INTEGRATING THE EPISTEMIC, CONCEPTUAL, AND SOCIAL ASPECTS OF SCIENTIFIC MODELING

By

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To Belinda Wade,
for her boundless commitment to her students and to her craft

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CHAPTER I

INTRODUCTION

Science education research has shifted from alternatively focusing on either conceptual development or on the acquisition of skills toward a more integrated characterization of science as practice (Duschl, Schweingruber, & Shouse, 2007; Lehrer & Schauble, 2006b). From this point of view, initiating students into important practices (e.g., modeling, representation, or argumentation) engages them in more authentic scientific activity, supporting them both in developing knowledge and understanding how scientific knowledge is generated (Duschl et al., 2007; Ford, 2008; Lehrer & Schauble, 2006b). Accordingly, researchers have explored means for supporting students' participation in practices such as representation and modeling (e.g., Danish & Enyedy, 2007; Schwarz et al., 2009), sought to understand how practices can be conceptually powerful for students (e.g., Sengupta & Wilensky, 2009), and explored challenges and supports for engaging students in social aspects of scientific activity, such as argumentation (e.g., Berland, 2011; Ryu & Sandoval, 2012).

Increasingly, researchers are recognizing that this agenda entails more explicitly relating the conceptual, epistemic, and social aspects of scientific practices in the design and representation of learning environments (Duschl, 2008; Ford, 2008; Kelly, 2008). The recent National Research Council's *Framework for K-12 Science Education* (2011) calls for these strands of activity to be integrated in student learning, but does not offer explicit guidance for what this integration might entail. In particular, two problems require further research. First, we need to better understand how to initiate novices into scientific practices and describe what is entailed in the long-term development of these practices (Ford & Forman, 2006; NRC, 2011). Second, we need to develop more precise ways to characterize the relationship between scientific practices and the development of scientific knowledge. The recent *Next Generation Science Standards* integrate scientific practices and content knowledge in grade-level expectations, suggesting, for example, that second graders "plan and conduct an investigation to determine if plants need sunlight and water to grow." However, there is, as yet, little research to guide the pairings of practices and concepts. Without images of how practices and content knowledge support each other in specific domains, it is difficult to design learning settings that integrate knowledge and practices or to develop appropriate supports for teachers. In the absence of guidance, teachers may resort to teaching a content topic on one day, then a practice on another, or use either ideas or practices superficially as a context for the other. Responses like these have characterized the enactment of science curricula designed to engage students in inquiry (Davis, Petish, & Smithey, 2006; Enfield, Smith, & Grueber, 2008; Furtak & Alonzo, 2010).

In these three papers, I adopt the view that constructing, testing, and revising models is at the heart of the scientific endeavor (Giere, 1990; Grandy & Duschl, 2007; Nersessian, 2008). In the National Research Council Framework, modeling is identified as one of eight scientific practices in which students should be engaged from elementary school. Several science educators seek to organize students' science instruction around modeling, arguing that it is not *one* core practice, but *the central scientific enterprise* (Lehrer & Schauble, 2006a; Passmore & Stewart, 2002; Windschitl, Thompson, & Braaten, 2008). Accordingly, I ask how students can be initiated into the modeling enterprise, what forms of practice are entailed in the development of modeling, and how this practice, in turn, supports the development of important disciplinary ideas.

Each of the papers addresses the relationship between the epistemic, social, and conceptual aspects of modeling practice. The papers share three features. First, they ask how learning environments can be designed so that conceptual, epistemic, and social activity bootstrap each other. Second, they represent the relations between these aspects of practice in students' activity. Finally, they take seriously the notion that practices are interactionally constructed, rather than merely adopted, and characterize the development of practice over time (Kelly, 2008; Wenger, 1998).

This first paper is a literature review that addresses how social activity might profitably be conceptualized within a science-as-practice framework. I focus on scientific argumentation, which has received a great deal of attention in the science education field and is often used to represent social interaction in general. The paper explains that scholars are increasingly noting that current assessments and supports fail to represent important aspects of scientific practice (e.g., Bricker & Bell, 2008; Ford & Forman, 2006; Ryu & Sandoval, 2012). These critiques follow from the acknowledgement that social practices are interactionally constituted in communities. From this perspective, more work is needed to construe argumentation as a practice that both emerges from and contributes to students' ongoing scientific activity. To contribute to this agenda, I conduct a review of the science studies literature to conceptualize argumentation as the social activity that problematizes and stabilizes modeling practice. I then propose three directions for future research: carefully designing uncertainty into students' activity, describing how students come to develop and critique not just what they know but the means by which they know it, and attending to the development of practice over longer periods of time. These recommendations inform the design and analysis reported in the next two papers.

The two empirical studies that follow are drawn from the same context, a multi-year design study conducted with third-grade students in a backyard ecosystem. Ecosystems are complex, involving numerous variables, multiple causes and consequences, and emergent structures that unfold across scales of time and space inaccessible to the casual observer (Jacobson & Wilensky, 2006). These systems pose significant challenges for practice and explanation. To make sense of them, experts have recourse to disciplined forms of modeling practice that privilege particular variables, relations, and explanatory forms (Collins & Ferguson, 1993; Hmelo-Silver, Marathe, & Liu, 2007; Latour, 1999). However, research on children's reasoning about ecosystems generally focuses on students' acquisition of conceptual structures (e.g., photosynthesis or matter cycling) or explanatory forms (e.g., complex causal chains) and typically does not address the material or representational challenges that these settings pose for students or how modeling might be leveraged to involve students in managing these challenges in conceptually fruitful ways (Hmelo-Silver et al., 2007; Leach, Driver, Scott, & Wood-Robinson, 1996; Perkins & Grotzer, 2000; Songer, Kelcey, & Gotwals, 2009). To explore these issues, I engaged students in developing explanations of the "wild backyard," a trapezoidal-shaped area behind their school (Figure 1). The school wall cast a changing pattern of shade on the backyard, resulting in differential sunlight and moisture and related patterns of plant distribution. In both empirical papers I use students' activity as a context within which to explore the co-development of modeling practice and ecological knowledge.

Figure 1. Students investigated the “wild backyard” (left), observing plants, inscribing plants and the places they were found, and using indoors investigations that represented important aspects of the system.

The second paper in my dissertation presents an analysis of the first year of instruction in the backyard setting. Its aim is to describe how students developed and used knowledge in shared modeling practice and to consider implications for designing learning environments that exploit the interrelated nature of knowledge and practice. The paper examines four phases of instructional activity, following the development of one disciplinary idea, the reproductive success of plants. The analysis demonstrates that over the course of the year reproduction became increasingly visible and useful, not only to individual students but to the community. Several relations between knowledge and practice are documented and explored: how representations made ideas visible to the community, how students’ participation in modeling activity allowed them to problematize and deepen ideas, and how ideas developed in one phase of modeling activity were recruited to support sophisticated modeling practices later in the year.

While the second paper examines practice-concept relations over the span of a year, the third paper explores how these relations build over a medium sized scale of activity (eight weeks), one that is long enough to investigate the development of ideas and practices but short enough to allow a more dense sampling of activity. Here, I examine students' work around one experiment, with which they sought to understand how different amounts of light might account for the pattern of plant distribution in the backyard. The experiment is a form of activity that, in professional science, is deeply embedded in the modeling enterprise (Gooding, 1990; Pickering, 1995); however, instruction generally removes it from this context and treats it as an atheoretical test of covariation (Lehrer, Schauble, & Petrosino, 2001; Windschitl et al., 2008). Drawing from the framework developed in my first paper and the design implications presented in my second paper, I sought to understand what aspects of modeling practice students engaged in as they worked with the experiment, how their practice made contact with ecological ideas, and how forms of practice and disciplinary understandings developed over the course of students' activity.

As a set, these three papers contribute to the agenda of supporting students in participating in important aspects of scientific practice. They explore how young students might come to see a need for the functions of scientific practices, develop those practices in interaction with each other, and refine important disciplinary ideas through practice. They illustrate productive contacts between the social, conceptual, and epistemic aspects of scientific activity that can be cultivated in instructional experiences that are typical in elementary school, e.g. reading books and conducting experiments. Finally, they present, test, and refine design principles for engineering learning environments in which knowledge-making is both accessible to students and a useful foundation for disciplinary understandings.

References

Berland, L. K. (2011). Explaining Variation in How Classroom Communities Adapt the Practice of Scientific Argumentation. *Journal of the Learning Sciences, 20*(4), 625-664.

Bricker, L. A., & Bell, P. (2008). Conceptualizations of argumentation from science studies and the learning sciences and their implications for the practices of science education. *Science Education, 92*(3), 473-498.

Collins, A., & Ferguson, W. (1993). Epistemic forms and epistemic games: Structures and strategies to guide inquiry. *Educational Psychologist, 28*(1), 25-42.

Danish, J., & Enyedy, N. (2007). Negotiated representational mediators: How young children decide what to include in their science representations. *Science Education, 91*(1), 1-35.

Davis, E., Petish, D., & Smithey, J. (2006). Challenges new science teachers face. *Review of Educational Research, 76*(4), 607-651.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268-291.

Duschl, R., Schweingruber, H., & Shouse, A. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, D.C.: National Academies Press.

Enfield, M., Smith, E. L., & Grueber, D. J. (2008). "A sketch is like a sentence": Curriculum structures that support teaching epistemic practices of science. *Science Education, 92*(4), 608-630.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423.

Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of research in education, 30*(1), 32.

Furtak, E. M., & Alonzo, A. C. (2010). The role of content in inquiry-based elementary science lessons: An analysis of teacher beliefs and enactment. *Research in Science Education, 40*(3), 425-449.

Giere, R. N. (1990). *Explaining science: A cognitive approach*. Chicago, IL: University of Chicago Press.

Gooding, D. (1990). *Experiment and the making of meaning*. Dordrecht: Kluwer Academic Publishers.

Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. *Science & Education, 16*(2), 141-166.

Hmelo-Silver, C., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*(3), 307-331.

Jacobson, M., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11-34.

Kelly, G. J. (2008). Inquiry, activity, and epistemic practice. In R. Duschl & R. Grandy (Eds.), *Teaching scientific inquiry*. Rotterdam: Sense Publishers

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard Univ Press.

Leach, J., Driver, R., Scott, P., & Wood-Robinson, C. (1996). Children's ideas about ecology 3: Ideas found in children aged 5-16 about the interdependency of organisms. *International Journal of Science Education, 18*(2), 129-141.

Lehrer, R., & Schauble, L. (2006a). Cultivating model-based reasoning in science education. In R. K. Sawyer (Ed.), *Cambridge handbook of the learning sciences* (pp. 371-388). Cambridge, UK: Cambridge University Press.

Lehrer, R., & Schauble, L. (2006b). Scientific thinking and scientific literacy. In K. A. Renninger & I. E. Siegel (Eds.), *Handbook of child psychology* (6 ed., Vol. 4: Child psychology in practice). Hoboken, N.J.: John Wiley and Sons, Inc.

Lehrer, R., Schauble, L., & Petrosino, A. J. (2001). Reconsidering the role of experiment in science education. In K. Crowley, C. D. Schunn & T. Okada (Eds.), *Designing for science: Implications from everyday, classroom, and professional settings* (pp. 251-278). Mahwah, N.J.: Lawrence Erlbaum.

Nersessian, N. J. (2008). *Creating scientific concepts*. Cambridge, MA: The MIT Press.

National Research Council. (2011). *A framework for K-12 science standards: Practices, crosscutting concepts, and core ideas*. Washington, D.C.: The National Academy of the Sciences.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching, 39*(3), 185-204.

Perkins, D., & Grotzer, T. (2000, April). *Models and moves: Focusing on dimensions of causal complexity to achieve deeper scientific understanding.* Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, LA.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. Chicago, IL: University of Chicago Press.

Ryu, S., & Sandoval, W. A. (2012). Improvements to elementary children's epistemic understanding from sustained argumentation. *Science Education, 96*(3), 488-526.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, Fortus, D., Shwartz, Y., Hug, B., Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654.

Sengupta, P., & Wilensky, U. (2009). Learning Electricity with NIELS: Thinking with Electrons and Thinking in Levels. *International Journal of Computers for Mathematical Learning, 14*(1), 21-50.

Songer, N., Kelcey, B., & Gotwals, A. (2009). How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity. *Journal of Research in Science Teaching, 46*(6), 610-631.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967.

CHAPTER II

REPRESENTING STUDENT ARGUMENTATION AS FUNCTIONALLY EMERGENT FROM SCIENTIFIC ACTIVITY

Introduction

Instruction often promotes a view of science as a set of established facts and laws (Driver, Leach, Miller, & Scott, 1996; Lemke, 1990). Authority, then, is vested in laws and the experts who have learned them: scientists or their proxy, the teacher. In scientific activity, however, what counts as knowledge is negotiated in practitioners' ongoing work, supported by particular forms of practice in which disciplinary trust has been vested over time. Some examples are experimental designs, modes of observation, and ways of producing and using canonical inscriptions (Bazerman, 1988; Goodwin, 1994; Latour, 1999; Shapin & Schaffer, 1985). Accordingly, researchers increasingly seek to support students' participation in scientific practices, particularly "epistemic practices," those that ground authority for knowing in the discipline (Duschl, Schweingruber, & Shouse, 2007; Ford & Forman, 2006; NRC, 2011). From this point of view, initiating students into participating in these practices engages them in more authentic scientific activity, supporting them both in developing knowledge and understanding how scientific knowledge is generated (Duschl et al., 2007; Ford, 2008; Lehrer & Schauble, 2006b).

However, framing science learning as participation in practice does not mean regarding students as junior scientists. Scientists engage in many practices, including developing experiments, taking measurements, seeking funding, and engaging in peer-review. Not all of these are productive for students. In addition, scientific practices do not transfer unproblematically from expert settings into classrooms; their purposes and forms tend to be unfamiliar to students (Hogan & Corey, 2001; Kelly, 2008). Therefore, it is necessary to determine both the forms of practice that are educationally most productive and ways to systematically support them in the classroom.

Argumentation is one practice that the science education community largely accepts as a useful focus for student engagement (Duschl et al., 2007; NRC, 2011). Across a range of literatures, argumentation is portrayed as a social process of constructing, supporting, and critiquing claims for the purpose of developing shared knowledge (Berland & Reiser, 2009; Driver, Newton, & Osborne, 2000; Latour & Woolgar, 1986; Longino, 1994). Therefore, it is believed that engaging students in this practice promotes movement past the positivist image of science that many curricula perpetuate, providing students access to deeper understandings of scientific activity (e.g., Driver et al., 2000; Duschl & Osborne, 2002). This perspective has motivated a substantial literature on students' scientific argumentation, particularly within the last decade.

Typically, research and intervention tools used in classrooms (e.g., assessments, coding schemes, structured supports) reflect the forms and processes of argumentation; they portray what scientists do and say when they engage in the practice. These representations have informed both the assessment of students' argumentation skills and the types of instructional support commonly used. However, scholars increasingly suggest that current representations are not sufficient for informing, characterizing, and supporting important aspects of scientific practice (e.g., Bricker & Bell, 2008; Ford & Forman, 2006; Ryu & Sandoval, 2012). These critiques follow from the acknowledgement that social practices are interactionally constituted in communities. From this perspective, more work is needed to construe argumentation as a practice that both emerges from and contributes to students' ongoing scientific activity. This paper takes up this agenda by describing current approaches, exploring critiques from a practice perspective, and undertaking a review of the science studies literature to propose some modifications for representing and supporting the development of scientific argumentation practice in K-12 settings.

Structure And Methods

First, I review three prominent trends in current portrayals of scientific argumentation: attention to structures, attention to processes, and attention to the disciplinary content of arguments. These approaches draw on recent work in argumentation theory, which represents the practice as dialogic, concerned with developing shared understandings, and tuned to particular contexts and disciplines. For each approach, I briefly describe characteristic assessment structures, implications that authors have drawn for instructional supports, and emerging critiques of the approach. I then synthesize and explore these critiques from a practice-based perspective, developing a definition of *epistemic practice* to guide further work on argumentation. In the next section of the paper, I use this definition to guide a review of the science studies literature, seeking to better understand the role of argumentation in scientific activity. Finally, I apply the implications of this review to the literature on student argumentation to generate proposals for future research.

To develop a theoretical basis for classroom representations of argumentation, I drew on literature from argumentation theory, philosophy of science, the sociology of scientific knowledge, and science studies disciplines. To understand how argumentation has been represented and supported in classroom settings, I conducted a review of literature in science education, the learning sciences, and developmental psychology. Because of my interest in supporting argumentation as a disciplinary, epistemic practice, I focused on studies in which argumentation was framed as a way to help students develop scientific knowledge (e.g., an understanding of the seasons or of light) or understand the process by which scientific knowledge is developed. I looked primarily at studies that took place in K-12 settings and discussed student learning (rather than teacher learning or practice). However, I also chose to read studies that did not fit my selection criteria in the cases where they were often cited by those articles that did. For this reason, my review includes some, but not many, studies that focus on socio-scientific argumentation (argumentation that addresses social issues, for instance whether funding should support cloning), argumentation in non-scientific contexts, or studies whose subjects are adults rather than students.

I sought to conduct a representative, rather than exhaustive, review of the literature. To locate relevant articles, I performed searches using the Web of Science, ERIC, and Psych Info databases, searching for peer-reviewed papers, dissertations, and chapters with “argument” or “argumentation” in the title and “science education” in the subject. To ensure that influential work was not overlooked, I mined the reference lists of argumentation work in science education, the learning sciences, and developmental psychology, including several recent reviews (Berland & Reiser, 2009; Bricker & Bell, 2008; Cavagnetto, 2010; Clark, Sampson, Weinberger, & Erkens, 2007; Erduran & Jimenez-Aleixandre, 2007; Zimmerman, 2007). In addition, I scanned issues of *Science Education*, *Journal of Research in Science Teaching*, *Journal of the Learning Sciences,* and *The International Journal of Science Education* published from 2007-2012 and reviewed the conference proceedings for the International Conference of the

Learning Sciences (2010) and the National Association for Research in Science Teaching (2010, 2011) to locate more recent relevant papers.

Representing the Structures, Processes, and Content of Scientific Argumentation

Many classroom studies emphasize the component parts or processes of students' argumentation. This focus is informed by the notion that the primary mode of argumentation is *rhetorical* or *dialogic* rather than *analytic* (Toulmin, 1958; Van Eemeren et al., 1996). At the heart of this distinction, which is mirrored in understandings of scientific knowledge generation, is the idea that knowledge cannot be derived directly from observational statements by way of generically prescribed, logically valid steps. Instead, it is socially constructed through agonistic, or argumentative, exchange (Blair & Johnson, 1987; Latour & Woolgar, 1986; Longino, 1994; Toulmin, 1958; Walton, 1996). In their review of the history of argumentation analysis, Van Eemeren, Grootendorst, and Henkemans (1996; p. 5) characterize argumentation as:

> …a verbal and social activity of reason aimed at increasing (or decreasing) the acceptability of a controversial standpoint for the listener or reader, by putting forward a constellation of propositions intended to justify (or refute) the standpoint before a rational judge…

On this view, arguments are produced during activity and are guided by participants' goals, e.g., persuading an audience and/or reaching a new common understanding. A key tenet of the dialogic approach is that the validity of an argument is judged in relation to a particular community or context. Arguments have audiences and it is these audiences they must convince. (Blair & Johnson, 1987; Toulmin, 1958).

The dialogic view has been widely accepted by scholars of education, who have tended to interpret it and put it to work in three ways. The first has involved looking to the argumentation literature to understand the means by which interlocutors convince each other, focusing on the *structures* that characterize argumentation. The second has focused on *processes* of persuasion and developing shared understandings. The third has attempted to specify what counts as convincing in scientific activity, building representations of the discipline-specific *content* of arguments. These three approaches are often used in conjunction with each other. Below, I describe each approach by characterizing its goals, describing typical representations, and outlining the implications that have been drawn for supporting students. I also address emerging critiques of each approach. These challenges reveal issues of context, goals, and constraints that hinder the development of argumentation as a meaningful practice for students.

Argumentation Structures

Representing the structure of arguments and then supporting students in adopting components of these structures is widespread in the argumentation literature. Structural frameworks categorize statements by their function in relation to an argument as a whole, describing which components of a "complete" argument students demonstrate and which they lack. They can be applied either to arguments written by individuals or those co-constructed by groups. Central to many frameworks is the notion that claims and justification should be present but distinct. This focus follows both from dialogic views of argumentation and from work by psychologists such as Kuhn (1991), who argue that the ability to distinguish one's theory, or claim, from the evidence supporting the claim is essential both to the construction of a dialogic argument and to individual reasoning processes.

Toulmin's (1958) *field invariant* form has been influential. According to Toulmin, a speaker who produces a claim justifies it with data, but must also show the data to be relevant to the claim by stating a warrant and backing. In addition, the speaker can specify the certainty of the claim, given the data (qualifier), and the conditions under which it would not hold (rebuttal). The Toulmin form has been adapted in education literature to represent both argument products (e.g., McNeill, Lizotte, Krajcik, & Marx, 2006) and processes (e.g., Erduran, Simon, & Osborne, 2004). Many studies have used the Toulmin Argument Pattern (TAP) developed by Erduran, Osborne, and their colleagues (Erduran et al., 2004; Osborne, Erduran, & Simon, 2004) to assess the quality of arguments constructed by groups of students. Levels of argument are ordered by which aspects of the Toulmin scheme are present in discussion; for example, a Level 1 argument includes claims and counterclaims, while a Level 3 argument is a series of claims and counterclaims that include data, warrants, backings, and some rebuttals. Two assumptions of this approach, and of other adaptations of argument structures, are that the sophistication of an argument can be characterized by the degree to which claims are grounded and that mastery of argumentation consists, at least in part, of using these argument components.

These analyses have uncovered several challenges for students. First, while students produce numerous claims over the course of argumentative activity and often justify their claims, they are less likely to provide warrants and backings (Bell & Linn, 2000; Erduran et al., 2004; Maloney & Simon, 2006; McNeill et al., 2006). Second, they usually do not spontaneously generate counterarguments and rebuttals (D. Kuhn, 1991; D. Kuhn & Udell, 2003). That is, they attend to explicating their own position, rather than identifying and addressing its weaknesses or attacking weaknesses in another participants' argument. A key implication that researchers using these forms draw for instruction is that argument components should be taught explicitly (D. Kuhn, 1991; Osborne et al., 2004). Teachers might define argumentation components and provide structured opportunities for practice (McNeill & Krajcik, 2009). Students can be supported with prompts or reminders to include component parts and processes of argument

(Bell & Linn, 2000; Chin & Osborne, 2010; D. Kuhn & Pease, 2008; McNeill et al., 2006; Reiser et al., 2001). These forms of support are often conceptualized as “scaffolds” that allow students to engage in argumentation before they are able to do so independently, then are faded out as students develop proficiency (McNeill et al., 2006; Quintana et al., 2004).

In practice, the Toulmin form has proved challenging to apply. It is often difficult to distinguish whether a particular statement is a claim, data, warrant, or backing and to reliably code implicit components of arguments (Erduran et al., 2004). Several researchers have responded to this ambiguity by collapsing warrant and backing to form a “reasoning” component (Berland & McNeill, 2010; McNeill et al., 2006). A more serious interpretation of this challenge, however, is that grounds and grounding procedures are context dependent. For example, Kelly, Druker, and Chen (1998) found that students working together on open-ended electricity problems often failed to warrant evidence not because they did not know how to, but because they shared a common understanding of problems, materials, and potential data sources that rendered a warrant unnecessary. The authors were able to trace categories of events in which a need for warrants arose, including questions and the presence of anomalous data. These findings raise serious questions about whether it is fair to assume that arguments lacking grounding are less sophisticated; instead, they might reflect an arguer’s awareness of the common ground shared by his or her audience. Therefore, a major challenge to this structure, and structural analyses of argument more generally, are that they are not sensitive to the dialogic and contextual nature of argumentation.

Argumentation Processes

Several authors have developed process-oriented frameworks that foreground the goals of argumentation, capturing the nature of discourse moves in order to understand how students engage in convincing each other. These frameworks often use aspects of the structural frameworks reviewed above but expand them to include other kinds of discourse moves, for instance to specify whether and when students are on or off task (Clark & Sampson, 2008) are involved in management as opposed to substantive discussion (De Vries, Lund, & Baker, 2002), or are engaged in persuasive activity in contrast to explanatory or knowledge seeking activity (Berland & Reiser, 2011; De Vries et al., 2002; Herrenkohl & Guerra, 1998; Maloney & Simon, 2006).

An often-cited example of a dialogic process framework is one used by De Vries, Lund and Baker (2002). Students wrote explanations of a sound phenomenon, then were directed to compare explanations and resolve differences with a partner in an online environment. The authors coded students' statements according to whether they demonstrated engagement in explanation, argumentation, problem resolution, or management. Explanatory activity involved expressing understanding of a concept or event in a non-argumentative context or checking on understanding, while argumentative talk involved extending theses that conflicted with a partner's idea, defending one's own idea, attacking a partner's idea, and making a concession or compromise. Problem resolution entailed evaluating and revising the text that partners were jointly tasked with producing. Other talk was coded as involving management of the task or social interaction. The coding scheme allowed researchers to understand the forms of activity in which students engaged as they worked on the task.

Dialogic process analyses have suggested that students may misunderstand or experience a tension around the goals of argumentation. De Vries and colleagues (2002) found that some students appeared to believe that the purpose of working together was to construct shared sentences rather than to understand each other's claims and clarify differences to reach an improved understanding. Berland and Reiser (2011) assert that argumentation consists of two goals, sense-making and persuasion. They argue that defending ideas and critiquing others' ideas are associated with the goal of persuasion, while constructing claims and questioning others' ideas are associated with the goal of sense-making, and that revising claims necessarily emerges from both goals. They used the coding of discourse moves in a comparative case study to demonstrate that one classroom appropriated a goal of sense making while another classroom was characterized by a stronger goal of persuasion. Berland and Reiser claim that the two goals may be in tension in classrooms and that both teachers and students can experience difficulty in reconciling them.

These analyses suggest that learning environments must provide reasons for students to participate in knowledge-building and persuasive activity. First, promoting dialogic exchange requires equipping students with the authority to construct and question knowledge and giving them the opportunity to exercise this authority (Chin & Teou, 2009; Duschl & Osborne, 2002; Jimenez-Aleixandre, 2007). This opportunity can be created using open-ended tasks with at least two possible plausible solutions (Berland & Reiser, 2011; Jimenez-Aleixandre, 2007). Second, students need to recognize that they disagree, and therefore perceive a need to convince each other; this need can be enhanced by first having students create initial explanations, then pairing students whose explanations differ (Clark & Sampson, 2008; De Vries et al., 2002). In addition, researchers argue for the need to make student thinking visible and clear enough for others to respond to; for example, by scaffolding the development of an explanation and providing explanation stems (Clark, D'Angelo, & Menekse, 2009) or providing explicit instruction in desired roles and dialogic moves (Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999).

Analyses of dialogic processes provide fine-grained descriptions of students' participation in argumentative activity. They also can support inferences about contextual factors and students' views about aspects of argumentation, such as its purpose. However, they are less suitable for allowing us to understand whether the argument that students participate in is scientific or contributes to scientific knowledge building. In the case of both structure-based and process-based representations, it is unclear what would make moves or components scientific. These frameworks are discipline-general; similar components and moves are presumed to be evident in arguments across disciplines and in everyday interaction. Disciplinary activity generates accepted problems, kinds of claims, and warrants and it is the *content* of these that distinguishes argumentation in one field from that in another. For these reasons, researchers have noted the need to move beyond Toulmin-like structures or descriptions of processes, or to complement them with other analyses focusing on disciplinary aspects of argumentation (e.g., Duschl, 2007; Sandoval, 2003).

Scientific Content

Several representations focus more explicitly on the scientific content of arguments. A key tenet of the dialogic view is that the validity or usefulness of argument is judged by its audience (Blair & Johnson, 1987; Toulmin, 1958). Communities develop criteria for what counts as a useful question, a possible claim, and relevant or sufficient justification (e.g., Bazerman, 1988; Mayr, 2004; Walton, 1996). There are two implications of this view: first, the need to consider the content of argument components, and, second, that content is judged according to the norms of a discipline. For this reason, scholars have turned their attention to describing what makes an argument "scientific," then seeking to understand how students appropriate discipline-specific processes and forms.

One way to describe scientific argumentation is to focus on science as an explanatory enterprise and to privilege claims that are explanatory or causal in nature. Berland and McNeill's (Berland & McNeill, 2010) learning progression for scientific argumentation distinguishes between claims that do and do not include a causal account, placing the causal accounts at a higher level. Many argumentation tasks use questions that require students to posit and defend causes. For example, students might be asked to explain why some finches survived a drought and some died (Berland & Reiser, 2009) or why objects that have been sitting in a room for a long time often feel as though they are different temperatures (Clark & Sampson, 2008). They might also be given questions that, while not explicitly causal in structure, form a context within which mechanisms are useful, for example, which of several graphs shows the temperature of water as it is being heated (Chin & Osborne, 2010). Several studies have taken this approach, posing "scientific" questions that require mechanistic explanations, then examining students' argumentation using domain-general structure or process representations (Bell & Linn, 2000; Chin & Osborne, 2010; Yeh & She, 2010).

A second approach has been to consider the scientific knowledge used in arguments. One method is to use a general measure of knowledge; for example, von Aufschnaiter (2008) characterizes statements as demonstrating concrete knowledge (referring to situations and objects), abstract-static (referring to invariant classes of situations and objects), abstract dynamic (variables classes), and systemic (making use of covariation). Another method is to specifically lay out conceptual levels particular to the topic of argumentation. For instance, Clark and Sampson's work (Clark & Sampson, 2008; Sampson & Clark, 2009) uses a facet analysis method, where prior conceptual change work is used to populate a coding scheme of non-normative, transitional, and normative ideas particular to that domain. Finally, numerous researchers have used qualitative methods to trace the process by which students work together to generate an explanation, analyzing the content of talk to understand what ideas students apply and how concepts develop through collaborative talk (Chin & Osborne, 2010; De Vries et al., 2002; Mason, 1996). A challenge in each of these forms of analysis is how to treat non-normative scientific ideas: do they indicate less sophisticated argumentation, or do they represent opportunities to develop concepts?

Other researchers characterize the use of particular forms of evidence as the hallmark of scientific reasoning and explore how students consider and use evidence in their argumentation. For example, many representations of scientific argumentation privilege empirical data in the form of observations or measurements over appeals to other sources of justification, such as plausibility (e.g., "it seems to make sense," "it could happen") or authority ("That's what the teacher told me") (Choi, Notebaert, Diaz, & Hand, 2010; Furtak, Hardy, Beinbrech, Shavelson, & Shemwell, 2010; McNeill, 2011; Sampson, Grooms, & Walker, 2011). However, notions of which data to use and how to use it are informed by theoretical commitments that include consideration of plausibility and established facts (Koslowski, 1996). Kelly and Takao (2002) draw from Latour's (1987) claim that scientific argumentation involves rhetorically stacking "epistemic levels:" moving from contingencies of experiments to theoretical claims. They focus on how students produce and connect geological statements at the following "levels" of generality: statements about data representations, identification of features from data, relational aspects of structure, illustrations of assertions, assertions in the form of theories or models, and general geological knowledge. Similarly, Sandoval and Millwood (2005) consider how students use evidence in data charts to make claims, identifying whether they include data, point to data representations, or actively interpret them. From this point of view, scientific activity involves moving between theoretical claims (often conceived as causal or mechanistic explanations) and empirical data; scientific argumentation consists of rhetorically tying the two together.

One major difference in representations of scientific argumentation is the specificity of alignment with the argument's target domain. Some authors have developed representations that, they argue, transcend particular contexts and domain understandings (Furtak et al., 2010; McNeill et al., 2006; Sampson et al., 2011). For example, McNeill characterizes facility with scientific argumentation as involving the use of "relevant" and "sufficient" evidence and reasoning, while Sampson and his colleagues focus on whether students use "empirical criteria," such as fit with evidence and sufficiency of evidence and "theoretical criteria" that include how sufficient the explanation is and how consistent it is with other scientific ideas, as opposed to "informal criteria," including appeals to authority and plausibility or moves to discredit the speaker (e.g., by arguing that another student never contributes in useful ways).

A contrasting approach is to explicitly specify the content and inference structures of the domain argument, including claims, evidence, and claim-evidence relations. For example, Sandoval (2003) constructed a framework for assessing students' explanations of species change in response to environmental pressure, a central form of evolutionary explanation. He privileged specific causal elements as necessary from a domain standpoint (e.g., environmental pressure, selective advantage) and described, for each causal element, both what might count as a claim and how data would need to be used to support that claim. Students' responses could then be assessed by how many of the elements they are articulated and how many they warranted. This framework allowed Sandoval to understand how well students could construct an *evolutionary* argument rather than an argument in general or even a "scientific argument."

While context-free representations appear to offer distinct advantages, in that they allow researchers to compare students' writing and talk across lessons or science units, upon closer examination, researchers using these representations always have to deal with context and domain understanding. Kelly and Takao (2002) noted that their "epistemic levels" representation did not assess whether the inferences the students used to move between data and theory were sensible from a disciplinary point of view; as a result, how they scored a student's argument and how the instructor scored it often differed substantially. In addition, when authors use criteria of "relevant" and "sufficient" evidence to assess argumentation skills, they need to translate these criteria for each question or task, for instance, by developing question-specific rubrics (McNeill, 2011; McNeill et al., 2006). As a result, comparing students' argumentation ability across content areas and questions is difficult. When McNeill represented elementary students' arguments with composite scores (combining scores for claim, evidence, and reasoning) and compared students' scores over the course of a school year, she noted precipitous increases and drops, rather than steady development, which she attributed to the demands of the context and necessary domain knowledge. Sampson and his colleagues (Sampson et al., 2011) avoided this issue by using the same question for their pre- and post-assessment of students' argumentation skills. Therefore, it is still unclear how to argue that students have developed "scientific argumentation skills" that transcend scientific tasks and sub-domains.

Studies that focus on students' understanding of scientific arguments have found that students initially struggle with several aspects of scientific argumentation. For example, they have difficulty maintaining an explicit focus on the explanatory purposes of scientific argumentation (D. Kuhn & Pease, 2008), understanding what counts as a good explanation in science (Sandoval & Reiser, 2004), using relevant data to support claims (Sandoval & Millwood, 2005), and linking claims to accepted theories (Sampson et al., 2011), Several authors characterize students' challenges as more fundamentally indicating the ways that their epistemological beliefs, or beliefs about knowledge, differ from those of scientists (D. Kuhn & Pease, 2008; Sandoval, 2003). For example, the students in Sandoval and Millwood's (2005) study included and referenced data displays in their written explanations (writing, for example, "see graph,") but rarely interpreted how specific features of the inscription supported their claim. The authors argued that students might believe that the data were self-evident, directly represented the natural world, and consequently had only one possible meaning.

Many researchers have devised structured forms of support, or scaffolds, for the development both of scientific argumentation skills and the beliefs about knowledge that undergird argumentation. For instance, computer environments might prompt students to apply causal reasoning by repeatedly asking them to identify whether a factor "makes a difference" or "makes no difference" (Kuhn & Pease, 2008). Students might be prompted to use relevant evidence by receiving reminders to avoid including measurements that are not properties (i.e., mass or volume) in their written explanations (McNeill & Krajcik, 2009). They might also be provided with descriptions of the structure of disciplinary explanations and the kind of data important for supporting different explanations (Sandoval, 2003). However, several authors argue that structural supports such as scaffolds must be one component in a larger activity system that includes ongoing engagement in argumentation and the development of community norms. Developing these systems poses challenges to teachers and students, including communicating the purposes of scientific argumentation (Berland & Reiser, 2011) and developing public discourse structures (Sandoval, 2003).

Describing what constitutes a scientific argument and inducting students into this form of practice is a daunting and complex task. First, there is variability in ideas of what constitutes scientific argumentation and whether it is useful to represent students' argumentation skills outside of the context of a domain-specific question. Even the aspect of argumentation that most representations privilege — the use of empirical evidence — has been questioned by several scholars, who argue that a focus on empirical evidence may constrain talk and fail to adequately represent the conceptual nature of the scientific enterprise, which involves both conjectural and empirical reasoning (Koslowski, 1996; McDonald & Kelly, 2012; Shemwell & Furtak, 2010).

In addition, conflicts between normative disciplinary views and dialogic views of argumentation are apparent and are consequential for how we interpret student difficulties and design supports. Definitions of scientific argumentation are generally pursued from a normative view, describing the arguments that scientists make (i.e. their causal nature, the role of empirical data, the need to interpret figures). But it is not clear that these features would be necessary to convince students' audience — their classmates, who likely do not initially hold these disciplinary values, or their teachers, who already "know the answer." As Sandoval and Millwood (2005) point out, it is difficult to interpret an aspect of scientific argumentation that students fail to incorporate in their argument, for example, interpreting a graph, as indicating something that they do not understand or as an assessment of a shared common ground (in the sense that they believe their teacher knows how to interpret the inscription). Researchers who have attempted to develop disciplinary argument with students have often noted struggles with issues of audience and context (e.g.,Kelly & Takao, 2002; Sandoval & Reiser, 2004).

A Practice Perspective: Interpreting Challenges Representing Argumentation as Structure, Process, and Disciplinary Content

Work on argumentation has supported shifts in classroom discourse that position students as authors of knowledge and allow them increased access to science as a social activity. Organizing classrooms and tasks around argumentation encourages students to interact directly with each other, as opposed to directing conversation exclusively to the teacher, who, in turn, evaluates comments. (Berland, 2011; Duschl & Osborne, 2002; Martin & Hand, 2009). Making argumentation structures visible to students encourages them to make their ideas explicit, promoting the elaboration, connection, and consolidation of scientific understandings (Bell & Linn, 2000; Chin & Osborne, 2010; Chin & Teou, 2009; de Lima Tavares, Jiménez-Aleixandre, & Mortimer, 2010; Keys, Hand, Prain, & Collins, 1999; von Aufschnaiter, Erduran, Osborne, & Simon, 2008). However, these portrayals of scientific argument, and the forms of support associated with them, have also been challenged, on the grounds that the structures used are insensitive to issues of context and audience and that they may unduly constrain the forms of activity valued in the classroom. As a result, students might participate in argumentation without understanding the purpose of their activity. These challenges suggest that more work is needed to support the development of argumentation as an epistemic practice in classroom communities.

First, specifying the desired structure and content of scientific arguments can cause insensitivity to the context within which argumentation occurs. Arguments are targeted to a particular audience; therefore, students' use of grounding procedures should be influenced by their perceptions of shared understandings and goals. Several authors have found that how and when students explicate data depends on their framing of the task and their communicative goals. For example, students tend to warrant claims more when they are challenging others or responding to challenges (Clark & Sampson, 2008; Kelly et al., 1998). Therefore, they might fail to justify or warrant ideas not because they do not know how to but because they do not need to. Researchers increasingly seek to understand the contexts in which students do and do not use argumentation and to learn how to design contexts in which students experience “a need” for the practice (Berland & Hammer, 2012; Berland & Reiser, 2011; Sampson et al., 2011).

One aspect of context that is likely to be essential is the audience for arguments: other students. The forms of support that are typically proposed provide entry into argumentation, in that they position students as authors of knowledge, provoke disagreement, and support individuals in using components of arguments. However, as noted above, it is not clear that the aspects of scientific argumentation typically favored in the literature (e.g., scientific accuracy, empirical evidence, rhetorically connecting theory and evidence, interpreting data displays) are necessary to convince other students, who are unlikely to hold these values. Few authors, as yet, have focused on how students become, over time, an increasingly scientific audience for each other’s work. It is possible that, to date, the field has attended too exclusively to skill appropriation and not sufficiently to the development of the scientific community in which argument plays a role (Kelly, 2008; Ryu & Sandoval, 2012).

In addition, argument structures may not adequately represent the varied forms of activity that support the development and defense of scientific knowledge claims. Structures that privilege the use of empirical evidence fail to represent the conceptual talk that is central to scientific sense-making (McDonald & Kelly, 2012; Shemwell & Furtak, 2010). For example, Shemwell & Furtak located examples of both empirical evidence and conceptually rich talk in middle-schoolers’ whole-class discussions, but found that stretches of talk were rarely characterized by both conceptual depth and evidentiary support. They argue that placing primacy on rigorous evidentiary support leads to constraints on goals and reasoning that hinder the use of personal, conjectural, and imaginative thinking. In addition, nonverbal modes of communication, such as gesture or visual representations, are essential modes of argumentation (Bricker & Bell, 2008; Latour & Woolgar, 1986; McDonald & Kelly, 2012; Ochs, Jacoby, & Gonzales, 1994). Both domain-general and disciplinary content-based structures represent one aspect of scientists' work, that is, final-form arguments of the type published in scientific journals, but may be less helpful for describing and supporting forms of activity that are, in fact, essential to the development of arguments. Their use as the main organizer of classroom activity risks limiting students' participation in important aspects of scientific practice.

Finally, research suggests that students sometimes misunderstand, or experience tension around, the persuasive and knowledge-building goals of the practice (Berland & Reiser, 2011; De Vries et al., 2002). They may adopt structures without understanding the purposes of the forms they are asked to use. For example, Kuhn and Pease (2008) asked students to include a statement of the purpose of inquiry in a written research report. Although 17 of the 18 students supported their claims with evidence and a majority correctly described key aspects of the procedure that allowed them to collect conclusive evidence, only half framed the investigation as allowing them to find out which of several factors mattered. Findings like these have been framed as a contrast between "doing the lesson" and "doing science" (Berland & Hammer, 2012; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000; Watson, Swain, & McRobbie, 2004). They suggest additional drawbacks of overemphasizing the use of argument forms (i.e., with the scaffolds described in the previous sections); students might adopt these forms because they are asked to do so without understanding their role in convincing others or developing scientific knowledge (Berland & Hammer, 2012; Sandoval, 2003).

These challenges gain additional focus when considered from a perspective on the nature of social practice. While practices manifest as routine structures, their forms are interactionally accomplished in communities to facilitate a shared enterprise (Wenger, 1998). Wenger describes routinized, describable practices as “reifications” that support community activity, but cautions that these routines are “double-edged” in the sense that they erase the negotiated activity that originally gave them meaning. Engaging students in doing what scientists do when they argue, for example, using evidence, interpreting graphs, or making coherent links between disciplinary ideas, constitutes an initiation into reifications of scientific argumentation. Yet, students might not understand the purpose of these forms of talk in the larger scientific enterprise. This is especially likely given that, unlike newcomers in scientific communities, they are surrounded by other newcomers, who are also unlikely to hold disciplinary values. Therefore, students can engage in argumentation activity without experiencing it as a knowledge-building practice for themselves in their scientific work. To accomplish this goal, the field will need to better theorize what it means for an *activity* to become an *epistemic practice* for students.

The term practice might be used to emphasize a contrast between the concrete and the abstract (i.e., practice vs. theory) or between knowing and doing (i.e., knowledge vs. practice) (Lampert, 2010; Lave & Wenger, 1991). From this point of view, any situated activity could be considered a “practice.” Other authors specify that practices have to be repeated or routine; on this view, a practice is an activity that is widespread and repeatedly enacted. I take practices, and epistemic practices in particular, to be repeated, situated, and shared, but also consider them to be *emergent* from a community enterprise (Barnes, 2001; Wenger, 1998). Thus, understanding a practice means attending to its relation to the goals and activity of a community, to the way that it participates in constituting the community, and to its development.

Shared enterprises, including scientific activity, processing and collecting claims, or navigating a marine vessel, involve common goals and generate repertoires of talk, tool-uses, and actions that allow members to align behavior and accomplish goals (Hutchins, 1995; Kitcher, 1993; Wenger, 1998). These practices have meanings, forms, and functions that are negotiated in situated activity. For example, Saxe and Esmonde (2005) traced how *fu*, a practice for embodying numerical quantities, evolved as it was recruited for new functions in a developing Oksapmin trade system. Changes in the larger trade system imposed new demands on communication; in turn, forms of *fu* shifted to take on new communication functions. Because practices are sedimentations of solutions to problems that emerge from goals and activity, they have a historical and situated character and do not transfer unproblematically to new participants or locales (Lave & Wenger, 1991). Understanding a practice must therefore include consideration of the activity and goals from which it emerges; the more that newcomers are initiated into these activities and goals, the more likely they are to develop the practice.

As practices emerge from activity, they participate in constituting the world within which people continue to act. Rouse (1996) argues that practices are better described as “meaningful ways of configuring the world” than as patterns of action. On this view, practices shape not only how people act, but also what objects are considered important, what they are important for, which other practices are sensible, and how social relations are conceived. The idea that practice, the community, and the world are co-constituted is central to practice theory and is evident in constructs such as Knorr-Cetina’s (1999) “epistemic cultures,” Holland et. al’s (1998) “figured worlds,” and Wenger’s (1998) “communities of practice.” For any epistemic practice, therefore, we should consider the ways in which it is used to stabilize knowledge in particular configurations of objects, actors, and meanings. Rather than focusing only on norms for the practice itself, we might study the wider network within which practices are constituted and which they, in turn, constitute, including knowledge, social networks, tools, and outcomes of actions (Atran, Medin, & Ross, 2005).

Finally, practices take on trajectories as they develop and are stabilized within a community. Practices are always enacted by individuals and their meanings are negotiated in ongoing activity; this means that they must be continually produced and reproduced (Barnes, 2001; Lave & Wenger, 1991). Individual representation and re-enactment of public practices are characterized by substantial variation and drift toward forms sensible to the enactor (Sperber, 1996). A community engaged in a shared enterprise constrains these processes of negotiation and drift, as the practice is sustained within and participates in sustaining a larger configuration of actors, actions, objects, and knowing (Rouse, 1996; Wenger, 1998). However, perturbation in one of these shared elements is likely to evoke change in practice, as in the case of the evolution of *fu.* In knowledge-building communities, therefore, there is likely to be significant evolution of the practice as new actors enter and as the development of knowledge opens new questions, challenges for activity, and meanings for objects (Hall & Greeno, 2008; Knorr Cetina, 2001).

Bazerman (1988) writes that while practices are often represented as "timeless expressions," or unitary, stable structures, instead:

> …we must account for the functional emergence of these regularities to account for what they are and what they do… we need to understand why regularities emerge, evolve, and vanish (p. 315).

Defining an epistemic practice as emergent, attending to its relation to the goals and activity of the community that it participates in constituting, and conceptualizing change as negotiated development rather than the adoption of stable forms focuses attention on new aspects of the practice of argumentation that must be represented and designed in classrooms. Rather than focusing only on what argumentation looks like, we should also account for its "functional emergence" in scientific activity. By doing so, we can generate implications for building a classroom enterprise that might give rise to the goals, challenges, and objects likely to support a related functional emergence in this different setting.

Revisiting Scientific Argumentation as an Epistemic Practice

In this section, I seek to understand argumentation as an epistemic practice that is emergent from scientific activity. Rather than beginning my conceptualization with distillations of expert forms of argumentation, I focus on the larger activity system and goals of the scientific enterprise, seeking to understand what it means to build knowledge and to describe the forms of activity scientists engage in to do so. I then ask what kinds of communities and community objects are constituted through practice and how social exchange plays a role in that constitution. I make the following three claims:

1. Science is an open-ended modeling endeavor that involves both representational and material work.
2. Problematization and subsequent stabilization are carried out socially as communities develop shared knowledge and the shared means of knowing.
3. The development of scientific argumentation is embedded in the development of other scientific practices and the constitution of scientific communities.

Science is an Open-Ended Modeling Endeavor that Involves Both Representational and Material Work

A recent characterization of knowledge-building activity, which I adopt to frame this analysis, is that of scientific activity as modeling (Giere, 1999; Hesse, 1966). Like philosophers of science, science education and learning sciences researchers increasingly agree that at its core science is a modeling enterprise (Lehrer & Schauble, 2006b; Schwarz et al., 2009; Stewart, Hafner, Johnson, & Finkel, 1992; Windschitl, Thompson, & Braaten, 2008). This view highlights the representational nature of scientific activity. Scientists produce abstract, predictive representations of the world (models) in the form of explanations, equations, and physical instantiations such as the Bohr model of the atom (Giere, 1988). They develop new concepts by bootstrapping tentative relations between target phenomena and potentially similar systems (Hesse, 1966; Nersessian, 1999). Models are judged by their perceived fit with the world, the actions that they allow scientists to take, and the work that they make possible; much of scientific activity consists of deepening and expanding models or constellations of models (Giere, 1990; T. Kuhn, 1996; Longino, 1994).

Modeling also has a highly material sense, in that scientists have to harness and interpret what Pickering (1995) refers to as nature's "agency." Similarly, Pera (1994) conceptualizes nature as having a "voice" or a "role" in scientific debate: his metaphor for the development of knowledge consists of a proposer who asks a question, nature that answers, and a community that comes to agreement about "what is to be taken as nature's official voice" (p. 11). Because nature does not always talk in ways we can easily understand, scientists attempt to "capture, seduce, download, recruit, enroll, or materialize" its agency (Pickering, 1995, p. 7). To do so, they make conceptual and material models of phenomena in the forms of experiments, machines, stem cell cultures, or animal models, and study those, using them to construct arguments about aspects of the world for which they intend them to stand in. From this point of view, any experiment or instrument is a model, a material conjecture that specifies target aspects of the world, their relations, and their manifestations.

Modeling activity is permeated with uncertainty; much of scientific activity is concerned with managing this uncertainty. Theories and explanations involve hypothesized events and unseen processes; they are by nature conjectural and revisable (Windschitl et al., 2008). But even the empirical observations that support these accounts are fundamentally uncertain; rather than merely finding or using evidence, scientists *make* it. Phenomena must undergo processes of "construal" to become objects of observation, reflection, and communication (Gooding, 1990). Instruments and experimental protocols do not simply represent construed phenomena; instead, they are developed over time and are subject to significant scientific energy (Knorr-Cetina, 1999; Nersessian & Patton, 2009; Shapin & Schaffer, 1985). Modeling can be considered an "open-ended process" (Pickering, 1995, p. 19), in which ideas, practices, and even goals are temporally emergent from ongoing activity.

A key implication of a view of science as modeling is that concepts and the practices that produce them are intricately bound together. Models are models *of* something and always involve variables selected for their conjectured role in a mechanism or causal relation (Hesse, 1966). Instruments, measures, and inscriptions are embedded in particular theoretical models; they always involve selection and representation (Hackmann, 1989; Latour & Woolgar, 1986). As Hanson (1958) writes, the moment something is seen or experimented on, it is theoretical, because it is *seen as*, and when it becomes part of an experiment it is already *theorized as* part of a discrete causal chain. In turn, the concepts that are developed through scientific activity are constructed by particular practices, rather than discovered with them (Gooding, 1990). What is "known" and the means by which it is known are stabilized only in relation to each other.

Pickering (1995) argues that facts are produced through stabilizations of *material work* consisting of the design and revision of machines and measures, *interpretive accounts* of material results, and *phenomenal accounts* that assign meaning or status to the natural objects that are the subject of their work. He provides as an example Giacomo Morpurgo's attempts to find evidence for or against the existence of quarks. This work consisted of making a machine that *could* find particles with fractional charges and seeing whether it did. In practice, it consisted of multiple iterations of revision of both the machine and the accounts of its action. In the end, Morpurgo concluded that he had found no evidence for quarks, though other scientists have since found evidence of their existence using other machines. Morpurgo's account was produced, and seen as reportable to the scientific community, not by certainty of its "truthfulness" but by stabilizations of his instruments, his accounts of them, and his accounts of the world.

Problematization and Stabilization Are Carried Out Socially as Communities Develop Shared Knowledge and the Shared Means of Knowing

The problematization and stabilization of model, practice, and machine occur in communities of scientists through social action and exchange. Latour and Woolgar (1986) traced how empirical results came to be considered as facts in a laboratory and the scientific community within which it was situated. They argue that facts emerge as contingent results in laboratories; are inscribed and made visible for others; become subject to debate over methods, theory, and even the qualities of the researchers who created them; and are gradually recruited into larger networks as they become useful to others. Eventually, statements that are taken as fact are stripped of the modal qualifiers that were integral in their creation. Over time, these facts become integrated into the discipline, reified in machines and instruments. Similarly, Nersessian and Patton (2009) describe the "interlocking models" needed to support the work of bio-medical engineering labs, where concepts, physical models, instruments, and measures are connected within the network that the scientists use to test and produce claims. Through argument, the scientific community questions, debates, and stabilizes not only what it knows, but also the means by which it knows.

Longino (1994) points out that by treating theories as models and studying the communities in which models are developed and contested, we can develop an account of why science has "advanced," in that we are continually better able to act in (or represent) the world. She writes:

> "If $S_1 \ldots S_n$ are members of an epistemic community [C], W is some real-world system or portion of a real-world system, and M is a model (of that system) then S1…S_n know W as M if and only if
>
> i. $S_1 \ldots S_n$ represent W as M and act with respect to W as if it were M;
>
> ii. a subset of elements of M is sufficiently isomorphic to a subset of elements of W to enable $S_1 \ldots S_n$ to satisfy their goals with respect to W ; and
>
> iii. $S_1 \ldots S_n$'s representing W as M is the result of warranting practices adopted by C in circumstances characterized by
>
>   a. public forums for critical interaction,
>   b. uptake of criticism,
>   c. public standards, and
>   d. equality of intellectual authority among diverse perspectives" (p. 135).

The first two criteria for shared "knowledge" treat theories as models that are isomorphic enough to aspects of the world to allow members of the community "to act" and "satisfy their goals" in relation to the world. This is a representational view that also privileges the performative acts of modeling and the tangible results of "knowing" (or having a model). The third criterion (iii) describes features of a "knowledge-constructive community" with public venues for problematizing models (see Kelly, 2008 for a discussion of these criteria). The model is subject to the scrutiny of a community that has developed warranting practices. Longino (1990) calls this view of knowledge-building "contextual empiricism":

> "It is empiricist in treating experience as the basis for knowledge claims in science. It is contextual in its insistence on the relevance of context—both the context of assumptions that supports reasoning and the social and cultural context that supports scientific inquiry—to the construction of knowledge" (p. 219).

In Longino's account, as well as those advanced by Pickering, Latour, Nersessian, and others, empirical data are the basis for knowledge, but they take meaning from a shared context formed from the debate and adoption of machines, experiments, facts, and warrants. From this point of view, scientific communities work simultaneously on constructing (and contesting) knowledge and shaping what counts as knowing. Argumentation might, then, be conceptualized as the activity that functions to construct, problematize, and over time stabilize both knowledge and the means of knowing, enabling communities to know, experiment, and do.

The Development of Scientific Argumentation is Embedded in the Development of Other Scientific Practices and the Constitution of Scientific Communities

Scientific arguments and scientific communities co-develop. Construction, contest, and stabilization give rise to a shared machinery for developing knowledge: linkages between the agency of nature and the statements, experiments, equations, and drawings that are accepted as adequately representing the world and allowing scientists to act in it. Newton, for example, developed facets of what we know as experiment and its place within a closed conceptual system as he responded to critics who challenged his optical prisms, accounts of experiments, and representations (Bazerman, 1988). Boyle developed the notion of witnessing as he attempted to harness his claims to his machine, changing the way everyone else tested phenomena as he defined and defended his arguments (Shapin & Schaffer, 1985). Developments like these give rise to "epistemic cultures" (Knorr-Cetina, 1999) characterized by different problems, machines, and representations.

Particular modes and forms of argument emerge from the scientific activity of the community and shift in time as other cultural practices change. Consider, for example, the experimental article, a central persuasive tool of scientific communities. Over time, what constitutes an experiment and the appropriate way to use an experiment to make an argument have undergone immense change (Bazerman, 1988). Originally, experimental articles presented experiments as any manipulation of nature (for example, methods for coloring marble). As articles became subject to debate, it became increasingly apparent that understanding what was happening during the manipulations, and why, was often problematic. The experiment became a way of solving a puzzle or supporting a claim. Methods of experiment were then scrutinized, leading to development in the careful reporting of method, the use of multiple trials, and deliberate attempts to eliminate alternative explanations. In the 19th and 20th centuries, experiments were positioned as ways to explore and further theories, and new criteria for arguments, for instance of demonstrating significance for theoretical advancement, became codified in the structure of the papers. Arguments, then, have evolved from descriptions of action to intricately constructed explications of theory, precise and repeatable procedures, and the justified interpretation of results. This trajectory is intimately related to trajectories in other practices, for instance the experiment.

Summary

When science is construed as a modeling endeavor, argumentation serves as the public activity that problematizes and stabilizes both what communities *"know,"* or the models they use, and their *means of knowing*. Thus, it works not only on claims, but on the entire machinery that supports claim making, including measures, instruments, experiments, inscriptions, and concepts. Participation in argumentation is, more fundamentally, participation in problematizing and stabilizing a community's material and representational activity. From this perspective, argumentation is embedded in scientific activity and the constitution of scientific communities.

Developing an Agenda for Representing and Supporting Argumentation as an Epistemic Practice in Classrooms

In this final section I return to the student argumentation literature, focusing on students' activity, in particular its material and representational nature and the opportunity it provides for students to develop not just what they know, but how they know it. The modeling perspective explored in the previous section suggests three implications for supporting students' scientific argumentation:

1. Involving students in uncertain material and representational activity
2. Representing how students develop both knowledge and their means of knowing
3. Designing for and describing the development of practice

In the following sections, I explore each of these implications, asking how they have been represented in the current literature on student argumentation and calling on a wider literature in science education and the learning sciences to make suggestions for representing and supporting argumentation practice in the classroom.

Involving Students in Uncertain Material and Representational Activity

If argumentation is functionally emergent from uncertain material and representational activity, then it should matter for students' argumentation whether they are engaged in these forms of activity. Both the science education and learning sciences scholarship have increasingly advocated a view of science as a modeling endeavor that entails representational and material work (Ford & Forman, 2006; Grandy & Duschl, 2007; Lehrer & Schauble, 2006a; Metz, 2004; Schwarz et al., 2009; Windschitl et al., 2008). Recent designs engage students in designing investigations, operationalizing variables, developing measures, creating data displays, managing uncertainty, and representing theories in the form of pictorial models. However, across studies that focus on scientific argumentation, students' engagement in these forms of activity varies widely. This section reviews this variation, then suggests fruitful directions for further research: increased design of uncertainty in students' material and representational activity, careful analysis of what about students' activity might be legitimately problematic, and long-term investigations that call for students to develop and refine their means of knowing (e.g., experiments or measures).

In a recent review of 54 argumentation interventions, Cavagnetto (2010) considered whether students were engaged in representational and material activity, using Ford's (Ford, 2008) notion of scientific activity as entailing "getting nature to speak" (what I have termed material activity) and "representing nature's voice," (here, representational activity). Cavagnetto found that 32% of argumentation studies engaged students in neither material nor representational work, 50% included representational but not material activity and 18% (10 articles) engaged students in material work that included specifying problems, posing questions, designing and conducting investigations, and explaining investigation choices to others. A review of the studies that Cavagnetto cited suggests that, even when students are involved in material and representational activity, how these forms of activity are conceptualized varies significantly.

When students' argumentative activity includes representational work, it generally consists of choosing and interpreting sources of evidence in order to generate an explanation. For instance, in work conducted by Jonathan Osborne and his colleagues (Osborne et al., 2004; Simon, Erduran, & Osborne, 2006), students are provided with lists of evidence statements that they are asked to use to weigh competing theories. In this case, representational activity involves deciding which statements are relevant and in what ways. Other studies place higher demands on students' representational work. For instance, in the ExplanationConstructor environment used by Sandoval (Reiser et al., 2001; Sandoval & Reiser, 2004), students search through large sets of data of various types, including field notes on particular species, rainfall graphs, and population graphs. They consider potentially relevant information, decide how to interpret data and data representations, and integrate information from multiple representations.

While fewer studies engage students in material work, there is still substantial variation within those that do. For instance, in Engle and Conant's (2002) analysis of an argument about whether orcas are whales, students generated their own question as they conducted research, spent significant time assembling evidence from a variety of sources, and engaged in disciplinary considerations of what would count as evidence. Their evidence necessarily came from secondary sources; for example, they did not examine orcas or develop taxonomies of anatomical features. In other studies (Kim & Song, 2006; Palincsar, Anderson, & David, 1993; Richmond & Striley, 1996), students designed experiments, developed data collection strategies, and carried out tests. However, few argumentation studies engage students in this level of material activity.

In addition, the studies cited above vary widely in how uncertain material and representational activity are from students' perspective. For students to participate in stabilizing their own scientific work, they must experience enough uncertainty that knowledge (e.g., an explanation, a stable description of a phenomenon) and the means of knowing are problematized. Watson, Swain, and McRobbie (2004) analyzed argumentation in an investigative activity that involved students in both the material and representational aspects of scientific work; students made paper chains, tested to see if a particular factor mattered for the strength of the chain, and represented their results as they argued about whether the factor mattered. However, all the methodological choices were specified by their previous work or intervention by the teacher.

Students produced little argumentation; they generally sought neither to justify nor to warrant claims. The authors attributed the lack of argumentation to the routinized nature of inquiry activity in the classrooms; in other words, the activity and expectations of the teacher provided a structure that constrained opportunities and there was little uncertainty for students to resolve. Palincsar, Anderson, and David (1993) compared two iterations of one scientific activity, demonstrating that the choices the designers made, for instance specifying (or not) for students what solvent to use and what constituted a "fair" test, were instrumental in determining the opportunities for students to engage in debate and the conceptual and scientific quality of their subsequent argumentation. When they were encouraged to grapple with uncertainty, students brought significant conceptual resources to bear on designing their investigation and engaged in prolonged discussion before developing a sophisticated measure of the investigation's target outcome.

Analyses like those conducted by Palinscar, et al.—that is, those that focus on the aspects of argumentation available to students based on the constraints and affordances of instructional tasks—are rare, but they are essential to productively support student argumentation. Educators often fear that uncertainty makes argumentation practice more difficult for students, and therefore tend to present evidence in the form of statements or limited data sets, including sets without irrelevant data, particularly in their work with younger students (Berland & McNeill, 2010; Chin & Osborne, 2010). When uncertainty has been emphasized, descriptions of design have tended to focus more broadly on whether multiple claims are possible (Berland & Reiser, 2011) or whether activity is "open-ended" (Kim & Song, 2006). However, if we expect argumentation to emerge from uncertain activity, it is likely to matter what it is about students' work that is uncertain, for example, which claim to select, which evidence to use, how to interpret evidence, or how to make evidence. It is worthwhile to analyze, in an instructional sequence, what decisions are available to students, where productive uncertainty might be conjectured to appear, and what means of resolving uncertainty students can take up.

Another implication of the perspective taken here is that argumentation should be integral to students' ongoing activity. Argumentation activities that span a single lesson, are unrelated to the subject matter knowledge students are in the process of developing, or serve as culminating activities are unlikely to make contact with the full scientific purposes of collaborative and agonistic exchange. Cavagnetto's recent review concluded that 63% of argumentation studies fell into one of these categories; only 37% involved students in argumentation activity that was "integral" to their inquiry. Even when argumentation was embedded in activity, it is not always clear what it means for argumentation to be *integral*. In some studies (e.g.,Naylor, Keogh, & Downing, 2007), students participated in argumentation to promote the need to investigate. In others, argumentation was conceptualized as an opportunity to revise explanations based on empirical data, but no additional empirical work was pursued (e.g.,Berland & Reiser, 2011; Clark & Sampson, 2008). These uses of argumentation might engage students in problematizing each other's ideas and possibly methods, but are less likely to support the stabilization of shared warrants and investigative procedures.

We might instead conceptualize the role of argumentation in students' ongoing activity as integral if it allows them to contest and agree on how they might know something, in turn, stabilizing particular models or inspiring new questions and models. For example, Herrenkohl and her colleagues (Herrenkohl & Mertl, 2010; Herrenkohl et al., 1999) involved students in developing theories that explained the data they were collecting. The class kept a public chart of theories, which they revised as they collected new information. In order to agree on what to include in the chart, they participated in protracted argumentation to define what would count as a theory, explored the mechanistic qualities of theories, and decided that their theories had to specify not only what happened, but also why it happened. In turn, this definition was integral to their further work because it allowed them to distinguish between theories that were worth exploring further and those that were underspecified and less useful for future work.

To develop environments characterized by productive forms of uncertainty and position argumentation as integral to students' activity, designers will need to specify more clearly the relationship between the concepts that they wish students to develop through argument and the means of knowing that are legitimately and productively problematic for building that conceptual understanding. They might foreground particular concepts or modeling practices (for example, measurement or instrumentation), then consider how students' activity could render the target concepts and practices problematic, and how students could participate in productive discourse about the problematic features of their activity.

Representing How Students Develop both Knowledge and their Means of Knowing

When students are encouraged to navigate the uncertainty of these aspects of scientific practice, there is a reason for them to pursue argumentation that problematizes and stabilizes knowing and the means of knowing in relation to each other. A modeling perspective suggests an expansive view of the target of contest: any aspect of activity in which students experience uncertainty and need to make decisions, including the development of instruments, measures, inscriptions, or interpretations of inscriptions, involves making guesses about how the world works and, as such, is a subject for argument (Passmore & Svoboda, 2011). Although studies have focused on how students develop knowledge through argumentation, there has been less emphasis on how students employ argumentation to problematize and develop shared ways of knowing.

Structures such as the Toulmin Form (Erduran et al., 2004), the Evidence-Based Reasoning Framework (Furtak et al., 2010), or McNeill's (2006, 2011) Claims-Evidence-Reasoning Framework generally treat an explanatory claim as the focus of the argument. For example, students might be asked to make claims about what a particular animal eats or whether objects in a room inevitably reach the same temperature. The drawback of these representations is that they flatten the work that goes into coping with uncertainty and making evidence (e.g., developing experiments, instruments, or measures) to a "warrants" or "reasoning" component. In these studies, it is still possible for students to contest how they know something; these contests are generally classified as challenges to warrants. However, these exchanges are usually only a few lines in length, in contrast to the extended arguments one might expect in scientific activity. In addition, representations do not tend to distinguish the different ways that warrants might be challenged, e.g., whether a form of data is valid, how a measure should be used, or how best to interpret a graph.

Some representations of scientific content do have room to represent the complexity of developing warrants. For example, Kelly and Takao's (2002) epistemic levels representation does not distinguish between claims and justification, but instead treats making a claim as involving a set of transformations that build from material, particular aspects of the world. Using a representation of this form, it might be possible to represent how students develop, contest, and relate the many parts of their activity needed to support a shared conclusion, for example, data, measures, or interpretations of inscriptions. Similarly, Sandoval and Millwood's focus on how students use inscriptions and data displays represents the complex process of moving from evidence to a conclusion. However, Kelly & Takao and Sandoval & Millwood's representations assessed written, final-form arguments, rather than interaction, where one might expect students to actively grapple with these forms of activity.

Instruction might support students in iteratively developing and contesting the grounds for knowing, for instance, what would count as an acceptable form of data, whether a particular instrument can be used and how, which interpretation of a graph is best, or whether a student-constructed data table adequately represents findings. To understand argumentation, one could then specify first what parts of activity were subject to variability and open to contest, and then describe how students participate in contesting and stabilizing them. For example, Radinsky (2008) explored how groups of students negotiated and co-constructed the meanings and purposes of GIS database inscriptions. He examined how references to data, to real-world objects such as oceans and particular continents, and to domain concepts (e.g., buckling or plate) were used in sense-making and related to each other in contradictions, questions, and claims. He identified instances of students participating, and becoming adept in, constructing and challenging data images that supported their claims, developing heuristics for identifying instances of disciplinary concepts, and problematizing and developing shared understandings of concepts when faced with messy data. Students developed productive epistemic practices as they problematized and stabilized geological concepts in relation to ways of constructing and interpreting data.

There is evidence that, from a young age, students can participate in problematizing and developing aspects of shared scientific activity. In one study (Lehrer, Schauble, & Lucas, 2008), teams of students presented in weekly "Research Meetings" where their classmates asked questions and made comments to support ongoing investigation and revision. The authors documented numerous instances where classmates challenged plans or findings based on the other students' grounds for knowing: students questioned procedures that confounded variables, asked others to explicitly identify their assumptions, and critiqued measures. Lehrer and Schauble have examined student participation in building other facets of scientific activity, including inventing and refining measures that support comparison, developing microcosms that serve as adequate investigation models, agreeing on representational conventions, and determining how to distinguish results from chance variation (Lehrer, Kim, & Schauble, 2007; Lehrer & Schauble, 2004; Lehrer, Schauble, Carpenter, & Penner, 2000). Each of these can be the subject of lengthy discussions and "side" explorations in service of a larger scientific goal, for instance, understanding plant growth or studying an aquatic microcosm. This work, as well as work by Metz (2004, 2011), Ford (2005, 2012) , and Passmore and Svobada (2011) suggests that students can recognize uncertainty, engage in productive discourse about it, and develop ways to deal with it in their ongoing scientific activity.

To date, most accounts of argumentation emphasize how students support knowledge claims rather than how they contest and develop their means for knowing. That is, most studies focus on how students use evidence, rather than how they participate in making it. As a result, a key function of argumentation is under-represented in the literature. If students are engaged in ongoing material and representational activity, it is likely that they will need to participate in many kinds of social activity, and that it would be difficult for one representation of structure, process, or scientific content to capture the varied ways they share and contest ideas (Bricker & Bell, 2008; Lemke, 1990; McDonald & Kelly, 2012). It might be more profitable to use a broad representation of dialogic activity, looking, for example, at how students participate in construction and critique (Ford & Forman, 2006), but focusing construction and critique around scientific activity. The focus of research would be dual: understanding both how positioning students to use dialogic processes around uncertain material and representational activity engages them in more authentic argumentation *and* how argumentation supports students in developing knowledge rooted in shared material and representational practices.

Designing for and Describing the Development of Practice

Finally, the field could productively turn its attention to understanding the *development* of practice. From the perspective outlined here, the development of argumentation is embedded in the development of other practices. We should expect that as students participate in productive argumentation, the basis of their scientific activity should shift. New questions should be asked. Ideas that were once problematic should be taken-as-shared. Measures, instruments, and ways of displaying data should be first challenged, then accepted and used. Some modes of argument should be privileged over others. One of the major struggles I identified for the prevailing images of students' scientific argumentation regards issues of context. It is unclear how to conceptualize arguments as both disciplinary and dialogic when the student audience does not "require" scientific arguments to be convinced. However, if we consider that argumentation situates the development of other shared practices, we might focus our attention on how, through engaging in argumentation, students come over time to form a scientific community, and how shifts in that community and its practice occur.

While many studies of argumentation focus only on interaction during single episodes, looking at students' use or adoption of argumentation practice, several recent studies have focused on longer time periods. For example, Ryu and Sandoval (Ryu & Sandoval, 2012) followed an elementary school class through a year of instruction in which argumentation was embedded. They located episodes in which students explicitly discussed or performed argumentation norms. In the case study classroom, students developed an initial norm of listening to each other, which then developed into a need for students to convince each other, a norm, in turn, refined to include backing up claims, then to showing evidence, and then explicitly justifying evidence. These studies, as well as work by Tang & Coffey (2010) and Engle and Conant (Engle & Conant, 2002) suggest that increasingly sophisticated forms and modes of argument can be usefully conceptualized as interactionally accomplished by students over extended activity.

Some studies have also shown how engagement in argumentation situates the development of scientific cultures that specify shared knowledge and particular means of knowing. For example, Foo and Looi (2008) compared differences within an instructional unit in students' early and late argumentation regarding how to distinguish plants, animals, and nonliving creatures. Early argument appeared to problematize students' notions of whether color or movement mattered and how to adequately describe these features for comparison. Later arguments included more qualifiers, an expanded definition of movement that involved geographical displacement, a new feature—that plants make their own food— and an accepted test for food making. Engle and Conant (2002) found that as students engaged in an extended argument about whether orcas are whales, they developed shared ideas about who to trust as a credible source of information and questioned the adequacy of using biological features to determine classification. In each of these cases, new forms of argumentation developed, but these forms were deeply rooted in the development of domain knowledge and shared standards for what counted as knowledge.

To support students in developing argumentation practice, we will need to continue to understand how practice can build from the resources that students bring to classrooms. Increasingly, researchers focus on understanding how children's practices are continuous with the purposes of scientific argumentation (Berland & Hammer, 2012; Radinsky, 2008). Ethnographic accounts of children's informal argumentation reveal important continuities: children adjust their argumentation strategies to particular situations and co-participants, draw on a wide range of resources to convince others, and participate in constructing social organization through agonistic exchange (Bricker & Bell, 2008; Hudicourt-Barnes, 2003). Ochs and Taylor (1992) argue that parents and children's dinnertime arguments have important parallels to scientific theory building. Participants challenge others' explanations on the basis of important causal links in stories, including definition of the problem, the relation of the problem to the described events, and what else is known. Of course, there are discontinuities too, as the research discussed in this paper has demonstrated. The question then, is how to design contexts in which students recruit the practices that they bring with them, seeing them as useful in these settings, but then also experience a need to refine those practices over time. There is evidence in other areas that students can participate in building sophisticated practices when the practices are founded in forms of thinking that that they bring to the classroom, then stretched by subsequent tasks and discussion (Carpenter, Fennema, Franke, Levi, & Empson, 1999; diSessa & Sherin, 2000; Lehrer & Lesh, 2002). However, this work requires extensive research to specify both students' resources and trajectories that build from those resources.

A challenge to the viewpoint presented here is the difficulty of assessing what individuals have learned from practice, that is, what lifts out of the context within which argumentation is meaningful. Representations of the structure, process, and disciplinary content of argumentation have a great advantage, in that they allow researchers to assess a skill acquired by individuals and present a measure of learning that is valued and understood by a wider audience. As Ford and Forman (2006) point out, educational studies focused on practice have not usually addressed the question of what an individual has learned from participation in practice. Ford and Forman propose that students might develop a "grasp of practice," by which they refer to an understanding of the scientific enterprise and the functions of practices within that enterprise. They argue that this understanding allows students to flexibly respond to a range of complex problems. For example, Ford (2005) described an instantiation of instructional design in which students investigated the effect of ramp steepness on the speed of a ball; students participated in constructing and stabilizing variables, measures, and experimental protocols. Using post-instruction tasks, he provided evidence that practices developed in activity, e.g., quantifying an outcome, standardizing a protocol, and representing results, were applied by groups of students to new scientific problems. He argued that students developed the proclivity to approach new problems as social, material, and representational challenges. Likewise, Ryu and Sandoval (2012) found that engagement in argumentation improved what they termed students' "epistemic understanding," in that students critiqued novel arguments on the basis of causal structure, use of evidence, and justification of evidence. Each of these studies set their sights on understanding the ways that participation in argumentation practice changed individuals' dispositions and understanding of the scientific enterprise. How best to describe and assess these dispositions is a question that will require more research.

Summary

Argumentation is the discursive practice that problematizes and stabilizes a community's modeling practice. To date, research has not tended to engage student in uncertain material and representational activity, involve them in problematizing and stabilizing aspects of their own activity, or represent trajectories of knowledge and practices. Therefore, there is much to learn about the circumstances in which scientific argumentation might be functionally emergent for students and how argumentation can support students' participation in a larger scientific enterprise.

This perspective offers several implications for classroom studies. Argumentation should productively build from resources students bring into the classroom, for instance familiar forms of participation: saying what they think, telling why, agreeing or disagreeing with others. Design should involve carefully selecting tasks that include forms of uncertainty conjectured to establish a need for practices and ideas. Researchers could then ask how students recruit resources to participate in activity and how their activity shifts over time. For example, they could follow whether methods that are originally questioned are later taken for granted and folded into scientific work. They might ask how concepts are first problematized, then come to be taken-as-shared, and then facilitate the next steps in conceptual work. This work will require an attention to multiple time-scales of student activity (Kelly, 2008; Lemke, 2000; Saxe & Esmonde, 2005).

Conclusion

To date, research on argumentation has focused primarily on describing the practice and representing students' talk as dialogic, scientific, and concerned with knowledge building. This work has made important contributions to our understanding of difficulties that students face and has suggested conditions necessary to support argumentative talk. However, these descriptions have a static nature and are often lifted out of the communal enterprise that makes argumentation productive in scientific communities. I have argued that a productive next step for the field involves shifting our attention to how argument comes to serve as an epistemic practice in scientific communities, then developing classroom environments to support the emergence and refinement of argumentation practice. I proposed three directions for future research: carefully designing uncertainty into students' material and representational activity, making visible how students develop their means of knowing, and attending more closely to the development of practice over longer periods of time.

Further research will be needed to specify the forms of practice that students develop when engaged in problematizing and stabilizing both what they know and how they know it. What changes may not so much be students' "argumentation" but their knowledge-building practices. These could include the development of measures, the justification of measures, the need to control variables, ways of considering instruments, or consensus on how to represent the center of a distribution. Research, therefore, could focus on understanding which knowledge-building practices are within reach of students, what types of activity make visible the need for these practices, and ways students can be supported in generating, challenging, weighing, and then selecting ideas. Future research should focus on the relationship of students' discursive moves, both collaborative and agonistic, to the more specific knowledge-building practices they propose, contest, and refine, rather than on argumentation as an isolated practice that is sufficient for developing an understanding of scientific knowledge-building.

This perspective also has implications for the design of learning environments that support initiation into practice. Two prominent strategies are specifying the desired forms of practice and simplifying the context in which the practice is enacted. However, as this paper has demonstrated, these approaches can lead to over-specification and remove the aspects of the context that lend meaning to the practice in scientific activity, thus obscuring the goal of the practice. A useful focus for further research will be to empirically investigate the kinds of representations and contexts that are simple enough to provide students an entrée to practice but complex enough to situate the need for communication and the development of scientific practices. As Engle and Conant (2002) argued, both problematization of content and the provision of resources are essential features of environments that support productive disciplinary engagement, but the two must be kept in balance with each other.

Finally, this review has implications for approaches to understanding epistemic practices more generally. The recent *NRC Framework for K-12 Science Education* and the *Next Generation Science Standards* list eight practices in which students should engage, including asking questions, developing and using models, analyzing and interpreting data, and engaging in argument from evidence. This sets an ambitious agenda for research, for we have much to learn about how to represent, assess, and support initiation into these practices. While a natural approach might be to isolate the practices, study students' challenges in relation to each one, then develop a learning trajectory and set of supports for each, this approach risks creating a list of activities with separate sets of rules and removing the context that lends meaning to practices. Instead, to support students in developing scientific dispositions and understandings, it will be important to foreground practices' functions in scientific activity, attend to the features of students' activity that would make those functions useful, and characterize the development of sets of related practices in communities engaged in a scientific endeavor.

References

Atran, S., Medin, D., & Ross, N. (2005). The cultural mind: Environmental decision making and cultural modeling within and across populations. *Psychological Review, 112*(4), 744-775.

Barnes, B. (2001). Practice as collective action. In T. Schatzki, K. Knorr Cetina & E. von Savigny (Eds.), *The practice turn in comtemporary theory* (pp. 17-28). London: Routledge.

Bazerman, C. (1988). *Shaping written knowledge: The genre and activity of the experimental article in science*. Madison, WI: University of Wisconsin Press.

Bell, P., & Linn, M. (2000). Scientific arguments as learning artifacts: Designing for learning from the web with KIE. *International Journal of Science Education, 22*(8), 797-817.

Berland, L. K. (2011). Explaining Variation in How Classroom Communities Adapt the Practice of Scientific Argumentation. *Journal of the Learning Sciences, 20*(4), 625-664.

Berland, L. K., & Hammer, D. (2012). Framing for scientific argumentation. *Journal of Research in Science Teaching, 49*(1), 68-94.

Berland, L. K., & McNeill, K. L. (2010). A learning progression for scientific argumentation: Understanding student work and designing supportive instructional contexts. *Science Education, 94*(5), 765-793.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education, 93*(1), 26-55.

Berland, L. K., & Reiser, B. J. (2011). Classroom communities' adaptations of the practice of scientific argumentation. *Science Education, 95*(2), 191-216.

Blair, J., & Johnson, R. (1987). Argumentation as dialectical. *Argumentation, 1*(1), 41-56.

Bricker, L. A., & Bell, P. (2008). Conceptualizations of argumentation from science studies and the learning sciences and their implications for the practices of science education. *Science Education, 92*(3), 473-498.

Carpenter, T., Fennema, E., Franke, M. L., Levi, L., & Empson, S. B. (1999). *Children's mathematics: Cognitively guided instruction*. Portsmouth, NH: Heinemann.

Cavagnetto, A. (2010). Argument to Foster Scientific Literacy. *Review of Educational Research, 80*(3), 336-371.

Chin, C., & Osborne, J. (2010). Supporting Argumentation Through Students' Questions: Case Studies in Science Classrooms. *Journal of the Learning Sciences, 19*(2), 230-284.

Chin, C., & Teou, L. Y. (2009). Using concept cartoons in formative assessment: Scaffolding students' argumentation. *International Journal of Science Education, 31*(10), 1307-1332.

Choi, A., Notebaert, A., Diaz, J., & Hand, B. (2010). Examining Arguments Generated by Year 5, 7, and 10 Students in Science Classrooms. *Research in Science Education, 40*(2), 149-169.

Clark, D. B., D'Angelo, C., & Menekse, M. (2009). Initial Structuring of Online Discussions to Improve Learning and Argumentation: Incorporating Students‚Äô Own Explanations as Seed Comments Versus an Augmented-Preset Approach to Seeding Discussions. *Journal of Science Education and Technology, 18*(4), 321-333.

Clark, D. B., & Sampson, V. (2008). Assessing dialogic argumentation in online environments to relate structure, grounds, and conceptual quality. *Journal of Research in Science Teaching, 45*(3), 293-321.

Clark, D. B., Sampson, V., Weinberger, A., & Erkens, G. (2007). Analytic frameworks for assessing dialogic argumentation in online learning environments. *Educational Psychology Review, 19*(3), 343-374.

de Lima Tavares, M., Jiménez-Aleixandre, M.-P., & Mortimer, E. (2010). Articulation of Conceptual Knowledge and Argumentation Practices by High School Students in Evolution Problems. *Science & Education, 19*(6), 573-598.

De Vries, E., Lund, K., & Baker, M. (2002). Computer-mediated epistemic dialogue: Explanation and argumentation as vehicles for understanding scientific notions. *Journal of the learning sciences, 11*(1), 63-103.

diSessa, A. A., & Sherin, B. (2000). Meta-representation: An introduction. *Journal of Mathematical Behavior, 19*(4), 385-398.

Driver, R., Leach, J., Miller, R., & Scott, P. (1996). *Young people's images of science*. Philadelphia, PA: Open University Press.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*(3), 287-312.

Duschl, R. (2007). Quality argumentation and epistemic criteria. In S. Erduran & M. P. Jimenez-Aleixandre (Eds.), *Argumentation in science education: Recent developments and future directions* (pp. 159-175). New York, NY: Springer

Duschl, R., & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education, 38*(1), 39-72.

Duschl, R., Schweingruber, H., & Shouse, A. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, D.C.: National Academies Press.

Engle, R. A., & Conant, F.R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399-483.

Erduran, S., & Jimenez-Aleixandre, M. P. (2007). *Argumentation in science education: Recent developments and future directions*. New York, NY: Springer.

Erduran, S., Simon, S., & Osborne, J. (2004). TAPping into argumentation: Developments in the application of Toulmin's argument pattern for studying science discourse. *Science Education, 88*(6), 915-933.

Foo, S. Y., & Looi, C. K. (2008). *Understanding elementary students' emergent dialogical argumentation in science*. Proceedings of the 8th International Conference for the Learning Sciences, Utrecht, The Netherlands.

Ford, M. J. (2005). The Game, the Pieces, and the Players: Generative Resources From Two Instructional Portrayals of Experimentation. *Journal of the Learning Sciences, 14*(4), 449-487.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423.

Ford, M. J. (2012). A Dialogic Account of Sense-Making in Scientific Argumentation and Reasoning. *Cognition and Instruction, 30*(3), 207-245.

Ford, M. J., & Forman, E. A. (2006). Redefining Disciplinary Learning in Classroom Contexts. *Review of research in education, 30*(1), 1-32.

Furtak, E. M., Hardy, I., Beinbrech, C., Shavelson, R. J., & Shemwell, J. T. (2010). A Framework for Analyzing Evidence-Based Reasoning in Science Classroom Discourse. *Educational Assessment, 15*(3-4), 175-196.

Giere, R. N. (1990). *Explaining science: A cognitive approach*. Chicago, IL: University of Chicago Press.

Giere, R. N. (1999). *Science without laws*. Chicago,IL: University of Chicago Press.

Gooding, D. (1990). *Experiment and the making of meaning*. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Goodwin, C. (1994). Professional vision. *American anthropologist, 96*(3), 606-633.

Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. *Science & Education, 16*(2), 141-166.

Hackmann, W. (1989). Scientific instruments: Models of brass and aids to discovery. In D. Gooding, T. Pinch & S. Schaffer (Eds.), *The Uses of Experiment: Studies in the Natural Sciences* (pp. 31-65). Cambridge: Cambridge University Press.

Hall, R., & Greeno, J. G. (2008). Learning and understanding concepts in practice. In T. Good (Ed.), *21st century education: A reference handbook.* Thousand Oaks, CA: Sage Publishing.

Hanson, N. (1958). *Patterns of discovery: An inquiry into the conceptual foundations of science*. Cambridge, U.K.: Cambridge University Press.

Herrenkohl, L. R., & Guerra, M. R. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. *Ethics & Behavior, 16*(4), 431-473.

Herrenkohl, L. R., & Mertl, V. (2010). *How students come to be, know, and do: A case for a broad view of learning*. Cambridge: Cambridge Univ Press.

Herrenkohl, L. R., Palincsar, A. S., DeWater, L. S., & Kawasaki, K. (1999). Developing scientific communities in classrooms: A sociocognitive approach. *Journal of the Learning Sciences, 8*(3), 451-493.

Hesse, M. (1966). *Models and analogies in science*. Notre Dame, IN: University of Notre Dame Press.

Hogan, K., & Corey, C. (2001). Viewing classrooms as cultural contexts for fostering scientific literacy. *Anthropology & Education Quarterly*, 214-243.

Hudicourt-Barnes, J. (2003). The use of argumentation in Haitian creole science classrooms. *Harvard Educational Review, 73*(1), 73-93.

Hutchins, E. (1995). *Cognition in the Wild*. Cambridge, MA: The MIT Press.

Jimenez-Aleixandre, M. P. (2007). Designing argumentation learning environments. In S. Erduran & M. P. Jimenez-Aleixandre (Eds.), *Argumentation in Science Education:* (pp. 91-115). New York, N.Y.: Springer.

Jimenez-Aleixandre, M. P., Rodriguez, A. B., & Duschl, R. A. (2000). Doing the lesson or doing science: Argument in high school genetics. *Science Education, 84*(6), 757-792.

Kelly, G. J. (2008). Inquiry, activity, and epistemic practice. In R. Duschl & R. Grandy (Eds.), *Teaching scientific inquiry*. Rotterdam: Sense Publishers.

Kelly, G. J., Druker, S., & Chen, C. (1998). Students' reasoning about electricity: Combining performance assessments with argumentation analysis. *International Journal of Science Education, 20*(7), 849-871.

Kelly, G. J., & Takao, A. (2002). Epistemic levels in argument: An analysis of university oceanography students' use of evidence in writing. *Science Education, 86*(3), 314-342.

Keys, C. W., Hand, B., Prain, V., & Collins, S. (1999). Using the science writing heuristic as a tool for learning from laboratory investigations in secondary science. *Journal of Research in Science Teaching, 36*(10), 1065-1084.

Kim, H., & Song, J. (2006). The features of peer argumentation in middle school students' scientific inquiry. *Research in Science Education, 36*(3), 211-233.

Kitcher, P. (1993). *The advancement of science: Science without legend, objectivity without illusions*. New York: Oxford University Press.

Knorr Cetina, K. (2001). Objectual practice. In T. Schatzki, K. Knorr Cetina & E. von Savigny (Eds.), *The practice turn in comtemporary theory* (pp. 175-188). London: Routledge.

Knorr-Cetina, K. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge, MA: Harvard University Press.

Koslowski, B. (1996). *Theory and evidence: The development of scientific reasoning*. Cambridge, MA: The MIT Press.

Kuhn, D. (1991). *The skills of argument*. Cambridge, U.K.: Cambridge University Press.

Kuhn, D., & Pease, M. (2008). What needs to develop in the development of inquiry skills? *Cognition and Instruction, 26*(4), 512 - 559.

Kuhn, D., & Udell, W. (2003). The development of argument skills. *Child Development, 74*(5), 1245-1260.

Kuhn, T. (1996). *The structure of scientific revolutions* (3rd ed.). Chicago: University of Chicago Press.

Lampert, M. (2010). Learning Teaching in, from, and for Practice: What Do We Mean? *Journal of Teacher Education, 61*(1-2), 21.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard University Press.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton, N.J.: Princeton University Press.

Lave, J., & Wenger, E. (1991). *Situated cognition: Legitimate peripheral participation*. New York: Cambridge University Press.

Lehrer, R., Kim, M. J., & Schauble, L. (2007). Supporting the development of conceptions of statistics by engaging students in measuring and modeling variability. *International Journal of Computers for Mathematical Learning, 12*(3), 195-216.

Lehrer, R., & Lesh, R. (2002). Mathematical learning. In W. Reyolds & G. Miller (Eds.), *Handbook of Psychology* (Vol. 7), (pp. 3-57-391). Wiley & Sons, Inc.

Lehrer, R., & Schauble, L. (2004). Modeling natural variation through distribution. *American Educational Research Journal, 41*(3), 635.

Lehrer, R., & Schauble, L. (2006a). Cultivating model-based reasoning in science education. *Cambridge handbook of the learning sciences*, 371-388.

Lehrer, R., & Schauble, L. (2006b). Scientific thinking and scientific literacy. In K. A. Renninger & I. E. Siegel (Eds.), *Handbook of child psychology* (6 ed., Vol. 4: Child psychology in practice). Hoboken, N.J.: John Wiley and Sons, Inc.

Lehrer, R., Schauble, L., Carpenter, S., & Penner, D. (2000). The interrelated development of inscriptions and conceptual understanding. In P. Cobb, Yackel, E., McClain, K. (Ed.), *Symbolizing and communicating in mathematics classrooms: Perspectives on discourse, tools, and instructional design* (pp. 325–360). Mahwah, N.J.: Erlbaum Associates

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive Development, 23*(4), 512-529.

Lemke, J. (1990). *Talking science: Language, learning, and values*. Norwood, N.J.: Ablex.

Lemke, J. (2000). Across the scales of time: Artifacts, activities, and meanings in ecosocial systems. *Mind, Culture, and Activity, 7*(4), 273-290.

Longino, H. (1990). *Science as social knowledge: Values and objectivity in scientific inquiry*. Princeton, N.J.: Princeton University Press.

Longino, H. (1994). The fate of knowledge in social theories of science. In F. F. Schmitt (Ed.), *Socializing epistemology: The social dimensions of knowledge* (pp. 135-158). London: Rowman & Littlefield Publishers.

Maloney, J., & Simon, S. (2006). Mapping children's discussions of evidence in science to assess collaboration and argumentation. *International Journal of Science Education, 28*(15), 1817-1841.

Martin, A. M., & Hand, B. (2009). Factors affecting the implementation of argument in the elementary science classroom. A longitudinal case study. *Research in Science Education, 39*(1), 17-38.

Mason, L. (1996). An analysis of children's construction of new knowledge through their use of reasoning and arguing in classroom discussions. *International Journal of Qualitative Studies in Education, 9*(4), 411-433.

Mayr, E. (2004). *What makes biology unique?: considerations on the autonomy of a scientific discipline*. Cambridge: Cambridge University Press.

McDonald, S. P., & Kelly, G. J. (2012). Beyond Argumentation: The rich complexity of discourse in the classroom. In M. S. Khine (Ed.), *Perspectives on Scientific Argumentation* (pp. 265-281): Dordrecht, the Netherlands: Springer.

McNeill, K.L. (2011). Elementary students' views of explanation, argumentation, and evidence, and their abilities to construct arguments over the school year. *Journal of Research in Science Teaching, 48*(7), 793-823.

McNeill, K. L., & Krajcik, J. (2009). Synergy Between Teacher Practices and Curricular Scaffolds to Support Students in Using Domain-Specific and Domain-General Knowledge in Writing Arguments to Explain Phenomena. *Journal of the Learning Sciences, 18*(3), 416-460.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences, 15*(2), 153-191.

Metz, K. E. (2004). Children's understanding of scientific Inquiry: Their conceptualization of uncertainty in investigations of their own design. *Cognition and Instruction, 22*(2), 219-290.

Metz, K. E. (2011). Disentangling robust developmental constraints crom the instructionally mutable: Young children's epistemic reasoning about a study of their own design. *Journal of the Learning Sciences, 20*(1), 50-110.

Naylor, S., Keogh, B., & Downing, B. (2007). Argumentation and primary science. *Research in Science Education, 37*(1), 17-39.

Nersessian, N. J. (1999). Model-based reasoning in conceptual change. In L. Magnani, N. J. Nersessian & P. Thagard (Eds.), *Model based reasoning in scientific discovery*. New York: Plenum Publishers.

Nersessian, N. J., & Patton, C. (2009). Model-based reasoning in interdisciplinary engineering. In A. Meijers (Ed.), *Handbook of the philosophy of technology and engineering sciences* (pp. 687-718). Amsterdam: Elsevier.

NRC. (2011). *A framework for K-12 science standards: Practices, crosscutting concepts, and core ideas*. Washington, D.C.: The National Academy of the Sciences.

Ochs, E., Jacoby, S., & Gonzales, P. (1994). Interpretive journeys: How scientists talk and travel through graphic space. *Configurations, 2*(1), 151-171.

Ochs, E., & Taylor, C. (1992). Science at dinner. In C. Kramsch & S. McConnell-Ginet (Eds.), *Text and context: Cross-disciplinary perspectives on language study* (pp. 29-45). Lexington, MA: DC Heath.

Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. *Journal of Research in Science Teaching, 41*(10), 994-1020. doi: 10.1002/tea.20035

Palincsar, A. S., Anderson, C., & David, Y. M. (1993). Pursuing scientific literacy in the middle grades through collaborative problem solving. *The elementary school journal, 93*(5), 643-658.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., Kyza, E., Edelson, D., Soloway, E. (2004). A scaffolding design framework for software to support science inquiry. *The Journal of the Learning Sciences, 13*(3), 337-386.

Radinsky, J. (2008). Students' roles in group-work with visual data: A site of science learning. *Cognition and Instruction, 26*(2), 145-194.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B., Steinmuller, F., & Leone, A. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. *Cognition and Instruction, 25*, 263–306.

Richmond, G., & Striley, J. (1996). Making meaning in classrooms: Social processes in small-group discourse and scientific knowledge building. *Journal of Research in Science Teaching, 33*(8), 839-858.

Rouse, J. (1996). *Engaging science: How to understand its practices philosophically*. Ithaca, NY: Cornell University Press.

Ryu, S., & Sandoval, W. A. (2012). Improvements to elementary children's epistemic understanding from sustained argumentation. *Science Education, 96*(3), 488-526.

Sampson, V., & Clark, D. B. (2009). The impact of collaboration on the outcomes of scientific argumentation. *Science Education, 93*(3), 448-484.

Sampson, V., Grooms, J., & Walker, J. P. (2011). Argument Driven Inquiry as a way to help students learn how to participate in scientific argumentation and craft written arguments: An exploratory study. *Science Education, 95*(2), 217-257.

Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. *The Journal of the Learning Sciences, 12*(1), 5-51.

Sandoval, W. A., & Millwood, K. (2005). The quality of students' use of evidence in written scientific explanations. *Cognition and Instruction, 23*(1), 23-55.

Sandoval, W. A., & Reiser, B. J. (2004). Explanation-driven inquiry: Integrating conceptual and epistemic scaffolds for scientific inquiry. *Science Education, 88*(3), 345-372.

Saxe, G. B., & Esmonde, I. (2005). Studying cognition in flux: A historical treatment of Fu in the shifting structure of Oksapmin mathematics. *Mind, Culture, and Activity, 12*(3-4), 171-225.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, Fortus, D., Shwartz, Y., Hug, B., Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654.

Shapin, S., & Schaffer, S. (1985). *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*. Princeton, NJ: Princeton University Press.

Shemwell, J. T., & Furtak, E. M. (2010). Science Classroom Discussion as Scientific Argumentation: A Study of Conceptually Rich (and Poor) Student Talk. *Educational Assessment, 15*(3-4), 222-250.

Simon, S., Erduran, S., & Osborne, J. (2006). Learning to teach argumentation: Research and development in the science classroom. *International Journal of Science Education, 28*(2), 235-260.

Sperber, D. (1996). *Explaining culture: A naturalistic approach*. Oxford: Blackwell Publishing.

Stewart, J., Hafner, R., Johnson, S., & Finkel, E. (1992). Science as model building: Computers and high-school genetics. *Educational Psychologist, 27*(3), 317-336.

Toulmin, S. (1958). *The uses of argument*. Cambridge: Cambridge University Press

Van Eemeren, F., Grootendorst, R., Henkemans, F., Blair, J., Johnson, R., Krabbe, E., Plantin, C., Walton, D.N., Willard, C.A. Woods, J. (1996). *Fundamentals of argumentation theory: A handbook of historical backgrounds and comtemporary developments*. Mahwah, N.J.: Erlbaum Associates.

von Aufschnaiter, C., Erduran, S., Osborne, J., & Simon, S. (2008). Arguing to learn and learning to argue: Case studies of how students' argumentation relates to their scientific knowledge. *Journal of Research in Science Teaching, 45*(1), 101-131.

Walton, D. (1996). *Argumentation schemes for presumptive reasoning*. Mahwah, NJ: Lawrence Erlbaum.

Watson, J., Swain, J. R. L., & McRobbie, C. (2004). Students' discussions in practical scientific inquiries. *International journal of science education, 26*(1), 25-45.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967.

Yeh, K.-H., & She, H.-C. (2010). On-line synchronous scientific argumentation learning: Nurturing students' argumentation ability and conceptual change in science context. *Computers & Education, 55*(2), 586-602.

Zimmerman, C. (2007). The development of scientific thinking skills in elementary and middle school. *Developmental Review, 27*(2), 172-223.

CHAPTER III

UNDERSTANDING THE CO-DEVELOPMENT OF MODELING PRACTICE AND ECOLOGICAL KNOWLEDGE[1]

Introduction

Recently, science education research has shifted from alternatively focusing on either conceptual development or on the acquisition of skills toward a more integrated characterization of science as practice (Duschl, Schweingruber, & Shouse, 2007; Lehrer & Schauble, 2006b). An emphasis on practice entails engaging students in disciplinary activity; privileging those activities that are epistemic (e.g., ground the authority for knowing in the discipline (Ford & Forman, 2006)); and attending to the social nature of scientific knowledge, especially the ways that recurrent forms of activity anchor the knowledge that scientific communities take as shared (Kelly, 2008; Lehrer & Schauble, 2006b). From this point of view, science education must balance and integrate the conceptual, epistemic, and social aspects of scientific practice (Duschl, 2008).

Analyses that separate practice from knowledge tend to produce distorted visions of both. Forms of practice and constituent concepts are closely bound together in scientific work (Pickering, 1995). Scientific knowledge influences what scientists observe (Hanson, 1958), becomes reified in instruments and measures (Latour & Woolgar, 1986; Pickering, 1995), and determines how findings are framed (Bazerman, 1988). Accepted practices such as developing experimental protocols, using instruments, communicating with representations, and generating causal explanations facilitate conceptual work, making it possible to see, privilege, and relate

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variables for the purpose of building coherent theories (Collins & Ferguson, 1993; Goodwin, 1994; Stevens & Hall, 1998). Likewise, researchers have demonstrated that asking students to enact scientific processes in knowledge-lean contexts impedes their ability to understand and apply those processes (Koslowski, 1996; Metz, 1995).

In this paper, I seek to understand how students develop shared scientific knowledge through their practice of science. The context of this work is a year long ecological investigation conducted with a class of third grade students in “the wild backyard,” an unmowed area behind their school. I conceptualize scientific practice as modeling, a choice explained below. I follow the development of one seminal disciplinary idea, plant reproduction, through students’ modeling practices to address the following questions:

1. What does it mean in this context for students to develop and use knowledge in shared modeling practice?
2. How does this case inform the task of designing learning environments that exploit the interrelated nature of knowledge and practice?

Scientific Practice as Modeling

Constructing, testing, and revising models is at the heart of the scientific endeavor (Giere, 1990; Grandy & Duschl, 2007; Nersessian, 2008). Increasingly, science educators seek to organize students’ science instruction around models and modeling activity (Lehrer & Schauble, 2006a; Passmore & Stewart, 2002; Schwarz et al., 2009; Windschitl, Thompson, & Braaten, 2008). Models can be conceived of as abstract, simplified representations that facilitate prediction and explanation, for example the Bohr model of the atom or the theory of natural selection (Harrison & Treagust, 2000). Numerous science educators have engaged students with developing and revising these forms of representation (Halloun, 2007; Passmore & Stewart, 2002; Schwarz et al., 2009). However, modeling also has a highly material face. Because the world does not present itself in a form that is immediately testable, scientists develop instruments, measures, machines, and experiments that allow them to interact with and interpret the natural world (Gooding, 1990; Nersessian & Patton, 2009; Pickering, 1995). For example, Nersessian and Patton (2009) describe how biomedical engineers attempting to understand blood vessels work with the "flow loop," an engineered model system that they subject to continual redesign that includes its parts, set-up, and the physical principles governing its design. Nersessian and Patton argue that the modeling system supporting the laboratory's work encompasses concepts, model systems such as the flow loop, instruments, equations, and images. Similarly, I take a "synthesis" view of modeling, one that includes both material and abstract representations (Lehrer & Schauble, 2006a; Windschitl et al., 2008).

Modeling is a conceptually powerful process (Hesse, 1966; Nersessian, 2008). Models and representations *reduce* the complexity of the natural world, *amplifying* particular objects and relations and increasing their visibility, transportability, and compatibility (Latour, 1999). These conceptual affordances have been exploited in many educational designs, demonstrating that modeling can be used to develop particular scientific understandings (Louca & Zacharia, 2011; Oh & Oh, 2010). Designers can organize instruction around models and representations that amplify desired ways of thinking. For example, Wilensky and his colleagues (Sengupta & Wilensky, 2009; Wilensky & Reisman, 2006) have engaged students with models that highlight individual agents and make emergent processes visible, demonstrating that these models help students explore and understand concepts that are usually difficult for them. Instruction can be carefully sequenced around a progression of models that, at each stage, both connect to students' current understanding and encourage refinement toward increasingly scientific ideas (Acher, Arcà, & Sanmartí, 2007).

Recent work emphasizes the value of engaging students in modeling activity, rather than positioning them as receiving or using particular models. Students may misunderstand the status and purpose of the models presented to them in traditional instruction, believing that models are "correct" representations of reality rather than tentative thinking tools that can be manipulated by the user to suit his or her needs (Harrison & Treagust, 2000). In contrast, in more recent designs, students are involved in constructing, testing, critiquing, and revising models (Lehrer & Schauble, 2006a; Passmore & Stewart, 2002; Schwarz et al., 2009; Windschitl et al., 2008). Here, students have the potential to develop not only conceptual understandings, but also a better understanding of, and facility with, modeling practice (Ford, 2008; Schwarz & White, 2005). Shifting to a focus on modeling activity entails an increased attention to the community within which activity is situated and the ways that practice and conceptual developments are jointly constructed in social interaction (Hall & Greeno, 2008).

Because modeling is a form of activity that is not immediately sensible to novices, students' modeling practice must be systematically developed. The research reported here builds from Lehrer and Schauble's (2000; 2006a; 2008) study of the development of modeling in mathematics and science instruction, which exploits young children's understanding of *representation*. Modeling with elementary age students begins with simple representational and material forms that exploit resemblance, such as drawings, maps, and physical microcosms. This work can be stretched into increasingly powerful and abstract representational activity as students participate in generating or adapting measures, experiments, and microcosms;

structuring and interpreting data; and evaluating fit and mis-fit between these representations and target phenomena.

The work presented in this paper seeks to harness the conceptual power of representations and models, with a commitment to engaging students in *modeling activity* that includes both material and representational work, is situated in social interaction, and is sensitive to supporting development in children's modeling capacities. This commitment informs the treatment of concepts, modeling activity, and their relations, as explained below.

Recent work positions students' conceptual entities as resources for seeing and using aspects of disciplinary concepts in particular settings and for particular purposes, rather than as stable unitary structures, or ideas that they either "have" or "don't have." (diSessa & Sherin, 1998; Hall & Greeno, 2008; Hammer, Elby, Scherr, & Redish, 2005). Individuals bring into the classroom myriad potentially productive ideas but must be supported to recruit, connect, and refine them. Therefore, in this paper "disciplinary concept" is used to refer to historically stable ideas that have epistemic power in the discipline. In contrast, terms such as "resource," "idea," and "meaning" are used to describe students' emergent conceptual entities. Both the instructional design and analysis of this study focus on the ways that conceptual meanings first become visible and useful to students in their practice of science, and then can be leveraged into increasingly connected and sophisticated forms.

The central conjecture of this work is that modeling activity can facilitate the recruitment and refinement of conceptual resources by engaging students in work with representations that amplify (Latour, 1999) aspects of disciplinary concepts, rendering them visible and useful. Figure 1 illustrates this framing within the context of the backyard investigation that serves as the case for this paper. In this investigation, students engaged with the disciplinary notion of differential success, a concept that is difficult to see in the backyard setting. As I will explain in the paper, one of the models introduced to make differential success more visible was a microcosm of the backyard, flats of soil in which students compared plants that were spaced out and plants that were crowded. As Figure 1 shows, a model system like this one amplifies both a condition, crowding, and the result of different conditions, plant success, allowing students to see and apply these ideas in the more complex setting (even as it reduces other attributes of the backyard).

Modeling activity is conceptualized in this framework as students' participation in *model making,* the selection and representation of features of the backyard in simplified forms like soil flats; *making claims in the model system*, including developing measures and visual representations to support work around the model; and *understanding the entailments* of the model, or deciding how the results of the system apply to the backyard and how new ideas can be operationalized there. This cycle is similar to more typical model construction-deployment-revision cycles (Louca & Zacharia, 2011; Windschitl et al., 2008) but was developed for the purposes of this work to be productive for the material nature of the models used and the focus on the relationship between modeling activity and conceptual development. Each phase of Figure 1 involves *practicing* one or more domain understandings— recruiting them to support selection, operationalization, representation, and model evaluation. This view of modeling, then, has implications for treatments of concepts in practice; what is important about disciplinary concepts, or students' conceptual resources, is not their accessibility as declarative statements but the work that they do in scientific settings and activity. The modeling activity framework informed both the design and analysis of student activity presented here.

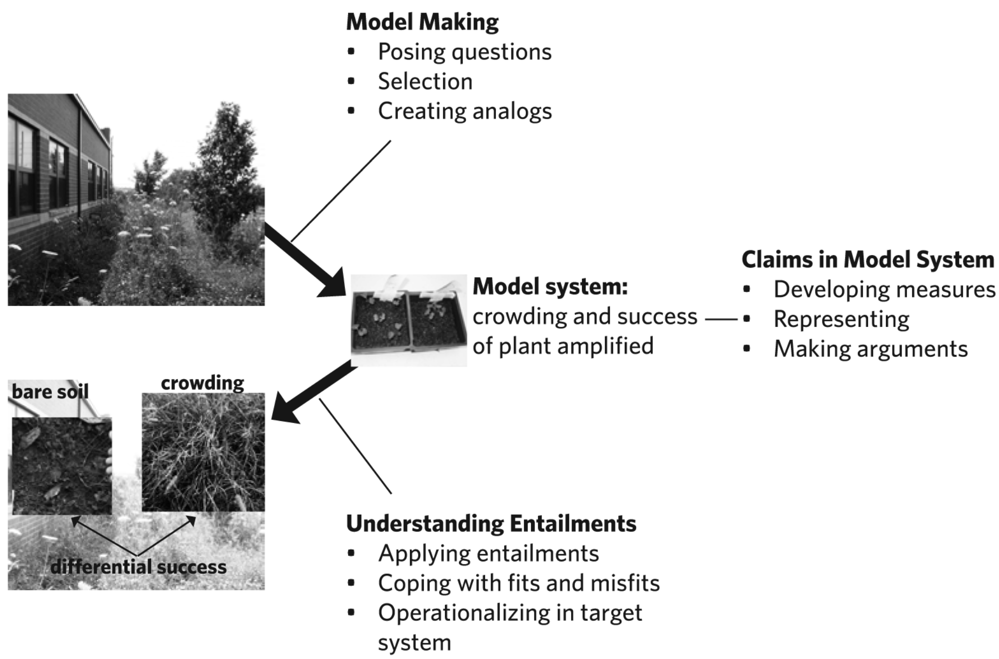

Figure 1. Conceptualization of modeling activity used in this paper

Domain of Focus: Ecosystems Understanding

The study of ecosystems is well suited as a venue for refining our understanding of the co-development of modeling practice and scientific concepts. Ecosystems are complex, involving numerous variables, multiple causes and consequences, and emergent structures that unfold across scales of time and space inaccessible to the casual observer (Jacobson & Wilensky, 2006). These systems pose significant challenges for practice and explanation. To make sense of them, experts have recourse to disciplined forms of modeling practice that privilege particular variables, relations, and explanatory forms (Collins & Ferguson, 1993; Hmelo-Silver, Marathe, & Liu, 2007; Latour, 1999). These include models of natural selection, sampling procedures, and heuristics for identifying and comparing species of organisms. Without these tools, one literally cannot see what the ecologist sees.

Research on children's reasoning about ecosystems generally focuses on their acquisition of conceptual structures (e.g., photosynthesis or matter cycling) or explanatory forms (e.g., complex causal chains) and typically does not address the material or representational challenges that these settings pose for students or how modeling might be leveraged to involve students in managing these challenges in conceptually fruitful ways (Hmelo-Silver et al., 2007; Leach, Driver, Scott, & Wood-Robinson, 1996; Perkins & Grotzer, 2000; Songer, Kelcey, & Gotwals, 2009). A few studies have emphasized these challenges, demonstrating that students' scientific practice and development of ecological concepts can be used to leverage each other (Lehrer et al., 2008; Metz, 2011; Roth & Roychoudhury, 1993). This work suggests that engaging students in modeling has the potential to concurrently develop modeling practice and an understanding of ecological concepts. However, to date, we know little about how particular conceptual meanings develop over the course of modeling practice and how particular material modeling practices support the development of ecological understanding.

This paper focuses on one disciplinary idea, reproductive success, tracing how this concept emerged from modeling activity and shifted in meaning as students participated together in modeling a backyard ecosystem. Reproductive success is integral to ecological and evolutionary explanations as a mechanism that links accounts of individuals to changes in populations (Anderson, Fisher, & Norman, 2002). Studying and explaining change in an ecosystem relies on knowing that individuals who meet their needs in the conditions of a particular place are able to reproduce and multiply. Being able to see and privilege reproduction, therefore, is a basis for exploring questions of dispersal, considering relations between conditions and presence of a species, and explaining succession. However, using ideas of reproduction to reason about change over multiple generations is known to be challenging for students (Metz, Sisk-Hilton, Berson, & Ly, 2010). To shift attention from the present and salient individual case to the individual's relation to future populations involves considering inferred and functional aspects of a system. This shift away from the immediately visible can seem unintuitive to novices and is unlikely to occur spontaneously without thoughtful instructional support (Hmelo-Silver et al., 2007; Perkins & Grotzer, 2000). Because the notion of reproductive success is central to ecological practice, but also difficult for students to see and use in ecological contexts, it was seen as a fruitful focus for this work.

Context

The context of this work is a design study (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) conducted with third grade students. Students were engaged in studying an ecosystem behind their school over the course of a school year, from October to May. The unusual duration of the investigation provided repeated opportunities to see youngsters struggling with the implications of their activity for their knowledge and beliefs and, in turn, extending their understanding of modeling and explanation as they developed new conceptual tools.

We engaged students in developing explanations of the "wild backyard," a trapezoidal-shaped area behind their school that was crowded with an impressive variety of weeds and overgrown grasses, ranging from ankle- to chest-high on an adult. The school wall cast a changing pattern of shade on the backyard, resulting in differential sunlight and moisture and related patterns of plant distribution. Students attempted to explain how this space came to have different kinds of plants than the neighboring lawn, and why there were different kinds of plants in different places within the backyard. From an expert's perspective, these questions evoke reasoning about differential success and succession, the process of change in the communities of organisms in an ecosystem. We identified two central disciplinary concepts as foci for students' practice: a) an understanding of plants' reproductive success, and b) the relation of needs of organisms to the conditions in which they live. These concepts are generative disciplinary ideas but also have entrees that are initially perceptually and conceptually available to students (i.e., in plant life cycles, seeds, and needs such as water or sunlight).

The study took place in a southeastern, urban elementary school (73% free and reduced lunch) with two successive cohorts of third grade students (ages eight and nine) and their classroom teacher (the same teacher each year). In this paper, I report on Year 1. There were 19 students in the class, 17 for the full year. The teacher had 30 years experience and was participating in her fourth year with the larger research project, a multi-school design study to understand the development of evolutionary reasoning through modeling activity. Although the classroom teacher had participated in significant professional development around modeling instruction, this form of science instruction was not standard within the district or school, where learning from texts and, less frequently, modular science "kits" were the norm. Therefore, modeling and investigation were new to the third grade students with whom we worked.

Because this was a design study, the research team developed conjectures about learning before instruction began, then refined them iteratively in local cycles of planning, enacting lessons, making conjectures about student learning, and redesign (Cobb et al., 2003). For this reason, methods, design, and results necessarily unfolded together. To clarify the study's "logic of inquiry" (Gee & Green, 1998), the methods section is presented in the following order: data collection and sources, pre-interviews, instructional design, post-interviews, and methods for retrospective analysis of students' activity during instruction. The remainder of the paper then describes the results of the retrospective analysis focusing on the relation between students' modeling practice and their ideas of reproductive success.

Methods

Data Collection and Sources

Instruction took place over the course of one school year, beginning in early October and ending in May (40 lessons of approximately 1-1.5 hours each). The author was the research team's primary liaison with the teacher and class, designing lessons and often co-teaching. Video records were made for all classroom work; one camera filmed classroom instruction and followed the teacher as she worked with students. During group work, a second camera was used, when possible, to capture partner work and short student interviews. Field notes consisted of time-indexed observations at the level of rough transcription, analytic notes, and short memos in the form of reflections (Schatzman & Strauss, 1973). All student artifacts were collected and scanned. A log of records was created with summaries of each lesson, including participation structures, topics, artifacts, and conjectures about students' intellectual accomplishments. Semi-structured interviews, which were audio-recorded and transcribed, were conducted pre- and post-instruction; six focal students participated in four additional interviews throughout the year.

Pre-Interviews

Pre-interviews were designed to assess a broad range of ecological understandings, as well as students' application of ecological ideas to explain complex phenomena. Students were asked open-ended questions, including what they thought would be important to understand about the backyard, why the backyard looked so different from the neighboring lawns, and why there were different plants in different places within the backyard. In addition, they were asked much narrower questions, for example to list the needs of a particular organism or to predict what would happen when a food chain (presented to them in pictorial format) was disrupted. Close attention was paid to students' answers to the guiding questions (how the plants got to the backyard and why there were different plants in different places) as well as to other open-ended questions that called on them to select or operationalize aspects of the environment, rather than simply to recall information. Analysis followed interpretive methods for inducing categories from the data (Miles & Huberman, 1994). Disciplinary distinctions were used to delineate or further separate categories of interest: for example, a distinction was made between reasoning about the needs of organisms and reasoning about needs of organisms in relation to comparative advantage in a particular place.

Early in the year, ideas of human agency or nature agency without mechanism were predominant in many students' thinking. These students accounted for the presence of different plants in the backyard by claiming either that people must have chosen to plant and care for them or that no explanation was needed—nature just "works that way." In contrast, a few students identified specific features of the environment that they then proposed as mechanisms for processes of dispersal or success in relation to conditions. Even during the pre-interviews, students sometimes delivered explanations that sounded deceptively sophisticated, as long as the interview questions quite specifically asked for them. Yet, these same ideas were not recruited in more open-ended questions that did not explicitly cue them. For example, when asked directly, students listed the needs of plants as sunlight, air, and water, but did not generally consider needs to explain why there were different plants in different places in the backyard.

We were repeatedly struck throughout this work with the complexity of considering what it means to “know” a biological concept. If “know” means “repeat a biological principle someone has told you,” then our third graders could be considered fairly knowledgeable, even, in relation to some ideas, at the beginning of instruction. However, if “knowing” includes recruiting information to decide on an appropriate form of inference, their knowledge in pre-interviews was relatively weak. We turned our attention, therefore, to how we might help students recruit potentially productive ideas to begin to explain ecological processes that they, as yet, did not see as requiring explanation or as related to their ideas.

Instructional Design

This section describes the design for the year of instruction in the wild backyard setting. It is important to note that, as this was a design study, the design itself necessarily unfolded in relation to students’ participation in instruction, our developing understanding of student thinking, and the teacher’s needs and capabilities.

Two driving questions (Krajcik et al., 1998) oriented instruction and investigation. In their initial visit, students readily noticed that the backyard looked very different from the manicured and mowed lawn that surrounded it. Following these noticings, we asked:

1. How did the plants get here?
2. Why are there different plants in different places?

These questions were intended to problematize students’ understanding of the backyard—that is, to pose phenomena that might seem self-evident to them as requiring explanation—and to set a context within which their previous conceptual resources, as well as newly introduced ideas, would come to take on explanatory power (Engle & Conant, 2002; Metz, 2011).

The year of instruction consisted of seven phases of activity, each conducted around particular models and representations, as summarized in Table 1. Each representation (Column 2) was meant to amplify aspects of a particular disciplinary concept (Column 3). Representational activities included reading books, magnifying and drawing artifacts such as seeds, and using analog systems such as flats of soil as models to test the effect of growth conditions. The conjecture was that through this activity, the backyard would be redescribed and populated with new privileged entities and relations that would, in turn, provoke questions that required new models and representations. In this way, the backyard could be successively transformed as an object of practice from an undifferentiated physical location, to a place that was wild and full of seeds and seed travel, then to one characterized by success in relation to needs, and finally, to a site for differential success in relation to conditions. Because the students were new to modeling, activities progressed from simpler to more complex in each of three aspects of representations: (1) the disciplinary concepts they were chosen to amplify, (2) their complexity, and (3) the phases of modeling activity in which students would need to participate (i.e., making models, claims in model system, and applying entailments to the backyard, as described in Figure 1).

From mid-October to early December (Table 1: Drawing Plants and Reading Books), trade books and student drawings were the primary representations used to support investigation of the backyard. These representations were intended to support students in seeing plant structures and processes that were otherwise invisible to them, in particular, differences in plant structures that served particular functions (i.e. roots or seeds) and life cycle processes such as reproduction and dispersal. Students participated in making models by selecting and representing plant features to study; they brought plant remnants indoors (for instance, each student dug up a “focus” plant and observed it) and drew plant parts to facilitate comparison and identification. They were asked explicitly to consider how the representations helped them understand the backyard to engage them in making claims using the representations and applying entailments to the backyard. For instance, they were asked which information from books was most useful for understanding the backyard system. They examined another student’s drawing of a plant and attempted to identify one like it in the backyard, commenting on the features of the student-made representation that facilitated identification. In this way, students considered both the structures and functions of plants and the representational features (in this case, text and diagrams) helpful for identifying and investigating plants.

In November through December, we also focused on empirical investigations of the life cycles of plants and the role of seeds in growth, reproduction, and dispersal (Table 1: Growing Plants and Making Claims about Seed Dispersal). During this phase, students were more deeply involved in all components of modeling activity. In November, Wisconsin Fast Plants™ were grown in light boxes to exemplify the life cycle of plants. As students made claims about plant growth, they developed measures such as height, number of leaves, and seedpods to make comparisons both across plants and time. Educators often presume that children understand and accept the model status of indoor systems, but we have found that they frequently fail to draw the connections that seem so obvious to adults. Therefore, they were asked explicitly to consider how the Fast Plants and growth system were both similar to and different from plants and conditions in the backyard, facilitating their participation in understanding the entailments of the model system for the outdoors.

Table 1. Progression of Representations and Modeling Activity

Instructional Phase	Models/ Representations	Disciplinary Concepts	Modeling Activity		
			Model Making	Claims in Model System	Understanding Entailments
Initial Question Posing 9/30- 10/06 3 lessons	Students visit backyard and generate noticings and questions				
Drawing Plants 10/13-11/03 6 lessons	Comparisons and representations of plants brought in from BY	Needs of plants; Form-function relations	Plant specimens chosen brought in from BY, students select features	Deciding whether plants same or not same, discussing features needed for identification	
Reading Books 10/08, 11/04-12/01 3.5 lessons	Books to support redescription of backyard as a wild place populated by seeds	Reproduction & dispersal, Needs	Book used by student to support claim, then made public to others	Selection	Asking students: how does this book help us understand the backyard, is it like this in the BY?
Making Claims about Seed Dispersal 12/01-12/09 3.5 lessons	Magnification of seeds using Flex-Cam, Testing of seed dispersal mechanisms indoors	Reproduction & dispersal, Form-function relations	Remnants from BY, designing tests that resemble BY	Selection of features; highlighting them in drawing, devel-opment of measures (i.e. distance seed traveled)	Asking whether conditions support same kind of travel in BY (i.e. enough rain for floods)
Growing Plants 11/01-12/17 6 lessons	Growing Wisconsin Fast Plants indoors to study plant life cycle	Growth, Reproduction & dispersal		Pressed plant specimens, measures of heights, counts and histograms of seedpods and seeds	Comparison to life cycle of plants in general and role of seeds in life cycle, Comparison of conditions to BY
Studying Needs 2/17-3/10 6 lessons	Germinating seeds in petri dishes to see if they can grow without sunlight or soil	Needs, Needs-conditions relations, Form-function relations	Mapping of aspects of system to backyard	Drawing to supply evidence, generation of concept of "success."	Discussion of soil formation and nutrient recycling in backyard
Using Flats to Test Conditions 3/10-5/12 12 lessons	Designing analog system to understand what might matter about the place where a seed lands for whether it is successful	Needs-conditions relations, Form-function relations, Reproduction & dispersal	Generating questions, designing and discussing analog systems	Drawing, counts, and measures to generate evidence, public discussion of claims and evidence	Discussion of similarities and differences, whether differences important for claims made in model

To investigate how plants (through their seeds) might have traveled to the backyard, students engaged in indoor tests of seed dispersal using a fan, a tub of water, surfaces to represent the ground, and cloths for seeds to stick on. They more fully participated in model making by designing aspects of the system that they considered "enough like the backyard" to constitute a useful test. For example, they proposed cardboard box tops that could be slanted and supplemented by softer surfaces to simulate properties of outdoor surfaces that could cause falling seeds to bounce or roll. They used drawings, measures, and textual descriptions in their science journals to support claims about how a focus plant's seed traveled in the indoor test setting, and subsequently, to consider what that told them about how it might have traveled to the backyard.

In February through May, students designed model systems that they investigated to make claims about relations between plant needs, conditions, and success (Table 1: Studying Needs and Using Flats to Test Conditions). The first representation used was plants grown in Petri dishes to test children's initial conjectures that plants could not "grow" without soil and sunlight. The model was used to problematize children's ideas about both plant success and growth conditions. Plants do not always either simply grow or die; many seeds can germinate in non-ideal conditions because of resources within the seed, but thereafter fail to thrive and reproduce. Places rarely receive "no sunlight" or "lots of sunlight;" nor is it helpful to describe parts of the backyard as having either "no soil" or "soil," although these were children's first descriptions of the levels of conditions that differentiated areas of the backyard. To make claims within this system, students had to think about how indicators of growth (i.e. germination, height, leaf size) could be represented, operationalized, and recruited to judge "success." We expected that involving students in making claims about plant success and applying the results of the investigation to understand the backyard would raise questions about students' dichotomies and provoke more sophisticated operationalizations and measures. As students sought to understand the entailments of their model for the backyard, they began to ask what it was about soil that plants needed and to compare sources of nutrients provided to Wisconsin Fast Plants™ (nutrient pellets) to natural cycles of soil formation and nutrient recycling outdoors.

In the final investigation (Using Flats to Test Conditions), students returned to the backyard to find places that differed in conditions important for plant growth. They then participated in model making by choosing questions to investigate, mapping aspects of the testing system (flats of soil, nutrient pellets, a wicking system, and seeds) to the backyard, and refining the test system to answer their question. For example, one group of children wondered about the effects of crowding on plant growth in the backyard and subsequently operationalized "spaced out" as five seeds distributed as equally as possible in the model flat and "crowded" as ten seeds dropped into a pile. Because different groups pursued different questions, representational and measurement demands in the model system were significantly higher than those in previous phases of instruction. Students needed to find ways to communicate their investigative setup and measures of success to others. When opportunities arose, students were encouraged to consider how their systems were similar to or different from the backyard, and how that mattered for testing their claims. For instance, when one of the systems intended to test crowding was not watered for several days, students asked whether it was legitimate to consider the health of the plants in that system as indicating the effects of crowding. One argued that it was still a fair test because in the backyard it does not rain every day; another countered that there was more soil in the backyard to hold the water. These discussions were seen as integral to modeling activity, because they involved students in thinking about whether and why a model can be considered as a reasonable context for understanding the target phenomenon in the "world out there."

In addition to planning the conceptual trajectory of the instructional design, we also had to consider its enactment. The emphasis on the development of modeling practice within communities (the social aspect of scientific practice) required the development of supportive classroom discourse structures to support student agency, the negotiation of uncertainty, and public revision (Lehrer et al., 2008; Schwarz et al., 2009). Accordingly, we worked with the teacher to develop norms and participation structures for supporting an emergent scientific community. Early in the year, students were encouraged to share their reasoning, listen to others, state whether they agreed or disagreed, and connect ideas. Later, they were supported in stating claims and evidence, asking for clarification, and revising their representations and writing based on feedback from other students.

Post-Interviews

The first goal of retrospective analysis was to describe changes in the ideas students applied to explain the backyard setting and remaining challenges. Our conjecture was that throughout the year, they had developed ideas about the dispersal of plants through seeds, plant success (including the production of seeds), and the relation of success to particular outdoor conditions, including rain, crowding, nutrients, and sunlight. These ideas had been developed through modeling activity, but we were still unsure how students saw, operationalized, and related them to explain the backyard setting. Therefore, a portion of the post-interview was conducted in the backyard setting, where students were asked to compare different plants, compare two different areas and explain how they might have come to have different plant distributions, and discuss how their model investigations related to the backyard setting. Due to time constraints, eleven students who represented the range of understandings in the class were selected for these interviews. Analysis began with a comparison of pre and post-interviews from the eleven students who participated in both.

One shift in the post-interview was especially prominent: students had developed ideas of reproduction that allowed them intellectual access to mechanisms for change across longer scales of time. At the beginning of the year, children did not talk about imagining change in the backyard, and many students were apparently confused at the invitation to explain its current appearance—to them, there was nothing in particular to explain. In contrast, at the end of the year, students animated the backyard as a world of seeds and successive generations of plants. Recent weather (i.e. a rainy, windy day) was proposed as a mechanism for seed travel, walls were described as surfaces seeds might bounce against, seeds on plants became evidence that plants were successful and would produce future generations, and dying plants were judged to be sources of nutrients for seeds landing near them. However, students used thinking relating the needs of plants and conditions in the backyard, the second conceptual target, less fluidly and within a narrower set of the interview questions, generally only when questions evoked the soil models used to test conditions. Because students so clearly showed change in their understanding and application of reproduction to explain the backyard setting, reproduction was identified as a useful starting point for a retrospective account of the interrelated development of modeling and conceptual understanding.

Retrospective Analysis of the Development of Reproduction

The focus of the retrospective analysis was the ways that ideas of reproduction emerged from, and shifted in relation to, students' modeling activity over the course of the year. Because they involved thinking about reproduction, four phases of the year (Table 1) were selected for close analysis:

1. Initial work of question posing
2. Reading books that highlighted seed dispersal
3. Making claims about seed travel
4. Using flats to test conditions

Video recordings of lessons from these four modeling phases were reviewed by a group of researchers, including those who participated in the initial design and enactment and others who did not. Group members made observations and hypotheses about activity, both in the clips and in relation to the transcript, and clips were played multiple times to review hypotheses (Jordan & Henderson, 1995). Three related lines of analysis were developed: conceptual meanings of reproduction, the understanding and use of these meanings in the community, and the positioning of concepts in relation to modeling activity. These analyses were then pursued as described below.

The first pass at the data focused on identifying conceptual meanings for reproduction. The theoretical framing of this work distinguishes between disciplinary concepts and the multiple resources and meanings that might be emergent for students in their activity. Therefore, all mentions of seeds, the end of a plant's life cycle, the dispersal of plants, or multiple generations were regarded as falling within the category of reproduction. All video and associated transcript for the four parts of the year selected for analysis were reviewed. A mention of reproduction by either the teacher or students, or the introduction of an artifact or representation connected to reproduction (i.e., seeds stuck to children's clothes, a plant with seedpods, or a book mentioning seeds), initiated an episode to analyze, with the aim of understanding how meanings for reproductive success were introduced into conversations and what meanings were available at particular times in the year. Comparison of episodes was used to describe how meanings shifted over time.

Because the site for idea negotiation and use is the classroom community, I sought to develop measures of the power of an idea within that community. I take collaborative activity as a way to read social organization, and shifts in observable qualities of group interaction as having analytic import (Engle, Conant, & Greeno, 2007; Erickson & Schultz, 1997). In initial video noticings, we distinguished between classroom talk we characterized as focused, where ideas were taken up and students proposed related meanings in consecutive turns of talk, and talk characterized as wide, where meanings were dispersive and the introduced artifacts or ideas did not appear to lead to the convergence of talk. These distinctions, *width* vs. *focus*, were used to categorize all sampled episodes. In addition, two kinds of shifts in participation from width to focus were noted and treated as productive sites for analysis: *explosions,* characterized by sudden increased student participation (more students talking, increased gesture, changes in tone that signaled excitement) and *arguments,* in which subsequent turns of talk indicated recognized disagreement and motivation to move to consensus. This analysis described which ideas and meanings, and in which contexts, were visible enough to constitute a common ground and support widespread participation (Engle & Conant, 2002; Staples, 2007).

Finally, to understand the relationship between the development of ideas of reproduction and modeling practice, I identified the aspects of modeling that the classroom community was engaged in for episodes that included reproductive talk, distinguishing among not using shared models or representations, making models, making claims in the model system, and generating entailments of the model. I sought to describe both how conceptual meanings were positioned by teachers and students in relation to modeling activity and how students were positioned, or positioned themselves, in relation to modeling activity.

Findings

This section describes change in meanings of reproduction used by the classroom community in relation to students' evolving modeling of the backyard. For each of the four time phases selected, I first present an overview of students' activity and the role of reproduction within that activity. I next present a representative section of classroom discussion to illustrate my analysis of that phase.

1. Initial Work of Question Posing

In late September, students were introduced to the backyard. They spent one 45-minute period outside and two inside sharing what they had noticed and posing questions for further study. Initial noticings were varied and generally focused on naming and describing features of the environment: leaves crunching, grasshoppers, spiders making webs, paths cut into the grass, tall plants and low plants. Several students mentioned ideas that we judged to be central to future work; for example, William said that he believed different plants might have different needs; Kadir noted seeds blowing off plants and believed that they might grow; and Chris introduced the idea that the backyard was called "wild" because "things grow on their own." While students shared numerous ideas, they made little connection among them in their talk. The classroom teacher and researchers attempted to build toward a shared enterprise of finding out about the backyard by making connections between students' statements, elaborating on and restating student questions, and explicitly describing students as finding out about unseen processes.

Example episode: Chris's idea of seed travel (October 6). The following example highlights the initial width of talk and the challenges of positioning student ideas as useful for shared scientific practice. It occurs between minutes 20 and 35 of the second discussion following the outdoors visit. The researchers and the teacher attempt to frame students as askers of questions about unseen processes in the backyard, encouraging them to coalesce their inquiry around how the plants got there. This episode begins when Jason comments on a student proposal to study the backyard using photographs. He explains that a photograph shows only one part of the backyard, and that there are "…different kinds of grasses and insects, and if it's different insects, it's just part and you can't see the whole thing."[2]

1. LS: It's reminding me of a question that we ask- that we talked about last week, which is sort of, how did all those different kinds of grasses and insects get back there? Do you remember we were wondering about that?
2. Jason: Because if he (*the school custodian)* starts not- not to grow- not to cut the grass, it will start growing more, umm... different kinds of seeds-different kinds of grasses will grow. And when it rains, sometimes it will attract flies.
3. LS: Flies?
4. Jason: Yeah. (*2 sec pause*)
5. LS: How do those different kinds of seeds get back there, is what I was wondering, though. I heard other people wondering that too.

Jason is concerned with describing the backyard, in particular the different kinds of insects and grasses that are there, a typical early take on "learning about it." The researcher, LS, sees Jason's question as an opportunity to make connections to the guiding question, which we had

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[2] Transcript conventions for this chapter: All student names are pseudonyms; Mrs. W: classroom teacher; EM, LS, RL: researchers; underlined emphasis; = latched speech; [ ] overlapping speech, aligned at start of overlap; … pause less than one second in duration; (*n sec*) duration of pause longer than one second, (*italics*) gesture; other punctuation (i.e. , and ?) is used to facilitate ease of reading.

introduced in the first discussion by elaborating on students' noticing different kinds of plants in different parts of the backyard. In contrast to Jason's, her orientation foregrounds curiosity about backyard processes, evident in her use of terms like "question" and "wondering."

Mrs. W. (the classroom teacher) joins in, saying that she would like to ask the custodian whether he planted the seeds in that backyard but can't, because he is on vacation. Again, students are portrayed as potentially finding out about the backyard, student ideas are reinterpreted as tentative claims that can be examined with further work, and mentions of seeds and plant travel are highlighted. She then asks Colby, "Do you have some ideas about that?" explicitly asking students to respond to each other's ideas.

6. Colby: I was thinking of using a microscope, so when you go into the wild backyard you can try to use a microscope and see all the plants and animals that live there.

While Colby, when questioned further, voices productive ideas about plants, animals, and the habitat provided by the backyard, he makes little connection to the ideas that Mrs. W. and LS have begun moving students toward. Here, the talk is characterized as "wide;" although LS has asked a question that Mrs. W. intended to build on and make a focus of classroom practice, neither Jason nor the following three participants pursues it.

Next, Mrs. W. calls on Chris, who does take up LS's question.

7. Chris: I want… I wanna- I want to know why- I'm gonna tell why- why some people call it the Wild Backyard.
8. Mrs. W: OK. (*She begins to put a new piece of chart paper on the board.*)
9. Chris: Because like, some people call it the wild backyard because it's some stuff in there that can grow on its <u>own</u>, like... like, the long plants can grow on its <u>own</u> that we saw there when we were <u>ob</u>serving and sometimes you can see the plant that somebody probably <u>plan</u>ted. Cause some- like, we, we was reading a book in second grade, it was about flowers, how the flowers, like the seeds in the flower, comes out the flower and then it and the wind push it, and then it might fall into the ground. And then if it rains, it grow- it starts-grows, and then if the sun shines on it, it grows some more.

Here, Chris suggests a mechanism whereby new plants might have arrived in the backyard without being planted. He offers a way of thinking about the backyard as a wild place with things that "can grow on its own." He elaborates this idea by claiming that some plants got there without being planted by people, an assertion he supports by retelling the story from a book he read the previous year. Mrs. W. then embellishes this idea and connects it to other students' experiences, reminding Kadir that he had seen a plant that he thought had lost seeds that could grow into new plants in the spot where they fell. She takes out a new sheet of paper, which she titles, "What questions do we have?" She and EM (the author) then frame students as asking questions about the backyard, as shown in the excerpt below.

10. Mrs. W: So... Let's think about what questions we have... we are asking about… Help me out, Miss Eve, here, since you were summarizing, about…
11. Students: seeds.
12. Mrs. W: How seeds travel.
13. EM: It sounds to .... is that.. what would-how would you turn that into a question? It sounds like you guys have what I would call a <u>guess</u> or a <u>hy</u>pothesis. Your <u>guess</u> is that the plants get there because…
14. S: It travels.
15. Kadir: It travels by wind.
16. EM: So could I turn that into a question? Could I say... <u>are</u> the plants there <u>because</u> the seeds travel?
17. Chris: Yes.
18. EM: I...uh..it's not my question uh... So I- that's one guess <u>I</u> have-but- I like- so you're starting with this <u>guess</u> but maybe we-you could figure that out? (*Mrs. W is starting to write on chart "1. How do seeds travel? How do they get places?"*)
19. Mrs. W: So how do they get places? How do seeds travel?
20. EM: It sounds like Chris is saying [how do <u>plants</u> travel]?
21. Chris: [<u>Wind</u>! By wind! The seeds come out]
(*A lot of students talking at this moment – unintelligible.*)
22. Mrs. W: Oh, how do <u>plants</u> get in the wild backyard? How do plants = (*writing*).
23. Chris: = When the wind blows and the flower's right there, and it like, it's a flower just sitting outside and it's not somewhere that you can, like, put it somewhere that it wouldn't have the seeds coming out. But, but it can just be <u>any</u>where because, like, it already comes with seeds. When it grows it has seeds in it. And then if the wind blows, the wind picks the seeds up out of the flower. Then the seed travels with the wind, and the wind might drop it somewhere… so it can grow

and then it rains and the sun is prob-the sun is shining *(Meanwhile Mrs. W. is writing on the board "How do plants get in the wild backyard? Did Mr. B….")*

24. Mrs. W: Alright, so this whole question about seeds and how they travel. Or did Mr. B. plant all the plants in the BY? (*Writes up on the board*) I heard somebody ask that question.

Chris acknowledges that he is sharing not a question but an explanation or idea ("I want to know- I want to tell why," Line 7). However, the teacher and researchers restate student ideas as questions or hypotheses. Mrs. W. begins a new sheet of paper called, "What questions do we have?" right after Chris brings up his idea of wildness and seed travel. She asks EM for help in restating Chris's idea as a question (Line 10). At this point, talk focuses on ideas of seed travel, but students do not appear to take on roles as question-askers; instead, they state ideas or answers. This is particularly evident in Lines 13-24, where EM attempts to restate what might seem like a fact to Chris as a "guess" or "hypothesis" (Line 13) that could be turned into a question for exploration. In Line 17, Chris answers, "Yes," appearing to believe that he is being asked whether plants are there because seeds travel. The difficulty in repositioning is evident in the next line (18) where EM simultaneously struggles with who owns the question and how to reinterpret what is a fact for Chris into a guess that could be "figure[d] out." It is not clear that Chris or other students take up this interpretation; as Mrs. W. attempts to capture questions on the chart paper, Chris continues to pose answers to the questions (Lines 21 and 23).

Summary: the relation of concept and modeling. This phase of activity is characterized by numerous productive ecological ideas and a nascent modeling practice supported almost entirely by adults, rather than shared representations and representational activity. The relation of modeling practice to conceptual meanings might be illustrated as in Figure 2. As they discuss the complex backyard system, students each see, privilege, and make public different objects and relations. Across these early episodes, it is not that ideas like reproduction are not "there";

students know, when asked, that seeds make new plants, Chris has some understanding of reproduction and dispersal, and other students mention the needs of organisms. These are aspects of the disciplinary concepts central to explaining the backyard. However, meanings are not consensual among students. Moreover, ideas appear to be formulated as noticings or facts, rather than as conjectures about unseen processes or questions that could be generative for scientific practice. From a modeling stance, there are no shared representations to amplify particular ideas. There is little to focus students on seeing or asking questions about the same thing. Our conjecture, therefore, was that students needed to be involved in simplifying and focusing on specific elements of the backyard in order to establish a shared practice of question asking and explaining.

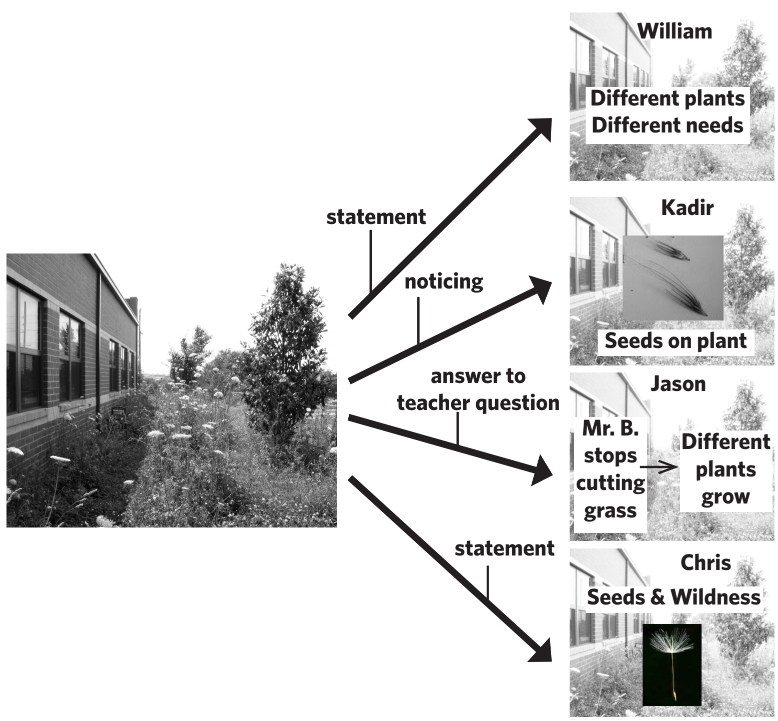

Figure 2. Students' participation in modeling activity during the question-asking phase

2. Reading Trade Books that Highlight Seed Dispersal

In the next phase of instruction, text became a key support for helping students see seeds as a focus for scientific activity and build ideas concerning how plants might have arrived in the backyard. Mrs. W. read aloud several books about seeds and plant growth, starting with the one that Chris remembered from second grade. Importantly, she explicitly positioned the texts as having utility for addressing students' questions, as below.

> *(Mrs. W sets the papers with the questions sheet side by side on the whiteboard)* …But one of the things you all thought about, too... that Mrs. W. (*referring to herself)* heard, whenever we were thinking about trying to figure out what's going on in the backyard, uh.... we heard from Chris and Colby that they read a book in second grade which really helped them think about seeds *(holds up book)* ... and Kadir, even as Mrs. W. looked back in his journal, umm…and he talked to us about it… Kadir even drew an up close and personal look at a seed, right, Kadir? So we thought that it might be a good idea, cause I heard Joshua say that sometimes reading books is a good idea to help us understand things that we don't know about.

Reading aloud the list of questions, posting them in a location visible to students during the reading of the book, and inviting students (Chris, Colby, Kadir, Joshua) into the process of using representations (the book and drawings) to make sense of questions sets up a practice of question asking and answering in which the book has a potential role to play. Mrs. W. positions the students as "trying to figure out what's going on in the backyard," again making explicit their relation to scientific practice – they are trying to understand and make conjectures about processes they do not yet know about.

The first book read to students, *The Tiny Seed*, by Eric Carle, tells the story of a flower that dies, scattering its seeds in the wind. Numerous seeds fall in places where they cannot grow, are eaten by birds, or are plucked or stepped on. The tiny seed travels farther and sprouts later than other seeds, grows into a huge sunflower, then dies and scatters its seeds. The second book, *From Seed to Plant*, portrays stages in the life cycle of various kinds of plants. These books amplify aspects of seeds and seed travel that might be difficult for students to experience in the backyard.

Next (November 17), the class spent one period writing an answer to the question, "Here's how I think plants got in the backyard," and sharing their ideas. Only one student now proposed, in either writing or discussion, that humans played an intentional role in placing the plants; all others generated ideas about "wild" mechanisms for the travel of seeds, generally those that had been mentioned in the books and elaborated with further discussion in the classroom. See, for example, the following entries:

> "Seeds travel to land by wind and water. If it rains and the seeds land on the soil, dirt, and sand the seeds will grow…Some seeds might look like a crom [*sic*] of bread and might be light as a feather."

> "Seeds could have washed away by water and then they landed in that area which is the wild backyard. I also know that some seeds have microscopic hooks on them that could that grab onto things…A bunch of different kinds of seeds could have fell into the BY. Then the plants that grew produced more seeds."

In these entries and in the representative episode provided below, students demonstrated that seeds and reproduction were increasingly *visible, interesting,* and often *powerful* for explaining questions of interest, and questions that became increasingly of interest once they were involved in explaining them. The texts supported a shared conceptualization of the backyard as "wild" and full of "wild" mechanisms, such as seeds, that may have been critical for motivating the shared practice of "finding out."

Example episode: seeing seeds as a focus of scientific work (November 4). The following conversations occurred on November 4th, when Mrs. W read *From Seed to Plant*, about a month after students read *The Tiny Seed* and several weeks after they asked the custodian, Mr. B., if he had planted the plants in the backyard. (Mr. B. replied that he had planted only grass seed and was not sure how the other plants had gotten there.) In the meantime, students had spent several class periods drawing and comparing plants in the backyard. In the first excerpt, Mrs. W. asks students to connect the book to their experiences outdoors.

1. Mrs. W: Oh... and who was this... let me think... Kadir where are you? *(points at him).* (Reads) Some seeds have hooks that stick to the fur or to the cloth of people's [clothes or of animals fur]
2. [*Anthony makes a fist pump*]
3. [*Kelly points to EM*]
4. Tyree: [That was on-]
5. Mrs. W: Later they drop [off onto the gr-]
6. Chris [that was on your] clothes (*pointing at Mrs. W.)*
7. Kelly: and it was on hers! *(pointing at EM)*
8. Mrs. W: That was on my clothes and it was on Kadir's and it was on=
9. Anthony: (*hand high up in the air*) = And [it was on mine].
10. EM: [my seeds in my garden!]
11. Anthony: It was on my shirt too! It stuck into my shirt (*reaches into shirt as if still feeling the seeds*).
12. Mrs. W: That's right, and remember the things that stuck to EM in her garden.
13. Kadir: Remember what Chris said about the helicopter? I have rocks and I throw them at the tree, and they come down (*makes helicopter motion with hand*), and I call them helicopters.
14. Mrs. W: Ohhh, so you have some seeds in your yard that look like that?
15. Anthony: And [one time]
16. Kadir: [they're in the tree and if you throw a rock at it (*indeciph*)]
17. S: [Those umm…]
18. *Several other students talking; indecipherable, several students make helicopter motions.*
19. Mrs. W: Wow! Oooh….You know what might really be helpful to us? If Mrs. W. gives you a baggie, could you bring us a lot of those so we can see how they work?

This excerpt was characterized as a moment of "explosion." Within seconds of Line 1, numerous students react both verbally and gesturally, pointing out others who have had "sticking" experiences (Kelly, Tyree, Chris) or reliving their own experiences (Anthony). This is the first time that seeds were generalized into categories such as "seeds that stick" or "seeds that fly." Students display intense excitement as their collective experience is named as a scientific phenomenon in the book. This example illustrates the movement between understanding the outdoors and exploring representations of it. Both seem essential for helping students build an idea of seeds as an appropriate subject of scientific inquiry – seeds abstracted to seeds that travel in a particular way. Mrs. W. explicitly encourages these connections, preparing students for making connections between the book and their experience, highlighting the connections that they bring up, and asking Kadir to bring something from home into the classroom to serve as a subject of inquiry ("…bring them in so we can see how they work," Line 19). Indoors becomes a place of naming, discussing, and abstracting what is seen and noticed outdoors.

A few pages later, Mrs. W. tries to make a connection between the way that the seeds in the book get rain and how plants in the backyard get water. Instead, Jason revisits the question of planting seeds. The argument that follows suggests that the question of how plants arrived in the backyard has become integrated into students' scientific practice.

1. Mrs. W: So is that still the same thing that's happening here?
   Students nod, a few "Yes's."
   Does this happen automatically in the backyard? (*Points to picture of rain over seed lying on ground.*)
2. S's: No *(including Jason).* Yes.
3. Jason: Mr. B. - Somebody has to plant them first.
4. Colby: Mr. B. [didn't plant them.]
5. Kelly: [No! ......Mr. B.] said [he didn't plant them.]
6. Mrs. W: [Mr. B. said he didn't] plant those.
7. Tayana: They [could have blown in the wind.]
8. Colby: [They're wild!]
9. (*There is an echo of the word wild, though it's impossible to tell who is echoing.*)
10. Jason: They're wild!
11. Mrs. W: They're all wild, they could have been brought by the wind.
12. Kelly: Blew [in the wind!]
13. Julie: [And then]= (*puts her hand up*)
14. S: [rain]
15. Mrs. W: =Uh-uh! Too many people starting to talk again. Yes, Julie?
16. Julie: Probably when one plant was growing, then the wind blowed on it. Then when the seed sets down, and then the rain, some mud or some dirt will cover it, and then that's probably how it gets the roots and starts growing.

This episode is another moment of explosion, with changes in posture, gesture, and the number of students engaged in discussion. It is a particular kind of explosion, a moment of spontaneous argument. Jason's comment reveals that the question of how plants got into the backyard is still alive for some students in the class. This is a very different discussion than the one used as an example in the question-asking phase. Now, meanings for reproduction in the backyard are positioned readily and echoed by several students in relation to the question. Three ideas appear to be used: that Mr. B. said he didn't plant the seeds (empirical evidence collected by students), that the backyard and the plants in it are "wild" (indicating widespread acceptance of Chris's argument that calling the backyard wild means that things happen "on their own" or without people), and a story for seed travel supported heavily by *The Tiny Seed*. Even Jason, who started the argument, calls out "They're wild!" after he hears the word, suggesting that he is using this idea to help him reconsider his claim. Here, students readily position themselves as making, supporting, and contesting explanations of backyard processes.

Summary: the relation of modeling and concept. In this instructional phase, students' varied ideas and experiences began to coalesce into a shared enterprise of explaining backyard processes using "wild" mechanisms, particularly seeds (Figure 3). Books provided simplified stories that amplified plant life cycle processes, i.e., seeds traveling, landing in a new place, and growing. Students developed a shared practice in which this information was useful for explaining a process of interest: how the plants might have gotten into the backyard. They were not yet using reproductive success to explain the backyard, but instead focused on the seeds of plants as a mechanical link between plants in one location and plants in another, or plants in one season and plants the next year. In addition, students were not yet fully engaged in modeling activity; while they selected and applied details from representations to explain the backyard, they neither made nor contested the representations.

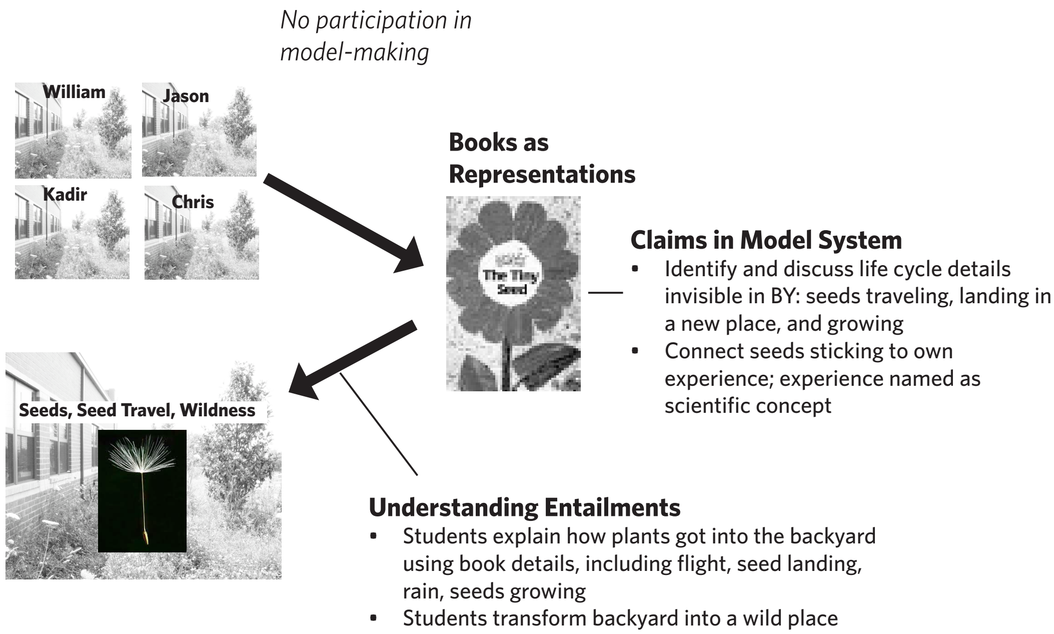

Figure 3. Students' participation in modeling activity during the book-reading phase

3. Making Claims about Seed Travel

From December 1-9, over four class periods, students generated their own arguments about how particular seeds traveled. Two modeling tools were central to this activity. The first was a FlexCam that magnified artifacts and projected them onto the whiteboard, making seeds visible to all members of the community and supporting the use of gesture to point out relevant features. The second was the testing of seeds indoors by modeling outdoor processes, including using a tub of water to mimic water travel, a fan for wind, hard surfaces for ground, and their own clothes to represent sticking. The texts used in the previous phase of instruction were already-made representations that children discursively connected to their experience. In contrast, during this phase, students participated in all three aspects of modeling activity. They selected seeds from the backyard for further analysis, amplified seed structures with the FlexCam, and created drawings to share with others. They were explicitly asked to consider how indoor tests of seed travel represented aspects of the backyard setting. They also began to think how they might make claims based on what they saw indoors, both in relation to the model system tests and the seeds' properties. For example, as they worked with the fan, they were asked to consider how they could measure the success of a seed traveling by wind, then settled on using a count of floor tiles to record and compare distances.

Increasingly, seeds were regarded as collections of properties that supported a particular mode of travel; students developed theories such as:

> "I would say that if other plants had like cotton or fuzzy stuff on it, it will float."
>
> "I look at the stuff that's on it and I look at the shape and if it has spiky stuff I can tell [it travels by sticking] or if it's just a smooth seed like an apple seed I can tell it won't stick because it doesn't have anything to stick to."

In addition, students considered the fit between their evidence in the model system tests and what might actually happen outside. Several students used features of the outdoors to make their argument plausible. Anthony argued that there are animals and people in the backyard. Tyree chose air travel over water for his seed because he thought it was unlikely that there were floods that generated enough water for water travel and then challenged Daria on the same point when she presented her argument to the class.

This phase involved a significant shift in discourse, for both teachers and students. Conversation moved between teachers a) arranging for students to see something and positioning them as noticers and explainers and b) positioning students as claim-makers who themselves need to select, arrange, and highlight relevant aspects of the situation. The first role, enacted initially during the book reading, was more firmly established in the classroom and appeared easier for the teacher to orchestrate. In the second role, students needed to decide what to see, what and how to measure, what to relate, and then organize those ideas to make a claim. For example, the first positioning was enacted as the teacher took two seeds (an acorn seed and milkweed), dropping them from the same height and blowing on them and asking students what they noticed about how the seeds fell, then asked which would travel farther in wind. In contrast, in the second positioning, students were asked to look at the milkweed and say whether or not they thought it was a seed that animals would bury to eat later, then justify their claim. As students became more adept at the latter forms of participation, what they saw and how they saw it were transformed. Seeds were partitioned into features that could promote particular models of travel and the backyard itself became populated with newly significant entities, e.g., wind that had the potential to blow seeds, animals that might carry them, and water that could take them to new places.

Example episode: Anthony's claims about sticking (December 9). Anthony's presentation in a "research meeting" demonstrates how students, models, and concepts were positioned in relation to each other and how teachers supported students to make and consider claims embedded in modeling activity. The research meeting (Lehrer et al., 2008) is a participation structure in which students present their claims, call on other participants to ask questions, and then ask for suggestions. In this first, simplified, use of this structure, students were asked to listen, to be ready to restate presenters' arguments and evidence, and to ask questions. From the backyard, Anthony had procured a small seed in a slightly larger seedcase with two spikes sticking out the end of it. He claimed that this seed traveled by sticking to animals.

1. Anthony: I think my seeds traveled best by clothing, fur, and feathers because animals walk back there and classes because it is on school property.
2. Mrs. W: OK, well keep going. What else did you write in there about how the seeds travel? What did you decide about how the seeds travel?
3. Anthony: That's it.
4. Mrs. W: Just say what you told Ms. W. earlier.

5. Anthony: I think...
6. Mrs. W: Look in your notes. How did you say that seed traveled?
7. Anthony: I thought it traveled by wind and water first. Then I changed my mind, because when I was at the wind center, it only flew two blocks [a distance of two tiles on the floor]. When I was at the water center, Ms. W., she moved the water and it didn't float around that much. So then I picked clothing, fur, and feathers because lots of people and animals walk around back there. And it sticks to their clothing, and it, like, sticks to something's fur.

Anthony's initial argument (Line 1) is constructed as a plausible story of dispersal based on features of the backyard. Mrs. W. encourages him to return to his notes and recall his earlier conversation with her. At that point he mentions several tests. However, he mentions neither his test of seed sticking, nor the seed's structure. Because Mrs. W. has worked with Anthony, she knows that there is a seed inside the seedcase that he is showing the class. She leads him to describe what was in there and why he opened it up to see it. EM takes out a seed and sets it by the other on the FlexCam. She then invites other students to participate.

8. EM: Who can restate Anthony's argument?
9. Mrs. W: I think Kelly says she's ready.
10. EM: Kelly, go ahead. How does Anthony think the seed <u>mainly</u> travels?
11. Kelly: By umm, clothing and feathers.
12. EM: Clothing and feathers. Anthony, is that what you were trying to tell everyone that you think is the way it mostly travels?
13. Kelly: And he said mostly.
14. Anthony: No. I was trying to say clothing, <u>fur</u>, and feathers
15. EM: clothing, <u>fur</u>, and feathers. Does that make sense? (*to Kelly*) Is that what you=
16. Kelly: =I forgot fur.
17. EM: And who can restate Anthony's evidence? Why did he <u>think</u> the seed traveled that way? What <u>made</u> him think that?
18. Mrs. W: Shawanda?
19. Shawanda: Because… (*2 sec*)
20. EM: I know it might be hard to say <u>all</u> of his reasons because he gave us a lot of rich information. Can you try <u>one</u> of the reasons he thinks?
21. Shawanda: Because of the hairy stuff. (*EM checks to see if others hear, Shawanda repeats more loudly.*)
22. EM: Was that one of your reasons, Anthony? (*He nods.*) Could you maybe call on someone else who can tell you another of your reasons?
23. Anthony: Colby.
24. Colby: Probably because... because he did all those tests with Miss Eve, Dr. Rich, and

Mrs. W. but-with the wind and it probably was a successful test, but on ground it probably didn't work, and so the water with Mrs. W., when she was spinning it around it didn't move a lot, right?

25. (*Anthony nods*.)

26. EM: Anthony, that's correct? He told you that back correctly?

27. Anthony: Umm hmm.

28. EM: Was there anything else, Anthony, that you think kids have not said, that's what you were also thinking was a piece of evidence?

29. Anthony: Mmm hmm. The little sticks on it, because I put it on my shirt and it was sticking by those little sticks.

Anthony is framed as having a claim (about sticking) and evidence. Note how much evidence he shares over the course of his presentation: plausible features of the backyard (animals and people), that the seed did not travel very far in the wind or water centers used to model outdoor processes, that it sticks to his clothes, and that it has “little sticks” on it. However, it takes significant work from the teachers and from other students to make his argument emerge and become subject to questioning and/or critique. Mrs. W asks him to recount what she and he talked about and reminds him to use his journal as a source of his argument (Lines 4 and 6). EM tries to make his ideas visible to other students by removing the seed from the casing, projecting it, and asking others to restate his argument. She asks Anthony to corroborate the summaries of his argument and evidence, framing him as their maker and providing an opportunity for him to become aware of how his statements are heard by his audience. As Anthony hears other students revoice his partial statements about aspects of the seeds and the model tests, he is able to add two pieces of evidence that he had not privileged in his initial talk: the sticks on the seed and the fact that he put the seed on his shirt and it stuck to his shirt (Line 29). The social work around the frame of the modeling activity (magnification, claim writing and sharing, and the use of model tests of seed dispersal) supports Anthony in communicating what he knows and how he knows it, coalescing his ideas and experiences into a coherent claim-evidence pairing.

Students are next encouraged to ask questions.

30. Tyree: So you said... is it like that the littlest one is the seed, and maybe the biggest one...the biggest one is the seed case?
31. Anthony: Yes (*nods*).
32. Tyree: So I'm saying, did you stick the seed case on you, or did you stick the regular seed?
33. Anthony: The seedcase, because the seed was still inside of it, and then after that, I took it off my shirt and opened it.
34. Tyree: So did you stick the seed on your shirt?
35. Anthony: (*1 sec*) No.
...
36. Julie: How long did the uhh...the seed stick on your shirt?
37. Anthony: A long time.
38. EM: Julie, what made you ask that question?
39. Julie: Because umm... a lot of the seeds don't stick that long, that's what I was wondering.
40. EM: And what would it tell you if it did not stick very long?
41. Julie: It would probably tell you… because maybe the hairs come... you can see like tiny hairs on your shirt, maybe that's how the seeds stick to your shirt probably.

In these lines, students are involved, albeit in simple ways, in attempting to understand and critique the models or investigations that others have used to make claims. Tyree begins to grapple with a potentially important distinction—the seed and the seedcase (Lines 30-35). Julie has begun to notice, perhaps from her experience testing her seed, that some seeds stick to material for just a short time. This remark constitutes a movement toward the need for a measure, a push past a dichotomous variable (sticking vs. not sticking) to duration of sticking time. This excerpt illustrates a new opportunity in the classroom: the making and critiquing of claims leads to emergent possibilities for students to realize their own role in creating model systems and designing measures of those systems that allow them to make claims that stand up in public.

Summary: the relation of modeling and concept. In this phase of activity, students participated more fully in all aspects of modeling activity (Figure 4), leading to new opportunities for conceptual development. Even with basic modes of amplifying and testing provided to (rather than invented by) them, students had to figure out how to see and what would count as showing something to another person. This work made new conceptual features of both the seeds and the outdoors apparent. For instance, as students magnified seeds and wrote arguments, seed structures and the function of those structures became increasingly evident. In addition, as they presented their arguments, social activity focused on communicating and understanding how individuals made models, using the model system to develop claims, and understanding entailments provided an opportunity for developing conceptual meanings. For instance, students were pushed to differentiate seeds from seed casings as other students sought to understand how they tested their seeds, as in Tyree's question to Anthony. In addition, they began to further differentiate outdoors conditions as they sought to apply their models to explain whether their seed would travel the same way outdoors as it had indoors.

During this phase students did not necessarily learn a new reproduction concept in the traditional sense. They had already listed all the ways that seeds travel, and no new methods of seed travel were proposed during the investigations. Rather than learning (in the sense of receiving) knowledge, they had to understand how to *make* shared knowledge, and in doing so appeared to further differentiate the idea of seed travel and its entailments in the backyard. Modeling brought into relief the relations between modes of travel, features of the seed, and features of the environment. As a result, both seeds and the outdoors became further differentiated: seeds into sets of structures (seed cases, sticks, fuzz, air), the outdoors into new partitions (amount of rain, windiness, presence of other organisms like animals and people) that mattered for the question at hand: an understanding of how the seeds traveled.

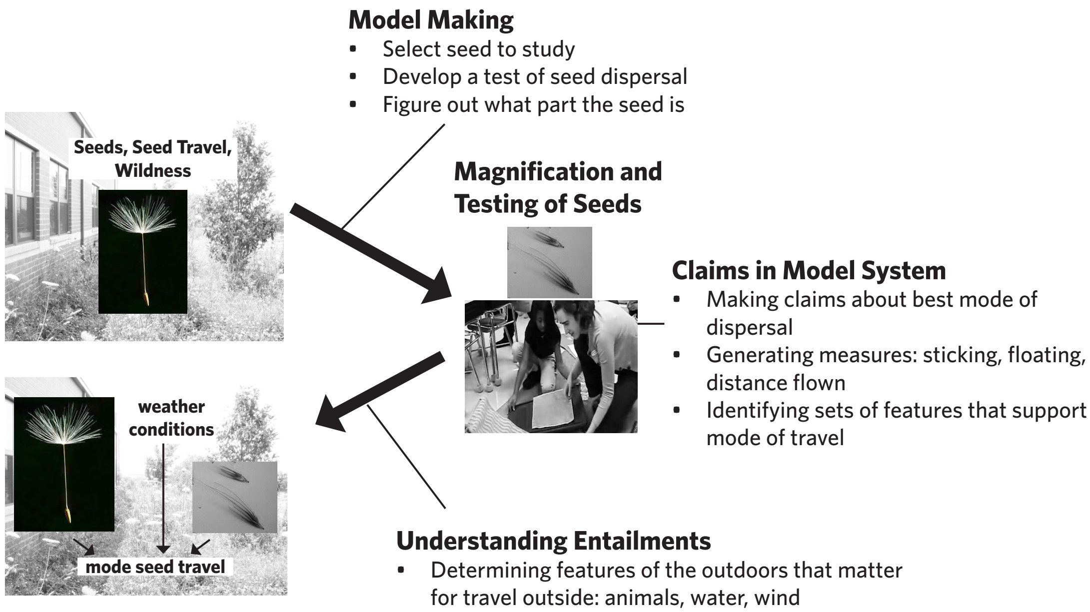

Figure 4. Students' participation in modeling activity during the seed claim-making phase

4. Using Flats to Test Conditions

During the winter, we involved students in asking whether every seed that landed in the backyard was likely to grow into a plant. Growing Wisconsin Fast Plants™ first in pots of soil in a light box and then in Petri dishes (without soil and sunlight) problematized notions and measures of growth. In early stages of growth, students differentiated and compared changes in attributes such as height, color, and size of leaves. As the Fast Plants grown in the light boxes came to the end of their life cycles, students noted that they were looking brown, dry, and unhealthy but that they were also producing seedpods and seeds. When teachers asked why a plant might want to produce seeds before it died, students readily explained that this would allow them to have children, or make more plants. At this stage, the term "successful" was introduced by teachers to encompass attributes (e.g., height, color, and seed production) that suggest a plant has gotten what it needs to develop throughout its life cycle. (We have found in previous work that the more readily used term, "healthy," tends to focus students only on the individual life cycle). Students were able to apply measures of success to compare the growth of plants in Petri dishes to those in the light box, concluding that plants can germinate without soil but will not be successful. However, because the plants in the Petri dishes were less successful on all measures than those in the pots, there was no need to privilege any particular measure.

Students next returned to the backyard to think about whether conditions across the backyard varied in any way that might matter for the success of seeds that landed there. After considering several possibilities, they decided to investigate amount of moisture, crowding, and nutrients. With assistance, they designed analog systems (flats of soil, nutrient pellets, water, a light box, and Wisconsin Fast Plant™ seeds) to test their ideas. During these investigations, seedpods emerged as one of the two most useful indicators of comparative success (the other being whether plants in one condition died, as occurred in some of the crowding conditions).

Unfortunately, a major weather event that closed the school limited students' opportunities to share and defend their claims about their systems when the plants had completed their life cycles. However, of the eleven students who participated in the post-interview, eight privileged seedpods as a primary source of evidence about which condition was more successful, explaining that seedpods meant that the plant made more of its kind. Of the three who did not, two students had crowding conditions in which all the plants in one condition had died and the other was studying moss, which did not produce seedpods. Over the course of this work, students' ideas of reproduction shifted substantially. Reproduction came to be seen and used as a measure in a new scientific enterprise. Moreover, it was a measure that could be theoretically justified and privileged over others.

Example episode: Julie and Kelly's system. The episode that follows took place on students' first day back at school after ten days out due to the weather event. During this time, the plants had flowered and grown seedpods. Mrs. W. began by asking students what they noticed changing. Julie and Kelly mentioned that they had seedpods, and that there were more in their "spaced out" condition as opposed to their "crowded" condition.

1. Mrs. W: So you see more <u>seedpods</u> in the one that is spaced out. Would you consider that <u>ev</u>idence [… about] which one you think is being more successful?
2. J&K: [Yes] (*nodding*)
3. Kelly: Yes Ma'am.
4. Mrs. W: Ok. Uh…Would anybody else see that as <u>ev</u>idence? Do you think? In... that Julie and Kelly are saying that they think because the one where their condition is more spaced out that it is being more <u>successful</u> than the one where it's crowded because it's producing more seedpods. Raise your hand if you think that would be a kind of [evidence.]
5. Kelly: [I only] have a little one (*undertone, referring to the crowded condition).*
6. Mrs. W: I'm seeing William, Shanequa, Chris's, OK. (*about half to two-thirds of hands are up*).
7. Mrs. W: And why… why, Julie, would you <u>consider</u> that to be evidence?
8. Julie: (*Pointing to spaced out condition*) Because I see, like, first the seedpods was like tiny, tiny like this, and now you see them, they're just growing so big and it seems like it's a lot. (*Reaches over to crowded condition.*) But when you look at the uh crowded one, it's it barely-well it has some seedpods, but it's still small.
9. Mrs. W: Why is that evidence? [...Why does] that matter?
10. Kelly: (*undertone*) [There's a big one] (*points to crowded condition*)
11. Julie: Because, uh, this one's (*points to spaced out condition*) growing seedpods first, before that one.

Mrs. W. shifts the conversation from noticing changes to using seedpods as evidence of success, explicitly asking students not only whether they would consider seedpods to be evidence (many of the students in the class concur, Lines 1-4), but *why* they should be considered as evidence. Thus, she repositions students from noticers of change to makers of claims within the model system who need to justify the use of measures. Julie does not initially participate in this justification; instead, she demonstrates a common form of practice in the classroom, differentiating an attribute to define it as a measure. She first mentions that one condition has more seedpods and bigger seedpods (Line 8), then, when pushed again by Mrs. W., differentiates the timing of seedpod growth across the two conditions (Line 11). Mrs. W. next rephrases and clarifies her question several times (Lines 12, 14, and 21):

12. Mrs. W:	Does that make any difference?
13. Kelly:	No because that one (*points to spaced out*) might die before this one (*points to crowded*).
14. Mrs. W:	Huh. Umm…but whenever we're thinking about it as evidence about whether or not the plants in <u>one</u> condition are more successful than the plants in <u>another</u> condition. (*2 sec*) Do you think seedpods matter?
15. J. & K.:	Yes.
16. Mrs. W:	Growth of seedpods.
17. J. & K.:	Yes.
18. Mrs. W:	And why would you think that?
19. Kelly:	Because if you have seedpods, then that's how you know that they're more successful, and if it you don't have any seedpods then [your…] plant wasn't that successful.
20. Mrs. W:	[Why, though?]
21. Mrs. W:	Why would having more seedpods <u>make</u> it more successful?
22. Kelly:	Well, then because you'll have more seeds to grow umm more plants.
23. Mrs. W:	Oh...because then you have more seeds to grow more <u>plants</u>... I see.

Mrs. W helps her students not only consider evidence as something that can be measured or compared across the two systems, but as something that can be theoretically justified, given what they know about plants and their prior scientific work. She stops probing only when Kelly explicitly states that success means making more plants and that seedpods help you "know they're more successful" (Lines 19 and 22). She then restates the justification, emphasizing the outcome of more plants. However, once reproduction as a proxy for making more plants is theoretically justified, another student challenges the way that the comparison is being made.

24. Tyree:	Umm... I really had something to kind of m-to add because umm, Kelly said that if it has seedpods, it's more successful, and if it doesn't have seedpods, it's <u>not</u> successful, but so you're just… you're just saying that if it like, it just has <u>flowers</u> it's not being really successful, but it could be on its way to <u>growing</u> the seedpods.
25. Mrs. W:	Ohh… OK. So you see the flowers as on their <u>way</u> to growing seedpods, so you think they could be just as successful, OK.

Tyree is concerned that one set of plants might be slightly ahead of another in timing, but could be "on their way" to reproducing, a valid concern and one that has emerged in each iteration of the design study. Measures simplify the system at hand, but they need unpacking and carefully justified operationalization to serve their purpose.

Summary: relation of modeling and concept. Here, the development of meanings of reproduction occurred as students applied and discussed it as a measure that enabled claim making in a new model system (Figure 5). Ideas from previous modeling activity were imported into this system as students called on their understanding of the role of reproduction in plant dispersal and multiplication to theoretically justify measures. During this activity, the idea of reproduction shifted in its use and meaning within the community toward disciplinary notions of reproductive success. Though students did not have access to genetic mechanisms, they considered it important that plants "make more of their own kind." This explicit connection across multiple generations of plants has the potential to serve as a link between the effects on an individual and predictions about future groups. In addition, students could challenge each other to justify the operationalization of the measure, providing an opportunity to deepen the ideas that substantiated it. For instance, reproduction could be considered not just as an endpoint in a plant's life, but as a stage linked by mechanisms (i.e., pollination) to other stages (i.e., flowering).

These are initial forms of engagement in sophisticated scientific practices and aspects of scientific argumentation. They are also highly conceptual. The positioning of reproductive success in relation to the activity described above underscores the inseparability of concept and practice. For students, the idea of reproductive success would have had little meaning outside their practice of investigating how the plants got to the backyard. Likewise, the practice of creating and understanding model investigations, then privileging reproductive success as a measure, relied on shared conceptions of seeds as agents responsible for plants being where they were.

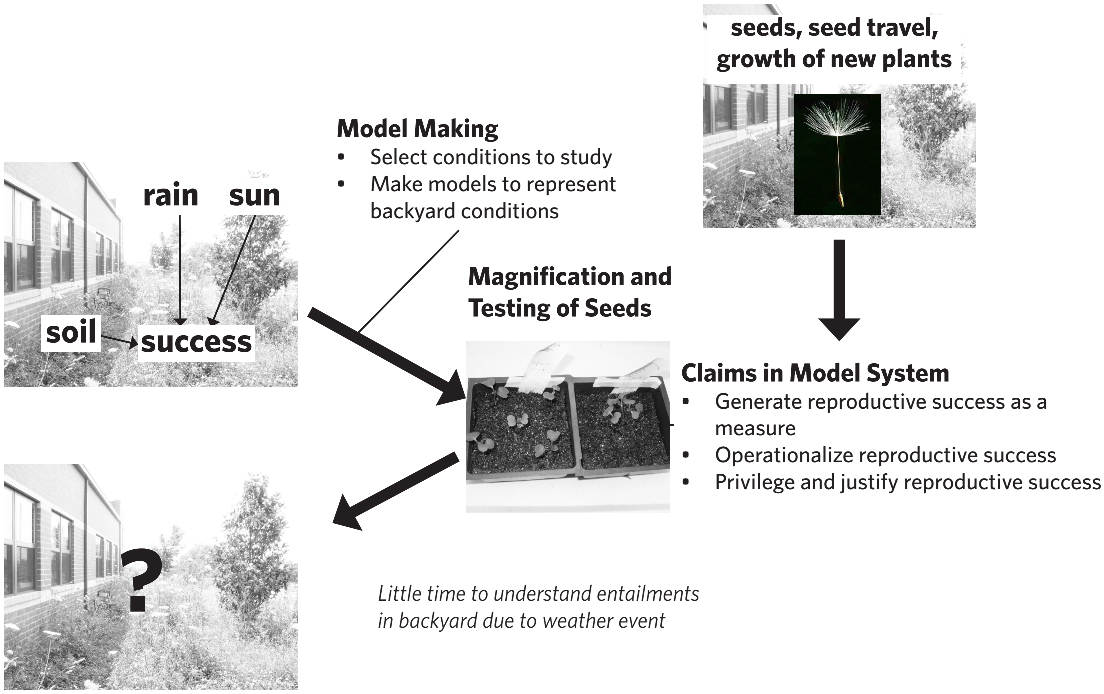

Figure 5. Students' participation in modeling activity during the soil flats phase

Summary of the Four Phases of Activity

A summary of the development of meanings for reproduction across the four phases of activity is presented in Table 2. Analysis of conceptual meanings suggests that students brought to instruction a varied set of productive ideas about seeds, which were eventually used to explain how plants got into the backyard, deepened as students developed differentiated ideas of seed structures and backyard conditions related to seed travel, and recruited for an approximation of the disciplinary concept of reproductive success. These meanings became increasingly powerful in community activity, as evident in the focus of talk around ideas of reproduction later in the year. Finally, the role of seeds and reproduction in students' modeling activity differed across the instructional phases. As students worked around shared representations, seeds were made visible and useful to backyard explanations, then functioned as the subject of model- and claim-making activity, and, finally, were recruited as a measure in a new enterprise.

Table 2. Summary of the conceptual, social, and epistemic aspects of students' work with ideas of reproduction over the four instructional phases.

Instructional Phase	Conceptual	Social	Epistemic: Position in Modeling Activity
Posing questions	• Plants make seeds • Seeds can travel • Seeds grow into new plants	• Talk wide	• No shared representations • Students do not seek to question or explain processes in BY
Reading books	• BY as wild • Plants populate the backyard through seed travel	• Talk focused • Spontaneous argument	• Seeds and seed travel made visible in representations • Concepts useful as they are applied to backyard
Seed travel claims	• Differentiation of seed structures and BY conditions	• Talk focused • Students respond to and question each other's ideas	• Seed travel as subject of model and claim-making • Concepts differentiated as students arrange and question models and model entailments
Soil models	• Notions of reproductive success	• Talk focused • Students respond to and question each others' ideas	• Seeds as a measure in a new enterprise • Differentiation/development occurs as measures are justified and defined

Discussion

In this paper, I described the co-development of ecological understanding and modeling practice in one third grade classroom in an effort to analytically integrate the conceptual, epistemic, and social strands of students' scientific activity (Duschl, 2008). To do so, I outlined an instructional design that engaged students in developing, exploring, and applying representations to explain the distribution of plants in a wild backyard area. Analysis compared the visibility and use of concepts of reproduction at four time periods in the year. This analysis suggests the utility of attending to student knowledge as it is used in practice and provides images of knowledge-practice relations that support productive scientific activity.

This perspective involves moving beyond determining whether students "have" or "do not have" ideas to focus on how ideas are used and refined in students' scientific activity (Duschl et al., 2007). Pre-instruction interviews and early classroom discussions demonstrated that students initially "had" an idea of reproduction; they knew that plants made seeds that, in turn, grew new plants. What changed over the course of the year was when and how they sought to use these ideas to pose questions and to make and defend new claims. In pre-interviews and early instruction, students generally mentioned seeds and reproduction only when asked explicitly about them. In later instruction and post-interviews, they recruited these ideas for a much wider set of questions and purposes, several of which exhibited nascent resemblances to sophisticated scientific practices. These results affirm that expertise resides not in the recitation of principles, but rather, in imposing conceptual structure to navigate complexity and opacity (Hmelo-Silver et al., 2007; Magntorn & Hellden, 2007). They also add to a growing body of work suggesting that elementary school students should be supported to participate in relatively complex scientific practices to develop conceptual understanding, rather than first being taught the concepts in isolation of practice or being initiated only into simple forms of practice such as observation or categorization (Lehrer, Schauble, Carpenter, & Penner, 2000; Louca, Elby, Hammer, & Kagey, 2004; Metz, 1995, 2011).

This study's treatment of the development of concepts in socially situated modeling practice builds from and extends recent perspectives on engaging students in disciplinary practice. The results demonstrate a case of the *development* of productive disciplinary engagement (PDE) (Engle & Conant, 2002) in the sense that over the course of the year, reproduction (a) increasingly sparked explosion in participation, argument, questioning, and elaboration by students and (b) facilitated activity that approximated important disciplinary practices, in this case material and representational aspects of modeling (Engle, 2011; Ford & Forman, 2006). Here, the focus on tracing one disciplinary concept, following methods for understanding PDE, made visible useful analytic distinctions in the relations of knowledge and practice in community activity. In the classroom described here, the concept of reproduction was used in a variety of ways: it was named and connected to experience; it became a constituent in argument and explanation; it was deepened and expanded by students through experimentation; and it was recruited to make sense of new systems and investigations.

In the context of recommendations to organize science instruction around fewer big ideas that are generative for practice (NRC, 2011), this study provides some evidence that reproduction is one such fruitful big idea. Within our larger project, the complexity and utility of concepts of reproduction for early elementary school students was something of a surprise. Reproduction is often mentioned in standards documents, but there is little specification of how it might be uncovered and explored, or what purposes it might serve for students' larger scientific activity. We have now come to see it as a critical idea that links young students' evolving conceptions of relations between organisms and populations and enables their practice of ecology. As we begin to follow the development of conceptual meanings in practice and to better understand the challenges of organizing shared scientific practice in relation to disciplinary concepts, we will be in a better position to determine which concepts to focus on and what trajectory to envision for them.

A second goal of this study was to explore implications for the design of learning environments that support the co-development of knowledge and scientific practice. The nature of modeling provides a venue where knowledge and practice can bootstrap, or iteratively push on and expand each other (Lehrer et al., 2008; Metz, 2011; Nersessian, 2008). Three forms of modeling and knowledge relations that appear to be productive for the design of instruction were evident in the analysis of student activity.

1. Representations Make Ideas Visible to Individuals and to the Community

This paper found evidence to support the use of models and representations in making objects and relations visible to students, thereby facilitating the development of disciplinary concepts (Louca & Zacharia, 2011; Penner, 2000). The study contributes to this literature in two ways. First, it highlights the importance of representations that not only make ideas visible to individuals, but also focus community activity, which can then push on and extend ideas made public by individuals. Second, to date, most studies in the domain of ecology have used computer-based simulations of ecosystems to make ecological concepts visible to students (Goel et al., 2011; Wilensky & Reisman, 2006). However, this study suggests that a broad set of representations, including texts, the magnification and drawing of plant parts, and physical microcosms, can be instrumental in helping students see and use concepts that are not immediately visible in the ecosystems they are investigating. Here, texts provided information that students then applied to naming and abstracting their own experience, such as the idea of seeds traveling by sticking (Episode 2). Bringing in and magnifying remnants allowed students to share and discuss features of seeds that might otherwise be invisible, for instance the distinction of seeds and seed cases discussed by Anthony and Tyree (Episode 3). Developing tests of seed dispersal helped students further differentiate aspects of seeds and of the backyard that might be relevant to particular travel modes (Episode 3).

2. Modeling Activity Provides Opportunities to Problematize, Broaden, and Deepen Understandings

The conceptualization of modeling activity presented here, the phases of model-making, making claims in the model system, and understanding the entailments of the model, made visible the opportunities that modeling activity provided for understandings to be applied, problematized, broadened, and deepened. This finding is consistent with previous research suggesting that through iterative cycles of model construction, deployment, and evaluation, students can develop increasingly sophisticated ideas both about the content domain and about how one makes knowledge within the domain (Louca & Zacharia, 2011; Schwarz & White, 2005; Windschitl et al., 2008). The results provide several examples of how this development might occur in relation to particular modeling practices. In the third instructional phase, mechanisms of seed travel, including the structures of seeds, were amplified and recruited as students developed and supported claims. As they coordinated their tests with the backyard to understand the entailment of the tests, they began to consider conditions observed there, for instance rain, wind, and animals moving through it. In the fourth instructional phase, as they needed to operationalize measures of plant success in order to make claims about the effect of conditions in the flat systems, additional facets of reproduction became potentially important. For instance, the timing of reproduction was problematized: does it matter whether one plant reproduces first; how long do you have to wait to see if a plant will ever reproduce? Future work might profitably focus on identifying and further describing conceptually fruitful modeling practices such as these.

3. Shared Conceptual Meanings Support Modeling Work and a Developing Notion of What It Means to Model

In this work, conceptual meanings for reproduction that were developed early in students' activity were essential for supporting more sophisticated modeling practices later in the year. In the excerpt described in Phase 4, students applied reproduction to make sense of a complex comparison with numerous potential outcome measures, participated in theoretically justifying its use as a measure, and challenged the operationalization of the measure. It is not a stretch to conjecture that this level of sophistication of practice would have been significantly less likely to occur without a shared conceptual basis from which to build. Knowledge might play a similar supportive role when students select questions to study or choose and argue which features of a complex system, and in what ways, to represent in a microcosm. While the integral role of knowledge in practice is already well-accepted, studies might do more to specify what conceptual understandings are called for to support desired forms of practice and how established understandings might be recruited for nascent practices.

The integration of these three model-concept relations across the year of activity begins to explain why students developed flexible notions of reproduction that were grounded in practice. The idea of reproduction resurfaced in multiple contexts, accomplishing related, but somewhat different work in each. Seeds emerged, and were amplified by representations, early in the year. It is likely that the extended, multi-faceted nature of students' scientific enterprise meant that seeds and reproduction continued to be powerful for students throughout their activity, with subsequent investigations nested within the overarching goal of explaining how the plants got into the backyard. The multiple uses for reproduction in relation to students' activity seemed to promote its stabilization in a network of shared practice. Nersessian and Patton (2009) argue that scientific activity is supported by interlocking models that include concepts, devices, and instruments. The participants in the study seemed to form a similar network, encompassing concepts, devices, instruments, and both mental and physical representations.

This conjecture is strengthened by comparing students' ideas of reproduction and the other focal concept, the needs-condition relation. As explained in the methods section, interview analysis demonstrated that students used the needs-condition relation less flexibly than ideas of reproduction. This concept was used by students in the post-interview only in those questions that were most parallel to the model investigations that they had used in the classroom, and these model investigations were almost always cited when students talked about the relation of needs to conditions in the backyard. In contrast to our early use of representations that made reproduction visible, we did little to represent the conditions in the backyard in relation to the needs of plants until later in the year. The concept of the relation of needs to conditions was represented only in the model system used to test the effect of conditions, introduced in March. A major focus of redesign in the next iteration of this design study was to represent and problematize place (as a conceptual resource for conditions) much earlier in the year, repositioning ideas of conditions in relation to practice in multiple ways throughout the year and exploring the effects of this alteration to the design.

There is much work yet to be done in understanding the complexities of this perspective on the development of content knowledge and determining how best to support teachers in orchestrating it. The models and representational activities reported here—sharing questions, reading books, testing seed dispersal, and investigating growth conditions—are typical of elementary school science education. However, both the extended nature of the investigation and the complex interrelation of learning goals present significant challenges for educators. These include understanding which representations are likely to provide fruitful entry points for student practice, developing trajectories for increased student participation in modeling decisions, and using recurrent forms of support that push on student practice without entirely constraining it. These are serious challenges, but the results in students' thinking and expanded access to sophisticated forms of practice suggest that they are challenges worth pursuing.

References

Acher, A., Arcà, M., & Sanmartí, N. (2007). Modeling as a teaching learning process for understanding materials: A case study in primary education. *Science Education, 91*(3), 398-418.

Anderson, D. L., Fisher, K. M., & Norman, G. J. (2002). Development and evaluation of the conceptual inventory of natural selection. *Journal of Research in Science Teaching, 39*(10), 952-978.

Bazerman, C. (1988). *Shaping written knowledge: The genre and activity of the experimental article in science*: University of Wisconsin Press Madison, WI.

Cobb, P., Confrey, J., diSessa, A. A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9.

Collins, A., & Ferguson, W. (1993). Epistemic forms and epistemic games: Structures and strategies to guide inquiry. *Educational Psychologist, 28*(1), 25-42.

diSessa, A. A., & Sherin, B. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268.

Duschl, R., Schweingruber, H., & Shouse, A. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, D.C.: National Academies Press.

Engle, R. A. (2011). The productive disciplinary engagement framework: Origins, key concepts, and developments. In D. Dai (Ed.), *Design research on learning and thinking in educational settings: Enhancing growth and functioning*. New York: Routledge.

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399-483.

Engle, R. A., Conant, F. R., & Greeno, J. G. (2007). Progressive refinement of hypotheses in video-supported research. In R. Goldman, R. Pea, B. Barron & S. J. Derry (Eds.), *Video research in the learning sciences* (pp. 239-254). Mahwah, N.J.: Lawrence Erlbaum Associates.

Erickson, F., & Schultz, J. (1997). When is a context? Some issues and methods in the analysis of social competence. In M. Cole, Y. Engestrom & O. Vasquez (Eds.), *Mind, culture, and activity: Seminal papers from the laboratory of comparative human cognition* (pp. 22-31). Cambridge: Cambridge Unversity Press.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423.

Ford, M. J., & Forman, E. A. (2006). Redefining Disciplinary Learning in Classroom Contexts. *Review of research in education, 30*(1), 1-32.

Gee, J. P., & Green, J. L. (1998). Discourse Analysis, Learning, and Social Practice: A Methodological Study. *Review of Research in Education, 23*, 119-169.

Giere, R. N. (1990). *Explaining science: A cognitive approach*. Chicago, IL: University of Chicago Press.

Gooding, D. (1990). *Experiment and the making of meaning*. Dordrecht: Kluwer Academic Publishers.

Goodwin, C. (1994). Professional vision. *American anthropologist, 96*(3), 606-633.

Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. *Science & Education, 16*(2), 141-166.

Hall, R., & Greeno, J. G. (2008). Learning and understanding concepts in practice. In T. Good (Ed.), *21st century education: A reference handbook.* Thousand Oaks, CA: Sage.

Halloun, I. (2007). Mediated Modeling in Science Education. *Science & Education, 16*(7), 653-697.

Hammer, D., Elby, A., Scherr, R., & Redish, E. (2005). Resources, framing, and transfer. *Transfer of learning from a modern multidisciplinary perspective*, 89-120.

Hanson, N. (1958). *Patterns of discovery: An inquiry into the conceptual foundations of science*. Cambridge: Cambridge University Press.

Harrison, A., & Treagust, D. (2000). A typology of school science models. *International Journal of Science Education, 22*(9), 1011-1026.

Hesse, M. (1966). *Models and analogies in science*. Notre Dame, IN: University of Notre Dame Press.

Hmelo-Silver, C., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*(3), 307-331.

Jacobson, M., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11-34.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences, 4*(1), 39-103.

Kelly, G. (2008). Inquiry, activity, and epistemic practice. In R. Duschl & R. Grandy (Eds.), *Teaching scientific inquiry*. Rotterdam: Sense Publishers.

Koslowski, B. (1996). *Theory and evidence: The development of scientific reasoning*. Cambridge, MA: The MIT Press.

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredericks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *Journal of the Learning Sciences, 7*(3-4), 313-350.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard Univ Press.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts*. Princeton, N.J.: Princeton Univ Press.

Leach, J., Driver, R., Scott, P., & Wood-Robinson, C. (1996). Children's ideas about ecology 3: Ideas found in children aged 5-16 about the interdependency of organisms. *International Journal of Science Education, 18*(2), 129-141.

Lehrer, R., & Schauble, L. (2000). Modeling in mathematics and science. In R. Glaser (Ed.), *Advances in instructional psychology: Educational design and cognitive science* (Vol. 5, pp. 101-159). Mahwah, NJ: Erlbaum Associates.

Lehrer, R., & Schauble, L. (2006a). Cultivating model-based reasoning in science education. *Cambridge handbook of the learning sciences*, 371-388.

Lehrer, R., & Schauble, L. (2006b). Scientific thinking and scientific literacy. In K. A. Renninger & I. E. Siegel (Eds.), *Handbook of child psychology* (6 ed., Vol. 4: Child psychology in practice). Hoboken, N.J.: John Wiley and Sons, Inc.

Lehrer, R., Schauble, L., Carpenter, S., & Penner, D. (2000). The interrelated development of inscriptions and conceptual understanding. In P. Cobb, Yackel, E., McClain, K. (Ed.), *Symbolizing and communicating in mathematics classrooms: Perspectives on discourse, tools, and instructional design* (pp. 325–360). Mahwah, N.J.: Erlbaum Associates.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive Development, 23*(4), 512-529.

Louca, L. T., Elby, A., Hammer, D., & Kagey, T. (2004). Epistemological resources: Applying a new epistemological framework to science instruction. *Educational Psychologist, 39*(1), 57-68.

Louca, L. T., & Zacharia, Z. C. (2011). Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. *Educational Review*, 1-22.

Magntorn, O., & Hellden, G. (2007). Reading new environments: Students' ability to generalise their understanding between different ecosystems. *International Journal of Science Education, 29*(1), 67-100.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071-1105.

Metz, K. E. (1995). Reassessment of developmental constraints on children's science instruction. *Review of Educational Research, 65*(2), 93-127.

Metz, K. E. (2011). Disentangling robust developmental constraints crom the instructionally mutable: Young children's epistemic reasoning about a study of their own design. *Journal of the Learning Sciences, 20*(1), 50-110.

Metz, K. E., Sisk-Hilton, S., Berson, E., & Ly, U. (2010). *Scaffolding children's understanding of the fit between organisms and their environment in the context of the practices of science.* Paper presented at the International Conference of the Learning Sciences, Chicago, Illinois.

Miles, M. B., & Huberman, A. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). Thousand Oaks, NY: Sage.

Nersessian, N. J. (2008). *Creating scientific concepts*. Cambridge, MA: The MIT Press.

Nersessian, N. J., & Patton, C. (2009). Model-based reasoning in interdisciplinary engineering. *Handbook of the philosophy of technology and engineering sciences*, 687-718.

NRC. (2011). *A framework for K-12 science standards: Practices, crosscutting concepts, and core ideas*. Washington, D.C.: The National Academy of the Sciences.

Oh, P. S., & Oh, S. J. (2010). What Teachers of Science Need to Know about Models: An overview. *International Journal of Science Education, 33*(8), 1109-1130.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching, 39*(3), 185-204.

Penner, D. E. (2000). Cognition, Computers, and Synthetic Science: Building Knowledge and Meaning through Modeling. *Review of Research in Education, 25*(ArticleType: research-article / Full publication date: 2000 - 2001 / Copyright © 2000 American Educational Research Association), 1-35.

Perkins, D., & Grotzer, T. (2000, April). *Models and moves: Focusing on dimensions of causal complexity to achieve deeper scientific understanding.* Paper presented at the Annual Meeting of the American Educational Research Association, New Orleans, LA.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. Chicago: University of Chicago Press.

Roth, W., & Roychoudhury, A. (1993). The development of science process skills in authentic contexts. *Journal of Research in Science Teaching, 30*(2).

Schatzman, L., & Strauss, A. (1973). *Field research: Strategies for a natural sociology*. New Jersey: Prentice Hall.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, D., . . . Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654.

Schwarz, C., & White, B. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*(2), 165-205.

Sengupta, P., & Wilensky, U. (2009). Learning Electricity with NIELS: Thinking with Electrons and Thinking in Levels. *International Journal of Computers for Mathematical Learning, 14*(1), 21-50.

Songer, N., Kelcey, B., & Gotwals, A. (2009). How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity. *Journal of Research in Science Teaching, 46*(6), 610-631.

Staples, M. (2007). Supporting whole-class collaborative inquiry in a secondary mathematics classroom. *Cognition and Instruction, 25*(2), 161-217.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking mathematics in school: Studies of teaching and learning* (pp. 107-149). Cambridge: Cambridge University Press.

Vattam, S. S., Goel, A. K., Rugaber, S., Hmelo-Silver, C. E., Jordan, R., Gray, S., & Sinha, S. (2011). Understanding complex natural systems by articulating structure-behavior-function models. *Educational Technology & Society, 14*(1), 66-81.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, a sheep, or a firefly: Learning biology through constructing and testing computational theories--an embodied modeling approach. *Cognition and Instruction, 24*(2), 171-209.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967.

CHAPTER IV

OPENING UP LIGHT BOXES AND BLACK BOXES: INITIATING YOUNG STUDENTS INTO EXPERIMENTATION AS A MODELING ENTERPRISE

Introduction

Understanding a scientific idea involves knowing something about how it is made and the purposes for which it is useful. Accordingly, science education is increasingly organized around engaging students in scientific practices, positioning them as makers of knowledge. However, there is significant uncertainty both about how to initiate students into these forms of practice and how domain knowledge and participation in practice should be integrated in instruction (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo-Silver, 2009; NRC, 2011). I address these challenges in the context of third grade students modeling plant diversity in a backyard ecosystem. In the course of their investigation, students implemented an experiment to understand whether patterns of sun and shade cast by their school wall could account for the distribution of plant types that they observed. I explore how the experiment served as a productive site for the development of multiple scientific practices (e.g. experimentation, argumentation, and measurement), as well as important ecological ideas (e.g., plant needs and reproductive success).

To date, research has tended to focus on identifying important practices and developing supports for initiating students into those forms of practice. One method for providing support is to explicitly teach a practice's structure, for instance, by directing students to write an argument in the form of claim, evidence, and reasoning (McNeill, Lizotte, Krajcik, & Marx, 2006), or to use a control-of-variables strategy to plan an experiment (Chen & Klahr, 1999). Another is to reduce the complexity of the setting; students might be asked to argue about social questions before they address scientific questions (Kuhn, 2010) or to interpret small data sets without irrelevant variables before tackling complex data (Berland & McNeill, 2010). However, these approaches have drawbacks. First, students can adopt the structures of taught practices without understanding their purposes (Berland & Reiser, 2009; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000). For example, Kuhn and Pease (2008) found that students sometimes control variables without realizing that the purpose for doing so is to find something out. Second, practices such as investigation, explanation, and argumentation are often investigated independently, an approach that provides little guidance about how to exploit their relationships with each other. Moreover, highlighting and simplifying practices can lead to their decoupling from core disciplinary ideas, so that students learn about a domain idea, such as plant needs, on one day, then a practice on another, or use either ideas or practices as a superficial context for the other, as has characterized the enactment of inquiry science curricula (Davis, Petish, & Smithey, 2006; Enfield, Smith, & Grueber, 2008; Furtak & Alonzo, 2010). Increasingly, the field is turning its attention to understanding the long-term development of practices in contexts where scientific knowledge is being fostered and the practices have genuine utility for students (Cavagnetto, 2010; NRC, 2011; Ryu & Sandoval, 2012).

To contribute to this agenda, I sought to design a learning environment that would highlight uses, rather than forms, of practices and ideas; establish a context in which these functions would be sensible to students; and situate the co-development of practice and knowledge. These goals were informed by treatments of knowledge and practice that emphasize their co-origination in meaningful activity (Lave & Wenger, 1991; Vygotsky, 1978). Ways of talking, acting, and using ideas have stable expressions in established disciplines, but their forms and functions are interactionally accomplished in communities as members attempt to align their behavior and accomplish goals (Hutchins, 1995; Saxe & Esmonde, 2005; Wenger, 1998). Similarly, for students to develop a "grasp of practice" (Ford, 2008), they must experience those practices as powerful for knowing something and see reasons for refining them.

With these goals in mind, I engaged students in using an experiment to understand the diversity of plant life in the backyard setting and allowed them to grapple with the challenges entailed in using an experiment to develop explanations. Both the topic—plants' need for light—and the form of investigation—an experiment—are typical foci for elementary school students. However, the approach taken here differed from typical treatments, which use experiments either to demonstrate facts about plants (e.g., their need for light or stages of growth) or to teach the structure of controlled variation. Instead, I treated the experiment as embedded in a modeling enterprise. I sought to engage students in constructing and critiquing the experiment as a model of the backyard that allowed them to "know" something about it. In the following section, I describe how I frame science as a modeling enterprise and explore the implications for supporting and representing students' practice. Next, I contextualize this approach within the backyard setting.

Science as a Modeling Enterprise

Constructing, testing, and revising models are at the heart of the scientific endeavor (Giere, 1990; Grandy & Duschl, 2007; Nersessian, 2008). In the National Research Council's (2011) *Framework for K-12 Science Education*, modeling is identified as one of eight scientific practices in which students should participate. Indeed, several science educators argue that it is not *one practice among others*, but *the central scientific enterprise* (Lehrer & Schauble, 2006;

Passmore & Stewart, 2002; Windschitl, Thompson, & Braaten, 2008). From this perspective, what unites scientists' work across disparate domains is the development of representations that simplify aspects of the world, facilitating description, prediction, and explanation (Giere, 1999).

Latour (1987, 1990, 1999) points out that modeling involves a series of transformations at each stage of which phenomena are *reduced*: some aspects are selected, and others fall away. In turn, reduction promotes *amplification,* in that the phenomena of interest are made more visible, manipulable, transportable, and subject to calculation and standardization. For example, understanding the activity of an endorphin might entail choosing the guinea pig as a model, isolating its gut, injecting hormones to study interactions, making contractions visible by hooking them up to a stylus, then publishing the inscription made by the stylus and using it to support statements about endorphin behavior (as described in Latour, 1987). Each of these transformations, from mammal to guinea pig, guinea pig to guinea pig gut, gut to gut contractions, contractions to marks on a paper, and marks on a paper to an account of hormone function, is an act of modeling with epistemic payoff, in that some aspect of the phenomenon is made more visible. "Knowing" about endorphin activity entails making (or accepting) the representational chain stretching from the statement about endorphins through the inscription to the piece of gut in a laboratory, taking each object to stand in for the previous one in the chain. As such, engaging in scientific activity entails building a system of carefully stacked "epistemic levels" (Kelly & Takao, 2002).

These transformations are conjectural and become stabilized in relation to each other in what Pickering (1995) calls the "mangle of practice." Scientists have to make guesses about how to make aspects of the world visible, then variabilize, manipulate, and relate them even before they fully understand them (Gooding, 1990; Shapin & Schaffer, 1985). When something goes wrong, they have to decide what part of the chain is at fault. Is the theory of endorphin activity wrong, is the measure of change mis-specified, is the use of the guinea pig rather than another animal a mistake, or has the technician just picked up a single “bad gut”? Peers can attack claims by calling transformations into question, for example by arguing that a measure misrepresents a phenomenon. As community members engage in iterations of construction and critique (Ford, 2008), they problematize and, over time, stabilize the entire system supporting their work, which includes the statements, experiments, equations, and drawings that they accept as adequately representing the world (Knorr-Cetina, 1999; Longino, 1994; Pickering, 1995).

From this point of view, scientific practices are ways of constructing and critiquing the transformations that allow an individual or community to “know” something. So, for example, using the mouse as a model of human sepsis (an immune system response that causes organ failure) has been a widespread practice in medical research, one that was recently challenged on the basis that genetic mechanisms for immune responses in mice and humans differ more than previously thought. Using a transect to estimate the abundance of a species is an ecological practice. Each of these practices is a solution to material challenges (it’s not ethical to test new medicines on people, it’s impossible to count all of the organisms in an ecological community), and each is embedded in an explanatory goal. In scientific activity, practices are entwined and are evaluated in light of each other. Challenges to the mouse model of sepsis emerged from new applications of genetic technology and were consequential because of their implications for explanations of immune system functioning. While this emphasis on the interconnection of practices is evident in recent science standards consensus documents (Duschl, Schweingruber, & Shouse, 2007; NRC, 2011), educational interventions and research studies have tended to focus on one practice at a time, probably in an attempt to simplify. The danger is that, by doing so, we remove so much of the context that students fail to understand, or even misunderstand, the purposes that practices serve.

Consider the experiment. From a modeling perspective, an experiment represents some aspects of the world that need to be wrestled into a testable form, and the “data” it produces are usually far from simple, often requiring further transformations. However, studies have generally focused on the structure of the experiment as a controlled, conclusive test of co-variation (Zimmerman, 2007). This focus does not foreground experiment’s role in the “modeling game” (Hestenes, 1992), and, in fact, can obscure it. As a result, young people and even many adults misunderstand the purpose of the experiment, positioning it as an atheoretical test of the relations between variables, rather than as a way to explain processes that are conjectural and difficult to manipulate (Driver, Leach, Miller, & Scott, 1996; Schauble, Glaser, Duschl, & Schulze, 1995; Windschitl, 2004).

What are more effective ways of making these functions visible and useful to newcomers through participation? How do novices come to understand that experiments are models that allow us to find something out, or that measures are developed so observers can compare attributes? How do they begin to critique the transformations that others have made, rather than taking their experiments or measures at face value? To explore these ideas, I situated students’ scientific activity in an experiment, a form of practice typically introduced to students in the elementary grades. However, I sought to open up the experiment, maintaining some of the complexity that establishes the need for related practices like measurement, operationalization of variables, and argumentation. There is evidence that young people can participate in these important practices as they develop and use experiments. For example, they can develop microcosms to model important aspects of target systems, construct variables and measures, and locate weaknesses in their own and others' experimental designs (M. J. Ford, 2005; Lehrer, Schauble, & Lucas, 2008; Lehrer, Schauble, & Petrosino, 2001; Masnick & Klahr, 2003; Metz, 2011).

My goal is to produce a close analysis of how these forms of practice develop in interaction, one that is consistent with the complexity of the practice in professional activity and also acknowledges the real challenges novices must negotiate to make progress in this nexus of interconnecting ideas and practices. When students are engaged in meaningful practice, we expect to see changes over time in what they find problematic, the resources they assemble to solve problems, the ideas and activities they "take-as-shared," and the purposes served (Enyedy, 2005; Kelly, 2008; Saxe, 2002; Yackel & Cobb, 1996). I sought, therefore, to understand what aspects of experiments young students would construct and critique, how their construction and critique shifted over time, and how participation in this activity supported the development of ecological understanding. Within the context of third grade students' work with an experiment, I asked:

1. How did students construct and critique the experiment as a system for knowing something?
2. How did experimentation serve as a venue for considering and refining ecological ideas?
3. How did scientific practice and ecological ideas co-develop?

In the next section, I contextualize this approach within students' attempts to understand the distribution of plants in a wild backyard setting.

The Ecological Context

The context of this work was a year long scientific investigation conducted with an urban third grade class in the "wild backyard," an unmowed area behind their school (Figure 1). The school wall cast a changing pattern of shade on the backyard, resulting in differential sunlight and moisture and related patterns of plant distribution. We[3] engaged students in noticing the diversity of plant life, then explaining how this space came to have different kinds of plants than the neighboring lawn, and why there were different kinds of plants in different places within the backyard (Manz, 2012).

Figure 1. Image of "The Wild Backyard" in August

This setting poses formidable challenges for the development of explanations. First, it is *complex* (Jacobson & Wilensky, 2006), in that processes with multiple causes unfold across larger scales of time and space than students can directly investigate. Second, it poses *material* problems. The plants are difficult to identify, and, in their initial work, students often have

[3] "We" is used throughout the paper to refer to the research team, who involved the classroom teacher, the author, Rich Lehrer, Leona Schauble, Michelle Cotterman, and Mayumi Shinohara.

trouble telling where one plant ends and another begins. Change is prominent: seasons shift, the pattern of light changes over the course of the day and the year, and plants develop features, lose them, and die, only to emerge in new places in spring. Rather than regarding complexity and materiality as impediments to the development of knowledge, we frame ecological understanding as centrally involving the ability to navigate these aspects of the setting and impose order on it (Goodwin, 1994; Hutchins, 2012; Lehrer & Schauble, 2012; Manz, 2012). Students bring facets of important ecological concepts to instruction (for example, understanding that living things have needs or that offspring resemble their parents). However, the contexts in which these ideas are visible and useful to them are likely to differ substantially from those in professional science (diSessa & Sherin, 1998; Hammer, Elby, Scherr, & Redish, 2005). We sought to create a context in which aspects of important ecological concepts were visible and useful to students and to support students in refining these ideas for increasingly powerful disciplinary uses.

In the early part of the year, each student chose one “focus plant,” which they located on a jointly constructed classroom map and frequently observed and represented. They noticed that different plants were in different places, then discussed and proposed conjectures about why. To explore these conjectures, they tested modes of seed travel and conducted an investigation of the relationship between light and moisture. In February we asked students to predict what might happen to the seeds of their focus plants if they landed in different areas of the backyard. We suspected that they would use the distribution of their plants in the fall to reason about where plants would grow in the spring and nominate different places as best sites for their focus plants. Our intent was to provoke the idea that “different plants need different amounts of light.”

Students readily developed explanations in the backyard setting, reasoned about plants’ needs, and thought that the conditions in an area, including light, made a difference for plant growth. But they did not generally relate the presence of plants to light conditions in order to make inferences about how much light their plants needed. The following three explanations are representative of students' forms of thinking:

1. *Alex states that his focus plant, Queen Anne's Lace (QAL) needs sun and shade. When EM points to a QAL plant near the wall and asks why it is growing there, he answers:*

   "I think it stuck there. Because if it had the choice, I know it wouldn't choose here. Like (*gesturing at the wall, looking up*), where do you find sun at, really?"

2. *Malik stands near the school wall in the middle of a patch of wild strawberry plants, where he and his partner observed them in the fall, and says:*

   "Here's the [strawberry plant's] leaf. I see the leaves but I don't see any plants (*touching the leaves*)."

   When asked whether his plant can grow in a place that doesn't have lots of sunlight he answers "No" *and explains:* "Since the sun is not, ummm, getting the plant, that's probably why the plant's not there [in the place he is standing]. It's probably dead."

3. *When Ellen is asked in an interview whether crabgrass and strawberry seeds would grow if they landed near the wall, she says:*

   "The shade, the plants can't grow in the shade. The plants can grow in the sun."

   When she is asked why there are some plants in the shade, she says:

   "The, the school wall ends right here, and that's the door, but it has a roof over it. And that's where the sidewalk is. So it might just grow, the strawberry plants are right there and then we get, we can see a little bit of sunlight crossing."

As illustrated in these three examples, several aspects of students' understanding of the backyard strongly influenced both what they saw and what they sought to explain:

Seeds and seed-travel: Students considered seeds as they thought about how plants might have arrived in the locations where they were growing, but for many students this was considered the only explanation needed. Therefore, in Example 1, Alex saw the presence of his plant, related it to a condition (shade), thought that shade was most likely a bad condition for his plant, and sought to explain how it had ended up in this sub-optimal area. To do so, he called on his understanding of seed travel and the spikes he had observed on his seeds to conclude that it must have "stuck there." For Alex, then, plants were in the places they were because that's where their seeds had landed.

Focus on individual health: When students visited the backyard in February, the primary concern for many was how their plant looked at that moment. Because it was winter, they commented on changes wrought by the seasons, exclaiming that their plant had "disappeared," "died," was "smushed down," or "looked like a bomb hit it." In fact, some of the plants that they thought had died were still present and alive. For example, Malik and Brady's plant (Example 2) was a variant of wild strawberry that had berries throughout the late summer and fall months. The plants over-winter; their vine-like stems and leaves remain green and visible. Malik and Brady, though standing among the plants' leaves and recognizing them ("I see the leaves but I don't see any plants"), were primarily concerned with the absence of the strawberry, which was, for them, the plant's defining feature. An ecological perspective would attribute change to seasonal variation. However, for students, what required explanation was how the plants looked now. Therefore, several concluded that the place that their plant had been growing in the fall must have been the wrong condition, as those were the places where their plants had "died."

Seeing and operationalizing light conditions*:* In interviews with researchers and during their work in the backyard, students associated different parts of the backyard with different amounts of light. They noted that the part of the backyard closest to the school wall was darker and cooler, and consistently referred to it as being in the "shade, " as opposed to the "sun." They readily connected sunlight to plants making food, which the class had discussed while observing plants' leaves earlier in the year. However, as they tried to use backyard conditions to explain where plants grow, challenges became apparent. For many students, "shade" and "sunlight" represented opposite and exclusive conditions, in which shade was considered either the absence of light or a condition providing coolness. Second, notions about how much light different areas received were unstable. Several students noticed that the sun moved through the sky and thought that the pattern of shade shifted throughout the day, but there was no shared understanding of the number of hours of sunlight that different parts of the backyard received. Depending on what students thought was the best condition for plants (usually either "sun" or "some sun and some shade"), they focused on finding mechanisms (nearby trees, the sun moving through the sky) that would produce that set of conditions in the area. As a result, they often did not agree on the conditions in a particular place, making it difficult to develop public agreement about the co-variation of light conditions and plant presence.

In summary, students had developed resources that were important for understanding the relations of plant success to growth conditions in the backyard. They knew about processes of seed dispersal, reasoned in terms of plants' needs, and partitioned the backyard into "conditions" affecting plant growth. However, the way they used these conceptual resources differed in consequential ways from the disciplinary practices and ideas that support explanations of differential success. Developing these explanations would involve "seeing" signs that plants could live in a particular place by noticing the presence of the plants in those places, as well as "seeing" conditions in those places (i.e., more and less light, more and less water), relating presence and condition to test co-variation (e.g., my plant doesn't grow near the wall or under the tree, but it does grow in the middle of the backyard), and then inferring a mechanism, for example, that plants are well-suited to the condition where they are found (I think my plant needs lots of light). In contrast, the students we worked with thought primarily about the status of individual plants rather than the success of populations of plants and did not share an operationalization of light in the backyard. These challenges affected both what they sought to explain and how they developed explanations.

The instructional challenge, then, was to create a learning environment in which ideas about reproductive success, light conditions, and plant needs would be visible and useful to students and where it would be sensible to relate these ideas in ways that approximated disciplinary practices of seeing the co-variation of plant presence and conditions. As Figure 2 shows, we conjectured that an experiment in which students grew plants in three different light conditions would allow students to consider the co-variation of success and conditions. We situated experimental activity within the context of modeling the backyard and created opportunities for students to further represent the experiment in the form of data models (e.g., drawings, measures of plant attributes, and displays that compared attributes). We engaged students in constructing and critiquing each of these transformations (from backyard to experiment, experiment to data model, data model to experimental conclusion, experimental conclusion to explanation of backyard processes). In this way, we hoped to maintain the integrity of the modeling enterprise.

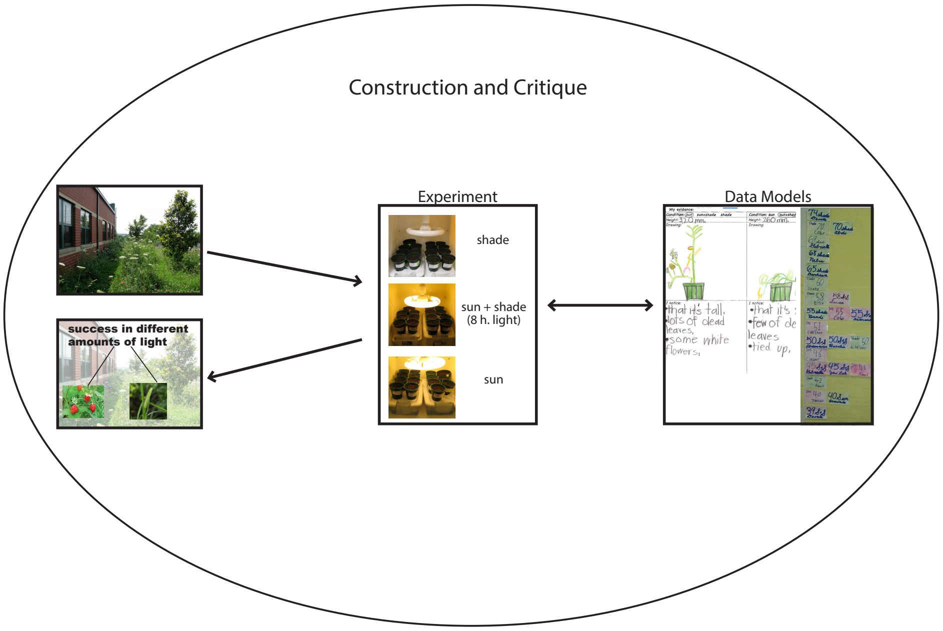

Figure 2. Design conjecture: Engagement in constructing and critiquing the experiment and data models would situate the need for modeling practices and the development of ideas of differential success in the backyard setting

Design of Instruction

This section explains our conjectures about how the experiment would support the development of ideas about plant growth and conditions. I then explain how we systematically included uncertainty in the experiment to situate the need for ideas and practices, and how we supported students to both construct and critique the experiment. I conclude by commenting on the ways that we sought to focus students' activity with tasks, representations, and information.

The Experiment

The experiment was intended as a representation of the backyard that would support the development of the disciplinary ideas described in Table 1. We provided students with Wisconsin Fast Plant™ seeds, lightboxes, pots of soil, and a wicking system that provided a constant moisture source, then asked them to think about how we could investigate whether the amount of light mattered for the growth of this seed and what its "just right" amount of light might be. With support, students decided to plant the seeds in three light conditions: lights on all the time, on for the time they were in school (7 hours) and off all the time.

Wisconsin Fast Plants™ were chosen as the model plant because they complete their life cycle in 42-50 days. Therefore, students could witness the stages in the plant's life cycle, including changes in height, leaves, the production of flowers, and the growth of seedpods. The short life cycle made reproduction visible and allowed us to engage students in comparing health-based (i.e., the color of the plant or its height) and reproductive (i.e., the number of seeds) measures of success. At the end of the investigation, we asked students whether we had learned about the needs of all plants in the backyard, motivating discussion of whether different plants are successful in different amounts of light.

The experiment also provided a venue for simplifying and controlling the complex backyard conditions. The lights in the lightboxes were used to represent the sun and could be turned off or blocked to represent shade. The third condition (7 hours of light) was added because many students thought that "some sun and some shade" was likely to be the best condition for all plants; turning the light on for only part of the day represented this condition. We expected that as students thought about how these conditions did and did not represent the backyard, they might begin to consider light intensity and light duration, complicating their notion of "shade" as "no light." The system's fluorescent lights do not produce much heat and a wick system provides constant moisture, effectively isolating the variable of light as "energy for photosynthesis."

Table 1. Components of the experiment, their backyard analogs, and conjectures about conceptual opportunities.

Experiment Component	Backyard (BY) Analog	Opportunities for developing aspects of disciplinary concepts
Wisconsin Fast Plants™	Plants in BY	• Growth and stages of plant life • Different plants need different amounts of light
Measures of "successful plants"	Measures of "successful plants"	• Shift from emphasis on individual plant characteristics to reproduction and presence of plants
Lightboxes	Sunlight; different "amounts" of sunlight	• How to conceptualize differing amounts of light (light vs. no light, intensity, hours per day) • Light provides energy for growth; amount and source of energy as key consideration
Wick System	Rain/water	• All conditions kept moist while in BY differing light conditions have differing amounts of moisture

Uncertainty

The investigation involved significant uncertainty that we conjectured would provoke a need for modeling practices and the development of shared concepts. This commitment to uncertainty was informed both by disciplinary views of scientific activity and design principles for promoting student agency and sense making (Engle & Conant, 2002; Lehrer et al., 2008). For example, rather than telling students what to use as a measure of success (for instance height or number of seedpods), we hoped that they would attend to different attributes (e.g., height, color, number of leaves, bending) that, over time, are contradictory (the tallest plants bend, the plants that produce seedpods die and turn brown). We expected them to debate measures and develop an understanding of plant death and reproduction. The design bet was that these sources of uncertainty would provide surprising results that would invite explanatory talk, provoke variability in student thinking that made disagreement visible, and establish a reason for students to question and clarify the content of speakers' talk to understand what others were seeing and thinking.

Engagement in Construction and Critique

Throughout the investigation, we positioned students as constructing and critiquing the experiment and supported them in these forms of discourse (Ford, 2008; Gresalfi, Martin, Hand, & Greeno, 2009). They were routinely asked in class (during this investigation and throughout the year) to tell what they were thinking and why they thought so. In addition, they were often asked to restate what other students had said and to respond by telling whether they agreed or disagreed with the speaker and why. We purposefully engaged children in forms of talk that are familiar and sensible to them. For example, we asked them to explain "why they thought so," rather than instructing them to use pre-defined forms such as empirical justification, warrants, or reasoning (Hudicourt-Barnes, 2003; Ochs & Taylor, 1992). By midyear, telling what one thought and why and agreeing or disagreeing with classmates appeared to be routine forms of discourse; students often took these forms of talk up spontaneously in classroom discussion and sometimes in small groups. During the investigation, each student was responsible for two pots of plants (in two of the three experimental conditions). This choice was intended to encourage communication, because no student would have knowledge of all three conditions. In addition, we implemented regular "research meetings" (Lehrer et al., 2008), in which a "presenter" explained which conditions he or she thought were most successful and why. Other students were invited to restate the speaker's ideas, pose questions, make connections to what they were seeing in their plants, and tell whether they agreed or disagreed. We hoped that this recurrent activity structure would position students as authors of ideas and practices (e.g., ways of measuring or judging success), make differences in their thinking visible, and encourage justification and revision.

Tasks and Representations

Engagement in problematic social and material activity does not always generate productive or sustained shared practices, either in professional practice or classroom settings (Berland & Reiser, 2011; Goldstein & Hall, 2007; Hogan & Corey, 2001; Hutchins, 1995). For this reason, we made use of representations, task structures, and information to focus activity (Engle & Conant, 2002; Lehrer, 2009). For example, students filled out a journal page two-three times weekly as they observed their plant; the page focused students on making a claim about which of their plants was most successful and using measures of height, drawing, and written evidence to support their ideas. During research meetings, the speaker's page was projected onto the front board with a document camera, to focus response and critique. In several instances, we made use of a task-structure that might be called "Outrageous Teacher Idea." In this format, the teacher proposed a patently mistaken procedure or idea. For example, she might demonstrate how to measure plants, but measure only the top part of one and from the base of the pot to the top of the other plant in order to provoke the need to agree on a common procedure for measuring. Finally, the classroom was populated with biological information that could be used to make sense of the results that students were seeing in the investigation and the backyard. As questions came up, teachers read books to students, provided them with information, or reminded them about information that they had learned previously.

Summary

Together, these design features span the social, conceptual, and epistemic dimensions of students' modeling activity and are meant to make the three dimensions mutually supportive. The conjecture was that constructing and critiquing an experimental system as a model of the backyard would situate the need for scientific practices as students moved between the backyard, the experiment, and data models, and in turn, support the students in redescribing the backyard in terms of success in different light conditions The investigation lasted from February 21 to May 3, including vacation weeks and weeks focused on other activity as students waited for results to unfold. As a result, there was time for challenges, debates, and student-generated questions to be considered, returned to, and stabilized into shared practices and models.

Method

Context and Participants

The study was conducted in a southeastern urban elementary school (approximately 70% free and reduced lunch). This work was embedded in a larger design study focusing on the development of model-based reasoning and evolutionary thinking in elementary through middle school students (Lehrer & Schauble, 2012). For the study of the wild backyard, we worked with three successive cohorts of third grade students (ages eight and nine) and their classroom teacher (the same teacher each year). In this paper, I report on Year 3, in which 18 (13 male, 5 female) students participated. The teacher had 30 years experience teaching and was participating in her fifth year with the larger research project. The forms of science instruction used here were a significant departure from typical science teaching within the school, where learning from texts or modular science “kits” was normal practice.

The investigation lasted between February 21 and May 3, though we did not work in the classroom for three of those weeks, due to testing and spring break. Sixteen lessons were conducted during this time: they occurred twice weekly, generally in the afternoons, and were between 1-1.5 hours long. In addition, students also observed and recorded information about their plants 1-3 times weekly, usually first thing in the morning.

Data Collection

Data sources included video-recordings, field notes, student work and artifacts, and interviews. During each lesson, a video was made of whole group discussion, usually positioned from the side to catch both the teacher and the students. During individual and small group work periods, one camera followed the teacher, while one to two additional cameras were used to capture the work of groups. Field notes for each lesson consisted of a record of events at the level of rough transcription and conjectures of challenges and student accomplishments. Student work was collected and scanned. Interviews with 6 focus students (selected to represent the range of understanding and engagement in the class) were conducted approximately every 6 weeks to understand how students were thinking about plant distribution in the backyard and how they were understanding the forms of activity pursued in the classroom.

Consistent with methods for design-based research, conjectures about students’ practice and productive means to support development were iteratively developed and refined over the course of the study (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Sandoval, 2004). Three scales of iteration are relevant. First, instruction was guided by our analysis of the previous year.

For example, in that iteration, students had studied the effects of different conditions (e.g., moisture and plant crowding) in small groups. The disparate nature of their inquiry, demands on the development and maintenance of conditions, and differences in measures of success across plant types (e.g., moss, grass, and Fast Plants) formed too challenging a context for students to develop shared experimental practice; therefore, we focused on one shared question for the study reported here. Second, instruction was guided by our on-going analysis of student learning. This analysis, based on the review of field notes, January interviews, and selected video, was conducted by the research team and shared and refined with the classroom teacher. Finally, tasks, representations, and related means of instructional support were refined in weekly research team meetings and meetings with the classroom teacher, based on our experience in the classroom, field notes, and review of student work. As the lead researcher in this classroom, I worked with the teacher and larger research team to design all activity, reviewed evidence of student learning to support ongoing re-design, and was as an active participant, sometimes a co-teacher, during lessons.

Interviews were conducted with all consented students (n=17) two weeks after the investigation ended (Appendix A). These interviews were semi-structured (Ginsburg, 1997): a set list of questions was posed, but interviewers used follow-up prompts as needed to probe ideas and explored ideas particular to individuals. Students were asked to explain why they thought the plants were in different places in the backyard and what made them think so (a question asked in each interview throughout the year). They were then asked to explain what they had learned from the Wisconsin Fast Plants™ experiment and whether it helped them understand the backyard setting. They were also shown an "evidence sheet" (an analog of the pages that they had used to observe the Fast Plants) created by a fictional student studying the effect of water on marigold plants, and were asked to critique the student's conclusion and evidence. The intent of these questions was to understand how forms of practice that we conjectured had developed during communal activity were appropriated and applied in a new context.

Retrospective Analysis

Analysis focused on understanding what aspects of scientific practice students engaged in as they worked with the experiment, how their practice made contact with disciplinary ideas of plant growth, success, and conditions, and how forms of practice and disciplinary understandings developed over the course of students' activity. Methods drew on the notion that practices emerge, are appropriated, and develop across several interconnected time-scales. At the *microgenetic* level (Cole, 1996; Saxe & Esmonde, 2005), individuals generate, adapt, and develop new forms or functions to meet their goals in moments of interaction (see also Hutchins' (1995) conduct of activity and Kelly's (2008) description of interactional events). At the *sociogenetic* level, as microgenetic events build across days, months, years, or longer, forms of practice are appropriated, adapted, and stabilized in communities. As individuals participate over time in these communities, they, in turn, are shaped by communal forms of practice, leading to *ontogenetic* development, or shifts in their habitual ways of thinking and practicing.

Analysis was initially conducted to answer the first research question: how students constructed and critiqued the experiment as a system for knowing. It focused on the microgenetic scale, sampling moments of interaction across the timescale of instruction, and yielded a coding scheme that described student practice. This scheme was then used as the foundation for answering the second and third research questions: understanding how students' practice made ideas visible and useful, and, at the sociogenetic level, how practice and ideas co-developed over time. The timescale of this study precludes strong statements about ontogenetic change, which one would expect to occur over longer time periods. However, to understand how individual students might have appropriated the accomplishments noted in my analysis, I coded and analyzed the final interviews by adapting the scheme originally constructed to describe classroom activity.

The analysis of classroom activity focused on thirteen lessons conducted during students' work on the investigation, between February 21 and May 3. These lessons were selected because students were talking explicitly about the design or interpretation of the experiment, and therefore their conversation provided dense opportunities to track changes in their ideas and practices. During three other lessons in this span of time, students were discussing other topics and/or were primarily carrying out procedures individually (e.g., planting plants); these lessons were reviewed to check on conjectures. An additional lesson (May 12, three lessons after the investigation ended) was also included in close analysis. In this lesson, students were making arguments about the conditions that were best for plants in the backyard. Hence, this lesson was useful for following the ideas and forms of practice developed around the experiment into the backyard setting.

Research Question 1: How did students construct and critique the experiment as a system for knowing something?

As explained in the introduction, I frame science as a modeling enterprise, and scientific practices as ways of constructing and critiquing the transformations that allow an individual or community to "know" something. The plant growth experiment was purposefully designed to allow students to wrestle with these transformations, that is to represent material aspects of the backyard (e.g., light and plant features) as variables, to relate these variables in statements of co-variation that supported claims about plants' needs, and to use the experimental findings to support new understandings of the backyard. At the microgenetic scale, I was interested in how parts of the experiment and backyard at different levels of transformation (e.g., plant features, variables or claims about plant needs) took on meaning as students recruited them to accomplish emerging goals (Saxe, 2002; Wenger, 1998). Therefore, I asked what parts of the experiment and backyard were evident in talk and described the purposes for which they were used. This analysis allowed me to develop a description of what it meant, in this classroom, to construct and critique the experiment as a system for knowing something about the backyard.

To conduct the analysis, I adapted a coding model developed by Kelly and colleagues (Kelly & Chen, 1999; Kelly & Takao, 2002) to represent Latour's (1987) notion of transformations by categorizing the "epistemic levels" of students' statements, that is identifying where statements lie on a continuum from specific, personal, grounded claims to more general, widely-shared, theoretical claims. For example, in Kelly and Takao's application of this approach to the writing of college oceanography students, the "lowest," or most grounded, level referred to students' descriptions of geological data, middle levels included relational aspects of structures, and the "top" levels were statements of theory and references to general geological knowledge. In Kelly and Takao's interpretation, one consistent with the framing of modeling adopted here, proficiency with scientific practice entails moving up and down these levels and making connections among them. While Kelly & Takao's model represented a normative view of geological arguments, I sought to develop a scheme of "epistemic levels" that was particular to students' work with the experiment and backyard, one that described what they found to be relevant to their activity.

To develop this scheme, I undertook the following stages of analysis. First, all video and associated field notes were imported into a searchable video coding database, then reviewed. I located periods of activity where students and teachers[4] were publicly constructing aspects of the experiment (e.g., telling what they thought about how to set up the experiment, which plants were more successful, or how to share data) and responding to, and potentially critiquing, ideas. These generally took place in whole-class discussion, but several periods of small group work were considered as well. Within these periods, I identified instances, the smallest units at which I could describe both what parts of the experiment interaction was focused on and how those parts were used to accomplish participants' goals. These instances were used to develop categories for epistemic levels. The codes were derived from analysis of five days of instruction (February 21, March 8, March 10, April 21, April 28), selected because they involved a high density of activity around the experiment and because they occurred at different phases of the investigation and were therefore likely to yield the greatest diversity of practice. The categories developed to describe these instances were refined as they were applied to moments of construction in all fourteen lessons during the analysis of co-development presented in relation to Question 3.

Category development yielded the epistemic levels scheme represented in Figure 3. The codes (e.g., noticings, definitions, variables) were evident in students' talk both about the experiment and the backyard setting, and could be related across the two contexts. Because I am interested in understanding how students used the experiment as a system for knowing something, including developing explanations of the backyard, I take the scheme as a whole to represent the potential system for knowing, and consider the epistemic levels (bold) and sub-

[4] "Teachers'" refers to the paper's author and the classroom teacher. Since both of us asked students questions and commented on their ideas, I treated both of our comments as framing and elaborating activity in ways consistent with "teaching."

categories (italics) to represent *parts of the system*[5] that students constructed and critiqued. The levels vary from those most grounded in material particulars, that is what individual students noticed (at the bottom of Figure 3), to general, high-induction statements, such as claims about how much light the experimental plants and backyard plants need (the top of Figure 3). As we move up the "epistemic levels," parts of the system are increasingly mobile (here, entailing being seen by different participants), stable, and combinable (Latour, 1987). There are also increasing ways to contest them; as Latour points out, these high-induction statements are ways of black-boxing transformations, but doubters can ask to be shown the transformations that made them. So, for example, students could, and did, challenge an operationalization of plant success (Epistemic Level 4) by arguing that it didn't take account of change over time (Epistemic Level 3), asking how the author defined the attribute (Epistemic Level 2), or arguing that they did not see the attribute in the author's plants (Epistemic Level 1).

Figure 3 highlights the fact that objects at different epistemic levels could be established both in the experiment and the backyard, as well as across the two contexts. Therefore we can describe students' activity as potentially moving both upwards and downwards within this figure, as well as across contexts. For example, implementing the experiment might involve noticing the amount of light in different places in the backyard, operationalizing light as a condition that could affect plant growth, and determining how best to operationalize light in the lightbox by fixing intensity as an attribute that could be measured and varied. Contest might involve moving to "lower" epistemic levels by challenging an interpretation of a data display or a definition. Therefore, as mentioned, development is not simply a matter of traveling "up" the epistemic

[5] This is not to say that students always had access to the whole system; as I show in the results, they developed relationships between parts of the system and understandings of the system as a whole during activity.

levels, but of being able to move fluently across them and across contexts to which they can appropriately be applied.

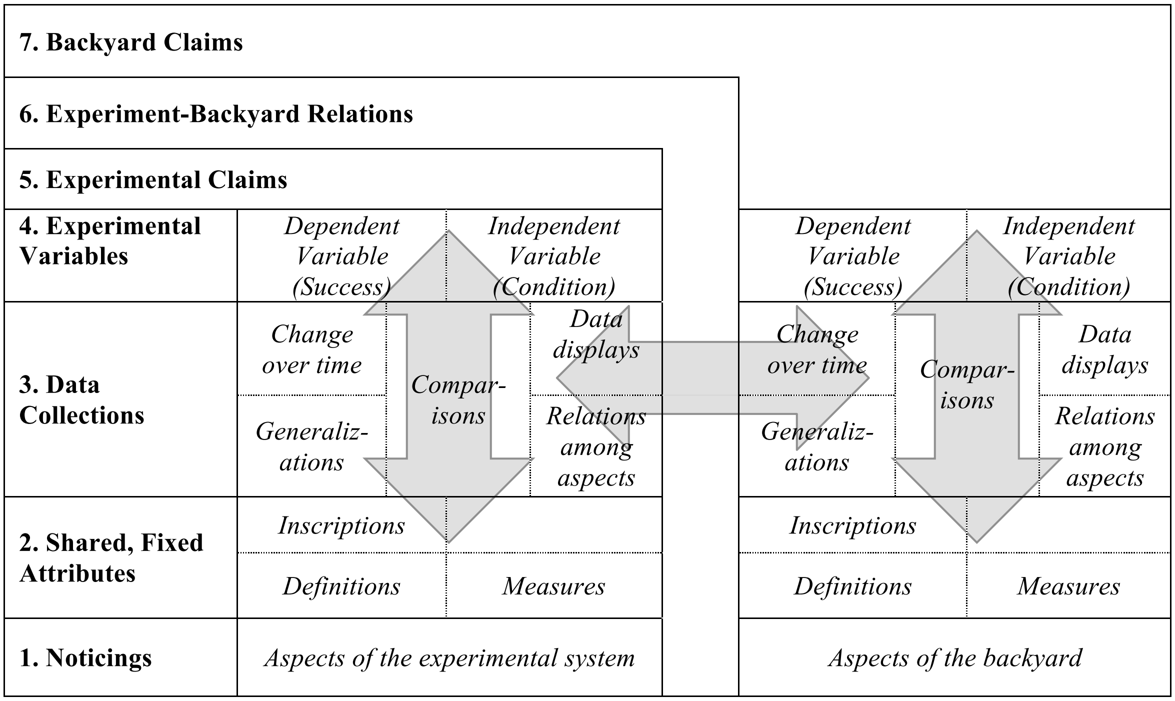

Figure 3. Parts of the experiment and backyard students recruited, constructed, and critiqued, organized by epistemic levels. Activity might involve transforming, or making connections that moved both up and down in this system as well as across contexts.

The scheme included the following epistemic levels (bold) and sub-categories (indicated with italics), which are further described in Table 2:

1. **Noticings:** Students noticed aspects of the backyard or experiment and introduced them into discourse, for example the color of a plant's leaves or the amount of water in the plants' tubs. I conceptualized these noticings as instances of selection (a form of transformation of the kind that Latour (1987) talks about) in that they reduce the many

possible parts of experience that could be relevant, allowing speakers to focus attention on just one.

2. **Shared, fixed attributes:** At a second level, parts of the system became fixed as public and shareable. As I will show in the results, there was no guarantee that "noticings" would be seen in the same way by other students. Therefore, they often needed to be transformed into objects that were "presentable" and "readable" to others (Latour, 1990). Parts of the system at this level include *inscriptions* (e.g., drawings of plants that highlighted particular features, like leaf size), *defined attributes* (e.g. size, death), and *measures*. Each of these highlights some dimensions of a selected aspect of the system so that others can "see" the same thing and fix it as an attribute.
3. **Data Collections:** Students used attributes as data that could be compared and related across multiple cases, conditions, and periods of time. For example, they made *comparisons across plant conditions* by noting that the plants in one condition were taller than those in another. They *generalized across cases* by noting something about many of the plants, for example "The plants in the sun are all dying." They constructed descriptions of *change over time.* They also used *attribute relations*, for example, noting that one plant was shorter but wider, or that the plants with seedpods were also dying. They developed *data displays* that made generalizations and relations visible.
4. **Variables:** At a fourth level, forms of data were operationalized as variables that could be related to each other to support claims about plant needs or success. This level highlights the difference between a student noticing that the leaves on the plants in one condition were darker than the other conditions versus a student making a claim that the plants in the one condition were most successful because their leaves were darkest. In the latter

example, leaves are framed as an *operationalization of plant success*; this nomination, could, in turn, be critiqued by other students. Students also used *operationalizations of conditions*: a student might comment on how best to describe shade in the backyard or in the plant experiment by indicating that some light was coming in through the sides of the boxes, and that, therefore, the lightbox with the light off should not be characterized as a "no light" condition.

5. **Experimental Claims:** Students made statements about how much light was best for the Wisconsin Fast Plants™ or the conditions where they appeared to be growing most successfully.
6. **Experiment-Backyard Relations:** Students noted relations between the experiment and the backyard system, for example by comparing the amount of light the plants in the sun (light on) condition received to the amount of light provided by the sun outdoors.
7. **Backyard Claim:** At the most "general" level considered here, students made a claim about the amount of lights needed by plants in the backyard or the places where backyard plants grew the best.

This coding scheme was applied to moments of interaction to understand how teachers and students talked about parts of the system at different epistemic levels as well as how, and when, they moved between epistemic levels. I sought to understand both how they *constructed* parts of the experiments at the different levels as well as how they *responded* to constructions, positioning other students as the authors of ideas and potentially engaging in *critique*. I then used the coding scheme and my understanding of construction and critique to support analysis for Research Questions 2 and 3, as I describe in the next sections.

Table 2. Epistemic Levels Coding Scheme

Epistemic Level	*Sub-Categories*	Description
7. Backyard Claims		Statement about how much light plants in the backyard need or where they are successful.
6. Experiment-Backyard Relations		Statement that relates elements or results of the experiment to the backyard system.
5. Experimental Claims		Statement about how much light the WFP's need or where they are more successful.
4. Variables	*Operationalization of condition*	Talk that makes use of or focuses on operationalizations of condition.
	Operationalization of Success	Talk that makes use of or focuses on an operationalization of plant success.
3. Data Collections	*Data Displays*	Talk/gesture that makes use of or focuses on a representation of multiple plants, change over time, or relations among aspects.
	Change over Time	Discussion of change over time as related to uncertainty: speakers make predictions, note that they don't know what will happen in the future, or call on issues of change and timing to problematize the current status of objects.
	Generalizations across cases	Talk focuses on multiple plants. Might involve a statement about the investigation plants in general or a student saying that they have seen the same thing with their plants that someone else has mentioned.
	Relations among aspects	Students note relationships between aspects of plants or aspects of places.
	Comparisons across conditions	Students use an attribute to make a comparison about plants or other features of two or more conditions.
2. Shared, Fixed Attributes	*Measures*	Speakers use a measure, discuss how an attribute should be measured, or critique a construction on the basis of measurements.
	Definitions	Speakers define an attribute, ask for an attribute to be clarified, or critique a construction on the basis of how an attribute is defined.
	Inscriptions	Speakers use inscriptions to support their claims or inscriptional choices are the focus of construction and critique.
1. Noticings		Talk introduces or challenges aspects of the system that can be "seen."

Research Question 2: How did experimentation serve as a venue for considering and refining ecological ideas?

Here, I was interested in how students' participation in constructing and critiquing the parts of the experiment explored in Question 1 supported the development of ecological ideas. As explained in the introduction, I was interested in how aspects of disciplinary concepts become visible and useful to students. Therefore, rather than looking only for particular forms of explanation (e.g., different plants do best in different conditions because they have different structures). I followed the small idea units that students recruited across their work with the system (e.g., plant features such as leaves, height, or seeds; processes of plant change such as maturation or death, and qualities of places), asking when they saw these ideas as relevant, and how they used, connected, and elaborated them. I was most interested in following ideas about plant needs, plant change, indications of plant success, and qualities of places, as these were relevant to the challenges students faced in understanding differential success in the backyard system. In the results, I refer to these idea units as "aspects of disciplinary concepts," "ecological ideas," or, simply, "ideas."

I began by selecting several episodes that I noted in my initial transcription and content logging were sites where new ideas were brought into discussion or where ideas were challenged and refined, treating them as hotspots that would be particularly informative. These episodes began with a construction by a student and spanned the talk by teachers and students that responded to and elaborated the construction, as well as talk on that day of instruction that revisited the construction or the response to it. A close transcript of each episode was made that was video time-linked and included gesture, emphasis, referenced artifacts, and the overlap of speech. Analysis described the epistemic levels were evident in students' talk and how students were recruiting, using, and challenging ecological ideas as they participated in talk at those levels. Across episodes, I sought to understand similarities and differences and to describe mechanisms that explained why these episodes situated productive contact between students' activity and aspects of disciplinary concepts. Each of these mechanisms, which are described in the results section, was used as a focus for theoretical sampling of the rest of the data corpus, allowing me to look for other instances where the same mechanism appeared to be at play and to refine my description of it (Glaser & Strauss, 1967).

Research Question 3: How did practice and ecological ideas co-develop?

In this stage, I employed the epistemic levels coding scheme (Figure 3) to understand the development of shared ideas and forms of practice over the timescale of instruction (eleven weeks). I was interested in how forms of activity (i.e., activity at the different epistemic levels I coded) changed or stabilized over time and whether ecological ideas took on new or more stable uses. Sequential, iterative coding of days of instruction was used to develop conjectures about forms of activity that students found sensible or problematic, how ideas about plant needs, plant change, and conditions were being used and refined, and what was developing (Cobb & Whitenack, 1996; Glaser & Strauss, 1967). Each day was divided into activity phases (Jordan & Henderson, 1995; Kelly & Chen, 1999). I determined the boundaries of these phases by looking for shifts in activity and topic that were recognized by participants. For example, a typical activity phase was a student presentation, which began with a student presenting his or her ideas while other students listened, and ended with questions from other students and comments by adults. Another activity phase might be an introduction to a task in whole group discussion, bounded by students dispersing to different parts of the room and collecting materials to start the task.

Within each activity phase, three forms of analysis were pursued. First, the talk structure of the phase was described; this involved characterizing whether students were expected to provide only known-answer questions or were engaged in construction, how teachers were supporting activity, and whether students were responding to each other's ideas. For activity phases where students were engaged in construction, this description was refined by using the epistemic levels codes (Table 2) to describe *what* teachers were inviting students to do and how students were engaging in activity around the epistemic levels. Finally, I described the ways that students were recruiting ideas at the different epistemic levels. I then looked across activity phases to prepare an overview for each day of instruction (Appendix B).

These overviews were used to generate conjectures about how practice and ecological ideas were co-developing. Each conjecture guided a closer analysis of development, which took the form of theoretical sampling, close analysis of representative episodes, cataloguing the frequency of practices or uses of ideas at different time points, and developing memos to trace change. For example, I noted during sequential analysis that, at the beginning of their work, students used an undifferentiated notion of "growing" to operationalize plant success, while later they used the more specific criterion of reproduction. This conjecture guided a review of all statements about which set of plants was more successful to refine a description of change in the group's criteria for plant success.

Interview Analysis

Finally, analysis of the final interviews conducted with all students in the classroom was used as an additional source of information about the ideas and practices that developed over the course of students' work with the experiment. Coding schemes were developed for each question to adapt the epistemic levels codes to students' answers. Six students' interviews (35%) were independently coded by the author and two additional coders; interrater reliability (with the author) was 92% across all questions and varied from 80% to 100% agreement for individual codes, with the exception of codes for students' understanding of the status of the experiment as a model of the backyard (67%). Disagreements were resolved by consensus; I then coded the remaining 11 interviews independently, checking codes with a second rater, particularly those regarding model status, when I identified ambiguity.

Results

In this section, I briefly address the first two research questions in order to provide an overview of students' practice and to illustrate the ways that this practice supported the development of ecological understanding. I then address the co-development of practice and knowledge by describing these forms of practice and their relation to ecological concepts over the course of students' work with the experiment and when they returned to the backyard to understand the places where plants grew best. I conclude by describing interview results, discussing how individuals appeared to take up the practices and ideas developed in classroom activity.

Overview

Students' engagement in construction and critique involved actively framing what they were noticing as having significance at particular epistemic levels and shifting the conversation to other levels to explore and contest ideas. These forms of practice both depended on and supported the refinement of ecological ideas. An illustration is a spontaneous argument from

April 5, during the period when students were debating in which condition the plants were more successful. The episode illustrates the multiple ways in which navigating and tying together epistemic levels became relevant to talking about and understanding the experiment. Figure 4 is a map of the conversation: statements are represented by boxes that show both the focus of construction or critique (a darker shade) and any other parts of the system recruited to support ideas. Inside the boxes, I note the ideas that were used. For example, Statement 1 shows that Dante noticed death, height (a plant feature), and lack of water (a quality of place related to plant needs), and used these ideas as an operationalization of success to support a claim that the plants in the sun & shade conditions were most successful. In this episode, Dante's talk is represented with a wavy border: he was positioned as the author, or constructor, of ideas to which teachers and students responded, providing him opportunities to clarify or revise his thinking.

Mrs. W. (the classroom teacher) asked students to share some of their thoughts about which plants were more successful. Dante volunteered that he thought that the sun & shade plants were more successful.[6]

1. Dante: I noticed that most of all the ones in the sun are either getting burned by the... kind of too much heat and they're dying… and- or either they're... just the water's almost gone and the-uh wisk *(note: he is referring to the wick that absorbs water from the tub below)* can't get the water and they're just dying.
2. Azhad: Huh (*turning and looking at Dante*)?
3. EM: Oh, and I- if the water's almost gone I'd better make sure to add in more water [then- because we'd-] we'd agreed that they were all going to get the same amount of water all the time.
4. Mrs. W: [I didn't check 'em yesterday]
5. Mrs. W.: Right.
6. Dante: And they're- [and]
7. Mrs. W.: [But] we did address that on Friday. You remember, Ms. W. added more water Friday?

[6] Transcription conventions: All student names are pseudonyms. Overlap of talk is indicated with [ ], self interruption is indicated with - , emphasis with CAPS, pauses with … for durations of less than 1 second and with (x secs) for longer pauses. Other punctuation is added to increase readability.

8. Dante: And that- all those plants are getting too tall and ea- they're taking up too much nutrients and then they're not (*undecipherable*) and the water's running out. And then the sun plus shade they're all... they're not really big like the suns and the- most of the water's all of it's still there.
9. EM: Interesting. So the water's getting used up faster in the sun than in the sun and shade? That's very interesting. I wonder why that is.

For the purpose of illustrating Dante's argument in Figure 4, I have collapsed Lines 1 and 8 into one "statement." Dante used and related several aspects of the system to support his claim that the sun plants were less successful. In his view, plants that are tall end up being less successful because they use up their nutrients and water and die; this is an idea that he initially expressed several weeks previous to this conversation. He explicitly compared the two sets of plants (sun vs. sun & shade conditions) using these criteria. In contrast, EM and Mrs. W. considered water as a variable to be controlled; they talked about filling up the water, and EM reminded students that they had "agreed" to keep the water the same (Lines 3-7; Statement 2 represents both teachers' ideas as framing water as a condition to be controlled). As Dante restated his idea, EM began to talk about the water level in a different way, as an interesting difference between the two boxes that might be explained. Note how she revoiced Dante's talk. She used his language, "running out" and "taking up," to compare the two conditions, but did not use this comparison to judge which condition was more successful (Line 9; Figure 4, Statement 3).

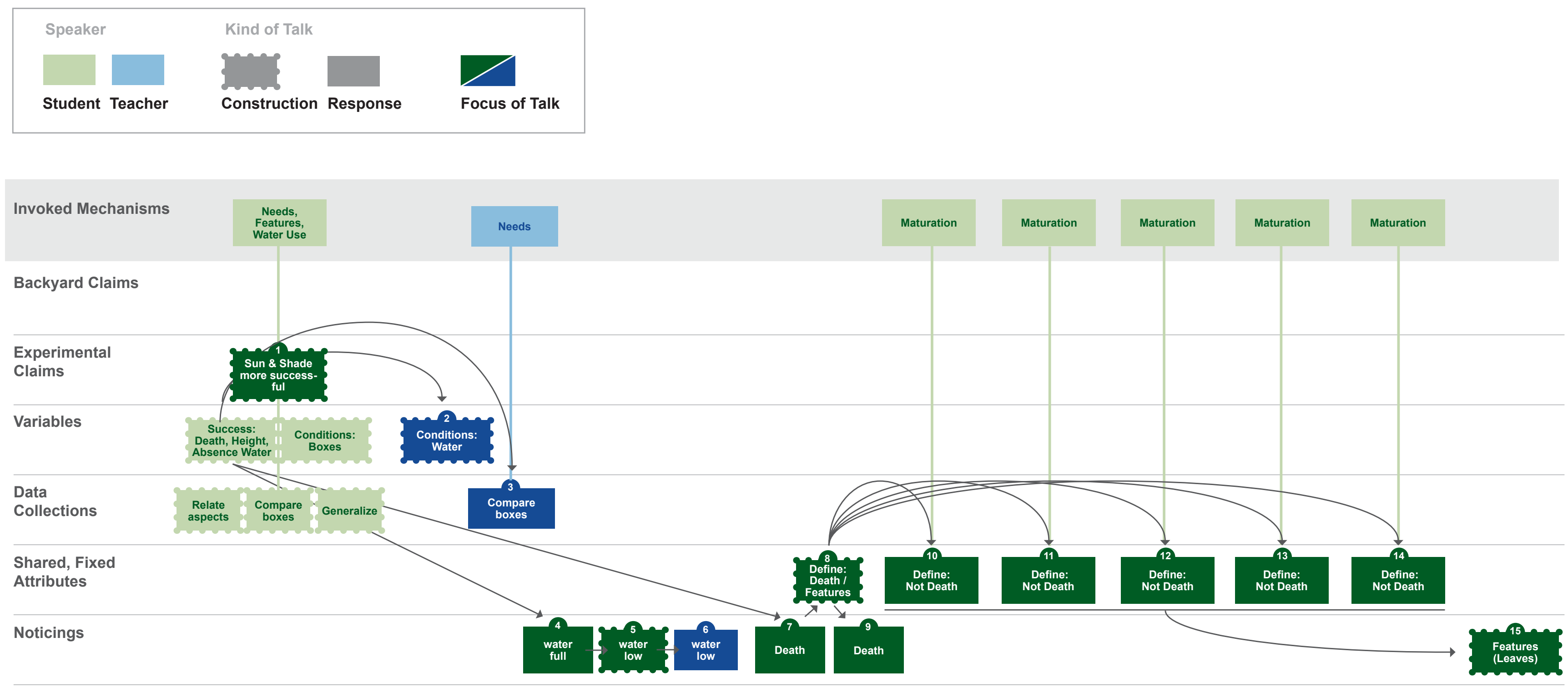

Figure 4. Map of the epistemic levels and concepts employed during the argument about Dante's claim.

Green signifies student talk, while blue represents teacher talk. Here, Dante was positioned by the class as the author, or constructor of ideas; his statements are represented with wavy edges. Each statement is represented by a set of boxes connected with a vertical line. Boxes represent the different parts of the system mentioned in each statement; a darker box signifies that a part was the focus of construction or critique. "Invoked mechanisms" are included to show the forms of explanation that supported activity. Arrows connect the parts of the system under discussion in order to highlight how epistemic levels shifted.

Azhad then began to argue against Dante, saying, “I disagree with Dante because all of the things he said it was the OPPosite.” First, he disagreed that the water was being used up, saying that the tub was still full. EM then walked over to the box to show that its water level was, in fact, lower (Figure 4, S4-S6). At this point, Dante took the floor again, asking “Now do you get what I mean, Azhad?” In turn, Azhad challenged another aspect of the system that Dante had used to operationalize success, that the plants in the sun condition were dying. He shifted the conversation to whether this was the case (S7-S14):

10. Azhad: No, because I don't see no one dying.
11. Dante: You don't see those leaves that are getting dried up? I know that some [plants]
12. Brady: [How] do you know it's dead though?
13. Britney: (*undecipherable*) drying up[7]
14. Dante: [I know it’s]
15. Alex: [Those are] OLD [leaves.]
16. Jasmine: [Those are] the seed leaves, [that's why they're dying.]
17. Chad: [No they're not.] (*walks over to the lightbox to check*)
18. Azhad: Those are the [leaves that grew first.]
19. Alex: [Those are the seed leaves.]
20. Madison: [Those are the old leaves.] They're trying to grow new ones.

Both Azhad and Brady contested the notion that Dante could “see” death. Azhad argued that he didn’t see it, while Brady positioned death as something that Dante needed to justify, saying, “How do you know it’s dead though?” In response, Dante defined dying by bringing in a new aspect of the system, “leaves that are getting dried up” (S8). In turn, students contested this definition. They argued that the leaves drying up were the “old leaves,” or seed leaves that they had learned come first and provide the initial food to the plant, and that their drying up might not have anything to do with death. After Mrs. W. reviewed students’ characterization of the leaves as seed leaves (not noted on the map because her talk did not shift

[7] Because it is unclear what this line and transcript line 18 refer to, they are not located on the map.

the level of conversation or introduce a new object), Dante (S15) went back to the plant boxes and said, "No, I see some spiky leaves that are brown." In doing so, he added information that could form the basis of a refined definition, though the conversation ended here.

This excerpt illustrates three ways in which students related and shifted between epistemic levels as they developed the experiment, conducted it, and applied its entailments to the backyard. The first is that making claims about which plants were more successful involved work at multiple epistemic levels: Dante noticed aspects of the system, related them to each other, and used them as evidence of success that could be compared across conditions. Second, making sense of the experiment involved figuring out how parts of the system were relevant. Once something was seen and made visible to others, it could still be positioned in different roles in relation to epistemic activity (i.e., as a condition, as an interesting difference, as evidence of success); participants could disagree (implicitly or explicitly) about the appropriate role. Third, as students disagreed with each other, they often shifted the focus of the conversation to a different epistemic level. In doing so, students *problematized* each other's ideas and required authors to elaborate or justify their ideas at other levels of the system (e.g., establishing a definition). In this case, Azhad's critique shifted talk by contesting death as an aspect of the system that could be "seen" and provided an opportunity to define what counted as death. Throughout my analysis, I found it useful to attend particularly to instances where students problematized ideas; these moments indicated that they spontaneously saw ideas or practices as interesting and/or uncertain.

During these forms of activity students were engaged with important functions of scientific practices; they were not only using parts of the experiment but also wrestling with making them relevant to their shared inquiry. This activity presented opportunities to recruit and refine ecological ideas. In particular, three forms of opportunity were pervasive in the data corpus. First, students *related* aspects of disciplinary concepts: they brought different aspects of the system into contact with each other in order to illustrate and defend their ideas. Second, as students were asked to define or show in inscriptions what they meant by terms like "big," "dying," "light," or "growing," they *differentiated* aspects of the system. Finally, students often posited or called on *mechanisms and predictable processes* as they sought to figure out whether, and how, what they were noticing mattered for their investigation.

Consider Dante's idea that the sun plants were less successful because they were dying. Dante's claim (Figure 4, S1) *related* death, height, and water using a *mechanism*: the idea that big plants use up their resources more quickly, prompting their death (noted as an "Invoked Mechanism" in Figure 4). This form of talk was prevalent: the experiment generated results that students sought to explain, and their explanations often related ideas of plants' needs to judgments of plant success. In this episode, responses shifted conversation to other epistemic levels, situating further conceptual work. As Dante was challenged by his classmates to show that the plant was dying, and conversation shifted to definition, he brought in new aspects of the system (the plants' leaves), *relating* them to death. When his classmates, in turn, contested the notion that brown leaves indicated death, they did so by proposing an alternative *mechanism,* in this case a *process* of maturation (S10-S14), to account for leaf change, arguing "those are the old leaves that are trying to dry up so they can grow new ones." As students contested the definition of death, leaves were *differentiated* into seed leaves (or "old leaves") and true leaves ("spiky leaves"). Here, definition was a highly conceptual process that pitted plant maturation against death. Recall that seeing and using ideas of maturation and plant life cycles was one of the challenges we noted in the backyard setting. Students' work in experimentation provided opportunities for them to make progress in their use of the ideas like these.

Moving between and connecting epistemic levels, as I illustrated in this excerpt from April 5, fundamentally involves questions about what counts as the basis of a claim or its warrants. In the excerpt above, students tried to understand what counted as success (or lack of success), as death, and as maturation. They recruited ideas about the needs of plants and processes of growth to support their work, which involved seeing the same thing, calling it by the same name, and using it for the same purpose, processes that are both consequential and highly conceptual in professional scientific activity (Gooding, 1990). Developing the system outlined by the epistemic levels scheme (Figure 3) involved a multitude of questions of what counted within the backyard, within the experiment, and as relations between the two contexts. In the next section, I explore how these questions became relevant to students and how they situated changes in ecological practice and understandings.

The Co-Development of Practice and Ecological Ideas

This section traces and relates the development of students' practice and the aspects of disciplinary concepts that were visible and useful to them. Students began the experiment with important resources for constructing and critiquing parts of the system at different epistemic levels. However, at the beginning of this work, teachers held much of the responsibility for framing students' activity as connected to an enterprise of understanding plant needs in the experimental and backyard systems. Over time, students' practice changed in consequential ways as they recruited new ideas, contested and stabilized uses for those ideas, and refined their understanding of what exactly their shared enterprise was. To illustrate these findings, I describe students' activity during three phases of the investigation: as they developed it, sought to understand its results, and applied them to the backyard system. In addition, I briefly describe how forms of activity developed within the investigation were used as students sought to make claims about the best conditions for different kinds of backyard plants.

Developing the experiment. During this phase, students were asked to consider how to represent light in the experiment and how the experiment would help them identify the best amount of light for the Fast Plants.[8] Activity was primarily involved with establishing the basic enterprise of using an experiment to understand how much light needed plants needed; this enterprise was not immediately transparent to students.

A first focus of discussion was what the experimental system exemplified, that is, the effects of light on plant growth, and how it should be designed to carry out this function. At the end of a discussion about how light mattered for whether the seeds of students' focus plants would grow in different places, Mrs. W introduced the Wisconsin Fast Plant™ seed, telling students that they would "do an investigation to see if it matters for this seed where it lands, if it lands in a place with…more or less light." As she introduced the materials, she noted that other aspects of the system were tools that would allow the class to think about light. For example, as she showed the students the "wicking system," a felt pad that sat underneath the plants with an end dipped in a tub of water below, she said,

> "Now, um, so and this is called- that's the wicking system so the soil's ALWAYS going to be damp. We don't have to worry about the amount of water because that's going to take care of that."

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[8] From an analytic point of view, the phase had several shortcomings for addressing the research questions. First, the design conjectures were not fully realized, partly due to faulty materials and time constraints. Second, several of the conversations about how to set up the experiment took place outside of the usual purvue of our research and our records of these conversations are in the form of field notes written after activity took place (rather than video or roughly transcribed talk during activity). My analysis, therefore, is brief.

Here, Mrs. W. structured the investigation as a matter of finding out about the effect of light on a plant (Experimental Claim) and framed "more" vs. "less" light as the condition of interest (Operationalization of Condition), with other conditions, e.g. water, as "take[n] care of" so that the students wouldn't have to "worry about" them. This form of talk, focusing on how the experiment would represent the effect of light conditions and treating other conditions, or aspects of light such as heat, as variables to be controlled, was typical during the introduction of the experiment.

As students worked in pairs to decide how they might use the materials (seeds, pots, soil, wick system, lightbox) to find out how much light was best for the fast plants, they readily generated several ways of varying light. These included using a lightbox with the light on vs. one with the light off, blocking the light in one lightbox, and varying the distance of the light from the plants. With support, they settled on comparing a lightbox with the light off, (to represent the shady areas of the backyard) one with the light on (to represent a "sunny" condition), and one with the light on part of the day (some sun and some shade). They agreed that they should block the back of the lightbox representing the shade condition, because the school wall casting the shade was opaque, but could allow some light to enter in the sides of the box, as there was nothing blocking light on the sides of the backyard. Here, students' operationalization of conditions was supported by their ideas of how best to copy the backyard, rather than an attempt to implement systematic variation in light's intensity or duration. Their ideas were not challenged by teachers or other students: there was little talk about how to define, measure, or relate aspects of light.

A second focus was to help students think about the investigation as an activity that would allow them to find out how much light the plants needed (i.e., to connect the idea of making a claim about needs to the studying the co-variation of success and light conditions). Conversation on two days involved asking students to predict what would happen in the boxes given different potential needs of the Wisconsin Fast Plant™. Students found it difficult to take a hypothetical stance about an amount of light needed by the plant (for example, what if this was a plant that needs lots of light, or a plant for which amount of light does not matter) and think about what they would see in that case. Rather, they each had an idea about how much light the plant needed, which they translated into, and had difficulty separating from, a prediction about where the plant would and would not grow. This conversation culminated in students telling how much light they thought the plant needed and what they thought would happen, then disagreeing about their predictions. EM, who was leading discussion, pointed out this disagreement as something that could be resolved with empirical evidence:

> "So one thing I would like to see if you guys agree with is this. By looking at the boxes and seeing where it grows best, will that give us evidence about whose hypothesis is right?"

Students appeared to agree with this comment. Steven built on it:

> "Yes, because, if we picked the right one it… uh like my dad always says like umm like if you say yours your uh prediction is smarter than somebody else's OK and like a few days later your all-your results come back and umm you see the test and yours is just the A and the other persons is the Bs and that tells who's better than."

Here, conversation linked the experimental claim with an operationalization of success ("grows best") in relation to conditions ("the boxes"). Neither success nor conditions was actively constructed by students or connected to other levels of activity in this talk.

At this entry point into the investigation, students were primarily being inducted into the basic form of the experiment. Teachers moved fluidly among epistemic levels in their talk; they made connections to the backyard system, referenced light as a variable that could be controlled and related to other variables, framed what happened in the lightboxes as useful for making a claim about how much light the plants needed, and began to reference forms of activity what would allow students to understand what was happening, for example, drawing and taking measures. Students readily participated in noting similarities between the setup of the experiment and the backyard, making predictions about what would happen in the experimental conditions, and thinking about how plants' needs might affect growth. However, they were clearly novices in how they related these forms of activity to the shape of the enterprise as a whole, that is, understanding that the experiment exemplified particular aspects of the backyard (hiding others, such as moisture) in order to provide results that would help them understand plants' needs.

Understanding the results of the experiment. This was the most protracted phase of the students' work with the system, and one in which students repeatedly made and defended claims about which of the plants were most successful. For this reason, my analysis is divided into describing students' early work with the system (March 8 – March 22) and their later work (March 24- April 27). Across this entire period of activity, students volunteered and contested ideas about what the plants looked like, why they looked as they did, and how they were changing. In doing so, they developed definitions, uses of measures, and accounts of plant maturation. Early on, the teacher was largely responsible for tethering these forms of activity to the enterprise of understanding how much light the plants needed; increasingly, students appeared to frame their activity as related to the work of understanding plant needs.

Early work. Students began observing their two pots of plants and determining which they thought were more successful. Mrs. W. routinely asked students to tell what they "noticed" about the Fast Plant systems, encouraging them to select aspects of the system that were interesting and potentially important. She often pushed on these noticings by asking students to conjecture about a cause or by asking whether this was true of both their conditions and whether others had seen the same thing, evoking comparison and generalization. As students reported what they noticed, she often asked, “What do you mean by…” or “How do you know?” These moves shifted student talk to sharing definitions and measures or explaining inscriptions. During each class period, students were asked “Which plants do you think are more successful?” and then were prompted to tell why if they did not do so spontaneously. The light conditions themselves were taken as stable and as something to be used and referred to in activity, rather than constructed.

Students took up the forms of activity initiated by Mrs. W., telling what they noticed, constructing claims about which plants were more successful, volunteering ways to operationalize success (e.g., plant height, color), and making what they saw visible with definitions, inscriptions, and measures. They also readily asked each other questions and disagreed with each other. They sought primarily to understand what they were seeing, to explain surprising results, and to deal with the plants as changing entities. Therefore, their questions and responses to each other generally moved back and forth between noticings, definitions, inscriptions, descriptions of change over time, and explanations. These findings are illustrated in the episodes that follow.

First, students often responded to other students’ noticings by problematizing them. For example, on March 10, during the first student presentation, Ellen said, “I noticed the bump that was coming up. The condition was sunny (gesturing to her journal page, shown in Figure 5).” Azhad then asked, “Is that bump, is it part of the leaf or part of the stem?” In doing so, he shifted conversation to defining an attribute, trying to understand what the bump was. Students offered several ideas: various students defined the bump as a leaf, a flower, or another part of the plant that was about to sprout out. Several definitions were predicated on the notion that the bump would become another feature. Talk shifted, therefore, to developing and justifying predictions. Mrs. W. highlighted the uncertainty of this enterprise by stating, “Do we have evidence yet about what that’s going to be?” This episode, and others like it, suggested that students found identification of features and change over time to be problematic and worthy of discussion from an early period in the investigation.

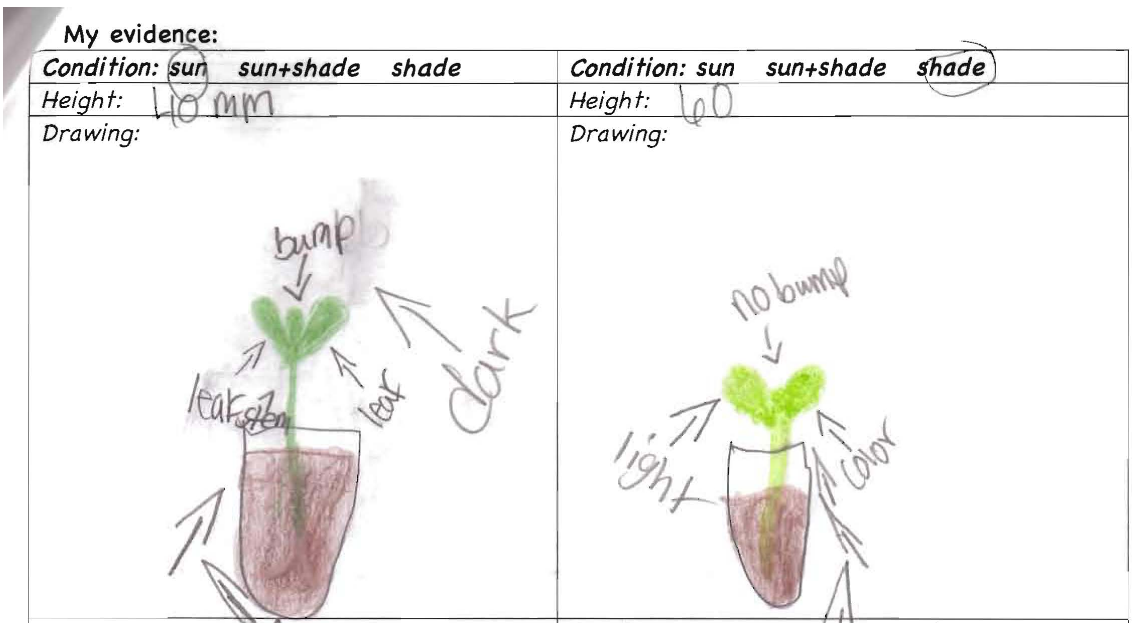


Figure 5. Ellen’s noticing and inscribing of the bump.

Students also readily sought to explain surprising results. For example, Ellen noticed a difference in color between the plants in her two conditions (represented in her inscription above). Alex generalized this noticing to his plants, then volunteered a mechanism to account for it:

> “Mine is the sun. I have the sun and the sun plus shade. The sun one is dark, well, it's dark green and the sun plus shade is light green. I was thinking that when it’s dark green it needs shade and when it’s light green it needs sun. Cause I know the sunflower plants they’re yellow and they take in a lot of sun.”

Other features that students sought to explain included the whiteness of the stems in the shade condition, the presence of "soft" (open) flowers on some plants in the sun condition and "hard" flowers or leaves (buds) on other sun plants, and the fact that the shade plants had initially been taller but were suddenly shorter than those in the other conditions.

In this early phase, teachers were largely responsible for tethering students' noticings, disagreements, and explanations back to the enterprise of understanding which conditions were best for the Fast Plants, often by framing their ideas as relevant to deciding how to operationalize success. Britney's presentation on the second day of student presentations (March 22) is an illustration of this finding. Britney had indicated in her journal page that the plants in the sun were more successful than those in the sun & shade and noted that those in the sun had flowers. Figure 6 represents Britney's presentation. As Britney projected her journal page (Figure 7) shared that she noticed flowers in the sun condition, Mrs. W. asked her to compare this attribute across the two conditions and animated Britney's idea that flowers were evidence of the sun condition's relative success (Statements 2-4). She then invited students to ask Britney questions. In the ensuing conversation, students responded, asking questions and disagreeing:

- Jewel: "Did you notice about the leaves?" (Statement 5)
- Ellen: "Do you think your sunny plant is going to stay more successful?" (S8)
- Brady: "Before the flowers bloomed, did they have a bump?" (S12)
- Azhad: "When you said it's about to bloom, when I look at your picture it already bloomed." (S14)
- Charles: "Do you think the white, the flower is going to change to a different color?" (S16)

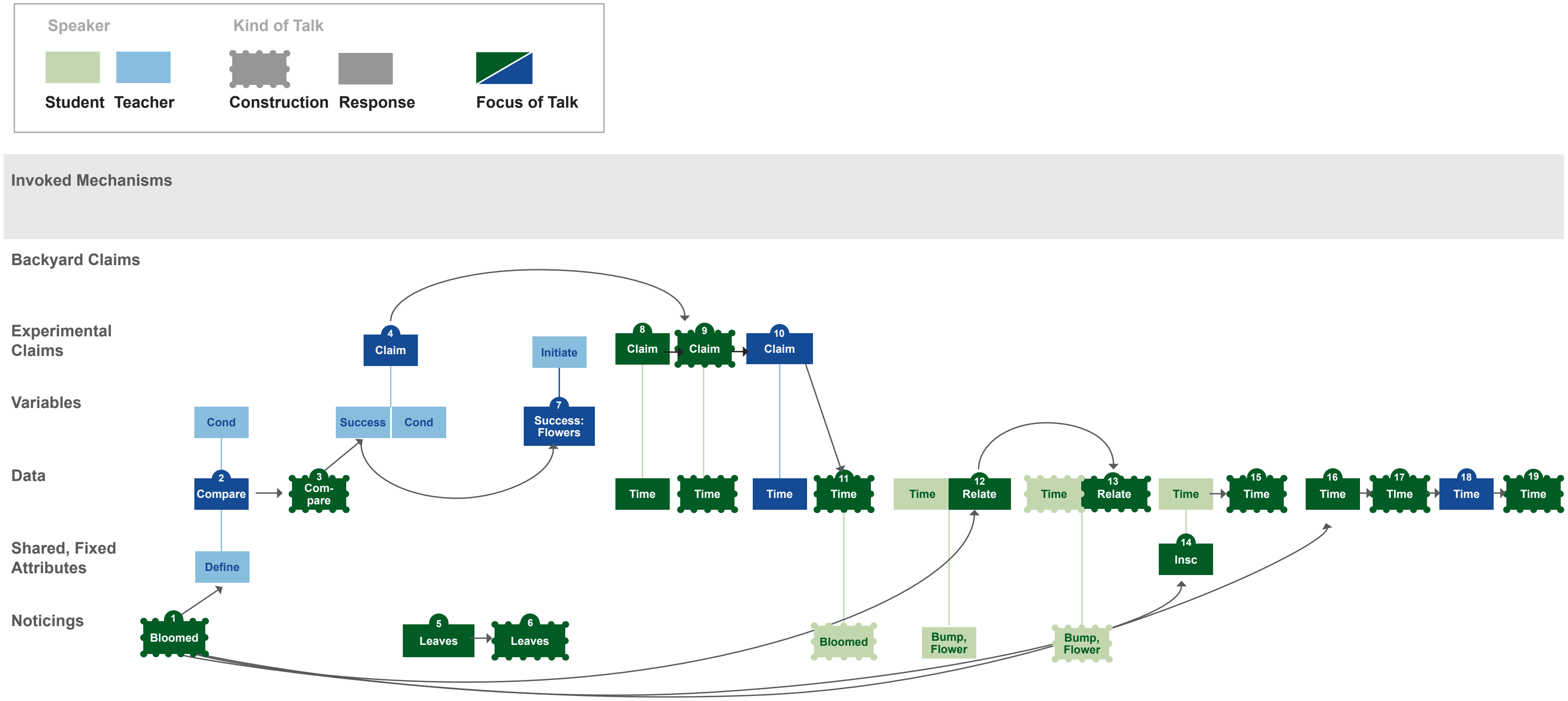


Figure 6. Discussion of Britney's journal entry.

Green signifies student talk, while blue represents teacher talk. Here, Britney was positioned by the class as the author, or constructor of ideas; her statements are represented with wavy edges. Each statement is represented by a set of boxes connected with a vertical line. Boxes represent the different parts of the system mentioned in each statement; a darker box signifies that a part was the focus of construction, response, or critique. Arrows connect the parts of the system under discussion in order to highlight how epistemic levels shifted.

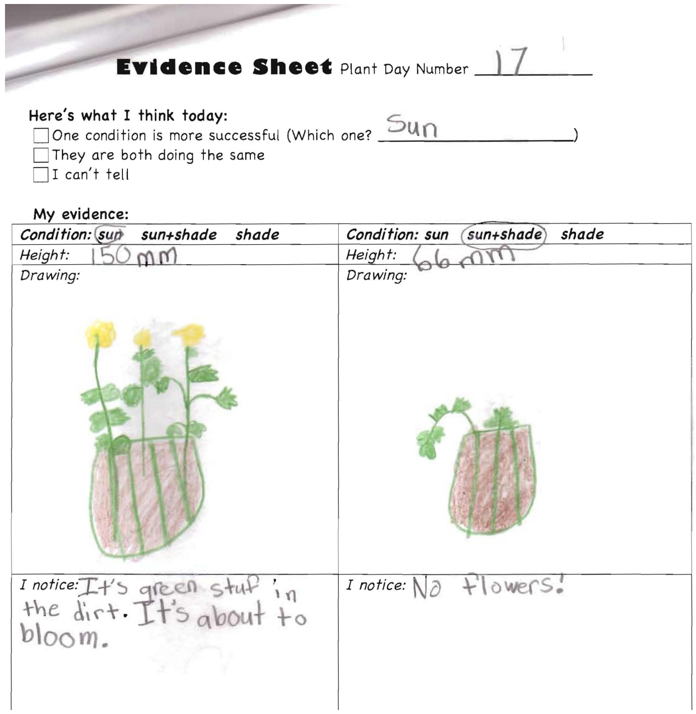


Figure 7. Britney's plant journal page, projected during her presentation.

In general, these questions focused on parts of the plants that Britney noticed (e.g., flowers and leaves) and requested information, particularly about how those parts were changing over time. Brady and Charles sought to understand the flower as a changing entity and Brady linked it back to the bumps that Ellen had noticed. Azhad challenged whether Britney's writing was consistent with her inscription, though it is unclear that he was trying to understand what she meant or that he linked her journal choices to a claim about plant success. Just one of these questions, Ellen's (S8), was explicitly linked to the question of which plants were more successful.

In contrast, Mrs. W. and EM encouraged students to think about Britney's claim that the sun plants were more successful and her use of flowers as evidence of success. In S7, Mrs. W. explicitly directed students to ask questions about the flowers, saying "Anybody else have questions for her about the flowers and no flowers? And why she thinks that is evidence for what she believes?" While students took up the subject she proposed in the next several lines, they did not focus on flowers as evidence of success. At the end of the episode (not represented in the diagram), EM asked students, "Can we really quickly restate her what her argument, or what she's thinking is and what her evidence was?" Steven initiated the excerpt that follows.

1.	Steven:	"I-you, you said that the sun is success. Cause on the top (*pointing at Britney's inscription, which is projected on the board*) you said-I can see on the top you said which one do you think is more successful and I can see that you drew sun and I can see on the picture that uh it's taller AND it's colorful."
2.	EM:	What was her main kind [of evidence] that the sun was more successful? What was the main kind of evidence she was talking about that told her the sun was more successful.
3.	Mrs. W.:	[Right.]
4.	Britney:	Charles?
5.	Charles:	Because it bloomed and had flowers.
6.	EM:	Was that right, Britney?

This part of the episode shows teachers trying to position students as choosing evidence of plant success. When Steven referred to Britney's evidence by pointing out features of her inscription, but did not use the kind of evidence that she focused on (e.g., the flowers), teachers did not accept his answer. Instead, they repeated the question and called on another student to volunteer. At this point, EM turned to Britney to ratify Charles's identification of flowers as her evidence. This is an example of what Stevens and Hall (1998) describe as experts "disciplining the perception" of newcomers, that is making it possible for them to see both what experts see and how they see it. Teachers cast evidence as something that Britney was constructing and other students' roles as understanding *her* evidence.

As students tried to describe what they were seeing and to make sense of how and why the plants were changing, they created opportunities to develop ideas. In their initial talk, students generally used undifferentiated notions of "growing" to describe plants and suggest what might make a plant successful (March 8 and March 10). As they began to inscribe the plants and respond to questions like “what do you mean by,” they increasingly used specific features (color, bending, height, width, buds, flowers, heart-shaped leaves, spiky leaves) to describe the plants. Processes of plant change quickly became central to students’ work as they asked others for predictions and reasoned about parts changing over time. These forms of activity provided a venue in which students related plant parts to each other, framing them as stages of the same plant, as was evident in talk about the “bump” during Ellen’s and Britney’s presentations. Therefore, students began to develop increasingly sophisticated visions of plant maturation, supporting development in relation to one of the ideas that was initially problematic in the backyard setting.

In addition, when students critiqued and questioned others’ ideas, they often initiated explanatory episodes. In many of these conversations, they needed to figure out how to consider results: as the outcome of different conditions, and therefore evidence of success, as the result of normal processes of plant change, or as some combination of the two mechanisms. For example, a question about why the shade plants had initially been taller and now were the shortest of the conditions (March 22) inspired a set of conjectures that included the idea that a) plants that grow better at first use up their resources, b) the plants needed sun because it helped them make food, and c) the result was not surprising, because plants can catch up with each other. Subsequently, teachers read a book that reminded students that seeds have food that supports initial plant growth, which prompted students to reason that the shade plants had initially grown because of food from the seed, but then were not able to make their own food after they depleted those resources.

During this part of their work, students varied in what they saw, how they explained it, and what they thought of as evidence of success. They were willing to ask each other questions and to directly critique each other's ideas, and appeared to actively try to understand what they were seeing in the experiment. In doing so, they differentiated their initial descriptions of plants (i.e., big, growing) into specific features that could be seen, inscribed, and related to each other. They raised ideas about the plants as changing entities and began to relate features to each other as part of a process of plant change (e.g., bumps, buds, flowers, and kinds of leaves). They readily made and supported claims about which of their plants were more successful when prompted to do so by the teacher and their investigation journals. However it was not clear how they regarded the relation between their noticings, their critiques, and their pursuit of an understanding of plant needs.

Later work. During this second part of their work with the experiment, students continued to share ideas about which plants they thought were most successful, developed data displays that showed the heights of the plants in different conditions, and compared seed production across conditions. In contrast to their early work, they problematized ideas about what makes a plant successful and explicitly operationalized the variables they used to indicate success. Their talk appeared to move more fluidly, and with less direct support from teachers, across the epistemic levels coded.

For example, consider the discussion on April 21 (Figure 8). Brady claimed that the sun & shade plants are most successful.[9] He pointed to his journal page (Figure 9) and said, "Before, on day 6 my shade was taller. And now my sun plus shade is 210 and now my shade is 0." He

[9] The available record from this day of instruction was on-line field notes recorded by a researcher who was observing (rather than participating in) activity. Therefore, transcription conventions are not used.

then added, “Flowers are growing and we have some seedpods sticking out and buds where flowers will grow.” Brady’s description of how he knew that his sun & shade plants were more successful (Figure 8, S1) incorporated many features (height, flowers, seedpods, buds) that he compared across conditions and related to each other across time (“buds where flowers will grow”).

The first student to respond, Dante (S2), asked, “Why do you think the sun and shade are best?” a response I interpret as a problematization, in that he questioned whether Brady had provided evidence that the plants in the sun & shade condition were doing better than all other conditions, for the sun condition was not represented in the two pots that Brady’s journal page showed (Figure 9). Brady appeared to interpret the question in this way; he answered (S3), “Because the sun, before the sun started to die, I thought the sun was better and now it’s sun plus shade.”

This second statement was the focus of the remaining responses. First, Dante questioned the timing of plant growth in the three conditions (S4-S5). Several students then questioned how Brady defined death and whether death was relevant to the question of which plants were more successful.

1.	Azhad:	I see mine (*referring to his sun plant)*; it’s not dead. Just a few leaves are dead and it’s tall.
2.	Brady:	If they keep dying, sun plus shade will be better.
3.	Azhad:	Oh
4.	Brady:	Like Britney’s plant is dying. Her leaves are big, and her seedpods are getting old.
5.	Steven:	When the plant dies the seedpods will grow and there’ll be more plants. The shade grew first then it died, then the sun plus shade will be like the sun they, they grew bigger. *(Steven continues to talk about seeds and growing, though so fast [the researcher] could not keep up with his full explanation).*
6.	EM	points out that Steven is giving reasons when he is telling whether he agrees or disagrees. One of his reasons is seeds, and the other is that the heights of the plants might switch.

Brady continues to call on students.

7. Malik: I disagree; he said earlier that before we had to plant the plant all over again but we planted them again and he said that the sun condition is growing well, about what he said about Britney's. Hers is not dying hers is still alive. It's just when the stem gets long it bends over.
8. Brady: Like the leaves are dying and the seedpods are dying. *Brady then points out that Malik's sun plant is also dying.*
9. Malik *looks at his tall, bent over, and totally brown plant and sighs*, "Yeah."

In this excerpt, students critiqued Brady's use of death in three ways. Azhad shifted talk to what was visible in the system by arguing that he did not see death (Line 1, S6). Brady responded by reframing death as "dying," a process that takes place over time and is indicated by features such as brown leaves and seedpods, and recruited another student's plant as an example (Line 2, S7). Malik (Line 7, S9) also questioned the notion of dying by arguing that a bent stem does not indicate death, but is the result of maturation, in that long stems bend. Steven (Line 5, S8) appeared to disagree that death was important by arguing that the plants would reproduce. He also called on students' shared history with the plants, which Brady had mentioned ("Before, on Day 6, my shade was taller"), by noting that the plants in the shade were initially the tallest, suggesting that the sun & shade plants might grow taller than the sun plants, which were currently tallest in general. When EM participated in the discussion, it was to make visible how Steven shifted discussion to reproduction and the uncertainty of timing.

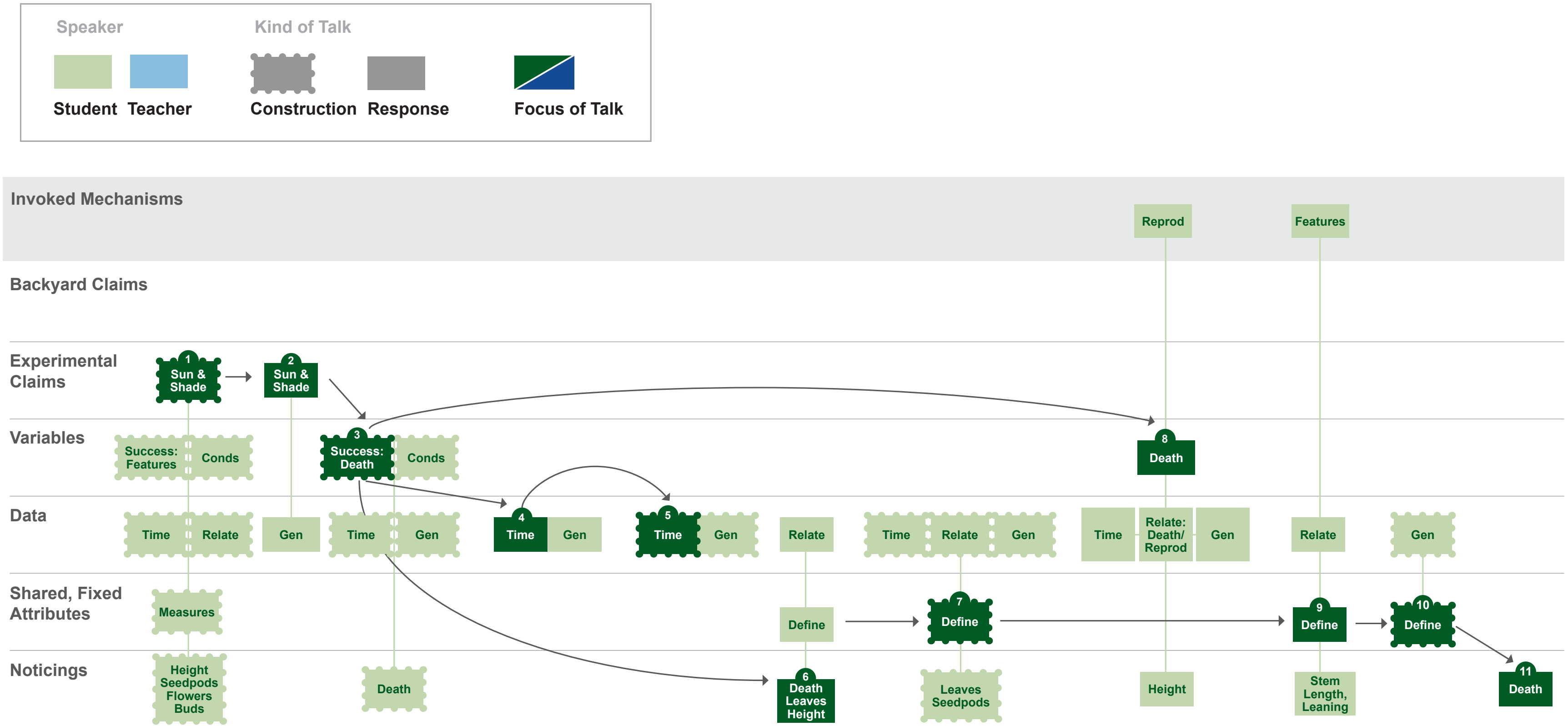


Figure 8. Discussion of Brady's idea that the sun & shade plants were most successful.

Green signifies student talk, while blue represents teacher talk. Here, Brady was positioned by the class as the author, or constructor of ideas; his statements are represented with wavy edges. Each statement is represented by a set of boxes connected with a vertical line. Boxes represent the different parts of the system mentioned in each statement; a darker box signifies that a part was the focus of construction or critique. "Invoked mechanisms" are included to show the forms of explanation needed to support activity. Arrows connect the parts under discussion in order to highlight how epistemic levels shifted.

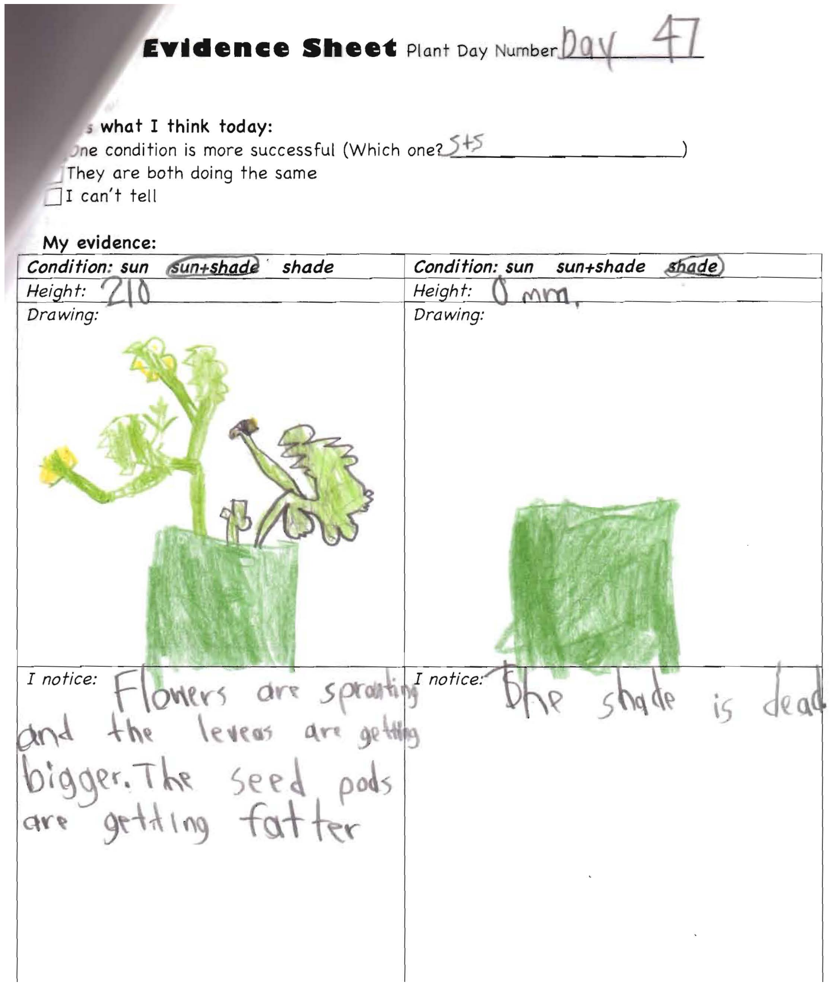


Figure 9. Brady's journal entry.

Note the differences between students' talk here and during Britney's presentation. While in both cases students made claims and posed questions, here the claims were more complex, in that they generalized across cases, related multiple features, and were predicated on notions of what might happen in the future. The critiques were more directly aimed at exploring how Brady knew that the plants in the sun condition were more successful; each critique explored a part of the experiment that was central to accepting his claim (e.g., did he look at all conditions, did he define death correctly, does dying even matter?) Finally, the representation in Figure 8 is entirely green (EM's comment did not introduce a new object or involve switching epistemic levels), indicating that students were managing their own discourse.

During this phase, students increasingly evoked maturation, death, and reproduction, using plant features to support claims that plants were engaged in one of these three processes. This is evident in the two episodes (April 5 and April 21), where students used color, leaf type, and bending to contest whether the plants were dying. Over time, processes of maturation, death, and reproduction were also related to, and often pitted against, one another. Contesting whether the plants were dying involved attributing change to predictable processes of maturation, as in students' responses on April 5 that the seed leaves were dying, and Malik's ascribing leaning to bending "when the stem gets long." As is evident in Steven's response (Line 5), privileging reproduction involved playing the investigation forward in time, thinking about how death would be followed by the growth of new plants. Death, maturation, and reproduction were defined by relating sets of features, then invoked as mechanisms to decide what counted as evidence of success.

In addition, students increasingly described the plants as involved in processes of change and attended to these processes rather than individual features at a moment in time. In fact, as we asked students to conclude which plants were more successful, this predilection caused difficulty. While they privileged seedpods as a sign of reproduction and therefore success, they had trouble deciding what counted as a seedpod. Several students argued that the pistils on the sun & shade plants, where flowers had fallen off but no seeds were growing, were "newborn" seedpods where seeds would grow. They supported this claim by arguing that the sun & shade plants had flowers, which develop into seedpods, and had not finished their life cycle yet, as evidenced by their green leaves. Another student interrupted a count of seedpods, saying "I have a question for people! There's this question I wanted to ask people, what if their seedpods are dead, does that count as a seedpod?” In this talk, students framed the seedpod as a maturing, dying entity, complicating its definition, which they realized was necessary in order to pursue a count. While these forms of thinking caused some difficulties with seeing a result in the experimental system, this disposition toward plant life cycles, rather than plant features or health, was a useful way of approaching the backyard system, one that would allow students to reason about evidence of success in that system.

Development. Early work with the system indicated important resources for the development of practice. Students framed the plants as changing over time and sought to understand how they were changing, attended to and problematized a variety of plant features (color, height, leaning, bumps, flowers), and volunteered ways to judge success. Initially, however, they did not appear to connect the enterprise of understanding plant features and plant change to developing ideas about how much light the plants needed. As the investigation proceeded, they increasingly related features to processes of maturation, death, and reproduction, seeking to understand which of these processes to attribute change to and justifying reproduction as an operationalization of success by relating and extending these processes beyond the individual plant’s life cycle. They also appeared to carry conversation more independently; they directly contested ideas central to the chain of reasoning supporting individuals’ claims, in particular, by questioning or elaborating operationalizations of success, change over time, and definitions.

At this point, therefore, students found it reasonable to use the co-variation of conditions and plant qualities to make inferences about the conditions in which plants were most successful. Most had changed their minds at least once about how much light the plants needed, either because the prediction that they initially made had been discounted or because in the early days of the investigation they thought the shade plants were more successful. They also appeared to be developing an understanding (or a shared set) of the transformations that were needed to use ideas about co-variation. In particular, they had transformed sets of plant features into shared indications of success. In this process, they developed shared uses for ecological ideas, which constituted shared ways of navigating the system of epistemic levels. However, they neither constructed nor critiqued the way that light was operationalized in the investigation. Instead, “the boxes” were used stably throughout this entire period to refer to light conditions. In the next phase, we turned out attention back to understanding the backyard, seeking to understand the consequences of students’ developing practice for how they navigated ideas of plant needs in this setting and to provoke contest about some of the aspects of the experiment that students saw as unproblematic.

Applying the entailments of the experiment to understanding the backyard system. During this next period of activity, we asked students to apply the experiment to the backyard, encouraging them to question its relation to the backyard setting and to develop new questions to focus further work. On April 28, students discussed what would happen if seeds from the Wisconsin Fast Plants™ landed in the backyard in a shady place, a sunny place, and a place with some sun and some shade. Mrs. W. asked them what they would see after 6 days, after 52 days (the age of the plants on that day) and over several years, encouraging a focus on the presence of plants in places where they reproduced. She then made an “outrageous claim,” arguing that, now that they had agreed that there would be more Fast Plants in the sunny areas of the backyard,

> “I think the just right amount of light for all plants in the backyard is sun. So when we go outside, I think we will find no plants in the shade, some plants in the sun and shade, and lots and lots of plants in the areas that always get sun.”

As students discussed what would happen in the backyard, it appeared that they had developed some stable resources (e.g., notions of reproduction, a differentiated notion of growth stages) that they called on to construct and contest ideas about the backyard, but that other aspects of the experiment (e.g., light) were problematic.

Students readily called on the experiment to make predictions about Fast Plant growth in the backyard. To predict what the plants in each condition would look like after 6 days, they referred to the results of the experiment, arguing that the plants would all would be alive and that the plants in the shade would be the tallest. They claimed that, at Day 52, the plants in the shade would be dead, those in the sun would be reproducing, and those in the sun & shade condition would be in the middle of their life cycle, referring to the idea, shared by many students, that those plants would still grow seedpods. When asked what he would expect to see after a few years, Brady said that the plants in the sun and sun & shade conditions would make more plants, initiating the following discussion.

1. Dante: Shade will too.

There is an immediate reaction to this in the class where several students are shaking their heads and saying no.

2. Dante: But Sh- shade still germinated though. [So it could]
3. Student: [Huh?]
4. Alex: [The seed fed it! The seed fed it!]
5. Brady: [It stopped!] (*pointing to the boxes where there are no shade plants still growing*)
6. Ellen: It stopped its [life!]
7. Alex: [The seed fed it!]
8. Azhad: [It's] dead [to the GROUND!]
9. Dante: [But remember, that's] inside! It has different light from outside. It's outside and inside. They're two [different ones.] So how d'you know?
10. Mrs. W.: [OOH… So you think] OUTside that it might germinate [in the shade] so we don't really know what might happen a year from now.
11. Dante: [It might grow *undecipherable*]
12. Brady: (*To Dante)* That's shade and outside is shade.
13. Mrs. W.: OK, so we would put a question mark, there you think, Dante?

14. Dante: Umm hmm.
15. Brady: (*To Dante, low voice)* They're the same kind of shade.
16. Dante: Uh uh!
17. Jewel: [Hold up! Will we have to do this for the whole YEAR?]
18. Brady: [They're both shade. They don't get any sun]
19. Dante: Because look, on that side *(pointing to the lightbox representing shade)* it is a little light coming through. Outside-
20. Brady: Yeah, but it's still not growing.
21. Dante: But it still germinated though.
22. Brady: Yeah, because of the food inside the seed.

Students' strong reactions to Dante's claim that there would be plants in the shade in a few years are reminiscent of what happens when a norm is broken (Goffman, 1974; Much & Shweder, 1978): the classroom erupted with noise, and students immediately disagreed with other. They readily called on parts of the experiment, and argued about whether they were relevant, to contest Dante's idea. First, Dante justified his claim that plants would grow in the shade outdoors by shifting attention back to the lightbox system, as indicated in Statement 4 in Figure 10 (here, talk about the lightbox experiment is represented with rectangles and talk about backyard with ovals to show which systems students were focusing on and when they brought the two in contact with each other). He used the fact that the shade plants germinated indoors to support his claim that they would make more plants outdoors. However, other students discounted the idea that the germination of the shade plants meant that they would reproduce outdoors. They noted that the shade plants had stopped growing and were now dead (S5-S8) and they proposed a mechanism for germination that might discount germination as a sign of success, arguing that the food from the seed fed the plant (S5). The speed, overlap, and intensity of their reaction suggests that, at least for several students, these were stable aspects of a shared system that enabled them to reason about the backyard and contest ideas.

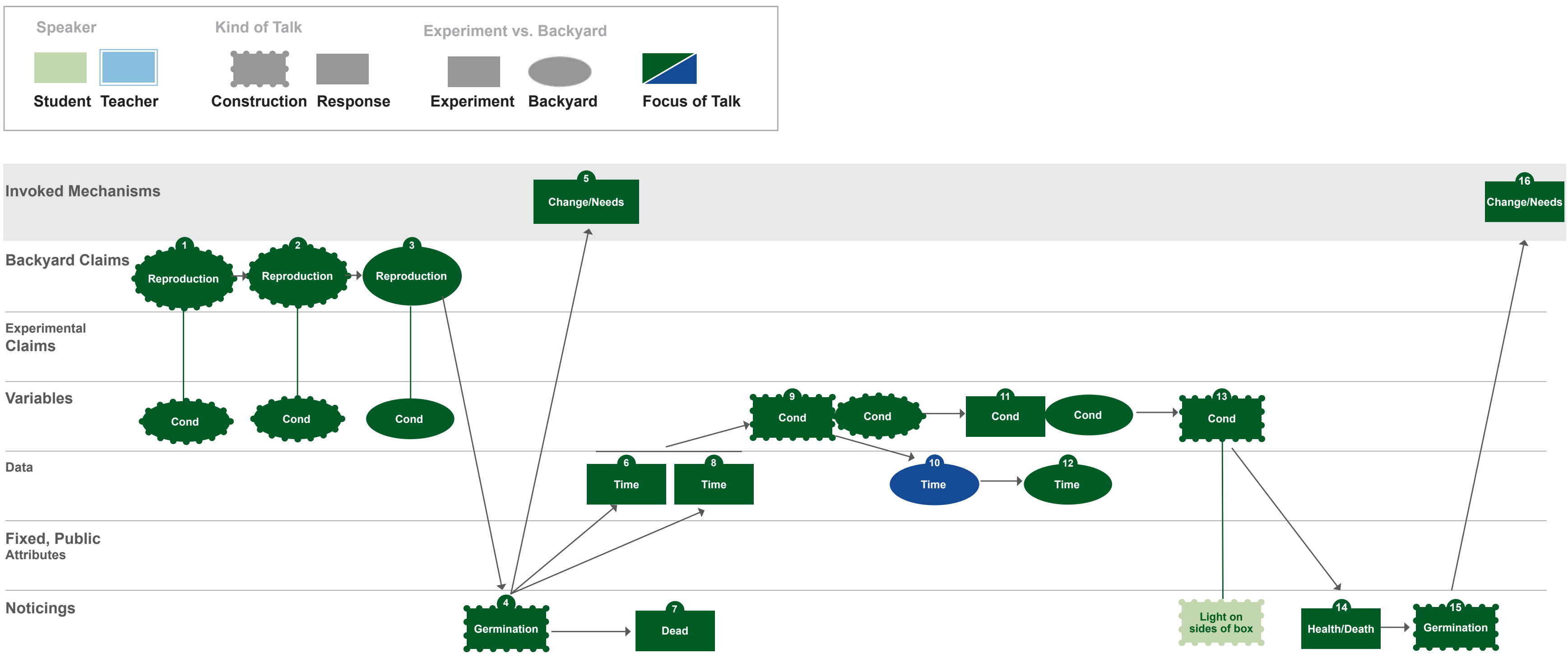


Figure 10. Discussion about where the Fast Plants would reproduce if they landed in the backyard

Green signifies student talk, while blue represents teacher talk. Here, Dante was positioned by the class as the author, or constructor of ideas; his statements are represented with wavy edges. Each statement is represented by a set of boxes connected with a vertical line. Boxes represent the different parts of the system mentioned in each statement; a darker box signifies that a part was the focus of construction or critique. Ovals indicate that talk concerned the backyard setting. “Invoked mechanisms” are included to show the forms of explanation that supported activity. Arrows connect the parts under discussion in order to highlight how epistemic levels shifted.

In turn, Dante called into question the relationship between the conditions in the backyard and in the model system (Line 9; Figure 10, S9), bringing the two systems into contact with each other. This is one of the first times that conditions were been explicitly discussed since students set up the investigation. Brady framed the two conditions as the same, in that both had “no light,” while Dante argued that he could see some light, pointing out the light coming in the sides of the shade container. As Brady noted, however, the seed “still didn’t grow” (S14) and so Dante’s use of mis-fits between the model system and the backyard was not convincing (though it is unclear what he was going on to say). In this discussion, the forms of practice outlined in the last section are evident: students disagreed not just about what they saw, but what it meant for understanding where plants would be successful. They attacked central aspects of Dante’s claim, called on shared understandings of plant maturation developed in their previous activity, and, at least in Brady’s case, maintained an extended focus on how the line of argument bore on predictions about what would happen in the backyard.

In the next several minutes of talk, students reviewed reasons why there would be more Fast Plants in the sunny conditions in the backyard over several years, noting, with no disagreement, that the plants in the sun conditions in the experiment would make more plants because “the life cycle keeps on going,” while shade couldn’t make new plants “because if it died and it didn’t leave any seeds, how could it grow again if it didn’t drop any seeds?” Here, students called on processes of seed production to move from counts of seedpods to predictions about the presence of plants in conditions where their needs were met and they therefore reproduced. Next, Mrs. W. presented her argument that she would expect to see lots of plants in the shade outside but no plants in the areas that were shady, extending conclusions about the Wisconsin Fast Plants™ to all plants.

As students reacted to her idea, recorded responses in small groups, and reported ideas the next day of instruction, they offered numerous reasons why they agreed and disagreed. Many of these arguments involved shifting between different epistemic levels and/or making connections between the experiment and backyard (Figure 11).

1. Several students agreed because "If it didn't happen here, it wouldn't happen outside," essentially applying the conclusion from the model system unproblematically to the backyard. Two students pioneered this idea; one was successful in recruiting his table group to his position, while the other was convinced by her seatmates to abandon the idea in light of the problems outlined below.
2. Some (at least three students) relied on mechanisms to justify why the sun condition would be the just right amount of light, for example "The shade won't have a lot of plants because it won't get a lot of sun and it will be too cold."

Others pointed out problems with Mrs. Wade's argument.

3. Many students used empirical evidence from outdoors, noting that their plants were not in "sunny areas." This form of thinking was evident in the conversation and written work of ten students.
4. Many also contrasted the kinds of plants in the backyard to those used in the experiment, arguing, for instance "These are Wisconsin Fast Plants. There are plants that fit in the shade. There are other plants that fit in the sun plus shade and there are plants that can grow in the sun." These students argued that plant type was relevant to the applicability of the experiment's conclusion to the backyard setting, and thus identified a key issue of model fit. Eight students indicated this form of thinking.

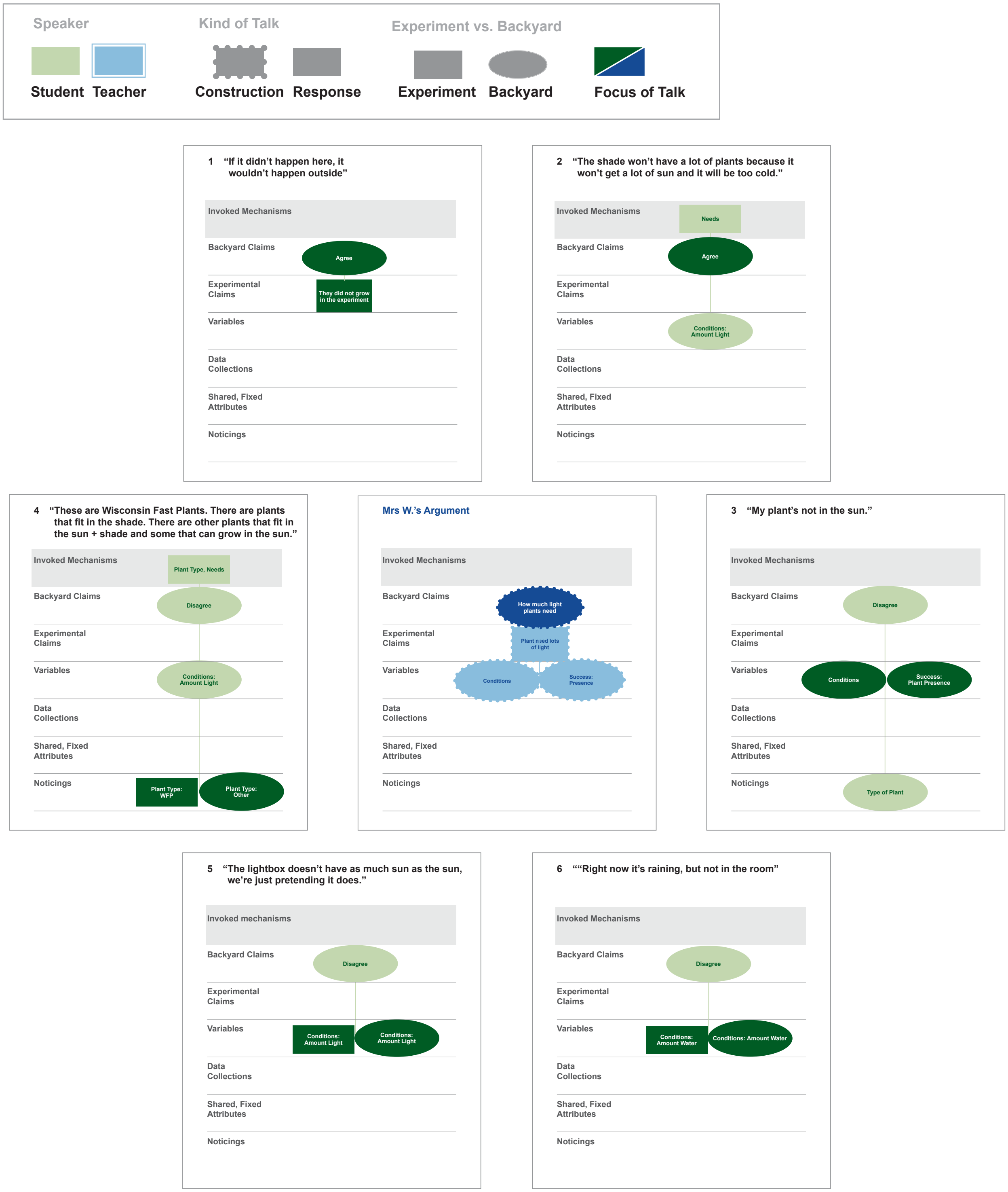


Figure 11. Responses to Mrs. W.'s argument.

Green signifies student talk, while blue represents teacher talk. Here, Mrs. W. was the author, or constructor of an idea; her statement is represented with wavy edges. Types of responses are shown as separate statements. Boxes represent the different parts of the system mentioned in each statement; a darker box signifies that a part was the focus of construction or critique. Ovals indicate talk about the backyard. "Invoked mechanisms" are included to show the forms of explanation that supported activity.

5. Others (three students) problematized the operationalization of conditions; for instance Steven called out “The lightbox doesn’t have as much sun as the sun, we’re just pretending it does.” Madison began to talk about how the shade outdoors was “not always in the shade because sometimes it was in the sun.” This form of argument also involved evaluating relations between aspects of the experiment and the backyard and considering their relevance for importing the experiment’s conclusion into the backyard setting. Here, students began to reconsider the categorical nature of their operationalizations. The notions of “as much light” and “sometimes” are moves toward rendering amount of light as a form of data (intensity, duration) that could be compared and measured.
6. Finally, at least two students began to consider possible differences in moisture between the backyard and experiment. Diego volunteered, “Right now it’s raining, but not in the room” as he sought to explain why some plants were growing in the shade outside. Ellen said “But water AND sunlight, they have to work together.” Again, these students considered issues of model-fit that might have relevance to applying the conclusion of the lightbox investigation to the backyard.

As students applied the results of the investigation to the backyard, focusing first on implications for the growth of Fast Plants and then for plants in general, new ideas were made visible and useful. To argue against Mrs. W., students differentiated plants into “kinds of plants.” They also differentiated conditions; they began to focus on *how much* light the plants received and whether moisture differences might also matter for the distribution of plants outside. Engaging in these forms of practice evoked mechanisms to justify the relevance of differences between the experiment and backyard. When Diego argued that the backyard got more water than the Fast Plant systems, students questioned why he thought water could make up for lack of sunlight. As students suggested that it was important that the Fast Plants were a different kind of plant than those in the backyard, Mrs. W. guided students toward thinking about why that might be true, provoking talk about plant structures and strategies and introducing a book that provided information about why different plants to do well in different conditions. These are ideas that had not been useful to students when they were discussing the experiment, in that they were stabilized by the experimental system, where only one kind of plant was considered and conditions were maintained in lightboxes that effectively "black-boxed" (Latour, 1987) intensity, duration, and moisture. Considering model-backyard relations created opportunities for students to differentiate new ideas and then consider how these ideas might explain differences in plant success.

Development. Students continued to problematize ideas by shifting conversation to different epistemic levels, invoking and contesting parts of the experiment such as germination, plant type, or light conditions. Some aspects of their activity appeared to have stabilized and served as resources for exploring new questions. For example, in the previous phase, students had justified reproduction as an operationalization of success by playing it forward into the future. Here, this narrative appeared to be stable across participants and allowed them to consider presence in the backyard as linked to success. Other aspects of plant growth were not considered permissible support for a prediction of future presence, as indicated in students' reaction to Dante's use of germination. Students appeared to have developed ideas about plant growth and plant life cycles that allowed them to see and reason about the presence of plants. However, new ideas, particularly ideas of plant kind and plant conditions, were made problematic as they applied the result of the investigation to the backyard. It was also noteworthy that *students* made these ideas problematic as they generated a variety of attacks on Mrs. W.'s claim about the backyard. Here, it appeared that the enterprise of reasoning about the needs of plants based on places they were in the backyard was sensible enough to students that it focused their activity as they rethought some of the transformations that supported the experimental system (e.g. what the light boxes stood for, how the type of plant used was important).

Making claims about the best conditions for plants in the backyard. Here, I briefly indicate the ways that the forms of practice developed during the plant growth experiment were used as students returned to the backyard in May. Building from students' ideas that different plants needed different conditions and their invocation of plants in the shady areas to support this idea, we asked students to characterize the plants they found in an area the size of a hula hoop located around their focus plant. They then were paired with a student whose hoop was in a different set of conditions, asked to compare and contrast their areas, and directed to develop an argument about the "just right" conditions for a plant that was in one or both of their hula hoops. On May 12, several pairs of students presented their arguments to the class in a research meeting format. Students' presentations and responses indicated that using presence to infer needs was a stable form of practice, that other practices used in the experiment were resources for outdoor work, and that ideas about light conditions were still problematic.

First, students generally applied the logic of looking for where their plants were, characterizing areas in terms of amount of light, and using co-variation to make claims about the conditions that were best for their plants. For example, Malik (who plot was near the wall, a "shady" plot) and Madison (whose plot was in the middle of the backyard) argued that a plant that was in both of their plots could live in a place with either sun or shade. Alex argued for Queen Anne's Lace:

> "I think it will grow in all two-I meant all three [conditions]. Because I've seen Queens Ant's Lace on the wall, down the fence, and in between. Where sun plus shade is, like on the close of sun plus shade, in sun plus shade, and sun."

As students responded to these arguments, they also commented on where they were finding the plants. Diego asked Alex and Dalton,

> "How do you all know if one is growing in the shade and some is growing sun? Both of yours are growing in the sun, so I wonder if you were walking around and looking at Queen Anne's Lace. I'm confused because I haven't seen any in the shade."

The next speaker, Dante, whose focus plant was Queen Anne's Lace, said "My Queen Anne's Lace is in the shade. It's right by the wall." At this point, most students focused on establishing the presence of kinds of plants in particular conditions in order to make inferences about the plants' needs, rather than looking for signs that individual plants were doing better and less well or developing plausible accounts without considering plant distribution.

In order to generalize from individual plants to kinds of plants, students needed to identify whether they had the same kind of plant. Here, there was evidence that the forms of practice they used in the investigation could be re-appropriated for this setting. For example, Alex reported:

> "The first time we looked at our plants we, we did not know that- the first time we had looked at our plants we didn't think we had much in common but- cause Dalton had more leaves than I did and-but we both had the purple clover. We had the- we had about the same amount of stems and we found out that he had a Queen Ant Lace."

Later in the presentation, he comes back to this experience:

> "I was asking him does he want to tell them about the age of them. Because my Queen Ant Lace is in a different part of, is in a different part of life than his (*pointing at their two drawings, which are projected onto the board*). Mine is dead (*points*) and his is young" (*points*).

Dante, whose focus plant was the Queen Anne's Lace, then commented,

> "I think your plant is more than two years old. Queens Anne's lace are biennial. They're - they only-when they're full grown that means they've been-they're two years old so yours might be more than two years old."

Here, students used their understanding of plant maturation to identify plants, an important form of definition for the work they needed to do in the backyard. This is not to say that these forms of thinking were unproblematic: as Alex mentioned, he and Dalton did not originally think that they had the same kind of plant, and one researcher helped them see that they did by encouraging them to grab hold of the stem that they were sitting near and pull the "top" of it toward them, allowing Alex to recognize that the flowers buds on top were like those of Queen Anne's Lace, which was his focus plant. Across the activity phases on this day of instruction, students saw the work of plant identification as relevant to establishing co-variation, called on inscriptions and their understanding of plant life cycles to reason about plant kinds, and challenged claims regarding proper identification.

The terms "shade," "sun" and "sun and shade" were still used stably and unproblematically by students. This posed problems for their activity, but they did not immediately recognize these problems. When students used these terms during their work on the experiment, the referents were stable (the boxes) and it was usually understood what condition they were referring to because they were drawing direct comparisons between two boxes. However, as students made claims about the conditions their plants could be found in outdoors, these uses posed several problems. First, when a student referred to "sun and shade" they could be referring either to "the sun condition" or "the shade condition" or "the sun and shade condition." Second, students each identified their area with a condition, but they did not share ways of identifying conditions. So, for instance, Dalton's plot was almost directly under a magnolia tree, but he identified it as being in the “sun,” perhaps because the previous time he was outside the sun was shining on him as he observed his plot. A few minutes later, Dante argued that there were Queen Anne’s Lace under the magnolia tree to support an argument that they grew in the shade. However, no one recognized the important differences in these characterizations and the difficulty they posed for agreeing on what conditions were best for the plants.

At this point, EM said she was getting “a little confused” about what students meant when they said “sun plus shade” or “sun and shade.” Students immediately referenced the lightboxes:

1. Jasmine: It means- like in the light box you meant like it comes on at 7 o'clock in the morning for when we come to school and 3:00 in the afternoon for when we leave school, it's like half of the day the light is on.

EM revoiced Jasmine’s comment as indicating that the sun & shade meant “sometimes in the shade.” At this point, Madison contributed:

2. Madison: She's WRONG actually, because after everybody leaves from the school, when Mrs. W., sometimes she's still here, it only goes- it goes- cause it's 24 hours. So when it goes off it-the thing is telling the plants that it is nighttime

EM then noted that there was nighttime in the backyard, and asked whether everywhere in the backyard got nighttime. Dante jumped in, making a statement that caused an explosion of activity:

3. Dante: There isn't really any sun in the backyard, it's just shade and sun plus shade.
4. Multiple S: What? Nuh uh!
5. Dante: Cause- Because look. At the daytime it's just sun and then at the nighttime it's shade. [So]
6. Jewel: [No it's] not! [It has shade and sun]
7. Dante: Yes it is! [It has]-there has [to be-there]
8. Azhad: [Yes it is]. [Nighttime there's not light.]
9. Dante: Cause half sun, half shade (*points each finger out*). So there is no sun. There is no always sun in the backyard.
10. Azhad: Yeah, I know. [I agree. That's what I was thinking]

11. Jewel: [I KNOW there's not always sun.]

In Line 3, Dante recast the conditions in the backyard using the lightbox conditions as categories. He argued that because there was no part of the backyard that got sun all the time, as nighttime creates darkness that is equivalent to shade (Line 5), the backyard should be considered as two categories of light: "shade" and "sun plus shade." This statement was initially taken as extremely problematic by the other students, but Azhad quickly entered conversation as an ally for Dante's argument. Even Jewel's statement is interesting; she said, "I KNOW there's not always sun" emphasizing the word "know" as if the point was obvious, because of course she knew that the sun goes down at night. This talk suggests how stable the lightbox conditions had become for the students and shows the beginnings of their disruption as the two systems were brought more explicitly into contact with each other.

At this point, Steven argued that the lights from the road were on at night:

12. Steven: But the streetlights are still on!
13. Madison: That doesn't matter!
14. Dante: But those aren't the same
15. Steven: It's like the lightbox (*gesturing to the boxes*). Doesn't it give light?
16. Dante: Those are far away from the backyard.
17. Alex: Those [are for the street.]
18. Steven: [Yeah, but it still]-What? (*To Alex*)
19. Alex: You said the streetlights.
20. Brady: It still can make sun. [It still can make sun].
21. Dante: [Those are only pointing to the] street.
22. Alex: How will THAT make sun?

When Steven introduced the streetlights, students began to think about what exactly the lightboxes represented. Madison emphatically declared, "That doesn't matter," and Dante argued, "But those aren't the same." Both students initiated the differentiation of aspects of light by dismissing the equivalence of the streetlights and the sun; in doing so, they shifted talk to defining what counted as light. Students' participation in this process of defining was nascent and not fully explicit. Steven equated the streetlights to the lightbox, arguing that they both gave light. Dante and Alex pointed out the location of the lights (which were over the hill from the backyard and at least 40 feet away), perhaps implicitly referring to their intensity. Both Brady and Alex considered whether the streetlights can "make sun" (Lines 20 and 22).

Here we can see students beginning to engage in the very activities they used earlier to differentiate and relate plant features and stabilize a notion of reproduction as an operationalization of success. Throughout their activity, they had used the lightboxes to stand in for the backyard conditions. It is evident how powerful and stable the category system was during the beginning of the conversation, as they recast the backyard conditions using the lightbox categories. This is a funny move since, of course, the lightbox settings were originally proposed to represent the backyard conditions. In turn, contest began to shift students' talk to considering light as a variable. First, they equated the reasons for absence of light (shade vs. nighttime); next, students began to reason about light as having qualities like duration and intensity. Here, processes of relation, differentiation, and calling on mechanisms were evident, but not fully taken up.

Development. Analysis of May 12 suggested that the same transformation processes that students had used to understand the experimental system and apply its results to the backyard setting were useful as they sought to understand the conditions that were best for plants in the backyard. They appeared to share a stable disposition toward establishing the co-variation of plant presence and conditions. With support, they engaged in new processes of definition to establish plant kinds by calling on descriptions of maturation developed during their experimental work. They did not independently realize that new forms of transformation would be needed to support shared uses of "conditions." However, when their attention was directed to defining what conditions meant, they began to engage in very similar processes of contesting ideas, then relating and differentiating them, providing opportunities to develop a variabilization that might more closely approximate disciplinary uses of light as a condition affecting plant growth.

Summary and Interview Results

In this section, I summarize the account of development and extend it into analysis of the interviews to determine how the accomplishments I describe were appropriated by individual students. Table 3 shows the forms of activity that students engaged in and distinguishes between parts of the experiment that were present in students and teachers' talk (gray boxes), parts that were the active focus of students' construction, in that they were making claims about those parts (black outline), and parts that students explicitly problematized (i.e., critiqued or requested more information about, marked with an X).[10]

Early on, students were introduced to the shape of the experiment. Talk focused on what it meant to represent light (relying on similarity to conditions noted in the backyard) and to relate conditions and success ("growing well") to develop a claim about how much light a plant needed (Table 3, Feb. 21, Feb. 24, March 4). As students began to work on the experiment, they readily participated in making claims about which plants were doing best. These claims were usually predicated on a plant feature (e.g., height, a bump, flowers) that they noticed and used to operationalize success. Students also readily asked questions about how the plants were changing over time and why, but rarely used these forms of thinking to problematize each other's ideas about which plants were most successful (e.g., see March 10 and March 22 in Table 3). In fact, it

[10] The criterion for marking as referenced, constructed, or problematized was at least one public use of this kind by a student.

was only late in their work with the system that they explicitly contested ideas about which plants were most successful and what counted as valid ways to make a judgment of success (April 21 and April 27). As students began to consider how the experiment's conclusions were relevant to understanding the backyard, they related and challenged plant success (here, indicated by presence) and conditions. These were forms of practice that they appropriated from their work within the experimental system. However, new parts of the system became problematic, namely the type of plant and students' understanding of light conditions (April 28, May 3, May 12).

Development involved students' increasing disposition to navigate the epistemic levels of the system as they made and responded to claims, making what they saw visible to others and relevant to a claim about plant needs. As students moved between these levels, they initiated conversations about how what they were seeing counted, and, in turn, invoked, differentiated, and related ideas. Over time, they developed stable uses for these ideas that supported their shared work. For example, they used reproduction and presence to indicate success, while they positioned maturation and death as part of plant life cycles that were necessary to consider when identifying plants and making judgments about reproductive success. In contrast, students used ideas about light stably throughout the investigation, referring to the "boxes" rather than constructing and problematizing conditions (Table 3), and only began to problematize light as a part of their work in the last phases of the investigation. Here, the co-development of ideas and practices meant that as students constructed and critiqued parts of the experiment, they worked through ideas, grappling with how they were relevant for their activity. These ideas, in turn, became a shared lens through which to see the system and supported students in contesting new parts of it.

Table 3. Parts of the system that students referenced, constructed, and problematized on each of the days analyzed.

Epistemic Level		Planning			Conducting Experiment								Applying to Backyard (BY)		BY
		2/21	2/24	3/04	3/08	3/10	3/22	3/24	4/05	4/07	4/21	4/27	4/28	5/03	5/12
Backyard (BY) Claim		X											X	X	X
BY-Exp. Relations												X	X	X	X
Experimental Claim				X			X		X		X	X			
Variables	Condition											X	X	X	X
	Success										X	X			
Data Coll's	Data Displays							X	X	X					
	Change over Time					X	X				X	X	X		X
	Gen's across Cases										X				
	Aspect Relations	X												X	X
	Comp's across Cond's										X				X
Shared Fixed Atts	Measures	X			X				X						
	Definitions						X		X		X	X			X
	Inscriptions					X	X				X				X
Noticings						X	X		X		X	X	X	X	X

Shaded areas indicate 1 or more uses of an epistemic object, black outlines indicate 1 or more instances of construction, and an x indicates one or more instances of problematization.

In analysis of the interviews, I consider whether, and how, individual students took up the explanations of plant needs, conclusions about the experiment, and understandings of the relationship between the experiment and the backyard that were developed in community activity. I then explore how they called on their experience with the experiment to critique a fictional claim about plant success; that is, which of the epistemic levels of their work they saw as relevant to a new context.

How did students explain the presence of different plants in different places in the backyard? In the final interview, fourteen of the seventeen students interviewed coupled an account of seed dispersal with an explanation that different plants were suited to different conditions to explain the distribution of plants in the backyard. When asked how they had figured out that this was the case, eleven students called on their experience in the backyard, noting that they had found that different kinds of plants were located in different conditions. The remaining three students talked about how the lightbox investigation had demonstrated that amount of light matters for plant growth. Two students used ideas of seed dispersal without considering conditions for growth.

How did students explain and justify their conclusions about how much light Wisconsin Fast Plants™ need? Here, I was curious about how stable across participants the experimental conclusion and the use of reproduction as evidence (as opposed to ideas about death or health) would be. Fourteen of the seventeen students argued that the plants in the sun condition were most successful, while two students thought the sun & shade condition was most successful, and one student could not tell if the sun or sun & shade condition was more successful. Twelve students mentioned seedpods as one of the ways that they knew which condition was most successful. Three used only features other than seedpods (a general notion of growth or height). Only one student explicitly privileged health, arguing that the sun & shade plants were more successful because they had not died. When students were asked "Which do you think is the most useful kind of evidence for understanding whether a plant is successful: height, color of leaves, or number of seedpods?" twelve students chose seedpods; nine justified this choice by explicitly linking the production of seeds to the plant making "more of its kind." As one student put it,

> "Because it kinda reminds me how a mother and father do, they have to do, being successful doesn't mean that they have a great life, I'd say being successful is having their child, meaning that if they don't have the child, that's not reproducing or I wouldn't say that's successful."

How did students understand the experiment as a model of the backyard; what relations did they find problematic? In the interview, we asked students why we did the lightbox investigation rather than going out to look at the plants in the backyard and whether there was a problem with using the investigation to understand the backyard. The intent of these questions was to understand how students thought about the experiment as a model of the backyard. Six students (Table 4) focused on how the experiment was similar to the backyard, mentioning features represented in both, for instance sun or water. More students, however, nine in total, thought about similarities and differences but explicitly noted their implication for understanding plant growth; these students appeared to consider the experiment as a way to represent and study growth processes. This is an important first step toward a disposition to modeling that is not always evident to students (Lehrer et al., 2008). Many of the fifteen students who focused on similarities or representing growth processes reasoned that we had probably chosen to do the investigation indoors for reasons of convenience or comfort, noting that it would be difficult to go outdoors every day, that it might have been too cold to grow plants during the winter, or that it was too hot in the sunny areas. Just one student noted that the lightbox investigation allowed for a control of conditions that was not possible in the backyard.

Twelve of the sixteen students who were asked about problems using the investigation to represent the backyard setting identified at least one issue (Table 4). Eight students noted that conclusions about Wisconsin Fast Plants™ could not be applied to all plant types, while four noted the differences in light conditions in the backyard as opposed to the lightbox (e.g., the sun condition in the lightbox provided light 24 hours of light a day, while in the backyard there was nighttime or the shade condition indoors provided no light to plants, while the shade outdoors provided some light). Four students appeared not to understand the question, or explained that

Mrs. Wade had predicted wrongly that there should be no plants in the shade and were unable to account for why her prediction might be wrong.

Table 4. Students' responses to questions that asked them to consider the status of the lightbox experiment as a model of the backyard.

Response	Example	# students
Control	"Because in the outdoors, you can't really tell about the conditions… you can make the conditions indoors"	1
Represent Processes	Well, we did it inside, cause we thought if it happened inside it's gonna happen outside.	9
	"None of these (Fast Plants) were in the backyard, so then it won't help you to know how much sunlight the back, the plants in the backyard needs.	
Similarities	"It's almost like outside, except it doesn't have the real sun, it has real water and has real dirt, but it doesn't have real sun, so it might be a little different."	6
Uncodeable		1
Identify at least one problem with using the experiment to draw conclusions about the backyard		12*
Plant Type	"Because these plants, they're from Wisconsin, and the ones in the backyard, they're not."	8
Amount of light	"There's a little bit of sun on the shade [in the backyard], but with the Wisconsin Fast Plants the shade plants, they didn't grow at all because they didn't have any sun."	4
Internal Problems	"At first it was hard to figure out how to make sun plus shade, then we got the idea to turn the light off."	2
Other conditions	"So that helps the plants grow, because there's a lot of moisture in the shade [outdoors].	1

* 16 (rather than 17) students were asked to identify problems with using the experiment to learn about the backyard

How did students call on the plant growth experiment to engage in critique? Finally, we were interested in understanding how students drew on their experience with the plant growth experiment to critique the conclusions of a fictional student conducting a similar investigation.

We used the context of a student who wanted to know what the “just right amount of water” was for marigold plants (a plant we had not studied with students). We created two evidence sheets (Days 4 and 42 of the investigation) that we conjectured might invoke responses at the different epistemic levels that students had navigated in the Fast Plants experiment. For example, on Day 4, the fictional student based his conclusion entirely on height, without noting other features of the shorter plant (a bump, a darker color) that were represented in his inscription (Appendix A). We wondered whether students would argue that height was insufficient evidence (Epistemic Level 4, Operationalizations of Success) or that they needed information from other points in time (Epistemic Level 3, Change over Time).

More students critiqued aspects of the fictional student’s evidence than used those aspects to discount the conclusion the student drew. For each sheet, three students indicated that the evidence provided was not sufficiently convincing, for example, because the student had only considered height. The majority of students indicated that they agreed with the fictional student’s conclusion on each of two evidence sheets, citing the empirical evidence provided by the student (Table 5). However, when students were asked whether they had any questions for the fictional student or whether the student could improve the evidence sheet in any way, the majority (twelve students) provided at least one critique using ideas that they had developed during classroom activity. These included explicitly contesting how the student operationalized success, requesting information about the plant’s maturation, requesting clarity on the author’s inscriptional choices, and wanting more information about features of the plant (usually, features that the class had used to consider success, such as leaf color or seeds). This result was reminiscent of the ways that students had initially problematized aspects of their experiment without explicitly tying the problems they cited to a conclusion about the needs of the Fast Plants.

Table 5. Students' critique of two fictional evidence sheets from different days of an investigation of the effect of water on marigold plants.

Response	Day 4	Day 42
Evaluates conclusion on empirical grounds	12	11
Evaluates based on whether empirical grounds are sufficient	3	3
Evaluates conclusion based on whether account is plausible	2	3
Requests at least one form of additional evidence	12	10
Operationalization of success insufficient	2	3
Need to understand more about change over time	4	4
Inscription not sufficiently clear	3	5
Request other information about plants	4	5

In summary, it appeared that many of the accomplishments noted in the description of development were appropriated by most, but not all, of the students in the class. About four or five of the students in the class were generally less likely to use the ideas and forms of practice developed in classroom activity; three of these students had often been absent from class due to "pull-out" supports that they received because of academic difficulties. Consistent with my description of instruction, the questions that required students to call on an understanding of the entire enterprise (or spanned the greatest number of epistemic levels) were most difficult; for example, most students did not see the experiment as a way to control parts of the backyard that were difficult to see and measure and did not apply their critiques of a fictional student's evidence to discount the claim he made about plant success.

Discussion

In this paper, I unpacked students' work around an experiment in order to understand how to support the development of practice and how practice, in turn, situates conceptual activity. I conceptualized science as a modeling enterprise that entails constructing and critiquing a series of transformations from the particular, concrete aspects of a system to more general, high induction statements. Experiment sits in the middle of this enterprise: it is a purposeful selection and manipulation of the world, but the results it produces are far from transparent and must themselves be transformed into claims. Here, I engaged young students (third graders) in these complexities of experimentation, which, in typical school science instruction, are usually unavailable to them (Schauble et al., 1995; Windschitl et al., 2008). My work showed that a) students were able to engage in constructing and critiquing many different parts of the experiment, including inscriptions, variables, and relations to the target system and b) that this work allowed them to see the target system in ways that better approximated disciplinary understandings.

In particular, I highlighted the importance of engaging students in moving between and connecting parts of the experiment, or what I called "epistemic levels," borrowing from Latour's notion of scientific rhetoric as entailing a careful stacking of material, instruments, and inscriptions (Kelly & Takao, 2002; Latour, 1987). I showed that students were able to make connections among parts of the experiment as they developed, questioned, and refined ideas. With the forms of support described here, students negotiated what they saw and what it counted for: What counted as death? Did death count as not being successful? How did the fact that all the plants in the experimental shade condition died (without reproducing) count for understanding the backyard? As students negotiated these questions, they differentiated ideas, invoked them as mechanisms, and related them in new ways; through these processes, they refined ideas about plant change, plant success, and conditions that were initially problematic for them to see and use in the backyard setting.

This paper contributes to the literature by suggesting the conceptual affordances of the very parts of experimental activity that are usually simplified for use with young students. For example, many studies have shown that students do not “see” what scientists see when looking at phenomena, and that this difference affects their participation in scientific practices, including how they interpret the results of experiments (Chinn & Malhotra, 2002; Eberbach & Crowley, 2009; D. J. Ford, 2005). As a result, young students are often presented with categorical variables or provided explanations that essentially tell them what to see and how to see it (Chinn & Malhotra, 2002; Klahr & Simon, 1999). In this study, however, wrestling with what was relevant and what it was relevant for (e.g., what a bump was, what counted as death or as a seedpod) was both an accessible activity for students and a site for conceptually rich talk. This is consistent with scientific activity, in which scientists have to figure out how to “construe” phenomena so that they are visible and manipulable both for themselves and an audience (Gooding, 1990). Likewise, dealing with the way that the experiment did and did not represent the target system not only allowed students access to important approximations of scientific practice but provided an opportunity to further differentiate and relate ideas (here, ideas about plant types and light). Systematically building practices like developing measures and exploring model fit into experimentation can help students better understand both the activity entailed in conducting investigations and the ideas that are the target of their investigations.

More broadly, this paper adds to the growing body of work showing that even young students can participate in sophisticated aspects of practice if those practices are supported in environments that build from students' resources and provide contexts in which they have utility for their work (Lehrer et al., 2008; Metz, 2011; Ryu & Sandoval, 2012; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). As the students in this study constructed, critiqued, and transformed parts of the experiment, they engaged in several practices that, from a functional point of view, resemble practices many studies have noted as difficult for students. For example, they actively contested, and increasingly cited, warrants for the claims that they made (e.g., McNeill et al., 2006). They recognized that inscriptional choices were consequential and challenged each other on the basis of those choices, rather than taking the meaning of data representations to be self-evident (Sandoval & Millwood, 2005). The close study of how these practices developed in interaction also raises two important issues:

Part of What Develops is Children's Notion of What the Enterprise Is

Recent work that emphasizes supporting students in developing scientific practices has highlighted the importance of embedding practices in scientific activity (Cavagnetto, 2010) and framing activity as "doing science," that is, finding something out, as opposed to "doing school," enacting procedures that the teacher has told you to (Berland & Hammer, 2012). The findings presented here support these design principles, but they also complicate them by suggesting that framing the enterprise is itself something that develops in interaction, rather than something achieved automatically by posing the right task or providing a clear explanation from the teacher. At each of the time periods I described, students were legitimately invested in developing explanations and engaging with each other around uncertain processes. In the backyard, they sought to explain why their plants looked different from earlier in the year. In early work with the experiment, they challenged each other's characterizations of features and sought to understand how and why the plants were changing over time. As they engaged around the investigation, supported over the course of weeks (rather than minutes) by tasks, representations, and teachers' instructional moves, they appeared to increasingly frame the purpose of their enterprise as one of linking plant success to conditions to make inferences about needs. This result is consistent with the way that questions and areas of study develop in professional scientific practice (Bowen & Roth, 2007; Pickering, 1995).

Therefore, as the field moves toward designing settings in which practices have utility for students' work and where the shape of the scientific enterprise is left intact, we will need to increasingly attend to the development of both practice and students' understanding of their enterprise, designing settings that provide entrée into important scientific functions of practices and developing supports that make these functions visible to students. For example, here students began their work by challenging what others saw and how it was relevant to processes of plant change, but needed support to understand the significance of these forms of activity for critiquing claims about plant success. Likewise, they understood how the experimental system allowed them to test the same processes of plant growth they saw in the backyard and commented sensibly on the similarities and differences between the two systems, but even at the end of instruction did not position these differences as ways to manipulate and control unruly aspects of the backyard. This does not mean that young students are not ready to participate in contesting what they see or relating experiments to the target systems they are meant to represent; but rather, that they will need careful forms of support to help them understand the connections among the forms of practice in which they engage. This is another reason to stress the integration of practices in instructional environments, rather than teaching them separately.

Problematization is Easier than Stabilization

The design principles described at the beginning of this paper appeared to be effective for supporting students to engage in problematization, that is, contesting ideas or posing questions about an aspect of the investigation. Students were comfortable agreeing and disagreeing with each other's ideas, produced variability in what they saw and thought (for instance, what counted as death, what were important signs of success), and often thought this variability was problematic enough to bring up in conversation. When they did not do so, we were able to provoke contest using an outrageous teacher claim (as in Mrs. W.'s argument that there should be no plants in the shady areas of the backyard). In turn, problematization appeared to provide productive opportunities for student to explore alternative accounts and differentiate or relate ideas. These were, therefore, moments of microgenesis in which ideas and practices were used in new ways for new purposes (Saxe, 2002).

However, to move beyond existence proofs of students' capabilities and of opportunitie*s* for learning, we must also ask how these moments of problematization can be translated into stable ideas and practices. In this study, stabilization was more difficult and required planned forms of support. These included pick-up and amplification by the teacher, new forms of representation (e.g., translating reproduction into presence), and the provision of needed pieces of information (e.g., reading about food from the seed to understand why the shade initially grew better). While students problematized ideas about both plant success and light conditions, the design supported stabilization in the development of measures of success (students' use of ideas of reproduction and plant timing) more effectively than the development of ideas about light. Mrs. W. repeatedly invoked variability in students' operationalizations of success, highlighted ideas about reproduction, and helped students construct accounts in which reproduction explained the presence of plants in the future. In contrast, she appeared less sure about what to do when ideas about conditions came up; there was little systematic support either at the beginning or end of instruction for students to translate variability and contest into shared definitions and measures. In future design iterations, we will capitalize on the findings, i.e., that students can problematize ideas about light during the development of experiments and explorations of model fit, and develop ways to help them engage more fruitfully around these questions as they emerge in instruction. We will also ask how the forms of practice appropriated by *most* students in the class can be amplified and made more accessible to all students.

Conclusion

There is an increasing consensus that students should enact scientific practices in knowledge-rich settings, so that knowledge and practice can bootstrap each other, as they do in professional science (Duschl et al., 2007; Metz, 2011). The *Next Generation Science Standards* (2013) exploits this relationship, in that each standard incorporates one of eight scientific practices with a target "core idea." For example, second grade students are expected to "plan and conduct an investigation to determine if plants need sunlight and water to grow" and "develop a simple model that mimics the function of an animal in dispersing seeds or pollinating plants" (NGSS, 2013, p. 17). However there is, as yet, little research to guide the pairings of practices and concepts in the Standards. In addition, the Standards do not yet acknowledge that neither practices nor concepts are likely to resemble their final form when seen in young students. This paper demonstrates that both of these issues will require attention if we are to design settings and teacher supports that foster the co-development of practices and central scientific ideas.

References

Berland, L. K., & Hammer, D. (2012). Framing for scientific argumentation. *Journal of Research in Science Teaching, 49*(1), 68-94.

Berland, L. K., & McNeill, K. L. (2010). A learning progression for scientific argumentation: Understanding student work and designing supportive instructional contexts. *Science Education, 94*(5), 765-793.

Berland, L. K., & Reiser, B. J. (2009). Making sense of argumentation and explanation. *Science Education, 93*(1), 26-55.

Berland, L. K., & Reiser, B. J. (2011). Classroom communities' adaptations of the practice of scientific argumentation. *Science Education, 95*(2), 191-216.

Bowen, G. M., & Roth, W.-M. (2007). The practice of field ecology: Insights for science education. *Research in Science Education, 37*(2), 171-187.

Cavagnetto, A. (2010). Argument to Foster Scientific Literacy. *Review of Educational Research, 80*(3), 336-371.

Chen, Z., & Klahr, D. (1999). All Other Things Being Equal: Acquisition and Transfer of the Control of Variables Strategy. *Child Development, 70*(5), 1098-1120.

Chinn, C., & Malhotra, B. (2002). Children's responses to anomalous scientific data: How is conceptual change impeded? *Journal of Educational Psychology, 94*(2), 327-343.

Cobb, P., Confrey, J., diSessa, A. A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9-13.

Cobb, P., & Whitenack, J. (1996). A method for conducting longitudinal analyses of classroom videorecordings and transcripts. *Educational Studies in Mathematics, 30*(3), 213-228.

Cole, M. (1996). *Cultural psychology: A once and future discipline*: Harvard University Press.

Corcoran, T., Mosher, F. A., & Rogat, A. (2009). *Learning progressions in science*: Center on Continuous Instructional Improvement, Columbia University, New York: Teacher College Press.

Davis, E., Petish, D., & Smithey, J. (2006). Challenges new science teachers face. *Review of Educational Research, 76*(4), 607.

diSessa, A. A., & Sherin, B. (1998). What changes in conceptual change? *International Journal of Science Education, 20*(10), 1155-1191.

Driver, R., Leach, J., Miller, R., & Scott, P. (1996). *Young people's images of science*. Philadelphia Open University Press.

Duncan, R. G., & Hmelo-Silver, C. E. (2009). Learning progressions: Aligning curriculum, instruction, and assessment. *Journal of Research in Science Teaching, 46*(6), 606-609.

Duschl, R., Schweingruber, H., & Shouse, A. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, D.C.: National Academies Press.

Eberbach, C., & Crowley, K. (2009). From everyday to scientific observation: How children learn to observe the biologist's world. *Review of Educational Research, 79*(1), 39-68.

Enfield, M., Smith, E. L., & Grueber, D. J. (2008). "A sketch is like a sentence": Curriculum structures that support teaching epistemic practices of science. *Science Education, 92*(4), 608-630. doi: 10.1002/sce.20252

Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and Instruction, 20*(4), 399-483.

Enyedy, N. (2005). Inventing Mapping: Creating Cultural Forms to Solve Collective Problems. *Cognition and Instruction, 23*(4), 427-466.

Ford, D. J. (2005). The challenges of observing geologically: Third graders' descriptions of rock and mineral properties. *Science education, 89*(2), 276-295.

Ford, M. J. (2005). The Game, the Pieces, and the Players: Generative Resources From Two Instructional Portrayals of Experimentation. *Journal of the Learning Sciences, 14*(4), 449-487.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423.

Furtak, E. M., & Alonzo, A. C. (2010). The role of content in inquiry-based elementary science lessons: An analysis of teacher beliefs and enactment. *Research in Science Education, 40*(3), 425-449.

Giere, R. N. (1990). *Explaining science: A cognitive approach*. Chicago, IL: University of Chicago Press.

Giere, R. N. (1999). *Science without laws*. Chicago: University of Chicago Press.

Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge: Cambridge University Press.

Glaser, B. G., & Strauss, A. L. (1967). *The discovery of grounded theory: Strategies for qualitative research*: Aldine de Gruyter.

Goffman, E. (1974). *Frame analysis: An essay on the organization of experience*. Boston, MA: Northeastern University Press.

Goldstein, B. E., & Hall, R. (2007). Modeling without end: Conflict across organizational and disciplinary boundaries in habitat conservation planning. In J. Kaput, E. Hamilton, S. Zawojewski & R. Lesh (Eds.), *Foundations for the future* (pp. 57-76). Mahwah, N.J.: Erlbaum.

Gooding, D. (1990). *Experiment and the making of meaning*. Dordrecht: Kluwer Academic Publishers.

Goodwin, C. (1994). Professional vision. *American anthropologist, 96*(3), 606-633.

Grandy, R., & Duschl, R. (2007). Reconsidering the character and role of inquiry in school science: Analysis of a conference. *Science & Education, 16*(2), 141-166.

Gresalfi, M., Martin, T., Hand, V., & Greeno, J. (2009). Constructing competence: An analysis of student participation in the activity systems of mathematics classrooms. *Educational Studies in Mathematics, 70*(1), 49-70.

Hammer, D., Elby, A., Scherr, R., & Redish, E. (2005). Resources, framing, and transfer. *Transfer of learning from a modern multidisciplinary perspective*, 89-120.

Hestenes, D. (1992). Modeling games in the Newtonian world. *American Journal of Physics, 60*(8), 732-748.

Hogan, K., & Corey, C. (2001). Viewing classrooms as cultural contexts for fostering scientific literacy. *Anthropology & Education Quarterly*, 214-243.

Hudicourt-Barnes, J. (2003). The use of argumentation in Haitian creole science classrooms. *Harvard Educational Review, 73*(1), 73-93.

Hutchins, E. (1995). *Cognition in the Wild*. Cambridge, MA: The MIT Press.

Hutchins, E. (2012). Concepts in Practice as Sources of Order. *Mind, Culture, and Activity, 19*(3), 314-323.

Jacobson, M., & Wilensky, U. (2006). Complex systems in education: Scientific and educational importance and implications for the learning sciences. *Journal of the Learning Sciences, 15*(1), 11-34.

Jimenez-Aleixandre, M. P., Rodriguez, A. B., & Duschl, R. A. (2000). Doing the lesson or doing science: Argument in high school genetics. *Science Education, 84*(6), 757-792.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences, 4*(1), 39-103.

Kelly, G. J. (2008). Inquiry, activity, and epistemic practice. In R. Duschl & R. Grandy (Eds.), *Teaching scientific inquiry*. Rotterdam: Sense Publishers.

Kelly, G. J., & Chen, C. (1999). The sound of music: Constructing science as sociocultural practices through oral and written discourse. *Journal of Research in Science Teaching, 36*(8), 883-915.

Kelly, G. J., & Takao, A. (2002). Epistemic levels in argument: An analysis of university oceanography students' use of evidence in writing. *Science Education, 86*(3), 314-342.

Klahr, D., & Simon, H. (1999). Studies of scientific discovery: Complementary approaches and convergent findings. *Psychological Bulletin, 125*, 524-543.

Knorr-Cetina, K. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge, MA: Harvard Univ Press.

Kuhn, D. (2010). Teaching and learning science as argument. *Science Education, 94*(5), 810-824.

Latour, B. (1987). *Science in Action*. Cambridge, MA: Harvard University Press.

Latour, B. (1990). Drawing things together. In M. Lynch & S. Woolgar (Eds.), *Representation in Scientific Practice* (pp. 19-68). Cambridge, MA: MIT Press.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. Cambridge, MA: Harvard Univ Press.

Lave, J., & Wenger, E. (1991). *Situated cognition: Legitimate peripheral participation*. New York: Cambridge University Press.

Lehrer, R. (2009). Designing to develop disciplinary dispositions: Modeling natural systems. *American Psychologist, 64*(8), 759-771.

Lehrer, R., & Schauble, L. (2006). Cultivating model-based reasoning in science education. *Cambridge handbook of the learning sciences*, 371-388.

Lehrer, R., & Schauble, L. (2012). Seeding evolutionary thinking by engaging children in modeling its foundations. *Science Education, 96*(4), 701-724.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive Development, 23*(4), 512-529.

Lehrer, R., Schauble, L., & Petrosino, A. J. (2001). Reconsidering the role of experiment in science education. In K. Crowley, C. D. Schunn & T. Okada (Eds.), *Designing for* *science: Implications from everyday, classroom, and professional settings* (pp. 251-278). Mahwah, N.J.: Lawrence Erlbaum.

Longino, H. (1994). The fate of knowledge in social theories of science. In F. F. Schmitt (Ed.), *Socializing epistemology: The social dimensions of knowledge* (pp. 135-158). London: Rowman & Littlefield Publishers

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071-1105.

Masnick, A., & Klahr, D. (2003). Error Matters: An initial exploration of elementary school children's understanding of experimental error. *Journal of Cognition and Development, 4*(1), 67-98.

McNeill, K. L., Lizotte, D. J., Krajcik, J., & Marx, R. W. (2006). Supporting students' construction of scientific explanations by fading scaffolds in instructional materials. *Journal of the Learning Sciences, 15*(2), 153-191.

Metz, K. E. (2011). Disentangling robust developmental constraints crom the instructionally mutable: Young children's epistemic reasoning about a study of their own design. *Journal of the Learning Sciences, 20*(1), 50-110.

Much, N. C., & Shweder, R. A. (1978). Speaking of rules: The analysis of culture in breach. *New Directions for Child and Adolescent Development, 1978*(2), 19-39.

Nersessian, N. J. (2008). *Creating scientific concepts*. Cambridge, MA: The MIT Press.

NRC. (2011). *A framework for K-12 science standards: Practices, crosscutting concepts, and core ideas*. Washington, D.C.: The National Academy of the Sciences.

Ochs, E., & Taylor, C. (1992). Science at dinner. In C. Kramsch & S. McConnell-Ginet (Eds.), *Text and context: Cross-disciplinary perspectives on language study* (pp. 29-45). Lexington, MA: DC Heath.

Passmore, C., & Stewart, J. (2002). A modeling approach to teaching evolutionary biology in high schools. *Journal of Research in Science Teaching, 39*(3), 185-204.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. Chicago: University of Chicago Press.

Ryu, S., & Sandoval, W. A. (2012). Improvements to elementary children's epistemic understanding from sustained argumentation. *Science Education, 96*(3), 488-526.

Sandoval, W. A. (2004). Developing learning theory by refining conjectures embodied in educational designs. *Educational Psychologist, 39*(4), 213-223.

Sandoval, W. A., & Millwood, K. (2005). The quality of students' use of evidence in written scientific explanations. *Cognition and Instruction, 23*(1), 23-55.

Saxe, G. B. (2002). Children's developing mathematics in collective practices: A framework for analysis. *Journal of the Learning Sciences, 11*(2-3), 275-300.

Saxe, G. B., & Esmonde, I. (2005). Studying Cognition in Flux: A Historical Treatment of Fu in the Shifting Structure of Oksapmin Mathematics. *Mind, Culture, and Activity, 12*(3-4), 171-225.

Schauble, L., Glaser, R., Duschl, R., & Schulze, S. (1995). Students' understanding of the objectives and procedures of experimentation in the science classroom. *Journal of the Learning Sciences, 4*(2), 131-166.

Shapin, S., & Schaffer, S. (1985). *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*. Princeton, NJ: Princeton University Press.

Stevens, R., & Hall, R. (1998). Disciplined perception: Learning to see in technoscience. In M. Lampert & M. L. Blunk (Eds.), *Talking mathematics in school: Studies of teaching and learning* (pp. 107-149). Cambridge: Cambridge University Press.

Vygotsky, L. (1978). *Mind in society* (M. Cole, V. John-Steiner, S. Scribner & E. Souberman Eds.). Cambridge, MA: Harvard University Press.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A., & Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. *Journal of Research in Science Teaching, 38*(5), 529-552.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Windschitl, M. (2004). Folk theories of" inquiry:" How preservice teachers reproduce the discourse and practices of an atheoretical scientific method. *Journal of Research in Science Teaching, 41*(5), 481-512.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967.

Yackel, E., & Cobb, P. (1996). Sociomathematical norms, argumentation, and autonomy in Mathematics. *Journal for Research in Mathematics Education, 27*(4), 458-477.

Zimmerman, C. (2007). The development of scientific thinking skills in elementary and middle school. *Developmental Review, 27*(2), 172-223.

APPENDIX A

INTERVIEW PROTOCOL

Post-instruction interview questions administered to all students in the class (selected questions that pertain to the Fast Plants investigation)

1. A few years ago, the backyard was just turf grass and the two magnolia trees. But that's not how it looks now. There are all these other plants and there are different kinds of plants in different places.

    a. How do you think all those plants got there?
    - *Probe if only mention human intervention:* Do you think there is a way that the plants could get into the backyard without people doing (X—whatever student said people did). How could that happen?
    - Tell me about what makes you think that plants got there by X (repeat what student said)
        - Probe: What's your evidence? If you were trying to convince someone that X is true, what would you say so that they would agree that this is how the plants got there?

    b. Why do you think there are different plants in different places? We mostly see strawberries by the wall, and then plants like the foxtail over by the fence. Why is that?
    - Tell me about what makes you think that X (repeat what student said)
        - Probe: What's your evidence? If you were trying to convince someone that X is true, what would you say so that they would agree that's why the plants are where they are?

    c. Probe for whether particular kinds of things matter:
    - *If student has not mentioned amount of sun:* Does the amount of sun in the backyard matter for where plants are? Tell me about where there is more and less sun. How did your class figure out that the amount of sunlight mattered?
    - *If student has not mentioned moisture:* Does the amount of moisture in the backyard matter for where plants are? Tell me about where there is more and less moisture. How did your class figure out that the amount of moisture mattered?
    - Is there anything else you think might matter for where plants are in the backyard?

2. Show picture of WFP question and investigation.
    a. Your class was trying to find out what the just right amount of light for Wisconsin Fast Plants is. What made you curious about that? What did it have to do with your work in the backyard?
    b. What did you find out the Just Right amount of light was?

c. How did you know? What was your evidence? (Probe once: Were there other kinds of evidence you used?)
d. Which do you think is the most useful kind of evidence for understanding whether a plant is successful: height, color of leaves, or number of seedpods? Why?
e. Why did you use WFP's and do an investigation indoors instead of just going right outdoors to look at the conditions in the backyard?
   - *Probe:* Does studying WFP's help you understanding anything about the plants or the conditions in the backyard?
   - *Probe:* Do you think there were any problems with using this investigation to understand what happens in the backyard?
      - Would it have been better if we used one of the plants in the backyard in our indoors investigation?
   - *Probe if student has NOT mentioned EITHER that there are different plants in the backyard or that the conditions in the backyard are different from the ones in our investigation*: Here was Mrs. Wade's argument at the end of the WFP investigation. Did you agree with it or disagree with it? Why?

> **Mrs. Wade's Argument**
>
> We found out that the just right amount of light for the Wisconsin Fast Plants is lots of light. I think that's the just right amount for all the plants in the backyard.
>
> So when we go outside, I think that we will find:
>
> - No plants in the shade
> - Some plants in the sun + shade
> - Lots and lots of plants in the areas that always get sun

3. You had to find out the Just Right amount of Light for the Wisconsin Fast Plants. Then you tried to figure out the Just Right amount of light for a plant in the backyard. Which was easier, figuring out the JR amount of light for the WFP or for your backyard plant? Why? Which do you feel more sure about? Why?

4. Another class set up an investigation to see if the amount of moisture mattered for the growth of the marigold plant. They had all the plants in lightboxes with the light on all the time. Some plants they gave 1 small cup of water to per day, some plants they gave 5 cups of water to per day, and some plants got 10 cups of water a day.

Show two students' evidence pages
   i. Day 4: one plant much taller than the other
   ii. Day 42: clear, neat drawing with labels, no evidence explained in writing

For each:
   - Say aloud: On Plant Day # X, this student said that X condition was more successful *point to relevant parts of evidence sheet.*

- Do you think that this student's evidence page is convincing? Does it do a good job of making you sure you agree? Why or why not?
- What questions would you ask to decide if you agreed with this student?
- How should the student improve his or her evidence page?

Evidence Sheet Plant Day Number 4

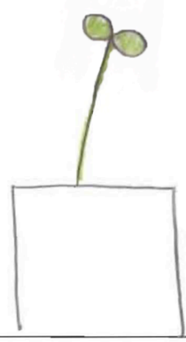
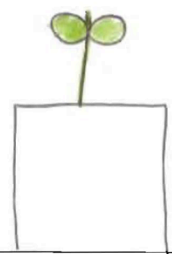
Here's what I think today:

☒ One condition is more successful (Which one? 10 cups)

☐ They are both doing the same

☐ I can't tell

My evidence:

Condition: 1 cup 5 cups 10 cups	*Condition: 1 cup 5 cups 10 cups*
Height: 40 mm	*Height:* 10 mm
Drawing: 	*Drawing:* 
I notice: This one is taller.	*I notice:* This one is shorter.

On the back of this page, write and draw about anything else you are noticing and wondering about

Evidence Sheet Plant Day Number 42

Here's what I think today:

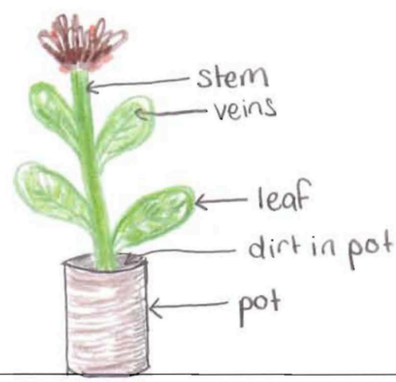
☒ One condition is more successful (Which one? 1 cup)
☐ They are both doing the same
☐ I can't tell

My evidence:

Condition: *1 cup* *5 cups* *10 cups*

Height: 200 mm

Drawing:

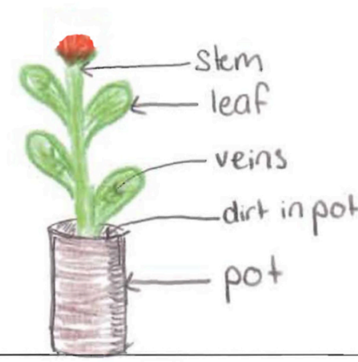


I notice:

Condition: *1 cup* *5 cups* *10 cups*

Height: 190 mm

Drawing:



I notice:

On the back of this page, write and draw about anything else you are noticing and wondering about

APPENDIX B

EPISTEMIC LEVELS OVERVIEW SAMPLE

	Teacher	Students construct	Students use	Students problematize	Aspects of disciplinary concepts
Invoked Mechanisms		EXP.			• Plant change: Stories of maturation • Plant needs: food from seed vs. making food from light • Plant needs: Plants dying if can't get enough nutrients/water • Qualities Place: light as burning plant
Backyard Claims					
Experiment-Backyard Relations		EXP. (R)			• Light as being like sun
Experiment Claims	EXP. animate, initiate	EXP.			
Op. Success	EXP. animate, use		EXP.	EXP. (Azh dying) EXP. (Azh water)	• Death • Plant Features: height, seedpods, true leaves, flowers • Growing/grown (can be defined)
Op. Conditions	EXP. position water as controlled		EXP.		
Comparison across conditions	EXP.	EXP.	EXP.		• Compare Feature (height) for purpose of making a claim about success
Data Displays	EXP. position	EXP.	EXP.	EXP.	• Plant Features (height)
Relating Aspects			EXP.		• Leaf kinds (contrast true and seed; use to indicate success/growth) • Signs of growth are multiple: seedpods, flowers, true leaves
Time	EXP.	EXP.			• Plant Features: height, seedpods, true vs. spiky leaves, height
Gen Cases	EXP. position	EXP.			
Measures	EXP.		EXP.	EXP. (R)	• Height • Problematize measure day (but apart from ideas of success)
Definitions		EXP.		EXP. (Dante's def)	• Size • Growing • Death
Inscriptions	EXP. animate				
Noticings	EXP. prob	EXP.	EXP.	EXP. (dying)	• Death • Plant Features: seedpods, seeds, flowers, true vs. spiky leaves, height, leaf size

EXP. = in experimental system, BY = in backyard system; R = Rare (one occurrence; not taken up)