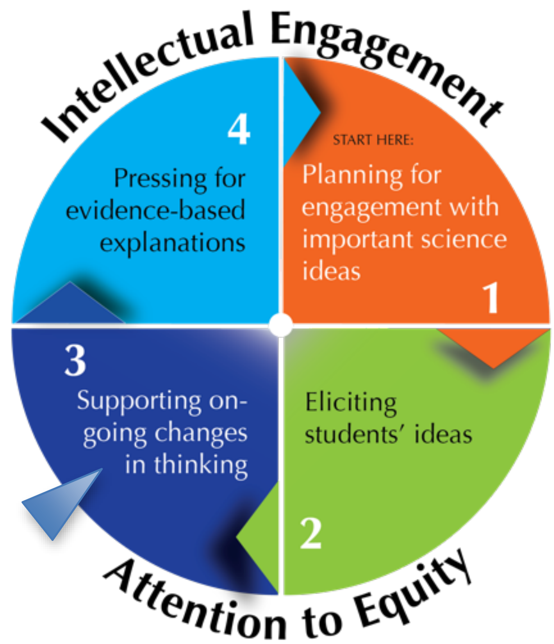
Teaching practice set: *Supporting on-going changes in student thinking*

Overview



Throughout a unit of instruction, students are frequently engaged in different types of activity. For example, students might do hands-on work with materials, use computer simulations, conduct observations of phenomena, design experiments, or collect and analyze different types of data. Students enjoy these activities because (ideally) they can make decisions about how to proceed, they can interact with peers as they work, they are challenged to think, and they like being recognized for doing science.

Unfortunately, the way activities are structured in many classrooms is far from ideal. Observations of these classrooms indicate that students typically follow rote procedures, they are rarely asked to wrestle with the conceptual underpinnings of the activity, and there are no attempts to link the activity with a larger phenomenon or set of science ideas. This is problematic because research on learning shows that mere exposure to hands-on activity does **not** lead to student understanding. Rather it is the sequencing and the type of sense making talk, orchestrated by the teacher, that prompts productive puzzlement, reasoning, and learning.

In this handout we provide you with a structure for thinking about the purposeful design of activity and for the critical forms of sense making talk that needs to be integrated with the activity. The practice set we describe with here is *supporting on-going changes in student thinking*. The 3 practices that make up this set are:

1) Introducing ideas to reason with
2) Engaging with data or observations
3) Using knowledge to revise models or explanations

The purpose of activity is to help students develop new ideas to use in revising their explanatory models for the anchoring phenomena. If the activity does not further this goal then it should be reconstructed or discarded.

Goals

- To ensure students understand why the activity makes sense to do at this point in the unit (“Why are we doing this? What gaps does this help me fill?”)

• To help students bridge the activity with a larger scientific idea (answers the question "What in the natural world does this activity help me understand, and how?") Students should be able to explain this activity in terms of some scientific idea.

• To support the development of students' academic language, using the activity as a context. One aspect of academic language support is helping students understand the conventions or symbolism used to represent the phenomena (typically in written or drawn form), as well as vocabulary and science-specific rhetoric (i.e. ways of talking about evidence, referring to models as tentative ideas, hypothesizing).

"What counts" as an activity?

• **Teacher demo**: Can run the spectrum from teacher driven to being changed at the students' request (in order to "see what happens" OR to test a hypothesis that makes sense to them)

• Students do a "**proof of concept**" demo, just to prove some relationship or fact. Example: Using Web-based traffic cams from around world to check patterns of day-night at different latitudes.

• Students in groups **design their own study** (within limits set by teacher—sometimes we give students choice of what variable to test), collect data, analyze it.

• Students in groups **working with second hand data** (meaning collected by someone else). Examples are data from the health department collected on the cases of asthma in urban areas OR data on ecosystem populations in Antarctic).

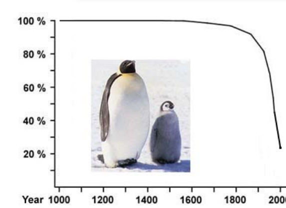
• Students in groups do a **paper and pencil task that simulates real data collection**. Examples are building an energy pyramid in a unit on ecology by passing down "energy" from one level to another. Here they are actually collecting data FROM a model.

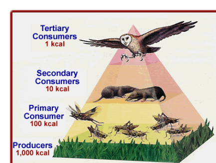
• Students in groups do **paper-and pencil activity not to collect data but to understand a concept**. An example is to use a topographic map to understand what a watershed is and its relationship to distributions of flora and fauna.

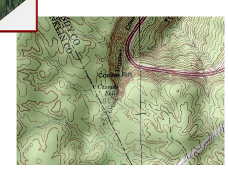
•Students in groups use a **computer simulation to produce data** that could not otherwise be collected. Again, they are actually collecting data FROM a model.

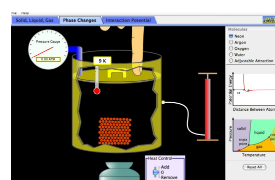
• Students in small groups circulate around room to different **stations** that each are brief demos, but all the stations target the same scientific concept. Examples are stations that demonstrate the Bernoulli effect (low and high air pressure).

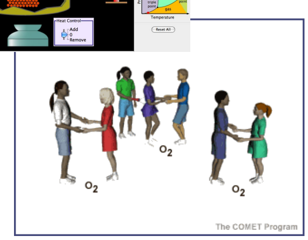
• Students act out "**Science Theater**"—physically representing some science idea with their bodies. Examples are molecular motion or interactions between species in a closed ecosystem.











Being purposeful about selecting activities

Activities should be carefully selected and *always* adapted for your students (never just used as is from the curriculum). The only criteria is that the activity should *help students understand some aspect of the anchoring phenomenon* or big ideas of the unit. This is why it's important for you as teacher to write out the full explanation for the anchoring event and draw the model before you plan activities for the unit. For every part of the underlying explanation, you should devote at least one learning experience for students. Many of these learning experiences can be grounded in activity. For example, if you are teaching about plate tectonics, then an activity around convection currents would be important.

A purposeful activity supports the development of the anchoring event. The purpose of these activities to establish a shared experience around which a common language and set of ideas can be built. For students, it is for them to explore:

- how an activity relates to other real world phenomena
- how to represent data related to the big idea
- how to represent ideas that make up a larger big idea
- how to use tools of science while they investigate the big idea
- how to measure things or processes and analyze data related to the big idea
- how to understand conventions used in various kinds of representations (what graphs or vector arrows in a model mean for example)

Purposeful activities also hold students accountable to identify and process "what is happening"—you should be assisting them, but not spoon-feeding them.
During activities, it can be tempting to become overly focused on "variables" talk, procedure writing, error analysis, lab report writing, etc. These are intellectually lean activities; resist the temptation to put these at the center of instruction. Rather, keep your focus on using the activity to develop the explanatory model.

When do you use this practice?

These practices are typically used sometime after you have worked to elicit hypotheses from students about how and why a relatively complex phenomenon happens the way it does. The kind of activity described in this handout can help students build understandings of key *parts* of the anchoring event (but *not the whole* big science idea).

How to enact this practice

Before we address the parts of these practices, we want to make clear that these should be repeated multiple times throughout a unit. ***Multiple activities*** and ***multiple rounds of sense making*** are required to build towards a deep understanding of an explanatory model. A single activity is not enough to accomplish this.

On the following pages we provide a description of each practice and a possible sequence of talk to guide you. We emphasize that these are not scripts. In our work with teachers we have never seen the same conversation with students twice, even using the same topics and curriculum.

1. Introducing ideas to reason with

This is a *time for telling* by the teacher. Students need ideas to use as leverage as they engage in the upcoming activity. What do we mean by this? The explanatory model that underlies your anchoring event will have unobservable processes, structures, events that explain what *is* observable. These might include features that are inaccessible (i.e. the layers of the earth or how the brain senses carbon dioxide levels in the blood), structures or processes that are too small (i.e. atomic structures, chemical reactions), or that are conceptual (i.e. selective pressure, the compression feature of sound waves, unbalanced forces).

For all the wonderful sense making that students are capable of, they cannot spontaneously invent these ideas when they engage in any form of activity. Students can see patterns and make sense of the observable, but they cannot "come up" with things like alleles, kinetic molecular motion, or the electromagnetic spectrum. In order for your students to make sense of activity, they need *ideas to reason with* as they do the activity, *we do not mean that the activity is designed to simply confirm what the teacher has told them.*

These conceptual ideas must be presented to students. This can be done with combinations of readings, media, or presentations by the teacher. Here is what we recommend (many of these recommendations can be used when you are trying to help students build a skill too, like graphing, using Punnett Squares, using topographical maps):

- Plan for 10-15 minutes of presentation, ask students to have their lab notebook out.
- Begin by linking verbally what was done by student previously to a need to know a new idea. Describe how this new idea can move their thinking forward. Students really appreciate knowing why this segment of teaching is important to them.
- Be explicit about any new vocabulary that you are introducing, what is this term? Why do we need it? Don't introduce too much.
- Try to link a new conceptual idea to a concrete example, or if that does not apply, try to think of a metaphor to help students visualize.
- Try to have two different representations of the same concept, and help students reason about the links between the two representations. What counts as a representation? These could be a picture, graph, chemical equation, a story, diagram, model, video, etc.
- Avoid all pronouns (it, this, that, them, they) because students often do not know what you are referring to.
- A couple times during your presentation, do "check-in questions" to see if your students can comprehend the representations you are using, or parts of the idea itself. Use the "turn and talk to your neighbor" to have them weigh in on an idea or about how one representation relates to another. Another version of the check-in is to ask a "what-if" question.
- Have a time at the end of the presentation to ask, what is puzzling you? What do you think you still need to know?
- After the presentation, it is time to introduce the activity.

2. Engaging with data or observations

Whatever your activity, provide written and verbal guidance; physically model the procedures if you have ELL students.

To start, here is your plan of action: You are going to have students working in small groups. You will have written about 4 good questions on an index card to refer to ask as you visit each group. These are called "back-pocket questions."

The purpose for visiting each group is not to check to see how far along they are procedurally (if they falter at this you need to revisit how you are giving directions and modeling what they are to do). Rather, your visits are to listen to their current thinking, then ask questions that either probe more of their thinking, to re-direct them to some part of the activity or representations they are working with that is important to further their understanding.

This is the first of two "laps" you are doing around the room. Because you want to hear the voices and thinking of as many students as possible, you will plan for about 3 minutes with each small group. You approach the group, get down at their eye level, you face the rest of the class (keep one eye on the whole room). The first minute is for listening. The remaining time is for asking back-pocket questions that are responding to what you have just heard from students. It is often helpful to pose a "leaving" question—it might sound like this: "OK, I want to leave you with this question, talk about among yourselves about [ask question or pose a small challenge for them].

Here is a representation that captures just a bit of what kind of interaction might happen in this phase. Bear in mind, that no representation of conversation can ever show all of what might happen through talk.

Teacher: What are you seeing here? (or similar broad questions about observation)	
Students might cite relevant observations, relationships. Students describe patterns as "meaning something."	**Students** might be focused on extraneous features of the activity.
Teacher: "Can you tell me how you came to that conclusion? Do others agree here?" "So what can we infer from this? Can you hypothesize what might be going on here based on our background reading?" (try to hear from everyone in the group). "What if" we changed something in this system? Don't respond with "Correct!" "That's right!"	**Teacher:** "But what do you notice about ___?" [Direct their attention to salient features of activity or observation]. Prompt them to recall an idea in a prior lesson: "So what have we been studying the past few days? What do we already know about ____? Or How do you think this is related to ____?"

Your second set of interactions in the small groups (your second "lap" around the room) should be an assessment of whether students understand how this activity connects to the big idea of the unit, or the anchoring event. As you circulate, you should be identifying for yourself any groups that have unique ideas or parts of an explanation. These students can be asked to share their ideas with the whole class in the next few minutes. You can prep your students about what and how to share in front of the class if they are nervous.

Teacher: Can you explain how this activity helps you understand [the anchoring event]? (this prompt should also be built into the directions for the activity)	
Students make connections between the activity and the anchoring event or essential question of the unit.	**Students** seem to hesitate or rely on vocabulary.
Teacher: How is what you are doing an example of [some process related to the big idea or anchoring event]? Follow-ups: "Can you tell me more?" "Do you all agree?" "Would anyone else like to add on?" "What else do you need to know now?" "Any gaps that you'd like to fill?"	**Teacher:** "What are you [analyzing, creating here, doing observations of]?" "Let's look at just this part of the activity or observation—is it anything like [the anchoring event]?"

In the next step you return to whole class conversation. This is where you can help students see broad trends or patterns of data for different groups in the classroom. You then need to help students "map" these onto a real world situation. Students' new questions should be addressed, not put on the shelf.

It's also important to note that teachers are trying to get students to talk to each other, not just to respond to the authority figure in the room. This happens in small groups and can be designed into whole class conversations.

<table>
<tr><th colspan="2">Teacher:
What do we think we know now, about our anchoring event (or essential question)?</th></tr>
<tr><td>Students make connections between the activity and the anchoring event or essential question of the unit.

Teacher:

Why do you think you saw the trends or differences that you did? [some process related to the big idea or anchoring event]?

I heard some different hypotheses when we were doing small group work, can anyone share their thinking with the class?

Follow-ups: “Can you tell me more?” “Do you all agree?” “Does anyone have a different idea?” “Would anyone else like to add on?”</td><td>Students seem to hesitate or rely on vocabulary.

Teacher:

Turn to your partner for a few minutes, decide what you found and how it might tell us something about the big idea.</td></tr>
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3. Using knowledge to revise models or explanations

In this step the whole class returns to some public representations of students’ thinking that you’ve chosen for this unit. One public record that is really necessary to work on is the *Summary Table*. You should always add to a Summary Table at the end of an activity. After adding to the Summary Table, you could:

1. Add to, revise, consolidate an explanation checklist
2. Use post-it notes to revise your small group models (you need to do this once in the middle of a unit, not after every activity).
3. You could cite a list of possible hypotheses for your anchoring event and ask the whole class, “Which of these do we think is now more likely? Why?”

Whatever the type of public record, have a whole class conversation about what should be added, taken off, linked together, questioned, etc.

Finally, ask “What questions does this leave us with?” “What are you not sure about after doing this activity?” “What additional information do we need?”

* * * * *

Glossary of terms often used to describe common classroom activity.

Inquiry. Inquiry, unfortunately, can mean anything that is not direct instruction. It is not useful to use with other teachers to explain what it is you are doing in the classroom.

Verification lab (use sparingly). This is an activity in which the teacher has presented a full explanation of some principle and the students simply carry out an activity to say "voila, it happened just as the teacher said it would." These are not entirely purposeless, at the beginning of a unit you may use this simply to demonstrate a phenomenon. But verification labs should never be the staple of classroom activity. As you can imagine, there is little sense of wonderment, curiosity or intellectual accomplishment. And, there is a low ratio of intellectual work material work (see definitions of these types of work below).

Discovery lab (avoid). This is the unfortunate opposite of the verification lab. This is a lab where teachers have so little structure that they expect the students to stumble upon the same explanation for a phenomenon that is took scientists years to formulate. Students cannot possibly discover on their own, theoretical or abstract things or processes. What students can do is observe, infer what might be causing some activity, and note patterns and trends in the observable data.

Lab. Like the word "inquiry", this term encompasses so many types of activity, that is has no real meaning. That is, teachers cannot use the term with one another to plan for specific types of intellectual engagement for students.

Material work. Material work is the portion of student activity that is "hands-on" and has relatively little intellectual work associated with it (setting up equipment, formatting posters, mapping out where recent earthquakes have occurred, drawing an ecosystem, etc.).

Intellectual work. This is activity in which students work towards creating some meaning of an idea or of observations. This includes meaningful problem-solving, generating ways to observe phenomena, analyzing data, making connections between ideas, etc. This can happen on the social level, or it can happen "in-the-head."

FYI: What the research says about supporting on-going changes in student thinking (note, this is in "researcher language")

If you are interested in the origins of this type of discourse practice, we present here the research background that supports it:

In this section we explore teaching practices described in the literature that supports progressive changes in student thinking and participation across a unit of instruction. We assume here that teachers are anchoring the instruction in a complex problem, that they have elicited students' initial ideas, and found ways to respond to the resources that students bring to learning this particular set of ideas. With these as pre-conditions, the important questions here become: What intellectual work will be valuable for learners to engage in on a regular basis? What is the purpose of these activities? and What frameworks exist for designing this work? Nearly all lines of research that are successful in documenting robust and equitable forms of learning depend upon practices that constantly monitor changes in student thinking about selected facets of a complex problem or question. These changes are prompted by new observations, ideas, and the logic expressed by others in the classroom, not merely by exposure to material work. To facilitate such changes teachers use repeated cycles of similarly structured activity, and often revisit with students the overarching problem of the unit to apply what has been learned.

The larger aim is not just refining a particular idea or moving toward a particular solution to a problem, but also to develop more capable thinkers over time (i.e. increasingly independent of guidance by the teacher) by helping students understand how to frame problems, use various social and conceptual resources, and to monitor one's own progress towards understanding. This broad vision is shared by a number of prominent frameworks for the design of learning environments, which draw from diverse literatures including cognitive science, social psychology, science studies, and cultural anthropology. Among these are Brown and Campione's *Fostering a Community of Learners* (1996), Engle and Conants' *Productive Disciplinary Engagement* (2002), Scardemialia and Bereiter's *Knowledge-Building Environments* (2006), and Nasir et al.'s (2006) *Learning as a Cultural Process*. These frameworks reflect different emphases—some on individual reasoning and complex content, some on learner identity and engagement, some on the disciplinary basis for instruction, and some on social processes in learning. Importantly however these frameworks all recognize that students' everyday experiences, ideas, and talk about science are not obstacles, rather this heterogeneity is the means by which the science knowledge of the collective can be made more elaborated, flexible, and durable.

Looking across these frameworks some commonalities are evident, not the least of which is their attention to all learners in the classroom. The principles below are reflected, explicitly or implicitly in each framework. They emphasize the conditions that have been known to foster more sophisticated disciplinary reasoning, including broadening what can be used as resources, scaffolding disciplinary talk and thinking, and making ideas the objects of critique and reflection. Rigorous and equitable instruction:

- problematizes the content while making it accessible to learners;
- makes thinking visible and public;
- makes tools and resources available for students to use in revising their thinking over time, this includes not only instructed concepts and designed experiences but also access to the ideas, questions, and confusion of others;
- uses discourse for its full range of productive purposes, that is, for building and reinforcing productive identities and relationships as well as for the on-going sharing and critique of ideas;
- makes disciplinary norms of talk and activity explicit while holding students accountable to these norms; and

• supports meta-cognition in terms of both reflection on work/thinking, and monitoring one's progress toward valued goals.

In the following section, we describe the instructional context into which most of the principles have been successfully integrated. That context involves scientific modeling.

Modeling as the context for advancing ideas over time

In the literature, extended intellectual work has increasingly taken place in the context of progressive modeling (also can be conceptualized as theory change over time). Modeling in simple terms is representing a set of inter-related ideas about a natural phenomenon, then changing the relationships within the model in response to observations, new ideas and argument. Students refine explanations using the evolving model as a tool to reason with and about. To be clear: we do not refer to computer models, graphs, maps, or physical replicas as the types of models that are commonly subject to change by students over time. In most classroom studies, models for model*ing* are drawn by students as roughly pictorial representations with labels for observable and unobservable features of phenomena. These are paper and pencil renderings—simple technology to be sure—but these are "owned" by students and effective for supporting reasoning.

There are several reasons why studies of modeling appear with increasing frequency in the literature on science teaching. Modeling is a fundamental disciplinary activity of 21st Century science that is intimately related with other knowledge-building practices. For example, models are catalysts for new questions and hypotheses to test, data are analyzed with the specific intent of filling conceptual gaps in models, and scientists use models to support claims and argue for explanations (Hempel, 1966; Knorr-Cetina, 1999; Kuhn, 1970; Latour, 1999; Longino, 1990; Ochs, Jacoby, & Gonzales, 1994). In accounts of classrooms that make modeling a central endeavor, the associated scientific practices encourage public theory-building and provide the contexts in which epistemic abilities, social skills, and cognitive capacities are developed (Duschl & Grandy, 2008; Gobert & Pallant, 2004; White & Frederiksen, 1998).

Unfortunately models are not typically used this way by teachers, they are more often employed to illustrate textbook ideas. Most teachers, for example, believe that models are useful only as visual aids to help explain canonical ideas to others, or to demonstrate abstractions (Cullin & Crawford, 2004; Smit & Finegold, 1995). Teachers rarely mention how models are used in making predictions or used as tools for testing ideas about targets that are inaccessible to direct observation (Harrison, 2001; Justi & Gilbert, 2002; Van Driel & Verloop, 2002). There is an awareness of the value of models in explicating science concepts but not of their value as tools for thinking about a range of phenomena or as the object of evidence-based revision. Even when teachers ask students to draw out their own understandings in the forms of pictures or diagrams, such displays are disconnected from knowledge-building activity—students simply "posterize" final form science ideas.

A very different vision of using models is expressed in several lines of classroom research that show significant gains in conceptual learning and gains in the sophistication of epistemic practices for students over time or in comparison with students who are learning content in more traditional ways. The subject matter ranges from forces and motion to natural selection; the grade levels range from kindergarten through high school (Chinn et al., 2008; Danish & Enyedy, 2012; Gobert, 2000; Lehrer & Schauble, 2012; Passmore & Stewart, 2002; Schwarz et al., 2011; Stewart, Cartier, & Passmore, 2005; White & Fredericksen, 1998). The general pattern of instruction in these studies begins with identifying a set of important science ideas and selecting a puzzling, complex event to anchor the unit of instruction (our first "core" practice, or cluster of practices). Students' ideas are elicited in order to adapt instruction, then iterative rounds of activity, talk, and reasoning are designed (our second "core" practice or cluster of practices). What typically follows in teaching practice is a succession of activities for students, some of which may be designing experiments, looking at second hand data, proof of concept demonstrations, the use of media, doing readings, presentations of ideas by the teacher, various forms of small group work, or discussion. Teachers and students regularly return to their models and assess whether changes need to be made and why.

There is nothing magical about models; in the studies cited above they are simply constructed public objects that make *changes* in thinking more visible and organized. They represent hypothesized relationships between ideas; as such they are well suited for understanding complex, puzzling phenomena that require the coordination of a number of ideas, theories, facts, and knowledge of situations in which the events or processes are embedded. There is general consensus in the literature that opportunities to explore relationships between ideas, and the contexts within which sense can be made of them, stimulates learning. For example, making references during instruction to natural events in the past and imagined future ones (something that models can support) facilitates transfer of ideas to new situations (Brown & Campione, 1996; Cole, 1996; Forman & Ansell, 2001), as does explicit requests to make sense of larger scale science ideas by referencing smaller, component ideas that have just been investigated, and linking multiple ideas and experiences together to understand a complex problem (Arzi, Ben-Zvi & Ganiel, 1985; Bango & Eylon, 1997; Linn, Davis, & Eylon, 2004; Perkins & Salomon, 1988). Understanding the connections among ideas enables learners to both organize them and integrate new ideas into what they already know (Bruner, 1960/1995; diSessa, 1993). Successful teaching supporting these integrations has scaffolded frequent comparisons between ideas and assisted students in reorganizing their ideas—both of these challenges are made more tractable in modeling environments (Linn, Davis, & Eylon, 2004; Parnafes, 2012).

Productive examples of modeling in classrooms share several characteristics: 1) thinking is made visible and public with models, 2) students build into their models relationships between observable and unobservable features of events, structures and processes, 3) models serve to connect ideas arising from multiple activities as students revisit and revise these over time, 4) teachers become more aware of student thinking and conceptual change, 5) models serve as concrete referents for students' hypothesizing and explanatory discourse, and 6) models allow students to critique one another's claims and use of evidence. What has been important in studying these classrooms is not isolating these features as variables, but to understand how such conditions work in concert with one another to influence students' learning and reflection.

Models are of greatest benefit when supporting purposeful lines of talk about how evidence might change the representation. In working with seventh graders on modeling the effects of exercise on muscles, Buckland et al. (2008) found that changes in the classroom norms of discourse coincided with opportunities to generate drawn artifacts which in turn supported more productive forms of whole-class argumentation. They concluded that to advance science ideas, students need frequent opportunities to combine talk of evidence with talk about the theory that is embedded in their current model. Roth et al., (2009) found that substantial learning gains in classrooms occurred when teachers not only selected analogies, metaphors, and visual representations that were clearly linked with the learning goals, but also when they engaged students in "creating, modifying, and analyzing various representations" (p. 12). In these examples and others, working with models is tightly linked with developing explanations.

This kind of teaching requires a repertoire of discursive moves by the teacher that allows everyone to work on ideas and in broader terms to use the social medium of talk to refine conceptual and epistemic stances toward different scientific claims. Michaels et al. (2009) examined the literature on discourse and learning to extract the moves that prompt students to recognize and compare ideas and to press for explanation. These include: revoicing (So let me see if I have your thinking right, you are saying that…), asking students to re-state someone else's reasoning (Can you repeat what she just said in a different way?), asking students to apply their own reasoning to someone else's reasoning (Do you agree? Why?), prompting students for further participation (Would someone like to add on?), asking students to explicate their reasoning and provide evidence (Why do you think that? What's your evidence?), and challenging or providing counter-example (Does it always work that way?). This language appears frequently in the dialogue of expert teachers (see Minstrell & Kraus, 2005; Lampert & Graziani, 2009; Lee, 2007; Sohmer, Michaels, O'Connor, & Resnick, 2009).

Helping teachers learn to use such talk productively has been mixed. In a quasi-experimental study Penuel et al. (2012) compared a group of earth science teachers who learned to use tools to orchestrate productive talk in classrooms (eliciting thinking and reasoning, using follow-up questions designed to probe students' thinking, re-voicing which allows for the student to agree with, challenge, or modify the teacher's inferences) with a similar group of teachers using the same curriculum but who did not have access to the tools. The experimental group outperformed the comparison groups' students in two different units of instruction. Qualitative observations of classrooms in the treatment group showed that the classroom had a slower pace, students were asked to imagine why answers they did not pick were reasonable, there were longer turns at talk, and student turns focused on reasons for their responses.

The orchestration of such discourse in some settings, however, can be highly problematic. In an analysis of affordances and constraints for scientific discussion in high school project-based science, Alozie et al. (2010) found that even with supports for productive discussion, teachers still relied on traditional recitation formats and low cognitive demand evaluative questions. Institutional pressures appeared to work against learning when teachers in this study expressed concerns that they needed to cover content quickly in abbreviated time periods in order to be seen as addressing state standards. In other cases it can be difficult for students from non-dominant groups who do not command middle class language practices to participated in or be understood in the restricted space of school discourse (Calabrese Barton & Tan, 2009; Warren et al. 2001). In some instances students are made to feel their everyday experiences and theories are of no value. In a study of how learners participate in discussions about climate change, Moje and her colleagues (2004) found that urban youth they followed in and out of the school settings rarely volunteered everyday knowledge in science classrooms, even when their prior experiences were relevant to the current science topic. These students were constantly trying to navigate between different cultures and different "rules of engagement" in the contexts of school, family, and peers, often with little assistance from teachers in making these transitions. When teachers make clear that different types of knowledge and experiences are welcome in the science classroom, they construct a discursive space that helps students navigate everyday and school worlds (Brown & Ryoo, 2008).

Inquiry as an under-theorized representation of science

The reader will note that to this point we have not often mentioned inquiry, and there are reasons for this. For the past 40 years, inquiry has been portrayed as the quintessential experience for learners in science. The previous National Science Education Standards (NRC, 1996) featured inquiry both as special disciplinary pursuit and a pedagogical approach that includes posing questions, designing studies and proposing explanations based on evidence. However, in classrooms during this time nearly everything that was not direct instruction (including library research, using equipment, group work, etc.) has flown under the banner of inquiry (see analyses by Blanchard, Southerland & Osborne, 2010; Luft et al., 2011; Minner, Levy & Century, 2010; Spillane, Reiser, Reimer, 2002). Inquiry does not have the characteristics of a practice, but rather it is a broad approach that makes its value for learning difficult to assess. Inquiry is often reduced to process skills that are not used to build theory, but to confirm known facts. In other cases inquiry is enacted through "The Scientific Method." This formula has been critiqued as conceptually narrow (Rudolph, 2005), as a "folk theory" about disciplinary activity that constrains how teachers plan for instruction (Windschitl, 2004), and as demonstrably inhibiting the intellectual work of students (Tang, Coffey, Elby, & Levin, 2009). The number of scientists who have refuted the notion of a scientific method is too long to recount here. References to The Scientific Method now appear less frequently in scholarly work as a serious representation of disciplinary practice, yet this caricature of science remains firmly entrenched in school culture around the world. Our view is that the education community has not been able to fashion an alternative image of investigative science that is comprehensible, intellectually honest, and that translates into meaningful classroom activity.

For these reasons and others, the National Research Council's Framework for the *Next Generation Standards* (NRC, 2012) has purposefully reduced the references to inquiry and instead refers to science practices. This new conceptualization of disciplinary work is viewed as an advance because "It minimizes the tendency to reduce science to a single set of procedures, such as identifying and controlling variables, classifying entities, and identifying sources of error. This tendency overemphasizes experimental investigation at the expense of other practices, such as modeling, critique, and communication" (p. 3-2). This view of science-as-practice also serves as a corrective to the tendency for inquiry to be experienced in isolation from science content. It is all too common for skills like hypothesis testing or data analysis, for example, to become the aim of instruction rather than a means of developing a deeper understanding of the concepts and epistemology of science.

Despite the ambiguities associated with inquiry, there is a history of engaging students in active investigations that deserves review. Studies that compare an inquiry approach with more traditional types of instruction report similar outcomes—that there are modest but statistically significant differences favoring the inquiry condition (Blanchard, Southerland, & Osborne, 2010; Fogleman, McNeill, Krajcik, 2010; Furtak, Seidel, Iverson & Briggs, 2012; Kahle, Meece, & Scantlebury, 2000; Lynch, Kuipers Pyke, & Szeze, 2005, Marx et al., 2004; Wilson, Taylor & Carlson, 2010). At the systems level, gains in student learning are more likely when the efforts of teachers, district coaches and administrators are coordinated around teaching in non-traditional ways, when teachers receive extensive professional development, and when classroom engagement in inquiry lasts for a prolonged period. In one such study, Marx et al. (2004) worked with middle school teachers, students, and district personnel in an inner city environment in Detroit, Michigan. This three-year program engaged approximately 8,000 students in inquiry-based and technology-infused curriculum units that were collaboratively developed by district personnel and staff. Results showed statistically significant gains on students' posttests, and that the strengths of the effects grew over the three years of the study. At the level of instruction, scaffolding appears crucial. In a recent meta-analysis of 37 experimental and quasi-experimental studies that contrasted different level of guidance for inquiry, Furtak et al. (2012) found that conditions in which teachers provided various types of guidance had a large positive effect size compared with unguided forms of inquiry and with traditional teaching conditions. Other studies have shown no significant differences or inconclusive findings (Lederman, Lederman, Wickman, & Lager-Nyqvist, 2007; Pine et al, 2006). In a number of these studies, however, the inquiry experience lasted only a matter of days, or there were weak supports for students in doing the work.

The clearest finding common to all the recent meta-analyses is that, despite crisp definitions of inquiry offered in documents like the former *National Science Education Standards*, how it is enacted in classrooms is quite inconsistent. In different investigations mentioned above, inquiry was taken to mean using curriculum kits, doing projects, doing hands-on work of various types, using the 5-E model, and/or having students engage in material activity rather than have the teacher do them as demonstrations. In the UK, the concept of "practical work" encompasses a similar swath of instructional arrangements—experiments, investigations, lab work, etc. (see Abrahams & Reiss, 2012). A review of inquiry in science education by Minner, Levy, & Century (2010) concludes that "It is precisely the lack of a shared understanding of the defining features of various instructional approaches that has hindered significant advancement in the research community on determining the effects of distinct pedagogical practices" (p. 476). The NRC (2012) notes that "[s]uch ambiguity results in widely divergent pedagogic objectives—an outcome that is counterproductive to the goal of common standards" (p. 3-2). Without clearer visions of authentic practice, there can be no cumulative knowledge base that develops on effective teaching and on learning environments in general. Even what one measures as outcomes becomes unclear. Most problematically, the lack of common vision works against the continual improvement of teaching—by individuals and by the field.

Summary

The work of science teaching is increasingly being conceptualized as supporting on-going changes in student thinking about challenging questions or puzzling situations associated with natural phenomena. These changes can take place in the context of scientific practices that draw upon inter-related conceptual, social, epistemic, and material activities. Of the principle scientific practices described in the literature, modeling appears to be unique in that it can serve as a super-ordinate activity, organizing and motivating engagement in other practices that, in total, support the iterative refinement of science ideas by learners. The images of instruction aligning with such practices are likely unfamiliar to most educators; there are few if any reports of teachers engaging in this type of work unless they have had extensive professional development with ambitious forms of pedagogy. Orchestrating this activity calls for a diverse tool kit of talk moves and strategies for continually working on productive social norms in the classroom. Attention to talk however is not all that should attract researchers' attention; students bring a whole range of resources to the classroom that we are just beginning to understand. Much more work is needed on how teachers recognize and capitalize on resources such as partial understandings, students' everyday language, and their everyday experiences to shape learning. There is strong anecdotal evidence that some teachers are pre-disposed to attend to student reasoning and to use students' ideas productively in instruction, while other teachers appear unable to recognize or cultivate student reasoning—the latter rendering many professional development efforts ineffective. Is responsiveness, which is crucial to ambitious teaching, "instructable" in teacher training or in professional development? The short answer is "We don't know."

Another under-theorized area of research is teacher' use of tools to help students accomplish various forms of intellectual work together. Given the promising accounts of the effects of scaffolding in science teaching, the door is open for investigations of how tools and created are used in classrooms by both teachers and students. There are scattered reports, for example, of how sentence frames, visual organizers for these, and guides for epistemic talk have not only supported student participation in important forms of collective work, but true to sociocultural paradigms have transformed the teaching practice itself.

The research described in this section encompasses two broad types of activity, each of which might constitute a core practice. One of these involves scientific work such as hypothesizing, carrying out studies, and making sense of data patterns and new ideas. The other involves using the knowledge products from such work to revise one's existing theories or models. These two complementary sets of activity could be used multiple times throughout a unit as students gradually work toward more coherent, elaborated, and accurate scientific understandings of complex phenomena. Clearly there are many possible representations of this work, however we have crafted this particular example by using principles that have an evidence base in the literatures we have cited in this section. We note that not all the principles we have articulated can be explicitly embodied in this concise description of practice.

Research-based Principles that should guide all variations of this practice

- To work on students' ideas, thinking must be made visible and public
- Learners cannot "discover" theoretical entities or processes; these must be introduced at strategic times by the teacher and used as tools to reason about phenomena, rather than be confirmed in activity.
- Students can learn to participate in science if the epistemic "rules of the game" are made explicit and modeled by others.
- Scientific practice best supports learning when treated as an ensemble of activities that derive meaning from one another.
- Knowledge production in the classroom and in science is supported when theories/models are revised over time to become more consistent with evidence and more internally coherent.
- Tools and scaffolding are necessary to do the intellectual and social work of science
- Material activity by itself is weakly linked with learning. Sense making talk during and after activity and opportunities for metacognition (thinking about one's own ideas/reasoning) are more strongly linked with learning.

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