hammer & van Zee, 2006). However, there were also substantial differences in the ways that various participants conceptualized responsiveness. Those similarities and differences are reflected in the chapters to follow.

The first two chapters introduce the idea of responsive teaching (Chapter 1) and synthesize existing research on teacher responsiveness in science and mathematics (Chapter 2). Chapters 3–11 unpack the substance of what teachers are doing as they respond to student thinking. These chapters address topics including
the intellectual products of students’ work in responsive classrooms (Chapter 3), how teachers and students experience responsive teaching (Chapters 4–6), additional constructs that may enhance our study of responsive teaching—such as affect, framing, and pedagogical content knowledge (Chapters 7–9), and methods for and considerations in assessment (Chapters 10 and 11).

The particular contexts include a variety of grades and science disciplines. There are supplemental documents for many of the cases, including video and extensive transcripts, which we make available at http://www.studentsthinking.org/rtsm. These provide readers with additional opportunities to immerse themselves in responsive classrooms and to see for themselves what these environments look and feel like. We hope to bridge multiple communities—K–12 and university, research and practice—by drawing from examples across the curriculum and by examining implications for both research and teaching.

Finally, this book came to be because of the thoughtful contributions of many. To the teachers whose classrooms we studied, we thank you for making your incredible work visible to us and for the privilege of sharing it with the world. To the conference participants whose ideas and feedback brought this book to life—Carolina Alvarado, Leslie J. Atkins, Leema Berland, Jessica Bishop, Eleanor Close, Hunter G. Close, Janet E. Coffey, Luke Conlin, Abigail R. Daane, Sharon Fargason, Brian W. Frank, Fred Goldberg, Kara E. Gray, Paul Hutchison, Lama Z. Jaber, Matty Lau, Daniel M. Levin, Jennifer Evarts Lineback, Melissa J. Luna, April Cordero Maskiewicz, Sam McKagan, Jim Minstrell, Jennifer Radoff, Jennifer Richards, Rosemary S. Russ, Miriam Gamoran Sherin, Tiffany-Rose Sikorski, Chandra Turpen, Jessica Watkins, and Michael C. Wittmann—this book is yours as much as it is ours, and we feel privileged to be a part of your community. To Naomi Silverman, commissioning editor, and all the folks at Routledge involved in bringing this book to publication, and to Norman Lederman, Teaching and Learning in Science Series Editor—thank you for seeing the potential of our work, and thank you for seeing it through to publication. To the administrative team at Seattle Pacific University—Kathryn Houmiel and Leanna Aker—to whose copyediting eyes and logistical savvy we owe the consistency of our APA formatting, as well as the presence of coffee at our conference, thank you: your work is important to us. And finally, to the people whose gentle care and shared passions shepherded us through the day—Justin Robertson, Dale Hailey, and Lauren Hammer—thank you; we couldn’t do this work without you.

Further Reading for Teachers and Teacher Educators


Responsive Teaching in Science website [Online]: http://cipstrends.sdsu.edu/responsive-teaching/


**References**


WHAT IS RESPONSIVE TEACHING?

Amy D. Robertson, Leslie J. Atkins, Daniel M. Levin, and Jennifer Richards

This book is about responsive teaching in science and mathematics. Before we explore nuances in the nature of responsive teaching, challenge common assumptions in the literature, and connect responsive teaching to other, relevant constructs—as do many of the chapters in this book—we first offer a rough sketch of what it is and what it looks like in practice. Our goal in doing so is not to make distinct analytical points or to add to the literature by challenging notions of responsive teaching; it is to give examples of responsive teaching and to show how each one instantiates this kind of instruction—to illustrate the phenomenon, so to speak, and to establish shared meaning for responsive teaching before we explore it together in the rest of the book.

Although different researchers, teachers, and teacher educators conceptualize, measure, and enact responsive teaching in distinct ways, there are certain themes that recur across conceptualizations and instantiations. In particular, the literature highlights that responsive teaching involves:

(a) Foregrounding the substance of students’ ideas. Responsive teaching involves attending to the meaning that students are making of their disciplinary experiences (Ball, 1993; Brodie, 2011; Carpenter, Fennema, Franke, Levi, & Empson, 2000; Coffey, Hammer, Levin, & Grant, 2011; Colestock & Linnenbringer, 2010; Duckworth, 2006; Gallas, 1995; Hammer, 1997; Hammer, Goldberg, & Fargason, 2012; Hammer & van Zee, 2006; Jacobs, Lamb, & Philipp, 2010; Lau, 2010; Levin, Hammer, Elby, & Coffey, 2012; Levin, 2008; Levin, Hammer, & Coffey, 2009; Pierson, 2008; Schifter, 2011; Sherin, Jacobs, & Philipp, 2011; Sherin & van Es, 2005, 2009; van Es & Sherin, 2008, 2010; Wallach & Even, 2005). It instantiates intellectual empathy, in that a primary aim of a teacher listening is to understand and be present to his
or her students’ thinking, rather than to evaluate or correct it. Teachers go beyond attending to whether or not students are sharing their ideas; they try to understand what students are saying, from the student’s perspective.

(b) **Recognizing the disciplinary connections within students’ ideas.** Responsive teaching is *disciplinary* in that the teacher listens for nascent connections between students’ meanings and the discipline (Ball, 1993; Chazan & Ball, 1999; Gallas, 1995; Goldsmith & Seago, 2011; Hammer, 1997; Hammer et al., 2012; Hammer & van Zee, 2006; Hutchison & Hammer, 2010; Jacobs, Franke, Carpenter, Levi, & Battey, 2007; Jacobs et al., 2010; Levin et al., 2012; Russ, Coffey, Hammer, & Hutchison, 2009; Schifter, 2011; Sherin & van Es, 2005), including “disciplinary progenitors” (Harrer, Flood, & Wittmann, 2013) or “seeds of science” (Hammer & van Zee, 2006). These seeds may be, for example, the beginnings of canonical understanding, the instantiation of specific scientific practices, or the affective experiences that promote experiences of pleasure in doing science. They may include children’s puzzlement over a phenomenon, their citing evidence to support an idea, their efforts toward precision, their using mechanistic reasoning (or the beginnings of it) to support their predictions or explanations, or their devising an informal experiment or suggesting an explanation; they could be the first flickers of scientific concepts, such as a sense of air as material, of living organisms as needing energy, or of energy as needing a source. In responsive teaching, the teacher “consider[s] the [discipline] in relation to the [students] and the [students] in relation to the [discipline]” (Ball, 1993, p. 394).

(c) **Taking up and pursuing the substance of student thinking.** Responsive teaching is *responsive* because it takes up and pursues the substance of student thinking (Ball, 1993; Carpenter, Fennema, Peterson, Chiang, & Loeffer, 1989; Colestock & Linnenbringer, 2010; Empson & Jacobs, 2008; Fennema et al., 1996; Fennema, Franke, Carpenter, & Carey, 1993; Gallas, 1995; Hammer, 1997; Hammer et al., 2012; Jacobs et al., 2010; Jacobs, Lamb, Philipp, & Shappelle, 2011; Lau, 2010; Levin et al., 2012; Lineback, 2014; Maskiewicz & Winters, 2012; Pierson, 2008; Russ et al., 2009; Schifter, 2011; Sherin & van Es, 2005). The short-term and, in some cases, long-term direction that the classroom activity takes emerges from the students themselves and from the connections that teachers and, in some cases, students make between students’ reasoning and the discipline. Teachers may, for example, invite students to assess one another’s ideas, draw connections between students’ ideas themselves, encourage students to design and conduct experiments to test their ideas, or plan entire units of inquiry that take up a student’s question.

This kind of teaching is grounded in an empirically and theoretically supported expectation that students’ intuitive thinking about science is productive and resourceful (diSessa, 1993; Hammer, 1996, 2000; Hammer, Elby, Scherr, & Redish, 2005; Hammer et al., 2012; Hammer & van Zee, 2006; May, Hammer, & Roy, 2006; Smith III, diSessa, & Roschelle, 1993):
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...this approach presumes—in fact it builds from—a view that children are richly endowed with resources for understanding and learning about the physical world: Engage children in a generative activity, and there will be productive beginnings to discover and support.

(Hammer et al., 2012, p. 55)

Responsive teaching serves multiple instructional goals, such as fostering productive scientific discourse and argumentation, promoting participation in scientific practices, and enhancing students’ conceptual understanding. See Chapter 2 for more on the benefits of responsive teaching.

It may be tempting to interpret these three characteristics as a checklist of sorts—a set of actions that cultivate or constitute responsive teaching. We suspect, instead, that responsive teaching grows out of and is grounded in a stance toward students and their ideas rather than through any particular structure of activities, and we caution readers against viewing this list as prescriptive. Likewise, highlighting these three may suggest that they are distinct acts in a performance—e.g., that the teacher may follow a routine of first eliciting ideas, then seeking out connections, etc.—when they are far more integrated in practice, as the examples below show. Finally, it may be tempting to think that these three characteristics cover the space of “responsive teaching moves”—that is, that these and only these activities will be at play in a responsive classroom. In reality, teachers balance a range of instructional goals, and they select and foreground ideas and activities for a variety of reasons, not always because of their substance and connection to disciplinary ideas and practices (e.g., a teacher may foreground an idea offered by a student who has spoken up for the first time in order to encourage that student’s participation in class discussions).

In the remainder of this chapter, we will explore what responsive teaching looks like in detail. First, we will use seminal examples from the literature to illustrate what we mean above by (a), (b), and (c), and then we will offer several classroom examples of responsive teaching across the curriculum, from K–12 to university science instruction. We show that responsive teaching takes different forms in different contexts—that teachers can recognize a variety of disciplinary opportunities within their students’ thinking, from opportunities to distinguish between experimental variables (Ann), to opportunities to pursue mechanistic thinking (Jenny), to opportunities to clarify what is meant by specific scientific language (Leslie and Irene), to opportunities to capitalize on students’ intuitive notions of force (David). We show that teachers take these opportunities up in diverse ways, including planning experiments to test students’ ideas (Ann), proposing that students investigate a student-generated number group (Ball), allowing students’ emergent ideas to influence the direction of classroom inquiry (many), and designing homework (Leslie and Irene) or clicker questions (David) on the basis of student thinking. We encourage our readers to sample from our examples according to their own purposes; one certainly need not read all six to get a feel for what we mean by responsive teaching.
Clarifying the Characteristics of Responsive Teaching: Seminal Examples From the Literature

The “Sean numbers” example from Ball’s “With an Eye on the Mathematical Horizon: Dilemmas of Teaching Elementary School Mathematics” (Ball, 1993) and the unit on electrostatics described in Hammer’s “Discovery Learning and Discovery Teaching” (Hammer, 1997) are two seminal, first-hand accounts of responsive teaching. In this section, we look to Ball and Hammer to clarify the three characteristics of responsive teaching articulated in the introduction: foregrounding the substance of students’ disciplinary ideas, recognizing the disciplinary connections within students’ ideas, and taking up or pursuing the substance of students’ ideas.

Responsive Teaching in Elementary Mathematics: Excerpts From Ball (1993)

In “With an Eye on the Mathematical Horizon: Dilemmas of Teaching Elementary School Mathematics,” Ball describes an example from her third-grade classroom in which students discuss what it means for a number to be even or odd. Sean, a student in the class, presents his idea that six is both odd and even, because it is made up of three (odd) groups of two (even). Mei and Ofala disagree with Sean. Mei argues that if six is both odd and even, so is ten, and Sean agrees with her—according to his definition, ten is both odd and even. Mei objects on the grounds that if you keep on going on like that, . . . maybe we’ll end up with all numbers are odd and even! Then it won’t make sense that all numbers should be odd and even, because if all numbers were odd and even, we wouldn’t be even having this discussion!

(p. 386)

Ofala also objects to Sean’s idea, on the basis of her sense of what makes a number even or odd: “even numbers have two in them, . . . and also odd numbers have two in them—except they have one left” (pg. 386), as in her drawing, replicated in Figure 1.1 below.

FIGURE 1.1 Ofala’s sense of what makes five odd: it has two groups of two and one left over.
Despite Mei’s, Ofala’s, and another student’s—Riba’s—protests, Ball tells us that Sean “persisted with this idea that some numbers could be both even and odd” (p. 386). She describes the dilemma she faced in deciding whether or not to encourage Sean and his classmates to explore patterns with “Sean numbers” as they also searched for patterns with even and odd numbers. On the one hand, she worried that doing so would confuse students, since the idea of “Sean numbers” is “nonstandard knowledge” and may therefore “interfere with the required ‘conventional’ understandings of even and odd numbers” (p. 387). On the other hand, exploring these numbers “had the potential to enhance what kids [were] thinking about ‘definition’ and its role, nature, and purpose in mathematical activity and discourse” and to “prepare the children for subsequent encounters with primes, multiples, and squares” (p. 387). Ultimately, Ball chose to “legitimate” the pursuit of “Sean numbers.”

**Foregrounding the Substance of Students’ Ideas**

Throughout this example, Ball foregrounds the substance of Sean’s, Mei’s, and Ofala’s mathematical ideas. In her writing, she describes each idea in detail; in the transcript, she attends to what Sean is saying by asking him whether Mei’s paraphrase of his idea is accurate, asking him, “Is that what you are saying, Sean?” (p. 386). In doing so, she maintains a stance of curiosity and openness toward what Sean means; she does not evaluate his idea against a predetermined instructional goal but instead seeks to make sense of his thinking. In the transcript that accompanies the online video of this discussion, she asks similar questions of other students, such as, “What are you trying to say?” (p. 4), “So, are you saying all numbers are odd then?” (p. 3), and “Why would that work?” (p. 4).

In addition, the students’ attention to the ideas of their peers—and to the embedded mathematics within these ideas—reinforces our sense that Ball consistently attends to and highlights students’ mathematical thinking. For example, after Sean presents his sense that six is both even and odd, Mei first revoices his idea—“I think I know what he is saying . . . I think what he’s saying is that you have three groups of two. And three is an odd number so six can be an odd number and an even number.” (p. 386)—and then challenges it with her own thinking, arguing that one possible consequence is that all numbers would then be called both odd and even, which doesn’t make sense to her. We suspect that this culture of peer responsiveness is at least in part initiated and sustained by the teacher’s attention to and curiosity about students’ mathematical ideas, and to her promoting this attention among her students. Regularly throughout the transcript of this extended interaction (see video online), Ball incites her students to listen to one another (“Can we listen to her one more time? Say again one more time what you’re saying the definition is of an odd number.” (p. 5)), to seek to understand one another (“Just a second, Sean. Let’s make sure people understand what she’s suggesting.”), to help one another out (“Could somebody help us out with this?” (p. 2)), to try on one another’s ideas (“Who thinks they could come up and try a number on
Recognizing the Disciplinary Connections Within Students’ Ideas

Throughout her reflection on the “Sean numbers” example, Ball consistently highlights the disciplinary connections within (and disciplinary potential of) her students’ ideas. For example, she recognizes that Ofala’s definition of odd numbers—that they “have two in them—except they have one left” (p. 386)—is “in essence, the formal mathematical definition of an odd number: $2k + 1$” (p. 386). She not only sees these connections between Ofala’s reasoning and the discipline; Ball also calls out the mathematics in what she is saying and doing in the course of instruction (see p. 4 of online transcript):

**Ofala:** [describing how she knows that nine is an odd number:] This two together, this two together, this two together, and this two together [drawing Figure 1.2]. There’s one left. And even numbers like six [drawing Figure 1.3], you can’t get anything in the middle. There isn’t one left.

**Ball:** So you’re saying the even numbers are the ones where you can group them all by twos, and the odd ones are the ones where you end up with one left over?

**Mei:** Yeah, I think I agree.

**Sean:** But, if six is an even number, then how come there’s three here and there’s not one left out?

**Ofala:** Because, even numbers are like things like this. They have—even numbers have two in them, and also odd numbers have two in them, except they have one left.

**Mei:** Yeah.

**Ball:** Okay, so, Ofala, you’re—you actually are suggesting a definition. I think. Let’s have everybody hear that one more time.

In this excerpt, Ball first revoices the implicit definition that Ofala is using—even numbers can be grouped by twos, and odd numbers have one left over—and then observes that she is proposing a definition for odd and even numbers. In addition, Ball sees the disciplinary potential in “Sean numbers” for fostering disciplinary practices around the role of definition and “its purpose in mathematical activity and discourse” (p. 387). She describes her experience of connecting students’ ideas to the discipline more generally, writing:

To do this productively, I must understand the specific mathematical content and its uses, bases, and history, as well as be actively ready to learn more about it through the eyes and experiences of my students . . . I must consider the mathematics in relation to the children and the children in relation to
What Is Responsive Teaching?

Ball also sees disciplinary connections between students’ mathematical ideas, nourishing the seeds of mathematical discourse within her classroom community. For example, she coordinates Sean’s proposal with Mei’s concern about its generality and with Ofala’s objection that it did not satisfy her definition of odd numbers. Just after Mei presents her argument (“if you keep on going on like that . . .”), Ball turns to the class and asks, “Are people following this disagreement? This is an important thing that I didn’t even realize we were disagreeing about. So it’s important to see if we can try to figure this out” (p. 4). This is when Ofala jumps in, and Ball consistently redirects the class’ attention back to the substance of what Ofala is presenting, inviting them to understand her definition and then try it out themselves.

Taking Up and Pursuing the Substance of Students’ Ideas

The ideas that emerge as Ball’s students “wor[k] with patterns with odd and even numbers” (p. 385) shape the short- and long-term direction that the class takes. In the moment, Ball maintained a focus on Sean’s definition and on Mei’s and Ofala’s counterarguments, inviting her students to assess one another’s ideas for their mathematical sensibility and consistency. When Ofala presents her definition
for odd numbers, she encourages students to “try some experiments with it, with numbers that they expected to work because they already knew them to be odd” (p. 386), again inviting students to seek consistency between Ofala’s definition and their existing knowledge about odd numbers. In the longer term, Ball takes up “Sean numbers,” suggesting that her students explore patterns with Sean numbers as they did so with odd and even numbers.

**Responsive Teaching in High School Physics: Example From Hammer (1997)**

In “Discovery Learning and Discovery Teaching,” Hammer describes a series of events that unfold in his high school physics course, beginning with “Camille’s discovery.” Camille notices that if she brings a neutral electrophorus near a charged foam plate and then touches the electrophorus with her finger, the foam plate lifts off the table, as shown in Figure 1.4. (We explore the science of this electrostatic phenomenon in endnote 4—and we do the same for other phenomena introduced throughout this chapter for those who wish to read further.)

Hammer names this phenomenon “the Marino phenomenon” after Camille, and the class goes on to explain it over the next several days. Amelia, Ning, and Joanne propose the “HAM theory,” a three-part charge separation model: (1) “charge is not created but separated”; (2) “the charges involved are the positive nuclei and negative electrons that... make up atoms”; and (3) “different materials have different tendencies to accept or give up electrons” (p. 509). Ning uses the HAM theory to explain the Marino phenomenon in terms of induced polarization: she argues that when the electrophorus is brought near the negatively charged foam plate, “negative charge is repelled toward the top of the electrophorus, and positive charge is attracted to the bottom” (p. 509). Negative charges leave the plate via the finger that touches the top, and the electrophorus is left with a net positive charge, which would then attract the negatively charged foam plate. Several students—including Steve, Susan, Bruce, and Sean—object to Ning’s explanation, arguing that “the electrophorus could [not] be charged one way on top and another way on the bottom” (p. 510).

![Neutral electrophorus](image1.png)

**FIGURE 1.4** Illustration of Camille’s discovery, from Hammer, *Discovery Learning and Discovery Teaching*, Cognition and Instruction, 1997, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).
The “HAM authors[‘] and adherents[‘] . . . account of the Marino phenomenon” (p. 510) (i.e., induced polarization) is reinforced by an experiment that Hammer conducts at his students’ suggestion. In the course of this experiment, Hammer shows his students that a pith ball is charged by a neutral electrophorus and then repels from the foil-covered straw when the foam plate is near, but “settles back” when Hammer moves the foam plate away.

While the “HAM adherents” explain the pith ball’s behavior in terms of induced polarization, Steve, Susan, Bruce, and Sean articulate their own explanation that the pith ball is charged by its proximity to the foam plate—the electrophorus acts as a “conduit of charge.” Other students offer additional explanations, including that a “spark” jumps between the electrophorus and the foam plate (Susan), or that the behavior is caused by an “aura” or “force field” (Bruce) (pp. 510–511).

![Neutral electrophorus with foil covered straw, touching a pith ball](image1)

![Charged foam plate](image2)

Bring the charged foam plate close to the electrophorus and the pith ball repeats away from the fell covered straw

Remove the foam plate, and the repulsion stops

FIGURE 1.5 Charging a pith ball with a neutral electrophorus, from Hammer, Discovery Learning and Discovery Teaching, Cognition and Instruction, 1997, reprinted by permission of the publisher (Taylor & Francis Ltd, http://www.tandfonline.com).
The class then “drew depictions of the competing accounts” (p. 511)—the HAM charge-separation model and the charging-by-proximity model—on the blackboard. Toward the end of the class period, Hammer tells us, the students identify a “serious problem with the latter: If the charges were moving through the electrophorus to charge the pith ball, the electrophorus and foam plate would have the same charge and thus should repel each other” (p. 512), but they know, from the Marino phenomenon and other experiments, that they attract.

Ning then suggests an experiment that she feels will confirm the HAM theory: rather than touching the top of the electrophorus, which presumably had a negative charge, she suggests they touch the bottom (presumed to be positively charged). Doing so would add negative charge to the neutral electrophorus, resulting in a net negative charge, and the foam plate would be repelled. Hammer does the experiment, which produces results inconsistent with Ning’s prediction; they end the class period with Hammer’s comment that “[they] would need to think further about this experiment and that [they] had not resolved the debate between the HAM and proximity explanations” (p. 512). The quiz the students take the next day asks them to defend their position in the debate, to address counterarguments, and to design an experiment that would distinguish between the two theories.

Foregrounding the Substance of Students’ Ideas

Throughout this example, Hammer maintains a focus on the substance of his students’ scientific ideas and practices. He describes in detail the students’ observations (e.g., the Marino phenomenon), explanations (e.g., the HAM theory and the charging-by-proximity model), and proposals for experiments (e.g., Ning’s suggestion that he touch the bottom—rather than the top—of the electrophorus), seeking to preserve the meaning they were making as they try to understand the Marino phenomenon and other investigations of charge. He invites students to bring their own models to bear on these investigations, and he seeks to understand how the authors of each model would make sense of new phenomena they observed (e.g., how (i) the HAM theory adherents and (ii) the charging-by-proximity adherents make sense of the pith ball’s behavior as the foam plate is brought close to the neutral electrophorus in Figure 1.5). He notices when students are making connections between phenomena—such as when Susan suggested that a “spark” jumps between the foam plate and the electrophorus, the way that “a charge can ‘jump’ across the ‘small space to another nerve’ in a synapse” (p. 510).

Recognizing the Disciplinary Connections Within Students’ Ideas

As he foregrounds the substance of students’ ideas, Hammer calls attention to the “seeds” of disciplinary ideas and practices embedded therein. For example, he sees in Camille’s discovery of the Marino phenomenon opportunities for students to participate in science as a socially constructed endeavor (“it was another
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opportunity to show the students that their discoveries mattered” (p. 508)), to see observation and exploration as central to scientific progress, and to build connections to physicists’ notions of induced polarization and charging by induction. He sees Steve’s, Susan’s, Bruce’s, and Sean’s original questions about the HAM theory in terms of a reasonable, disciplinary alternative—they thought “charge [was] a property of the object as a whole, so they were troubled by an account of different parts of the electrophorus having different charges” (p. 510). He weighs the epistemological and conceptual affordances and constraints of Susan’s, Sean’s, Greg’s, and Bruce’s use of terminology (e.g., that the behavior of the pith ball when the foam plate is brought near the electrophorus is because of a “spark,” a “current,” an “aura,” or a “force field”): he was “pleased that these students were looking for connections and ideas from other phenomena” but was “daunted by the very different notions they were expressing about charge and current” (p. 511). He searched for the scientific “beginnings,” wondering “whether some of what they were saying might serve as seed for the physicist’s concepts of an electric field or an electric potential” (p. 511).

Taking Up and Pursuing the Substance of Students’ Ideas

Over the course of these several days, Hammer “elevate[s]” his students’ ideas “to the level of curriculum” (p. 513), adapting his instruction as specific ideas and proposals for experiments emerge. Students’ ideas and observations form the basis of the inquiry that takes place in both the short- and long-term. Hammer deviates from the intended order of the worksheets his students are completing to pursue explanations for the Marino phenomenon, and two competing theories surface that the class then investigates, seeking to accumulate evidence and counterevidence for each one. As they go, Hammer invites students to conduct experiments that test their ideas (e.g., Ning’s suggestion to touch the bottom of the electrophorus rather than the top). In all of this, he promotes classroom practice that mirrors that of science: students are encouraged to explore their observations, to explain what they see in terms of models, to consider competing models and counterarguments, and to reconcile inconsistencies between their models and their observations.

Illustrating Responsive Teaching Across the Curriculum: Examples From K–12 and University Classrooms

Now that we have used examples of responsive teaching from the literature to illustrate what we mean by foregrounding the substance of students’ ideas, recognizing disciplinary connections within students’ ideas, and taking up and pursuing the substance of these ideas, we turn to more recent examples from K–12 and university science classrooms, gleaned from research and professional development projects in which we have been involved. In doing so, we aim to showcase a diversity of ways in which responsive teaching is enacted while continuing to illustrate its central characteristics.
Responsive Teaching in Elementary Science: Example From Ann’s 5th-grade Discussion of Magnetism

The following example comes from the classroom of a 5th-grade teacher, Ann, who participated in a professional development project that engaged teachers—and, by proxy, their students—in drawing on their own experiences to construct causal explanations of scientific phenomena. This example highlights a teacher’s recognition of an emergent opportunity to engage students in disambiguating variables, an important practice for clarifying and making progress on the specific questions they are seeking to answer. This example also represents a large-scale adaptation from the intended lesson, which was originally focused on preparing for a test.

Example From Ann’s class

Ann’s 5th-grade class is approaching a statewide standardized test that requires students to define force as a push or a pull and to identify different types of forces (e.g., gravity and magnetism). To initiate a review conversation, Ann poses a question about magnetism, raised previously by a student: “Can magnets work underwater?” Although she indicates that the class cannot spend much time on the “whys of magnetism,” she encourages students to think about the question and to consider how it relates to forces.

Students talk in groups at their tables about whether or not magnets work underwater, and Ann pulls them together for a whole-class discussion. (See http://www.studentsthinking.org/rtsm for a full transcript of the discussion.) The discussion quickly evolves into a back-and-forth about some of the “whys” that Ann initially tried to minimize. Some students argue that the magnets are going to try to connect under water, as on land, depending on how strong they are, whereas other students argue that the pressure of the water will prevent them from sticking together. As the discussion continues, Ann recognizes that some students are thinking of different scenarios than the one she originally imagined:

Caroline: The force of the water when it pushes it down, like the, um, force pushes, pushes, pushes it down, it probably, um, won’t, like, stick together because all the pressure, all the water-
Ann: The pressure from the water is going to be—overcome the magnetism?
Caroline: Yeah, so I say no, but Wendy says yes.

(Many students start contributing; Ann reminds them to be active listeners.)
Ann: Um, Allan, why do you say no?
Allan: Because, just like Elena said, there’s too much force on them for them to stick together.
Ann: The water pressure is too much?
Allan: Yeah because sometimes if the waves are strong, the magnets will separate and fall apart.
Student: What if it’s just a little bit of water?
Ann: Okay, so that’s just what I was going to ask you . . .

Ann indicates that she was thinking of testing the magnets in small containers of water, rather than the bigger bodies of water she hears Caroline and Allan talking about. Allan changes his mind because “there’s only a little bit of space in that cup” but also makes a bid to try it out in a pool. Ann considers using the sink before pausing for a question from Kimmy:

Kimmy: Are you all, are you saying that—it’s based on—the force is based on the amount of space the water has in the ()?
Ann: Well—Allan and Caroline, you want to answer Kimmy’s question?
Caroline: Well, () in the cup, um, there’s not enough water because the magnets are going to be like right next to each other because of the cup. But say if we put it in the sink, they’ll probably be far away, so all the pressure from the water will probably keep them apart. And basically it’s about how much water and how much space ()

Several students suggest ways to tweak Ann’s setup so the magnets are farther apart. Ann indicates they can try the experiment in a variety of ways, but she also seeks to draw students’ attention to the fact that they are now considering two variables in their explanations—the presence or absence of water, and the distance between the magnets. She gets two magnets and holds them progressively closer to each other until they finally click, showing that they have to be relatively close together to attract, even in the air:

Ann: So what we’re sort of trying to figure out is—two things. First of all, will they work at all in water? But then Caroline, you guys have sort of also brought up the whole idea of how close they have to be.

The class spends the rest of the period talking about why it would be harder for magnets to work underwater (e.g., water is “stronger than air,” in that we can walk through air but have to push through water when we swim), trying various ways to test whether magnets work underwater, and discussing students’ findings. They only return to an explicit discussion of forces in the last five minutes of class.

How This Example Instantiates Responsive Teaching

The conversation in Ann’s class reflects the three characteristics of responsive teaching articulated earlier in the chapter, intertwined in the flow of classroom practice. Throughout the discussion, Ann listens to and revoices students’ ideas, often in a questioning tone to invite student feedback (e.g., “The water pressure is too much?”). She also keeps track of how students’ ideas and questions relate to one another and facilitates students’ direct talk with each other when appropriate,
As Ann attends to the substance of students’ reasoning, she recognizes particular disciplinary connections and adapts her instruction responsively at several scales. For instance, Ann notes distinct variables inherent in students’ thinking (water and distance) and seeks to engage students in the scientific practice of disambiguating variables in the course of their joint exploration (Ford, 2005). This emergent objective represents a larger-scale adaptation to Ann’s original plan for the day—to review forces for the upcoming test. Other adaptations are smaller-scale in nature (e.g., allowing students to alter her planned experimental setup).

In an informal interview after class, Ann reflects on the larger-scale adaptation as creating tension for her. She notes the strong tension she feels between pursuing questions that the class finds interesting and making sure her students are prepared for the standardized test. While she foregrounds test preparation in subsequent lessons, the class returns to the question of whether magnets work underwater after the test and engages in a week-long inquiry that expands from whether magnets work underwater to whether anything can block magnetism (Richards, Johnson, & Nyeggen, 2015).

**Responsive Teaching in High School Biology: Example From Jenny’s 10th-Grade Class Discussion of Diffusion and Osmosis**

The following example comes from Jenny’s 10th-grade biology class. Jenny participated in a professional development project that focused on supporting secondary science teachers in developing practices of attending and responding to students’ ideas and reasoning. This example in particular highlights how a teacher attends to and leverages students’ nascent mechanistic ideas as she supports them in constructing an understanding of a biological phenomenon. As in the case of Ann, the example is situated within certain institutional constraints—Jenny is accountable to high-stakes standardized tests and standardized curricula—and so illustrates some of the pressing instructional tensions that teachers navigate as they are responsive to their students.

**Example From Jenny’s Class**

In this example, Jenny shows her students a stanza from Samuel Taylor Coleridge’s poem “The Rime of the Ancient Mariner” and asks them to explain what they think the following two lines mean:

\[
\text{Water, water everywhere and all the boards did shrink} \\
\text{Water, water everywhere, nor any drop to drink}
\]
The high school biology curriculum guide used in Jenny’s district suggests this activity and places it after students have studied processes of diffusion and osmosis, intending to give students an opportunity to apply their understanding of osmosis and associated vocabulary (e.g., hypertonic and hypotonic solutions) to their interpretation of the poem. Jenny’s students have already explored diffusion, but instead of having the discussion when the curriculum guide suggests, Jenny decides to explore how her students reason about the mechanisms at work before they have been formally introduced to osmosis and related terminology. She sees this as a valuable opportunity to understand and leverage students’ thinking in order to build their understanding.

At the beginning of the lesson, Jenny projects the two lines from “The Rime of the Ancient Mariner” on the screen. She tells the students that the lines are from a poem, written from the perspective of a man lost at sea, and she asks them to write what they think the poem means in their notebooks. After they have written quietly for a few minutes, Jenny asks them to share their interpretations with the rest of the class.

As the conversation begins, students immediately recognize that the sailor cannot drink the salt water of the ocean. As Andrew says, “I think it’s some guy that’s stranded in the middle of the ocean, and he’s stuck on one little board, and he can’t drink the water because it has salt in it.” Jenny picks up on Andrew’s idea:

**Jenny:** The salt water—why can’t we drink the salt water?

**Toàn:** Because of the salt.

**Jenny:** So what does the salt do?

**Hawaney:** It makes you more thirsty. It dehydrates you.

**Grace:** I think the salt absorbs the water.

**Jenny:** So salt absorbs water? The way . . . a sponge absorbs water?

**Brian:** It doesn’t like get rid of it, but it gets . . . enough of it . . .

**Rachel:** Isn’t it like so your body can’t use it? . . . Like it’s still there but it’s in a form that your body can’t use.

**Jenny:** So maybe it alters the water—is that what you’re saying?

**Rachel:** I mean, I guess it would be some kind of chemical process where it wouldn’t exactly be water any more. It would be like a form that your body couldn’t use.

Here, Jenny revoices Grace’s idea that salt absorbs water and works to understand more specifically how Grace thinks this occurs (e.g., similar to how a sponge absorbs water). Similarly, she revoices Rachel’s idea that the salt makes it “so your body can’t use [the water]” and checks to make sure she understands Rachel’s meaning.

As the conversation continues, Jenny asks the students to consider the first part of the stanza, “Water, water everywhere and all the boards did shrink.”
Jenny: So—why would they shrink?
Brian: Oh!
Rachel: Well, I know that um if you take a drum that’s too tight, and you put water on it, or sometimes you like hold it like over a fire, then it’ll tighten, so I think like maybe if it evaporates … (trails off)
Jenny: If … the water evaporates … then …?
Rachel: Maybe because the molecules come together and get in the way somehow.
Metzy: Like a sponge.
Jenny: Okay … why would the water evaporate?

Jenny picks up on Rachel’s idea, based on her personal experience, for why something wet might shrink. She presses Rachel to explain what would happen if the water evaporates and then, a turn later, why the water would evaporate. Through Jenny’s pressing Rachel to articulate what happens when the water evaporates and why the water evaporates in the first place, the mechanism for shrinking within Rachel’s idea becomes clearer: the water molecules that were originally in the wood leave, and the wood molecules then get closer together, shrinking the board.

With Rachel’s idea clarified, Jenny reflects it back to the rest of the class, asking them whether it makes sense. When some students say that it does not, Jenny again breaks Rachel’s response into two parts, first asking whether they agree that there is water in the wood. Andrew asserts that there is water in the wood so long as “it just came off a tree or something.” Shortly after this, Brian synthesizes the class discussion up to this point:

Brian: Okay. So the tree—so wood comes from trees … and the tree, and trees need water in order to uh survive, when you cut the tree down and make the uh, wood, there’s still water left inside of it, but when you put it in salt water the salt water will evaporate the actual water inside of it.

Here Brian identifies the entities (“actual water” and “salt water”) and activity (“evaporation,” in this case referring generally to the process by which the water leaves the wood) that could be used to form a mechanistic explanation (Russ et al., 2009). After a short clarification from Moyatu—who points out that wood typically absorbs water—Jenny returns to Brian’s claim, revoices it, and then asks, “Why would salt water evaporate water?”

The conversation proceeds for several minutes with the students proposing multiple different explanations for why the water will evaporate from the wood, including that water is the “universal solvent” and is dissolving the wood (such that the board shrinks) and that the water inside the tree combines with salt and “the tree would just not want it.” Each time a student offers a new explanation, Jenny revoices it, and often she asks the rest of the class what they think. When Tina presents her
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claim that the tree “would not want” the water, Jenny presses back, pointing out that the tree is not only taking in water, and asking what else the tree is doing. Several students argue that the tree also expels water, and Jenny once again challenges them to articulate a mechanism. Tilson suggests “osmosis,” and Jenny asks him to say what he means; he answers that “water moves from [a] high-density place to a low-density place.” The students take this up, offering examples of both osmosis and diffusion, and Jenny asks them whether these mechanisms “come into play here.”

Students begin to make connections between osmosis and the scenario under consideration (e.g., Rachel considers the concentration of oxygen in the salt versus fresh water), as well as continue to offer explanations for why the water might evaporate from the wood (e.g., Metzy posits that “it’s gonna go through the water cycle thing”). Jenny takes up the mechanism in Rachel’s idea—that oxygen moves from high to low concentration—and again asks the students how it “applies here.” Haja and Grace begin to argue that there is a higher concentration of water in the board than in the ocean, with Grace explaining that “the water in the ocean is a mixture of NaCl and H₂O but the water in the board is just H₂O so that’s a higher concentration.” Brian sums this up, saying:

Brian: So if you took like a—if you took like a drop of salt water and compared it to a drop of just regular water, there’d be more of the regular water in the regular water because there’s also salt in the salt water so the salt water has a lower concentration of water since it’s mixed with the salt, so the water molecules would move to the outside of the board where there’s a lower concentration.

They go on to consider together how the mechanism by which water leaves the board is analogous to the process by which one’s body dehydrates, connecting “all the boards did shrink” and “not a drop to drink” in the original poem.

How This Example Instantiates Responsive Teaching

Throughout this example, we see Jenny’s efforts to foreground her students’ thinking and to try to understand their meaning rather than evaluating or correcting it. For example, she attends to Grace’s idea that salt absorbs water and to Rachel’s idea that salt water is in a form the body cannot use, and she attempts to understand both students’ meaning. Her response to Rachel’s idea leads Rachel to draw on her knowledge of the disciplinary core idea of a chemical process changing the nature of a substance (NGSS Lead States, 2013).

Jenny also elicits students’ mechanistic thinking—for example, when she presses Grace to explain how salt absorbs water—and recognizes the nascent mechanistic reasoning in what her students are saying. In picking up on Rachel’s drum example, Jenny supports Rachel in instantiating the disciplinary practice of constructing plausible mechanistic accounts for phenomena (both in Rachel’s
own past experience and in the “thought experiment” invoked by the poem). An interview with Jenny after class supports this interpretation of Jenny’s questions to Rachel. When asked what she thought about Rachel’s idea, Jenny said:

*Jenny:* I think what she’s saying there is she knows that the drum head is going to shrink in that process so the boards are going to shrink . . . and to me that’s the mechanism [she has] available . . . to explain why some things can get smaller. Evaporation means that it’s going to go away and therefore it’s going to get smaller.

The drum exchange also illustrates how Jenny adapts instruction on the basis of her students’ ideas. While Jenny did not expect the idea of evaporation to come up in this conversation geared toward diffusion and osmosis, she takes up Rachel’s idea and follows it, using it as a starting point for further exploration. Rather than Jenny pointing out that the phenomenon suggested by the poem is not evaporation but instead osmosis, she makes space for the idea of osmosis to emerge from the class’ consideration of what would make the water evaporate.

**Responsive Teaching in Pre-service Elementary Teacher Education:**

*Example From Leslie and Irene’s Undergraduate Course Developing Ideas About Blurriness*

In this section, we provide an extended example from a university course, *Scientific Inquiry*, that is structured to be wholly responsive: the content and direction of the course proceeds from students’ ideas, investigations, and conversations. It is a course for undergraduate pre-service elementary teachers at California State University, Chico, co-taught by a biologist (Irene) and a physicist (Leslie). Unlike other courses offered in the major, this course is designed to address the “inquiry” standards from the last iteration of the California State Science Standards (California State Bureau of Education, 1998) by engaging students in the practices of science as they model complex phenomena (e.g., an eye, a pinhole theater, the tides, or the pitch from a glass of water when struck with a fork). The explicit lack of any predetermined content to be covered allows for increased attention to students’ reasoning, a focus on students’ own language, and an emergent curriculum.

**Extended Example From Leslie and Irene’s Class**

In the example below, students have already dissected an eye and are now collaborating in four-person groups on questions related to how the eye works. Some groups are using lenses, curious about how the lens of the eye affects images we see; others are constructing a model of the eye, beginning with a hole in a box; still others are paying careful attention to patterns in visual phenomena (e.g., they find that they cannot focus on objects that are too close to their faces).
Early on, it became clear to the instructors that all groups had, in one way or another, been examining “crisp” and “blurry” images, so they ask the six groups to share an example of “blurriness” with the class. They anticipate that a whole-class conversation around these observations might help students identify ways in which their investigations are illustrating similar or different phenomena. Where the ideas are similar, an understanding of how images are constructed (whether it’s with a pinhole, lens, or eye) might emerge. Where the ideas are different, students might gain more precision in what is meant by “focused” and “blurry” images, and how those differ from related ideas, like low-resolution images.

In response to Leslie’s and Irene’s request for an example of “blurriness,” the groups offer the following six observations:

1. Hold your finger really close to your eye. You cannot focus on it; it’s blurry.
2. Stare straight ahead at some writing, you cannot read things in your peripheral vision; they’re blurry.
3. Look at the image made by a large pinhole camera. It is blurry.
4. Shine a Maglite on an object. The shadow cast by this object is not blurry, but you can make it seem blurry if you give that object a “ragged edge.”
5. Shine light through a cut-out “R” shape that is covered with a translucent paper (a light post-it note). It will appear blurry, but if there is no paper then it is not blurry.
6. Stare at an image and then close your eyes. The afterimage (the hazy negative you see with your eyes closed) has a blurry “edge.”

Noticing that few groups have developed detailed explanations for why these phenomena appear blurry, the instructors begin the conversation by asking students, quite simply, “So what is blurriness?”

In the transcript below, groups begin to describe—and progressively explain—the six observations, articulating that the location of an image on the retina matters, referring to a model for the reflection of light that they had previously discussed in class, and then connecting that model to the phenomena of blurry and focused images (see video at http://www.studentsthinking.org/rtsm):

Amanda: We kind of talked about we did this thing with like peripheral vision . . . when [light] comes in, you know, straight in, the lens is directing it and it comes to a center spot. And we were talking about peripheral vision how it’s like more unfocused and maybe that’s because the light from those—from, y’know this area over here [in the periphery] is coming in at like angles so the lens can’t like focus it right to the middle as well, and we talked about how there’s that little spot on the back and we think—of the retina whatever it’s called.

Breanna: The fovea [central part of the retina].

Amber: And we were thinking maybe that has to do with like how you focus, like focus on images ‘cause when you’re looking straight at
something that light that’s coming into your lens is directed back to that center spot—

Breanna:  Or closer to the center spot.

Irene:  Let me see—you’re saying that the peripheral vision is more blurry and fuzzy. It’s not as crisp because it’s [the light from the object is] not hitting towards the center of your retina.

Amanda:  Yeah.

Here the group is articulating an idea that is not obvious to most students—that images are not simply out there in the world to be seen, but that the eye must somehow direct (if not construct/project) that image onto the retina. However, the group offers no mechanism by which the peripheral image is blurry.

The group that originally proposed that light coming through a cut-out L projects a crisp L on the wall and that light coming through a translucent R projects a fuzzy blob of light (observation (5), see previously) speaks up immediately after Amanda, Amber, and Breanna. Caitlin offers a mechanistic description, linking what happens to the light rays with the blurriness of the image:

Caitlin:  We were talking about with the R that we couldn’t see it was like spread out because it kooshes [leaves the R in all directions] off of the post-it. And so [the light is] like spread out—but then with like the L through the aluminum it doesn’t koosh so it’s crisp.

Irene:  How would you—like, could you draw that or do you have a way of like representing that or another way of thinking of it.

Caitlin:  I don’t know—do you? [Laughter.]

The reasoning presented here suggests a nascent model of blurriness—the R image is blurry because the light “kooshes” off the post-it note, spreading out in all directions (as in Figure 1.6), while the L image does not “koosh.” Caitlin does not elaborate on why the “spread out” light is blurry.

At this point Leslie sketches the two masks (L & R) on the board (Figure 1.7). Students describe the light rays, and Leslie draws the rays and notes the phrases they use on her diagram: the light rays that leave the L do not overlap; with the L there is just one ray landing in each place on the screen, so it is dim; the rays leaving the R go in many directions; these rays will hit the screen “all over;” the rays are “fragmented” by the R; they “spread out” and “overlap” at the screen.

The ideas are still quite tentative, offered as suggestions, and students describe characteristics that might matter but do not yet link these ideas to why the image might be blurry. When a student suggests that the L should be brighter because the rays do not fragment, Breanna offers what seems like a counterargument—that fragmenting light makes for “too much” light reaching any one spot. Students seem to be conflating “too much”—which suggests that the intensity of the light causes the blurriness—with “too many”—which suggests that rays from too many
FIGURE 1.6 Two incoming light rays reflect diffusely from two points on the “R” and send multiple scattered light rays to the screen, at right.

FIGURE 1.7 A diagram of light through an opening (L) and light through a translucent opening (R).
places cause the blurriness. As Breanna elaborates her ideas, she takes up the latter, clarifying that rays from multiple different points on the translucent R overlap on the screen:

*Breanna:* But I think that that would kind of be the opposite [that the R should be brighter]. Because, um, this, the top one [the L drawn on the board in Fig. 1.6] there’s no overlapping. It might be more dim. And then the bottom one if there’s overlapping it would be brighter.

*Leslie:* And you say it’s dim because just one ray got here [for the L] while in this one [the R] it will fragment and send many rays here? (writes on board)

*Breanna:* Yeah. What I think is there’s so many little fragmented rays, they’re going many different directions that’s why it’s going blurry.

*Leslie:* So because they went many directions from here (points to translucent R)—

*Breanna:* And they’re hitting the paper all over. There might be a lot of them but they’re hitting so many spots on the paper that it doesn’t make a crisp image.

Breanna’s description of why the R is blurry—rays “fragment” upon striking the R shape (the “kooshing” that Caitlin calls our attention to), and those fragmented rays are projected to many spots on the paper—is consistent with scientific descriptions. Moreover, it suggests that a “focused” or “crisp” image would be one in which rays do not fragment, or, if they do, they are somehow brought back together.

Within this conversation about blurriness, Leslie and Irene recognize some students productively modeling light rays as they seek to describe blurriness, and they use that as the foundation of a homework assignment that asked students to create their own diagrams and explanations for the blurry R that Caitlin’s group had created. After students completed the assignment, the class met in small groups to create whiteboards of their work and then discussed the whiteboards as a class. Students quickly reached consensus around the idea of blurriness. As Breanna summarizes, “Overlapping rays from multiple origins . . . will cause an image to be blurry.” The direction that the remainder of the unit took emerged from connections that students made between this definition and their original observations, and between other phenomena of interest. They came to consensus on a final description of focus: “All the rays from an originating point come back together in the same spot on the retina.”

**How This Example Instantiates Responsive Teaching**

Throughout this extended example, Leslie and Irene enact responsive teaching that weaves together the three characteristics articulated in the introduction to this chapter. When Irene revoices Amber’s, Amanda’s, and Breanna’s ideas—and
later, when Leslie diagrams at the board—they do so based on the students’ ideas and descriptions, foregrounding the students’ explanations rather than the instructor’s expertise. While the instructors notice whether or not the examples students offer fit a canonical understanding of focused and blurry images—which is certainly one way to seek out connections between students’ ideas and the discipline—their primary task is to recognize disciplinary opportunities in those ideas. They see in these ideas opportunities for rich scientific conversations in which students model phenomena, and they imagine ways to support students in moving from a cataloging of things that are “hazy” in appearance towards a more nuanced view that determines whether or not these phenomena are governed by similar mechanisms. The homework assignment that Irene and Leslie ultimately ask students to complete focuses on using their own ideas and diagrams to explain the observation made by one of the student groups, requiring students to attend to and make sense of one another’s thinking, and to do so in a way that preserves and highlights their own (individual) ideas. In addition, this assignment capitalizes on and extends the productive mechanistic reasoning inherent in Caitlin’s and Breanna’s explanation for blurriness.

We often think of responsive teaching as adapting instruction to address students’ ideas: a preplanned lesson meets with an unexpected question or idea, and the instructor takes up and pursues this idea instead of continuing with the lesson as planned. The nature of this Scientific Inquiry class means that describing it as “adapting instruction on the basis of students’ ideas” is a bit misleading; student ideas determine the instructional sequence. Although the instructors plan in advance, generally meeting for an hour after class to discuss students’ ideas and a sequence of activities for the next day, the plans are loose and designed to take up and pursue students’ scientific ideas. In this extended example, Leslie and Irene recognized a theme—blurriness—among the students’ explorations, and this observation prompted them to ask students to share an example of blurriness. The nature of the examples that students shared—more focused on the ways to produce the phenomenon than on explanations of blurry images—inspired Leslie and Irene to press students to articulate what blurriness is. Students’ own explanations for the images they had been exploring became the grounds for collective representation and negotiation of blurriness.

Trying for Responsiveness in a University Physics Lecture: Example From David’s Introductory Physics Course Discussion of Forces

Unlike the example above, where the content of the course is largely driven by students’ ideas, David has been trying to incorporate responsiveness in a class with very clear content objectives—a large introductory physics lecture. In doing so, he has faced a number of challenges. Goals of “covering content” make it difficult to spend time listening to students’ reasoning. Students take the course for many different reasons and as part of many different programs, which makes it important
to stay with the planned syllabus. Another difficulty is the number of students: David has had as many as 180, and at some institutions, introductory courses have several times more than that. It is only possible to hear directly from a fraction of the students, those who speak up or whom the instructor can hear while students work in groups. Another means of hearing from the class as a whole is through “clickers”—instructors pose multiple-choice questions and students click in their answers (Dufresne, Gerace, Leonard, Mestre, & Wenk, 1996; Mazur, 1997).

While it is not possible in lecture settings to follow students’ thinking in the ways we show in the other examples in this chapter, there is room for responsiveness in smaller ways in the flow and substance of a lecture session, such as we illustrate here. It can also happen in somewhat larger-scale ways, such as with homework or exam problems that pick up on reasoning that arose from students.

Example From David’s Class

The following example (available at http://www.studentsthinking.org/rtsm) is from David’s calculus-based introductory physics course at Tufts University. About 75 students enrolled in the course. During the first lecture of the course, David poses a short series of questions about striking a bowling ball or a basketball to get it moving. Students laugh at the idea of his using his foot—kicking the bowling ball would hurt! So he uses a heavy rubber mallet, and when he poses the question, a significant majority predict that if he swung the mallet “in the same way”—that is, raising it to the same height and trying to make the same motion—the basketball would move much faster than the bowling ball. Several students explain that the bowling ball has more mass, so the same force would have a smaller effect.

Another question asks students to compare the force by the mallet on the ball to the force by the ball on the mallet. Most of the students have taken high school physics, and most answer that these would be equal in strength. David then puts up a slide asking, “Was the force by the mallet on the bowling ball equal to the force by the mallet on the basketball?” Almost all students say “yes.”

David uses the opportunity to point out a contradiction: that would mean that the force by the bowling ball on the mallet would be the same strength as the force by the basketball on the mallet. But everyone knows it would hurt to kick a bowling ball! Doesn’t that mean kicking a bowling ball exerts a greater force on your toe?

The class discusses this for several minutes, but David leaves the question unresolved and assigns it as part of their problem set due the following week (see http://www.studentsthinking.org/rtsm for a copy of the homework question). One week later, just after the students hand in their assignment, David poses the question again. Ninety-one percent still answer yes, the mallet exerts the same magnitude force on the bowling ball as on the basketball. David asks students to explain why they voted as they did. Emma is the first to volunteer; she explains
that “it’s the same force, except the basketball has very little mass, so it accelerates a lot. And the bowling ball has a lot of mass, so it doesn’t really accelerate.” David responds by reiterating her reasoning, to her satisfaction, “if you give the same force . . . but one has a much smaller mass, the acceleration will be much larger.” But he challenges it:

*David:* So that would help me understand that if the forces are the same, this is why the basketball shoots out so fast. But what I want to know is, if the forces are the same, why does it hurt my toe, to hit one, how do I account for that?

*Emma:* Because, if you [pause] your foot isn’t going to accelerate as much [kicking the basketball].

He and Emma have a brief exchange to clarify that she is saying his foot would not accelerate as quickly on kicking the basketball. Taylor agrees:

*Taylor:* Basically it takes your foot a shorter time to come to rest when it hits the bowling ball than when it hits the basketball. It’s, like, more of an abrupt coming to rest.

Immediately following, Taylor goes on to compare the situation to a person jumping off a building onto a trampoline, saying that it takes more time for the person to come to rest.

*David:* That sounds like, would I be correct to say that my foot has a higher acceleration, kicking the bowling ball?

*Taylor:* Yes.

*David:* I would be correct to say that.

*Taylor:* Or it has the same, but it just [inaudible]

*David:* Well, all right, so you said it’s a more abrupt stop for the foot, and ‘more abrupt stop’ sounds like higher acceleration. Mary?

*Mary:* It takes more force for the bowling ball to overcome friction, it takes more force to accelerate. But you’re kicking each, the basketball and the bowling ball with the same force it’s going to hurt your foot more with the bowling ball because it takes more force to push the bowling ball versus pushing the basketball. And that’s why it hurts.

*David:* Oh, I see. More of the force goes into my foot when kicking the bowling ball. [to Shivani] Go ahead.

*Shivani:* I just want to add that the bowling ball has so much mass that it doesn’t change shape upon the impact. So when you kick it, a very small surface area of your foot gets injured.

*David:* Oh, it’s a small surface area of my toe, and it gets more spread out for the basketball.
Another student says “something similar,” and then David calls on “one more” saying he had a question he wanted to ask. Nikhil gives “a counterargument” to Shivani’s reasoning.

**Nikhil:** If you had a basketball that had the same hardness, and like the same flexibility as the bowling ball, but it had less mass, it would still hurt less.

**David:** So if I had a light, stiff basketball that doesn’t dent at all.

**Nikhil:** Yeah.

After Nikhil presents his argument, David constructs a new clicker question, repeating Taylor’s reasoning.

**David:** When I go to kick the bowling ball, my foot stops more abruptly. My question back to you is . . . is it correct to say that my foot’s acceleration is higher?

He rephrases the question to focus on the mallet, “because I like my feet,” and the poll shows 59% say yes, the mallet has a higher acceleration when it hits the bowling ball than when it hits the basketball. With 59% not a very strong majority, he suggests students talk in groups to try to sort it out. After a couple of minutes (omitted from the video) he polls again to find 72% now say yes, a more abrupt stop means a higher acceleration.

In the discussion that followed, Maayan explains that the acceleration must be the same across the two balls, because it was a “premise of the question” that the force is the same, and by Newton’s Second Law the acceleration must be the same too. David had been thinking of this connection too, which showed a new version of the contradiction: if the total force on the mallet is the same, its acceleration must be the same, but the mallet seems to stop more abruptly when it hits the bowling ball.

**How This Example Instantiates Responsive Teaching**

In modest ways, this example illustrates David’s foregrounding of student ideas. He does so on aggregate, via clicker questions, and on smaller scales in his request that students offer arguments to support their answers and in his revoicing the reasoning that they give. For example, when Shivani argues that “when you kick it [the bowling ball], a very small surface area of your foot gets injured,” David does not evaluate her response but reflects her meaning back to her, saying, “Oh, it’s a small surface area of my toe, and it gets more spread out for the basketball.”

David’s in-the-moment choices reflect his sense of disciplinary potential in students’ thinking, with respect to conceptual substance as well as disciplinary engagement. Shivani’s argument, for example, that the force for the bowling ball
is more concentrated in “a very small surface area of your foot,” and Nikhil’s response, showed both students working toward sensible, coherent mechanistic understanding. They were “doing physics,” and doing it well. Moreover, the number of students interested to speak up, and the class’s animated conversations when they broke into groups, reflected aspects of disciplinary engagement that David hoped to cultivate.

In addition, David’s initial choice of question—kicking a bowling ball and a basketball with your foot—reflects his anticipation, both of students’ conceptual resources for understanding physical phenomena and of their likely epistemological stances toward physics. He had found this to be an effective “launching question” (Hammer et al., 2012), in that it taps into students’ productive knowledge about physical phenomena. At the same time, he expects that this kind of question will violate students’ expectations at the start of his course about what the course will entail. That is, David chose a question that would allow him to be responsive in a way that a more traditionally posed physics question (e.g., “a force applied to a more massive object”) would not.

Finally, this example shows David taking up and pursuing his students’ thinking, including in his spending more time on the topic than he had planned and in his using student reasoning to shape the flow of the discussion from that point forward. The students’ sense that the mallet stops more abruptly gave David his next clicker question, and it helped that 72% of the students agreed that “stopping more abruptly” meant “higher acceleration.”

Discussion

In this chapter, we have shown that the form that responsive teaching takes can vary across contexts; that teachers can recognize a variety of disciplinary opportunities in what their students say and do—from mechanistic thinking, to the beginnings of canonical understanding, to nascent scientific practices; and that teachers may take up their students’ ideas in different ways, from planning experiments to test a student’s idea, to proposing that students investigate patterns in “Sean numbers,” to allowing students’ emergent ideas to dictate the direction of the class’s inquiry. Despite this variation, we have articulated three characteristics that help us understand what it is that responsive classrooms have in common: they foreground the substance of students’ disciplinary ideas, recognize the disciplinary connections within students’ ideas, and take up and pursue the substance of students’ ideas.

As we look across the classroom cases presented above, we also notice some similarities and differences in the time-scales over which the teacher is responsive, in the constraints and competing goals that the teachers experience as they attempt to be responsive, in the knowledge that is entailed in teaching responsively, and in the classroom cultures that are displayed in these examples. Here we briefly discuss these themes before closing the chapter.
Responsive teaching may entail adapting instruction in-the-moment and responding on the microscale to students’ ideas as they emerge. In some cases it may also involve elevating students’ ideas to the level of the curriculum, such that students’ questions and observations frame and guide an entire unit of instruction.

At the grain size of moment-by-moment responsiveness, Ball invites students to experiment with Ofala’s definition of odd numbers; Hammer tries experiments that his students suggest; Ann recognizes that her students are talking about two different variables that may affect the behavior of magnets; Jenny presses Grace to articulate a mechanism for how water absorbs salt; Leslie and Irene connect students’ definitions of blurriness to one another; and David authors clicker questions on the spot that are based on the ideas he hears in his lecture. In some cases, this moment-by-moment responsiveness is accompanied by longer-term responsiveness. Ball chooses to elevate “Sean numbers” to the same level as even and odd numbers in her students’ explorations of number patterns; a multi-day investigation of induced polarization in Hammer’s high school physics course is initiated by Camille’s discovery of the “Marino phenomenon;” Ann plans a unit around the questions and nascent experiments that emerge in the magnetism discussion; and the idea to pursue blurriness as a phenomenon—and the resulting direction of the students’ inquiry in Leslie and Irene’s class—emerged from the natural direction taken by students’ investigations of how the eye works. That each of these is an example of responsive teaching suggests that it is possible to have both responsive moments and responsive units; it happens at multiple grain sizes.

Ball’s (Ball, 1993) and Hammer’s (Hammer, 1997) first-hand accounts (and others’, e.g., Chazan & Schnepp, 2002; Levin, 2008; Levin et al., 2009; Maskiewicz, this volume) illuminate the tensions that teachers often feel when students offer ideas that are both canonically incorrect and productive toward other instructional goals (e.g., building a mathematical or scientific community), or, more generally, when there are competing goals at play. Hammer (1997) defines this as the “instructional tension”:

For the purposes of this article, I adopt this description of the instructional tension, which I suggest is both genuine and legitimate: It is legitimate for me to want students to understand that some materials conduct electricity and others do not; it is also legitimate for me to want students to explore phenomena, design experiments, and invent their own explanations. Ultimately, I know, these two agendas should not conflict; they are both aspects of the same overall goal that the students develop scientific understanding.
But what I hope will happen ultimately is of little help in this moment, as I try to decide how to respond.

(p. 488)

This tension may take the form of feeling torn between two seemingly-in-conflict instructional agendas, as in the quote above; other times, it may take the form of discerning whether one is really listening to and understanding students’ ideas without projecting one’s own (or the canonical) meaning onto what they have said; still other times it may take the form of balancing or coordinating the myriad ideas that students put forth.

These “instructional tensions” are at the heart of responsive teaching; they are a natural consequence of seeking to embody a practice that “is, at once, honest to mathematics and honoring of children” (Ball, 1993, p. 394) and that enacts an expansive vision of “content”—one that includes and strives for more than canonical correctness. Ball suggests that teachers must embrace, rather than try to resolve, such “pedagogical dilemmas,” and that doing so empowers teachers to really listen to their students.

The teachers in our examples likewise experienced such instructional tensions. Ann was faced with a decision between foregrounding students’ ideas about the magnetism question and reviewing particular canonical content (in this case, forces) for the upcoming standardized test. She articulated both sides of this tension in a conversation after class—she felt a sense of “commitment to the kids that I don’t want them to see something on the test that we’ve never even talked about,” yet she preferred and ultimately chose to honor students’ demonstrated interest in the magnetism discussion. Similarly, Jenny teaches in a high-stakes testing environment, where teachers are accountable for students’ passing scores on an exam that is required for graduation. As a result, her content goals are never far from her mind, and they must be balanced with her attention to students’ thinking. Thus Jenny occasionally tries to guide her students to the canonical answer. For example, after allowing the conversation to proceed with the term “evaporation” for a while, Jenny asks students to recall what they learned about diffusion, and the language of the possible mechanism shifts from evaporation to what students remember about diffusion. David likewise acknowledges the many constraints imposed by the nature of his lecture course: expected content coverage, large numbers of students, and a need to stick to the syllabus.

In spite of these tensions and constraints, teachers in these courses both value and instructionally prioritize students’ ideas, and students experience their ideas as meaningful to the teacher and central to the construction of their own understandings. For example, as the discussion in Jenny’s class comes to a close, Haja asks her, “Do you have your own analysis on this?,” suggesting that she believes that the consensus they have come to has been directed by their (rather than Jenny’s) understandings.
Knowledge: Intellectual Demands of Responsive Teaching

These examples also highlight the role that knowledge of the discipline plays in responsive teaching. Hammer (1997) argues that “this view of the coordination of inquiry and traditional content places substantial intellectual demands on the teacher” (p. 517). For example, locating “a substantive connection” between (i) physicists’ conceptions of charge, electric fields, and/or electric potential and (ii) Susan’s notion of a “spark” or Bruce’s notion of “aura” or “force field”; understanding how adherents of two competing theories are making sense of a new experiment in the moment; recognizing the conceptual and epistemological potential of Camille’s discovery of the “Marino phenomenon”; and figuring out why Ning’s experiment didn’t work all drew on Hammer’s extensive knowledge of the content and practices of the discipline. Not only this, Hammer (and others) must coordinate the many different ideas—as well as multiple, often competing, goals—as he listens for the science in students’ thinking.

Likewise, we see that Ann brings her knowledge of experimental design to bear on her teasing out Caroline’s conflation of the variables of distance and environment; Jenny presses Grace to explore the mechanism underlying the “absorption” of salt by water, knowing that the pursuit of mechanistic reasoning is central to science; Leslie and Irene tease apart which of their students’ accounts of blurriness offer descriptions and which ones offer explanations; and David recognizes that “stopping more abruptly” implies a higher acceleration of his foot. Thus each of these teachers brings his or her knowledge of both the content and the practices of science to bear as he or she recognizes and seeks to build on the “seeds of science” in their students’ ideas, embodying a practice that is “both responsive to students and responsible to [the discipline]” (Ball, 1993, p. 396).

Classroom Culture: Responsiveness to Nascent Practices of Responsiveness Among Students

Although we have focused on what makes teaching responsive, we notice that across our examples students are also listening, responding to, and building on one another’s ideas. For example, Mei revoices Sean’s idea and then challenges its generality; and Amanda, Amber, and Breanna collaboratively share out their explanation for blurriness, building on and adding to one another’s contributions. We suspect that responsive teaching is often embedded in responsive classrooms (Bresser & Fargason, 2013) and that in such classrooms teachers model and reinforce responsiveness to the substance of scientific ideas.

Conclusion

In this chapter, we have articulated three actions that the literature often highlights as characteristic of responsive teaching, and we have illustrated what responsive
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Responsive teaching looks like across examples from the literature and from K–12 and university science classrooms. These examples illuminate the diversity of forms that responsive teaching can take, and they showcase that it occurs across multiple timescales, is intellectually demanding, and is often embedded in a classroom culture of responsiveness, and that when teachers instantiate it, they often experience an “instructional tension.” We hope that in immersing themselves in these examples—in getting a glimpse of responsive teaching in action—our readers are better prepared to engage with the scholarship in the remainder of this book.

Acknowledgments

The authors gratefully acknowledge the support of NSF grant numbers ESI 0455711, DRL 0822342, DUE 0837508, EHR/DUE 0831970, DRL 1140785, and DRL 0733613. We also wish to thank Abigail R. Daane, David Hammer, and Rachel E. Scherr for their thoughtful feedback.

Notes

1 See Chapter 2 for a detailed discussion of several different conceptualizations of responsive teaching and for an overview of some of the reasons that research and teaching communities value responsive teaching.


3 To view video of this discussion, see the following link: http://deepblue.lib.umich.edu/handle/2027.42/65013.

4 Generally speaking, an electrophorus is an object (usually a capacitor) that can be charged by induction. In this case, the electrophorus is “charged by induction” when it is brought near the negatively charged Styrofoam plate: the positive charges in the electrophorus are attracted to the Styrofoam plate, and the negative charges in the electrophorus are repelled from the plate. The result is that the negative charges move toward the top of the electrophorus, and the positive charges move toward the bottom, closer to the Styrofoam. When the finger touches the electrophorus, some of the negative charges leave—in part because the negative charges near the finger are repelled from the other negative charges that have accumulated near the top of the electrophorus—and the electrophorus thus obtains a net positive charge. The electrostatic force between the electrophorus and foam plate (a function of the net charges on each one) increases, and the Styrofoam plate is attracted toward the electrophorus, lifting it off the table.

5 All students’ names are pseudonyms.


7 We adopt Russ et al.’s (2009) criteria for mechanistic reasoning: mechanistic explanations specify the “activities” (the components that “produce change”) and the “entities” (the “things that engage in those activities”), and they “describe how each stage of the mechanism progresses to the next stage” (called “chaining,” p. 880). Russ et al. say that mechanistic reasoning “involves more than just reasoning about causality itself—it is
more than identifying the ‘X’ that causes ‘Y’ to happen.” It “also requires that students think about how ‘X’ brings about ‘Y’” (p. 881). For example, a mechanistic explanation for why the pressure of a gas increases as temperature does would consider that pressure is caused by the collisions of the particles of a gas with the walls of its container and would describe how increasing the temperature would increase the frequency and intensity of those collisions. The beginnings of mechanistic reasoning might include connecting entities and activities or causal sensemaking.


9 In a hypertonic solution, solute concentration is higher on the outside of a membrane (e.g., a cell membrane). In a hypotonic solution, the solute concentration is higher on the inside.

10 To briefly summarize how a blurry image is formed, we explain observation (5). A light ray reflecting off of any point on a translucent R is scattered in all directions (see Figure 1.6). When these rays fall on a screen (as shown in the diagram) or a retina, they will not project a “crisp” or “focused” image, but will overlap with rays that reflect off of other points on the object. However, if a pinhole (an opaque surface with a tiny opening) is inserted between the object and the screen, a clear, upside-down image will be created because only “one” ray from each spot on the object reaches the screen. A lens creates a crisp image by bending rays such that the rays that scattered from one point are brought back together on the screen (creating a clear and bright image). The eye, with its lens and pinhole-like pupil, employs both mechanisms to project a clear image on the retina lining the back of the eye. When the pinhole is large (such that more than one ray from each spot on the object reaches the screen) or the screen/retina is not at the ideal location, the image will appear blurry. In our peripheral vision, the receptors are so far apart that we cannot see fine details, regardless of whether or not the image projected on the retina is blurry.

11 In earlier conversations, the class modeled light rays leaving an object in all directions, similar to the pattern of rubber strands from a koosh ball.

12 Special thanks to David Hammer for providing detailed notes, on the basis of which this section was written.

13 Newton’s Third Law says they must be equal: all forces come in equal and opposite pairs, by object A on object B and by object B on object A.

14 The force by the mallet on the bowling ball, hitting at the same speed, is larger than the force by the mallet on the basketball. One way to see this is to think of kicking the two balls, which is part of this discussion—kicking a bowling ball hurts! Another way to see it is to focus on the mallet. It is moving at the same speed, just before it hits either ball. When it hits the basketball, it slows down, but it keeps moving forward. When the mallet hits the bowling ball, on the other hand, it comes to an abrupt stop; it even bounces backward a little. So the bowling ball has a much stronger effect on the mallet’s motion. In more formal terms, the mallet has a larger acceleration, hitting the bowling ball, which means there’s a larger force on it—and the force by the ball on the mallet must be equal and opposite to the force by the mallet on the ball.

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