Cultivating 21st Century Skills in Science Learners: How Systems of Teacher Preparation and Professional Development Will Have to Evolve

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In this document I offer recommendations for the design of teacher preparation and professional development models that can sustain the career-long development of ambitious pedagogy— including approaches to instruction that can cultivate 21st Century skills in young learners. I begin by describing what it means to be a "reform-oriented teacher," articulating characteristic performances of advanced instruction with the kinds of 21st Century skills they foster in young learners. Following this I review the landscape of science instruction in classrooms today, then use the current literature to build a case for a different vision of teaching and what it would take to prepare educators to support this vision. Finally, I summarize the evidence around how teachers take up practices that are pedagogically sophisticated but rarely modeled in classrooms.

Current vision of reform science and its relationship with 21st Century skills

Over the past five years, ideas about effective instruction in science classrooms have achieved new clarity through converging scholarship across the areas of science studies, student learning, assessment, and curriculum (summarized in National Research Council, 2005a; National Research Council, 2005b; National Research Council, 2007). The recent volume *Taking Science To School* (NRC, 2007), for example, identifies four strands of proficiency for students *and for teachers* who are responsible for guiding young science learners. Students and teachers should be able to:

- Understand, use, and interpret scientific explanations of the natural world
- Generate and evaluate scientific evidence and explanations
- Understand the nature and development of scientific knowledge, and
- Participate productively in scientific practices and discourse (p. 334).

These proficiencies are embodied most clearly in classroom activities such as content-rich inquiries and non-routine problem-solving. What these proficiencies "look and sound like" in practice however, has not been well-translated into models for teacher performance (such as a Learning Progression for teachers), nor have underlying skills and understandings required for these performances been articulated.

In the following table I lay out eight specific elements of reform teaching. For each of these elements I then describe the teacher skills and understandings necessary to enact this kind of instruction and the 21st Century skills for students that these teacher performances might support. The purpose of the table is *not* to outline a template for effective teaching, but to provide a picture of the types of pedagogical skills necessary to help students learn complex concepts, participate in authentic scientific practices, problem-solve with others, and self-monitor their learning.

<table>
<tr><th>Selected features of reform-based science teaching</th><th>Skills/knowledge needed by teacher</th><th>21st Century Skills involved for students</th></tr>
<tr><td>1. Teacher identifies in curriculum the most fundamentally important scientific ideas; treats these as the basis of instruction.</td><td>• Requires understanding of core concepts and explanatory theories in a domain, how these are connected with one another and how they apply to a range of phenomena.</td><td rowspan="2">• Complex communications: Students organize their beginning understandings of an idea in terms of verbal descriptions, analogies, diagrams, tentative models, other representations. Skills in processing and interpreting both verbal and non-verbal information from others in order to respond appropriately.
• Systems Thinking: Students initially attempt to understand how a system works, how an action or change in one part of the system (i.e. model) affects the rest of the system.</td></tr>
<tr><td>2. Teacher elicits students' initial conceptions of focal phenomena; guides students to represent what they know, then adapts further instruction based on these understandings.</td><td>• Requires ability to craft questions or tasks that are "rich"—i.e. have potential to reveal multiple facets of student thinking about target idea.
• Requires analysis of student responses and comparison against target understanding, to make principled judgments about how to design further instruction.</td></tr>
<tr><td>3. Teacher co-constructs with students hypotheses and problems related to scientific phenomenon. Focuses these with an essential question that organizes both instructional flow and students' intellectual work.</td><td>• Requires understanding of the nature of scientific knowledge-building, how hypotheses and questions emerge jointly from observation and tentative models underlying phenomena.
• Requires discursive strategies for making several ideas—some of them competing hypotheses— public and testable for students.
• Requires vision of what type of question is complex enough to be meaningful and can sustain inquiry over days.</td><td>• Complex communications: Students "try out" scientific discourses of posing hypotheses; they connect questions and hypotheses with initial models or problem. Students asked to craft a model-grounded scientific question.
• Systems Thinking: Includes abstract reasoning about how different elements of a natural system interact.</td></tr>
<tr><td>4. Teacher provides students with resources, experiences relevant to answering essential question. These could be readings, technology, other tools, hands-on work. Also supports students in deciding what other kinds of resources and experiences needed.</td><td>• Requires understanding key conceptual components of the big idea, how they fit together, should be sequenced.
• Requires understanding of how to help students "see" ideas in individual representations and how to make more complex forms of meaning across representations (meta-representational competence).
• Requires understanding of how experiments and other forms of testing are designed, understanding the data these observations yield, and how this data can be used as evidence to support solutions or explanations.</td><td>• Self-management: Students decide which resources or experiences are relevant to answering big questions. They design (with guidance) scientific tests that will generate evidence.
• Systems Thinking: Students hypothesize how a system works, how an action, or change in one part of the system affects the rest of the system; adopt a "big picture" perspective on work.
• Non-routine problem solving: Students examine broad span of information, recognize patterns, narrow information to reach diagnosis of the problem.</td></tr>
<tr><td>5. Teacher supports students in monitoring their own progress toward defined goals.</td><td>• Requires understanding of how to model and foster metacognition, self-regulation in students.
• Requires specialized discourses around the questions: "What additional information do I need?" "How do we know we've solved the problem?" "What evidence will count to support an explanation?" "How do we address alternative hypotheses?"</td><td rowspan="2">• Non-routine problem solving: Students use metacognition—the ability to reflect on whether a problem-solving strategy is working— and to switch to another strategy if the current strategy isn't working.
• Self-management: Students able to work in teams, but also able to think and work autonomously. Students' ownership of problems encourages self-monitoring.</td></tr>
<tr><td>6. Teacher monitors student understanding of science ideas and engagement in authentic scientific discourse and practice.</td><td>• Requires broad repertoire of formative assessments. Understands in what contexts they should be used, how they can provide both teacher and student with targeted feedback.</td></tr>
<tr><td>7. Teacher presses students to compare and integrate ideas across different representations, use secondary data and primary data as evidence to support explanatory models and arguments relevant to essential question.</td><td>• Requires understanding of how to weigh different forms of evidence, coordinating evidence and explanations, differentiating between theory and evidence.
• Requires orchestrating productive discourse by students in collaboratively evaluating solutions to problems or explanatory models.
• Requires understanding of the rhetorical practices of authentic science.</td><td>• Complex communications: Students select key pieces of a complex idea to express in words, sounds, and images, in order to build shared understanding.
• Non-routine problem solving: Students move beyond diagnosis to a solution requires knowledge of how the information is linked conceptually. Students use creativity to generate new and innovative solutions, integrating seemingly unrelated information; and entertaining possibilities others may miss.
• Systems Thinking: Students adopt a "big picture" perspective, reasons abstractly about how the different elements of a model interact.</td></tr>
<tr><td>8. Teacher asks students to critique the intellectual work of others in ways consistent with scientific practice and in ways that advance the thinking of others.</td><td>• Requires ability to manage a "community of practice" in classroom. Needs to model discursive interactions over ideas that are appropriately challenging, based on evidence, and civil. Needs to model how one learns from feedback, how one re-considers ideas in light of input from others.</td><td>• Complex communications: Students use skills in processing and interpreting both verbal and non-verbal information from others in order to respond appropriately. Negotiate ideas with others through social perceptiveness, persuasion, and instructing.</td></tr>
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The vision of how 21^{st} Century skills play out in classrooms is closer to *studio-based science* rather than to laboratory–based science environments (in which "hands-on" activity often shapes the organization of teaching and learning, to the point of being valuable for its own sake). By studio science I mean that the primary focus of student work is to solve complex problems, and that multiple forms of learning activity by students (gathering relevant information, collecting data, testing models, learning new concepts needed to understand the problem, etc.) is always in the service of producing an evidence-based solution to a problem. The studio science approach is characterized by a focus on a few key science ideas, purpose-driven group work, student ownership of problems and problem-solving approaches, the on-going public vetting of multiple solutions and models as they are being developed, and the use of feedback to refine ideas and solutions. I should note here that the studio orientation to science learning involves students in *generating* and *re-framing* problems— a skill that is actually more fundamental than the five 21st Century skills listed currently.

Some explanation may be helpful for understanding how the features of reform-based teaching listed in the table above lead to different 21^{st} Century skills in students. In Row 1 of the table, the teacher's ability to identify big ideas in science is crucial to the development of problems and inquiries that are appropriately challenging and worth exploring in depth. Although the knowledge needed by teachers here does not correspond directly with a particular 21^{st} Century skill, it lays the foundation for the design of extended engagements with problems that are pre-requisites for students to develop various 21^{st} Century skills.

In Row 2, the elicitation of learners' current conceptions requires that students, individually or in groups, develop representations of their thinking to share with the teacher or other students. A teacher may, for example, ask students at the beginning of a unit of instruction to imagine what the key features of a pulley system are, including visible features and as well as what can't be seen. This requires students to identify salient features, make decisions about how to represent these, and how to present such a model to an audience (complex communication). It also requires them to interpret both representational conventions and the ideas behind the representations that other students have developed. Inevitably, students attempt to reason out how systems like pulleys (or cells in hypotonic solutions, or convection currents in the Earth's atmosphere) operate, and in particular how changes in one part of the system affect changes in other parts of the system (systems thinking).

In Row 3, the teacher prompts students to develop hypotheses or small-scale theory about what is happening to cause a natural phenomenon. What students learn here is to communicate in a disciplinary language. They learn not only "what counts" as hypotheses or explanations, but how these terms fit into a specialized rhetorical system of evidence-based argumentation (complex communication). Because the teacher asks students to move beyond describing a phenomenon to offering potential explanations that involve underlying events or processes, students are pressed to reason abstractly about how the elements—both tangible and theoretical—influence one another (systems thinking).

In Row 4, teachers place partial responsibility on students to make decisions about what kinds of information resources and experiences they need to develop solutions to the central problem or develop an explanatory model for the central phenomenon (self-management). Because multiple sources of information, activities, and representations are now being brought into the mix, teachers must help students see patterns across broad spans of information (non-routine problem solving) and integrate these into sensible mental frameworks (systems thinking).

Rows 5 and 6 describe both student self-monitoring and teacher awareness of what students' current state of understanding are. On the teachers' part this is accomplished by employing a range of formative assessment strategies. The teacher, however, has to have the skills to scaffold both the metacognition and self-regulation in students (self-management). Because reform science teaching is predicated on the regular pursuit of big questions or complex problems, students' ability (and habits of mind) to reflect on what they know and what they need to know is crucial. The self-management skill by students is almost never developed in traditional classroom settings, where students often exposed to multitudes of poorly connected concepts, are told what to use as information resources, told how to conduct activities, and told how to interpret the significance of these activities. In short, *the common teacher-centered classroom and typically overfilled curriculum obviate the entire suite of 21st Century skills*. Advanced placement courses in high schools are notorious for this type of instruction.

In Rows 7 and 8, the teacher supports students in coordinating all previous learning experiences in order to represent an argument for why a particular problem solution or an explanatory model is best supported by evidence. This again requires complex communication among students who are working in small groups, and requires communication by groups of students to their peers. No one solution is considered in isolation from the others. As in authentic science there are multiple possibilities that have unique trade-offs (in problem-solving tasks) or bodies of evidentiary support (in inquiry or research scenarios). These solutions or explanations require systems thinking and non-routine problem-solving as well as communication skills. The communication skills here again involve the specialized disciplinary rhetoric of science. Social perceptiveness, negotiating ideas with others, and even students teaching one another all play a role in the culminating phase of reform teaching (complex communication). Teachers must understand how to make explicit to students the ways in which these forms of argument unfold in group settings and "what counts" as viable solutions or valid explanatory models.

In the description above I have not mentioned the 21st Century skill of adaptability. Adaptability, in my opinion, is not explicitly fostered by reform-based teaching. While the tasks students engage in (and the task goals) could change substantially over the course of a unit of reform-based instruction, the types of change students would need to adapt to are not of the scope or character described in the outline of the 21st Century skills.

What does classroom teaching look like today?

The instructional patterns outlined in the previous section are unfortunately *not* common in American science classrooms. Recent studies indicate that U.S. science students routinely engage in various forms of classroom inquiry without understanding connections to important scientific concepts, nor do they reason well about evidence and explanation. In an analysis of the TIMSS video data from science classrooms, Roth and Garnier (2007) note that in American classrooms "almost one-third of the lessons narrowly focused students' attention on performing activities with no attempt on the teachers' part to relate these activities to science ideas" (p. 20). In a study of 180 science lessons collected from a national sample, Weiss et al. (2003—referred to as the "Inside the Classroom" study) noted that only a quarter of these lessons were judged to include adequate sense-making.

In another international study (PISA), American students fell significantly below the average on two subscales: explaining phenomena scientifically and using scientific evidence (Baldi, et al., 2007). Related findings from the *Inside the Classroom* study (Weiss et al., 2003) show that few lessons engaged students with concepts in a way that allowed them to understand the nature of science, specifically how scientific knowledge is generated, enriched, and changed.

Fewer than 10% of science lessons required students to use data or examples as evidence in supporting or critiquing conclusions.

Banilower, Smith, Weiss, and Pasley (2006) found that only 14 percent of all lessons in a national sample exhibited intellectual rigor, and that questioning was among the weakest elements of instruction. This apparent inattention to how classroom discourses influence learning is compounded by the fact that only about half of all science teachers can adequately interpret students' level of understanding and adjust instruction accordingly (Horizon Research International, 2003). A national survey of over 2,500 science teachers indicates that only about one in six lessons included pre-assessments to determine what students understood about a topic before instruction (Weiss, Banilower, McMahon, & Smith, 2001). A later study indicated that 35 percent of lessons contained some form of elicitation, however in some cases the prompt was not well-aligned with the learning goal stated by the teacher and was therefore unlikely to bring out relevant student ideas (Weiss, et al., 2003). Clearly American science teaching does not do a good job of developing ideas in depth, connecting ideas with material activity, or attending to student thinking as a way to shape instruction. It is noteworthy that the most problematic features of science teaching *do not* involve lab work, experiments or otherwise engaging students in material activities. Rather, it is the ineffective use of *classroom discourse* to probe students' ideas, to press students for explanation, or to encourage sense-making.

Teacher skills/understanding required for reform-based learning

While there are many skills and understandings one needs to teach science well, four broad abilities are crucial to reform-based teaching and teaching 21st Century skills.

1. *Deep interconnected content knowledge, ability to "see" big ideas in curriculum and understand how to teach these as big ideas*. Teachers' content knowledge is related to the science teaching strategies they use (Carlsen, 1993; Cronin-Jones, 1991; Roth & Anderson, 1991) and to student learning (Magnusson, Borko, Krajcik, & Layman, 1992). Teachers with stronger content knowledge are more likely to teach in ways that help students construct knowledge, pose appropriate questions, suggest alternative explanations, and propose additional inquiries (Alonzo, 2002; Brickhouse, 1990; Cunningham, 1998; Gess-Newsome & Lederman, 1995; Lederman, 1999; Roehrig & Luft, 2004; Sanders, Borko, & Lockard, 1993). Inquiry science teaching also demands that teachers have specific knowledge of *how to support students* in developing researchable questions, planning an investigation, collecting and interpreting data and presenting results (Gess-Newsome & Lederman, 1999; Shulman, 1986). There is extensive support for both a focus on content knowledge in general and *specific forms of content knowledge* that best support teaching practice (Hill, Rowan, & Ball, 2005). Our own research (Windschitl, Thompson, & Braaten, 2009; Thompson, Windschitl, & Braaten, 2009) further indicates that specific forms of reasoning with content knowledge are critical to reform teaching, the most important being the ability to identify fundamentally important science ideas underlying common curriculum topics. Because the context of teaching of 21st Century skills depends so heavily upon students' sustained engagement with complex problems, it stands to reason that teachers can only organize such high-quality curricular challenges if they themselves have deep and well integrated understandings of the content and the practices of science. I address these ideas in more detail later.

2. *Ability to engage students in specialized classroom discourses aligned with reform goals*. In considering the knowledge and skills necessary for laboratory work, it may seem intuitive to focus on the abilities of the teacher to design and manage *activities* for students. Recent scholarship, however, has emphasized that meaningful learning is a product *not of activity per se*, but of *sense-making discourse* aimed at developing conceptual understanding and the links between theory and observable phenomena (Mortimer & Scott, 2003). In this view, learning is not accomplished through the transmission of knowledge from person to person, but rather through an ongoing process of comparing and checking one's own understandings with those that are being rehearsed on the social plane of the classroom.

In addition to using dialogue to facilitate conceptual understanding, other researchers have employed classroom discourse as a way to engage learners in the canonical practices of science— that is, "to formulate questions about phenomena that interest them [students], to build and criticize theories, to collect, analyze and interpret data, to evaluate hypotheses through experimentation, observation, measurement, and to communicate findings" (Rosebery, Warren & Conant, 1992, p. 65). Language, in the form of purposeful talk, reading, and writing, mediates all these activities (for examples of teachers reflecting on their own use of discourse in middle school settings see Rosebery, Warren, & Conant, 1992; for high school see van Zee & Minstrell, 1997; for college see Hammer, 1997). This emphasis on sense-making discourse is echoed in the policy literature aimed at clarifying what it means to get students to "think" in classrooms. Thompson and Zeuli (1999) state that "By think, we mean that students must actively try to solve problems, resolve dissonances between the way they initially understand a phenomena and new evidence that challenges their understanding, put collections of observations or facts together into patterns, make and test conjectures, and build lines of reasoning about why claims are or are not true. Such thinking is generative. It literally creates understanding in the mind of the learner" (p. 346). Because complex communications are fundamental to 21st Century skills, teachers' understanding of how language and other representations are used to create meaning in classroom contexts is crucial.

3. *Understanding the full range of assessment strategies, purposes and contexts within which they should be used*. Students' conceptual learning and sophisticated disciplinary performance are achieved in part by eliciting information from them through assessments as a means of gauging where they are in their progress toward a goal (Duschl & Gitomer, 1997), and by providing ongoing targeted feedback to them (Butler, 1987; Crooks, 1988). Research also suggests that understanding is supported when learners are asked to take an active part in determining what they understand and how they came to that understanding (National Research Council, 2000). Classroom practices that aid this kind of metacognition include peer and self assessment, reflection on one's progress and determining what needs further improvement, and activities geared toward allowing students to make sense of new concepts through talk or writing, which in turn allows teachers to gather information on student understanding to guide his or her next steps (Sato, Wei, & Darling-Hammond, 2008; Palnicsar & Brown, 1984; Scardemalia, Bereiter, & Steinbach, 1984; White & Fredericksen, 1998). All these pedagogical skills support the 21st Century skills of student self-regulation, self-monitoring, and metacognition.

4. *Understanding how to learn from one's practice*. There is a growing consensus within the field of teacher education that equipping novices with a repertoire of competent classroom

practices is no longer considered an adequate professional preparation. Because initial training can only begin new educators on the long trajectory towards expert teaching, it is equally important that these programs help novices develop strategies and habits of mind to *learn from practice* as they enter the profession, laying the foundations for career-long development (Darling-Hammond & McLaughlin, 1995; Fullan, 1993; Hiebert, Morris, Berk, & Jansen, 2007; Lieberman & Miller, 2001; Nemser, 1983). Broadly speaking, learning from teaching is best achieved through systematic cycles of inquiry into practice and using evidence generated by these inquiries to re-shape instruction (Grossman & McDonald, 2008; Little, 2007). Some of the most promising of these types of inquiries draw upon records of practice from the participating teachers—in particular, samples of student work (e.g., Borko, Jacobs, Eiteljorg, & Pittman, 2008; Cobb, Dean, & Zhao, 2006; Jacobs, Franke, Carpenter, Levi, & Battey, 2007; Kazemi & Franke, 2004; Lewis, Perry, & Murata, 2006; Sherin & Han, 2004). Learning from one's practice should begin in teacher preparation and extend into one's professional career. Because the teaching of 21st Century skills is about *how* students learn, as well as *what* they learn, the regular examination of artifacts of student thinking or discourse may be the only way for teachers to ultimately judge and refine their own practice towards these ends.

What do we know about how teachers learn to teach science?

Content knowledge. To develop competence in subject matter instruction, teachers must have a deep foundation of factual and theoretical knowledge, and understand these facts and ideas in the context of a conceptual framework (Bransford, et al. 1999). These foundations begin with undergraduate work where subject matter knowledge and knowledge of the disciplinary activities of science are developed.

Unfortunately, research into undergraduate preparation indicates that the content knowledge gained is often superficial and not well integrated. The traditional didactic pedagogy to which teacher candidates are often exposed in university science courses provides only minimal conceptual understandings of their science disciplines (Duschl, 1983; Gallagher, 1991; Pomeroy, 1993). As a result, many pre-service teachers hold serious alternative conceptions about the science content, similar to those held by their students (Anderson, Sheldon, & Dubay, 1990; Sanders, 1993; Songer & Mintzes, 1994; Westbrook & Marek, 1992). In a year-long study of prospective biology teachers (Gess-Newsome & Lederman, 1993), participants reported never having thought about the central ideas of biology or the interrelationships among the topics. The teachers, all biology majors, could only list the courses they had taken as a way to organize their fields. They knew little about how various ideas were related to each other, nor could they readily explain the overall content and character of biology.

These findings confirm those from a substantial literature on arts and sciences teaching in colleges and universities that has clearly documented both elementary and secondary teachers lacking a deep and connected conceptual understanding of the subject matter they are expected to teach (Kennedy, Ball, McDiarmid, & Schmidt, 1991; McDiarmid, 1994).

Understanding scientific practice. With regard to prospective teachers' exposure to science as a knowledge-building enterprise, much of what new teachers learn about inquiry comes from their experiences as undergraduates, which are not unlike the confirmatory laboratory experiences found in secondary schools (Trumbull & Kerr, 1993). In addition to the problem of being subjected to models of highly-structured inquiry, pre-service teachers are rarely exposed to ideas about science as a discipline at the college level and do not participate in discussions of how new knowledge is evaluated (Bowen & Roth, 1998; Wenk & Smith, 2004). Not surprisingly, the studies that have been done on inquiry in teacher education programs indicate that pre-service teachers lack basic knowledge of methodology and do not think in terms of theory as they attempt scientific investigations (Lemberger et al., 1999; Roth, 1999; Shapiro, 1996).

In multi-case studies of pre-service secondary science teachers' understandings of authentic inquiry practices during science methods courses (Windschitl, 2004; Windschitl & Thompson, 2006) most participants subscribed to a "folk theory" about scientific inquiry in which forms of knowledge and specialized disciplinary rhetoric that are crucial to reform-based teaching (e. g. model development, explanation, argument) had little or no role. The emphasis by these pre-service teachers was on collecting and analyzing data, but not on connecting this data to an underlying explanation. Two factors shaped participants' thinking about these inquiries. One was previous school-related research experience which influenced not only what they recognized as explanations or models but also the way they believed these could be incorporated into inquiry. The other was a widely-held simplistic view of "the scientific method" which constrained the procedures and epistemic frameworks they used for investigations.

Learning to teach. We currently have limited understandings of how individuals develop the skills, knowledge, and habits of mind to become proficient teachers. Much of what we know comes from expert-novice studies, but these have not followed individuals over a period of years. Rather, these studies compare the thinking and practice of novices with separate groups of more experienced practitioners (see Berliner, 2001). Developmental pathways and a list of critical experiences that can advance the practice of novices over time have not been empirically validated. There are other kinds of research, however, that provide important clues to what might help or hinder teachers' learning throughout their careers. I outline these below.

In a previous section of this paper, I described how pre-service teachers have pre-conceptions about science *content and inquiry*. They also enter preparation programs with pre-existing hypotheses about *how people learn*. One personal theory that many new teaching candidates hold about learning is that it amounts to a simple "transfer" of information from texts and teachers to students who acquire it from listening, reading, and memorization (Feiman-Nemser & Buchmann, 1989; Richardson, 1996). This shapes their thinking about what kind of teaching is appropriate and possible in classrooms (National Center for Research on Teacher Learning, 1991). When we consider the kinds of knowledge-building, problem-solving, metacognition, and collaboration that are part of 21st Century learning, such an oversimplified view of teaching seems a major impediment. These preconceptions, developed in teachers' "apprenticeship of observation", also condition what they then learn in training experiences (Linn, Eylon, & Davis, 2004). If this initial understanding is not engaged/confronted during teacher preparation, they may fail to grasp new concepts about teaching and learning or they may learn them for the purposes of a test, but revert to their preconceptions later (Darling-Hammond & Bransford, 2005).

We also know that even when novice teachers are exposed to powerful conceptual frameworks to help them think about organizing instruction and analyzing classroom events (Bransford & Stein, 1993; Grossman et al., 2000) they will either not know how or when to enact these ideas when they enter the classroom, or, they will simply reject these frames and rely instead on conservative teacher-centered instruction (see Abd-El-Khalick, Bell, & Lederman, 1998; Appleton & Kindt, 2002; Brickhouse & Bodner, 1992; Mellado, 1997; Palmquist &

Finley, 1997; Simmons et. al, 1999; Windschitl & Thompson, 2006). Reform-based teaching methods are often fundamentally different from how student teachers were taught and sometimes how teacher educators themselves learned as students (Borko & Mayfield, 1995). Short term interventions have shown little capacity to change teacher pre-conceptions (Wideen and others, 1998). In contrast, longer term approaches that explicitly seek to elicit and work with novice teachers' initial beliefs have shown some success in fostering reform-based teaching (Fosnot, 1996; Graber, 1996; Windschitl & Thompson, 2006).

Although studies that follow novices from their preparation experiences into the first years of teaching are remarkably rare, the few that have been reported portray similar transitions into professional work: newcomers are willing to try out some non-traditional strategies when they enter their classrooms, but for a variety of reasons, they often bring few principled pedagogical practices with them from their pre-service training (Bransford & Stein, 1993; Goodlad, 1990; Grossman et al., 2000; Kennedy, 1999; Nolen, Ward, Horn, Childers, Campbell, & Mahna, in press; Simmons et al., 1999).

Part of the challenge in helping novices take up reform-based practices is that, as they begin their careers, they are not merely being apprenticed into a set of teaching strategies, but often into an intuitionist epistemology of professional knowledge and problem-solving (Goodlad, 1990). In his classic study of school teachers, Lortie (1975) noted that practitioners saw their pedagogy styled around personal preferences rather than grounded in an accepted body of knowledge. Teachers used—and still use—little more than informal observations of students to assess their own instructional efficacy and depend upon a kind of untested folk wisdom to deal with dilemmas of practice. Huberman (1995) has more recently characterized this approach to practice as "bricolage" or tinkering. In this view teachers develop as independent artisans, picking up a new activity here and a new technique there, choosing these to fit within their own styles and work settings. Both Huberman and Lortie suggest that these tendencies are reinforced by the everyday intellectual isolation of the classroom (see also Goodlad, 1983; Jackson, 1968; Little, 1990; McGlaughlin & Talbert, 2001) and by the absence of a shared and explicit vision of good teaching that could support conversations about how to improve practice.

Given the over-reliance on personal intuition, the isolation, and the lack of models for effective teaching, interventions designed to foster ambitious pedagogy in novice educators must consider new ways of making public "what counts" as accountable practice. Apprenticing teachers, and in particular novice teachers, into this type of teaching however, is complicated by the "hard wired" routines of low-level questioning in classrooms (e.g., I-R-E discourses and discourses of teacher control), by the lack of clear models of more sophisticated practice, and by inexperienced educators' limited understanding of students' capacities to engage in challenging work (Elmore, 2005). This seems particularly problematic for reform-based science teaching and for developing the ability to cultivate 21st Century skills in young learners. Teaching for 21st Century skills is quite unlike the kinds of science teaching in today's classrooms. Reform-based teaching for example:

- demands a range of specialized discourses (both teacher-to-student discourse and student-to-student),
- relies on constant assessment of student thinking and subsequent "disciplined improvisation" by teachers to adapt to where students are/need to go next, and
- requires a deeper understanding of both science content and of disciplinary practices than do traditional forms of instruction.

In a later section, we build upon this logic to suggest the development of a set of tools for teachers to support these kinds of transitions from traditional to reform-based instruction.

Characteristics of teacher preparation to promote 21st Century skills

General features of effective teacher preparation programs. Some teacher preparation programs have graduates who report significantly greater feelings of preparedness, and are more highly-rated by employers who say they seek out these candidates because they are more effective in the classroom from the first days of teaching. A study of seven such programs found these common features (Darling-Hammond, 1999):

- "A shared vision of good teaching that is consistent in courses and clinical work.
- Well-defined standards of practice and performance that are used to guide the design and assessment of coursework and clinical work.
- A common core curriculum grounded in substantial knowledge of child or adolescent development, learning, and subject matter pedagogy, taught in the context of practice.
- Extended clinical experiences (at least 30 weeks) that reflect the program's vision of good teaching, are interwoven with coursework, and carefully mentored.
- Strong relationships, based on common knowledge and beliefs, between universities and reform-minded schools.
- Extensive use of case study methods, teacher research, performance assessments, and portfolio examination that relate teachers' learning to classroom practice."

The same program features and pedagogical tools are noted in other studies of strong programs (see for example, Cabello, 1995; Graber, 1996). Other studies (Bianchinni & Solomon, 2003; Lumpe, Haney, & Czerniak, 2000) indicate that a coherent science focused pre-service program and the number of methods courses positively relate to the implementation of reform-based science instruction. Luft, Roehrig, and Patterson (2003) say *multiple* methods courses, coordinated with an extended student teaching experience, may be critical to providing novice teachers with practices for reform-based teaching.

Coherence of a vision for good teaching throughout all early learning-to-teach contexts is important. When student teaching placements, for example, are *consistent with the programs' vision* of teaching and learning, and when a *shared understanding* of the purposes and activities of student teaching exists between student teachers, cooperating teachers and university supervisors, more powerful learning takes place (Koerner, Rust, & Baumgartner, 2002; LaBoskey & Richert, 2002; also see Grossman, Smagorinsky, & Valencia, 1999).

Novices have also benefited from repeated chances to try out high-leverage practices in real classrooms with mentoring that focuses on learning. When a well-supervised student teaching experience precedes or is jointly conducted with coursework (the coherence theme again), students are more able to connect theoretical learning to practice, become more comfortable with the process of learning to teach, and are more able to enact what they are learning in practice (Chin & Russell, 1995; Darling-Hammond & Macdonald, 2000; Koppich, 2000, Snyder, 2000; Sumara and Luce-Kapler, 1996; Whitford, Ruscoe & Fickel, 2000). Other studies show that when teachers learn content-specific strategies and tools that they are *immediately able to try and continue to refine with a group of colleagues* in a learning community, they are more able to enact new practices effectively (Cohen & Hill, 2000; Lieberman & Wood, 2003).

Both student teaching and induction experiences should maintain a focus on student learning. This includes time to plan and debrief lessons together with a mentor. Mentoring (this was not conclusive data) can be an effective strategy to reduce teacher attrition and improve teacher quality (Lopez, Lash, Schaffner, Shields, & Wagner, 2004). This research, however, refers to "being mentored" as seeing a more experienced colleague only once a month, at maximum.

In a review of literature on challenges facing new teachers, Davis, Petish, and Smithey, (2006) note that establishing collegial relationships in general with other new teachers, cooperating teachers, more experienced fellow teachers, or even researchers helps novices to develop improved understandings of instruction (see also Crawford, 1999; Tobin & LaMaster, 1995; Zembel-Saul et al., 2002) and of learning environments (see also Eick, 2002; Loughran, 1994; Luft et al., 1999).

Science-specific teacher preparation features. Subject matter knowledge clearly influences how and how well teachers teach (Borko et al., 1992; Borko, Livingston, McCaleb, & Mauro, 1988; Carlsen, 1993, 1997; Druva & Anderson, 1983; Ferguson & Womack, 1993; Goldhaber & Brewer, 2000; Hill et al., 2005; Leinhardt & Greeno, 1986; Monk, 1994; Monk & King, 1994; Stein et al., 1990; Stodolsky, 1988). Teachers' academic preparation in science has a positive influence on students' science achievement. One study found that having an advanced degree in science was associated with increased student achievement from the 8th to 10th grade (Goldhaber & Brewer, 1997). The NRC Committee on Science and Mathematics Teacher preparation stated that "studies conducted over the past quarter century increasingly point to a strong correlation between student achievement in K-12 science and the teaching quality and level of knowledge of their K-12 teachers." However, Wilson, Floden, & Ferrini-Mundy (2001) conclude that "…we know next to nothing about *high quality teaching* in subject matter courses that are part of the preparation of teachers" (p. 11). In addition, the mechanisms through which such knowledge enters teachers' thinking and practice are not well understood (Hiebert, Morris, Berk, & Jansen, 2007).

Teachers with limited subject matter preparation tend to emphasize memorization of isolated facts and algorithms; they rely on textbooks without using student understandings as a guide to planning lessons; they use lower-level questioning and rule-constrained classroom activities; furthermore, they employ only limited use of student questions or comments in classroom discourse which results in marginal student development of conceptual connections and misrepresentations of the nature and the structure of the discipline (Carlsen, 1991; Gess-Newsome, 1999; Talbert, McGlaughlin, & Rowan, 1993). Kennedy (1998) notes that some take a minimalist view of necessary content knowledge by requiring teachers to only know the subject mater actually covered by the curriculum, reasoning that this knowledge is exactly what the teachers will be teaching. Kennedy and others argue, however, that if students can ask questions that extend beyond the formal curriculum (our own research shows that this happens *frequently*) and if teachers must respond to those questions, teachers need knowledge that goes far beyond the curriculum being taught (e.g. Hilton, 1990).

Early career: Induction support

Induction refers to continuing support for novice teachers during their first two to three years of professional work. Induction support can include periodic mentoring, helping new teachers become adjusted to local school culture and routines, assistance with classroom management, and other forms of technical help. This is important from a practical standpoint because first-year teachers assume responsibilities similar to those of experienced teachers while learning their job with little preparation (Kagan, 1992; Wideen, Mayer, & Moon, 1998). In the absence of post graduate support in the form of induction, students can revert back to more traditional practices and beliefs (Luft, Roehrig, & Patterson, 2003; Windschitl, Thompson, & Braaten, 2009; Thompson, Windschitl, & Braaten, 2009). In their study of new secondary science educators, Adams and Krockover (1997) found cases where new teachers failed to use the constructivist forms of instruction they had been taught in pre-service education, until two years after they had become practicing teachers. They noted that the key influence for these changes was a professional development experience that provided these individuals time to reflect on their own teaching and consider how it compared with what they had learned in their pre-service experience.

There is little research in this area that indicates how induction affects teaching and learning. In one of these few studies, Luft, Roehrig, and Patterson (cited in Wang et al., 2003) compared groups of new teachers who experienced different kinds of first year support: one group had induction that attended to the specific pedagogical needs of science teachers, one group had induction that focused only on general pedagogical support, and one group had no formally structured induction. Teachers in the first two groups ended up using practices more congruent with standards-based reforms. Those in the science-specific group were also more likely to hold beliefs about student-centered practices, implement more student-centered inquiry practices and feel fewer constraints in their teaching. A later study by Luft (in press) reported similar findings.

If the cultivation of 21st Century skills is a target of pedagogical support, then I would advocate that the core of induction support takes the form of discipline-specific, collegial inquiry into practice, by examining records of practice (video, student artifacts, etc.). This inquiry into practice must be science-specific and focus on high-value types of student performance. Our own research, described in a later section, provides evidence that spending the first year of induction collaboratively analyzing student work can promote reform-based classroom practices in novices.

Analyzing learning artifacts has helped teachers generate and test hypotheses about instructional decisions (Hiebert, Morris, Berk, & Jansen, 2007; Nave, 2000; Wheatley, 2002), pushed them to think beyond routine, familiar activity in the classroom (Kazemi & Franke, 2004; Sandoval, Deneroff, & Franke, 2002), and led to improved student learning (Crespo, 2002; Goldenberg, Saunders, & Gallimore, 2004). Sato et al. (2008) found, for example, that during preparation for National Board Certification, that collegial analysis, reflection, and constructive critique of videotaped lessons, sharing of teaching strategies, and the analysis of pupil work against performance standards as “tools for critique” allowed teachers to enact high teaching standards in specific classroom practices and gave them feedback about what they were doing and how well.

The analyses of teaching practices form the core of professional development activities in several Asian countries whose students perform very well in international comparisons of math and science achievement (Lewis & Tsuchida, 1997; Ma, 1999; Marton & Tsui, 2004; Paine & Ma, 1994; Stigler & Hiebert, 1999; Yoshida, 1999). Hiebert et al. (2007) note that “Although many factors account for the apparent success of continued teacher learning in these countries, the relentless focus on analyzing classroom practice and testing hypothesized improvements clearly support the growth of expertise among these teachers.” In contrast to this focus on student learning, many U.S. teachers think of instruction in terms of implementing activities. They focus often on repairing problems with these activities rather than analyzing effects of instruction on students' learning (Fernandez & Cannon, 2005; Sandoval, Deneroff, & Franke, 2002).

Characteristics of effective professional development

As with teacher preparation and induction, there are general conditions that have been associated with effective professional development. I describe these below and then suggest how some of the 21st Century skills might be incorporated into professional development designs. There are some consistent findings with regard to how *structural elements* of professional development (the broad temporal, participatory, and instructional contexts associated with professional development) and *core features* (characteristics of the learning experiences within the professional development structure) influence change in teacher practice.

In a study of 1,027 science and mathematics teachers, Garet et al. (2001) identified the core features of professional development that have significant effects on teachers' self-reported increases in knowledge and skills and changes in classroom practices: a) a focus on content knowledge; b) opportunities for active learning; and c) coherence with other learning activities. It is primarily through these core features that the following structural features significantly affect learning: a) the form of the activity (e.g. reform oriented preferred over traditional workshop); b) collective participation of teachers from the same school, grade, or subject; and c) duration of the activity. In a longitudinal study of 207 science and mathematics teachers from 30 schools, Desimone et al. (2002) reported similar findings—that professional development is more likely to change teacher practice when it has: a) the collective participation of teachers from the same school, department, or grade; b) active learning opportunities such as reviewing student work or obtaining feedback on teaching; and c) coherence, for example, linking to other activities or building on teachers' prior knowledge. Reform-type professional development also had a positive effect.

With regard to activity type, there is broad consensus among teacher learning researchers that "reform-oriented" professional development (activities such as teacher study groups) tends to result in more substantive changes in practice than "traditional" (workshops or college courses) professional development (Loucks-Horsley, et al., 1998; Putnam & Borko, 2000). For example, professional development in which teachers have themselves engaged in science inquiry activities have resulted in changes in practice *and* positive student learning outcomes (A. L. Brown & Campione, 1996; Fishman & Krajcik, 2003). Other reform-oriented professional development, according to Garet et al.'s (2001) definition, includes being mentored or coached, participating in a study group, or engaging in an internship. These predictors had been identified by others as contributing to the quality of professional development (Hawley & Valli, 1999; Loucks-Horsley, Hewson, Love & Stiles, 1998; Loucks-Horsley & Stiles, 2001).

With regard to duration of professional development (in terms of both time span and total contact hours). Supovitz & Turner (2000) found that more extended time spans permitted learning opportunities for teachers to integrate new knowledge into practice (J.L. Brown, 2004) and to create "investigative cultures" in science classrooms, as opposed to stimulating superficial changes in practice. In a curriculum implementation study of teachers served by 28 different professional development providers, Penuel, Fishman, Yamaguchi, and Gallagher (2007) found that the incorporation of time for teachers to plan for implementation and the provision of technical support were important for promoting changes in teaching. They hypothesize it is likely that there is an interaction between the duration of professional development and other structural and core features, such as the employment of reform-oriented professional development. Referring to Desimone et al., 2002 who found that the duration of the professional development had *no effect* on outcomes, Penuel et al. (2007) hypothesize that the factor of time is important only to permit the experiences of community, coherence, and experimentation with new practices to unfold in meaningful ways.

With regard to collective participation, evidence from a wide range of studies examining school reform suggest that those that make extensive use of teacher collaboration are particularly successful in promoting implementation, in part because reforms have more authority when they are embraced by peers (Bryk & Schneider, 2002; Frank, Zhao, & Borman, 2004). Gamoran et al., (2003) hypothesized about the underlying mechanisms behind the benefits of collective participation in their study of six school sites where science and mathematics teachers were collaborating with university researchers to teach for understanding. They found supporting evidence for the following: 1) the shift from conventional teaching to teaching for understanding makes teachers' uncertainty more salient in all areas of teaching: curriculum, instruction, assessment, and teacher knowledge about student reasoning; and 2) professional communities of teachers provide the social mechanisms through which uncertainty can be managed, allowing teachers to respond to one another's affect, beliefs, ideas, to provide support and encouragement to try out ideas in the classrooms, and help each other maintain the practices that resonate with newly developing ideas about how to teach for understanding. Other professional development efforts have successfully utilized the dynamics of communities to initiate and sustain reform efforts among teachers. Among these are Looking at Student Work (LASW), Japanese Lesson Study, and the Coalition of Essential Schools.

With regard to coherence, this characteristic refers to teachers' perceptions of how well aligned the professional development activities are with their own goals for learning and their goals for students. Teachers filter policy demands and messages from professional development providers through their own interpretive frames (Coburn, 2001; Cuban, 1986; Cuban, Kilpatrick, & Peck, 2001). The social context of schools had strong influence on these interpretive frames and thus teachers' decisions on how to enact (or resist) particular innovations (Rivet, 2006). Frequently, teachers assimilate only bits and pieces of new activity into their own repertoire with little substantive change, or they reject these changes suggested in professional development setting altogether (Coburn, 2004; Tyack & Cuban, 1995). Curricular reforms are particularly difficult in this regard because they require most teachers to make systemic changes to implement them well (Bybee, 1993; Crawford, 2000).

Penuel et al. (2007) refer to a coherence-related construct— *proximity to practice* (the degree to which professional development coincides with actual curriculum and classroom conditions that teachers are familiar with) as a feature that results in learning outcomes for teachers most directly translatable to practice (Darling-Hammond & McGlaughlin, 1995; Kubitsky & Fishman, 2006). A number of studies have focused on site-based or curriculum linked professional development (Fishman et al., 2003; Slotta, 2000). Site-based professional development for example provides assistance at school, in the context of teachers' enactment, using approaches such as coaching (Veenman & Denessen, 2001). Curriculum-linked professional development focuses specifically on how to enact pedagogical strategies, use materials, and administer assessments associated with particular curricula. There is growing consensus that to make changes, teachers need professional development that is interactive with their teaching practice, allowing for multiple cycles of presentation and assimilation of, and reflection on their developing knowledge (Blumenfeld, Soloway, Marx, Guzdial, & Palincsar, 1991; Kubitskey, 2006). A large-scale study conducted in California found this type of professional development far more effective than workshops focused on general pedagogical strategies in promoting changes in teachers' practice (Ball & Cohen, 2001).

In sum, the most important factors of professional development that can influence reform-based teaching and the understanding of how to cultivate 21st Century skills in learners are:

1. The collective and collaborative participation by teachers from the same school, grade, or subject areas.
2. The collective development of an evidence-based "inquiry stance" by participants towards their practice.
3. Active learning opportunities that focus on science content, scientific practice, and evidence of student learning.
4. Coherence of the professional development with teachers' existing knowledge, other development activities, with existing curriculum, and with standards in local contexts.

Findings from the Teachers' Learning Trajectory Initiative

Our own research program—the Teachers' Learning Trajectory Initiative—has investigated the question of how teacher preparation and early career support can be designed to foster reform-based instruction in novice educators. We place our results here in this paper because this research encompasses both pre-service training and the type of induction support that could be used as professional development for experienced teachers. The work documents links between novices' development of pedagogical reasoning and the evolution of their classroom practices.

We completed a multi-case study of 15 secondary science pre-service teachers, following them for three years through their preparation program, into student teaching, and through this first full year of teaching. A major feature of their preparation program was a methods course which focused heavily on four aspects of reform teaching. These four aspects are part of what we refer to as "ambitious pedagogy" (See Appendix A); more specifically it is teaching about and with model-based inquiry (see Windschitl, Thompson, & Braaten, 2008b).

The first of these four elements of ambitious pedagogy was *teachers' selection and treatment of key ideas from the curriculum*, in which the goal was to help novices see fundamental ideas in common curricula. Ideally this teaching would place significant focus on unobservable and/or theoretical processes in the natural world or on the relationships among science concepts. The second of these elements was *working with students' ideas*. To achieve competence here, novices would elicit and use students' current conceptions of science ideas to inform the direction of classroom activity and conversation. They would engineer productive classroom conversations, or consciously re-shape students' lines of thinking across multiple lessons. The third aspect of reform teaching was *working with science ideas in the classroom*. The goal here was for novices to highlight with students tentative explanatory models as the basis for investigating a phenomenon. The novice uses models as a referential representation of ideas before, during and after an inquiry, building in background knowledge of key science concepts and models as the inquiry progresses. The fourth aspect of reform teaching was called *pressing for explanation,* in which the novice asks students to use theoretical or unobservable processes to tell a causal story of why a target phenomena unfolded in particular ways. The novice unpacks/scaffolds "what counts" as an accountable scientific explanations with students.

These elements of pedagogy were modeled in the methods class; participants then had opportunities to try out these approaches through lesson planning and micro-teaching in the methods course.

We found all participants, to varying degrees, appropriated more sophisticated epistemological views of how models, theory and evidence are used in scientific inquiry. These ideas ultimately *supported a shift in their goals for scientific investigation*— from "proving" a hypothesis, to testing and revising generalizable models.

Other ideas and practices, however, were not unproblematically appropriated. Scientific argument, for example, was rarely incorporated into participants' day-to-day discourse. While the majority of participants were eventually able to conduct independent inquiries and construct scientific arguments that coordinated their data with conjectured theoretical mechanisms, the regular use of argument as a specialized form of rhetoric was not evident during the course. A second example of conceptual stasis involves participants who could not "let go" of the idea of the scientific method. Some of these individuals spoke in terms of the scientific method being a separate enterprise from model-testing, while others saw the scientific method as the data-gathering core of activity within the larger model-testing process.

During student teaching, more than half (8 of the 15 that student-taught) prompted their own students to use models, explicitly or implicitly, to make predictions, connect observations with underlying explanatory processes, and refine scientific ideas. Their pre- and post-course ratings of understanding models were roughly predictive of the degree of sophistication they employed in using model-based instruction with young learners.

The second phase of our study involved induction, during their first year of professional work, that was focused on the collaborative analyses of pupil work. We tested the hypothesis that novices in their first year of teaching could take up forms of ambitious pedagogy under the following conditions: 1) that a defined set of reform-based pedagogical practices introduced in teacher preparation would be the focus of sustained self-inquiry throughout the first year of teaching, 2) that participants use the analysis of their own pupils' work as the basis of critique and change in practice, and 3) that special tools be employed that help participants use a common frame of reference for hypothesizing about relationships between instructional decisions and student performance.

These special tools included a rubric that defined increasingly sophisticated levels of student performance in key areas of reform-based learning, and a protocol for guiding discussions during the collaborative examination of pupil learning artifacts. Over the course of their first year of teaching, *more than a third of the participants developed elements of expert-like teaching*, with the greatest gains made in pressing their students for evidence-based scientific explanations— a practice that *they* chose as the focus of their regular examination of student work (buy-in was important here, we pressed them a bit in this direction). This subset of participants held to the most problematized (i.e. sophisticated) images of the relationships between teaching and learning. This orientation influenced how they selected and analyzed their students' work, how they framed dilemmas to peers, and the degree to which they were able to participate in pedagogically productive discussions of practice during the collaborative analyses of pupil work. Despite variances in participation, most individuals in the study regularly taught in more reform-based ways than their curricula required them to during student teaching and their first year of professional work.

For a majority of participants, the system of tools (rubrics and protocol) was critical in allowing deep analyses of students' work and supporting a shared language that catalyzed conversations linking "what counts" as scientific explanation with the re-calibration of expectations for students, which in turn helped them envision more specialized forms of scaffolding for learners. On one level, the structure and language of the rubric allowed participants to see evidence of understanding in pupil work and to mediate understandings with peers (and in some cases their own students) about high-level expectations for learning science. On another level, when used together with the protocol during the collaborative analysis sessions, these tools pressed participants to be accountable for understanding science ideas they were trying to teach and for understanding the thinking represented in student work.

This research indicates that pre-service and first year teachers are capable of productively analyzing student work. Furthermore, these analyses can play a significant role in helping some early career teachers achieve expert-like classroom performances. We also found, however, that the nature of individuals' participation in systems of tool-based practices reflected their underlying assumptions of what counts as learning and what counts as good teaching. Those who held a more a problematized view of the relationships between teaching and learning were not only more likely to engage early in more skilled teaching, but also to benefit more from evidence-based collaborative inquiry into practice. This kind of "professional momentum" was more difficult to achieve for those beginning their careers with simplified conceptions of teaching and learning. Another clear finding from this study: *Unless participants were able to identify big ideas* (fundamental underlying models for phenomena) in common curricula and consider how to begin teaching these ideas as models, *all other elements of reform-based teaching were much less likely to be enacted*. This suggests that special forms of content knowledge are important to teaching 21st Century skills and the ability to reason pedagogically *with* these forms of content knowledge is equally important.

We are currently exploring the links between our findings and the emerging theoretical construct of *adaptive expertise for teachers*. The most sophisticated early career teachers in our study exhibited many of the characteristics of adaptive expertise listed in the literature (cognitive flexibility, monitoring their own learning, striving for innovation). Similarly, our struggling teachers fit the profile of routine practitioners (seeking efficiencies, satisficing, etc.). Whether or not this theory of expertise can be used as a tool to stimulate individuals to grow into an adaptive stance to teaching, it does appear that *teaching for 21st Century skills will require teachers to become adaptive experts* and become proficient at the skills themselves.

Recommendations

In making recommendations to the NAS committee I am aware of the need to provide an evidence-based picture of what kinds of teacher preparation, induction, and professional development "work." To this point I have given examples of program attributes and early career experiences that appear to influence the ability for teachers to facilitate learning effectively. Two challenges arise, however, when searching for what works at the program and professional development levels. The first challenge is that teacher preparation programs are comprised of so many potentially influential and interactive experiences for candidates that attributing success (however that is construed) to particular variables is difficult. The second challenge is that little systematic research has been done on preparation, induction, and professional development programs. More often, stakeholders from these programs publish self-evaluations that accentuate the positives, and do not include empirical tests of assertions about teaching or learning performances. Consequently, comparisons between programs based on teacher performance or student learning is nearly impossible (see, for example, how the AACTE's document—Preparing

STEM Teachers; The Key to Global Competitiveness—describes "evidence of teacher effectiveness" for over 70 teacher preparation institutions). Some professional development programs are very promising in their design and goals, for example the CONNECT-ED initiative sponsored by Rider University. This program provided opportunities for teams of teachers and scientists to collectively identify important content ideas from local curricula and develop "big idea modules" that were cohesive, conceptually-rich and pedagogically powerful. However, evaluations of how this changed teacher practice or student learning have not been conducted yet.

Despite the lack of a substantial knowledge base in teacher preparation and professional development, some recommendations are warranted by the evidence. I summarize these and then recommend a specific suite of tools that may help efforts at fostering reform-based teaching.

Teacher preparation. The broad characteristics of effective teacher education programs have already been articulated (for example Darling-Hammond, 1999, 2000). The following recommendations relate to science-specific preparation.

1. Science content preparation should not simply be a sampling of undergraduate courses whose content has no unifying threads (i.e. not integrated). An undergraduate major should be a coherent, connected experience. This could be accomplished by identifying and coordinating fundamental ideas that tie together all the courses in the major and by requiring some capstone experience in the major that synthesizes not only the content of the major, but the methodological and epistemological framework that guides contemporary inquiry in that domain.

2. In teacher education programs, all secondary science teachers should participate in science-specific methods courses that include regular opportunities to engage in the kinds of reform pedagogy described by the *National Science Education Standards*, and the intellectual work characterized by the 21st Century skills.

3. During practice teaching, pre-service teachers should be placed in schools with cooperating teachers who practice reform-based instruction, are competent with meaningful inquiry work and fostering 21st Century skills, and understand how to use all forms of assessment to give feedback to students and modify instruction. Also, cooperating teachers should understand how to scaffold novices as they try out these practices themselves.

Induction. The first two years of teachers' professional work should be supported by subject-specific mentoring and collaborative work that focuses primarily on student learning and its connections to instruction, rather than focusing on management issues or locating classroom materials. There should be opportunities for the regular analyses of pupil work with a group of colleagues sharing the same reform goals. This analysis should focus on high-leverage, reform-based practices, such as supporting students' attempts at evidence-based explanations of scientific phenomena or other forms of non-routine problem solving.

Professional development. The following characterizes elements of high quality continuing support for science teachers:

1. The collective and collaborative participation by teachers from the same school, grade, or subject areas.

2. The collective development of an "inquiry stance" towards practice.

3. Active learning opportunities that focus on science content, scientific practice, and evidence of student learning.

4. Coherence of the professional development with teachers' existing knowledge, other development activities, with existing curriculum, and with standards in local contexts.

New forms of tools and resources for teaching 21st Century skills. In addition to the broad recommendations above, teacher preparation, induction, and professional development would benefit from whole suites of tools to get novices to purposefully move their practice towards new kinds of expertise. I say this because, as mentioned previously, the kind of teaching required to foster 21st Century skills is a radical transformation of what is accepted as "good instruction" today. Specifically, 21st Century instruction:

- is unlike instruction that most teachers and teacher educators have participated in or witnessed
- is underspecified (i.e. lacks detailed performance language that can act as a guide for planning, execution and reflection on teaching)
- is discourse intensive, requiring understanding of different "genres" of productive talk that, taken as a system, facilitates problem-solving by students
- places many learning decisions and activities in the hands of students that were formerly determined by the teacher
- places equal emphasis on learning subject matter, learning how to problem-solve with others, and learning how to learn
- depends upon the skilled monitoring of student thinking about complex problems or inquiries and relies as well on on-going targeted feedback to students.

The tools we need include:

1. A set of *representations of practice* for what these reform-based teaching approaches look like, enacted in a variety of classrooms at different levels of sophistication. These representations could take the form of learning progressions for teaching 21st Century skills, and video cases that richly contextualize examples of reform-based teaching found in the learning progression.

2. Tools to help teachers understand *how to identify "big ideas"* in curricula and how to treat those ideas as testable, revisable, generalizable models with students. This might be a stand-alone tool or it could be incorporated into curricula itself. Davis & Krajcik (2005) have used the term "educative curriculum" to describe *teaching materials that teachers can learn from*. They maintain that it is crucial for curriculum developers to design materials that support science teaching practice by embedding features that are explicitly educative for teachers who use these materials (Ball & Cohen, 1999; Remillard, 2000). Davis and Krajcik (2005) found that educative curricula helped pre-service as well as experienced teachers learn to employ principles of inquiry-oriented science instruction over time and across settings.

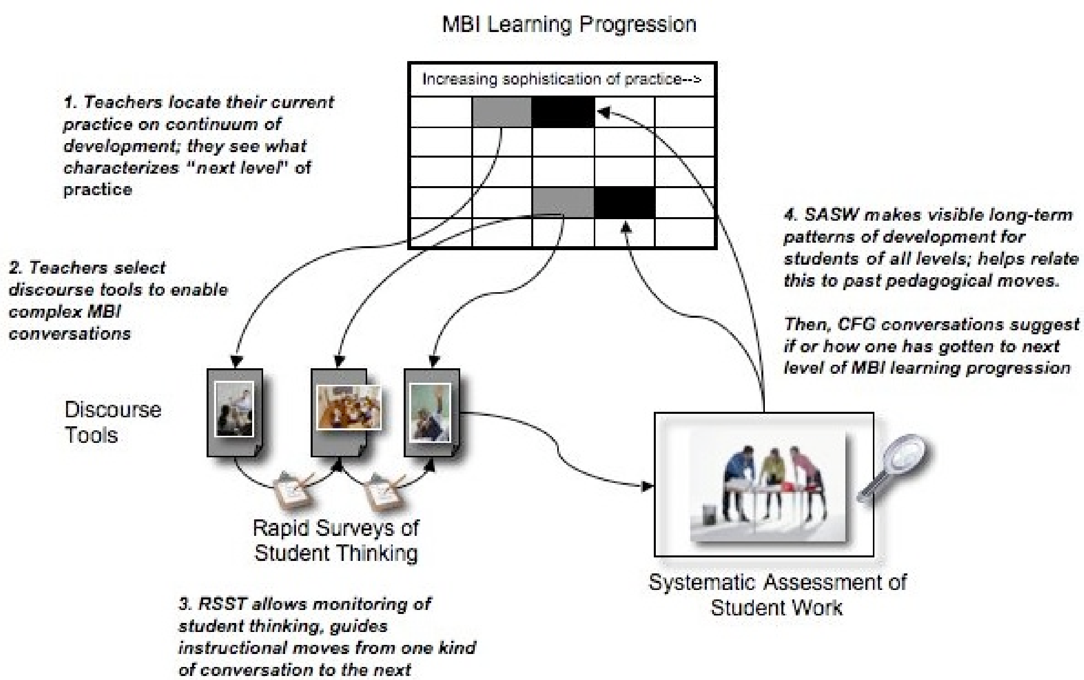
3. *Rubrics that help teachers imagine and assess "cases of student performance"* in different areas of reform-based learning. These rubrics could describe student performances in several key 21st Century skill areas, for example, "students select key pieces of a complex idea to express in words, sounds, and images, in order to build shared understanding", "use expert thinking to examine a broad span of information, recognize patterns, and narrow the information to reach a diagnosis of the problem", or "understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a "big picture" perspective on work." These student activities currently are underspecified and lack the

kinds of contextualization that would help teachers make sense of then as part of their imagined practice.

4. *Discourse tools to help teachers mediate new forms of learning* that go beyond transmitting information to students. These discourse tools could provide general sequences of questions or prompts that experienced teachers use, along with common patterns of students' responses, and schemes for capitalizing on these responses to help students achieve particular intellectual goals. Our own research has identified a lack of whole-class discourse skills as a major impediment for new teachers attempting reform-based instruction. For example, we are currently developing discourse tools for "eliciting students' conceptions about science ideas," "pressing students for evidence-based explanations," and others.

5. *Collaborative analysis routines and tools to help teachers learn with each other from their own practice*. These would include protocols for selecting and analyzing student work, relevant to reform science and/or 21st Century skills, and for meeting in groups to link evidence of student learning to one's practice.

These tools will likely work together in more powerful ways than they can work individually. I include here a diagram of a tool system that we are currently developing, in which the individual elements of the system work together to support early career teachers' attempts at reform instruction (model-based inquiry—MBI).



Closing

In a paper with so much detail, it is helpful to offer synthesis statements that remind the reader of major themes tying together a number of big ideas. These are not recommendations, but reminders of the scope of the challenge of re-envisioning science education for the future.

1. Reform-based teaching practice or practices that can foster 21st Century skills are rare in classrooms in part because they are under-specified for practitioners—and rare on another level because they call for a fundamentally different vision of "what counts" as learning than do traditional forms of instruction.

2. Learning to teach competently depends upon a years-long continuum of experiences that cohere conceptually and build upon one another.

3. Throughout this continuum, it is most productive for teachers to be focused on recognizing and strategically fostering student learning in the forms of deep conceptual understanding of core scientific ideas and engagement with authentic scientific practices—not merely managing classroom experiences (e.g. labs) for students or exposing them to well-defined scientific ideas.

4. Throughout early learning-to-teach contexts (coursework in teacher preparation programs, student teaching, the induction years), novices should be brought up within a culture of evidence-based decision-making about the design of instruction, using student performance artifacts and other records of practice as the basis for the refinement of teaching.

5. Preparing teachers to engage in reform-based instruction and foster 21st Century skills will require systemic changes in order to be successful, tying together new visions of undergraduate preparation, teacher preparation, professional development standards and the re-conceptualization of K-12 curricula. In sum, the goals we seek require more than well-intentioned changes in isolated components of our educational system, rather, *it will require a movement that fundamentally alters the nature of the "game being played," and re-defines how stakeholders interact with one another to achieve ambitious new goals.*

Appendix A.

Four dimensions of inquiry-based instruction, ranging from least sophisticated practices on left to practices representing ambitious pedagogy on right.

1) Selection and treatment of key ideas from the curriculum

Topic focus	*Process focus*	*Model/Theory focus*
• T selects "things" as topic for instruction. • In class, T's press is on describing, naming, labeling, identifying, using correct vocabulary.	• T selects natural processes as topics, but without any connections to underlying causes. • In class, T focuses on "what is changing" in a system or descriptions of how a change happens within a condition.	• T able to see fundamental ideas in the curriculum. • T has Ss focus on unobservable and/or theoretical processes or on the relationships among science concepts.

2) Working with students' ideas

Monitoring, checking, re-teaching ideas	*Eliciting Ss' initial understandings*	*References Ss' ideas & adapts instruction*
• T begins instruction with *no knowledge* of S's conceptions. • Instruction centers on delivering correct information. • Whole class conversations are only to check for nominal understandings. • T engages in one-on-one tutoring to see if students 'get it."	• T elicits Ss' *initial* hypotheses, questions, or conceptual frameworks about a scientific phenomenon. • This information not consciously used to shape subsequent instruction.	• *Within and across lessons* T elicits and uses Ss' current conceptions of science ideas to reshape direction of classroom conversations. • T engineers productive classroom conversations, or consciously re-shapes Ss' line of thinking across multiple lessons.

3) Working with science ideas in the classroom

Scientific Method focus	*Discovering or Confirming Science Ideas*	*Forwarding science ideas to work on*	*Model-Based Inquiry focus*
• T asks Ss to identify variables in a system and describe an experimental set-up. • Science concepts are played down to afford time to talk about designing investigations. • Talk with Ss around method is about error and validity.	• T has Ss "discover" conceptual relationships for themselves (with minimal background ahead of time) OR • T has Ss use an activity as "proof of concept."	• T foregrounds key science concepts and asks Ss to use an investigation to make sense of the concepts. • Focus is on sense-making between data and developing science concepts.	• T set-up for inquiry and data collection is purposeful; highlights tentative explanatory models as the basis for investigation into a phenomenon. • T uses model as a touching point before, during and after an inquiry; builds in background knowledge of key science ideas and models before, during and following an inquiry.

4) Pressing for explanation

"What happened" explanation	*How/ partial why explanation*	*Causal explanation*
• T asks Ss to provide a description of a phenomenon or thing, or may ask S's to put into words a given scientific correlation.	• T asks students to articulate correlations between variables and how these help a system work.	• T asks Ss to use theoretical or unobservable processes to tell causal story of what happened. • T unpacks/scaffolds "what counts" as an accountable scientific explanations with Ss.