Principles and Grand Challenges for the Future: A Prospectus for the Computer-Supported Collaborative Learning (CSCL) Community

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Abstract: Six principles of future learning environments have emerged from the CSCL research community. These include: greater "sightlines" into learner, teacher and peer cognition; an increasingly salient role for modeling; increased connectivity between people, concurrent with a greater sense of individualization or "one-to-oneness"; fluid contextual mobility in learning, such as between virtual and real contexts or interoperability of individual, social and machine knowledge forms; and higher interactional bandwidth, or capacity of the environment to mediate meaningful content. Four grand challenges – large, worthy, and difficult tasks should occupy the attention of the CSCL community. Each is a frontier: a more visible and vibrant role for the tools and metaphors of the CSCL community in a troubled era of globalization; means for extending collaboration beyond cognitive models to a broader range of human experience; vitality in learning and collaboration through the life cycle; and unlocking group "flow" in the science of collaboration.

Introduction

There are two purposes to this paper. The first is to discuss six principles or metaphors for learning environments of the future. The second purpose is to identify four grand challenges for the CSCL research community. The paper thus takes the form of a prospectus for directions that are underway as a result of work by this community and for directions that are possible. A grand challenge can be taken to mean a large task for the community, one that is vital, difficult and noble. It can be simply formulated, as in "put a man on the moon." In this context, though, attainment is evolutionary and not readily documented by a single event but rather by a pattern of events and trends. Grand challenges are worth organizing people and resources. The outcomes of a grand challenge are not certain and the consequences of failure are high. In contrast, the principles of future learning environments are in motion. What is at stake in not whether we realize or attain these principles, because in fact they are being realized. What is not known is how thoroughly the principles are elaborated -- and how well the community exploits them to accomplish the larger grand challenges.

The paper is prepared from a somewhat unusual background as a former division director at NSF involved in funding and in being able to observe many of the most important research projects in this community until 2003. More recently, our research center at the US Air Force Academy (USAFA) has been involved in developing and researching new approaches to future learning environments, with NSF-supported work in networking pedagogical agents over collaborative workspaces using new interfaces (2004) and in advancing work originated by Lesh, Kaput and others on models and modeling as a foundation for future mathematics education (Lesh, Hamilton et al. 2007). Additionally, we have organized various research community development projects under NSF support in the areas of new teaching pedagogies and more recently in distributed learning and collaboration (e.g., Hamilton, Carmona et al. 2006). These three vantages – as a funder, as a researcher developing new learning environment frameworks, and in research community development – contribute to the analysis here of principles for future learning environments and grand challenges for the CSCL community.

The six principles are not meant to be provocative so much as to encode some of the large accomplishments of the field and to suggest some important aspects of them. There is no shortage of candidate principles, or indeed of potential grand challenges for the future for the CSCL community. This paper does not claim to offer ideal formulations. Bell and Sabelli (2006), Koschmann and colleagues (Koschmann, Hall et al. 2002; Bereiter, Koschmann et al. 2004) and others have reflected on CSCL directions and have encouraged dialog about those directions. They have forcefully advocated deepening the integration and strengthening of the multiple theoretical frameworks that guide the community. That integration is an ongoing and daunting task. While this paper cites work from multiple theoretical frameworks, such integration is beyond the paper's contribution. The central goal of the paper instead is to stimulate additional discussion within the CSCL community about the ways we describe future learning environments and the ways we understand the largest, most vital and consequential tasks on our horizon. Do these resonate? Do they clarify where we are going and where we should go? What might be more accurate or insightful ways to describe forward progress, opportunity and responsibility?

- *Increased sightlines in the classroom* – a greater ability for everyone in a classroom, teachers and students alike, to see usable representations of conceptual models used by others in the classroom;
- *Increased emphasis on models and modeling* – a greater stress on systems of ideas and relationships both in how learning "tasks" are structured and in how assessment is carried out;
- *Increased connectedness* – learners more meaningfully connected to each other and those outside of the classroom;
- *Increased "one-to-one-ness"*– greater individualization and customization for the individual learner under the management of a teacher, emulating a one-to-one tutoring experience.
- *More fluid contextual mobility in learning* – transfer to and from virtual systems, greater emphasis on heterogeneous competencies functioning at unison, greater integration of cognitive, social and affective dimensions of learning, more hybridization and interoperability of individual-social-machine knowledge forms.
- *Increased interactional bandwidth* – the capacity of the learning environment to mediate meaningful content and affective representations that are shared by participants in that environment.

Table 1: Six Principles of Future Learning Environments

Two more preliminary notes. For the purposes of space, much of the discussion below, at least on principles of future learning environments, is confined to P16 formal educational settings. Such settings may include physical classrooms or more distributed and/or online settings. Many elements of these principles characterize other types of environments, such as companies or networks as "learning organizations" or broader social structures and communities. These principles, while not comprehensive, are attempts to be both simple in formulation and deep in substance. The discussion of grand challenges is not confined to formal educational settings. Second, the expression "computer-supported collaborative learning" conveniently fixes some baseline assumptions about the CSCL research community. Its principal pursuits are about deep and effective collaboration, about deep and effective learning, and how collaboration and learning can interact and enhance one another. Investigating how information and communication technologies such as computers mediate or help to co-create learning and collaboration as the central work of the community is a given. That is, these themes can rightly be stipulated as both principles of future learning environments and grand challenges. Given that stipulation – that we are all seeking means to advance deep and effective learning and collaboration – this paper seeks to elaborate on some dimensions of our common quest.

Principles for Learning Environments of the Future

In a recent global colloquium on engineering, our research group summarized three important metaphors and principles for future learning environments (Hamilton 2006), to which this discussion adds three others.

Principle 1: Increased "sightlines" in the classroom

The "classroom of today" is a vague but still useful starting point for any discussion about the future because today's classroom structures commonly have so many evident shortcomings. One characterization, though, that is not frequently invoked may be one of the modern classroom's most deleterious shortcomings. Classroom environments are steeped in a culture of *guesswork by teachers* about what students bring to class conceptually, how they are cognitively and affectively engaged while in class, and what they have learned by the time that a class session or grading period has concluded. And classrooms are steeped in a culture of *guesswork by students* about conceptual structure, what they should know, what is salient to the teacher, and what they know relative to their peers. (Although the latter is to be expected, in collaborative environments the ability to assess the knowledge of one's peers is important.) The mass production classroom is a social structure that requires constant sensemaking inference and speculation by teachers (and students also, in a different way) about what the students are experiencing, and what instructional or classroom management decisions are appropriate based on those inferences and speculations. Of course, successful educators hone their intuitions about their students to an impressive level of accuracy. But we have become so inured and adapted to following large hunches and guesses about learner, teacher and peer cognition that we accept it as a fixed limitation. *It no longer needs to be so.*

And guesswork extends to content matter. Textbooks and other pre-digital tools are inherently limited in exposing structural relationships in mathematical, scientific and social phenomena. Search tools and other just-in-time media are becoming more ubiquitous for instant access to declarative knowledge and data. In this light, most or all of the CSCL community would agree that the traditional but superficial information-dispensing role of schools is increasingly subordinate to a more critical role of building competencies in understanding, connecting, making sense of and manipulating dynamic, complex systems and social structures. This requires, perhaps above all else, greater tools for visual representation of the structure of ideas that are shared and co-generated, and for visual representation of student and teacher conceptual structures. Virtual systems, games and simulations, by dint of exposing new structural relationships, certainly fall into this category.

- Teachers will see learner cognition more clearly.
- Students will see structure more clearly
- Students will see each other's cognitive states more clearly.
- Social cognition will be more visible.
- Students will see teacher cognition more clearly.
- Ontologies and visual maps of cognition relative to content more refined

Table 2: Types of New Sightlines

Learning environments of the future will have a greater functionality in multiplying what might be called "sightlines" into learner cognition. New conceptual and electronic tools for teachers and students – both learners – provide ways to see concepts and cognition far more accurately than in the past. Such classrooms will provide richer and more effective ways to allow a teacher to understand the cognitive and motivational state of students. The CSCL research community has played an essential role in multiplying the lines of sight in learning environments. One of the most vivid examples or metaphors in this area, for purposes of illustration, involves participatory simulations (e.g., Colella 2002; Wilensky and Shapiro 2003; Stroup, Carmona et al. 2005), using visualization tools that a) change the types of mathematical thinking students can undertake; b) allow students to see real-time representations of their own mathematical behavior more clearly; c) allow students to see real-time representations of their peers mathematical behavior more clearly, and d) allow teachers to see representations of the thinking of all of the students. This example is vivid but not lonely. Being able to see more – in terms of cognition, conceptual structure, and social networks -- is an implicit (and often explicit) theme of a large slice of CSCL research.

A very rudimentary example of new sightlines involves classroom or audience response systems (Roschelle and Penuel 2003; Banks 2006), that sample student responses periodically during an instructional sequence. More substantive response, feedback and interaction systems such as the Classroom Presenter (Anderson, Anderson et al. 2007), WriteOn (Tront, Eligeti et al. 2006) and GroupScribbles (DiGiano, Tatar et al. 2006) are now coming on line. Each involves tablet computing and the more powerful knowledge modeling that they permit. One potent example involves the blending of fully collaborative workspace networks of tablet devices, allowing the teacher to see thumbnails or full screens of each student engaged in writing activity (such as in mathematics). When the teacher can see more representations of cognition (such as in a workspace), the role that the teacher exerts will fundamentally shift and become more informed. This applies, further, to tools that give *researchers* a greater line of sight into learner activity. Examples include through innovative video observation systems (Pea, Mills et al. 2004), use of model-eliciting activities (below) and the refinement of ontologies that expose cognitive pathways taken by individuals and collaborative teams (Hoppe, Pinkwart et al. 2005). More examples follow in the discussion of the other principles of future learning environments, because increased sightlines plays such an important role in them.

Principles 2: Increased "modeling" in the learning environment

Modeling and its emphasis on formation of connected knowledge forms, the adaptation of large ideas to new contexts, just-in-time learning, and complex reasoning in collaborative arrangements is a healthy departure from the traditional and persistent tendency of schools to function primarily as dispensers of declarative and procedural knowledge. There are many flavors of modeling in education research. Collectively, they form a viable suite of approaches for rethinking and "re-mixing" curriculum in future learning environments. A common theme in modeling research involves variations of emphasis on systems thinking, abstract reasoning and the role of developing mathematical and scientific interpretations from context. This trend has a well-established lineage in the CSCL community (e.g., Hmelo, Holton et al. 2000; Kolodner, Camp et al. 2003). In science education, the *Modeling Across the Curriculum* (MAC) project (Buckley, Gobert et al. 2004) leads and exemplifies this trend with the development of replacement modules across multiple areas of the high school curriculum. In mathematics, Lesh, Yoon et al (2007) turn a phrase associated with teachers who make "mathematics practical", gently suggesting instead the possibility of making "practice mathematical." Work in mathematical modeling in the curriculum has included a strand referred to as *model-eliciting activities* or MEAs (Lesh and Doerr 2003), that is largely the basis of efforts advocating modeling as a foundation for future mathematics curriculum (Lesh, Hamilton and Kaput, 2007).

NSF's Research, Evaluation and Communication Division (now part of the Division of Research and Learning), which plays a prominent role in supporting PIs associated with this community, routinely has relied on metaphors such as modeling and simulation to describe features of its research investments. Many of those investments fall into the different category of modeling in artificial intelligence. Virtual reality environments, including those that transition games to learning, will simply overpower more traditional instructional environments as their features more authentically structure formal educational goals as primary design considerations that are not subordinate to entertainment design. This community is on the vanguard of such developments (Dede 2003; Galas and Ketelhut 2006; Shaffer 2007; Ketelhut, Dede et al. (in press)). One prominent instantiation of modeling in the future will involve variations of intelligent tutoring systems (e.g., Koedinger, Aleven et al. 2003). Similarly, the interaction of artificial pedagogical agents and avatars is promising. Advances in gesturology, affect, and personality engineering in agents enhance their anthropomorphic credibility and usability (Cole, Vuuren et al. 2003; Baylor and Kim 2005; Maldonado, Lee et al. 2005).

Principles 3 and 4: Increased "connectedness" and "one-to-one-ness" in the classroom

Learning environments that furnish greater sightlines into learner cognition and that emphasize, highlight, or rely on modeling lead to greater connectedness in collaboration. In our "Agent and Library Augmented Shared Knowledge Area" (ALASKA) project we look for ways to use collaborative workspaces and pedagogical agents to allow the teacher to see the work of students as they engage in their own work using tablet computers (Hamilton 2004). Such systems also enable *peers* to more effectively see what their classmates are doing when collaboration is allowed. Another example of the change in sightlines is the nascent movement in open-learner-modeling (OLM) (Bull, Abu-Issa et al. 2005). OLM offers promise to a student giving a better sense of how the learning environment is tracking the student's cognitive modeling, by creating what are called "scrutable models" allowing the student to see how the system is representing their cognition against an ontology related to the particular subject matter.

These are among developments afforded by learning technologies and artificial intelligence systems that increase what teachers and students see in the classroom. They address the primitive of the CSCL community – deeper connectedness, the third principle of future learning environments. Such connectedness is a raison d'etre of the CSCL community. Every paper in this conference reflects efforts to exploit communication technologies to create social spaces that foster learning. The examples highlighted here emphasize how connectedness changes when lines of sight change. Sight that allows one to see the structural contribution of collaborators will be fundamentally clearer and less ambiguous in the future than it is now. Representational tools that clarify or highlight conceptual structure manipulated by others makes deep collaboration possible. They allow structure rather than merely constituent elements to be salient and visible.

The example of OLM is important, because it stretches our understanding of the notion of collaboration – collaboration intrinsically refers to working with *others*, at least by the light of traditional interpretation. Yet increasingly learning scientists acknowledge and investigate the meta-roles of *self* in learning, the self *collaborating with self*. Metacognitive and self-regulatory behavior, for example, corresponds to one set of functionalities observing, managing traffic, and directing other functionalities. Learning environments of the future will not only permit deeper collaboration between individuals, but will permit the individual deeper harmony with himself or herself in learning. Individuals *who become more sophisticated about learning become more sophisticated learners*.

A fourth theme of learning environments of the future involves a reference to another seemingly fixed feature of the classrooms of today, that mass education inevitably requires students to conform to the instructional approach of one teacher per class. Whether the students' learning styles align with the teacher's teaching style is a hit-or-miss proposition, a situation that can only be reliably avoided in one-to-one learning settings with a tutor who can adapt to the individual needs of the learner. Ever since Bloom's classic two-sigma claim of the advantage of tutoring over classroom instruction (1984), personalized or "tutored" instruction has been the idealized contrast to traditional or "many-to-one" student to teacher classroom configurations. One-to-one human tutoring is an impossible-to-attain ideal, yet in the future the metaphor may give way to more realistically attainable means to emulate and exceed that ideal. We use the term "one-to-one-ness" as a metaphor for the cognitive and motivational advantages that can follow from a ratio of one tutor to one student. The advantages include dynamic shifting of strategies of teaching to match a student's learning style, more immediate feedback loops, opportunity to probe for clarifications with no wait states or delays, and more interactions and responses that map intuitively and closely to a perceived affective state. Classrooms that have the greater sightlines and connectedness mentioned above will be positioned to emulate and to exceed the vision of customized learning that a one-to-one model represents. In the ALASKA system we are developing, for example, customization through a method that can flexibly invoke short-term, dynamically available and technologically-mediated help from peers; furnish intelligent or affectively astute virtual agents; furnish tailored digital knowledge resources; use open-learner-modeling techniques mentioned above to give the learner more feedback on learning progressions; and free the teacher's cognitive load from routine instruction to devote cognitive resources to more demanding or complex pedagogical tasks such as those that can be undertaken in one-to-one tutoring arrangements. Each of these features amplifies and diversifies individual resources for learning, resources that were not available when Bloom first enunciated the human tutoring double sigma advantage in 1984. Virtually everything in the learning environments of today is colored and constrained by the economic impossibility of attaining a true one-to-one learner to teacher ratio. Yet, appropriately structured, future learning environments may "work around" or even surpass that goal.

Principles Five and Six: Fluid Contextual Mobility and Increased Interactional Bandwidth in Learning

As modes of collaborative learning, interactivity and new technologies abound, one of the most compelling developments in future learning environments will be how they are combined and how learners and educators transition between them and customize them. The flexible or seamless adaptation of learners to rapidly shifting channels in the environment may one of the most interesting developments of future learning environments. And this contextual mobility is not limited to attentional shifts (such as transfer to and from virtual systems) but to shifts and hybrids that might be more sublime, such as participating in while studying the domain space, or moving in and out of a social network space. Several examples appear in Table 4. The construct of contextual mobility has risen to a prominent place in our ALASKA Project. As a multifaceted scaffolding system, ALASKA requires students and teachers to flexibly move in and out of different modes or function in multiple hybrid modes simultaneously. In some cases, collaborative mediators (which might be a teacher or might be an artificial agent) allow students to seek help and to give help, and to do so remotely. Artificial agents that broker connections and collaborative workspaces lower the cost of such help giving and seeking.

- In and out of virtual and real contexts
- Blending real and video face-to-face interactions
- Participating in and being part of the content space
- Greater emphasis on heterogeneous competencies functioning at unison
- Adaptation to interoperable scaffolding from peers, digital content, artificial tutors and teachers
- Moving in and out of collaboration, individual effort and reflective activity
- Transition in and out of fully absorbing flow states
- Interoperability of individual, social and machine knowledge forms

Table 3: Types of Contextual Mobility

Each of the preceding five principles reflects one of numerous possible ways to highlight important trends that may be useful to understand and to leverage for CSCL research. Each has some intersection with the others. For example, customization in classrooms depends increasing the sightlines so the instructor can calibrate activities on a more personalized basis. Increased sightlines create more connections with the teacher, and certainly between students. Developments of this nature enhance what we have referred to as the "interactional bandwidth" of a learning environment, or the capacity of the environment to mediate meaningful content and affective representations shared by participants and to and compress and layer interactions in that environment (Hamilton, DiGiano et al. 2004). *A sixth principle of future learning environments is that they will entail much greater interactional bandwidth.* We are only at the beginning of understanding how much more bandwidth is possible. In a sense, we are at 9600 bps bandwidth environment when 100Mbs is possible. In system networking, bandwidth in measured in speed, with the effects understood in terms of how much richness (e.g., video versus text) is carried over the connections. In learning environments*, the vision is not for frenetic and high-speed activity, but for depth and layering of interaction with others and with content. It is a matter of intensifying human experience, connection and meaning in learning, in ways we could not imagine earlier, and for more of our students.*

Four Grand Challenges for the CSCL Community

These six principles are all inherently optimistic about the prospects for building more effective and humane learning environments, and with good reason. They characterize paths that not only are possible but are already being explored or followed. As the CSCL field continues in the development, theoretical integration and empirical studies that will help incrementally advance such compelling possibilities for the future, it may also be useful to situate the research community more largely relative to a global society. In that spirit, the paper offers candidate "grand challenges" that are less intended to encode developments already under way than to provoke discussion on the larger roles that the community might exert in the future.

Grand Challenge 1: Break-out role influencing society with innovative tools and ways of thinking about collaboration

Conferences on learning technologies and educational research routinely invoke the well-being of society, yet these allusions are often illusions, in the sense that there is a poorly articulated connection between research and society. Virtually everyone in this field has likely grappled deeply with the issues of transferring research to practice. It is not so in all sciences or research endeavors, but in ours, where the research traditions are young, the "laboratories" are complex settings, and research funding is driven by the need to demonstrate impact, connecting research to practice looms large. But perhaps not large enough. The tools and ways of thinking that the community is pioneering are desperately needed in a world where polarization along countless dimensions of human experience is exacerbated, ironically, by the miraculous technologies that few of us could imagine in our youth. Our world is in deep trouble. It is survival-threatening trouble. There is no guarantee that we will not see cataclysmic destruction in our lifetimes in one form or another. Averting such disaster will require a lot of the medicine this research community is brewing. It is in our hands to find ways to instantiate new tools of collaboration in areas or ways that are not typical for this community.

People who understand each other and who collaborate are not eager to destroy one another. I am a civilian researcher in a United States military academy, and believe our best hope for building peace is by building bridges of understanding and generosity of spirit. It is not difficult to say to the CSCL choir that collaborative technologies are a great means to that end. This is not idealism, this is reality. While this community is not the arbiter of the sometimes small, sometimes large, sometimes harrowing conflicts that polarize our cities, country, and global society, it can and should elevate its sense of identity, to understand that it can play an absolutely crucial role in forging deeper understanding between people, and in finding ways to express benefits to one another and to convey and to receive generosity. Good will is a limitless human commodity in the right circumstances. The world desperately needs that endless commodity, to create the circumstances for it to be expressed. In my estimation, it is critical to understand the central importance of building understanding between people and cultures as a responsibility of this research community to civilization and prosperity. The CSCL community has in hand the tools and approaches that can play a large role in cross-cultural bridging.

What might this look like? What are specific ways that CSCL researchers can promote bridge-building? The most imaginative and creative approaches will emerge as the community expands its sense of identity and sees that it has a role in promoting connections in a troubled world. We are just beginning some efforts in this direction in our research group. We are in the process, for example, of carrying out research seminars that entail students from the UK (Hamilton, Lesh et al. 2007) and the US, and from the Peoples Republic of China (Hamilton, Tao et al. 2007) and the US and between the Mideast and the US to work together on finding solutions to specific mini-engineering humanitarian problems involving developing countries. This work is co-funded by the US NSF, the British Economic and Social Research Council, and the Chinese Natural Science Foundation. A related project is now starting involving collaborating engineering students in the Mideast and the US. Distributed teamwork is increasingly prevalent in multidisciplinary engineering design, for example, and it is an ideal area for rapid escalation of international computer-supported collaborative learning. The emergence of

- *Break-out role influencing society innovative tools and ways of thinking about collaboration.* The great research frontier: Deploying CSCL in ways that build substantial, authentic bridges of collaboration in place of polarization.
- *Ultra-deep model collaboration: sharing human experience* – CSCL research is at the center of helping individuals assimilate, share and co-create complex knowledge models. The great research frontier: assimilation, sharing and co-creating models that integrate cognition more fully with broader dimensions of human experience such as affect, motivation, intuition and identity.
- *Agility in learning through the life cycle* – The life cycle is lengthening and changing; work, play and society demand continual expansion of individual competencies and multiple start-from-scratch novice-to-expert transitions. The great research frontier: Agile learning throughout the life cycle.
- *Unlocking group "flow" in the science of collaboration* – Work over the past thirty years has enabled greater understanding of individualized and phenomenological conditions that produce optimal and immersive performance in challenging settings, often called the zone or flow. The great research frontier: Uncovering conditions that permit zone or flow conditions for collaborative teams.

Table 4: Four Grand Challenges

engineering education programs with a humanitarian and developing nations emphasis is a salutary development in this overall movement (Mulrine 2006). Most such programs involve individual courses or course sequences. The Humanitarian Engineering Minor at the Colorado School of Mines in the US, the first of its kind, will hopefully be emulated elsewhere. These typically, however, are costly to expand or to scale, and do not yet capitalize prominently on collaborative technologies. The projects referenced above, with Chinese, British, Mideast and US students will actually involve no face-to-face contact, but will rely heavily on collaboration tools to simulate such contact. The research questions will focus on the scalability of such interactions and the tradeoffs that they involve in genuine model-solving activities. In another network project, we are attempting to link US high school students with students in African countries through an effort originally started by the Quality Education for Minorities (QEM) organization (McBay 2005) and through an African mathematics and science education network organized by Hiroshima University. The goal is to position students to collaboratively solve problems that can be modeled mathematically and that are authentic to each other's societies. Children in Topeka and the Four Corners and Seattle should be communicating with children in Kampala or Rio or Istanbul, and not at the level of pen pals, but in ways that become routine and substantive and build permanent bridges to the future. The sophistication of the collaborative tools we are using – collaborative spaces, virtual agents, voice and video over IP, dynamic web spaces -- is fairly high yet there is limitless potential to grow. The conceptual tools center on theories of models and modeling. Our vision is to promote a robust system of exchanges between students internationally, creating a way of thinking about cross-cultural communication that is not only available, but actively pursued by educational systems in different countries. The vision for the CSCL community is to play an expansive role in finding ways to sustain robust international collaborative learning, and thereby alter evolving definitions and descriptions of globalization.

Grand Challenge 2: Ultra-deep model collaboration: sharing human experience

Largely through representational and computational tools, CSCL facilitates sharing and cogeneration of cognitive models. What is the next level beyond cognitive models? Will collaboration exchange go further than cogeneration and sharing of the conceptual and extend to deeper and more complex modeling processes that engage broader dimensions of human experience? One way to think of this is through the frames of experiential reference. Understanding and integrating multiple frames of references is a key indicator of the research area of intellectual maturity. William Perry (1980) and then the team of King and Kitchener (1994) have delineated stage models for moving from egocentric and narrowly defined frames of reference to more complex reasoning forms that recognize the legitimacy of multiple ways to approach a problem. Currently, it is difficult to find ways to move individuals along a developmental continuum. It may be that a key to nurturing maturation in the adaptation of multiple frames of reference is by understanding more holistically that frames of reference are embedded in a series of human dimensions that extend beyond cognitive boundaries. Some of the broader dimensions include affect, identity, socialization, motivation, and belief systems. Damasio's *Descartes' Error* (1994) highlights how the *cogito ergo sum* of Descartes' mind-body dualism has systematically relegated non-cognitive elements of learning to secondary status. CSCL has reached a certain sophistication in metaphors and methods for collaboration around conceptual or cognitive systems, but not to collaborations allowing individuals to impart a fuller range of meaning that is not only rich with cognitive structure but also with affective valence, intuition, and personal meaning, and have those models shared and understood by their collaborators. That deeper sharing can occur in collaboration is not a special insight, but neither is it deeply understood nor systematically attainable. We are only at the very beginning of that journey.

Grand Challenge 3: Agility in learning through the life cycle

The life cycle is lengthening and changing. Work, play, and society will demand continual expansion of individual competencies and multiple start-from-scratch novice-to-expert transitions over each of our lifetimes and those of our descendants. The "learn then earn" paradigm of 20th century industrial society is fundamentally inadequate for the future. Stagnation in knowledge is an increasingly untenable life strategy. Issues of cognitive vitality throughout the life cycle are increasingly recognized by the many industrialized counties with declining birth rates. The severe pressures from this demographic phenomena are repeatedly stressed in policy documents of multilateral organizations such as OECD as well as national policy commissions. This is especially true in countries such as Japan and China, where the birth rate has fallen below that needed to sustain population levels. While low birth rates mitigate overpopulation, they produce societies whose median age climbs and who rely increasingly on the competencies of an older workforce. By most lights and conventional wisdom, an aging workforce is not as agile or competent in evolving new ways of thinking and using technological tools as younger counterparts. Yet one of the most important advances emerging from brain science has been research in neural plasticity through the life cycle and documentation that knowledge construction and acquisition potentials are far greater in the aging process than previously thought (della-Chiesa 2003). It is fortuitous that science is undermining the myth that agile and rich learning can only occur primarily in youth. Researchers such as Gerhard Fischer (e.g., Fischer and Konomi 2005) are investigating means by which CSCL tools can nurture creativity and continued dynamism and creativity, and reshape what we understand to be the learning potentials through the life cycle. This era is the first in recorded history in which it can be argued that the younger generation has greater facility with the tools and artifacts of knowledge formation and knowledge sharing than the preceding generation, it is also arguable that in the future, a youth-dominant society is one that has failed to exploit the vibrancy of all ages of society.

Grand Challenge 4: Attaining group "flow" in collaboration

Both education research and learning science research writ large involve the quest to optimize human performance in teaching and learning. In that respect, other human performance research domains should be relevant to education and learning science research. An area of research with such emphases on high performance should be of particular interest to the CSCL community. One example involves studies of human flow – optimum performance and creativity in challenging circumstances, entailing deep absorption in tasks that are at the outer edge of the individual's abilities. There are multiple design and emergent factors associated with flow, and most of them are related to how an individual functions in a(n) (learning) environment. Introduced as a psychological construct by Csikszentmihalyi (1975), it has been widely researched – often in the context of examining intrinsic enjoyment or satisfaction while engaged in work or play, fully concentrated absorption whereby an individual loses a sense of time, or optimal or heroic performance in extreme (highly challenging, enjoyable or desperate) circumstances.

The CSCL community has indirectly but very powerfully addressed a sublime question: Can the experience of flow while *learning* be routinely induced, and how? There is very limited research on flow *induction* compared to descriptive, measurement or correlational studies of flow experience. This paucity is even more severe in research on flow in learning (see Shernoff, Csikszentmihalyi et al. 2003). On the positive side, research on areas such as immersive simulations and virtual environments, digital media, and engagement in electronic games has produced mounting evidence that it is possible to structure favorable conditions for high performance and fully engaged activity at the edge of one's abilities. One large challenge for that portion of the CSCL community devoted to virtual reality research is to find and accelerate means for exploiting immersive and high performance play into a broader swath of learning and modeling activities (Klopfer, Perry et al. 2005; Shaffer 2007). *As daunting as that challenge might be, a larger one strikes at the heart of research on flow, namely the transference of this experience from a highly autotelic, individual and private phenomenon to one that is shared by collaborative teams, especially in learning environments.* Modern classrooms, for example, are not structured to induce flow. The basic necessary conditions – lack of distractions, lack of fear of failure, understanding of what to do next, i.e., deep sense of executing a tacit model -- are alien to current learning environments. What is the analog for collaborative teams? It would go from Michael Jordan's history-making *individual* game to open the Chicago Bulls' 1992 NBA Finals against Portland *("…I didn't know what was happening. I was in a zone. What can I say? I don't know how to explain it. You know it's got to end, it has to, but when? It's like it doesn't matter what they do.")* to the stunning rally and come-from-behind *team* win by the Bulls against Phoenix a year later, when Horace Grant and John Paxson passed up a guaranteed layup to tie at game's end. Without hesitation and knowing exactly where each other was on the court, they skipped the tie and in one fluid motion bet the world championship on a three-point shot. It went in. Grant and Paxson were in a collective flow.

Another example is the performance of an orchestra, whose members keep a perfect sense of timing but collectively lose their sense of time. How can such experiences of sublime and deep immersion be routinely approached in our so-often-pedestrian learning settings, and how can high performance and optimally creative collaboration be induced? Is the non-linear jump of consciousness to the stratosphere of individual or collective performance so emergent that it can only be appreciated but not replicated? Perhaps, or perhaps we don't know enough about it to make that judgment. Why not understand it well enough to find conditions that might be likely to elicit it? Especially in the realm of collective performance, the domain of this research community? We have argued that it is at least a researchable question (Hamilton 2007; Hamilton and Hurford in press) for computer-supported collaboration. Research in group flow is a tremendous frontier whose building blocks involve networks furnishing rapid feedback loops, calibration of participant task abilities in a collaborative environment, progressively deep levels of task immersion, shared models of task, and shared models of social structure within the collaborative space. Our research group is trying to understand conditions, adding to these building blocks the facilitating feature of heterogeneous agent network flow to mediate feedback loops. The sort of phenomena we envision is significantly beyond anything we have been able to effect, but we have been able to elicit more sustained engagement in learning settings (Hamilton and Hurford in press), for example. Producing high performance collaboration conditions, including the representational and feedback tools needed for tasks whose calibrations are at the outer edges of a team's competencies, in circumstances of urgency, vitality, or other significant challenge, is a task worthy of the CSCL community.

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