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Draft White Paper 4
New assessments and environments for knowledge building

Marlene Scardamalia, John Bransford, Bob Kozma, and Edys Quellmalz

The Assessment and Teaching of 21st Century Skills project was created by Cisco, Intel and Microsoft and launched at the Learning and Technology World Forum 2009 in London. During 2009, the project operated with five Working Groups, each of which produced a White Paper. These papers will be fully edited into a volume that will be published electronically on the project website (www.atc21s.org). Print publication is also being considered.

As a report to the Learning and Technology World Forum 2010 in London, final drafts of the papers are collected together in this set and posted on the project website for Forum participants and others who can freely access them on the website. These drafts are not for formal citation. All persons registered on the project website for updates will be advised when the final publication has been posted on the site.

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Abstract

In this paper we review literature on knowledge-creating organizations to identify sequences leading from entry-level 21st century skills to mature levels of the skills defined by the *Assessment and Teaching of 21st Century Skills project*. We suggest a developmental scheme to allow students and teachers in any classroom to find a starting point and advance along dimensions identified. In a fully developed knowledge building environment, the ways people and ideas interact are critical to the integration of deep understanding, knowledge creation, and practical action. After proposing a framework for moving toward high-end knowledge environments we consider basic principles of learning and developmental trajectories relevant to them. We distinguish two approaches: "working backward from goals" and "emergence of new skills." We discuss how modern technologies can help integrate and enhance these different approaches, how formative assessments can be used to increase the pace of innovation, and how a broader systems perspective might inform large-scale summative assessments.

An analytic framework, with developmental trajectories defined by 21st century skills, is provided for analyzing environments in light of the extent to which they support knowledge creation. Our goal is to provide a scheme comprehensive enough to identify starting points, as well as pathways to higher-order achievements for all, from elementary through to tertiary education, and applicable to out-of-school contexts, so as to support an inclusive model of 21st century knowledge building. We also aim to distinguish efforts that prepare students for work in knowledge-creating organizations after they leave school from those that aim to transform schools to operate as knowledge-creating organizations in their own right. We end with suggestions for new initiatives to help advance education for a knowledge-building society.

New assessments and environments for knowledge building

Marlene Scardamalia, John Bransford, Bob Kozma, and Edys Quellmalz

Knowledge societies and the need for educational reform

There is general agreement that the much heralded ‘knowledge society’ (Drucker, 1994, 1968; Bell, 1973; Toffler, 1990) will have profound effects on our health, educational, cultural, and financial institutions, and create an ever-increasing need for robust lifelong learning, innovation, and the knowledge and skills to solve problems of the future. This need for innovation is emphasized by the shift from manufacturing-based to knowledge-based economies, with the health and wealth of nations tied to the innovative capacity of its citizens. Furthermore, Thomas Homer-Dixon (2000) points out that problems such as global climate change, terrorism, information glut, antibiotic resistant diseases, and the global financial crisis, create an *ingenuity gap*: the critical gap between our need for ideas to solve complex problems and our actual supply of those ideas. More and more, prosperity—if not survival--will depend on innovativeness and the creation of new knowledge.

Poor countries and citizens with less or poor education are particularly vulnerable. As elaborated by David and Foray (2003), disparities in the productivity and growth of different countries have far less to do with natural resources than with the capacity to create new knowledge and ideas: “The ‘need to innovate’ is growing stronger as innovation comes closer to being the sole means to survive and prosper in highly competitive and globalised economies.” (p.22)

The call to action that launched this *Assessment and Teaching of 21st Century Skills* project, titled *Transforming Education*: *Assessing and Teaching 21st Century Skills,* elaborates the need for systemic education reform to address the new challenges that confront us:

> The structure of global economy today looks very different than it did at the beginning of the 20th century, due in large part to advances in information and communications technologies (ICT). The economy of leading countries is now based more on the manufacture and delivery of information products and services than on the manufacture of material goods. Even many aspects of the manufacturing of material goods are strongly dependent on innovative uses of technologies. The start of the 21st century also has witnessed significant social trends in which people access, use, and create information and knowledge very differently than they did in previous decades, again due in many ways to the ubiquitous availability of ICT. These trends have significant implications for education. Yet most educational systems operate much as they did at the beginning of the 20th century and ICT use is far from ubiquitous. Significant reform is needed in education, world-wide, to respond to and shape global trends in support of both economic and social development.

According to one popular scenario, the introduction of technological advances into education will democratize knowledge and the opportunities associated with it. However, the current project is based on the assumption—shared by many (Laferrière, 2001; Raizen, 1997; Law, 2006)--that there is little reason to believe that technology combined with good intentions will be sufficient to make the kinds of changes that need to happen. To address these challenges, education reform must be systemic, not just technological. Systemic reform requires close ties between research-based innovation and practice, in order to create the know-how for knowledge-age education and workplace productivity. It also requires alignment between policy and other components of the system (Darling-Hammond, 1997, 2000). As the call to action indicates,

> Systemic education reform is needed that includes curriculum, pedagogy, teacher training, and school organization. Reform is particularly needed in education assessment. … Existing

models of assessment typically fail to measure the skills, knowledge, attitudes and characteristics of self-directed and collaborative learning that are increasingly important for our global economy and fast changing world.

In 21st century schools and other educational settings, knowledge and technological innovation will be inextricably related, as is currently the case in many knowledge-creating organizations. These organizations provide models for high-level 21st century skills in action and the knowledge building environments that support them. Once information and communication technology (ICT) becomes integral to the day-to-day, moment-to-moment workings of schools, organizations, and communities, a broad range of possibilities for extending and improving designs for knowledge-building environments and assessments follow. Accordingly, the goals for this paper are:

- to derive an analytic framework for analyzing environments and assessments that characterize and support knowledge-creating organizations and the knowledge building environments that sustain them;
- to apply this framework to a set of environments and assessments to better understand models, possibilities, and variations in the extent to which they engage students in or prepare them for work in knowledge-creating organizations;
- to derive technological and methodological implications for assessment reform;
- to propose an approach to research that extends our understanding of knowledge building environments and needs and opportunities for promoting 21st century skills.

We start by discussing two concepts that underlie our whole treatment of assessment and teaching of 21st century skills: *knowledge-creating organizations* and *knowledge-building environments*.

Knowledge-creating organizations

A popular saying is that the future is here now, it's simply unevenly distributed. *Knowledge-creating organizations* are examples; they are companies, organizations, associations, and communities that have the creation, evaluation, and application of knowledge either as their main function or as an essential enabler of their main functions. Examples include research institutes, highly innovative companies, professional communities (medicine, architecture, law, etc.), design studios, and media production houses.

Creating new knowledge entails expectation and means for going beyond best practice. Its goals are *emergent*, which means that they are formed and modified in the course of pursuing them. If computer design had not been characterized by emergent goals, computers would still be merely very fast calculating machines. Emergent outcomes cannot be traced back to subskills or subgoals, because they come about through self-organization—structure that arises from interactions among simpler elements that do not themselves foreshadow the structure. Color is the classic example of emergence; individual molecules do not have any color, but through self-organizing processes molecular structures arise that do have color. System concepts are similarly applied to explaining the evolution of complex anatomical structures (Dawkins,1996) and to accounting for creativity (Simonton, 1999)—one of the widely recognized 21st century skills. Creative work and adaptive expertise (Hatano & Inagaki, 1986) are alike characterized by emergent goals. This makes them especially relevant to 21st century skills.

The goal in developing 21st century skills is to equip students for productive and satisfying lives in a society where emergent goals characterize most real-world problems and where information technology plays an increasing role. Adapting education to meet 21st century needs cannot be achieved through skill development alone; values, habits, and disciplinary and world knowledge are clearly important, and some would argue more important than specifiable skills. But skills represent a challenge educational organizations of all kinds will need to face. According to a survey reported by Barth (2009), "Over two-thirds of employers said that high school graduates were 'deficient' in problem solving and critical thinking." A different perspective on skill needs is provided by a survey in which about 3000 graduates of the University of Washington, 5 to 10 years after graduation, rated the importance of various abilities they actually used in their work (Gillmore, 1998). The top-ranked abilities were (1) *defining and solving problems, (2) locating information needed to help make decisions or solve problems,(3) working and/or learning independently, (4) speaking effectively,* and (5) *working effectively with modern technology, especially computers.* These were the top-rated abilities by graduates from all the major fields. Regardless of the students' field of study, these outranked knowledge and abilities specific to their field. They correspond fairly closely to items that appear on 21st century skill lists generated by business people and educators. Accordingly, it seems evident that they represent something important in contemporary work life, although precisely what they represent is a question yet to be addressed.

The fact that so much of the pressure for teaching 21st century skills is coming from business people has naturally provoked some resistance among educators. The main objections are to the effect that education should not be reduced to job training and that the private sector should not be dictating educational priorities. These are legitimate concerns, but they can be answered straightforwardly:

- Teaching 21st century skills is a far cry from job training. It is developing abilities believed to be of very broad application, not shaped to any particular kind of job. Indeed, as The North American Council for Online Learning and the Partnership for 21st Century Skills state (2006): "All citizens and workers in the 21st century must be able to think analytically and solve problems if they are to be successful—whether they are entry level employees or high level professionals." (p.7)

- Employability is, however, an important consideration for today's students. Contrasting the changes taking place today with those of the Industrial Revolution, Peter Drucker (2003) pointed out that very little relearning was required for a farm worker to become a factory worker, but that extensive learning is required for a factory worker to become a knowledge worker—learning that is best started in childhood. (The despair expressed by auto workers who have recently lost their jobs sometimes directly acknowledges this predicament.)

- Crawford (2006) has questioned the emphasis on skills in the processing of abstract information. It is not expected that everyone will become what Reich (1991) called "symbolic analysts," but symbolic analysis and the use of technology for carrying it out are becoming increasingly essential for otherwise "manual" occupations (Leonard-Barton, 1995).

- Well-accepted educational values require that whatever is done to promote 21st century skills should not be confined to an elite. It must be inclusive, foster equal participation, address issues of citizenship and multiculturalism, and provide for deliberative governance (Hearn and Rooney, 2008; Treviranus, 1994, 2002).

- Increasing the level of knowledge-related skills is not only important for the managers and developers in an organization but is also important for empowering workers at all levels "to assume more responsibilities and solve problems themselves." (U.S. Department of Commerce, U.S. Department of Education, U.S. Department of Labor, National Institute of Literacy, and the Small Business Administration, 1999: p.1).

- It is not assumed that modern corporations, research laboratories, design studios, and the like represent ideal models for education to emulate. There is probably as much to be learned from studying their shortcomings as from studying their successes. What they do represent that is valuable for education systems is social organizations that function to produce knowledge rather than only to transfer and apply it. Thus they offer insight into a deeper level of constructivism than is characteristic of even the more active kinds of school learning (Scardamalia & Bereiter, 2003).

The last bullet point suggests an approach that will be developed further in this document. Instead of taking at face value the 21st century skills identified by committees of educators and business people, we may start by considering what constitutes knowledge creation at its best and what traits and abilities enable it. It is characteristic of “soft” skills of all kinds (of which 21st century skills are a subset) that everyone possesses them in some degree (unlike “hard” skills, such as solving simultaneous equations and tooth filling, which may be totally lacking in the untrained). Thus for each skill identified as relevant to knowledge creation, we may establish a continuum running from the skill level almost everyone may be assumed to have up to a level sufficient for engaging in creative knowledge work. The skills and competencies required for productive work in innovative organizations and professions provide a foundation for designing environments, practices, and formative assessments to help schools and education systems meet 21st century expectations (Treviranus, 1994, 2002; Wiggins & McTighe, 2006; Anderson, 2006).

Knowledge-building environments

Although the term “knowledge building” now appears in three quarters of a million web documents, about half as frequently as the term “knowledge creation,” it is almost never defined. In documents with a business orientation the term is used as a synonym for “knowledge creation,” with rough equivalence to concepts such as collective intelligence, intellectual capital, knowledge work, and innovation. In education documents it is used more generally, as a synonym for “constructivist learning”, with rough equivalence to concepts such as active learning, discovery learning, and inquiry- and project-based learning.

Our literature review indicates that the term “knowledge building,” was originally introduced into the educational literature in 1989 (Bereiter & Scardamalia, 1989, p.388), and had its basis in studies of expertise and innovation, summarized in the book *Surpassing Ourselves: An Inquiry Into the Nature and Implications of Expertise* (Bereiter & Scardamalia, 1993). The phrase “progressive problem solving” was used to denote the process by which experts become experts and continue to develop their expertise (in contrast to becoming experienced non-experts)—through investing surplus cognitive resources into boosting problems to higher levels. The same basic idea, applied to knowledge building, took the form of a contrast between shallow and deep constructivism. If we imagine a line with shallow constructivism at one end and deep constructivism at the other, most of what is called “constructivist learning” in schools would be located toward the shallow end. (The extreme being the ubiquitous “project,” which one long-time observer of the school scene described as using a computer to make a scrapbook.) Knowledge building would be located at the opposite end, signifying the deepest levels of work with ideas, leading to emergence of new ideas and continued efforts to improve them (Scardamalia & Bereiter, 2003).

In the history of thought, the idea of knowledge as a human construction is relatively new. Designing environments to support knowledge creation is newer yet. Schools were not built for that purpose, and to this day many would claim they should not be, or could not be. Yet universal access to the process whereby new knowledge is created depends on it.

In brief, w**e** use the term “knowledge-building environments” to refer to supportive contexts for emergence and further development of new ideas--knowledge creation in organizations of all kinds. Conceptually, economically and technologically, it may be necessary to connect currently distinct environments for creative work with ideas (e.g., knowledgeware) and those for learning (e.g., courseware, tutorials, simulations) to encourage the integration and easy movement between these different and essential aspects of mature knowledge work. What would a more integrative approach look like? We say more about that below. For now we elaborate the concept of knowledge building environments, with focus on features that favor emergence of new skills.

Knowledge-building environments provide special supports for creative work with ideas, so that ideas may grow from nascent form to something of greater consequence than imagined initially. Improved ideas emerge as ideas are generated in multiple and varied contexts and entered into communal spaces. Within these more public spaces collaborators and competitors can elaborate, critique, reframe, link, re-position, create higher-order structures, explore and devise uses for ideas, and in other ways work creatively with them. It is through such sustained and varied engagement that ideas, like colorless molecules, acquire new properties through structural organization. In line with this *emergence* perspective, a knowledge-building approach considers the "promisingness" of an idea, recognizing that through new combinations and sustained work something brilliant might emerge. In creative knowledge work it is important both to avoid wasting resources on unpromising ideas and to guard against killing off ideas that have promise. As the designer of a program for forest conservation remarked in response to criticisms of the plan, "an imperfect program which can be improved is better than none at all." ("Saving the rainforest: REDD or dead?" 2009)

In summary, a knowledge building environment, virtual or otherwise, is one that enhances collaborative efforts to create and continually improve ideas. It exploits the potential of collaborative knowledge work by situating ideas in a communal workspace where others can criticize or contribute to their improvement. In these collaborative, open contexts discourse that is democratic and directed toward idea advancement compounds the value of ideas, so that collective achievements exceed individual contributions. A local knowledge building community gains strength as it connects to a broader one. The local community not only draws upon but affords participation in the larger one, with possibilities for symmetrical knowledge advances. A successful knowledge-building environment will bring innovation closer to the central work of an organization. It is an environment in which members are continually contributing to and enhancing the shared intellectual resources of the organization. Each advance precipitates another, so that at both the individual and group level there is continual movement beyond current understanding and capacity. Emergence becomes a way of life, different from but both more productive and more personally satisfying than a life restricted to following known paths to known goals. Innovation, as Peter Drucker (1985, p.151) put it, becomes "part and parcel of the ordinary, the norm, if not routine."

New goals and methods to support the emergence of new skills

Advocates for the adoption of 21st century skills generally look for this to have an overall transformative effect on the schools. However, the nature and extent of this envisaged transformation can range from conservative to fundamental, as suggested by the following three levels:

1. Additive change. Change is expected to result from the addition of new skill objectives, new curriculum content (nanotechnology, environmental studies, cross-cultural studies, systems theory, technology studies, etc.), and new technology. Changes to existing curricula will be required to make room for additions.

2. Assimilative change. Instead of treating work on 21st century skills as an add-on, existing curricula and teaching methods are modified to place greater emphasis on critical thinking, problem solving, collaboration, and so forth. This is the most widely recommended approach and reflects lessons learned from the disappointing results of a previous wave of "higher-order thinking skills" instruction that took the additive approach (Bereiter, 1984).

3. Systemic change. Instead of incorporating new elements into a system that retains its 19th century structure, schools are transformed into 21st century organizations. Toward this end we present a case for schools operating as knowledge-creating organizations. The envisaged educational change is not limited to schools, however. Knowledge creation by young people can and often does take place in out-of-school contexts.

The present authors clearly favor systemic change but recognize that the realities of public education often mean that assimilative change and in many cases additive change is as far as a school system will go in adapting to 21st century opportunities and needs. Accordingly, approaches to teaching and assessing 21st century skills need to be applicable and potentially transformative at any of the three levels. That said, however, we suggest that countries whose schools are transformed into knowledge-creating organizations may gain a tremendous advantage over countries that struggle to incorporate knowledge-age education into industrial-age curricula and structures.

Two general strategies are applicable to pursuing the practical goals of advancing 21st century skills, and we argue that both are important and need to be used in a complementary fashion. One is the approach of *working backward from goals*. The other is one that, for reasons that will become evident, we call an *emergence* approach,

"Working backward from goals" to construct a system of subgoals and a path leading from an initial state to the goal is one of the main strategies identified in Newell and Simon's classic study of problem solving (1972). It will be recognized as the most frequently recommended way of designing instruction. As applied to educational assessment, it comprises a variety of techniques, all of which depend on a clearly formulated goal, the antecedents of which can be identified and separately tested. Although working backward is a strategy of demonstrable value in cases where goals are clear, it has two drawbacks in the case of 21st century skills. Most 21st century skills are "soft" skills, which means among other things that there is an inevitable vagueness and subjectivity in regard to goals, which therefore makes "working backward" not nearly so well structured as in the case of "hard" skills (such as ability to execute particular algebraic operations). A more serious difficulty, however, is that working backward from goals provides no basis for discovering or inventing new goals—and if 21st century education is to be more than a tiresome replication of the 1970s "higher-order skills" movement, it has to be responsive to potential expansions of the range of what's possible.

In the context of teaching and testing 21st century skills, "working backwards from goals" needs to be complemented by a working-forward approach growing out of what has been called the "systems revolution" (Ackoff, 1974). Self-organization and emergence are key ideas in a systems approach to a vast range of problems. An "emergence" approach, when closely tied to educational experimentation, allows for the identification of new goals based on the discovered capabilities of learners. The observation that, in advance of any instruction in rational numbers, children possess an intuitive grasp of proportionality in some contexts, led to formulation of a new goal (rational number sense) and development of a new teaching approach that reversed the traditional sequence of topics (Moss, 2005). Results suggest that both the traditional goals (mastering appropriate algorithms) and the path to achieving them (starting by introducing rational numbers through models that connect children's whole number arithmetic) were misconceived even though almost universally accepted. If that can happen even on such a well-traveled road as arithmetic teaching, we must consider how much riskier exclusive reliance on a working backwards approach might be to the largely untried teaching of 21st century skills. But the drawback of the emergence approach, of course, is that there is no guarantee that a path can be found to the emergent goal. Invention is required at every step, with all its attendant uncertainties.

Two concrete examples may help clarify the nature of an "emergence" approach and its benefits. The first example expands on the previously cited work of Moss (2005). The second example, drawn from work on scientific literacy, points to a potentially major 21st century skill that has gone unrecognized in the top-down and "working backward" approaches that have dominated mainstream thinking about 21st century skills.

4. <u>Beyond rational number skills to proportional thinking</u>. Failure to master rational numbers is endemic and has been the subject of much research. Much of the difficulty, it appeared, is that students transferred their well-learned whole number arithmetic to fractions and thus failed to grasp the essential idea of proportionality and also the idea that fractions are numbers in their own right. The standard way of introducing fractions, via countable parts of a whole, was seen as reinforcing this tendency. Joan Moss and Robbie Case observed, however, that children did already possess an idea of proportionality, which they could demonstrate when asked to pour liquid into two different-sized beakers so that one was as full as the other. Once proportional reasoning was recognized as a realistic goal for

mathematics teaching, “working backwards” could then be applied to devising ways of moving toward that goal. Moss (2005) developed a whole environment of artifacts and activities the purpose of which was to engage students in thinking proportionally. Instead of introducing fractions as the starting point for work on rational numbers, Moss and Case started with percents, as being more closely related to spontaneous understanding (consider the bars on computer screens that register what percent of a task has been completed). In final assessments, students in grades 5 and 6 out-performed educated adults. Another name for proportional thinking is rational number sense. Greeno (1991) characterized number sense as knowing ones way around in a numerical domain, analogous to knowing ones way around in a geographical area. It is not something that is directly taught, but rather something that emerges from experience in crossing and re-crossing a domain in different directions and with different purposes. It is assessable, but it is not specifiable in the way that hard skills are. And, quite obviously, proportional thinking or rational number sense is a more fundamental and more skill-enhancing outcome than mastering (or not quite mastering) a number of rational number algorithms.

5. Beyond “scientific method” to theory building. The second example of an emergence approach, more directly related to 21st century skills, comes from work on theory building. Broadly conceived, creative knowledge work of all kinds—planning, inventing, and so forth—is theory building. Even the Wright Brothers, known to the world as exceptionally clever tinkerers, were explicitly engaged in theory building at the same time they were engaged in building an airplane (Bereiter, 2009). Ability to construct, test, and improve theory-like knowledge structures could therefore rate as a top-level 21st century skill. It does not appear on 21st century skill lists, however, possibly because it is not readily described in skill terms and because little is known about what students are capable of in this respect. Expert opinion would suggest work on theory building should wait until high school (Smith & Wenk, 2006) and that the learning progression should start with hypothesis testing and control of variables (Kuhn, Schauble & Garcia-Mila, 1992; Schauble, Glaser, Duschl, Shulze & John, 1995). Instructional results from this approach have not been encouraging with respect to scientific literacy, and there have been many efforts to find new approaches (Carey, Evans, Honda, Jay, & Unger,1989; Carey & Smith, 1993; Honda, 1994, Smith, Maclin, Houghton, & Hennessey, 2000), with further confirmation of the conventional expert wisdom that theory building is beyond the capacity of young students. When free to pursue problems of understanding under their own initiative, however, students were observed to engage spontaneously in a good deal of theorizing (Scardamalia & Bereiter, 2006). A small experiment was carried out in which grade 4 students in a class where such knowledge building was the norm were compared with similar students who had followed a more traditional inquiry approach (Bereiter and Scardamalia, 2009). In the knowledge building class there was no explicit teaching of “scientific method” and no carrying out of pre-specified experiments. Instead, the students were supported in creating, exploring, and considering theories from multiple perspectives. Results showed significantly higher levels of theoretical work and scientific literacy and superior scientific writing for the emergent goals approach (Bereiter and Scardamalia, 2009; Chuy, Scardamalia, & Bereiter, 2009). Theory building, it turns out, is not only possible in 10 to 12-year-olds but even earlier. A kindergarten teacher in the same school learned of the findings and thought her students might have relevant, untapped capacities. She asked them to generate theories about why some trees in their schoolyard had no new leaves in the early spring while other trees did. The children not only generated a number of reasonable explanations but connected these with supportive facts. It would seem, therefore, that theory building could justifiably gain a place among 21st century skills developed and tested from early childhood on up.

In a later section on technology to support the emergence of new skills (pp,39ff) we discuss the specific forms of support that enabled exceptional levels of proportional reasoning and theory development. As the preceding examples suggest, discovering new goals is not simply a matter of turning students loose in an environment and waiting to see what happens. Discovering new goals is scientific discovery, and rarely is such discovery accidental. People know in a general way what they are looking for, and particular moves may be carefully calculated, but the process as a whole is structured so as to allow room for unexpected insight. When Darwin set sail on the Beagle he did not know he was out to explain the origin of species, but he was not just a collector of curious specimens either.

Most current school reform efforts, whether involving new management structures or the introduction of new standards and curricula, are additive as far as their treatment of 21st century skills is concerned. Changes are based on conservative practices and templates drawn from instruction in traditional subjects. More transformative change requires that goals and methods be considered anew. Education for 21st century skills may in fact have no "tried and true" methods to draw on, so riskier approaches are required. It is difficult to get excited about 21st century education reform if it is nothing more that extending existing goals to more demanding performance levels. It should include such goals—performance demands are indeed liable to rise and there will no doubt continue to be students who need help in meeting even today's modest standards. But anything that deserves the name of education for the 21st century needs new kinds of objectives, not simply higher standards for existing ones.

In the following sections we examine 21st century skills as these are enacted in knowledge-creating organizations. We focus on what is involved in knowledge creation as carried out by experts actually working in knowledge creating organizations. This provides a sharpened focus for "working backward" to identify methods and goals that might apply to schools, while allowing us to go beyond the identification of desirable traits and skills as viewed by employers wishing to hire people for knowledge work. We then consider the knowledge building environments that support work in knowledge-creating organizations, followed by consideration of learning and assessment theory. In section on specific investigations (pp.42ff) we propose specific investigations within an emergence framework, using findings from the working backward approach to test transfer and generalization effects so as to achieve a best-of-both-worlds synthesis of working-backwards and emergence approaches.

Characteristics of knowledge-creating organizations

How do businesses succeed in a knowledge economy? How are knowledge-intensive firms organized and how do they function? How are jobs different in a knowledge economy? And what kinds of skills are needed?

Industry- or firm-level studies in the U.S. (Stiroh, 2003), the U.K. (Borghans & ter Weel, 2001; Dickerson & Green, 2004; Crespi & Pianta, 2008), Canada (Gera & Gu, 2004; Zoghi, Mohr, & Meyer, 2007), France (Askenazy, Caroli, & Marcus, 2001; Maurin & Thesmar, 2004), Finland (Leiponen, 2005), Japan (Nonaka & Takeuchi, 1995), and Switzerland (Arvanitis, 2005), have found many similar results. A major factor in the success of highly productive, innovative firms is the use of ICT (UNESCO, 2005). Of course, productivity and innovation increases did not come merely with the introduction of new technologies. Rather, the technology use must be associated with a pattern of mutually reinforcing organizational structures, business practices, and employee skills that worked together as a coherent system. Also, organizational structures have become flatter, decision-making has become decentralized, information is widely shared, workers form project teams, within and across organizations, and work arrangements are flexible. These changes in organizational structures and practices have been enabled by the application of ICT for communication, information sharing, and simulation of business processes. For example, a U.S. Census Bureau study (Black and Lynch, 2003) found significant firm-level productivity increases associated with changes in business practices that included reengineering, regular employee meetings, the use of self-managed teams, up-skilling of employees and the use of computers by front-line workers. In Canada Zohgi, Mohr, and Meyer (2007) found a strong positive relationship between both information sharing and decentralized decision-making and a company's innovativeness. Recent studies of firms (Pilat, 2004; Gera & Gu, 2004) found significant productivity gains when ICT investments are accompanied by other organizational changes, such as new strategies, new business processes and practices, and new organizational structures. Murphy (2002) found productivity gains when the use of ICT was accompanied by changes in production processes (quality management, lean production, business re-engineering), management approaches (teamwork, training, flexible work and compensation) and external relations (outsourcing, customer relations, networking).

These changes in organizational structure and business practices have resulted in corresponding changes in hiring practices of companies and the skills needed by workers. A study of labor tasks in workplaces found that, commencing in the 1970's, routine cognitive and manual tasks in the U.S. economy declined and non-routine analytic and interactive tasks rose (Autor, Levy, & Murnane, 2003). This finding was particularly pronounced for rapidly computerizing industries. The study found that as ICT is taken up by a firm, computers *substitute* for workers who perform routine physical and cognitive tasks but they *complement* workers who perform non-routine problem solving tasks. Similar results were found in the U.K. (Borghans & ter Weel, 2001; Dickerson & Green, 2004), France (Maurin & Thesmar, 2004), the Netherlands (Borghans & ter Weel, 2001), and Canada (Gera & Gu, 2004).

Because repetitive, predictable tasks are readily automated, computerization of the workplace has raised demand for problem-solving and communications tasks such as responding to discrepancies, improving production processes and coordinating and managing the activities of others. In a survey of U.K. firms, Dickerson and Green (2004) found an increased demand for technical know-how, high-level communication skills, planning skills, client communication skills, horizontal communication skills, problem-solving skills and checking skills. There was a decreased demand for physical skills. The net effect of these changes is that companies in the U.S., the U.K. and other advanced economies (Lisbon Council, 2007) are hiring workers with a higher skill set. It is also interesting that many of these skills (e.g. communication, collaboration, flexibility) are often referred to as "soft skills" yet are some of the most important for success and some of the most difficult to help people develop to high levels of refinement.

The creation of knowledge as a social product (Scardamalia & Bereiter, 2003; 2006) is a major part of that higher skill set. It requires collective responsibility for accomplishments and is something that scientists, scholars and employees of highly innovative companies do for a living (Nonaka & Takeuchi, 1995). An interesting example is the design of Boeing 787 aircraft, built by nearly 5,000 engineers (excluding production workers) from around the world. The design and engineering work is taking place simultaneously at multiple sites, over a long period of time, and yet all the parts ultimately fit nicely together (Gates, 2005). In a collaborative, creative endeavor of this nature, team members need to understand the top-level goal and share responsibility for the interrelated network of ideas, sub-goals, and designs, with success dependent on all members rather than concentrated in the leader. They share responsibility for establishing effective procedures, for assigning and completing practical tasks, for understanding and facilitating team dynamics (Gloor, 2006), for remaining cognitively on top of activities and ideas as they unfold (Leonard-Barton, 1995), and for the process as a whole. As issues emerge, they collectively shape next steps, build on each other's strengths, and improve their ideas and designs. Members create the cultural capital of their organization as they refine the "knowledge space" and products that represent their collective work.

Of course this work includes timelines, specified goals, and deadlines. The idea of collective responsibility is not to ignore such aspects, but to engage participants in setting deadlines, taking responsibility for achieving them, and redefining goals and schedules as necessary. It also requires commitment to work in public spaces, to making one's thinking and processes explicit and available, and to entering artifacts into the shared knowledge space that advance the state of the community knowledge. If everyone is doing the same thing (as is often the case in school) the redundant, repetitive work interferes with productivity. The shared problem space must grow, based on shared goals and helpful, diverse contributions from all members.

This cluster of changes—organizational structure, business practices, and more-complex employee tasks and skills—is particularly pronounced for knowledge-intensive, knowledge-creating organizations. Probably the most intensive knowledge creating organizations are research laboratories. Current research in the sociology and anthropology of science has focused on two aspects of the work of scientists: the distributed nature of scientific work over time, resources, and place and the moment-by-moment coordination of instruments, representations, and discourse as scientists construct meaning from the results of their research.

In contemporary science, creating new knowledge requires the coordination of activities through time and across space to assemble methods, tools, and theories, building on previous findings to conduct new research and generate knew knowledge (Fujimura, 1992). To achieve this spatial and temporal coordination, scientists develop technological and social systems that support the movement of specialized scientific objects, like ideas, data, sketches, and diagrams, across this distributed network. This coordination within and across organizations and across time, place, and objects was apparent in Kozma's study (Kozma, Chin, Russell, & Marx, 2000; Kozma, 2003) of chemists in a pharmaceutical company. Here the synthetic products of one group were frequently the starting materials of another group, as activities related to the creation of a new drug were distributed across laboratories, chemists with different specializations, and equipment with different purposes. This coordination was maintained, in part, by standardized procedures and, in part, by labels with diagrams of chemical structures that were attached to the vials that moved from lab to lab.

The laboratory is where the moment-by-moment work of science is done. Much of this moment-by-moment work is done around instruments and representations. In their collaborative activities, scientists talk and visually represent their ideas to each other in supportive physical spaces (Ochs, Gonzales, & Jacoby, 1996). The indexical properties of these physical spaces and representations are essential to how scientists collaborate and establish shared meaning (Goodwin & Goodwin, 1996; Hall & Stevens, 1995; Suchman & Trigg, 1993). In their discourse, scientists make references to the specific features of diagrams and data visualizations as they coordinate these representations to understand the products of their work (Kozma et al., 2000, Kozma, 2003). The features of these representations are often used as warrants for competing claims about their finding as scientists try to adjudicate their different interpretations.

These research findings on the practices, organizational structures and needs of innovative, knowledge creating organizations have significant implications for the practices and organizational structures of environments needed to support the acquisition of 21st century skills and for finding productive connections between in- and out-of-school learning environments. Knowledge-creating organizations rank high on all of the 21st century skills listed in various documents and articles (for example, The Partnership for 21st century skills, 2009; Binkley, et al., 2009; Johnson, 2009). Consequently, an analysis of knowledge-creating organizations additionally provides high-end benchmarks and models to guide the design and implementation of modern assessment. For example, the literature on how distributed teams have managed to successfully produce more and better outputs helps operationalize concepts such as collaboration, group problem solving, use of ICT, etc. Also included are the social, material and technological practices and organizational structures in which members of knowledge-creating organizations operate.

Table 1 describes in condensed form characteristics of knowledge-creating organizations mapped onto the 21st century skills presented in White Paper 1. Our goal is to align these different perspectives and, as elaborated below, provide an analytic framework for educational environments and assessments to identify those most in keeping with characteristics of knowledge-creating organizations.

There are major differences between 21st century skills as they figure in school curricula and the skills manifested in knowledge-creating organizations. In schools the skills are frequently treated separately, each having its own learning progression, curriculum, and assessment. In knowledge-creating organizations different facets of work related to these skills represent a complex system with the skills so intertwined that any effort to separate them in contexts of use would undercut the dynamic that gives meaning to them.

Table 1: 21st century skills as experienced in knowledge-creating organizations

21st century skills	Experience in knowledge-creating organizations
Creativity and Innovation	Work on unsolved problems; generate theories and models, take risks, etc; pursue promising ideas and plans
Communication	Knowledge building/progressive discourse aimed at advancing the state of the field; discourse to achieve a more inclusive, higher order analysis; open community knowledge spaces encourage peer-to-peer and extended interactions
Collaboration/teamwork	Collective or shared intelligence emerges from collaboration and competition of many individuals and aims to enhance the social pool of existing knowledge. Team members aim to achieve a focus and threshold for productive interaction and work with networked ICT. Advances in community knowledge are prized, over-and-above individual success, while enabling each participant to contribute to that success
Information literacy / research	Going beyond given information; constructive use of and contribution to knowledge resources to identify and expand the social pool of improvable ideas, with research integral to efforts to advance knowledge resources and information
Critical thinking, problem solving and decision-making	High-level thinking skills exercised in the course of authentic knowledge work; the bar for accomplishments is continually raised through self initiated problem finding and attunement to promising ideas; participants are engaged in complex problems and systems thinking
Citizenship – local and global	Citizens feel part of a knowledge-creating civilization and aim to contribute to a global enterprise; team members value diverse perspectives, build shared, interconnected knowledge spanning formal and informal settings, exercise leadership, and support inclusive rights
ICT literacy	ICT integrated into the daily workings of the organization; shared community spaces built and continually improved by participants, with connection to organizations and resources worldwide
Life and career skills	Engagement in continuous, “lifelong” and “life-wide” learning opportunities; self-identification as a knowledge creator, regardless of life circumstance or context
Learning to learn / meta-cognition	Students and workers are able to take charge at the highest, executive levels; assessment is integral to the operation of the organization, requiring social as well as individual metacognition
Personal and social responsibility – incl. cultural competence	Team members build on and improve the knowledge assets of the community as a whole, with appreciation of cultural dynamics that will allow the ideas to be used and improved to serve and benefit a multicultural, multilingual, changing society

Characteristics of knowledge-building environments

Knowledge-building environments represent *complex systems* that support *emergent outcomes*. They are places that, like knowledge-creating organizations, produce public knowledge—knowledge that does not just reside in the minds of individuals but that is available to others to build on and improve. Public knowledge develops through discourse, in which declarative statements play a necessary role, as do models, theories, and artifacts that are available to the community as a whole. Having students become active agents in knowledge construction is an important theme in the literature on school reform and knowledge building processes (Engle & Conant, 2002; Herrenkohl & Guerra, 1998; Lamon, Secules, Petrosino, Hackett, Bransford, & Goldman, 1996; Lehrer, Carpenter, Schauble, & Putz, 2000; Paavola & Hakkarainen, 2005; Tabak & Baumgartner, 2004). Of particular interest in this regard is *collective cognitive responsibility,* which requires taking responsibility for the state of public knowledge (Scardamalia, 2002).

As the Boeing example suggests, networked, communal knowledge spaces are at the heart of work in knowledge creating organizations. Accordingly, the work of participants has an "out-in-the-world" existence. The intellectual life of the community—objectified as theories, inventions, models, plans, and the like—is accessible, in tangible form. In the business world, this is referred to as the organization's corporate knowledge; in the knowledge building literature, it is referred to as "community knowledge" (Scardamalia, 2002). This community knowledge space is typically absent from classrooms, making it hard for students' ideas to be objectified, shared, examined, improved, synthesized, and used as "thinking devices" (Wertsch, 1998) to enable further advances. It also makes assessment difficult because students' ideas are neither explicit nor in tangible form. By contrast, the commitment to work in open, shared spaces not only renders ideas objects of discussion and improvement but opens the door for concurrent, embedded, and transformative assessment, as we elaborate below. In turn, these communities can sustain work at the high end of 21st century skills, as identified in Table 1.

Group learning

Group learning and cognition may well become the dominant theme of technology in the next quarter-century, just as collaborative learning was in the previous one (Stahl, 2006). Group learning is learning *by* groups, which is not the same as learning *in* groups or individual learning through social processes. The term *learning organization* (Senge, 1990) reflects this emphasis on the organization itself operating as a knowledge-advancing entity and reflects the larger societal interest in knowledge creation. Knowledge building is a group phenomenon, even when contributions come from identifiable individuals. Members are responsible for the production of public knowledge that is of value to a community. Again, this maps directly onto the Boeing example presented above. The community may be a research or design group or the world at large or it may be a group of learners—in which case it is important to distinguish individual learning from the group's knowledge-building accomplishments. Neither one can be reliably inferred from the other, although the interaction between the two is vital and deserving of study in its own right. We return to this issue in the final sections of this paper.

In a knowledge-building group, the crucial assessment questions are about the group's achievements in advancing the state of knowledge—comparable to the "state of the art" reviews common in the disciplines and professions. Self-assessment by a knowledge-building group can be valuable both for helping the group progress and for individual learning (Lee, Chan, & van Aalst, 2006). External assessment can serve purposes of troubleshooting and management. Evidence available suggests that such an approach increases individual learning, not just group learning, because the group needs each individual's contribution. There is thus social pressure to perform. However, this is a finding much in need of replication and extended study.

Knowledge building developmental trajectory

Building on the characteristics of knowledge-creating organizations and what it is we know about learning, we can begin to specify the characteristics of knowledge-building environments and the implications they have for educational practices. Table 2 is an elaboration of Table 1 and provides a developmental framework for analyzing learning environments. For each 21st century skill, the table suggests a continuum running from the entry level characteristics that may be expected of students who have had no prior engagement in knowledge building to a level characteristic of able participants in a knowledge-creating enterprise. The continuum is an "emergence" continuum—a developmental trajectory from active or constructivist learning as the entry point, to complex systems of interactivity and knowledge work that enable the generation of new knowledge, the capacity to exceed standards, and the drive to go beyond best practice at the high end.

In the section on needed research (pp.40ff) we propose experiments to develop this scheme, including additional points along the continuum, to indicate how designing environments with sights set on the high-end of the scale can facilitate the advancement of any school, any teacher along these lines.

Table 2: Developmental trajectory for knowledge-creating environments

21st century skills	Characteristics of knowledge-creating organizations	
	Entry Level	High
Creativity and innovation	Internalize given information; beliefs/actions based on the assumption that someone else has the answer or knows the truth	Work on unsolved problems; generate theories and models, take risks, etc; pursue promising ideas and plans
Communication	Social chit chat; discourse that aims to get everyone to some predetermined point; limited context for peer-to-peer or extended interactions	Discourse aimed at advancing the state of the field and at achieving a more inclusive, higher order analysis; open community knowledge spaces encourage peer-to-peer and extended interactions
Collaboration/ teamwork	Small group work: divided responsibility to create a finished product; the whole is the sum of its parts, not greater than that sum	Shared intelligence emerges from collaboration and competition and enhances existing knowledge. Individuals interact productively and work with networked ICT. Advances in community knowledge are prized over individual success, while enabling each participant to contribute.
Information literacy/ research	Inquiry: question-answer, through finding and compiling information; variable testing research	Going beyond given information; expansion of social pool of improvable ideas, with research integral to efforts to advance knowledge
Critical thinking, problem solving and decision-making	Meaningful activities are designed by the director, teacher or curriculum designer; learners work on predetermined tasks set by others	High-level thinking skills exercised in authentic knowledge work; the bar for accomplishments is continually raised by participants as they engage in complex problems and systems thinking
Citizenship – local and global	Support of organization and community behavioral norms; “doing one’s best”; personal rights	Citizens feel part of a knowledge-creating civilization and contribute to a global enterprise; team members value diverse perspectives, build shared knowledge in formal and informal settings, exercise leadership, and support inclusive rights
ICT literacy	Familiarity with and ability to use common applications and web resources and facilities	ICT integrated into the organization’s daily work; shared community spaces built and continually improved by participants, with connection to organizations and resources worldwide
Life and career skills	Personal career goals consistent with individual characteristics; realistic assessment of requirements and probabilities of achieving career goals	Engagement in continuous, “lifelong” and “life-wide” learning opportunities; self-identification as a knowledge creator, regardless of life circumstance or context
Learning to learn / meta-cognition	Students and workers provide input to the organization, but the high-level processes are under the control of someone else	Students and workers are able to take charge at the highest, executive levels; assessment is integral to the operation of the organization, requiring social as well as individual metacognition
Personal and social responsibility – incl. cultural competence	Individual responsibility; local context	Team members build on and improve the knowledge assets of the community, with appreciation of cultural dynamics that allow the ideas to be used and improved to benefit a multicultural, multilingual, changing society

Advancing domain knowledge and 21st century skills in parallel

In knowledge building environments deep disciplinary knowledge is at the center of all knowledge work and 21st century skills are inseparable, serving as enablers. 21^{st} century skills—often labelled “soft” or “generic” skills--have been widely recognised as central to innovative capacity and hence vital for success in a 21^{st} Century global economy. Although 21^{st} century skills are recognized in recent curriculum standards, the main emphasis in standards and assessments is on “hard” skills in

Figure 1: Centrality of deep disciplinary knowledge to all knowledge work

language and mathematics as well as "hard" factual knowledge. There is concern that attention given to "soft" skills will detract from efforts to improve the skills and subject-matter knowledge for which the schools are held accountable. The consensus among researchers in the learning sciences is that the two are not in conflict (Bransford, Brown, & Cocking, 1999; Darling-Hammond, et al., 2008); their interdependence is suggested in Figure 1. In formal education beyond the most basic "3 Rs" level, hard skills are generally treated as a part of domain knowledge. Ability to solve quadratic equations, for instance, is part of algebraic domain knowledge. Hence, as modelled in Figure 1, domain knowledge and hard skills are combined to constitute the focus of formal education, while a common set of soft skills surrounds expertise in all domains.

Making 21st century skills universally accessible rather than the province of knowledge elites requires that the environments that support knowledge creation be made accessible to all. From the *emergence* perspective, the challenge is to shift to environments that take advantage of what comes naturally to students across the full range of 21st century skills (e.g., idea production, questioning, communication, problem solving, and so forth) and engage them in the kinds of environments for sustained idea development that are now the province of knowledge elites. These knowledge building environments, environments that score at the high end of all the developmental continua identified in Table 2, increase innovative capacity through engagement in a knowledge building process--the production of public knowledge of value to others so that processes of collective responsibility for knowledge advancement can take hold (Scardamalia & Bereiter, 2003). That is how idea improvement, leading to deep disciplinary knowledge, gets to the center of the enterprise, with 21st century skills inseparable and serving as enablers.

Comparative research and design experimentation are needed to add substantially to the knowledge base on relations between inquiry and knowledge building activities and the meeting of traditional achievement objectives. The research and design experiments proposed in the final section should help address these issues through use of formative assessment, combined with other assessments, selected to evaluate advances in both "hard" and "soft" skills, and changes over time supported through work in information rich knowledge building environments. The proposition to be tested: *Collective responsibility for idea improvement in environments that engage all students in knowledge advancement should result in advances in domain knowledge in parallel with advances in 21st century skills*. This argument is in line with that set forth by Willingham (2008): "Deep understanding requires knowing the facts AND knowing how they fit together, seeing the whole."

This notion that deep understanding or domain expertise and 21st century skills are inextricably related has led many to argue that there is not much new in 21st century skills—deep understanding has always required domain understanding and collaboration, information literacy, research, innovation, metacognition, and so forth. In other words, 21st century skills have been "components of human progress throughout history, from the development of early tools, to agricultural advancements, to the invention of vaccines, to land and sea exploration" (Rotherham & Willingham, 2009).

But is it then also true that there are no new skills and abilities required to address the needs of today's knowledge economy? One defensible answer is that the skills are not new but that their place among educational priorities is new. According to Rotherham & Willingham, "What's actually new is the extent to which changes in our economy and the world mean that collective and individual success depends on having such skills. … If we are to have a more equitable and effective public education system, skills that have been the province of the few must become universal." "What's new today is the degree to which economic competitiveness and educational equity mean these skills can no longer be the province of the few" (Rotherham, 2008). Bereiter and Scardamalia (2006) have argued, however, that "there is in fact one previously unrecognized ability requirement that lies at the very heart of the knowledge economy. It is the ability to work creatively with knowledge per se." Creative work with knowledge –with conceptual artifacts (Bereiter, 2002)—must advance along with work with material artifacts. Knowledge work binds hard and soft skills together.

The deep interconnectedness of hard and soft skills has important implications for assessment, as does the commitment to individual contributions to collective works. As Csapó, Latour, Bennett, Ainley, & Law (2009) state, "how a domain is practiced, taught, and learned impacts how it should be assessed… the real promise of technology in education lies in its potential to facilitate fundamental, qualitative changes in the nature of teaching and learning" (Panel on Educational Technology of the President's Committee of Advisors on Science and Technology, 1997, p.33). Domains in which it is most important to include technology in the assessment of 21st century skills include, according to Csapó el al., those in which technology is so central to the definition of the skill that removing it would render the definition meaningless (e.g., the domain of computer programming), those is which higher levels of performance depend on technology tools, and those that support collaboration, knowledge building, and the social interactions critical for knowledge creation. We would argue that, to make knowledge building and knowledge creation broadly accessible, technological supports for knowledge building also need to be broadly accessible.

Assessment of "soft" skills is inherently more difficult than assessing the "hard" skills that figure prominently in educational standards. Assessing knowledge creation processes may be even harder. Nonetheless, this core capability should be further enhanced and clarified through programs of research and design that aim to demonstrate that the processes that underlie knowledge creation underlie deep understanding; knowledge building environments promote both. We return to these ideas below.

Advancing literacy and closing gaps

Among the skills needed for life in the knowledge age, literacy is perhaps the most crucial. Without the ability to extract and contribute useful information from complex texts, graphics, and other knowledge representations, one is in effect barred from knowledge work. Print literacy (as with other literacies) has both hard skill and soft skill components; e.g., in reading, fluent word recognition is a testable hard skill, whereas reading comprehension and critical reading are important soft skills. Soft-skill components of reading are mandated and tested but traditional schooling typically deals with them through often ineffectual "practice makes perfect" approaches.

Although there are diverse approaches to literacy education, most of them treat it as an objective to be pursued through learning activities that have literacy as their main purpose. For the most part, with school-based reading, motivation comes from the interestingness of the reading material itself. Consequently, the unmotivated reader, who is frequently one for whom the decoding of print is not fluent, is a persistent problem (Gaskin, 2005). During the past decade, however, new approaches have developed in which the focus is not on literacy as such but on collaborative inquiry, where the primary motivation for reading is solution of shared problems of understanding. Effects on literacy have been as great as or greater than those of programs that emphasize literacy for its own sake (Brown & Campione, 1996; Sun, Zhang, & Scardamalia, 2008). Work in Knowledge Forum technology, specially developed to support knowledge building, has provided evidence of significant literacy gains through ICT (Scardamalia, et al., 1992; Sun, Zhang, & Scardamalia, 2008; in press). Whereas literacy-focussed programs typically engage students with reading material at or below their grade level, students pursuing self- and group-directed inquiry frequently seek out material that is above their grade level in difficulty, thus stretching their comprehension skills and vocabularies beyond those normally developed. Rather than treating literacy as a prerequisite for knowledge work, it becomes possible to treat knowledge work as the preferred medium for developing the literacies that support it, with student engagement involving a full range of media objects, to support multi-literacies. This approach raises major research issues, which we return to in the final section of this paper.

Knowledge building analytic framework

We have developed a *Knowledge Building Analytic Framework* to advance the two goals presented in the introduction to this paper:

- to derive an analytic framework for analyzing environments and assessments that characterize and support knowledge-creating organizations and the knowledge building environments that sustain them
- to apply this framework to a set of environments and assessments to better understand models, possibilities, and variations in the extent to which they engage students in or prepare them for work in knowledge-creating organizations.

In the White Paper 4 Annex (p.46) we have included a template that can serve as a scoring scheme to apply to a broad range of environments and assessments, making it possible to characterize strengths and weaknesses of knowledge building environments and assessments. The scheme is the same as presented above, in Table 2. It is simply set up in the Annex as a scoring scheme to encourage users to assess specific environments and compare scores by different assessors for the same environment. Users have reported that it is a helpful instrument for reflection on key aspects of the environment analyzed, and increasingly beneficial once they have a chance to view and discuss ratings of the same environment by different raters. The discussion of rationales for different ratings facilitates understanding of the dimensions and functions associated with knowledge-creating organizations. Graduate students studying in the field of knowledge creation tended to rate environments lower than the proponents of those environments (see the second section of the Annex, p.45), but not much can be made of this, as the sample is very small. We offer the template to foster the sort of conversation engendered through analysis of a developmental framework related to characteristics of a knowledge-creating organization.

Learning theory

Creating environments that help students prepare for the knowledge society and to participate in, contribute to, and benefit from knowledge-creating organizations must be informed by what we know about how people learn and the changes in learning environments that this implies. An emphasis on collaborative knowledge building can both benefit from, and contribute to, existing theories of learning. For example, consider the “How People Learn” framework, shown in Figure 2, that was used by a National Academy of Science Committee to organize what is known about learning and teaching (NRC, 2000). The Framework’s four components highlight areas where we can learn from existing research; but the goals of the current project require us to elaborate on this work as well.

The How People Learn Framework involves a set of four lenses that can be used to analyze learning environments that range from homes, community centers classrooms, schools and higher levels of educational organization. The components of the framework involve a focus on four areas that need to be flexibly balance depending on current goals and needs. Each area of the framework

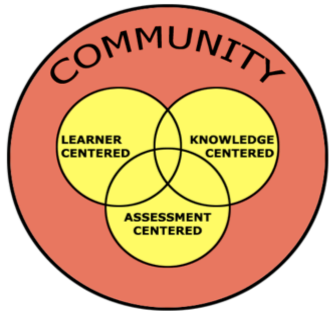

Figure 2: The 'How people learn' framework

is accompanied by set of questions that are useful for exploring the design of learning opportunities, particularly those that support knowledge building.

1. Knowledge-centered: What needs to be taught to meet changing needs of people and societies? (Answering this question is fundamental to this entire project.)

2. Learner-centered: How can new information be connected with learners' existing beliefs, values, interests, skills and knowledge so that they learn with understanding and can flexibly use what they know?

3. Community-centered: How can we develop communities of learners that value excellence as people work together to build new knowledge for the common good? And how can we broaden our sense of community and explore opportunities for learning that connect activities in- and out-of schools?

4. Assessment-centered: How can we develop frequent and useful opportunities for students, teachers, school system and nations to assess the progress they are making toward 21st century skills?

Teachers and those designing educational environments must balance all four components of the How People Learn Framework. We begin by discussing each component separately and then explore the balancing act that effective teachers and designers must continually orchestrate in order to help all students succeed.

Knowledge-centered

The Knowledge Centered aspect of the How People Learn framework seems obvious at first glance –so obvious that it hardly requires discussion. It is easy to fall into the trap of assuming that schools should teach what we learned when we grew up. However, as discussed above, the world has changed and different kinds of skills and knowledge are required for successful and productive lives in the twenty-first century. Many of the skills identified above are not associated with traditional subject domains, such as the sciences, mathematics, history, etc. Of course, these will continue to be important in the 21st century. Research in the learning sciences has explored expert understanding and performance, and how deeper understanding can help build connections between domain knowledge and 21st century skills and inform designs of effective knowledge building environments.

Expertise and knowledge organization

Experts' knowledge is much more than a list of disconnected facts about their disciplines. Instead, their knowledge is connected and organized around important ideas of their disciplines. This organization of knowledge helps experts know when, why and how aspects of their vast repertoire of knowledge and skills are relevant in any particular situation (see Bransford, Brown, & Cocking, 1999). Knowledge organization especially affects how information is retrieved and used. For example, we know that experts notice features of problems and situations that may escape the attention of novices (e.g. see Chase & Simon, 1973; Chi, Feltovich, & Glaser, 1981; de Groot, 1965). They therefore “start problem solving at a higher place” than novices (de Groot, 1965).

Courses and curriculum guidelines are often organized in ways that fail to develop the kinds of connected knowledge structures that support activities such as effective reasoning and problem solving. For example, texts often present lists of topics and facts in a manner that has been described as “a mile wide and an inch deep” (e.g. see Bransford, Brown, & Cocking, 1999). This is very different from focusing on the “enduring ideas of a discipline” (Wiske, 1998; Wilson, 1999). Wiggins and McTighe (1997) argue that the knowledge to be taught should be prioritized into categories that range from “enduring ideas of the discipline” to “important things to know and be able to do” to “ideas worth mentioning.” Thinking through these issues for 21st century skills, and coming up with a set of “enduring connected ideas” is an extremely important aspect of educational design.

Adaptive expertise

An especially important analysis of expertise focuses on differences between “routine experts’ and “adaptive experts” (e.g. Hatano & Inagaki, 1986; Hatano & Osuro, 2003). Both routine experts and adaptive experts continue to learn throughout their lifetimes. Routine experts develop a core set of skills that they apply throughout their lives with greater and greater efficiency. In contrast, adaptive experts are much more likely to change their core skills and continually expand the breadth and depth of their expertise. This restructuring of core ideas, beliefs and skills may reduce their efficiency in the short run but make them more flexible in the long run. These processes of restructuring often have emotional consequences that accompany realizations that cherished beliefs and practices need to be changed. Research by Anders Ericsson and colleagues (2009) show that a major factor in developing expertise is to resist plateaus—in part by continually moving out of one’s comfort and engaging in “deliberate practice.” This analysis of expertise highlights the need for unlearning as well as learning, and for the kinds of social collaboration that are often invisible when we see write-ups of “experts” in the research literature or the media (e.g. see Bransford & Schwartz, 1999)

This research has implications for the design of environments to support knowledge building. First, an emphasis on building a deep understanding of key ideas is important. This serves as the basis for organizing facts that would otherwise depend on shear memorization. Second, understanding regarding the adaptability of knowledge structures highlights the need to support processes of review and reflection.

Learner-centered

The Learner Centered lens of the How People Learn Framework overlaps with Knowledge Centered but the learner-centered lens specifically reminds us to think about learners rather than only about subject matter. Many educators deal with issues of understanding learners in ways that allow them to engaging in culturally relevant teaching (e.g., Banks, et al., 2007). This includes learning to build on peoples’ strengths rather than simply seeing weaknesses (e.g. Moll, 1986). Several important aspects of being learner centered are discussed below.

Understanding the constructive nature of knowing

The constructive nature of knowing grew out of the work of Swiss psychologist Jean Piaget. Piaget used two key terms to characterize this constructive nature: *assimilation* and *accommodation*. In Piaget’s terms, learners assimilate when they incorporate new knowledge into existing knowledge structures. In contrast, learners accommodate if they change a core belief or concept when confronted with evidence that prompts such as change.

Studies by Vosniadou and Brewer illustrate assimilation in the context of young children's thinking about the earth. They worked with children who believed that the earth is flat (because this fit their experiences) and attempted to help them understand that, in fact, it is spherical. When told it is round, children often pictured the earth as a pancake rather than as a sphere (Vosniadou & Brewer, 1989). If they were then told that it is round like a sphere, they interpreted the new information about a spherical earth within their flat-earth view by picturing a pancake-like flat surface inside or on top of a sphere, with humans standing on top of the pancake. The model of the earth that they had developed—and that helped them explain how they could stand or walk upon its surface—did not fit the model of a spherical earth. Everything the children heard was incorporated into their pre-existing views.

The problem of assimilation is relevant not only for young children, but for learners of all ages. For example, college students often have developed beliefs about physical and biological phenomena that fit their experiences but do not fit scientific accounts of these phenomena. These preconceptions must be addressed in order for them to change their beliefs (e.g. Confrey, 1990; Mestre, 1994; Minstrell, 1989; Redish, 1996). Creating situations that support accommodation is a significant challenge for teachers and designers of learning environments.

Connecting to students' previous experiences

Previously acquired knowledge can lead people to understand in ways that differ from what others intended. But another aspect of being learning centered is to understand that previously acquired knowledge can also provide a powerful boost for new learning.

Ideally, what is taught in school builds upon and connects with students' previous experiences, but this is not always the case. A number of researchers have explored the benefits of increasing the learner centeredness of teaching by actively searching for "funds of knowledge" in students' homes and communities that can act as bridges for helping then learn in school (e.g., Lee, 1992; Moll, 1986; Moses, 1994). Examples include helping students see how the carpentry skills of their parents relate to geometry; how activities like riding the subway can provide a context for understanding algebra; how everyday language patterns used outside of school often represent highly sophisticated forms of language use that may be taught in literature classes as an academic subject yet not linked to students' out-of-school activities.

Learner centeredness, metacognition and basic cognitive processes

Being learner centered also involves an awareness of some basic cognitive processes that impact learning for all people. "Metacognition" is the field of psychology that can be used to help people learn about the cognitive processes that underlie their own abilities to learn and solve problems. Several cognitive processes are particularly important.

<u>Attention & fluency</u>

Learning about attention is one important part of becoming a metacognitive learner. First, we can selectively attend to information. There are important constraints on how much we can attend to at any particular point in time. The amount of attention that we must devote to a task depends on how experienced and efficient we are at doing it. For example, unlike a novice driver, an expert can drive a car and carry on a conversation at the same time. Over time, driving has become "fluent" or "automatized" (highly efficient) which then frees up attention to do other things like converse with fellow passengers. But even for the experienced driver, intense weather or driving conditions can produce demands on attention that shut down the ability to also converse or, in some cases, even listen to the radio.

A number of studies have explored the concept of attentional demand and its relationship to fluency. When learning to read, for example, the effortful allocation of attention to pronouncing words can make it difficult to also attend to the meaning of what one is reading. The attentional demands that accompany attempts to learn anything new mean that all learners must go through a period of “klutziness” as they attempt to acquire new skills and knowledge. Whether people persist or bail out during these “klutz” phases depends in part on their assumptions about their own abilities. Some people may decide “I’m not good at this” and give up trying before they have a chance to learn effectively (e.g. Dweck, 1986). Wertime (1979) notes that an important part of being learner centered is to help students learn to persist in the face of difficulty by increasing their “courage spans.”

Transfer

Learning about ourselves as learners also involves thinking about issues of transfer—of learning in ways that allow us to solve novel problems that we may encounter later. The mere memorization of information is usually not sufficient to support transfer. Learning with understanding typically enhances the experience (e.g. NRC 2000). An important goal for transfer is cognitive flexibility (e.g., Spiro, Feltovich, Jackson, & Coulson, 1991). Experts possess cognitive flexibility when they can evaluate problems and other types of cases in their fields of expertise from many conceptual points of view, seeing multiple possible interpretations and perspectives. Wiggins and McTighe (1997) argue that understanding complex issue involves being able to explain them in more than one way. Spiro et al. (1991) argue that the inability to construct multiple interpretations in analyzing real-world cases can result from instruction that oversimplifies complicated subject matter.

Motivation

Helping students learn to identify what motivates them is also an important part of being learner centered. Researchers have explored differences between extrinsic motivators (grades, money, candy, etc.) and intrinsic motivators (wanting to learn something because it is relevant to what truly interests you). Both kinds of motivation can be combined; for example, we can be intrinsically interested in learning about some topics and interested in receiving extrinsic rewards as well (e.g. praise for doing well, a consultants fee). However, some people argue that too much of an emphasis on extrinsic rewards can undermine intrinsic motivation because people get too used to the external rewards and stop working when they are removed (e.g., Robinson & Stern, 1997).

There appear to be important differences between factors that are initially motivating (the assumption that learning to skate board seems interesting), and factors that sustain our motivation in the face of difficulty (“hmm, this skate boarding is harder to learn than it looked”). The social motivation support of peers, parents and others is an especially important feature that helps people persist in the face of difficulties. It is also important to be provided with challenges that are just the right level of difficulty—not so easy that they are boring and not so difficult that they are frustrating. Creating the right kinds of “just manageable difficulties” for each student in a classroom constitutes one of the major challenges and requires expert juggling acts. Explorations of the literature on motivation can be found in Deci and Ryan (1985), Dweck (1986) and Stipek (2002).

Agency

An important aspect of meta-cognition and motivation is the need for people to develop socially responsive agency. That is, students must learn to make their own choices, experience the social consequences that arise from them, and revise their strategies when necessary. This is a progressive process of moving from the situation where the teacher makes decisions about student learning to one where students are increasingly responsible for their own learning activities.

An example involves a recent set of studies on Science Kits for middle school students (Shutt, Phillips, Van Horne, Vye, & Bransford, 2009). They involve hands-on activities such as working with and studying (without harming them) fish, isopods and a variety of creatures. Throughout the course of the year, the goal is to develop a sense of key variables (e.g. range of temperatures, ranges of acidity, etc) that affect the life of all species. As originally developed, the science work is extremely teacher-directed and the hypothesis to be tested and methods to be used (e.g. to determine if isopods desire most or dry soil) is specified by the teacher. Redesigns of these teaching situations have given much more agency to the students. They are given a terrarium and told that their task (working in groups) is to keep their organisms (e.g. isopods) alive. To be successful, they have to choose what questions to ask, how to run the studies, how to do the kind of background research (via technology needed), and so forth. The initial findings (more precise data will be available soon) show that the sense of agency is very important to students and they take their work very seriously. This kind of activity can hopefully strengthen other skills such as global sensitivity since the students all do their work with the well being of others (even though they are non-humans) foremost in their minds.

Community-centered

The preceding discussion explored a number of issues relevant to being knowledge-centered and learner-centered. The community-centered aspect of the How People Learn framework is related to being knowledge and learner centered, but it focuses special attention on the social, material, and temporal nature of learning.

The social aspects of learning

The social aspects of learning often include the norms and modes of operation of any community we belong to or are joining. For example, some classrooms represent communities where it is safe to ask questions and say, “I don’t understand this, can you explain it in a different way?” Others follow the norms of “Don’t get caught not knowing something.” A number of studies suggest that – in order to be successful – learning communities should provide people with a feeling that members matter to each other and to the group, and a shared belief that members' needs will be met through their commitment to be together (Alexopoulou & Driver, 1996; Bateman, Goldman, Newbrough & Bransford, 1998). Many schools are very impersonal places, and this can affect the degree to which people feel part of, or alienated from, important communities of professionals and peers.

Concerns that many schools are impersonal and need to be smaller in order to be more learner and community centered can also be misinterpreted as simply being an argument for helping students feel good about themselves. This is very important, of course, but more is involved as well. More includes searching for “funds of knowledge” in students’ lives and communities that can be built upon to enhance their motivation and learning. The more we know about people the better we can communicate with them and hence help them (and us) learn. And more they know about one another, the better they can communicate as a community.

The importance of creating and sustaining learning communities can be traced to Vygotsky’s theory in which culture and human interaction plays a central role in developmental processes. Vygotsky focused on the intersection between individuals and society through his concept of the zone of proximal development (ZPD)—the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance, or in collaboration with more capable peers (Vygotsky, 1976:86). What a child can perform today with assistance she will be able to perform tomorrow independently, thus preparing her for entry into a new and more demanding collaboration. The emphasis here is on the ways learners draw on each other for ideas and resources that support or scaffold their own learning.

The material aspects of learning

Vygotsky also emphasized the ways in which material resources, such as tools and technologies, change the nature of tasks and the cognitive skills that are required to perform them. This is

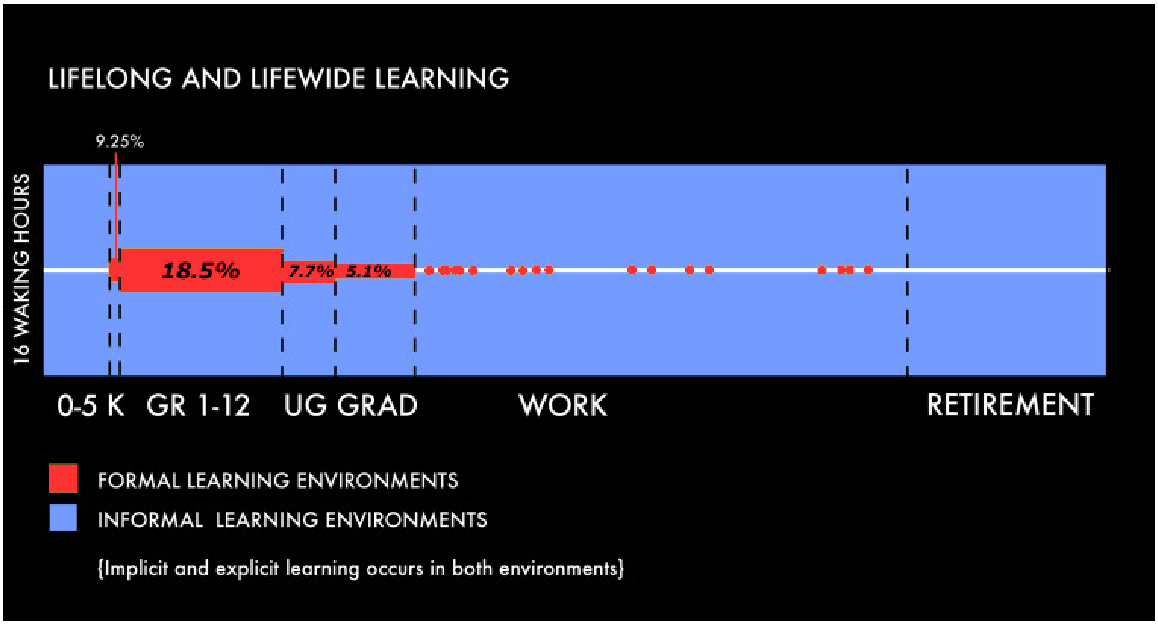

Figure 3: Time spent in formal and informal learning across a typical lifespan

particularly important in the 21st century, not only because of the ways in which technologies have changed the nature of task and work in the world outside of schools but because students increasingly use a wide range of technologies in their everyday lives and bring these technologies with them into schools. Often teachers do not take advantage of these technologies or use the skills and experiences that students bring with them as a way to increase students' knowledge of school subjects or further develop their 21st century skills. Learning and assessment are far different if students have access to a range of technological tools, digital resources, and social support than if they learn or are assessed without access to these resources. Yet the real world of work and students' social environments are filled with these tools and resources and they can be effectively built into the learning environment (Erstad, 2008).

The temporal aspects of learning

At a broader level, being community centered also means reaching beyond the walls of the schools in order to connect with students' out-of-school experiences, including experiences in their homes.

Figure 3, from the LIFE Center, demonstrates the approximate time spent in formal (school) and informal (out of school) environments. A great deal of learning goes on outside of school (Banks et al., 2007), but often teachers do not how to connect these kinds of experiences to school learning. Earlier we discussed the idea of searching for "funds of knowledge" that exist in communities and can be built upon to help students succeed. The challenge is to help students build strong social networks within a classroom, within a school, and between classrooms and in- and out-of-school contexts.

Assessment-centered

We've discussed knowledge, learner and community centered; now we turn to assessment centered. It is easy to assume that assessment simply involves giving tests to students and grading them. Theories of learning suggest roles for assessment that involve much more than simply making up tests and giving grades.

First, teachers need to ask what they are assessing. This requires aligning their assessment criteria with the goals for their students (part of being knowledge centered) and the "readiness" of students in their classroom (learner and community centered). Assessing memorization (e.g. of properties of veins and arteries) is different from assessing whether students understanding why veins and arteries have various properties. Similarly, assessing whether students can answer questions about life cycles (of frogs for example) is different from assessing whether they will spontaneously retrieve this information when attempting to solve problems.

At the most general level, issues of what to assess relate to issue of what students need to know and be able to do in order to have fulfilling lives once they graduate. Because of rapid changes in society, this is an issue that constantly needs to be reconsidered. Debates about standardized tests include concerns that they may "tip" teaching in a direction that is counter-productive for students because some teachers spend most of their time teaching to the tests, yet the tests do not assess the range of skills, knowledge and attitudes needed for successful and productive lives in the twenty first century.

Different kinds and purposes of assessment

An especially important aspect of the assessment-centered lens in the How People Learn framework is its emphasis on different kinds of assessments for different purposes. When most people think about assessments they think about <u>summative assessments</u>. These include standardized tests at the end of the year, final exams at the end of a course, and unit exams at the end of a unit. Summative assessments come in all forms: multiple choice tests, essays, presentations by students, and so forth. These assessments are very important as an accountability mechanism for schools, teachers, and students. Often they reveal important information that teachers wish they had seen earlier. This is why <u>formative assessments</u> are important. These are used for the purpose of improving teaching and learning. They involve making students' thinking visible as they progress through the course, giving them feedback about their thinking, and providing opportunities to revise.

Assessment and theories of transfer

It is also important for teachers to understand ways in which assessment practices relate to theories of transfer. Consider summative assessments, for example. We all want to make sure that these provide an indication of students' ability to do something other than simply "take tests." Ideally, our assessments are predictive of students' performance in everyday settings once they leave the classroom.

One way to look at this issue is to view tests as attempts to predict students' abilities to <u>transfer</u> from classroom settings to everyday settings. Different ways of thinking about transfer have important implications for thinking about assessment. Central to traditional approaches to transfer is a "direct application" theory and a dominant methodology that Bransford & Schwartz (1999) call "sequestered problem solving" (SPS). Just as juries are often sequestered in order to protect them from possible exposure to "contaminating" information, subjects in experiments are sequestered during tests of transfer. There are no opportunities for them to demonstrate their abilities to learn to solve new problems by seeking help from other resources such as texts or colleagues or by trying things out, receiving feedback and getting opportunities to revise. Accompanying the SPS paradigm is a theory that characterizes transfer as the ability to directly apply one's previous learning to a new setting or problem. We call this the Direct Application (DA) theory of transfer. Some argue that the SPS methodology and the accompanying DA theory of transfer are responsible for much of the pessimism about evidence for transfer (Bransford & Schwartz, 1999).

An alternative view that acknowledges the validity of these perspectives also broadens the conception of transfer by including an emphasis on people's "preparation for future learning" (PFL). Here, the focus shifts to assessments of people's abilities to learn in knowledge-rich environments. When organizations hire new employees they don't expect them to have learned everything they need for successful adaptation. They want people who can learn, and they expect them to make use of resources (e.g., texts, computer programs, and colleagues) to facilitate this learning. The better prepared they are for future learning, the greater the transfer (in terms of speed and/or quality of new learning). Examples of ways to “prepare students for future learning” are explored in Schwartz and Bransford (1998), Bransford and Schwartz (1999) and Spiro, Vispoel, Schmithz, Samarapungavan, and Boeger (1987).

The sole use of static assessments may mask the learning gains of many students, plus mask the learning advantages that various kinds of educational experiences provide (Bransford & Schwartz, 1999). Linking work on summative assessment to theories of transfer may help us overcome the limitations of many existing tests. Examples of SPS versus PFL assessments of learning and transfer are discussed in Bransford and Schwartz (1999).

The “How people learn” framework in action

We have discussed all four components of the How People Learn framework, but we noted earlier that learning occurs most effectively when all four components are balanced. Underemphasizing one or more of the components can make it harder for all students to succeed. For example, teachers can be overly learner centered and community centered yet fail to emphasize the acquisition of important concepts and skills (knowledge centered) that students need for successful lives. And if teachers are not assessment centered (especially in their use of formative assessments), they may fail to realize that students are not making adequate progress until the year is over and it’s too late for them to help.

This balance is particularly important when considering the conditions for knowledge building environments, a consideration we turn to next. But in brief, we can see that an environment is more likely to support knowledge building if it emphasizes the process of building upon and using key ideas in a domain, draws on and extends student experiences and develops their capacity to learn, provides learners with social, material and temporal supports for their learning, and offer frequent feedback on their progress.

Implications for assessment reform

Two distinct approaches to the design of environments and assessment have been described. One involves working backward from goals to construct a system of subgoals and learning progressions from an initial state to the goal. The second approach involves e*mergent goals* that are not fixed in advance but take shape as learning and thinking proceed. We have indicated the trade-offs associated with both *working-backward* and *emergence* approaches, and below, after reviewing assessment challenges related to 21st century skills, we specify needed research for an integrative approach.

21st century skills can be addressed, as suggested in our introduction, via additive, assimilative, or transformative models, and the assessment issues vary depending on what one sets out to pursue. In the additive model the “21st century skills” curriculum is added to the traditional curriculum, although often the goal is more in line with assimilative efforts to merge skill and content elements or to piggy-back one upon the other. The problem, exacerbated if each 21st century skill is treated separately, is that the current “mile wide, inch deep” curriculum will grow miles wider and shallower, with the 21st century skills curriculum taking valuable time from traditional skills. The goal of the transformational model is to effect a deeper integration of domain understanding and 21st century skills. The rationale, elaborated in section on the parallel advance of domain knowledge and 21st century skill (pp.17ff) is that if deep understanding of domain knowledge is achieved through exercise of 21st century skills, the result will be enhanced understanding in the domain as well as advances in a broad range of 21st century skills. That is the guiding principle underlying the knowledge building approach. The Knowledge Building Analytic Framework in the Annex (p.46) helps those wishing to engage in this transformation to consider progress along its multiple dimensions. Since these dimensions represent a complex, interactive system, treating them separately may prove more frustrating than helpful. Fortunately, this also means that tackling one dimension is likely to lead to advances along several dimensions. The implication for assessment is that we must anticipate and measure generalization effects. We elaborate possibilities for design experiments to integrate working backward and emergence models in section on specific investigations (pp.42ff). But first we discuss a broader set of issues regarding assessment challenges and 21st century skills.

Assessment challenges and 21st century skills

The quest for evidence-based assessment of 21st century skills is hindered by many factors. First, there are huge variations in formal and informal learning environments and the kinds of assessment that are possible in those settings. Second, knowledge and skills about the media and technologies used within a domain need to be distinguished from domain-specific knowledge and skills (Bennett, Persky, Weiss, & Jenkins, 2007; Quellmalz & Kozma, 2003). Third, methods for designing 21st century assessments and for documenting their technical quality have not been widely used (Quellmalz & Haertel, 2008). Fourth, assessments need to be coherent across levels of educational systems (Quellmalz & Pellegrino, 2009; Pellegrino, Chudowsky, & Glaser, 2001). Coherence must start with agreement on 21st century skills and their component knowledge and skills. Moreover, designs of international, national, state and classroom level tests must be clarified and aligned or assessments at different levels will not be balanced and inferences about student performance compromised.

Evidence-centered design (Messick, 1994; Mislevy & Haertel, 2006) links 21st century skills to task features and reports of evidence that characterize student performance and progress. In the sections immediately below we describe how evidence-centered design can be used to develop formative assessments that are embedded in learning environments and that link these formative assessments to large-scale, summative assessments.

Cognitively-principled, evidence-centered assessment design

As described above, research on the development of expertise in many domains indicates that individuals proficient in a domain have large, organized, interconnected knowledge structures and well-honed domain-specific problem-solving strategies (Bransford, Brown & Cocking, 2000). The designs of assessments, therefore, should aim to measure both the extent and connectivity of students' growing knowledge structures and problem-solving strategies (Pellegrino et al., 2001; Glaser, 1991). For example, in the domain of science, core knowledge structures are represented in models of the world built by scientists (Hestenes, Wells, & Swackhamer, 1992; Stewart & Golubitsky, 1992). Technologies are seen as tools that support model-based reasoning by automating and augmenting performance on cognitively complex tasks (Norman, 1993; Raizen, 1997; Raizen, Sellwood, Todd & Vickers, 1995).

The NRC report, *Knowing What Students Know,* presents advances in measurement science that support the integration of cognitive research findings into systematic test design frameworks. In brief overview, evidence-centered assessment design involves relating the learning to be assessed, as specified in a *student model*, to a *task model* that specifies features of the task and questions that would elicit observations of learning, to an *evidence model* that specifies the student responses and scores serving as evidence of proficiency (Messick, 1994; Mislevy et al., 2003; Pellegrino et al., 2001). These components provide a structure for designing assessments of valued 21st century skills and also for evaluating the state of current assessment practices. Evidence-centered design (Messick, 1994; Mislevy & Haertel, 2006) can be used to design formative assessments and link these to large-scale, summative assessments.

The role of domain knowledge

An issue for large-scale 21st century assessments is the role of knowledge about topics and contexts in a discipline or specialization required to complete tasks and items using technology. Large-scale assessments of 21st century skills cannot assume that all students will have learned particular academic content. Fortunately, assessments of 21st century skills within learning environments *can* identify the content knowledge within which assessments of 21st century skills will be situated. In academic subjects, current assessments of problem solving and critical thinking skills, if they are directly assessed and reported at all, are typically reported as components of the subject matter achievement (i.e., math problem solving, science inquiry), not as distinct 21st century skills. In addition, in core school subjects and informal settings, students may use common or advanced technologies, but students' technology proficiencies tend not to be tested or reported. Therefore, to assess and report progress on 21st century skills, designs of assessments of students' performance relevant to them must specify the knowledge and skills to be tested and reported for each skill (see White Paper 1), either the cross-cutting processes such as problem solving or communication, or abilities to use technologies in a range of academic and practical problems. An important feature of knowledge-building environments and assessments of ICT skills within them will be to test not only the use of ICT tools, simple and advanced, but also the learners skill with using a range of ICT tools to extend and build their knowledge and strategies within increasingly more complex tasks. In addition, learners adaptive expertise, i.e., abilities to transfer their existing knowledge and strategies to novel problems, will need to include direct assessments of learners abilities to use and learn new technologies.

Assessments embedded in technology-rich environments

The design of assessments must begin by specifying their purposes and intended uses AERA/APA/NCME, 1999. These specifications then lead to validity questions such as "Does the assessment support the inferences and actions based on it?" The two conventional distinctions are between summative and formative purposes. As indicated above, summative assessments are administered at the end of an intervention or a unit within it to judge if goals have been met. Formative assessments are administered during interventions to inform learners and instructors in time for midcourse corrections. A recent definition proposed in the U.S. by the Formative Assessment for Students and Teachers (FAST) state collaborative supported by the Council of Chief State School Officers is that "Formative assessment is a process used by teachers and students during instruction that provides feedback to adjust ongoing teaching and learning to improve students' achievement of intended instructional outcomes." According to the FAST definition, formative assessment is not an instrument, but the process of using information about progress toward a goal to improve learning. Important attributes of formative assessments are that the outcomes are *intended* and clearly *specified* in advance, the methods are deliberately planned, the *evidence of learning* is used by teachers and students, and *adjustments occur during instruction*. Attributes of effective FAST formative assessment include: clearly articulated learning progressions; learning goals and criteria for success clearly identified and communicated to students; evidence-based descriptive feedback; self and peer assessment; and collaboration of students and teachers on working toward learning goals. Formative assessments of 21st century skills therefore, would specify the 21st century outcomes and systematic methods for monitoring progress and providing feedback, and clear criteria for success. Formative assessments for 21st century skills could be employed for all of the 21st century skills in all kinds of learning environments.

This FAST prescription of formative function of 21st century assessments is quite different from uses of embedded assessments to validate large-scale assessment results or to augment the evidence that could be collected in a one-time, on-demand test. A third function of embedded assessments can be to collect detailed information about processes and progress for research purposes, and to begin to create a more coherent integration of formative and summative assessment.

What evidence will be sought?

Within an evidence-centered design assessment framework, broad 21st century skills such as problem solving or communication need to be further specified into component targets to assess. Problem solving targets in mathematics might involve planning solution strategies or evaluating solutions. In science, problem solving may involve targets such as planning investigations or interpreting data in visualizations (Quellmalz & Kozma, 2003). In literature, problem solving may involve analyses of Shakespeare plays for recurring symbolism related to the plot. Problem solving targets to assess in a practical situation might involve selecting a green technology, such a wind turbines, and analyzing potential environmental impacts. The assessment targets for 21st century problem solving skills will be at a more general level for applications across domains and situations and in more specific terms as problem solving applies in specific domains. Problem solving assessment tasks will need to represent highly structured problems with known solutions and problems with multiple appropriate solutions. In domain-centered learning environments, assessment tasks will go beyond repetition of previously performed experiments to open-ended tasks permitting multiple appropriate methods for eliciting evidence of how well learners plan, conduct, and interpret evidence for solving a problem or achieving a goal.

Evidence-centered assessment design requires that embedded assessments articulate the qualitative or quantitative information that would document achievement of each 21st century skill and its component targets. For formative assessments, a crucial feature is that the evidence and criteria be understandable and usable by teachers and students. For example, self and peer assessment are key features of effective formative assessment. Such activities are familiar in classes that use peer review of drafts of compositions, or peer critiques of presentations. In workplaces, peer review is a hallmark of professional publications.

While common Internet and productivity tools are often integrated across contexts and disciplines, the “tools of the trade” differ in humanities, sciences, and social sciences, etc., as well as in post secondary learning environments, the workplace, and the professions. In primary and secondary formal schooling, common Internet and productivity tools are often integrated across contexts and disciplines. Once again, the knowledge and skills will need to be specified and further decomposed as they apply in different learning environments. Evidence of achievement will also need to be specified in a way shareable with learners and teachers. Thus embedded assessments of use of specific technologies will vary according the context and domains emphasized. Nonetheless, new assessment possibilities are opening up through efforts to create tools that are usable across domains and that link domain-specific environments with more general environments.

An important value is that 21st century skills that are difficult to assess in a timed, on-demand large-scale test, can be monitored over time in learning environments. For example, creativity and innovation can be assessed in relation to how learners go beyond what was specified in learning activities. Collaboration with present and virtual peers and experts can be monitored throughout formation of teams, integration of contributions and feedback, to reflection on the effectiveness of the team processes and achievement of goals.

Design of assessments to elicit evidence of 21st century skills

Systematic, direct assessment of 21st century skills in classrooms is rare. Although students may be taught to use common and advanced tools, teachers tend not to have specific standards for 21st century skills that students must meet nor testing methods to gather evidence of student skill in using the technologies. In either formal or informal learning environments, the teachers are typically left on their own to figure out how to integrate technology into their curricula or the informal learning activities. The state of practice for assessing 21st century skills integrated into learning activities remains in its infancy.

Assessment must be designed to elicit evidence of learning related to each assessment target. Research on effective formative assessment describes types of formal and informal observations of learning, from questions to and from learners, to examinations of work in progress, and evaluations of work products. But, these observations should be planned for in advance with criteria for success laid out and shared with learners. For example, systematic observations of groups during collaboration activities can be structured to document types and quality of interactions. These observations can be summarized and reviewed with groups and individuals.

The 21st century skills integrate learners' use of a range of technologies in the contexts and domains in the learning environments. Central to 21st century skills is learner skill in selecting and using appropriate technologies during processes such as innovation, communication, collaboration, problem solving, and citizenship. Technologies offer many possibilities for designing richer, deeper, wider ranging learning activities and assessments. Possibilities for technology-supported reform of learning environments and assessments include:

- Offer authentic, rich, dynamic environments
- Support access to collections of information sources and expertise
- Support formal and informal forms of collaboration and social networking
- Present phenomena difficult or impossible to observe and manipulate in classrooms
- Represent temporal, causal, dynamic relationships "in action"
- Allow multiple representations of stimuli and their simultaneous interactions (e.g., data generated during a process)
- Allow overlays of representations, symbols
- Allow student manipulations/investigations, multiple trials
- Allow student control of pacing, replay, revision
- Make student thinking and reasoning processes visible
- Capture student responses during activities (e.g., research, design, problem solving)
- Allow use of simulations of a range of tools (internet, productivity, domain-based)

Below, in the section on assessment and the knowledge building developmental trajectory (pp.34ff) we extend this list. But first we introduce an assessment profile and elaborate on the potential for new environments and assessments to inform and be informed by large-scale assessments.

Assessment profile

The purpose of the Knowledge Building Analytic Framework (see Annex, p.46) is to determine the extent to which an educational environment is moving toward a knowledge-creating enterprise, in line with the developmental trajectories defined in Table 2. The assumption underlying the Knowledge Building Analytic Framework is that educational environments should be evaluated, not just students. But of course the work of students must also be analyzed, and for this purpose these dimensions need to be translated into measures of individual and group performance. We propose such work as part of a needed program of research (see pp.40ff). But for now we offer six dimensions of assessment to support use and coverage of all manner of assessments to measure 21st century skills, across all classrooms, so as to insure quality assessments and guide instructional practices.

Alignment between assessments and 21st century skills. Assessment instruments may not assess or support one or more of the 21st century skills, so it is helpful, for each target 21st century skill, to determine if there is (1) full, (2) partial, or (3) no alignment.

Purpose and intended use of assessments. Assessment data, tasks and items may serve as (1) formative assessments so students and instructors can monitor learning and adjust instruction as it proceeds, (2) summative evidence of end-of-instruction achievements, or (3) project evaluation or research, not shared with learners and instructors. For each 21st century skill it is worth tracking its purpose: (1) formative, (2) summative; or (3) research on teaching and program effectiveness.

Construct Representation. Assessment tasks and items may produce evidence about only portions of the targeted constructs*,* desired knowledge or skills*.* For example, if the target is systems knowledge, components or simple interactions may be tested rather than dynamic, emergent behaviors. Or basic facts or steps may be tested rather than higher level, integrated knowledge and skills. When constructs are partially tested important components are underrepresented. For each 21st century skill it can be determined if available evidence represents (1) the construct; (2) part of the construct; or (3) none of the construct.

Integration into learning activities. Assessments in learning environments may be more or less integrated into ongoing activities. Integrated, ongoing assessments may gather evidence of learning throughout activities. Interim assessments less directly linked to ongoing activities may be periodically administered as checks. Or, de-contextualized, external assessments may be dropped in. Thus it is helpful, for each 21st century skill, to determine the extent to which tasks and item responses (1) are fully integrated into learning activities; (2) are assessed after, separate from learning activities; or (3) are not assessed.

Feasibility. Assessments in learning environments may also differ in the feasibility of their use. They may be easily completed and interpreted by learners and instructors or require access to technologies that are available readily or only periodically. Thus it needs to be determined if the assessment is (1) easily used, with minimal or no support; (2) possible to use, but requiring ongoing support; or (3) complex, requiring specialized methods and support.

Technical quality. The assessments may require levels of expertise to administer and score that are beyond the training of most instructors. Technical quality evidence would include confirming that the assessments provide credible information for their intended uses in the environments (e.g., formative or summative), and that the interpretations of observations and evidence are reliable across instructors and environments. Thus it is important to clarify if technical quality is (1) fully, or (2) only partially established.

Connecting learning environments and formative assessments to large-scale tests

Currently, there are different, often competing approaches to assessing 21st century skills. One approach focuses on assessment *of* technology, such as the International Computer Driving License and technology proficiency tests in some states in the U.S. These tests measure the facts and procedures needed to operate common Internet and productivity tools, while the content or the academic or applied problem and context are deliberately selected to be familiar background knowledge (Venezky & Davis, 2002; Crawford & Toyama, 2002). The cognitive processes addressed in 21st century skills such as problem solving, communication, collaboration, innovation, and digital citizenship are not targeted by tests *of* technology operations.

In a second approach, 21st century skills emphasize learning *with* technology by presenting test problems and items that *integrate* measurement of technology operations, strategic use of technology tools to solve problems, and subject matter knowledge and processes through carefully designed sets of tasks and items related to complex academic and real world problems.

In a third approach, testing is implemented *by* technology. Assessments *by* technology simply use technical infrastructures to deliver and score tests that are designed to measure other content and skills in subjects such as math and reading. These test designs aim to reduce or eliminate the demands of the technology, treating it as an irrelevant construct. Equivalence of paper-based and technology-based forms is the goal. Technology-based tests are increasing rapidly in large-scale state, national, and international testing, where technology is being embraced as a means to reduce the costs and logistics of assessment functions such as test delivery, scoring, and reporting. Technology-based tests typically assume that supporting technology tools such as calculators or word processors are irrelevant to the content constructs being tested and therefore, not to be measured separately. Since these types of testing programs seek comparability of paper and online tests, the tests tend to present static stimuli and use traditional constructed-response and selected-response item formats. For the most part, these conventional, online tests remain limited to measuring knowledge and skills that can be easily assessed on paper. Consequently, they do not take advantage of technologies that can measure more complex knowledge structures and extended inquiry and problem solving included in the 21st century ICT skills described in the *Assessment and Teaching of 21st Century Skills* project and reported in White Paper 1 (Csapó, 2007; Quellmalz & Pellegrino, 2009). In short, a technology delivered and scored test of traditional subjects is not an assessment of 21st century ICT skills and should not be confused as one. 21st century skills assessments will not just use technology to support assessment functions such as delivery and scoring, but will also focus on measuring the application of 21st century skills while using technology.

Large-scale assessments of 21st century skills could provide models of assessments to embed in learning environments, but current large-scale tests do not address the range of 21st century skills in ways that would advance knowledge-building environments. In the U.S., the new 2012 Framework for Technological Literacy for the National Assessment of Educational Progress sets forth three major assessment areas: Technology and Society, Design and Systems, and Information Communication Technologies (see naeptech2012.org). Technological literacy in the framework blends understanding of the effects of technology on society, 21st century skills, and technology design. The 2012 assessment will present a range of long and short scenario-based tasks designed to assess knowledge and skills in the three areas. In the U.S., assessments of 21st century skills and technological literacy are required for all students by grade 8. However, state tests or school reports are considered sufficient to meet this requirement, and school reports may be based on teacher reports which, in turn, can be based on questionnaires or rubrics students use in ICT-supported projects. Most teachers do not have access to classroom assessments of 21st century skills or professional development opportunities to construct their own tests. Moreover, the lack of technical quality of teacher-made and commercially developed classroom assessments is well documented (Wilson & Sloane, 2000). Even more of a problem is the lack of clarity for teachers on how to monitor student progress on the development of 21st century skills, not only tool use, but ways to think and reason with the tools. Teachers need formative assessment tools for these purposes.

Concurrent, embedded and transformative assessment for knowledge building

In line with the emergence approach and knowledge-creation imperative to go beyond best practice, we elaborate new forms of data from classroom environments that make it possible to provide richer, more comprehensive, and more readily available accounts of student performance than possible through traditional testing. We have already discussed embedded, formative, and summative assessment, now we add the concepts of concurrent and transformative assessment. Concurrent assessment means the assessment is available on demand and instantaneously. Through effective designs, feedback can inform high-level processes as well as more straightforward procedures. Transformative means that the evaluation is not simply an account of past performance, pointing to immediate next-steps, but additionally provides indication of ways individuals and teams can tackle broader problems and situate their work relative to that of other team members and other teams, both within and beyond the school walls.

When student discourse is central to the operation of the community, with members contributing to shared, public knowledge spaces, and building on each other's ideas, vast new possibilities for assessment to enrich the community's work and to enable concurrent and transformative assessment are possible. The discourse to be analyzed may include online interactions as well as face-to-face interactions that are recorded through video or conferencing software and transcribed. Examples of profiles of student work that can be generated easily from such data are presented below. Even at this early stage, there is a great deal of excitement among researchers, teachers and students who have pilot tested these tools in their classrooms. Teachers and students alike readily see their advantage and generate ideas for improving them.

In the examples presented, data is generated automatically from student discourse and artifacts, and as suggested below, the tools can be used to identify patterns and support continual improvement in practice and student achievement. A substantial part of the challenge in advancing concurrent, embedded, and transformative assessment will be avoiding pitfalls while taking advantage of substantial new opportunities.

Contributions. A contribution tool can provide measures of the number of notes created, nature of entries (based on keywords, media type, etc.), an overview of content areas participants worked in, and so forth. Contributions related to a specific problem can be traced, thus making it possible to begin investigations of individual and group problem solving. The teacher can use the tool during or immediately after each session to determine how productive each student has been (e.g., how many notes were read, created or modified). Such information helps the teacher direct attention to students who may need more support or instruction, and helps them identify barriers preventing students from participating fully in the knowledge building community. Students can use the tools, if the teacher enables access, to see where they are in the class distribution (no names shown).

"Thinking types" or scaffolds to support 21st century skills. Scaffolds can be built, based on theory-driven accounts of advanced knowledge processes (see the section on technology to support emergence of new skills, pp.39ff)**.** Computer-mediated and customizable scaffold supports allow teachers and students to use scaffolds and rubrics flexibly and for students to tag their notes by thinking type (Andrade, 2000; Chuy, et al., 2009; Law & Wong, 2003; Lai & Law, 2006). As a result of indicating the 21st century skill they are engaged in (problem solving, theory development, research, decision making etc.) students become more cognizant of these skills. And once text is tagged searches by scaffolds make it easy for students and teachers to find, discuss, and evaluate examples. Formative assessment tools can be used to provide feedback regarding patterns of use and help extend students' repertoires.

Use of new media and multiliteracies. Students can contribute notes representing different modalities and media such as text, images, data tables, graphs, models, video, audio, and so forth. Results suggest growth in textual and graphical literacy are important by-products of work in media rich knowledge building environments (Sun, Zhang & Scardamalia, 2008; Gan, Scardamalia, Hong & Zhang, 2007).

Vocabulary. A vocabulary tool can provide profiles for individuals and groups, including rate of new word use, use of select words from curriculum guidelines (or from any set of words), and so forth. It is also easy to look at the growth of vocabulary relative to external measures or benchmarks, such as a grade-level lists. Thus teachers can determine if important concepts are entering the students' productive vocabularies, the extent of use of words at or above grade level, growth in vocabulary based on terms at different levels in curriculum guidelines, and so forth. Information about the complexity and quality of notes can also give the teacher direction as to the type of instruction the class may need. Early, informal use of these vocabulary tools suggests students enjoy seeing the growth in their vocabulary, and begin to experiment with new words used by others in the class.

*Writing***.** Measures of writing start with basic indicators (e.g. total and unique words, mean sentence length). There are many sophisticated tools already developed and open source arrangements will make it increasingly easy to link discourse and writing environments.

Meta-perspectives. A brainstorming tool (Nunes, Nunes, & Davis, 2003) can be used to foster students' metacognitive thinking about specific skills and support students in the exercise of creativity, leadership and collaboration. Tools can also be built to allow students to tag notes containing questions asked but not answered, claims made with no evidence, etc. Once tagged, visualization tools can bring to the forefront of the knowledge space ideas needing extra work.

Semantic Analysis. This tool makes it possible to work in many and flexible ways with the meaning of the discourse. A semantic-overlap facility extracts key words or phrases from user-selected subsets of the discourse and shows overlaps. For example, one application of this tool is to examine the overlap between a participant's discourse and discourse generated by experts in a discipline or in curriculum guidelines. Other applications include the examination of overlap between two or more participants or student writing and assigned readings. A semantic field visualization

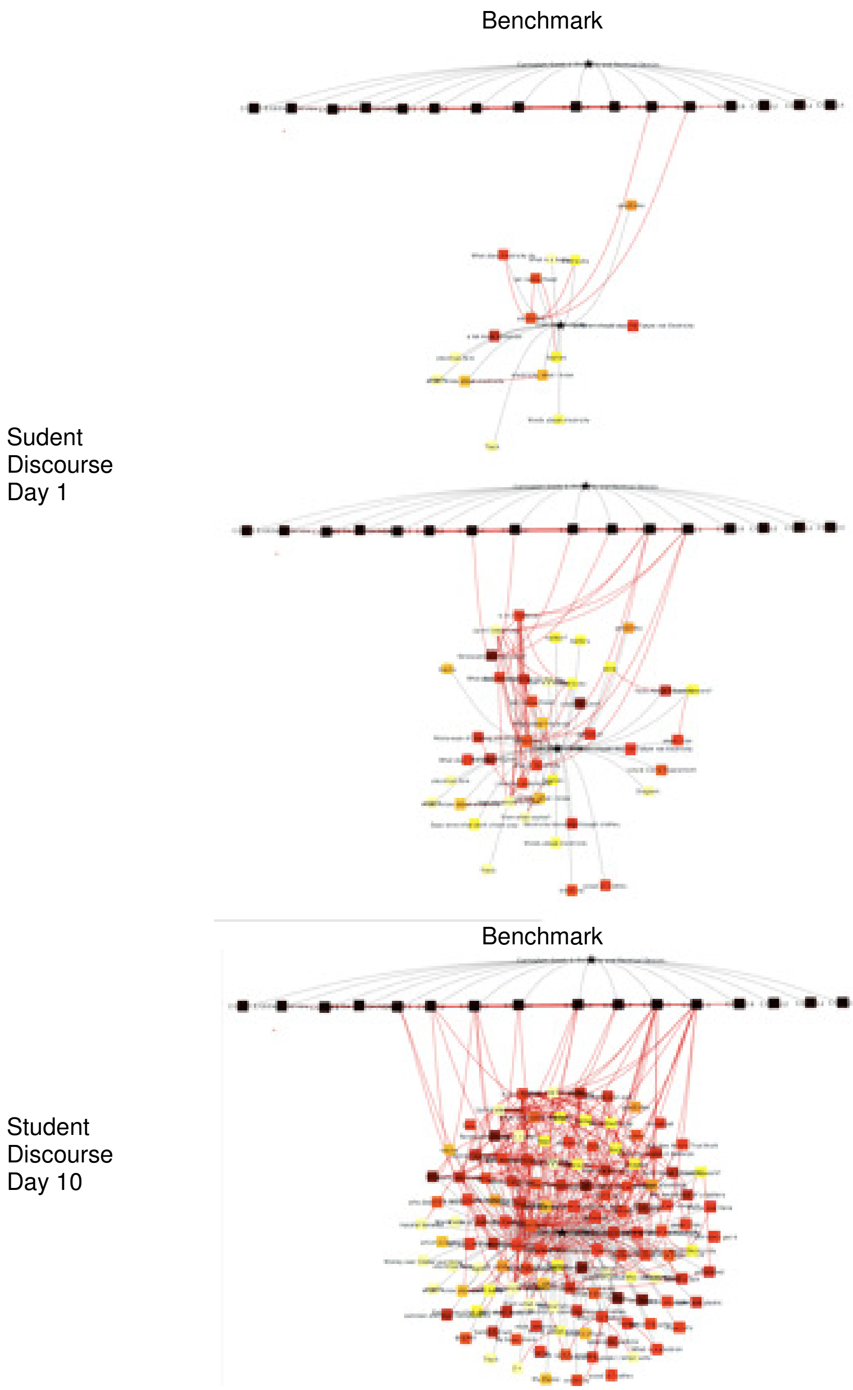

Figure 4: Social network analysis of a classroom over ten days

provides graphical displays of the overlap of the semantic fields of subsets of the discourse by employing techniques from latent semantic analysis. For example, a benchmark can be identified, representing a specific domain. The tool can show the growing overlap of semantic fields between the students' discourse and the benchmark representing any complex knowledge domain of interest, as the following visualizations suggest. The benchmark, at the top of each graph, might be the semantic space for curriculum guidelines, for test items, for authoritative sources or for any selected text or set of texts.

Social Network Analysis. Social Network Analysis tools display the social relationships among participants based on patterns of behavior (e.g., who read/referenced/built on whose note). A Social Network Analysis Tool can help teachers to better understand who the central participants are in the knowledge building discourse and to see if existing social relationships are limiting or impacting positively on the community's work. The tool draws the teacher's attention to children who are on the periphery and makes it more likely that these children will receive the direct support they may need to be more integral to the work of the class.

Increasing levels of responsibility for advancing collective knowledge is facilitated when student contributions to classroom work are represented in a communal knowledge space. Below are graphics generated from the social network analysis tool to give some sense of how it is possible to uncover classroom practices associated with advances in student performance—practices that would be impossible to uncover without use of communal discourse spaces. The work reported in Figure 5 (Zhang, Scardamalia, Lamon, Messina, & Reeve, 2007; Zhang, Scardamalia, Reeve, & Messina, 2009) is from a Grade 4 classroom studying optics. The teacher and students worked together to create classroom practices conducive to sustained knowledge building. Social network analysis and independently generated qualitative analyses were used to assess online participatory patterns and knowledge advances, focusing on indicators of collective cognitive responsibility. The social network graphs generated by the *Social Network Analysis tool* indicate increasingly effective procedures for advancing student knowledge corresponding to the following social organizations: (a) Year 1—fixed, small-groups; (b) Year 2—interactive small groups working together throughout their knowledge work; and (c) Year 3—opportunistic-collaboration, with small teams forming and disbanding under the volition of community members, based on emergent goals that arose as they addressed their shared, top-level goal of refining their knowledge of optics. The third-year model maps most directly onto the organic and distributed social structure in real-world knowledge-creating organizations. Among the three designs, the opportunistic-collaboration model resulted in the highest level of collective cognitive responsibility, knowledge advances, and dynamic diffusion of information. This 3-year account, as shown from the perspective of the social network analysis tool, is shown in Figure 5.

Design principles for knowledge-building environments include: (a) Empower users and transfer greater levels of agency and collective responsibility to them; (b) View assessment as integral to efforts to advance knowledge and to identify problems as work proceeds; (c) Enable users to demand changes and customization of tools so the environments are powerful enough to be embedded in the day-to-day workings of the organization; (d) Support the community in self-directed rigorous assessment, so there is opportunity for the community's work to exceed, not simply meet expectations of external assessors; (e) Incorporate standards and benchmarks into the process, so they are entered in digitized form and become objects of discourse, where they can be annotated, built on, linked to ongoing work and risen above; (f) Support inclusive design, so there is a way in for all participants. This challenge brings with it special technological challenges (Treviranus, 1994, 2002); (g) Provide a public design space to support discourse around all media (graphics, video, audio, text, etc.) with links to all knowledge rich and domain specific learning environments; (g) Encourage openness in knowledge work. Once these requirements are met participants are engaged with ICT in meaningful, interactive contexts, with reading and writing part of their expressive work across all areas of the school curriculum. They can then make extensive use of forms of support that prove so helpful in knowledge creating organizations--connections with other committed knowledge workers and world-class knowledge resources.

Combining ICT-enabled discourse environments and open resources sets the stage for breakthroughs in charting and enhancing development in knowledge building environments. For example, student discourse environments can be linked to powerful simulation, tutorial, intelligent tutoring system, and other domain-specific tools, such as those reported by Quellmalz & Haertel, 2008; Tucker, 2009; Open Learning Initiative, 2009; and Open Educational Resources, 2009. It is then possible to combine the benefits of these different tools and promote interactions surrounding their use. As elaborated by The Open Learning Initiative, Carnegie Mellon University, it is possible to build assessment "into every instructional activity and use the data from those embedded

Year 1

Year 2

Year 3

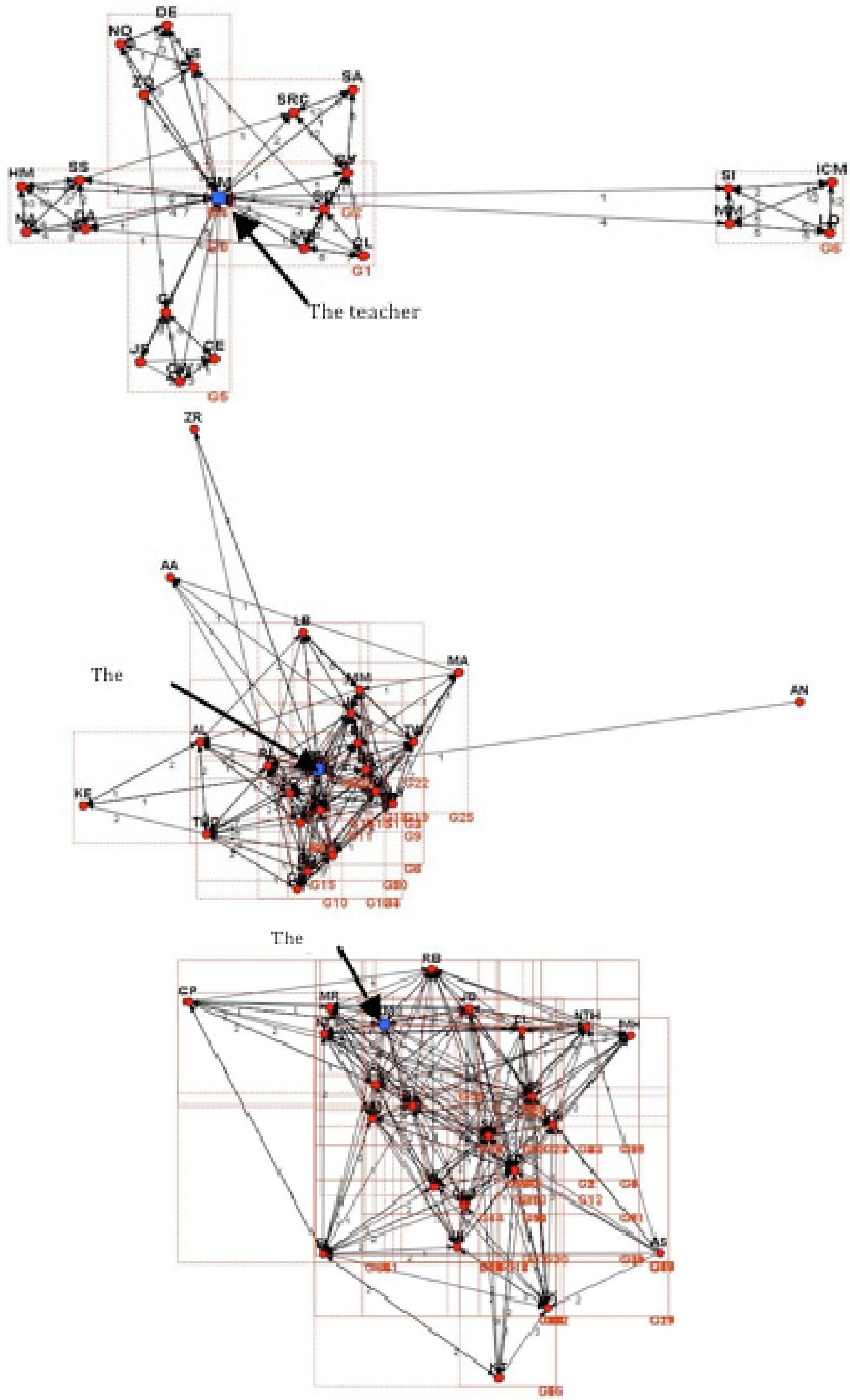

Figure 5: The emergent process of knowledge building over three years

assessments to drive powerful feedback loops for continuous evaluation and improvement." Assessments from these tutorials, simulations, games, etc. can complement those elaborated in the section on open-source software.

Programming interfaces (pp.34ff), combined with interoperability of applications, allow us to further break down barriers between various environments and assessments that have traditionally been separate and disconnected, and search and compile information across them. Open resources make it possible to assemble information regarding learning progressions, benchmarks, and learning modules. Curriki is an example of a web site where the community shares and collaborates on free and open source curricula (http://www.curriki.org/). Creative Commons licenses further expand access to information to be shared and built on, with an expanded concept of intellectual property.

These open resources, combined with data from discourse environments, make it possible to build student portfolios, based on classroom work and all web-accessible work across topics and simulations, games, etc, in- or out-of-school (dealing with ethical issues represents a different, significant challenge). Extended student portfolios will allow us to chart student progress in relation to various and changing developmental benchmarks, as well as foster development through formative feedback. For example, "nearest neighbor" searches, based on student semantic spaces, can identify other people, in the same class or globally, as well as local or global resources, with similar content. These can then be made available, just in time, anytime, to meet both teacher and student needs. These supports can help the class as a whole operate as a 21st century organization, in addition to supporting individual student achievement.

We envision worldwide teams of users and developers taking advantage of new data mining possibilities, intelligent web applications, semantic analysis, machine learning, natural language processing, and other new developments to advance the state of the art in education.

Technology to support emergence of new skills

Two recent books discuss in depth the effect that new technologies can have in shifting education on to a new basis for the 21st century. One is *Rethinking Education in the Age of Technology: The Digital Revolution and Schooling in America* (Collins & Halverson, 2009). Collins and Halverson argue that new technologies create learning opportunities that challenge traditional schools. They envision a future in which technology enables people of all ages to pursue learning on their own terms. Figure 3 above indicates that more time, by far, is spent in out-of-school contexts, across the entire lifespan. If these become primary contexts for learning, tasks designed especially for school will pale by comparison in impact on education. The second book is *The World Is Open: How Web Technology Is Revolutionizing Education* (Bonk, 2009). Bonk explains ways in which technologies have opened the education world to anyone anywhere. He discusses trends such as web searching, open courseware, real-time mobility, portals, and so forth that will impact learning in the 21st century. These technologies are not envisaged as a cafeteria line for students to pass along and pick and choose (which, unfortunately, seems to have been the formative concept in many instructional support systems); instead, they are envisaged as constituting an environment supportive of a more fully engaged community of learners, more open to the world's cognitive and social riches.

These ideas are in line with our earlier discussions of emergence of new skills and open resources. Rather than simply extrapolating from existing goals or expert-identified objectives, new goals can emerge from capacities students demonstrate in supportive environments—such as the capacities for proportional reasoning and theory building revealed in the reported examples. Both these experimental approaches have, in fact, made use of computer-supported knowledge building environments that provide support for the creation of public knowledge (Moss & Beatty, 2006; Messina & Reeve, 2007). Among the technical affordances serving this purpose are "thinking types" or scaffolds, described above, "rise-above" notes that serve purposes of synthesis and the creation of higher-order representations of ideas, and graphical backgrounds for creating multiple representations and organizing ideas (Scardamalia & Bereiter, 2006).

In the theory-building work elaborated above (pp.7ff) scaffolds supported theory building. The "theory supports" included the following phrases: "My theory," "I need to understand," "Evidence for my theory," "Putting our knowledge together," "A better theory." To use these scaffolds students simply need to click on one of these phrases, arrayed on a panel to the left of their writing space, and a text field containing the phrase moves into their text at the appropriate point. Text that the student inserts into the text field to complete the phrase is automatically tagged according to the scaffold name. This simple support increases the use of these phrases in student writing, and as results suggest, enhances the high-level knowledge processes represented by them. In the Knowledge Forum environment, used in the theory-building example, scaffolds are customizable so these discourse supports can easily be changed to fit any 21st century goal. (They can also be used after the fact, to mark text already written.) These scaffolds foster metacognitive awareness, as students use them to characterize their discourse. The scaffold supports also serve as search parameters, further motivating their use and allowing students and teachers to easily search their communal knowledge space to determine what different theories are in the database, what evidence is used to defend them, the nature of theories that are considered to be improvements on earlier theories, and so forth. And it is quite easy with these tagged "thinking types" to build formative assessments to enhance student development. For example, it is possible to create profiles of student or group activity to determine if students and the class are generating lots of theories but providing no evidence. Or perhaps they are providing evidence but not able to put their ideas together to generate an improved theory. Patterns of use make it possible to detect underrepresented knowledge processes and to inform and advance such work.

An important role for technology is to support individuals in constructive contributions to the group. The scaffolds help. At the group level the essential question is: Has the public knowledge shared by a group progressed? To what extent is this knowledge emergent from a group process as opposed to an aggregation of individual products? New Web developments under the banner of Web 3.0 are known as the "semantic web," in that the units of primary interest are ideas or meanings rather than words. Some educational evaluation tools have already made this leap (Teplovs, 2008); we can look forward to further developments in this sphere that align the powerful machinery of Web technology with the educational interests of a knowledge-creating culture. We elaborate these ideas in the section on technological and methodological advances to support the development of 21st century skills (pp.44ff).

Although findings from an emergence approach are very limited, they suggest that students so engaged demonstrate advances across a broad range of 21st century skills (Chuy, et al, 2009; Gan et al, 2007; Sun et al. 2008, in press), and that an emergence approach may contribute genuinely new discoveries to inform large-scale assessment. Positive results of an emergence approach also suggest that defining and operationalizing 21st century skills one-by-one, while important for measurement purposes, may not be the best basis for designing educational activity.

As technology blurs the line between in- and out-of-school contexts, and knowledge becomes a social product situated in open worlds, the need for environments and formative assessment that span educational contexts and support "community knowledge" and group or "collective intelligence" will become increasingly important.

Needed Research

This section identifies important areas of research and development related to the overall goal of developing new assessments and environments for 21st century knowledge building. We start with research and development to improve formative assessments in current learning environments and then shift to studies and advances in formative assessment to transform schools in the image of knowledge creating organizations.

Analysis of 21st century skills in current learning environments

A research program on reforming assessments of 21st skills would benefit from greater understanding of 21st century skills as found in current learning environments. Projects could be selected to represent different learning environments and assessments would focus on 21st century skills frameworks and developmental trajectories such as those proposed by ATC21S. We anticipate that all of the learning environments will show limits in the extent to which they address 21st century skills, and this analysis could provide important information for evidence-centered initiatives to promote these skills.

The second phase of the study would analyze the technical quality of the projects' assessments and their utility for providing formative evidence during instruction. Using the evidence-centered design framework, we anticipate weak links between assessments of 21st century skills, learning tasks used to elicit those skills, and evidence that teachers and students can use to understand development of the skills.

A third phase of the study would involve the creation of evidence-centered classroom assessment systems with representative projects to address all or many of the 21st century skills. Technical quality data would be collected for reliability and validity for classroom formative purposes. In addition, the designs of the formative 21st century assessments would be linked to the more compressed, constrained designs of large scale, summative 21st century assessment tasks being designed by all ATC21S working groups. Classroom formative assessments would be embedded in the learning activities, provide evidence of ongoing learning processes related to 21st century skills such as problem solving, collaboration and communication, and provide rich, deep, frequent streams of evidence to be used by learners and instructors during the learning activities to monitor and support progress. For example, in domain-centered learning environments, such rich, embedded formative assessment would be made possible by digital capture of student processes during domain-specific learning activities such as information research, use of simulations, and network analyses. The study would examine formative utility and technical quality of the assessments and their value added to interim benchmark summative assessments and to even more distal large scale state, national, and international assessments. The research on the design of quality formative assessments of the full range of 21st century skills that could be embedded in projects in each of the different learning environments would serve as models for reforming and transforming 21st century formative assessments in learning environments.

Social and technological innovations for emergence of new skills

The goals currently being promoted for 21st century skill development are, as previously noted, based mainly on expert and stakeholder analysis of goals. In this section we complement this top-down approach to goal identification with a bottom-up approach based on the capacities, limitations, and problems learners reveal when they are actually engaged in knowledge-creating work. The first step in mounting such research is to identify or establish schools able to operate as knowledge-creating organizations—given, as Laferrière and Gervais (2008) suggest, that at this point it may be difficult to locate schools able to take on such work. The proposed research has the dual purpose of (a) discovering previously unrecognized skill goals and (b) developing way to assess these emergent skills through minimally intrusive instruments along the lines of those discussed in section on learner-centered approaches (pp.22ff).

Sites thus engaged, willing to take on an ambitious new research agenda, and equipped with appropriate technology could then support a broad-based research and development effort aimed at addressing questions related to knowledge practices and outcomes and a more inclusive knowledge-building society. At a policy level we would begin to collect data and evidence to address issues that divide educators. For example, many educators favour curriculum procedures and processes that are well-defined and have a step-by-step character. Knowledge creation is not an orderly step-by-step process. Knowledge-creators go where ideas take them. How is the challenge of engaging students in more self-directed and creative work with ideas to be reconciled with the classroom routines and activity structures that many educators feel to be essential for teachers, students, and curriculum coverage? How does self-organization, an important component of knowledge creation, actually combine with intentional development of ideas at the process level?

How are promising ideas worthy of further development sorted out from the large pool of ideas students often generate? How can “pooling of ignorance” be avoided?

The “pooling of ignorance” problem looms large in discussions about open discourse environments for naïve learners. Although “making thinking visible” is one of the advantages claimed for constructivist computer environments, this increases the chances of “pooling ignorance” and spreading “wrong” ideas. Teachers, accordingly, are tempted to exert editorial control over what ideas get made public in student inquiry; and students, for their part, may learn that it’s best to put forward authoritative ideas rather than their own. Research is needed, first to determine whether “pooling ignorance” is a real or only an imagined problem, and second—if it does prove to be real—to carry out design research to find a constructive way to deal with the dilemma.

Concurrent, embedded, and transformative assessments (pp.34ff) need to be geared to demonstrations of new ways around old problems. We can then collectively test the notion that formative assessments, built into the dynamics of the community, will allow for a level of self-correction and focus on high-level goals unparalleled in most educational contexts.

Challenges related to complex interventions

Brown (1992); Collins, Joseph and Bielaczyc (2004); and Frederiksen and Collins (1989) discuss theoretical and methodological challenges in creating complex interventions and problems of narrow measures. They stress the need for design experiments as a way to carry out formative research to test and refine educational designs based on theoretical principles derived from prior research. It is an approach of “progressive refinement.” As Collins, Joseph and Bielaczyc (2004) explain, design experimentation

> involves putting a first version of a design into the world to see how it works. Then, the design is constantly revised based on experience… Because design experiments are set in learning environments, there are many variables that cannot be controlled. Instead, design researchers try to optimize as much of the design as possible and to observe carefully how the different elements are working out. (p.18)

White Paper 2 raises a number of methodological issues regarding assessment of 21st century skills. The proposed research could contribute to progress on each of the issues raised there: (a) *distinguishing the role of context from that of the underlying cognitive construct*—the experiment would allow us to find examples of the construct across different national and domain contexts; (b) *new types of items that are enabled by computers and networks*—the network we propose would implement new designs and explore uses of new item types; (c) *new technologies and new ways of thinking to gain more information from the classroom without overwhelming the classroom with more assessments*--we propose to engage a network of international, multilingual, cross-domain sites to explore issues and determine how concurrent, embedded, and transformative assessments might begin to save teachers time; (d) *right mix of crowd wisdom and traditional validity*—“crowd wisdom” and traditional procedures can easily be combined in the environments we propose; (e) *information and data availability and usefulness*--we can directly explore what it takes to translate data into feedback to drive knowledge advancement; and (f) *assessments for 21st century skills that are activators of students’ own learning*—through use of scaffolds, adaptive recommender systems, stealth assessments, visualizations, etc, we can explore assessments that facilitate students’ own learning.

Specific investigations within the emergence framework

We propose that an international network of pilot sites be established both to cooperate in multifaceted design research described below and to collaborate with local researchers in creating and testing new designs tailored to their own conditions and needs. A given site may collaborate in all or a subset of the specific investigations, but in any event the data they produce will be available for addressing the full range of research questions that arise within the network. The following, therefore, should be regarded as an initial specification, subject to modification and expansion.

Charting developmental pathways with respect to 21st century skills. As indicated in the sections on embedded assessment (pp.34ff) and technology to support the emergence of new skills (pp.35ff), computer-based scaffolds can be used to support the development of 21st century skills and formative assessments related to their use. An intensive program of research to develop each skill would allow us to determine what students at various ages are able and not able to do related to various 21st century skills, with and without supports for knowledge creation. We would then be in better position to elaborate developmental progressions set out in Table 2.

Replicating findings suggesting that knowledge building pedagogy may save educational time rather than add yet a new and separate set of skills to an already crowded curriculum. Currently, learning basic skills and creating new knowledge are thought by many to compete for school time. In knowledge building environments students are reading, writing, producing varied media forms, using mathematics to solve problems—not as isolated curriculum goals but through meaningful interactions aimed at advancing their understanding in all areas of the curriculum. Rather than treating literacy as a prerequisite for knowledge work, it becomes possible to treat knowledge work as the preferred medium for developing multiliteracies. Early results indicate gains in subject-matter learning, multiliteracies, and a broad range of 21st century skills. These results need to be replicated and extended.

Testing new technologies, methods, and generalization effects. The international network of pilot sites would serve as a test bed for new tools and formative assessments. In line with replication studies, research reported by Williams (2009) suggests effective collaboration accelerates attainment in other areas. This "generalization effect" fits with our claim that, although defining and operationalizing 21st century skills one-by-one may be important for measurement purposes, educational activities are better shaped by a more global conception of collaborative work with complex goals. Accordingly, we propose to study relationships between work in targeted areas and spread to areas not targeted. For instance, we may develop measures of collaborative problem solving, our target skill, and then examine its relationship with collaborative learning, communication, and other 21st century skills. We would also measure outcomes on an appropriate achievement variable relative to the subject matter of the target skill. Thus we would test generalization effects related to the overall goal of educating students for a knowledge-creating culture.

Creating inclusive designs for knowledge building. It is important to find ways for all students to contribute to the community knowledge space, and to chart advances for each individual and for the group as a whole. Students can enter into the discourse through their preferred medium (text, graphics, video, audio notes) and perspective, which should help. Early results show advances for both boys and girls, rather than the traditional finding in which girls out perform boys in literacy skills. This suggests that boys lag in traditional literacy programs because they are not rewarding or engaging, whereas progressive inquiry engages both boys and girls. New designs to support students with disabilities will be an essential addition to knowledge building environments to support inclusive knowledge building.

Exploring multilingual, multiliteracy, multicultural issues. Our proposed research would engage international teams, thus it would be possible to explore the use of multilingual and multicultural environments. More generally, the proposed research would make it possible to explore knowledge-building society issues that can only be addressed through a global enterprise.

Administering common tests and questionnaires. While there is currently evidence that high-level knowledge work can be integral to schooling, starting at least in the middle elementary grades (Zhang et.al., 2009), data is needed to support the claim that knowledge building is feasible across a broad range of ages, SES contexts, teachers, and so forth, and that students are more motivated in knowledge building environments than in traditional environments. To maximize knowledge gains from separate experiments it will be important to standardize assessment tools, instruments, and data formats. Through directed assessment efforts it will be possible to identify parameters and practices that enable knowledge building (Law, Lee & Chow, 2002).

Identifying practices that can be incorporated into classrooms that are in keeping with those in knowledge-creating organizations. By embedding practices from knowledge-creating organizations into classrooms we can begin to determine what is required to enable schools to operate as knowledge-creating organizations and to design professional development to foster such practices. Data on classroom processes should also allow us to refine the developmental trajectory set out in Table 2, and build assessments to chart advances at the individual, group, and environment levels.

Demonstrating how a broader systems perspective might inform large-scale, on-demand, summative assessment. We have discussed the distinction between a "working backward" and "emergence" approach to advancing 21st century skills and connections between knowledge building environments, formative assessments, and large-scale assessment. Within the emergence approach, connections between student work and formative and summative assessment can be enriched in important ways. For example, as described above, scaffolds can be built into the environments to encourage students to tag "thinking types." As a result, thinking is made explicit and analytic tools can then be used to assess patterns and help inform next steps. With students more knowledgeably and intentionally connected to the achievement of outcomes to be assessed, they can become more active players in the process. In addition to intentionally working to increase their understanding relative to various learning progressions and benchmarks, they are positioned to comment on and exceed them. As is the case in knowledge-creating organizations, participants are aware of the standards to be exceeded. One of the authors of this paper recounts the story of a teacher who, toward the end of student work in a particular area, published curriculum standards in the students' electronic workspaces so they could comment on them, and how their work stood up in light of them. The students noted many ways in which their work addressed the standards. They also noted important advances they had made that were not represented in the standards. We daresay productive dialogues between those tested and those designing tests could prove valuable to both parties. Semantic analysis tools open up additional possibilities for an emergence framework to inform large-scale assessments. It is possible to create the "benchmark corpus" (the semantic field from any desired compilation of curriculum or assessment material), the "student corpus" (the semantic field from and desired compilation of student-generated texts such as the first-third of their entries in a domain versus the last third), and the "class corpus" (the semantic field from all members of the class, first third versus last third), and so forth. Semantic analysis and other data mining techniques can then be used to track and inform progress, with indication of semantic spaces underrepresented in either the student or benchmark corpus, and changes over time.

Technological and methodological advances to support knowledge building

Technology advances, especially those associated with Web 2.0 and Web 3.0 developments, provide many new opportunities to support a multicultural, multidisciplinary, multidimensional model of development of 21st century skills. These advances also offer supports for interoperability of environments to develop domain knowledge and to support student discourse in those domains. Through coherent media rich online environments it is possible to bring ideas to the center and support concurrent, embedded, and transformative assessment. As indicated above, it is now possible to build a broad range of formative assessments to greatly enrich classroom work.

A key characteristic of Web 2.0 is that users are no longer merely consumers of information but rather active creators of information that is widely accessible by others. The concomitant emergence of online communities such as MySpace, LinkedIn, Flickr, and Facebook has led, ironically and yet unsurprisingly, to a focus on individuals and their roles in these communities as reflected, for example, in counting "friends" to determine connectedness. There has been considerable interest in characterizing the nature of social networks, with social network analysis employed to detect patterns of social interactions in large communities. Web 3.0 designs represent a significant shift to encoding semantic information in ways that make it possible for computers to deduce relationships among pieces of information. In a Web 3.0 world the relationships and dynamics among ideas are at least as important as relationships and dynamics among users. As a way of understanding such relationships we can develop an analog of social network analysis--idea network analysis. This is especially important for knowledge building environments where the concern is social interactions that enable idea improvement (see Teplovs, 2008). Idea network analysis offers a means of describe relationships among ideas, much as social network analysis describes the relationships among actors. Visualizations of idea networks and related metrics such as network density will allow us to characterize changes in social patterns and ideas over time. The demanding conceptual and research challenge, then, is to understand and support the social dynamics that lead to knowledge advancement.

Through additional design work aimed at integrating discourse environments, online knowledge resources, and formative and summative assessments we can greatly extend where and how learning might occur and assessment of it. By tracking the semantics of participant discourses, online curriculum material, test items, texts of experts in the field, etc. we can map one discourse or corpus to another and track growth of ideas. With collaborative online discourse integral to the operation of knowledge-building communities we can further enhance formative assessments to encourage participants to seek new learning opportunities and a broader range of experts.

Effectively designed environments should make it possible to develop communication, collaboration (teamwork), information literacy, critical thinking, ICT literacy, and so forth in parallel—a reflection of how things work in knowledge creating organizations.

White Paper 4 Annex: Knowledge building analytic framework

Template for analyzing environments and assessments

1. DESCRIBE AN ENVIRONMENT AND/OR ASSESSMENT AS IT CURRENTLY EXISTS.
(*Use as much space as you need)*
2. INDICATE WHETHER THE EXAMPLE FITS PRIMARILY INTO AN ADDITIVE OR TRANSFORMATIVE MODEL OF SCHOOL REFORM. TO PROVIDE THIS EVALUATION YOU SIMPLY NEED TO ASSIGN A SCORE FROM 1 (definitely additive) to 10 (definitely transformative), AND PROVIDE A BRIEF RATIONALE. NOTE: Score = 1 (the goal is *additive* if the environment or assessment presented is designed to add a task or activity to school work that remains little changed in overall structure, other than through the addition of this new task, project, environment or assessment*); Score = 10 (the goal is transformative if the environments or assessment alters conditions of schooling in a substantial way, so students become enculturated into a knowledge-creating organization that is supported by a knowledge building environment integral to the operation of the community).*
SCORE _______
RATIONALE FOR SCORE: (*Use as much space as you need)*
3. PLEASE USE THE FOLLOWING EVALUATION FORM TO ASSESS THE CHARACTERISTICS OF THE ENVIRONMENT AND/OR ASSESSMENT IN ITS CURRENT FORM

21st Century skill (from White Paper 1)	**Characteristics of knowledge-creating organizations: a continuum that maps onto 21st century skills** **1 5 10**
Creativity and Innovation	SCORE FROM 1 (Internalize given information; beliefs/actions based on the assumption that someone else has the answer or knows the truth) to 10 (Work on unsolved problems; generate theories and models, take risks, etc; pursue promising ideas and plans) SCORE_______ RATIONALE FOR YOUR SCORE: (*Use as much space as you need)* DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP. (*Use as much space as you need)*
Communication	SCORE FROM 1 (Social chit chat; discourse that aims to get everyone to some predetermined point; limited context for peer-to-peer or extended interactions) to 10 (Knowledge building/progressive discourse aimed at advancing the state of the field; discourse to achieve a more inclusive, higher order analysis; open community knowledge spaces encourage peer-to-peer and extended interactions) SCORE_______ RATIONALE FOR YOUR SCORE: (*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Collaboration/Teamwork

SCORE FROM 1 (Small group work—divided responsibility to create a finished product; the whole is the sum of its parts, not greater than that sum) to 10 (Collective or shared intelligence emerges from collaboration and competition of many individuals and aims to enhance the social pool of existing knowledge. Team members aim to achieve a focus and threshold for productive interaction and work with networked ICT. Advances in community knowledge are prized, over-and-above individual success, while enabling each participant to contribute to that success)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Information Literacy/Research

SCORE FROM 1 (Inquiry: question-answer, through finding and compiling information; variable testing research) to 10 (Going beyond given information; constructive use of and contribution to knowledge resources to identify and expand the social pool of improvable ideas, with research integral to efforts to advance knowledge resources and information)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Critical Thinking, Problem Solving and Decision-making

SCORE FROM 1 (Meaningful activities are designed by the director/teacher/curriculum designer; learners work on predetermined tasks set by others.) to 10 (High-level thinking skills exercised in the course of authentic knowledge work; the bar for accomplishments is continually raised through self initiated problem finding and attunement to promising ideas; participants are engaged in complex problems and systems thinking)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR

ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Citizenship – local and global

SCORE FROM 1 (Support of organization and community behavioral norms; "doing one's best"; personal rights) to 10 (Citizens feel part of a knowledge-creating civilization and aim to contribute to a global enterprise; team members value diverse perspectives, build shared, interconnected knowledge spanning formal and informal settings, exercise leadership, and support inclusive rights)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

ICT literacy

SCORE FROM 1 (Familiarity with and ability to use common applications and web resources and facilities) to 10 (ICT integrated into the daily workings of the organization; shared community spaces built and continually improved by participants, with connection to organizations and resources worldwide)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Life and career skills

SCORE FROM 1 (Personal career goals consistent with individual characteristics; realistic assessment of requirements and probabilities of achieving career goals) to 10 (Engagement in continuous, "lifelong" and "life-wide" learning opportunities; self-identification as a knowledge creator, regardless of life circumstance or context)

SCORE_______

RATIONALE FOR YOUR SCORE:
(*Use as much space as you need)*

DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP.
(*Use as much space as you need)*

Learning to learn / meta-

SCORE FROM 1 (Students and workers provide input to the organization, but the

cognition	high-level processes are under the control of someone else) to 10 (Students and workers are able to take charge at the highest, executive levels; assessment is integral to the operation of the organization, requiring social as well as individual metacognition) SCORE_______ RATIONALE FOR YOUR SCORE: *(Use as much space as you need)* DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP. *(Use as much space as you need)*
Personal and social responsibility – incl. cultural competence	SCORE FROM 1 (Individual responsibility; local context) to 10 (Team members build on and improve the knowledge assets of the community as a whole, with appreciation of cultural dynamics that will allow the ideas to be used and improved to serve and benefit a multicultural, multilingual, changing society) SCORE_______ RATIONALE FOR YOUR SCORE: *(Use as much space as you need)* DO YOU SEE A WAY TO IMPROVE YOUR ENVIRONMENT OR ASSESSMENT ALONG THIS DIMENSION? IF SO, PLEASE PROVIDE A BRIEF ACCOUNT OF HOW YOU MIGHT DO THAT, OR HOW THE IDEAS IN THIS WORKING PAPER MIGHT HELP. *(Use as much space as you need)*

Results obtained by means of analytic templates

Table 3 provides descriptive statistics for the ratings of environments and assessments selected by (a) Assessment and Teaching of 21st Century Skills project (ATC21S) volunteers versus those selected by (b) graduate students.

Table 3: Ratings of environments and assessments

21st Century Skills	ATC21S (N= 7)				Grad Students (N=11)			
	Mean	SD	Max	Min	Mean	SD	Max	Min
Creativity	7.57	1.81	10	4	5.73	2.53	9	2
Communication	8.00	1.29	9	6	5.50	3.46	9	1
Collaboration	7.86	1.35	9	5	5.59	3.23	9	1
Information literacy	7.57	2.15	9	4	5.55	2.50	10	2
Critical thinking	7.14	1.86	9	4	6.27	3.07	10	2
Citizenship	7.14	2.91	9	2	4.50	2.52	8	1
ICT literacy	7.71	2.69	10	2	4.27	3.10	10	1
Life/career skills	7.57	2.51	9	3	5.86	2.79	10	1
Meta-cognition	8.00	2.00	10	4	4.32	1.95	7	1
Responsibility	7.71	2.21	9	4	4.00	2.76	8	1

Figure 6 provides a graphical representation of the ratings of environments and assessments selected by (a) Assessment and Teaching of 21st Century Skills (ATC21S) volunteers versus those selected by (b) graduate students and shown in Table 3.

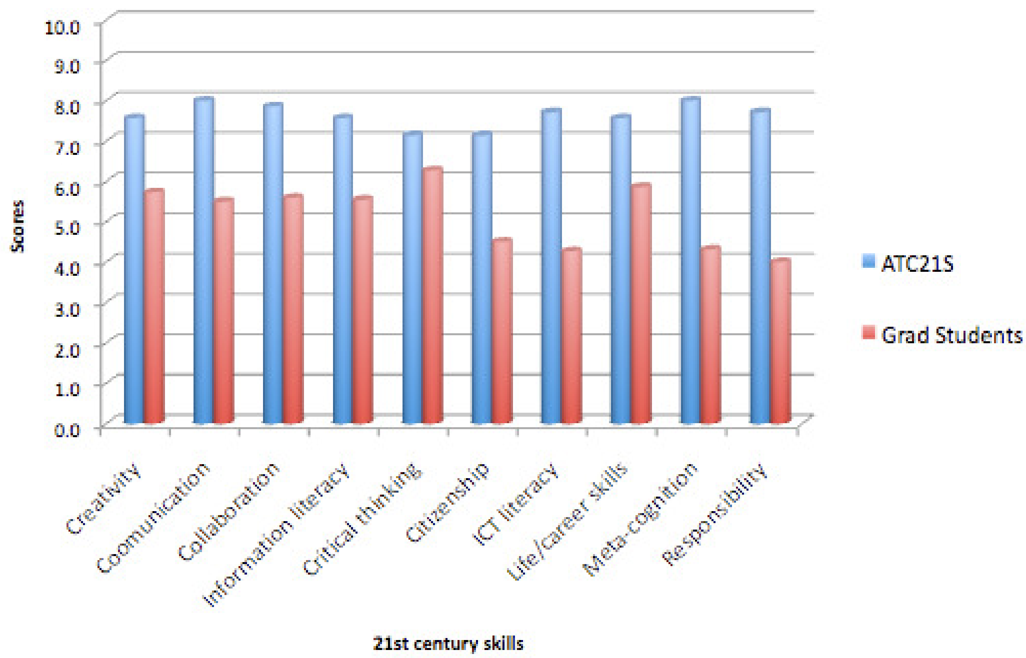

Figure 6: Ratings of environments and assessments

References

Ackoff, R.L. (1974). 'The systems revolution', *Long Range Planning*, *7*, 2–20.

Alexopoulou, E., & Driver, R. (1996). Small group discussion in physics: Peer interaction modes in pairs and fours. *Journal of Research in Science Teaching, 33*(10), 1099-1114.

American Educational Research Association, American Psychological Association, & National Council on Measurement in Education (AERA, APA, NCME). (1999). *Standards for educational and psychological testing*. Washington, DC: AERA.

Anderson, C. (2006). The Long Tail: Why the Future of Business is Selling Less of More. New York: Hyperion.

Andrade, H. (2000). Using rubrics to promote thinking and learning. *Educational Leadership*, *57*(5), 13-18.

Arvanitis, S. (2005). Computerization, workplace organization, skilled labour and firm productivity: Evidence for the Swiss business sector. *Economics of Innovation and New Technology, Taylor and Francis Journals, 14*(4), 225-249.

Askenazy, P., Caroli, E., & Marcus, V. (2001). *New organizational practices and working conditions: Evidence from France in the 1990's*. CEPREMAP Working Papers 0106, downloaded on October 4, 2009 from http://www.cepremap.cnrs.fr/couv_orange/co0106.pdf.

Autor, D., Levy, F., & Munane, R. (2003). The skill content of recent technological change: An empirical exploration. *Quarterly Journal of Economics, 118(4),* 1279-1334.

Banks, J.A., Au, K.A., Ball, A.F., Bell, P., Gordon, E., Gutierrez, K.D., Brice Heath, S., Lee, C.D., Lee, Y., Mahiri, J., Suad Nasir, N., Valdes, G., & Zhou, M. (2007). Learning in and out of school in diverse environments: Life-Long, Life-Wide, and Life-Deep. http://www.life-slc.org/

Barth, P. (2009). What do we mean by 21st century skills? *American School Board Journal.* Retrieved on October 8, 2009 from http://www.asbj.com/MainMenuCategory/Archive/2009/October/What-Do-We-Mean-by-21st-Century-Skills.aspx

Bateman, H. V., Goldman, S. R., Newbrough, J. R., & Bransford, J. D. (1998). Students' sense of community in constructivist/collaborative learning environments. *Proceedings of the Twentieth Annual Meeting of the Cognitive Science Society* (pp.126-131). Mahwah, NJ: Lawrence Erlbaum.

Bell, D. (1973). The Coming of Post-Industrial Society: A Venture in Social Forecasting. New York, NY: Basic Books.

Bennett, R. E., Persky, H., Weiss, A., & Jenkins, F. (2007). Problem solving in technology rich environments: A report from the NAEP technology-based assessment project, Research and Development Series (NCES 2007-466). U.S. Department of Education, National Center for Educational Statistics. Washington, DC: U.S. Government Printing Office.

Bereiter, C. (1984). How to keep thinking skills from going the way of all frills. *Educational Leadership*, *42*(1), 75-77.

Bereiter, C. (2002). *Education and mind in the knowledge age*. Mahwah, NJ: Lawrence Erlbaum Associates.

Bereiter, C. (2009). Innovation in the absence of principled knowledge: The case of the Wright Brothers. *Creativity and Innovation Management, 18* (3), 234-241.

Bereiter, C., & Scardamalia, M. (1989). Intentional learning as a goal of instruction. In L. B. Resnick (Ed.), Knowing, learning, and instruction: Essays in honor of Robert Glaser (pp.361-392). Hillsdale, NJ: Lawrence Erlbaum Associates

Bereiter, C., & Scardamalia, M. (1993). Surpassing ourselves: An inquiry into the nature and implications of expertise. Chicago and La Salle, IL: Open Court.

Bereiter, C., & Scardamalia, M. (2006). Education for the knowledge age: Design-centered models of teaching and instruction. In P. A. Alexander & P. H. Winne (Eds.), Handbook of educational psychology (2nd ed., pp.695-713). Mahwah, NJ: Lawrence Erlbaum Associates.

Bereiter, C., & Scardamalia, M. (2009). Teaching how science really works. *Education Canada, 49*(1), 14-17.

Binkley, M., Erstad, O., Herman, J., Raizen, S., Ripley, M., & Rumble, M. (2009). Developing 21st Century Skills and Assessments. White Paper from the Assessment and Learning of 21st Century Skills Project.

Black, S.E., & Lynch, L.M. (2003). What's driving the new economy: The benefits of workplace innovation. *The Economic Journal, 114,* 97-116.

Bonk, C. J. (2009). The world is open: How web technology is revolutionizing education. San Francisco: Jossey-Bass.

Borghans, L., & ter Weel, B. (2001). Computers, skills and wages. Maastricht, Netherlands: MERIT.

Bransford, J. D., Brown, A.L., & Cocking, R.R. (1999). *How people learn: Brain, mind, experience,* and *school*. Washington, DC: National Academy Press.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

Bransford, J. D., & Schwartz, D. (1999). Rethinking transfer: A simple proposal with multiple implications. In A. Iran-Nejad & P. D. Pearson (Eds.), *Review of Research in Education* (Vol. 24 pp.61-100). Washington, DC: American Educational Research Association.

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions. *Journal of the Learning Sciences, 2*(2), 141-178.

Brown, A. L., & Campione, J.C. (1996). Psychological theory and design of innovative learning environments: On procedures, principles, and systems. In L. Schauble & R. Glaser (Eds.), *Innovations in learning: New environments for education* (pp.289-325). Mahwah, NJ: Lawrence Erlbaum Associates.

Carey, S., Evans, R., Honda, M., Jay, E., & Unger, C. (1989). An Experiment Is When You Try It and See if It Works": A Study of Junior High School Students' Understanding of the Construction of Scientific Knowledge. *International Journal of Science Education*, 11(5), 514-529.

Carey, S., & Smith, C. (1993). On Understanding the Nature of Scientific Knowledge. *Educational Pscyhologist*, 28(3), 235-251.

Center on Continuous Instructional Improvement (CCII). (2009). *Report of the CCII Panel on Learning Progressions in Science*. CPRE Research Report, Columbia University, New York.

Chase, W.G., & Simon, H.A. (1973). Perception in chess. *Cognitive Psychology, 1,* 33-81.

Chi, M.T.H., Feltovich, P.J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121-152.

Chuy, M., Scardamalia, M., & Bereiter, C. (2009, August). Knowledge Building and Writing Development. Paper presented at the Association for Teacher Education in Europe Conference (ATEE), Palma de Mallorca, Spain.)

Collins, A. & Halverson, R. (2009). Rethinking Education in the Age of Technology: The Digital Revolution and Schooling in America. New York, NY: Teachers College Press.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences, 13*(1), 15-42.

Confrey, J. (1990). A review of research on student conceptions in mathematics, science programming. *Review of Research in Education 16*, 3-55, C.B. Cazden, ed. Washington, DC: American Educational Research Association.

Crawford, M. B. (2006). *Shop Class as Soulcraft.* The New Atlantis, 13, 7-24. Retrieved on October 10, 2009 from http://www.thenewatlantis.com/docLib/20090526_TNA13Crawford2009.pdf

Crawford, V. M., & Toyama, Y. (2002). WorldWatcher Looking At The Environment Curriculum: Final External Evaluation Report. Menlo Park, CA: SRI International.

Crespi, F., & Pianta, M. (2008). Demand and innovation in productivity growth. *International Review of Applied Economics, 22*(6), 655-672.

Csapó, B. (2007). Research into learning to learn through the assessment of quality and organization of learning outcomes. *The Curriculum Journal*, 18(2) 195-210.

Darling-Hammond, L. (1997). The right to learn: A blueprint for creating schools that work. San Francisco: Jossey-Bass.

Darling-Hammond, L. (2000). Teacher quality and student achievement: A review of state policy evidence. *Education Policy Analysis Archives, 8*(1).

Darling-Hammond, L., Barron, B., Pearson, P.D., Schoenfeld, A. H., Stage, E. K., Zimmerman, T. D., Cervetti, G. N., & Tilson, J. L. (2008). Powerful Learning: What We Know About Teaching for Understanding. San Francisco: Jossey-Bass.

David, P.A., & Foray, D. (2003). Economic fundamentals of the knowledge society. *Policy Futures in Education, 1*(1), 20-49.

Dawkins, R. (1996). The *Blind Watchmaker*: Why the Evidence of Evolution Reveals a Universe without Design. New York: W. W. Norton.

Deci, E.L., & Ryan, R.M. (1985). *Intrinsic Motivation and Self-Determination in Human Behavior*. New York: Plenum.

de Groot, A.D. (1965). *Thought and Choice in Chess.* New York:Basic Books.

Dickerson, A., & Green, F. (2004). The growth and valuation of generic skills. *Oxford Economic Papers, 56,* 371-406.

Drucker, P. F. (1968). The age of discontinuity: Guidelines to our changing society. New York: Harper & Row.

Drucker, P. (1985). Innovation and entrepreneurship: Practice and principles. New York: Harper and Row.

Drucker, P.F. (1994, November). The age of social transformation. *Atlantic Monthly,* pp.53-80.

Drucker, P. F. (2003). A functioning Society: Selection from Sixty-Five Years of Writing on Community, Society, and Polity . New Brunswick: Transaction Publishers.

Dweck, C.S. (1986). Motivational processes affecting learning. *American Psychologist, 41*, 1040-1048.

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

Ericsson, K.A. (Ed.). (2009). Development of Professional Expertise. Toward Measurement of Expert Performance and Design of Optimal Learning Environments. New York, NY: Cambridge University Press.

Erstad, O. (2008). 'Trajectories of remixing – digital literacies, media production and schooling'. In C. Lankshear & M. Knobel (eds.) *Digital literacies*. *Concepts, Policies and Practices.* New York: Peter Lang. pp.177-202.

Frederiksen, J. R., & Collins, A. (1989). A system approach to educational testing. *Eucational Researcher, 18*(9), 27-32.

Fujimura, J. (1992). Crafting science: Standardized packages, boundary objects, and translation. In A. Pickering (Ed.), *Science as practice and culture*. Chicago: University of Chicago Press.

Gan, Y. C., Scardamalia, M., Hong, H.-Y., & Zhang, J. (2007). Making thinking visible: Growth in graphical literacy, Grades 3 and 4. *Proceedings of the International Conference on Computer Supported Collaborative Learning 2007* (pp.206-208). Rutgers, The State University of New Jersey, NJ.

Gaskin, I.W. (2005). Success with struggling readers: The Benchmark School approach. New York: Guilford.

Gates, D. (2005). Boeing 787: Parts from around world will be swiftly integrated. *The Seattle Times*, September 11, 2005.

Gera, S., & Gu, W. (2004). The effect of organizational innovation and information technology on firm performance. *International Performance Monitor, 9.*

Gillmore, G.M. (1998, December). Importance of specific skills five and ten years after graduation. OEA Research Report 98-11. Seattle: University of Washington Office of Educational Assessment. Retrieved, May 12, 2004, from http://www.washington.edu/oea/9811.htm

Glaser, R. (1991). Expertise and assessment. In M. Wittrock & E. Baker (Eds.), *Testing and cognition* (pp.17-30). Englewood Cliffs, NJ: Prentice-Hall.

Gloor, P.A. (2006). Swarm creativity: Competitive advantage through collaborative innovation networks. Oxford, UK: Oxford University Press.

Goodwin, C., & Goodwin, M.H. (1996). Seeing as a situated activity: Formulating planes. In Y. Engeström and D. Middleton (Eds.), *Cognition and Communication at Work.* (pp.61-95). Cambridge: Cambridge University Press.

Greeno, J. G. (1991). Number sense as situated knowing in a conceptual domain. *Journal for Research in Mathematics Education*, *22*, 170-218.

Hall, R., & Stevens, R. (1995). Making space: A comparison of mathematical work in school and professional design practices. In S. L. Star (Ed.), *The cultures of computing* (pp.118-145). London: Basil Blackwell.

Hatano, G., & Inagaki, K. (1986). Two courses of expertise. In H. Stevenson, J. Azuma & K. Hakuta (Eds.), *Child development and education in Japan* (pp.262–272). New York, NY: W. H. Freeman.

Hatano, G., & Osuro, Y. (2003). Commentary: Reconceptualizing school learning using insight from expertise research. *Educational Researcher; 32*, 26-29.

Hearn, G., & Rooney, D. (Eds.) (2008). *Knowledge Policy. Challenges for the 21st Century*. Northampton: Edward Elgar Publishing, Inc.

Herrenkohl, L. R., & Guerra, M. R. (1998). Participant structures, scientific discourse, and student engagement in fourth grade. *Cognition and Instruction, 16*, 433-475.

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *Physics Teacher, 30,* 141-158.

Homer-Dixon, T. (2000). *The ingenuity gap*. New York: Knopf.

Honda, M. (1994). Linguistic inquiry in the science classroom: "It is science, but it's not like a science problem in a book."Cambridge, MA: MIT Working Papers in Linguistics.

Johnson, P. (2009). The 21st century skills movement. *Educational Leadership, 67*(1), 11-11.

Kahin, B., & Foray, D. (Eds.) (2006). *Advancing knowledge and the knowledge economy*. Cambridge, MA: MIT Press.

Kozma, R.B. (2003). Material and social affordances of multiple representations for science understanding. *Learning Instruction, 13*(2), 205-226.

Kozma, R.B., Chin, E., Russell, J., & Marx, N. (2000). The role of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of the Learning Sciences, 9*(3), 105-144.

Kuhn, D., Schauble, L. & Garcia-Mila, M. (1992). Cross-domain development of scientific reasoning. *Cognition and Instruction*, 9, 285–327.

Laferrière, T. (2001). Collaborative teaching and education reform in a networked world. In M. Moll (Ed.), *But it's only a tool! The politics of technology and education reform* (pp.65-88). Ottawa: Canadian Teachers Federation and Canadian Centre for Policy Alternative.

Laferrière, T., & Gervais, F. (2008). Communities of practice across learning institutions. In C. Kimble, P. Hildreth, & Bourdon, I. (Eds.), Communities of Practice: Creating Learning Environments for Educators, Vol 2 (pp 179-197). Information Age Publishing Inc.

Lai, M., & Law, N. (2006). Peer Scaffolding of Knowledge Building through Collaboration of Groups with Differential Learning Experiences. *Journal of Educational Computing Research, 35*(2), 121-142.

Lamon, M., Secules, T., Petrosino, A.J., Hackett, R., Bransford, J.D. & Goldman, S.R., (1996). Schools for thought: Overview of the project and lessons learned from one of the sites. In L. Schauble & R. Glaser (Eds.), *Innovation in Learning: New environments for education* (pp.243-288). Hillsdale, NJ: Lawrence Erlbaum.

Law, N. (2006). Leveraging technology for educational reform and pedagogical innovation: Polices and practices in Hong Kong and Singapore. *Research and Practice in Technology Education and Learning*, 1(2), pp.163-170.

Law, N., Lee, Y., & Chow, A. (2002). Practice characteristics that lead to "21st century learning outcomes". *Journal of Computer Assisted Learning*, 18 (4), pp.415-426.

Law, N., & Wong, E. (2003). Developmental Trajectory in Knowledge Building: An Investigation. In B. Wasson, S. Ludvigsen & Hoppe, U. (Ed.), *Designing for Change in Networked Learning Environments* (pp.57-66). Dordrecht: Kluwer Academic Publishers.

Lee, C.D. (1992). Literacy, cultural diversity, and instruction. *Education and Urban Society* 24:279–291.

Lee, E.Y.C., Chan, C.K.K., & van Aalst, J. (2006). Students assessing their own collaborative knowledge building. *International Journal of Computer-Supported Collaborative Learning, 1*, 277-307.

Lehrer, R., Carpenter, S., Schauble, L., & Putz, A. (2000). Designing classrooms that support inquiry. In R. Minstrell and E. Van Zee (Eds.). *Inquiring into inquiry learning and teaching in science* (pp.80-99). Reston, VA: American Association for the Advancement of Science.

Leiponen, A. (2005). Organization of knowledge and innovation: The case of Finnish business services. *Industry and Innovation, 12*(2), 185-203.

Leonard-Barton, D. (1995). Wellsprings of Knowledge: Building and Sustaining the Sources of Innovation. Harvard Business School Press, Boston, MA.

Lisbon Council (2007). *Skills for the future*. Brussels: Lisbon Council.

Maurin, E., & Thesmar, D. (2004). Changes in the functional structure of firms and the demand for skill. *Journal of Labor Economics, 22*(3), 639-644.

Messick, S. (1994). The interplay of evidence and consequences in the validation of performance assessments. *Educational Researcher, 32*, 13-23.

Messina, R., & Reeve, R. (2006). Knowledge building in elementary science. In K. Leithwood, P. McAdie, N. Bascia, & A. Rodrigue (Eds.), *Teaching for deep understanding: What every educator should know* (pp.110-115). Thousand Oaks, CA: Corwin Press.

Mestre, J.P. (1994). Cognitive aspects of learning and teaching science. In S.J. Fitzsimmons and L.C. Kerpelman, (Eds.). *Teacher Enhancement for Elementary and Secondary Science and Mathematics: Status, Issues, and Problems.* (pp.3-1 – 3-53). NSF 94-80, Arlington, VA: National Science Foundation.

Minstrell, J. (1989). Teaching science for understanding. In L. Resnick & L. Klopfer (Eds.), Toward the thinking curriculum: Current cognitive research. 1989 Yearbook of the Association for Supervision and Curriculum Development (pp.129-149). Washington, DC: Association for Supervision and Curriculum Development.

Mislevy, R. J., Chudowsky, N., Draney, K., Fried, R., Gaffney, T., Haertel, G., Hafter, A., Hamel, L., Kennedy, C., Long, K., Morrison, A. L., Murphy, R., Pena, P., Quellmalz, E., Rosenquist, A., Songer, N., Schank, P., Wenk, A., & Wilson, M. (2003). *Design patterns for assessing science inquiry* (PADI Technical Report 1). Menlo Park, CA: SRI International, Center for Technology in Learning

Mislevy, R. J., & Haertel, G. D. (2006). Implications of evidence-centered design for educational testing. *Educational Measurement: Issues and Practice, 25*(4), 6-20.

Moll, L.C. (1986). Creating Strategic Learning Environments for Students: A Community-Based Approach. Paper presented at the S.I.G. Language Development Invited Symposium Literacy and Schooling, Annual Meeting of the American Educational Research Association, San Francisco, CA.

Moll, L.C. (1986). Writing as a communication: Creating strategic learning environments for students. *Theory into Practice* 25:102–108.

Moses, R. P. (1994). The struggle for citizenship and math/sciences literacy. *Journal of Mathematical Behavior*, *13*, 107-111.

Moss, J. (2005). Pipes, tubes, and beakers: Teaching rational number. In J. Bransford and S. Donovan (Eds.), *How Children Learn: History, Science and Mathematics in the Classroom* (pp.309-350). Washington, DC: National Academies Press.

Moss, J. & Beatty, R. (2006). Knowledge building in mathematics: Supporting collaborative learning in pattern problems . *International Journal of Computer Supported Collaborative Learning* Volume 1, Number 4 441–465.

Murphy, M. (2002). *Organizational change and firm performance*. OECD Working Papers, downloaded on October 3, 2009 from http://puck.sourceoecd.org/vl=18659355/cl=20/nw=1/rpsv/workingpapers/18151965/wp_5lgsjhvj7m41.htm.

National Research Council (2000). *How people learn: Brain, mind, experience, and school* (Expanded version; J. D. Bransford, A. L. Brown, & R. R. Cocking, Eds.). Washington, DC: National Academy Press.

Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.

Nonaka, I., & Takeuchi, H. (1995). The knowledge creating company: How Japanese companies create the dynamics of innovation. New York: Oxford University Press.

Norman, D. A. (1993). *Things that make us smart*. Reading, MA: Addison-Wesley Publishing Company.

Nunes, C. A. A., Nunes, M. M. R., & Davis, C. (2003). Assessing the inaccessible: Metacognition andattitudes. *Assessment in Education, 10*(3), 375-388.

Ochs, E., Gonzales, P., & Jacoby, S. (1996). “When I come down I’m in the domain state”: Grammar and graphic representation in the interpretive activity of physicists. In E. Ochs, E. A. Schegloff, & S. Thompson (Eds.), *Interaction and grammar* (pp.328-369). New York: Cambridge University Press.

Paavola, S., & Hakkarainen, K. (2005). The knowledge creation metaphor - An emergent epistemological approach to learning. *Science & Education, 14*, 535-557.

Panel on Educational Technology of the President's Committee of Advisors on Science and Technology (1997, March). *Report to the President on the use of technology to strengthen K-12 education in the United States*. Retrieved on December 1, 2009 from http://www.ostp.gov/PCAST/k-12ed.html.

Partnership for 21st Century Skills. (2009). Retrieved on October 1, 2009 from http://www.21stcenturyskills.org/

Pellegrino, J., Chudowsky, N., & Glaser, R. (2001). *Knowing what students know: The science and design of educational assessment*. Washington, DC: National Academy Press.

Pilat, D. (2004). *The economic impact of ICT: A European perspective.* Paper presented at a conference on IT Innovation, Tokyo.

Quellmalz, E. S., & Haertel, G. D. (2008). Assessing new literacies in science and mathematics. In D. J. Leu, Jr., J. Coiro, M. Knowbel, & C. Lankshear (Eds.) *Handbook of research on new literacies*. Mahwah, NJ: Erlbaum.

Quellmalz, E. S., & Kozma, R. (2003). Designing assessments of learning with technology. *Assessment in Education*, *10*(3), 389-407.

Quellmalz, E.S., & Pellegrino, J.W. (2009). Technology and testing. *Science,* 323, 75-79.

Raizen, S. A. (1997). Making way for technology education. *Journal of Science Education and Technology*, *6*(1), 59-70.

Raizen, S. A., Sellwood, P., Todd, R. D., & Vickers, M. (1995). *Technology Education in the Classroom: Understanding the Designed World.* San Francisco: Jossey-Bass.

Redish, E. F. (1996). *Discipline-Specific Science Education and Educational Research: The Case of Physics.* Paper prepared for the Committee on Developments in the Science of Learning, for The Sciences of Science Learning: An Interdisciplinary Discussion.

Reich, R. B. (1991). The work of nations: Preparing ourselves for 21st century capitalism. New York, NY: A.A. Knopf.

Robinson, A. G., & Stern, S. (1997). *Corporate Creativity. How Innovation and Improvement Actually Happen.* San Francisco: Berrett-Koehler Publishers, Inc.

Rotherham, A. J. (2008). *21st-Century skills are not a new education trend but could be a fad*. Retrieve October 8, 2009 from http://www.usnews.com/articles/opinion/2008/12/15/21st-century-skills-are-not-a-new-education-trend-but-could-be-a-fad.html

Rotherham, A. J., & Willingham, D. (2009). 21st Century skills: The challenges ahead. *Educational Leadership, 67*(1), 16-21.

Saving the rainforest: REDD or dead? (2009). Retrieved on December 19, 2009, from http://edition.cnn.com/2009/WORLD/europe/12/18/un.redd.program.rainforests/index.html

Scardamalia, M. (2002). Collective cognitive responsibility for the advancement of knowledge. In B. Smith (Ed.) *Liberal education in a knowledge society* (pp.67-98). Chicago: Open Court.

Scardamalia, M., Bereiter, C., Brett, C., Burtis, P. J., Calhoun, C., & Smith Lea, N. (1992). Educational applications of a networked communal database. *Interactive Learning Environments, 2*(1), 45-71.

Scardamalia, M., & Bereiter, C. (2003). Knowledge building. In *encyclopedia of education* (2nd ed., pp.1370-1373). New York: Macmillan Reference, USA.

Scardamalia, M., & Bereiter, C. (2006). Knowledge building: Theory, pedagogy, and technology. In K. Sawyer (Ed.), *Cambridge Handbook of the Learning Sciences* (pp.97-118). New York: Cambridge University Press.

Schwartz, D. L., & Bransford, J.D. (1998). A time for telling. *Cognition & Instruction, 16(4),* 475-522.

Senge, P. M. (1990). *The Fifth Discipline*. London: Century Business.

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

Shutt, K., Phillips, R., Van Horne, K., Vye, N., & Bransford, J. B. (2009). *Developing science inquiry skills with challenge-based, student-directed learning.* Presentation to the LIFE Center: Learning in Informal and Formal Environments, University of Washington, Seattle WA.

Simonton, D. K. (1999). *Origins of genius: Darwinian perspectives on creativity*. New York: Oxford University Press.

Smith, C. L., Maclin, D., Houghton, C., & Hennessey, M. G. (2000). Sixth-Grade Students' Epistemologies of Science: The Impact of School Science Experiences on Epistemological Development. *Cognition and Instruction*, 18(3), 349-422.

Smith, C. L., & Wenk, L. (2006). Relations among Three Aspects of First-Year College Students' Epistemologies of Science. Journal of research in science teaching, 43(8), 747-785.

Spiro, R. J., Vispoel, W. L., Schmitz, J., Samarapungavan, A., & Boeger, A. (1987). Knowledge acquisition for application: Cognitive flexibility and transfer in complex content domains. In B. C.

Britton & S. Glynn (Eds.), *Executive control processes in reading* (pp.177-199). Hillsdale, NJ: Lawrence Erlbaum Associates.

Spiro, R. J., Feltovich, P. L., Jackson, M. J., & Coulson, R. L. (1991). Cognitive flexibility, constructivism, and hypertext: Random access instruction for advanced knowledge acquisition in ill-structured domains. *Educational Technology 31*(5), 24–33.

Stahl, G. (2006). Group cognition: Computer support for building collaborative knowledge. Cambridge, MA: MIT Press.

Stewart, I., & Golubitsky, M. (1992). *Fearful Symmetry: Is God a Geometer?* Oxford: Blackwell Publishers.

Stipek, D. (2002). Motivation to Learn: Integrating Theory and Practice, 4th edition. Needham Heights, MA: Allyn and Bacon.

Stiroh, K. J. (2003). Growth and innovation in the new economy. In D. Jones, (Ed.), *New Economy Handbook* (723-751). San Diego and London: Elsevier/Academic Press.

Suchman, L. A., & Trigg, R. H. (1993). Artificial intelligence as craftwork. In S. Chaiklin & J. Lave (Eds.), *Understanding practice: Perspectives on activity and context* (pp.144-78). New York: Cambridge University Press.

Sun, Y., Zhang, J., & Scardamalia, M. (2008). Knowledge building and vocabulary growth over two years, Grades 3 and 4. *Instructional Science*. doi:10.1007/s11251-008-9082-5

Sun, Y., Zhang, J., & Scardamalia, M. (in press). Developing deep Understanding and Literacy while Closing the Gender-Based Literacy Gap. *Canadian Journal of Learning and Technology*.

Tabak, I., & Baumgartner, E. (2004). The teacher as partner: Exploring participant structures, symmetry, and identity work in scaffolding. *Cognition and Instruction, 22*(4), 393-429.

Teplovs, C. (2008). The Knowledge Space Visualizer: A tool for visualizing online discourse. In G. Kanselaar, V. Jonker, P. A. Kirschner & F. J. Prins (Eds.), Proceedings of the International Conference of the Learning Sciences 2008: Cre8 a learning world. Utrecht, NL: International Society of the Learning.

The Carnegie Foundation for the Advancement of Teaching (2009). Garnegie, Gates, Hewlett Foundations Unite to Tackle Roadblocks to Student Success. Retrieved October 1, 2009 from http://www.carnegiefoundation.org/news/sub.asp?key=51&subkey=2945.

The North American Council for Online Learning & the Partnership for 21st Century Skills (2006). *Virtual Schools and 21st Century Skills*. Retrieved on October 8, 2009 from http://www.inacol.org/research/docs/NACOL_21CenturySkills.pdf

The William and Flora Hewlett Foundation (2009). Open Educational Resources. Retrieved on October 1, 2009 from http://www.hewlett.org/oer

Toffler, A. (1990). Power Shift. Knowledge, Wealth, and Violence at the Edge of the 21st Century. New York, NY:Bantam Books.

Trevinarus, J. (1994). Virtual reality technologies and people with disabilities. *Presence: Teleoperators and Virtual Environments, 3*(3), pp.201-207.

Trevinarus, J. (2002). Making yourself at home – Portable personal access preferences. In K. Miesenberger, J. Klaus, & W. Zagler (Eds.), *Proceedings of the 8th International Conference on Computers Helping People with Special Needs* (pp.643-648). London, UK: Springer-Verlag.

Tucker, B. (2009). The Next Generation of Testing. Retrieved on December 10, 2009 from http://www.ascd.org/publications/educational_leadership/nov09/vol67/num03/The_Next_Generation_of_Testing.aspx

UNESCO (2005). *Towards knowledge societies.* Paris: United Nations Educational, Scientific, and Cultural Organization.

U.S. Department of Commerce, U.S. Department of Education, U.S. Department of Labor, National Institute of Literacy, and the Small Business Administration (1999). Report retrieved on October 8, 2009 from http://www.inpathways.net/_ACRNA/21stjobs.pdf

Venezky, R. L., & Davis, C. (2002). "Quo Vademus? The Transformation of Schooling in a Networked World." Version 8c. OECD Centre for Educational Research and Innovation, Paris. http://www.oecd.org/dataoecd/48/20/2073054.pdf

Vosniadou, S., & Brewer, W. F. (1989). The Concept of the Earth's Shape: A Study of Conceptual Change in Childhood. Unpublished paper. Center for the Study of Reading, University of Illinois, Champaign, Illinois.

Vygotsky, L. (1986). Thought and language (A. Kozulin, Trans.). Cambridge, MA: MIT Press. (original English translation published 1962)

Wertime, R. (1979). Students' problems and "courage spans." In J. Lockhead and J. Clements (Eds.), *Cognitive process instruction*. Philadelphia: The Franklin Institute Press.

Wertsch, J. (1998). *Mind as action.* New York: Oxford University Press.

Wiggins, G. P., & McTighe, J. (1997). *Understanding by Design*. Association for Supervision and Curriculum Development, VA.

Wiggins, G. P., & McTighe, J. (2006). Examining the teaching life. *Educational Leadership, 63,* 26-29.

Williams, S.M. (2009). The impact of collaborative, Scaffolded Learning in K-12 Schools: A Meta-Analysis. Report commissioned to The Metiri Group, by Cisco Systems.

Willingham, D. (2008, December 1). Education for the 21st century: Balancing content knowledge with skills. Message posted to http://www.britannica.com/blogs/2008/12/schooling-for-the-21st-century-balancing-content-knowledge-with-skills/

Wilson, E.O. (1999). *Consilience: The Unity of Knowledge*. London: Vintage Books.

Wilson, M., & Scalise, K. (in press). Assessment to improve learning in higher education: The BEAR Assessment System. *Higher Education*.

Wilson, M., & Sloane, K. (2000). From principles to practice: An embedded assessment system. *Applied Measurement in Education*, 13(2), 181-208.

Wiske, M. S. (1998). What is teaching for understanding? In M. S. Wiske (Ed.), *Teaching for understanding : linking research with practice* (pp.61-86). San Francisco, Calif.: Jossey-Bass Publishers.

Zhang, J., Scardamalia, M., Lamon, M., Messina, R., & Reeve, R. (2007). Socio-cognitive dynamics of knowledge building in the work of nine- and ten-year-olds. *Educational Technology Research and Development, 55*(2), 117-145.

Zhang, J., Scardamalia, M., Reeve, R., & Messina, R. (2009). Designs for collective cognitive responsibility in knowledge building communities. *The Journal of the Learning Sciences (18),* 7-44.

Zohgi, C., Mohr, R., & Meyer, P. (2007). *Workplace organization and innovation (Working Paper 405).* Washington, D.C.: Bureau of Labor Statistics.