Toward a Model and Theory for Transdisciplinary Graduate Education

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Sharon J. Derry, University of Wisconsin-Madison

Gerhard Fischer, University of Colorado-Boulder

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Abstract

Science, technology, engineering, and mathematics (STEM) graduate education is experiencing a period of profound transformation. Phenomena such as the information technology revolution, globalization, expectations of universal digital fluency, the outsourcing of cognitive tasks, and the need to participate effectively in diverse collaborative organizations are changing graduate populations and creating new educational demands. Many innovative graduate programs and practices have been developed over the past 10 years: it is no longer true that graduate education is always degree-oriented or that it transpires only in traditional settings by traditional means within traditional time frames. However, graduate education has been the subject of little systematic research. The studies that do exist tend not to be *well-grounded theoretically* or to employ the *power of new media* in visionary or effective ways.

The goal of our research is to strengthen theoretical and empirical foundations for STEM graduate education while addressing the following questions: What and how should graduate students learn in order **to be educated citizens** and **to find and do interesting and important work** in the 21st century? We are exploring these questions from a lifelong learning perspective, beginning with 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.*

We are pursuing a *transformative design agenda*, using our own courses and research labs as test beds for the scientific design and study of new theory-based models of practice for transdisciplinary graduate study. Our research focuses on the co-evolutionary interdependence of theory building and design as we investigate four interrelated themes: (a) *distributed intelligence*; (b) *reflective communities*; (c) *lifelong learning*; and (d) *innovative media.*

Grounded in this evolving theoretical framework, we are attempting to (a) define *core transdisciplinary competencies and mindsets* for graduate study; (b) design new *sociotechnical learning environments* for cultivating those competencies and mindsets; (c) study *learning within these environments* and perfect their design; (d) seed *communities* (e.g., among graduate students and alumni; among researchers of graduate reform and organizations that employ graduate students), involving them in our work and helping to ensure its scalability and sustainability.

1. Introduction

The goal of the research described here is to explore new foundations for science, technology, engineering, and mathematics (STEM) graduate education in the 21st century, beginning with the following proposition derived from a lifelong learning perspective:

> *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 and mindsets*** *that prepare students for having meaningful and productive lives in such a world.*

Our focus on *transdisciplinary competencies and mindsets* addresses abilities and attitudes required for successful lifelong and transdisciplinary learning that we believe are important for all students in all disciplines and that should be acquired *in addition to and along with* in-depth knowledge in particular specialties. We use the term *transdisciplinary* (National-Research-Council, 2003) instead of *interdisciplinary* to emphasize that interdisciplinary collaboration may create new knowledge domains outside or in between disciplines and in the process fundamentally transform the disciplinary identities of the collaborating researchers.

Using our own courses and programs as contexts, we are pursuing a *transformative design agenda*, iteratively designing, implementing, and studying *new prototype models of practice*. This work, still in early stages, addresses fundamental research questions facing graduate education today, as identified in a recent NSF workshop (Lorden & Slimowitz, 2003):

- ***What should students learn?*** — We specifically target *knowledge and problems that cut across disciplinary boundaries,* including:
  a) complex and ill-defined real-world problems for which answers are not known and that require simultaneous problem framing and problem solving; and
  b) abilities and habits for productive lifelong learning through problem solving within sociotechnical communities;
- ***How should students learn?*** — We believe graduate study should include *scaffolded participation in reflective transdisciplinary learning communities* that engage in socially-important problem solving and that require, develop, and assess transdisciplinary competencies and mindsets.
- ***How should we design new sociotechnical environments for advanced learning?*** — Within our own courses and communities, we are investigating innovative sociotechnical systems for

supporting transdisciplinary learning through *scaffolded social discourse and collaborative design.*

- ***What are the fundamental roles for communities in graduate education?*** — We are attempting to create and study learning and work within homogeneous communities of practice and heterogeneous communities of interest that bring together graduate students, faculty, and alumni, as well as researchers interested in transformative design agendas for graduate education.

We focus our research primarily on the following *graduate fields* (based on the expertise of the PIs and the importance of these fields for STEM graduate education): computer science, cognitive science (broadly defined to include the field of study referred to as the learning sciences), and STEM teacher education (including teaching improvement for STEM college faculty). However, the frameworks and principles evolving through this work are broadly applicable to other fields, including social sciences and humanities, and we both draw from and contribute to a broader learning-science research base relevant to the entire lifelong learning continuum.

2. Problems and Challenges

STEM graduate education is experiencing a period of profound transformation. Phenomena such as the information technology revolution, globalization, expectations of universal digital fluency (National-Research-Council, 1999), the outsourcing of cognitive tasks (Levy & Murnane, 2004), and the need to participate effectively in diverse collaborative organizations (Brown & Duguid, 2000) are changing graduate populations and creating new educational demands. Today's graduate students need to be educated for a world that does not yet exist and that will continue to change throughout their lives. This makes it imperative that they become self-directed, lifelong learners.

In response to these challenges, many university professors are exploring pedagogical innovations (Lorden & Slimowitz, 2003), and there are currently several notable national initiatives in STEM graduate education reform (CID, 2005; CIRTL, 2005). However, little systematic research has been conducted on these initiatives (Lorden & Slimowitz, 2003). To support current innovations, there is a need for research on STEM graduate education that is *well-grounded theoretically* and that employs *the power of new media* in visionary and effective ways. Our research is attempting to address this need.

Our paper will describe five core research activities that we are currently undertaking:

1. Defining a *theoretical framework* leading to a model for transdisciplinary graduate education.
2. Based on this framework and drawing from a broad research community, developing a set of *transdisciplinary competencies and mindsets*, including specific ideas for how those competencies can be cultivated and assessed.
3. *Developing and studying prototype graduate courses*, viewed *as sociotechnical communities,* that illustrate theory-based practices designed to help students develop transdisciplinary competencies and mindsets. These environments provide contexts for *design experiments* that will help further develop theory and refine these new models for graduate study.
4. Building on previous work, *adapting and improving technologie*s for supporting learning and collaborative design within sociotechnical learning environments for graduate study.
5. *Seeding and exploring the value of communities in graduate education,* including communities of practice and interest that will connect undergraduates, graduates students, and alumni, and *communities of researchers* who share our interest in STEM graduate education reform.

3. Toward a Model for Transdisciplinary Graduate Education

Our theoretical work examines five challenges for transdisciplinary graduate study: (a) orchestrating distributed intelligence, (b) building capacity for reflective community, (c) educating lifelong learners who are knowledge builders, not just knowledge users (Paavola, Lipponen, & Hakkaraininen, 2004) and (e) developing appropriate and innovative roles for new media in sociotechnical design (Abell, 1996). We reflect on each of these challenges below.

3.1. Orchestrating distributed intelligence

Most significant real-world problems are framed and solved by multicultural and transdisciplinary communities and organizations rather than by individuals. Human creativity emerges from activities that take place in contexts in which there is interaction among people and artifacts (e.g., tools, technologies, designs, represented ideas) that embody knowledge from various constituent communities (Bennis & Biederman, 1997; Csikszentmihalyi, 1996; Engeström, 2001). Hence *goals* for graduate education must include preparing citizens and professionals to live and work productively in a world in which intelligence is *distributed* across networks of human and artifacts (Hollan, Hutchins, & Kirsch, 2001; Hutchins, 1994; Salomon, 1993).

If we are to take the challenge of orchestrating distributed intelligence seriously, then one thing we must do, in our research laboratories and our courses, is engage graduate students in transdisciplinary sociotechnical communities in which participants with varied backgrounds tackle complex problems that require sharing of knowledge and resources. Toward this end, throughout the past decade we have explored teaching, learning and working as distributed intelligence in the context of complex design problems in tool-rich environments. *Examples from Fischer's work include* fostering lifelong learning (Fischer, 2000b), engaging people in social creativity and transdisciplinary collaboration (Fischer, 2000a), and educating active learners (Fischer, 2002). *Examples from Derry's work include* online courses for teachers as designers (Derry, 2005; Derry & Hmelo-Silver, 2005; Derry et al., 2005) and studying interdisciplinary teams redesigning education (DuRussell & Derry., 2005). These efforts have repeatedly shown that bringing different and often conflicting viewpoints, methods and tools together to create a shared transdisciplinary understanding in the context of design — and especially to use such opportunities as a way of helping graduate students acquire transdisciplinary competencies and mindsets as they bring knowledge of their specialties to bear on complex problems — is an extremely challenging enterprise. "We do not in fact learn to participate in every activity just by participating in it" (Lemke, 2002, p. 37). Learning through collaborative work while learning to *do* collaborative work is a complex design problem involving the orchestration, scaffolding, and management of distributed intelligence (Cummings & Kiesler, 2003; Derry, Schunn, & Gernsbacher, 2005).

Our framing of this problem views distributed intelligence as a complex entity with multiple interacting dimensions (Fischer, 2004) that must be managed including:

- *knowledge distribution* — the availability and orchestration of tools and ideas from different disciplines (DuRussel & Derry, 1998; Fischer, 2001; Olson, Malone, & Smith, 2001).
- *spatial distribution*, when there is physical distance between interacting agents (Olson & Olson, 2001);
- *temporal distribution*, as when an open-source system or other artifact is repeatedly modified by different user-creators over time (Fischer et al., 1992; Moran & Carroll, 1996; Thimbleby, Anderson, & Witten, 1990).
- *technological distribution* (Barab, 2004; Engelbart, 1995; Norman, 1993), involving understanding which tasks (or parts of tasks) and other knowledge forms are better reserved for an educated human mind and which should be taken over or aided by media, tools, and technologies (Landauer, 1988).

Distributed intelligence also has a critical social dimension. Theorists writing about interdisciplinary learning and collaboration have long recognized that achievement of excellence requires ideational collisions brought about by controversy and debate (e.g. Flower, 2000; Graff, 2003; Wells & Claxton, 2002). Rival ideas are essential for knowledge growth, but taking advantage of them requires norms and communication practices that invite openness and lead to analysis and integration. Yet people working together often do not address communication processes openly, and they may remain unaware when communication processes are deficient (e.g., DuRussel & Derry, 2005). Status characteristics associated with gender, disciplinary and institutional affiliation, and minority group membership work to make some ideas dominant while others, perhaps more worthy, are squelched (O'Donnell & Derry, 2005). Working and learning across time, space, people and tools, especially when different disciplines are involved, requires a community-wide social intelligence that is often not present in working groups (e.g., Derry, Schuun, & Gernsbacher, 2005).

3.2. Building capacity for reflective communities

We propose that graduate schools help build a global capacity for orchestrating distributed intelligence by focusing, not on 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 educating *reflective practitioners* (Schön, 1983; Schön, 1987) who are expected to become members of *reflective communities* (Fischer, 2005). Our goal is to achieve social environments that will permit a flourishing of *deep* individual expertise that is shared with willingness and ability to collaborate across disciplines.

Our thinking about this issue is strongly influenced by Campbell's (1969) *fish-scale model*, which aims to achieve *"collective comprehensiveness through overlapping patterns of unique narrowness. . . . collective achievement made possible by the overlap of narrow specialties"* (p. 348). Figure 1 illustrates this concept applied to transdisciplinary learning. In the example, a team of STEM teachers and graduate students are designing learning environments. Some are experts in software development; others have deep knowledge in other STEM domains. Rather than regard these specialists as representing exclusive groups, placing one discipline in service to another, the goal is that students reach mutual understandings through working together that go beyond those of any contributing discipline (see Model 4 in Figure 1).

The capability to transfer methods and knowledge from one discipline to another is currently limited; yet developing this capability is a necessary condition for pushing the boundaries of students' thinking and better preparing them for life and work. Mutual learning and the ability to join problem framing with problem solving in a cooperative transdisciplinary environment are crucial to understanding today's intricate societal problems. By empowering and scaffolding transdisciplinary work in graduate schools, we aim to help future STEM professionals develop competencies and mindsets that will enable them to team up in the working world to find more adequate solutions to complex problems.

But exactly what competencies and mindsets will bring disciplines together? Three at the top of our list are: (a) knowledge about boundary objects; (b) knowledge about communities; and (c) metacognitive skills that foster reflective community.

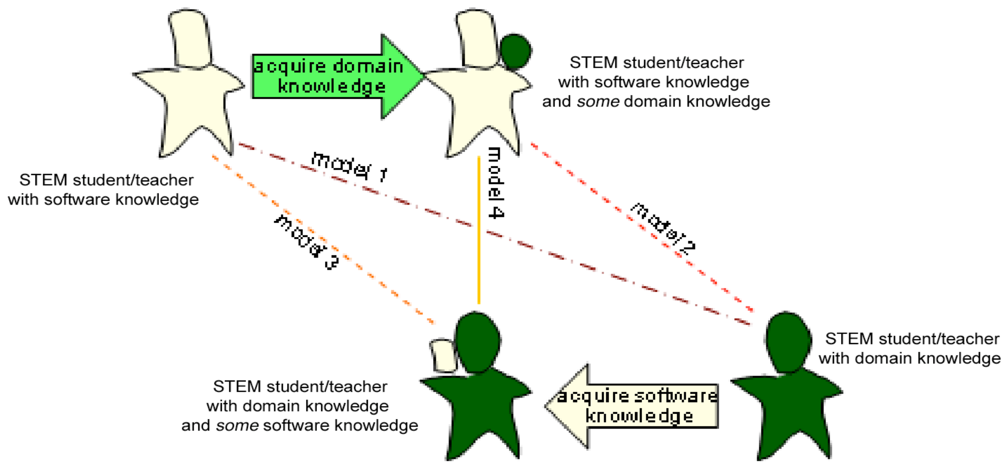

***Figure 1*. A Model for Transdisciplinary Collaboration.**

Knowledge of Boundary Objects. Campbell's model suggests that knowledge is never complete within a single fishscale (an individual mind), but that an important robustness 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 hosts — researchers, students, journals, bureaucracy. Her unique work has examined an important part of the multifaceted apparatus that mediates the connecting of ideas across people and disciplines: categories and standards. Every organization and group (every building, journal, network and or other infrastructure underlying disciplinary and interdisciplinary communication) develops a myriad of categories and standards. She points out that crafting, using and adapting such standards and category systems is always imbued with politics and disparate viewpoints and ambiguities, and that it constitutes an important form of transdisciplinary work.

Transdisciplinary education should include inquiry into the nature of categorical infrastructures, the systems of both formal and informal standardization which are used in work across disciplines. For example, there are important meta-data categories (e.g., the Dublin Core) that have been adopted for integration and standardization of STEM resources on the Internet, such as those incorporated into the National Digital Science Library. Such standards become important *boundary objects* (e.g., Star, 2005) for scientific work that can both impede and facilitate transdisciplinary understanding.

Knowledge about communities. Scholars convening at a recent NSF workshop on the future of graduate education concluded that *community* is of overarching importance for the future of graduate education (Lorden & Slimowitz, 2003). We ask, however: (a) which categories of community provide good models for educational design in which contexts? and (b) what essential features of these categories promote desired transdisciplinary outcomes? For example, Paavola et al.(2004) compare three models for knowledge creation communities: The Knowledge-Creating Company (Nonaka & Takeuchi, 1995), the Model of Expansive Learning (Engeström, 2001), and Bereiter's (2002) model of knowledge building. While these models are derived from different theoretical histories (activity versus participation metaphors), are implemented in different educational contexts (work environments versus schools), and conceptualize the outcomes learning in different terms (tacit and explicit knowledge, new activity structures, or conceptual artifacts), they all have in common a commitment to *collective knowledge creation while developing shared objects of activity*. This common essence helps define an important core model for transdisciplinary scholarship, although we have found it useful to further differentiate this concept into *communities of practice* (being homogeneous) and *communities of interest* (being heterogeneous) (Brown & Duguid, 1991; Fischer, 2001; Wenger, 1998). Such evolving research-based concepts of community provide key discussion points for a discourse on a rethinking of graduate education, and should also become key elements of discourse within a transdisciplinary curriculum in virtually all graduate schools.

Metacognitive skills supporting reflective community. Reflection is a primary form of *metacognition* strongly associated with ability to learn (Brown, 1980). Characterized in Flavell's classic *American Psychologist* article as *thinking about and monitoring thinking* (Flavell, 1979), *metacognition* has been a powerful and enduring concept in studies of individual self-regulation during a period when a cognitive science of the individual mind has been the dominant paradigm. Schön's (1983) influential work on professional education divided metacognition into "reflection-in-action" and "reflection-on-action. A question that interests us now is how to broaden and adapt these powerful ideas to better fit the goal of achieving reflective communities that can intelligently monitor and control their own processes.

Radinsky (2000) suggested one interesting model in which there are three contexts for reflection by members of collaborating groups: data, task, and role. Reflections in the data context focus on representations of what students are figuring out, involving domain concepts and models, sets of data, and real-world items which data represent. Reflections on the task address the functioning of the system of activity by which the work is being accomplished. Reflections on role are meta-cognitions about students' modes of participation in work and inquiry. Presumably, all three modes of reflection should be observable in well-functioning communities. Radinsky aligned his model of reflection with the pedagogical theory of Dewey (1933), noting that "Dewey placed reflection at the center of his model of teaching and learning" (p.10). Reflectiveness is not seen as a momentary phenomenon, but rather as dispositional and enduring characteristics of individuals that can develop during participation in activities.

In our view, a major goal of transdisciplinary graduate education should be to help students develop these dispositions and characteristics that, if exhibited collectively by many participants, would support emergence of adaptive intelligence within learning communities. Designers and facilitators of reflective communities must learn to scaffold and teach these metacognitive skills, and researchers must further develop and refine their models to fit new contexts of reflection associated with collaborative learning and work in sociotechnical communities.

3.3. Lifelong learning and design

Lifelong learning blends and balances formal "scholastic" learning that occurs in schools with the task-related social learning that enables productive and successful participation in a global workforce, and the informal learning of everyday practical and leisure activity. Graduate programs that cultivate mindsets and skills for lifelong learning (Dohmen, 1996; Fischer, 2000) will enrich the cultures of work and education (Gardner, 1991) and the personal lives of learners. 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 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. Yet little of their previous educational experiences have prepared them to do any of this.

Mindsets and skills for lifelong learning prepare students for a world increasingly beset with change and uncertainty. One cannot predict or learn in graduate school what one will need to know during a lifetime of work. Coverage is impossible; obsolescence guaranteed. Hence graduate programs must empower students to learn on demand *throughout their lives*, exploiting the emerging powers of collaboration and new media of the knowledge age (Snow, 1993). That students may come to graduate school with mindsets resistant to this view is illustrated by this student comment from a questionnaire recently administered in one of our courses: "I will continue to reinforce my strengths by continuing to study in the method that I have developed over the past 15 years."

Central to our vision of lifelong learning is the concept of design activity, a model of work that encourages a high level of creative professional engagement (e.g., viewing teachers as designers, not just curriculum implementers). *Work as design* is open-ended and long-term in nature, incorporates personalized and collaborative aspects, and combines technical and aesthetic elements. The relationship between lifelong learning and design is the central research theme of the Center for Lifelong Learning and Design at CU-Boulder.

Design. We are educating today's leaders for a world that does not yet exist but that is constantly under design. A world is emerging in which people of all ages and backgrounds participate in a global network of socio-technical learning communities made possible by new media. A vision that seemed Utopian only a few years ago is today easy to imagine. We observe its coming, in various stages and forms and venues, in non-profit Internet forums, newsgroups, and learning communities, and in diverse and profitable enterprises such as massively multi-player video games, online courses, and a huge array of consumer services (AARP, Match.com, Amazon.com, etc.). This socio-technical world employs "old media" such as print and radio, and "new media" such as Internet technology and cell phones, to cut across socioeconomic and international lines. And while access is a continuing issue, there are many "ways in," so public participation is rapidly increasing.

Graduate schools should and can play a significant role in helping us understand this rapidly advancing and complex socio-technical future, including its power for reshaping the face of education, both locally and globally, both positively and negatively. In particular, graduate schools should play major roles in helping conceptualize, design, and lead this future. They are potentially our best source of relatively unbiased knowledge about socio-technical phenomena, our best hope of understanding it technically, socially, artistically, morally, and psychologically. Importantly, graduate schools produce much of the intellectual and technical talent that is available to guide and manage development of new and evolving socio-technical systems. To the extent that graduate schools are largely driven by the search for knowledge and social problem solving and remain relatively detached from profit motives, they are well positioned to encourage good socio-technical solutions for education and training, solutions that represent creative and thoughtful designs — technically sound, scientifically valid, and socially and morally responsible.

3.4. Designing Sociotechnical Environments Exploiting Innovative Media

There is no media-independent communication or interaction: tools, materials, and social arrangements always mediate activity (McLuhan, 1964). The processes of thinking, learning, working, and collaborating are 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 human 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 envision graduate education for a world of "omnipotent and omniscient technology" (Landauer, 1988) and "pervasive computing, with always-on Internet access, reliable quality of service networks, and sufficient levels of technological fluency" (Pea, 2004), we are facing new opportunities and new educational needs.

Many current educational uses of technology are restricted to what can be thought of as *gift wrapping* (Fischer, 1997): that is, technology is used as an add-on to existing practices rather than as a catalyst for fundamentally rethinking what education and learning should and could be (Papert, 1995). Traditional frameworks—such as instructionism, fixed curriculum, memorization, and decontextualized learning—are *not* changed by technology alone (Goldman & Maxwell, 2002). This is true whether we use computer-based training, intelligent tutoring systems, multimedia presentations, or distance learning.

Gift-wrapping of traditional approaches is not good enough (Tsichritzis, 1999); students need to practice the cognitive, interactional, social, and technical skills necessary for self-directed, lifelong learning in the 21st century. The objectives associated with our agenda are the design, development, and assessment of *sociotechnical environments* that will support and sustain distributed intelligence, transdisciplinary collaboration, lifelong learning, and reflective communities of learners. Hence a *theory of communities* (Galegher, Kraut, & Egido, 1990; Wenger, 1998) must be incorporated into computational media. Media and technologies for learning must not only deliver predigested information to individuals, but also provide supports and resources for discussion, social debate and collaborative design (Bruner, 1996).

Our approach supports graduate students in learning *with* new media (changing the *how* by learning differently) (Collins, Neville, & Bielaczyc, 2000), as well as learning *about* new media (changing the *what* by learning different things) (National-Research-Council, 2002). In addition, we *actively involve* graduate students in creating and evolving sociotechnical environments in which they learn, using a process of participatory design (Schuler & Namioka, 1993).

Specifically, we are developing a *courses-as-seeds* model (dePaula, Fischer, & Ostwald, 2001), which aims to create sociotechnical environments for collective inquiry, with the goal of developing permanent information repositories that can extend temporal boundaries of semester-based classes. The sociotechnical environment supports interaction among people and between people and artifacts that they develop and share, embodies the concept of community knowledge building, and addresses spatial, temporal, conceptual, and technological dimensions of distributed intelligence. As an alternative to the structuring role of the syllabus in traditional STEM education, the courses-as-seeds model is structured by a *framework for evolutionary learning* in which learners construct knowledge as relevant to tasks at hand.

Within this model, students are provided with educational opportunities and scaffolding to be *reflective practitioners* (Schön, 1987) and to form and participate in *reflective communities* (see section and Figure 1). They exploit different knowledge backgrounds and education levels through the process of creating and sharing artifacts (e.g., designs, documents, etc.). Collaborating around evolving artifacts promotes horizontal and vertical participation (section 5). Participants learn from each other; teachers function as guides on the side who seed discussions, create opportunities for knowledge construction, and provide the innovative media necessary to support evolution of the course over time.

Sociotechnical environments based on the courses-as-seeds model provide access not only to existing information and knowledge (Arias, Eden, Fischer, Gorman, & Scharff, 1999), but also to a persistent information space capable of growing and evolving according to the course activities and student-initiated contributions. This *seeding, evolutionary growth, reseeding* (SER) process model (Fischer & Ostwald, 2002), which will be further developed and tested in this project, supports periods of unplanned and creative evolution of the information space alternating with planned and coordinated activities of seeding and reseeding. In addition to needing an information-space system for supporting this model, we need systems to scaffold individual and community knowledge-building processes while distributing the work of learning and teaching across students, faculty and technology (technological distribution) and across university locations (spatial distribution). We also need environments to support conceptually distributed collaboration and the structure of transdisciplinary learning (Figure 1). Toward these ends, we have engaged in a substantial amount of development work over the past decade. These developments include sociotechnical environments for:

- *critiquing* (Fischer, Nakakoji, Ostwald, Stahl, & Sumner, 1998);
- *prompting* (Carmien et al., 2005);
- *online problem-based learning* (Derry & Hmelo-Silver, 2005); and
- *collaborative design* (Arias, Eden, Fischer, Gorman, & Scharff, 2000; Eden, 2002).

In sum, our prior work provides a foundation of previously tested technologies and social organizations that we are bringing to bear on the problem of designing transdisciplinary knowledge-building communities for graduate education..

4. Transdisciplinary Competencies and Assessments

Following from our *theoretical perspective,* but also informed by our *design experiments* (described next) and the thinking of others engaged in related work (CID, 2005; CIRTL, 2005; Nyquist, 2002), we are conceptualizing a set of *transdisciplinary competencies* for graduate students in our target settings, for which we are developing *local* (for use in our courses) and *distal* (for use in program evaluation studies beyond our project) frameworks, procedures, and instruments for formative and summative assessment. In brief overview, the general categories of transdisciplinary competencies that we have targeted and a few ideas for assessment approaches are given here.

- The ability to participate productively in *reflective, transdisciplinary communities*, based on a deep understanding of the nature of communities, effective communication and metacognitive skills, as well as mindsets for engaging in transdisciplinary work and study (Arias et al., 1999; Schön, 1987). We plan to assess this with written assessments of knowledge and thinking about communities, including case studies of personal experiences within communities; *in situ* self, peer and faculty evaluations of student participation in transdisciplinary community activities; questionnaires, interviews, observation protocols, and essays designed to provide faculty with in-depth understanding of students' developing mindsets and attitudes related to community.
- *Mindsets and metacognitive skills* enabling lifelong learning, including critical thinking skills, learning on demand, and self-directed learning (Fischer, 1999). Assessment ideas for these

skills are: tasks, performance assessments, and observations *in situ* designed to measure students' abilities and tendencies to identify important learning issues in varied contexts, to critically evaluate and integrate appropriate information sources, to conduct research on demand, and to engage in processes of reflection in action and reflection on action.

- The ability to *understand, exploit, and design innovative sociotechnical environments*, requiring fluency in using digital media for personally meaningful tasks (Arias et al., 2000; Collins et al., 2000). (A simple example of a personally meaningful task might be developing a blog or web portal in support of an important scientific-political-social concern.) Assessments for technological fluency might measure whether the value and frequency of engaging in such tasks is increased as the effort expended in carrying them out is reduced.
- The ability to develop, fund, and guide *knowledge-building communities* as contexts for teaching and learning (dePaula et al., 2001; Linn, Davis, & Bell, 2005; Scardamalia & Bereiter, 1994). Assessment ideas for these abilities are: Opportunities to mentor and to obtain feedback on mentoring performance; feedback and discussion of essays on teaching and case studies of personal teaching experiences; performance feedback on authentic tasks requiring participatory design of learning environments; feedback resulting from scaffolded performance on grant writing and small project management tasks.
- Concern about *real-world needs*, willingness to become an *engaged citizen* (Schön, Sanyal, & Mitchell, 1999). Assessment ideas for these concerns are: identification of expectations followed by both formal (written) and informal (discursive) assessments of understanding of key social/global issues. Opportunities to participate and to obtain feedback on participation in socially important work.

In our envisioned system of assessment, such competencies *intertwine*; they cannot be examined, conceptualized, or even discussed in isolation from one another. Thus concern for global issues is demonstrated through skillful involvement in socially important communities of interest; the creation of an innovative learning environment is in also a demonstration of knowledge integration and learning on demand. And while we have little doubt that a variety of these assessment forms are currently in use throughout graduate schools, we also believe that they are typically experienced in an ad hoc manner. Effectively integrating transdisciplinary performance assessment into graduate education will require innovative programming that makes transdisciplinary opportunities more widely available in a systematic way. Next we describe steps that two independent professors are taking to offer such opportunities to students at their universities.

5. Design Research with Innovative Graduate Courses

Although STEM graduate education encompasses much more than coursework (Brown & Duguid, 2000), *the course* (and especially the graduate seminar) is a strongly entrenched historical and institutional practice that will continue to play a vital role. Courses are excellent organizational units for testing and seeding innovation in graduate education. They represent complex learning systems in microcosm, offering excellent contexts for conducting research leading to a scientific understanding of cognitive and social development in rich, theory-based learning environments. Yet, very little scientific research has been conducted on course design at the graduate level (Lorden & Slimowitz, 2003).

We are designing, offering and assessing learning within *two innovative, technology-rich courses* that represent evolving hypotheses regarding the educative experiences likely to engender transdisciplinary competencies (section 3.2) and community goals (section 3.1) consistent with our developing theoretical analysis:

- At the University of Colorado at Boulder (CU-Boulder), a course titled *Design, Learning, and Collaboration* is promoted to graduate students interested in computer science, cognitive science, and the creative practices.[1]
- At the University of Wisconsin–Madison (UW-Madison), a course titled *Transdisciplinary Studies in STEM Education* is being planned in collaboration with the Delta program (http://www.delta.wisc.edu/), a major NSF-funded STEM initiative on graduate education. This course will be promoted to STEM graduate students, including doctoral students in traditional STEM disciplines, students enrolled in interdisciplinary programs in the cognitive sciences, and STEM K-12 teachers pursuing advanced study.

Our research in these courses seeks to develop a deep understanding of the transdisciplinary social processes and cognitive outcomes fostered by our course design. Our aim is to create (a) scientific knowledge about student development in a theory-based sociotechnical environment designed to foster transdisciplinary competencies and (b) specific recommendations and design criteria for graduate course design, including assessments and learning technologies that can be adapted to different contexts. The work will perfect two courses that might be adaptively scaled and offered as parts of required curricula through programs and organizations participating in our broader community (sections 3.5 and 5). For example, the goal for the UW course is that it will eventually be scaled up to serve the community of the Center for the Integration of Research on

[1] In the IT community, "creative practices" describes work in which technology supports inventive, intellectual production within and across fields such as art, music, science, engineering, or education.

Teaching and Learning (CIRTL), a major multi-institutional program of graduate reform and faculty development.

Course characteristics. Both courses encourage collaborative learning in reflective communities supported by sociotechnical environments. In both, the teachers function as *guides on the side* and *meta-designers* (Fischer, 2000) who seed the courses with materials and structures and then provide opportunities, processes, and media support for evolutionary growth (dePaula et al., 2001). Both courses engage a diverse student body by promoting *horizontal* (transdisciplinary) and *vertical* (multilevel) participation and by recruiting participation from underrepresented groups. Both courses engage students in design projects that require problem framing and definition.

Our vision for teaching in these courses coheres with Freire's key principles of critical pedagogy (Shor, 1992), which include:

- participatory engagement and democratic egalitarian process;
- dialogue based on mutuality, collegiality, solidarity, and collective production of knowledge and action;
- situatedness in participants' daily lives, interests, cultures, and modes of communication;
- respect for multiple modes of intelligence, including emotions, creativity, and aesthetics in addition to intellect;
- uncovering of hidden, tacit, silent issues, making them public and salient for scrutiny;
- problematizing and reflexivity involving examination of values, assumptions, socialization, knowledge, power relations, and openness to revision and transformation;
- praxis: testing the validity of knowledge through practice, reflection and dialogue on action.

A major hypothesis 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 alumni as field-based resources for better connecting graduate coursework to evolving real-world issues and resources. Another purpose is to use graduate courses to stimulate positive *social change* (Schön et al., 1999), by bringing students and alumni together as communities of interest that employ university resources to support them in socially important collaborative work.

For example, the community emerging from the CU-Boulder course is organized around a deep understanding of, and practical experiences in creating, theoretically grounded sociotechnical environments in support of distributed intelligence, reflective communities, and lifelong learning. The community grown from the UW-Madison course will support educators in designing and offering socially relevant immersive science and mathematics instruction for all students. In both cases, the sociotechnical information environment will be a central feature (as described below), will be integrated with national resources (such as the National Science Digital Library), and will exist for the next 10 years. Both courses will encourage former students to return to this environment to participate in the seeded community. Our design will include repeated offerings of the courses, continued engagement of the PIs and their institutions, and continued redesign of the sociotechnical environments to meet the communities' evolving needs.

Design, Learning, and Collaboration. This course focuses on creating a *new understanding of design, learning and collaboration* (as fundamental human activities) and their support with *innovative computational media and technologies* (for examples see: http://l3d.cs.colorado.edu/~gerhard/courses/). The course is based on the fundamental 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 to play an *active* role by exploring topics of personal interest in a self-directed way and by 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 facilitate *transdisciplinary collaborations* by emphasizing horizontal (students from different disciplines) and vertical (undergraduates and graduates) 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.

Transdisciplinary Studies in STEM Education. The companion course at UW-Madison, which will be offered for the first time in spring 2006, will bring together graduate students from different fields and levels (vertical and horizontal integration) who are interested in improving mathematics and science teaching in Grades 6 – higher education. We expect the cohort to include

- Experienced middle and secondary STEM teachers working toward graduate degrees;
- STEM graduate students (Delta scholars;) who intend to teach at the college level and are personally interested in learning about and supporting efforts to improve STEM education in Grades 6 – higher education;
- Learning or cognitive science graduate students (from psychology, education administration, computer science, teacher education, etc.) interested in designing STEM learning environments;
- Undergraduate preservice science or mathematics teacher education students;
- Retired master teachers who volunteer in classrooms (taking advantage of the power of the "third sector" of volunteer workers, as described by (Rifkin, 1995); and
- Multiple professor leaders (e.g., one STEM, one cognitive science).

The course will be seeded with initial assignments and discussions to activate thinking on key topics of distributed intelligence, reflective communities, mindsets for transdisciplinary collaboration, and lifelong learning in the context of work. With both STEM and cognitive science faculty as facilitators, course members will set goals for collaborative classroom design projects that involve supporting immersion science and/or mathematics implementations in various school settings. (The concept of *immersion science and mathematics* is borrowed from the NSF-funded Mathematics and Science Partnership (MSP) known as SCALE and refers to in-depth, project-based experiences in science and mathematics that are offered every year to all MSP children, regardless of curriculum implementation.) UW students will conduct research and collaborate on instructional design projects, engaging in learning on demand (Fischer, 1991) and transdisciplinary collaboration. Their work will be supported by a *community knowledge base*. As course participants engage in projects, they will document their experiences and add new cases and resources to the evolving community knowledge resource and will help make decisions about the organization and management of their knowledge environment. Activities will be scaffolded by tools and faculty to provide a rich learning context for developing transdisciplinary competencies and mindsets. Although the primary goals of the course are to promote transdisciplinary scholarship, secondary goals of the course include (a) demonstrating a model for sustainable community seeded by a graduate course; and (b) exploring an alternative model for scaling instructional innovation.

Design Research. Although there are documented studies of knowledge-building learning communities in other contexts [e.g., (Linn et al., 2005; Scardamalia & Bereiter, 1994), there is little systematic research on this form of education, and its problems and possibilities for transdisciplinary graduate study are unexplored. It is a promising but complex and demanding class of pedagogy that raises many unresolved design challenges. For example, do projects end with the completion of each course offering, or will they be built upon from year to year (the problem of temporal distribution; section 3.1)?

To address these and other questions, beginning in the next academic year we will systematically study and evolve our courses through *design research* (Lave, 1988; Rogoff & Lave, 1984; Suchman, 1987). Recent special journal issues on design research (Barab, 2004; Barab & Kirshner, 2001) describe the layers of analysis associated with this method and offer several models for conducting such studies. We will adapt methods described by (Roth, 2001) and (Cobb, Stephan, McClain, & Gravemeijer, 2001)**.** The purposes of our analyses will be to *observe and understand the emergence of transdisciplinary competencies and practices* (both predicted and unpredicted), *make design decision*s, and *formulate and reformulate our explanatory theories about student development and course design*. Our goal is to produce *accounts of cognition, learning, teaching, and individual and community development within our course communities, and to use these accounts both to develop theory and to inform the design of the learning environments*. This research can be characterized as *theory and hypothesis development* and *implementation and documentation of interventions* with respect to NSF's cycle of innovation (Olds, 2002; Rand-Mathematics-Study-Panel, 2002), a stage of work for which qualitative (rather than controlled experimental) methods are appropriate.

Our design-research cycle will involve the following phases:

- Efforts by the designer-teachers to anticipate how designed features of the learning environments will give rise to desired practices and competencies;
- Interviews with each student before and after the course;
- Ongoing recording of reflections and field notes by the researchers;
- Videotaping of selected class periods;
- Ongoing assessments of students and faculty;
- Regular meetings of research teams during and between the design experiments to analyze the accumulating field data.

We will also break out of a normative observer's perspective by engaging students in reflectively studying and designing their learning environments.

6. Community Building

To help disseminate knowledge and integrate our work with other ongoing national and international efforts to reform STEM graduate education (CID, 2005; Lorden & Slimowitz, 2003; Nyquist, 2002), we are attempting to foster community among members of our targeted fields: among graduate students; among faculty interested in research on innovation in STEM graduate education; among researchers shaping STEM graduate education for the future; and among stakeholders in industry and the public sector who seek employees with master's and doctoral degrees as well as graduate training for their employees.

One of our strategies for building community will be to organize *workshops* to which we will invite colleagues with a strong interest and expertise in graduate reform to share their work, and we will propose and discuss collaborative projects related to reform of graduate education. We will pursue the most promising ideas through follow-up visits and meetings designed to further the collaborative agenda. A recent NSF-sponsored evaluation report of the Knowledge and Distributed Intelligence (KDI) Initiative underscores the value of such meetings in bringing about successful collaborations involving multiple disciplines (Cummings & Kiesler, 2003).

7. Concluding Comments

Graduate programs must themselves learn how to be reflective transdisciplinary communities that bring issues and problems and people together with the knowledge represented by fields such as learning science, computer science, humanities, the physical sciences, business, and education, to conceptualize, study and "do" sociotechnical design. As Freire observed in describing his 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). Accepting this, graduate programs themselves must overcome existing institutional boundaries and invent alternative social organizations that will permit the flourishing of interdisciplinary 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 problems through socio-technical intervention, how can they hope to foster lifelong learners, leaders capable of carrying out such work following their graduate education?

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