Transdisciplinary Graduate Education

Sharon J. Derry

University of Wisconsin-Madison

Gerhard Fischer

University of Colorado-Boulder

Draft: September 15, 2006

Comments invited

This paper is based on the symposium, *Socio-technical Design for Lifelong Learning: A Crucial Role for Graduate Education,* presented at the 2005 meeting of the American Educational Research Association, Montreal, Canada

Table of Contents

Abstract

Graduate education is experiencing a period of profound transformation with a strong resurgence of interest in interdisciplinary scholarship. But even as new approaches are being called for and developed, graduate education has been the subject of little systematic research, is not *well-grounded theoretically*, and does not employ the *power of new media* in visionary or effective ways. These problems exist despite development of important applicable theoretical and practical knowledge in interdisciplinary fields such as The Learning Sciences and Cognitive Science. We call for a transformative theoretically-based research agenda for graduate education. The approach we describe is grounded in the following proposition: "*If the world of working and living relies on collaboration, creativity, definition and framing of problems and if it requires dealing with uncertainty, change, and intelligence that is distributed across cultures, disciplines, and tools—then graduate programs should foster transdisciplinary competencies that prepare students for having meaningful and productive lives in such a world.*"

Introduction

Graduate education today is experiencing a period of profound transformation. Phenomena such as the information technology revolution (National-Research-Council, 1999), globalization (Friedman, 2005), increasing trends to outsource high-level cognitive tasks (Aspray, Mayadas, & Vardi, 2006; Levy & Murnane, 2004), and the need to participate effectively in diverse collaborative organizations addressing complex world problems (Brown & Duguid, 2000) are changing graduate populations and their goals. Requirements increase for Ph.D. graduates to enter work environments requiring collaboration with experts from multiple fields, pursue several career paths addressing different problems, and to interact and work with people of diverse backgrounds including those from outside academe (Golde, 2006; Panofsky & Rhoten, 2005; Rhoten, 2005). Such changes create new educational demands: graduate students need to be educated for a diverse, technical, problem-oriented world that does not yet exist, which makes it imperative that they become self-directed, lifelong learners who can thrive and participate in collaborative environments with ever-changing disciplinary boundaries.

In response to such challenges, an active debate on graduate education is now taking place, and a number of national initiatives are promoting graduate program reform (e.g., CID, 2005; CIRTL, 2005; Golde, Walker, & Associates, 2006; e.g., Lorden & Slimowitz, 2003; Nyquist, 2002; Panofsky & Rhoten, 2005; Shulman, Golde, Bueschel, & Garabedian, 2006). Notably, many such efforts are concerned with fostering transdisciplinary[1] scholarship, which is considered essential for addressing complex and pressing social and scientific problems of our time. Such problems must be addressed by organizations, not individuals; creative solutions emerge within socio-technical contexts (Mumford, 1987, 2000), in which there is interaction among people and artifacts (e.g., tools, technologies, designs, represented ideas) that embody knowledge from various constituent communities (National Research Council, 2003). These contexts are often conceptually, socially and technically diverse (e.g., consider the technology-poor school district that joins forces with a technology-rich university research group), as well as physically and temporally dispersed. Orchestrating the intelligence that is distributed throughout

---

[1] Authors variously use the terms *multidisciplinary, interdisciplinary*, and *transdisciplinary* to describe collaborations, often without clearly distinguishing among them. Generally, multidisciplinary is used to describe loose cooperative interaction among scholars of different disciplines, whereas interdisciplinary refers to problem solving in which there is cross-disciplinary learning and intensive blending of ideas from disciplines. Transdisciplinary tends to describe collaborations that transcend specific disciplines to define new knowledge in between and at the borders of disciplines. Transdisciplinary scholarship may transform the disciplinary identities of participants, such as when a psychologist or computer scientist begins to identify with a neuroscience community. Because successful interdisciplinary collaborations are essentially transdisciplinary in nature, we follow the National Research Council (2003) in using the term *transdisciplinary* throughout this paper.

such transdisciplinary organizations in service of the problems they are created to address is a complicated challenge.

Interest in transdisciplinary scholarship is far from new (Klein, 1990), but it is now experiencing a strong resurgence. A striking example is a recent report by top Harvard University professors that offers a critique of Harvard's *"antiquated organizational structure based on powerful, insular fiefdoms"*, and calls for *"changes that would encourage collaborations in emerging fields, push science teaching away from staid lecture formats to more hands-on approaches, and do more to improve science literacy and science education in Greater Boston and the world"* (Cook, 2006). Many graduate schools are currently revitalizing transdisciplinary teaching and hiring, and both government and foundation funding agencies are actively promoting graduate-level transdisciplinary programs (Cummings & Kiesler, 2003; Derry & Schunn, 2005; Panofsky & Rhoten, 2005; Shulman, Golde, Bueschel, & Garabedian, 2006). Yet the problems of bringing different disciplines together have presented major challenges to academic communities for a very long time, as Snow's (1993) classic analysis of academic cultures powerfully argues. Recent research continues to indicate that these challenges are not yet understood, much less mastered (Cummings & Kiesler, 2003; Derry, DuRussel, & O'Donnell, 1998; L. A. DuRussel & S. J. Derry, 1998)

Although several major transdisciplinary graduate initiatives have recently been evaluated (Cummings & Kiesler, 2003; Panofsky & Rhoten, 2005), there is very little theoretical research on which to base design of transdisciplinary learning environments. This is true despite the relevance of a rich world of ideas and theory emerging from transdisciplinary fields -- such as The Learning Sciences, Human-Computer Interaction (HCI), and Computer Support for Collaborative Learning (CSCL) -- at the borders of education, cognitive science, and computer science. What studies exist support the value of transdisciplinary scholarship as having tremendous potential for increasing discovery and innovation, but they also uncover serious communication difficulties and examples of failure that are especially acute when team members are separated by distance, which is typical (Cummings & Kiesler, 2003; DuRussel & Derry, 2005). Such outcomes point to the need for principled knowledge about contemporary transdisciplinary scholarship, considering especially the revolutionary pedagogical and collaborative possibilities that new media afford. There is need for a transformative program of research focused on graduate education that is based on theoretically-grounded models of transdisciplinary teaching and learning, that promotes the use of new media in visionary and effective ways, and that is aimed toward the preparation of citizen-scholars who can effectively work and teach within, as well as help design and manage, 21st century learning communities.

Developing Transdisciplinary Competencies

The basic argument proffered here is captured in the following proposition*:* If the world of working and living relies on collaboration, creativity, definition and framing of complex problems -- and if it requires dealing with uncertainty, change, and intelligence that is distributed across cultures, disciplines, and tools -- then graduate programs should foster transdisciplinary competencies that prepare students for having meaningful and productive lives in such a world.

Transdisciplinary competencies refer to knowledge and skills required to identify, frame and address important scientific and practical problems that cut across disciplinary boundaries. Such problems are complex and ill-defined (Simon, 1996) requiring (a) integration of problem framing and problem solving, (b) communication and collaboration among people from different disciplines and educational levels, and (c) intelligent use of technologies and resources that support collective knowledge construction and extend human problem-solving capability. Although similar in major respects to the 21st century *soft skills* discussed by Collins and Halverson (2006), Bereiter & Scardamelia (2006) and others, we prefer the term *transdisciplinary competencies* in the context of discussing graduate education, to emphasize that these capabilities transcend disciplines; they are important goals for all students in all fields.

Transdisciplinary competencies are increasingly significant and should be developed in graduate schools in addition to and along with in-depth disciplinary knowledge associated with students' major fields of study. Ideally such competencies are nurtured as well at educational levels prior to graduate study. But graduate schools will remain important places to further develop them because, more than any other phase of education, graduate study represents a transition from a world of learning by being taught (an unfortunate but appropriate characterization for most secondary and undergraduate curricula), to a complex socio-technological world in which there is a requirement to guide one's own learning and life's work.

Agreeing with Bereiter and Scardamalia (2006), we propose that the concept *transdisciplinary competencies* requires further analysis and definition with respect to the following: What are they? How are they alike and different from alternative conceptions such as soft skills, multiple intelligences, or habits of mind? How can they be developed and assessed within graduate schools? The discussion that follows is essentially a proposal for how scholars can begin addressing these questions through design-based research in graduate schools. It is a program of research can realistically be implemented by professors teaching within graduate programs, without major institutional reorganization or extraordinary financial incentives, and it has potential immediate payoff for participating graduate students.

The Problem

Experts writing about graduate education inevitably address the problem of finding an appropriate balance between depth and breadth of training. In discussing the case of neuroscience, for example, Hyman (2006) argues that "every successful doctoral trainee must have mastered at least one constituent discipline or approach . . ." (p. 235). However, he continues, "Without adequate strength across a range of neuroscience areas, one might be limited in the choice of problem to study, and one could not be an effective collaborator" (p. 236). Other analysts also consider breadth of training as an essential aspect of graduate study that enables students to collaborate effectively (Berliner, 2006; Metz, 2001). And yet too much breadth could produce investigators "who are conversant in many fields but expert in none" (Z. W. Hall, 2006, p. 212).

Although we essentially agree that a balance between breadth and depth is necessary, our proposal reflects a bias toward designing graduate programs to encourage flourishing of deep individual expertise that is shared with a willingness and ability to collaborate with and learn from others who possess deeply specialized knowledge in different fields of study. In preparing students to live and work in the "knowledge age" (Bereiter, 2002), one cannot predict or learn in graduate school what one may need to know during a lifetime of work (Brown, 2005; Drucker, 1994). Coverage is impossible and obsolescence is guaranteed. Rather than trying to broadly cover too much territory, graduate programs could do a better job of empowering all students to learn on demand, exploiting the powers of collaboration and new media as tools for lifelong learning (Fischer, 2000). This approach stands in contrast to programs encouraging broad ″interdisciplinary mindsets″ (Panofsky & Rhoten, 2005). Our viewpoint is inspired by Campbell’s (1969) classic fish-scale model, a call for academic organizations that aim for “collective comprehensiveness through overlapping patterns of unique narrowness. . . . collective achievement made possible by the overlap of narrow specialties” (p. 348).

If we take seriously the challenge of nurturing this type of scholar, then one thing we must do, in our research laboratories and our courses, is arrange for graduate students' mentored participation in distributed socio-technical communities in which participants with specialized backgrounds work together to frame and address important problems requiring sharing of disciplinary knowledge and resources over significant periods of time. But while there is no dearth of important problems in today's world (Gore, 2006; Haglund & Still, 2005), coalescing collaborative research projects around them for educational purposes is no simple matter.

Deepening problem understanding through transdisciplinary scholarship, while simultaneously fostering ability to participate in future transdisciplinary scholarship, is a complex instructional design problem that has not been studied and that we do not understand. Setting aside for now the logistical challenges of assembling transdisciplinary organizations across academic departments and schools, an important pedagogical issue remains: "We do not in fact learn to participate in every activity just by participating in it" (Lemke, 2002).

The sociocultural perspective (Lave, 1988; Vygotsky, 1963; Wertsch, 1991; Wertsch & Kazan, 2003), that development occurs within supportive communities of practice (Wenger, 1998) in which knowledgeable others provide important guidance that gradually fades as competence develops, generally points the way toward a community-based apprenticeship model for transdisciplinary graduate education. Our own explorations of this pedagogical model have been fruitful in many ways, but these efforts have proved demanding for both students and faculty alike, and we face numerous unresolved tensions and challenges including: (1) Who owns collaborative work? (2) Is it cheating or stealing to appropriate and build on others' work? (Norman, 2005) ; (3) How do students and researchers contribute to a collaborative culture and also meet career demands? (Raymond & Young, 2001); and (4) When does one project stop and another begin? Importantly, these issues are not easily brought forward in an academic culture that rewards individual achievement, in which problems are often "owned" by the senior scholars, and that typically refrains from addressing communication issues openly (DuRussel & Derry, 1998; DuRussel & Derry, 2005).

Studies of learning communities exist in other contexts (Engeström, 2001; Rogoff, Matsuov, & White, 1998; Scardamalia & Bereiter, 1994), but little systematic research and theory are available for designers of graduate learning communities. This situation motivates our proposal to share our own accumulating knowledge and experience and to encourage other faculty to use their own courses, research groups, and programs for theoretical design and study of models for transdisciplinary graduate education. Such design-based research employs limited available theory and systematic observation, including both quantitative and qualitative approaches, to guide evolution of progressively better instructional designs over a series of design versions (e.g., Cobb, Stephan, McClain, & Gravemeijer, 2001; R. Hall, 2001; Halpern, 2003; Lehrer & Schauble, 2004; Roth, 2001). A community-based program of design-based research (DBR; Barab & Kirshner, 2001) on transdisciplinary graduate education should be focused to accomplish the following five goals:

- *Identify a community* of scholars who share interest in theory, research and reform for graduate education.

- Strengthen our *theoretical framework* for advanced transdisciplinary scholarship, providing the basis for research and pedagogical design as well as the conceptual content for transdisciplinary curriculum.
- *Sharpen our concept of transdisciplinary competencies*, including specific ideas for how those competencies can be cultivated and assessed in graduate programs.
- *Design, implement, study, and improve prototypes*, including courses and new forms of communities based on innovative media that illustrate theory-based models for developing transdisciplinary competencies and mindsets.
- *Design, test, and disseminate advanced technologie*s for supporting transdisciplinary collaboration and learning within and across graduate programs.

When such design projects are carefully reported as case studies, comparison of findings over multiple cases can support generalization of findings and the development of stronger theory and programs. However, because it is difficult to compare cases if they do not address similar questions or use similar types of observation instruments, a tension exists between the need for developers and researchers to have creative license versus their need to standardize work across projects so that a portfolio of comparable projects will result. Our proposal is that a community of researchers can address this tension by coalescing their early enterprise around some common theoretical themes.

Dimensions of an Emerging Conceptual Framework

We suggest seven themes as a starting point for discourse and research on transdisciplinary graduate education. We chose them because they are important concepts from interdisciplinary fields concerned with collaborative learning in technology-rich environments, including The Learning Sciences, Human-Computer Interaction (HCI),and Computer Support for Collaborative Learning (CSCL)), and they have proved useful to us as tools for thinking about our own research and teaching. We hypothesize that mastering these ideas, by both graduate students and faculty, will promote more successful transdisciplinary collaborations. Mastery is used in the sense discussed by Wertsch and Kazak (in press): knowing *how* to make use of ideas to inform teaching and work, rather than just knowing about them. The themes are:

- *models of community* (Fischer, 2001), and how shared knowledge and common ground is created to support mutual learning and collaborative problem-solving;
- *distributed intelligence* (Hutchins, 1995; Salomon, Pea, & Brown, 1996), the idea that intelligence is not located in a single mind but is distributed among people and tools that work together and emerges in the process of problem solving;

- *reflection*, cognitive skills that help individuals and communities intelligently monitor, assess, and adapt their work through such processes as "reflection-in-action" and "reflection-on-action" (Schön, 1983).
- *boundary objects* (Star, 1989) entities, such as products, standards or ideas, that serve as communicative interfaces between members of different communities and may help or hinder collaboration;
- *soft leadership* (Hmelo-Silver, Katic, Nagarajan, & Chernobilsky, in press), subtle management skills that are distributed across group members and that emerge to facilitate work and collaboration in successful groups;
- *lifelong learning* (Dohmen, 1996), representing a fundamental reconceptualization in which education becomes an integral part of working and living rather than taking place primarily in schools, and requiring *agency* (Bandura, 2006), the capability to accomplish important goals through individual and joint action; and
- *sociotechnical design* (Mumford, 2000), the evolutionary creation of effective learning and problem-solving environments made possible with new media and having interacting social and technical components.

Next we elaborate each of these themes further, emphasizing their relevance for transdisciplinary education. In a subsequent section we illustrate how we have tried to bring these themes together as a basis for design of courses and other forms of graduate education.

Models of Community.

Scholars convening at a recent NSF workshop on the future of graduate education concluded that *community* is of overarching importance to graduate schools (Lorden & Slimowitz, 2003). If true, then program designs should be informed by the substantial body of research literature on communities. Designers of programs should ask, which extant models of learning communities provide adequate guidance, not only for graduate program design but for helping graduate students understand how to participate in and design learning communities within their later professional and personal lives? Models for effective transdisciplinary graduate education may well exist within the current literature on learning communities, and research is needed to determine this

For example, in our work we have differentiated between *communities of practice,* which are homogeneous and monodisciplinary (Brown & Duguid, 2000; Wenger, 1998) and *communities of interest* (Fischer, 2001), which are heterogeneous and involve multiple disciplines. Other models reviewed by Paavola et al. (2004) include: the Knowledge-Creating Company (Nonaka &

Takeuchi, 1995), Expansive Learning (Engeström, 2001), and Collaborative Knowledge Building (Bereiter, 2002; Scardamalia & Bereiter, 1994). These concepts of learning community are major examples, but there are numerous other conceptualizations (e.g., Freire, 1998; Renninger & Shumar, 2004; Riel & Polin, 2004; e.g., Rogoff, Matsuov, & White, 1998). Such models are derived from different theoretical histories (e.g., activity theory versus distributed cognition), are implemented in different educational contexts (work environments versus schools), and conceptualize the outcomes of learning in different ways (e.g., tacit versus explicit knowledge, new activity structures, or conceptual artifacts). Yet they all have in common a commitment to *collective knowledge creation while developing shared objects of activity*. This common idea, consistent with design-centered models of learning and instruction (Bereiter & Scardamalia, 2006; Fischer, 2002), is possibly an important key for creating effective transdisciplinary learning communities.

Distributed Intelligence.

Work within transdisciplinary communities is distributed across people, tools, places, and times that are separated by distances. A recent evaluation of an NSF-sponsored transdisciplinary initiative raised awareness that physical distance among collaborating team members can substantially reduce their effectiveness (Cummings & Kiesler, 2003). However, orchestrating collaborative intelligence is a more complex problem than this report indicates, for many types of distances must be addressed (Fischer, 2005a). In addition to physical separation among people and tools (Olson & Olson, 2001), collaborative organizations must cope with:

- *conceptual distances* — the different ways of seeing the problem that are inherent in collaborators' prior knowledge and the tools they bring to a collaboration (DuRussel & Derry, 1998; Fischer, 2001; Olson, Malone & Smith, 2001);
- *temporal distances* — the time spaces that occur when a creative product (a design, a problem model, a solution) is built and modified by different user-creators over time (Moran & Carroll, 1996; Thimbleby, Anderson, & Witten, 1990);
- *technological distances* — the disconnections created when some tasks or parts of tasks are reserved for an educated human mind while others are distributed ("outsourced") to external media, tools and technologies (Barab, Kling, & Gray, 2004; Engelbart, 1995; Norman, 1993); and
- *social distances* — the inequities that occur when gender, disciplinary, institutional, minority, or other group membership, make some ideas dominant while others, perhaps

more worthy, are squelched (O'Donnell & Derry, 2005; Schön, Sanyal, & Mitchell, 1999).

We hypothesize that transdisciplinary groups can be more successful if they are able to recognize what distances affect their work and employ strategies and tools for overcoming them. For example, successful groups might employ technology-based strategies (e.g., effective use of discussion boards, Wikis) to bridge physical and temporal distances. A research hypothesis worthwhile to explore is whether scholarship can be significantly improved by deliberately teaching graduate students about overcoming distances in transdisciplinary collaborations.

Reflective Communities

Graduate schools are well positioned to help build a global capacity for orchestrating deeply specialized distributed intelligence by focusing, not on broadly educating individual, unaided minds (the Renaissance scholar envisioned as a human being knowing all important things (Shneiderman, 2002) is an inadequate model for the 21st century), but on deeply educating reflective practitioners (Schön, 1983), who can also become contributing members of reflective communities (Fischer, 2005b). *Reflection* has been a powerful and enduring concept in studies of individual self-regulation. Schön’s (1983) influential work on professional education divided metacognition into “reflection-in-action” and “reflection-on-action."

A question of importance is whether adapting and generalizing these powerful ideas to collaborating groups within graduate schools might help equip broader society with scholar-citizens who are capable of leading and contributing to problem-solving communities that intelligently monitor and control their processes. Research (e.g.,DuRussel & Derry, 2005; e.g.,Radinsky, 2000) suggests that successful groups publicly express reflective behavior related to various aspects of the task at hand (e.g., the data, the communication process, individuals' personal roles), although unsuccessful groups do not. Research is needed to determine if transdisciplinary scholarship would benefit if graduate students were taught to reflect in and on actions (Schön, 1983), in private and shared discourse, and on different aspects of collaborative activity (Radinsky, 2000).

Boundary Objects

Campbell’s fish-scale model suggests that because knowledge is never complete within a single person (scale), an important wholeness derives from overlap across many scales. But what exactly overlaps? And how does knowledge move from scale to scale? Star (2005) emphasizes that knowledge does not travel through the air, that it requires *boundary objects* which serve as interfaces among people representing different disciplinary communities. Boundary objects are entities (such as ideas, standards, products or designs) which can be shared by organizational members and used for communication and negotiation among them, although they may be understood differently by people in different fields and with different educational levels (Star, 1989; Star & Griesemer, 1989; Wertsch & Kazak, in press). Every working organization develops boundary objects. Crafting, using and adapting them as work progresses are activities imbued with politics, disparate viewpoints, and ambiguities, and constituting important transdisciplinary work (Star, 2005).

To foster reflective practitioners, graduate schools should incorporate into their curricula, not only opportunities to participate in transdisciplinary process, but also concepts that provide boundary objects for reflection and discussion of communication across disciplines. A curriculum of such ideas (as illustrated by this article) is itself a boundary-object proposal: what scholars from all fields need to know to successfully engage in transdisciplinary scholarship.

Scholars should be aware of the power of both formal and informal boundary objects. Explicit examples include:

- formal systems of standardization, such as meta-data categories (e.g., the Dublin Core) that have been adopted for standardization of STEM resources on the Internet and have been incorporated into the National Science Digital Libraries;
- informal boundary objects, such as the representations that good teachers develop to help students understand disciplinary concepts, a specialized knowledge of one's discipline known as *pedagogical content knowledge* (Shulman, 1986; , 1987).

We postulate that graduate students should be guided to develop *transdisciplinary content knowledge*, a system of examples, analogies, illustrations and other representational artifacts that can help make major ideas in one's specialty comprehensible to specialists in other fields.

Soft Leadership.

Successful collaborations in socio-technical environments are characterized by emergence of *soft leaders* (Hmelo-Silver, Katic, Nagarajan, & Chernobilsky, in press). Soft leaders encourage others to explain and justify their thinking, help maintain an agenda, assist in monitoring group progress and dynamics, and engage participants in collective knowledge building. Soft leaders carry on a subtle interplay of facilitating a group’s progress and contributing directly to group work. Soft leadership roles are fluid and shared among different group members at different times. Soft leaders do not dominate; they demonstrate humility and sensitivity to fellow group members.

A detailed study of a well-known expert teacher revealed a teaching style that resembled soft leadership (Hmelo-Silver & Barrows, 2006). Research shows that groups can and do appropriate the skills of expert facilitation and take over responsibility for their own group learning (Derry, Hmelo-Silver, Nagarajan, Chernobilsky, & Beitzel, in press). We hypothesize that good graduate teaching for the 21st century is largely about modeling and fostering soft leadership.

Lifelong Learning

A significant weakness of current educational systems is that they do not deliberately educate for lifelong learning. Rather, current systems require that at a certain point in their development, learners in all walks of life leave school in which they were mostly consumers of educational material and throw a "big switch" to become socially competent, responsible, self-directed learners who successfully use tools and technologies to enrich their personal and working lives and who collaborate with one another to solve local and global problems (Illich, 1971). Yet little of their previous educational experiences have prepared them to do any of this.

Graduate schools could help enrich the cultures of work and learning (Gardner, 1991) and the personal lives of learners by cultivating mindsets and skills for lifelong learning (Dohmen, 1996; Fischer, 2000). Students must be prepared, not only to excel in traditional academic settings, but to contribute knowledge and effort to a world increasingly beset with change, uncertainty and pressing transdisciplinary problems and that will require new forms of scholarship, publication, communication and participation.

Lifelong learning requires *personal agency*, defined by Bandura (2006) as the ability and motivation to intentionally influence one's functioning and life circumstances (p. 164). Scardamalia and Bereiter (1991) discussed agency in terms of learners' taking responsibility for their own learning. They emphasized the importance of staging collaborations that support learners in moving forward within their zones of proximal development (ZPD; Vygotsky, 1963) as a key to learners' increasingly taking control of their own learning. Support for learning is strategically faded while challenge is simultaneously strategically increased until learners are fully self-directed.

One may argue that many graduate programs already approximate this process well enough to help most students develop agency; that the forms of agency learners are required to demonstrate in graduate programs are developmentally appropriate and have legitimate relationship to their developing identities as researchers and professionals; that graduate environments expose students to many models of the expertise to which students are supposed to aspire. While we agree with this in part, we believe that academic fields of endeavor must not blindly perpetuate their current organizational cultures, but should deliberately consider what changes are needed in response to larger global concerns. For example: *An Inconvenient Truth* (Gore, 2006), a startling but well-documented book and movie, illustrates that addressing pressing world problems of our day will require *collective* agency, and that academics have very important roles to play. Bandura (2000) described *collective agency* as shared beliefs in the power to make things happen through joint action. Collective agency suggests how graduate schools might foster faculty and students' going beyond academic *interest in* to getting *actively involved in* complex real-world issues, which students cannot hope to influence if working alone.

Socio-technical Design

There is no media-independent communication or interaction: tools, materials, and social arrangements always mediate activity (McLuhan, 1964; Postman, 1985). The processes of thinking, learning, working, and collaborating are all functions of our media (Bruner, 1996). Cognition is shared not only among minds, but among minds and the structured media within which minds interact (Resnick, Levine, & Teasley, 1991; Salomon, 1993). Major advances in the development of the human race and societies have come not from increases in brain size, but rather from the steady accretion of new tools for intellectual work (the major development being the transition from an oral to a literate society (Goody, 1968). As we enter a world of "pervasive computing, with always-on Internet access, reliable quality of service networks, and sufficient levels of technological fluency" (Pea, 2004), we must address how socio-technical design *will* shape 21st century graduate education.

Many current educational uses of technology in graduate schools are restricted to what can be thought of as *gift wrapping* (Fischer, 1998): that is, technology is used as an add-on to traditional practices rather than as a catalyst for fundamentally rethinking what education and learning should and could be (Papert, 1995). But shortcomings of traditional practices—such as lecturing, fixed curriculum, memorization, and decontextualized learning—are not overcome by introducing technology (Goldman & Maxwell, 2002), whether that technology takes the form of intelligent tutoring, multimedia presentations, or distance learning.

Using technology to repackage traditional pedagogies is not sufficient for today's graduate schools (Brown, 2005) Graduate students aspire not only to achieve knowledge and skills, but also to form social networks and become creatively and passionately engaged in current issues (Florida, 2002; Rhoten, 2005). Graduate schools must improve opportunities for students to intelligently align their career interests with important social issues and to deeply explore these issues during graduate study. Within colleges and universities, innovative media and technologies can not only provide emerging scholars with access to organized bodies of information, but also with supports and resources for discussion and social debate, and opportunities for joining existing transdisciplinary communities and for forming new ones organized around common interests in important problems (Bruner, 1996). A theory of communities (Galegher, Kraut, & Egido, 1990; Wenger, 1998) should be incorporated into the computational media designed and maintained by graduate programs.

Further, not only should graduate students learn *with* new media (changing the *how* by learning differently) (Collins, Neville, & Bielaczyc, 2000), they must also learn *about* new media (changing the *what* by learning different things) (National Research Council, 2002). A major aspect of our vision for graduate schools involves *socio-technical design* (Fischer, 2002; Simon, 1996), a model of work that encourages graduate students and faculty to become active shapers of their disciplines and professions as situated within and connected to a larger technological context. Graduate schools are educating tomorrow's leaders for a world that does not yet exist but that is constantly under design. The world emerging is one in which people of all ages and backgrounds participate in a global network of learning communities made possible by new socio-technical environments. Graduate schools produce much of the intellectual talent available to understand, influence and develop this world.

Thus graduate students should be actively involved in creating and evolving socio-technical environments that support their learning and research (Schuler & Namioka, 1993). As recent experiences with successful online professional learning communities illustrate, sociotechnical design in the service of learning is a community effort, not the province of technology experts who impose designs upon users (Renninger & Shumar, 2004). Enabling communities to evolve their own socio-technical environments is the basic idea behind "metadesign" (Fischer, Giaccardi, Ye, Sutcliffe, & Mehandjiev, 2004), an important concept for the future of graduate education.

Transdisciplinary Competencies and Assessment

In light of this discussion, we now briefly summarize our concept of *transdisciplinary competencies*, characterizing them further by providing examples of formative and summative assessment ideas for research and for program and student evaluation.

Community Competencies

These are a collection of abilities and mindsets required for participation in reflective transdisciplinary communities. They include: an understanding of how communities work; awareness of the strengths and limits of one’s own knowledge; strategies for negotiating distances in distributed systems; willingness and ability to reflect on group process; transdisciplinary content knowledge for communication with other disciplines; soft leadership skills; and a belief in the power of groups to accomplish significant work. Student development in this area can be evaluated in various ways, including:

- written assessments in which students' understanding of communities, metacognitive reflection, and other boundary concepts are applied in analyzing cases of success and failure in transdisciplinary collaborations, including personal experiences with such collaborations;
- *in situ* self, peer and faculty evaluations of student participation in transdisciplinary groups;
- questionnaires, interviews, and structured observations designed to gauge students' developing community competencies as revealed through their discourse and attitudes.

Competencies for Self-directed Lifelong Learning

Capabilities and tendencies enabling lifelong learning include critical-thinking skills for analyzing what to learn and how to learn it, for evaluating information and evidence, for monitoring self-directed learning, and for effectively utilizing human and technological resources to support significant self-directed learning (Halpern, 1998, , 2003). Assessment approaches include performance tasks, interviews and structured observations *in situ* designed to evaluate and provide feedback to individual students on their developing abilities to:

- identify important learning issues in varied contexts;
- critically evaluate and integrate appropriate information sources when problem solving;
- learn significant content through unguided research;
- assess their own self-directed learning ability toward the goal of improving it.

Socio-Technical Knowledge

This knowledge represents ability to understand, exploit, and design socio-technical environments, requiring fluency in using digital media for meaningful tasks (Arias, Eden, Fischer, Gorman, & Scharff, 2000; Collins, Neville, & Bielaczyc, 2000). Assessment tasks could include:

- performance evaluation on individual and team projects that require students to develop and use socio-technical environments (e.g., blogs, web portals, games) to communicate, explain, support and disseminate research findings, relating them to important scientific-political-social concerns.

- surveying students to determine whether graduate training has increased frequency and perceived value of socio-technical design and use, and whether perceptions of effort expended to conduct such activities is reduced.

21st Century Teaching

Successful knowledge-age educators will need to embrace "design-centered models of teaching and instruction" (Bereiter & Scardamalia, p.695). Such expertise includes capability to develop, fund, and guide knowledge-building communities as contexts for mentoring students engaged in processes of problem solving and design (dePaula, Fischer, & Ostwald, 2001; Linn, Lewis, Tsuchida, & Songer, 2000; Scardamalia & Bereiter, 1994). Assessment ideas for developing these abilities are:

- opportunities to mentor and to discuss and receive expert (beyond student ratings) feedback on cases of personal teaching and mentoring experiences;
- performance feedback on authentic tasks requiring participatory design in learning environments (for example, a departmental web community that enhances student learning; a new cross-campus online community of interest in a cognitive science topic)
- feedback resulting from scaffolded performance on grant writing and small project management tasks.

Engaged Citizenship

Graduates of professional and academic programs should be willing and able to address real-world issues, to become engaged citizens (Schön, Sanyal, & Mitchell, 1999). Ideas for assessing development of such concerns include:

- explicitly identifying these expectations as goals of graduate programs, followed by both formal (written) and informal (discursive) assessments of understanding of key social/global issues in relation to one's academic specialty.
- opportunities to participate in and obtain feedback on participation in socially important work within transdisciplinary communities that could benefit from the student's specialty.

In our envisioned system of assessment, such competencies intertwine; they cannot be examined, conceptualized, or even discussed in isolation. Thus concern for global issues is demonstrated through documenting skillful involvement in socially important communities of interest; the creation of an innovative learning environment may also demonstrate knowledge of technology and ability to learn on demand. And while some of these assessment forms may currently be in use throughout graduate schools, we propose that they are typically experienced in an ad hoc manner and not by all students. Effectively integrating transdisciplinary performance assessment into graduate education will require new designs that make transdisciplinary opportunities more widely available in a systematic way. We now describe steps that the two authors are engaged in creating examples of ways individual faculty can offer such opportunities to students.

Design Research with Innovative Graduate Courses

Although graduate education encompasses much more than coursework (Brown & Duguid, 2000), the course (especially the graduate seminar) is a strongly entrenched historical and institutional practice that will continue to play a vital role. We describe two innovative, technology-supported courses as concrete examples of our ideas about implementing transdisciplinary graduate education. The goal of research in these courses is perfect a develop a model for education that promotes mindsets and skills for transdisciplinary learning and deep engagement in personally and socially relevant activities (Fischer, 2002).

Design, Learning, and Collaboration.

This course at the University of Colorado-Boulder (CU-Boulder) focuses on creating a new understanding of design, learning, and collaboration as fundamental human activities that interact, and on how to support them with innovative computational media (for examples see: http://l3d.cs.colorado.edu/~gerhard/courses/). It is based on the assumption that design, learning, and collaboration are a function of the media used in these activities. The goals of the course are:

- to engage students in actively exploring technology projects of personal interest in a self-directed way, contributing knowledge derived from their own work;
- to support peer-to-peer learning and the emergence of a community by providing opportunities and rewards for participants to learn from each other in discussions and by working on collaborative course projects;
- to provide opportunities for transdisciplinary collaborations by recruiting for horizontal (e.g., students from different disciplines) and vertical (e.g., undergraduates, graduates, post-docs, professionals) integration;
- to seed the course environment with relevant information and to provide the technical possibilities and social reward structures for all participants to contribute; and
- to explore the unique possibilities that computational media can have in impacting and transforming these activities by transcending “gift-wrapping” and “techno-determinism” in order to create true innovations.

Hands-On Environmentalism.

At an earlier stage of maturity, a credit-generating graduate course and online community entitled *Hands-On Environmentism* is under development at the University of Wisconsin-

Madison by Derry in collaboration with scientist Steve Ackerman and teacher professional development expert Margaret Wilsman. This course, modeled partly on the CU-Boulder effort, will be promoted to masters-level teachers and doctoral students in science who wish to extend their knowledge of Earth Systems Science and explore transdisciplinary collaboration in the context of teamwork with local service agencies (e.g., The Nature Conservancy). Focusing on environmental activism as a theme, the broad goals of the course are to provide students with opportunities to:

- help develop a community organized around a common interest in taking a scientific approach to improving local and regional environmental conditions;
- deepen one's scientific and social knowledge of local/regional environmental issues through project-based collaborative learning that provides access to resources, including scientists and national digital libraries;
- acquire, practice, and receive feedback and assessment designed to foster transdisciplinary competencies as major learning objectives.

Course Characteristics.

Both courses encourage collaborative learning in reflective communities supported by socio-technical environments. In both, the teachers function as guides on the side and meta-designers who seed the courses with materials and structures and then provide opportunities, processes, and media support for evolutionary growth (dePaula, Fischer, & Ostwald, 2001). In both courses, the socio-technical information environment is a central feature. Both courses engage students in interesting, controversial discussions and collaborative design projects that require problem framing and definition.

Our research is evolving a model for transdisciplinary pedagogy called the *courses-as-seeds approach* (CASA) (dePaula, Fischer, & Ostwald, 2001), which aims to create socio-technical environments for collective inquiry, with the goal of developing permanent information repositories that can extend temporal boundaries of semester-based classes. In CASA, the socio-technical environment is designed to support interaction between people and artifacts that they develop and share, embodying the concept of community knowledge building. The design of the learning environment, which is reflectively evolved by the community at large, addresses the need to bridge temporal, conceptual, technological, and social distances of distributed intelligence.

As an alternative to the structuring role of the syllabus in traditional graduate education, CASA is structured by a philosophy of evolutionary learning in which participants deeply explore systematic bodies of knowledge as relevant to their evolving projects, and are supported in developing mindsets for lifelong learning. Socio-technical environments for CASA require more than access to existing information and knowledge (Arias, Eden, Fischer, Gorman, & Scharff, 1999); they require substrates for persistent information spaces capable of growing and evolving according to the course activities, and community- and student-initiated contributions (O'Reilly, 2006). To accomplish this aim we are exploiting available technologies as well as creating new tools, using technological approaches such as dynamic web sites (e.g., DynaSites; Fischer, 2002), Wikis, and online problem-based learning (Derry et al., 2005; Derry, Hmelo-Silver, Nagarajan, Chernobilsky, & Beitzel, in press), which view the web as a collaboration rather than a broadcast medium.

One hypothesis we are exploring is that we can develop design criteria enabling the courses to extend and sustain themselves as productive communities beyond the traditional boundaries of the university. One purpose of building these communities is to actively engage course alumni as field-based resources to better connect graduate coursework to evolving real-world issues and resources. Another purpose is to use graduate courses to stimulate positive social change (Schön, Sanyal, & Mitchell, 1999) by bringing students together with members of a larger community that will leverage university resources to support them in socially important collaborative work of interest. For example, the community grown from the UW-Madison course will support K-12 educators who wish to foster their and their students' deep understanding of Earth Systems Science along with mindsets to engage in community-based problem solving. Such programs have strong potential to expand interest in science beyond traditional groups.

Concluding Comments

In this paper, we raised fundamental research questions facing graduate education today such as: (1) what should students learn? (2) how should students learn? (3) how should we design socio-technical environments for advanced learning? and (4) how are transdisciplinary competencies enacted and how do we help them develop within designed communities? To address these questions, we called for the creation of community supporting a science of transdisciplinary learning in graduate schools — a community that can facilitate data sharing and analysis, construction and dissemination of new knowledge, and integration of research with other ongoing national and international efforts to reform graduate education (CIRTL, 2005; Golde, 2006; Lorden & Slimowitz, 2003; Nyquist, 2002). Only as scholars develop, study and share multiple case studies will we begin to see consistencies across cases as evidence for connections between learning and design decisions, developing generalizable principles for achieving best practices in transdisciplinary graduate education and scholarship.

We argued that reflective transdisciplinary communities supported by socio-technical environments that bring issues and problems and people together with the knowledge represented by diverse fields are a necessity and not a luxury for facing the educational needs of the knowledge age. As Freire observed in describing his learning-community concept of culture circles, "knowledge emerges only through intervention and re-invention, through the restless, impatient, continuing, hopeful inquiry human beings pursue in the world, with the world, and with each other" (Freire, 1970, p. 72). Accepting this, graduate programs themselves must overcome existing institutional boundaries and invent alternative social organizations that will permit the flourishing of transdisciplinary work *in* the world, as well as new socio-technical designs to support this work. For if graduate schools cannot themselves foster successful transdisciplinary communities that work to address important problems, how can they hope to foster lifelong learners, leaders capable of carrying out such work following their graduate education?

Acknowledgements

The authors would like to thank the participants — Ricki Goldman, Sasha Barab, Louis Gomez, and Christian Schunn — in the 2005 AERA Symposium *"Socio-technical Design for Lifelong Learning: A Crucial Role for Graduate Education"* for their contribution to the ideas and models discussed in this paper.

References

Arias, E. G., Eden, H., Fischer, G., Gorman, A., & Scharff, E. (1999). *Beyond access: Informed participation and empowerment*. Paper presented at the Proceedings of the Computer Supported Collaborative Learning (CSCL '99) Conference, Stanford, CA.

Arias, E. G., Eden, H., Fischer, G., Gorman, A., & Scharff, E. (2000). Transcending the individual human mind: Creating shared understanding through collaborative cesign. *ACM Transactions on Computer Human-Interaction, 7*(1), 84-113.

Aspray, W., Mayadas, F., & Vardi, M. Y. (2006). Globalization and Offshoring of Software - A Report of the ACM Job Migration Task Force. from http://www1.acm.org/globalizationreport/

Bandura, A. (2000). Exercise of human agency through collective efficacy. *Current Directions in Psychological Science, 9*, 75-78.

Bandura, A. (2006). Toward a psychology of human agency. *Perspctives on Psychological Science, 1*, 164-180.

Barab, S. A., & Kirshner, D. (2001). Rethinking methodology in the learning siences: Special issue, Journal of the Learning Sciences. *Journal of the Learning Sciences, 10*.

Barab, S. A., Kling, R., & Gray, J. (Eds.). (2004). *Designing virtual communities in the service of learning*. Cambridge, MA: Cambridge University Press.

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

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* (pp. 695-713). Mahwah, NJ: Lawrence Erlbaum Associates.

Berliner, D. C. (2006). Toward a future as rich as our past. In C. M. Golde & G. E. Walker (Eds.), *Envisioning the future of doctoral education: Preparing stewards of the discipline, Carnegie essays on the doctorate* (pp. 268-289). San Francisco: Jossey-Bass.

Brown, J. S. (2005). New learning environments for the 21st century [Electronic Version] from http://www.johnseelybrown.com/newlearning.pdf.

Brown, J. S., & Duguid, P. (2000). *The social life of information*. Boston, MA: Harvard Business School Press.

Bruner, J. (1996). *The Culture of education*. Cambridge, MA: Harvard University Press.

Campbell, D. T. (Ed.). (1969). *Ethnocentrism of disciplines and the fish-scale model of omniscience*. Chicago: Aldine Publishing Company.

CID. (2005). Carnegie Initiative on the Doctorate. from http://www.carnegiefoundation.org/CID/

CIRTL. (2005). Center for the Integration of Research, Teaching, and Learning. from http://cirtl.wceruw.org/

Cobb, P., Stephan, M., McClain, K., & Gravemeijer, K. (2001). Participating in classroom mathematical practices. *The Journal of the Learning Sciences, 10*(1&2), 113-164.

Collins, A., & Halverson, R. (2006). The second educational revolution: From apprenticeship to schooling to lifelong learning (forthcoming).

Collins, A., Neville, P., & Bielaczyc, K. (2000). The role of different media in designing learning environments. *International Journal of Artificial Intelligence in Education, 11*, 144-162.

Cook, G. (2006). Faculty critiques Harvard turf wars: Says university needs new way to study science. *The Boston Globe*.

Cummings, J., & Kiesler, S. (2003). *KDI Initiative: Multidisciplinary scientific collaborations* (No. IIS-9872996): National Science Foundation.

dePaula, R., Fischer, G., & Ostwald, J. (2001). *Courses as seeds: Expectations and realities*. Paper presented at the Proceedings of the second European conference on computer-supported collaboration learning (Euro-CSCL' 2001), Maastricht, Netherlands.

Derry, S. J., DuRussel, L. A., & O'Donnell, A. (1998). Individual and distributed cognitions in interdisciplinary teamwork: A developing case study and emerging thery. *Educational Psychology Review, 10*, 25-57.

Derry, S. J., Hmelo-Silver, C. E., Feltovich, J., Nagarajan, A., Chernobilsky, E., & Halfpap, B. (2005). *Making a mesh of it: A STELLAR approach to teacher professional development*. Paper presented at the Proceedings of Computer Support for Collaborative Learning (CSCL) 2005, Taipei, Taiwan, Mahwah, NJ.

Derry, S. J., Hmelo-Silver, C. E., Nagarajan, A., Chernobilsky, E., & Beitzel, B. (in press). Cognitive transfer revisited: Can we exploit new media to solve old problems on a large scale? *Journal of Educational Computing Research*.

Derry, S. J., & Schunn, C. D. (2005). Introduction to the study of interdisciplinarity: A beautiful but dangerous beast. In *Interdisciplinary collaboration: An emerging cognitive science* (pp. xii - xx). Mahwah, NJ: Lawrence Erlbaum Associates.

Dohmen, G. (1996). *Lifelong Learning - Guidelines for a Modern Educational Policy*: German Federal Ministery of Education and Research.

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

DuRussel, L. A., & Derry, S. J. (1998). *Analogical Reasoning in a Natural Working Group*. Paper presented at the Proceedings: Twentieth Annual Conference of the Cognitive Science Society, Madison, WI.

DuRussel, L. A., & Derry, S. J. (1998). Analogical reasoning in a natural working group. In M. A. Gernsbacher (Ed.), *Proceedings of the Twentieth Annual Conference of the Cognitive Science Society* (pp. 309-314). Madison, WI: Lawrence Erlbaum Associates.

DuRussel, L. A., & Derry, S. J. (2005). Schema (mis)alignment in an interdisciplinary working group. In S. J. Derry, C. D. Schunn & M. A. Gernsbacher (Eds.). Mahwah, NJ: Lawrence Erlbaum Associates.

Engelbart, D. C. (1995). Toward augmenting the human intellect and boosting our collective IQ. *Communications of the ACM, 38*(8), 30-33.

Engeström, Y. (2001). Expansive learning at work: Toward an activity theoretical reconceptualization. *Journal of Education and Work, 14*(1), 133-156.

Fischer, G. (1998). Making learning a part of life--beyond the 'gift wrapping' approach of technology. In P. Alheit & E. Kammler (Eds.), *Lifelong learning and its impact on social and regional development* (pp. 435-462). Bremen, Germany: Donat Verlag.

Fischer, G. (2000). Lifelong learning -- More than training. *Journal of Interactive Learning Research, Special Issue on Intelligent Systems/Tools in Training and Life-Long learning (Eds: Riichiro Mozohuchi and Piet A. M. Kommers), 11*(3/4), 265-294.

Fischer, G. (2001). *Communities of Interest: Learning through the Interaction of Multiple Knowledge Systems*. Paper presented at the 24th Annual Information Systems Research Seminar In Scandinavia (IRIS'24), Ulvik, Norway.

Fischer, G. (2002). Beyond "couch potatoes": From consumers to designers and active contributors, in First Monday (Peer-reviewed Internet journal). *First Monday* December 2. Retrieved July 28, 2004, from http://firstmonday.org/issues/issue7_12/fischer/.

Fischer, G. (2005a). Distances and diversity: Sources for social creativity. In *Proceedings of Creativity and Cognition* (pp. 128-136). London.

Fischer, G. (2005b). *From reflective practitioners to reflective communities*. Paper presented at the Proceedings of HCI International Conference (HCII) (Published on CD), Las Vegas.

Fischer, G., Giaccardi, E., Ye, Y., Sutcliffe, A. G., & Mehandjiev, N. (2004). Meta-design: A manifesto for end-user development. *Communications of the ACM, 47*(9), 33-37.

Florida, R. (2002). *The rise of the creative class and how it's transforming work, leisure, community and everyday life*. New York: Basic Books.

Freire, P. (1970). *Pedagogy of the oppressed*. New York: Continum.

Freire, P. (1998). *Pedagogy of freedom: Ethics, democracy, and civic courage*. Lanham, MD: Rowman & Littlefield Publishers, Inc.

Friedman, T. L. (2005). *The world is flat: A brief history of the twenty-first century*. New York: Farrar, Straus, & Giroux.

Galegher, P., Kraut, R., & Egido, C. (Eds.). (1990). *Intellectual teamwork*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Gardner, H. (1991). *The unschooled mind*. New York: Basic Books.

Golde, C. M. (2006). Preparing stewards of the discipline. In C. M. Golde & G. E. Walker (Eds.), *Envisioning the future of doctoral education: Preparing stewards of the discipline, Carnegie essays on the doctorate*. San Francisco, CA: Jossey-Bass.

Golde, C. M., Walker, G. E., & Associates (Eds.). (2006). *Envisioning the future of doctoral education: Preparing stewards of the discipline, Carnegie essays on the doctorate*. San Francisco: Jossey-Bass.

Goldman, R., & Maxwell, J. (2002). The Comprehensive Handbook of Psychology

Perspectivity Technologies: Computers, The Internet, and New Media for Learning. In W. Reynolds & G. Millar (Eds.): Wiley.

Goody, J. (Ed.). (1968). *Literacy in Traditional Socities*. Cambridge: Cambridge University Press.

Gore, A. (2006). *An inconvenient truth*. New York: Rodale Books.

Haglund, B. M., & Still, T. W. (2005). *Hands-on environmentalism*. San Francisco: Encounter Books.

Hall, R. (2001). Schedules of practical work for the analysis of case studies of learning and development. *The Journal of the Learning Sciences (Special Issues on Design Research), 10*(1&2), 203-222.

Hall, Z. W. (2006). Maintaining vitality through change: Graduate education in neuroscience. In C. M. Golde & G. E. Walker (Eds.), *Envisioning the future of doctoral education: Preparing stewards of the discipline, Carnegie essays on the doctorate* (pp. 211-225). San Francisco: Jossey-Bass.

Halpern, D. L. (1998). Teaching critical thinking for transfer across domains: Dispositions, skills, structure training, and metacognitive monitoring. *American Psychologist, 53*, 449-455.

Halpern, D. L. (2003). *Thought and knowledge: An introduction to critical thinking*. Mahwah, NJ: Lawrence Erlbaum Associates.

Hmelo-Silver, C. E., & Barrows, H. S. (2006). Goals and strategies of a problem-based learning facilitator. *Interdisciplinary journal of problem-based learning, 1*, 21-39.

Hmelo-Silver, C. E., Katic, E., Nagarajan, A., & Chernobilsky, E. (in press). Soft leaders, hard artifacts, and the groups we rarely see: Using video to understand peer learning processes. In R. Goldman, R. D. Pea, B. Barron & S. J. Derry (Eds.), *Video research in the learning sciences*. Mahwah, NJ: Lawrence Erlbaum Associates.

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

Hyman, S. E. (2006). The challenges of multidisciplinarity: Neuroscience and the doctorate. In C. M. Golde & G. E. Walker (Eds.), *Envisioning the future of the doctorate: Preparing stewards of the discipline, Carnegie essays on the doctorate* (pp. 226-243). San Francisco: Jossey-Bass.

Illich, I. (1971). *Deschooling society*. New York: Harper and Row.

Klein, J. T. (1990). *Interdisciplinarity: History, theory and practice*. Detroit, MI: Wayne State University Press.

Lave, J. (1988). *Cognition in practice*. Cambridge, United Kingdom: Cambridge University Press.

Lehrer, R., & Schauble, L. (2004). Modeling natural variation through distribution. *American Educational Research Journal, 41*(3), 635-679.

Lemke, J. L. (2002). Becoming the village: Education across lives. In G. Wells & G. Claxton (Eds.), *Learning for life in the 21st century*. Oxford, UK: Blackwell Publishing.

Levy, F., & Murnane, R. J. (2004). *The new division of labor: How computers are creating the next job market*. Princeton: Princeton University Press.

Linn, M. C., Lewis, C., Tsuchida, I., & Songer, N. (2000). Science lessons and beyond: Why do US and Japanese students diverge in science achievement? *Educational Researcher, 29*(4).

Lorden, J., & Slimowitz, J. (2003). NSF workshop examines the future of graduate education. *CGS Communicator, 36*(5), 3-5.

McLuhan, M. (1964). *Understanding Media: The Extensions of Man*. Cambridge, MA: The MIT Press.

Metz, M. H. (2001). Intellectual border crossing in graduate education: A report from the field. *Educational Researcher, 30*, 12-18.

Moran, T. P., & Carroll, J. M. (Eds.). (1996). *Design rationale: concepts, techniques, and use*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Mumford, E. (1987). Sociotechnical systems design: Evolving theory and practice. In G. Bjerknes, P. Ehn & M. Kyng (Eds.), *Computers and Democracy* (pp. 59-76). Aldershot, England,: Avebury.

Mumford, E. (2000). *Socio-technical design: An unfulfilled promise or a future opportunity*. Paper presented at the Proceedings of the IFIP TC9 WG9.3 International Conference on Home Oriented Informatics and Telematics, If at Home: Virtual influences on everyday life: Information, technology and society.

National-Research-Council. (1999). *Being Fluent with Information Technology*. Washington, DC: National Academy Press.

National Research Council. (2002). *Technically speaking: Why all Americans need to know more about technology*. Washington, D.C.: National Academy Press.

National Research Council. (2003). *Beyond productivity: Information technology, innovation, and creativity*. Washington, DC: National Academy Press.

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: Defending human attributes in the age of the machine*. New York: Addison-Wesley.

Norman, D. A. (2005). In defense of cheating [Electronic Version]. *Ubiquity*, 6. Retrieved Aug 11, 2006 from http://www.acm.org/ubiquity/views/v6i11_norman.html.

Nyquist, J. D. (2002). The Ph.D.: A tapestry of change for the 21st century. *Change*, 13-20.

O'Donnell, A., & Derry, S. J. (2005). Cognitive processes in interdisciplinary groups: Problems and possibilities. In S. J. Derry, C. D. Schunn & M. A. Gernsbacher (Eds.), *Interdisciplinary collaboration: An emerging cognitive science*. Mahwah, NJ: Lawrence Erlbaum Associates.

O'Reilly, T. (2006). What is web 2.0 - Design patterns and business models for the next generation. from http://www.oreillynet.com/pub/a/oreilly/tim/news/2005/09/30/what-is-web.20.html

Olson, G. M., Malone, T. W., & Smith, J. B. (Eds.). (2001). *Coordination Theory and Collaboration Technology*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

Olson, G. M., & Olson, J. S. (2001). Distance matters. In J. M. Carroll (Ed.), *Human-computer interaction in the new millennium* (pp. 397-417). New York: ACM Press.

Paavola, S., Lipponen, L., & Hakkarainen, K. (2004). Models of innovative knowledge communities and three metaphors of learning. *Review of Educational Research, 74*(4), 557-576.

Panofsky, A., & Rhoten, D. (2005, October). Innovative, integrative, interdisciplinary graduate education and training: New concepts for assessment: Second interim report to IGERT program directors. Retrieved May 10, 2006, from http://www.ssrc.org/programs/knowledge/publications/SSRC.ASU.IGERT.StudySecondInterimReport101505.pdf.

Papert, S. (1995). Technology in schools: Local fix or global transformation? , from http://kids.www.media.mit.edu/projects/kids/sp-talk.html

Pea, R. D. (2004). The social and technological dimensions of saffolding and related theoretical concepts for learning, education, and human activity. *The Journal of the Learning Sciences, 13*(3), 423-451.

Postman, N. (1985). *Amusing ourselves to death--Public discourse in the age of show business*. New York: Penguin Books.

Radinsky, J. (2000). *A framework for studying students' development of reflective inquiry dispositions*. Unpublished Doctoral dissertation, Chicago, IL.

Raymond, E. S., & Young, B. (2001). *The cathedral and the bazaar: Musings on Linux and open source by an accidental revolutionary*. Sebastopol, CA: O'Reilly & Associates.

Renninger, K. A., & Shumar, W. (2004). The Centrality of culture and community to participant learning at and with The Math Forum. In S. A. Barab, R. Kling & J. H. Gray (Eds.), *Designing for vitrual communities in the service of learning* (pp. 181-209). Cambridge, UK: Cambridge University Press.

Resnick, L. B., Levine, J. M., & Teasley, S. D. (Eds.). (1991). *Perspectives on Socially Shared Cognition*. Washington, DC: American Psychological Association.

Rhoten, D. (2005). Mind the gap. *Inside Higher Education* Retrieved June 9, 2006, from http://insidehighered.com/workplace/2005/04/04/rhoten.

Riel, M., & Polin, L. (2004). Online learning communities: Common ground and critical differences in designing technical environments. In S. A. Barab, R. Kling & J. H. Gray (Eds.), *Designing for virtual communities in the service of learning*. Cambridge, UK: Cambridge University Press.

Rogoff, B., Matsuov, E., & White, C. (1998). Models of teaching and learning: Participation in a community of learners. In D. R. Olsen & N. Torrance (Eds.), *The handbook of education and human development--New models of learning, teaching and schooling* (pp. 388-414). Oxford: Blackwell Publishing.

Roth, W.-M. (2001). Situating cogition. *The Journal of the Learning Sciences, 10*(1&2).

Salomon, G. (Ed.). (1993). *Distributed Cognitions: Psychological and Educational Considerations*. Cambridge, United Kingdom: Cambridge University Press.

Salomon, G., Pea, R., & Brown, J. S. (Eds.). (1996). *Distributed cognitions: Psychological and educational considerations*. New York: Cambridge University Press.

Scardamalia, M., & Bereiter, C. (1991). Higher levels of agency for children in knowledge-building: a challenge for the design of new knowledge media. *Journal of the Learning Sciences, 1*(1), 37-68.

Scardamalia, M., & Bereiter, C. (1994). Computer support for knowledge-building communities. *The Journal of the Learning Sciences, 3*(3), 265-283.

Schön, D. A. (1983). *The reflective practitioner: How professionals think in action*. New York: Basic Books.

Schön, D. A., Sanyal, B., & Mitchell, W. J. (1999). *High technology and low-incoming communities*. Cambridge, MA: The MIT Press.

Schuler, D., & Namioka, A. (Eds.). (1993). *Participatory Design: Principles and Practices*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Shneiderman, B. (2002). *Leonardo's laptop — Human needs and the new computing technologies*. Cambridge, MA: The MIT Press.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Education Leadership, 15*(2), 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1-22.

Shulman, L. S., Golde, C. M., Bueschel, A. C., & Garabedian, K. J. (2006). Reclaiming education's doctorates: A critique and a proposal. *Educational Researcher*, 25-32.

Simon, H. A. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, MA: The MIT Press.

Snow, C. P. (1993). *The two cultures*. Cambridge, United Kingdom: Cambridge University Press.

Star, S. L. (1989). The structure of the ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. In L. Gasser & M. N. Huhns (Eds.), *Distributed Artificial Intelligence* (Vol. II, pp. 37-54). San Mateo, CA: Morgan Kaufmann Publishers, Inc.

Star, S. L. (2005). Categories and cognition: Material and conceptual aspects of large-scale category systems. In S. J. Derry, C. D. Schunn & M. A. Gernsbacher (Eds.), *Interdisciplinary collaboration--An emerging cognitive science* (pp. 167-186). Mahwah, NJ: Lawrence Erlbaum Associates.

Star, S. L., & Griesemer, J. R. (1989). Institutional ecology, 'translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science 19*, 387-420.

Thimbleby, H., Anderson, S., & Witten, I. H. (1990). Reflexive CSCW: Supporting long-term personal work. *Interacting with Computers, 2*(3), 330-336.

Vygotsky, L. (1963). *Thought and language (Translation of the Russian original, published 1934)*. Cambridge, MA: The MIT Press.

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

Wertsch, J. V. (1991). *Voices of the mind*. Cambridge, MA: Harvard University Press.

Wertsch, J. V., & Kazak, S. (in press). Saying more than you know in instructional settings. In T. D. Koschmann (Ed.), *Theorizing learning practice*. Mahwah, NJ: Erlbaum.

Wertsch, J. V., & Kazan, S. (2003, November). *Saying more than you know in istructional settings*. Paper presented at the Coupling Theories of Learning and Research on Practice Workshop, Timothy D. Koschmann, Organizer, Champaign-Urbana, IL.