A walk on the WILD side How wireless handhelds may change computer-supported collaborative learning

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Designs for CSCL (Computer-Supported Collaborative Learning) applications usually presume a desktop or laptop computer. Yet future classrooms are likely to be organized around Wireless Internet Learning Devices (WILD) that resemble graphing calculators, Palm, or Pocket-PC handhelds, connected by short-range wireless networking. WILD learning will have physical affordances that are different from today's computer lab, and different from classrooms with 5 students per computer. These differing affordances may lead to learning activities that deviate significantly from today's images of K-12 CSCL activities. Drawing upon research across a range of recent handheld projects, we suggest application-level affordances around which WILD-based CSCL has begun to organize: (a) augmenting physical space, (b) leveraging topological space, (c) aggregating coherently across all students, (d) conducting the class, and (e) act becomes artifact. We speculate on how CSCL research may consequently evolve towards a focus on kinds of systemic coupling in an augmented activity space.

Keywords: Handhelds, design, wireless networking, collaborative learning architectures, CSCL controversies, WILD (Wireless Internet Learning Devices), shared knowledge, augmentation frameworks, classroom workflow, data mining

Introduction

Handheld computers will become an increasingly compelling choice of technology for K-12 classrooms because they will enable a transition from *occasional, supplemental* use to *frequent, integral* use (Soloway et al., 2001; Tinker, 1997).

This transition is driven partly by the relationship between cost and the student-computer ratio. With desktop technology, cost is high, and computer resources must be shared. Today the typical student-computer ratio is 5:1, with computers in schools most often located in special computer labs rather than the ordinary classroom (Cattagni & Ferris, 2001). A teacher must schedule lab use and move the class there (Becker, 1999). This practice guarantees occasional, supplemental computer use at best, a challenge to integrating it with other learning materials and activities in the classroom. Further, this limits the possible overall impact of computing in education: if an instructional resource is used infrequently, it is unlikely to have a large effect. Large screen size may be useful, to be sure, but comes at these significant costs.

By comparison, handheld computers are more affordable, making a 1:1 student-computer ratio and ready-at-hand computing feasible with their smaller physical size. Today many math classes either purchase a classroom set of graphing calculators, or require every student to purchase their own unit, enabling frequent, integral use. Some reform-oriented mathematics texts require handheld technology (whereas almost no widely-sold curricula require desktop computers, because of their limited availability). In the near term, Wireless Internet Learning Devices (WILDs) will likely become available in the same price range as today's Palm devices or advanced graphing calculators, and include short-range wireless networking. WILDs will be at least as powerful as early Macintosh computers, and far more powerful than Apple IIs — allowing a range of powerful learning software. And WILDs will be portable, so students can take them into the field for scientific data gathering (Gay et al., 2001; Soloway et al., 1999; Staudt & Hsi, 1999), to their study hall, on the bus, to a museum (Bannasch, 1999), or anywhere learning happens. Already, companies such as Texas Instruments, Palm, Handspring, Symbol Technologies, Mindsurf, Classroom Connect, and Scholastic are directing attention to creating and supporting WILD classrooms. Evaluation data collected from over 100 K-12 teachers who had 1–2 semesters of experience using 1:1 e-learning in their classrooms after receiving Palm Classroom Teacher Awards (from a pool of 1400 applicants) was overwhelmingly positive (Crawford & Vahey, 2002). More specifically:

> "Handhelds were seen as having positive effects on student learning, on teaching practices, and on the quality of learning activities. Teachers also stated that handheld technology can make technology more integral to teaching and learning. When asked to indicate their degree of agreement or disagreement with statements about handhelds, teachers' responses were as follows: 96.5%

indicated that they believed handheld computers were effective instructional tools for teachers, and 93% stated that the use of handheld computers contributed positively to the quality of the learning activities their students completed. The following benefits of handheld technology were cited most often: portability and ease of access, the integration of computing into a wide variety of educational activities, promoting autonomous learning and student organization, promoting student motivation, promoting student collaboration and communication (using infrared beaming), and supporting inquiry-based instructional activities. Although teachers were very favorable in their evaluation of handheld computers for teaching and learning, they did report some problems, including the following: damage to the handheld devices (especially the screen), problems with synchronization of handheld computer data with desktop computers, and some inappropriate use (such as game playing and off-task beaming)." (Crawford & Vahey, 2002, Executive Summary)

Given the continuing emphasis on collaborative and communicative processes in subject matter standards such as NCTM and the National Science Education Standards (in the US), many WILD classrooms should become classrooms more characterized by computer-supported collaborative learning. Students will work towards shared understanding in groups. Students will build joint representations of their knowledge. To enhance understanding, students will point to, annotate, and use external representations in diverse sense-making and discourse practices (Pea & Gomez, 1992). And teachers will have a strong role in managing a learning process that involves many active, communicating learners. Yet, because of the differences in WILD classrooms vs. computer labs, we conjecture that CSCL applications may have to radically change, and that new research questions will surface. Our paper is devoted to documenting, reflecting on, and exploring these new directions.

Like conventional computer labs, WILD classrooms should support computational media with cognitively-empowering representations (e.g., simulations, manipulable mathematical notations, modeling tools, diagramming tools). And like recent computer labs, WILD classrooms should support network communication both among local peers and to distant servers. But unlike desktops, WILD classrooms will likely feature relatively small screens. Battery life and heat dissipation issues will prevent intensive use of streaming media or broadband networks for years (Ledbetter, 2001; although be sure to track developments in ultra wideband wireless networks given February 2002 FCC approvals). And the basic functional characteristics (screen size, processing power, memory, network speed) of handhelds are not rapidly increasing with Moore's Law; improvements have been slight over the last 3 years.

Perhaps even more importantly, WILD classrooms will have affordances not available today that are ripe for new CSCL uses. In particular, CSCL should support peer-to-peer communications, and handhelds provide the affordances to do so. WILD devices have the capability of directed communication (IR, or infrared beaming) to a specific person via a physical gesture, instead of selecting a logical name or typing it in. WILD classrooms can thus naturally support peer-to-peer and multicast network topologies, beyond today's predominant client-server computing style. Peer-to-peer communication is naturally supported by beaming, and as Napster makes clear, can have very different collective characteristics and emergent phenomena than client-server communication. Multicast will be supported because radio-based wireless is naturally multicast in a classroom-sized space.

Further, although CSCL research brought to light theories of distributed intelligence (Pea, 1993) or distributed cognition (Hutchins, 1996), that knowledge was only visible in two kinds of places in typical CSCL activities: a student's head or a computer display. In a WILD classroom, there may arise more differentiated places for information and knowledge, and highly differentiated "things that make us smart" (Norman, 1994): devices with different characteristics may proliferate (some larger screens, some with more computational power, some with more colors, or special graphics co-processors) and special purpose information appliances may emerge (e.g., "SmartProbes" that can store data,[1] Lego MindStorms™ robots, wireless printers driven by IR and Bluetooth beaming). Students are more likely to be choosing appropriate assemblages of devices for their knowledge work than in conventional desktop-based CSCL, highlighting a growing need for the development and deployment of meta-tool knowledge. In this paper, we consider how these changing affordances may change CSCL applications.

Our article begins by surveying several early WILD applications, in order to abstract some application-level affordances of WILD (as compared to the physical-level capabilities we discussed above). We then suggest some of the differences these application-level affordances may bring to CSCL, and highlight how WILD is likely to create a new application type, along the lines of augmented activity spaces. Beyond thinking about possible application types, we may speculate about the fault lines that might organize future CSCL research.

A look at WILD in the wild

Although classroom research using handheld computers has been going on for years, and has spawned some large research grants recently, there are no formal surveys of WILD applications. We forego assembling a complete survey here, instead describing a handful of WILD application types involved in one or more projects at SRI, or that have been described at past CSCL meetings. The SRI projects include *CILT* — the Center for Innovative Learning Technologies (http://cilt.org, a distributed center with broad-based participation from hundreds of organizations in collaborative projects on themes including "Ubiquitous Computing"), the *Palm Education Pioneers* program (awarding competitive grants of free handheld computers to every student and teacher in over one hundred classrooms), *SimCalc* (a mathematics project that has investigated handheld learning for 4 years), and a U.S. Department of Education grant that developed a handheld assessment tool. We only include application types that: (a) have been used by multiple researcher/developers in building WILD prototypes, and (b) have some early evidence that the prototypes yield interesting classroom experiences.

We will consider the systems in the following list:

1. *ClassTalk* is a networked classroom communication system in which any of five question types (multiple choice, numeric, short and long text, algebraic expressions) can be provided by a teacher to students, so that when their answers are submitted, a histogram of their aggregate work is displayed to the students and the teacher so as to guide subsequent classroom discourse about student learning and difficulties with specific aspects of the subject materials (Dufresne et al., 1996; Abrahamson et al., 2000; Mazur, 1997).

2. *ImageMap* is an assessment feedback system for supporting media-rich learning conversations that we are developing at SRI International. An image (e.g., graph, map, photo) is distributed to each student with a handheld networked device, a question is asked about the representation, and each student annotates the image with a response. A server receives these responses from the pool of students, aggregates their responses by superimposing their annotations in some manner on the image that was distributed, and projects them on a public display, allowing students and teachers to see the distribution pattern of different answers.

3. *Probeware* describes the use of probes and sensors connected to computers (whether handheld or desktop) to collect and display real-time measurements of environmental parameters such as temperature, light, motion,

force, sound and electrical power (Tinker & Krajcik, 2001). Thornton (1997) demonstrated that high school students' intuitive ideas about motion, velocity, acceleration, and force become more accurate when using probeware than using any other instructional strategy, including lectures, problems, or traditional labs.

4. Mobile computing has been shown to enhance *field study* using digital imagery (in educational studies involving botanical species identification: Gay, Reiger, & Bennington, 2001).

5. *Participatory Simulations* is a phrase increasingly used to describe a paradigm in which small wearable computer 'badges' or handheld computers are used to create life-size simulation activities in which participants can represent conceptual entities in a complex system so as to simulate, for example, the spread of viruses, or cars in traffic (e.g., Colella et al., 1998; Wilensky & Stroup, 1999). After experiencing a simulation, participants work together to analyze data, create hypotheses, and conduct experiments to infer underlying rules for their simulation.

6. Building on the work of the SimCalc project on the *"Hubcalc"* concept of connecting many handheld devices to the teacher's computer (Wilensky & Stroup, 2000), Texas Instruments developed a wireless classroom communication system that connects handheld graphing calculators so that programmed tasks can be sent within a classroom to calculators for students to work on. Wilensky and Stroup (2000) developed such a task, where students each control a traffic light on a projected traffic grid and the class as a whole has the goal of setting up rules for smooth traffic flow. Additionally, a NSF-funded project is investigating classroom wireless networks of handheld computing versions of SimCalc environments for learning the mathematics of change and variation (e.g., Kaput & Hegedus, 2002).

7. In one CILT project, the Exploratorium is exploring use of a wireless network and handheld computers to provide information and scaffolding for museum visitors as they virtually explore an outdoor setting. Visitors walk through the landscape with a handheld networked device, linked to a wealth of information and media related to their direct experience of the ecosystem. The online information is navigated through a visual representation of the trails and of the wetlands at large; at the same time, sensors in the environment read the movements of the visitor, enabling the delivery of information specific to that location (http://www.exploratorium.edu/lagoon; for related work, see Bannasch, 1999; Exploratorium, 2001).

In addition to this list, there are many functional WILD uses in classrooms that are not particularly collaborative: organizer, attendance, and student record keeping. Here we maintain the emphasis on inquiry processes, social constructivist analyses, and distributed cognition designs that are characteristic of CSCL (Koschmann, 1996).

Analysis of WILD application-level affordances

In this section, we will generalize across the list of WILD applications above, and describe application-level affordances that seem characteristic of this emerging technology.

1. Augmenting physical space with information exchanges

We find that virtually all the WILD applications above either augment or amplify an existing physical space with information exchanges (Engelbart, 1962); the space the students are engaged in during their activity includes the devices, but is not limited to the space within the screen. Participatory Simulation activities illustrate this robustly; the badges or devices overlay information exchanges on the physical movements of the students, and the information and students' memory of their movements are the focus of inquiry. Probeware and the museum scenarios share this characteristic, but it is less prominent in the HubCalc, NetCalc and ClassTalk scenarios, although the activity space is still very much a physical classroom space (the "moves" enacted by the teacher and students are, significantly, moves in the classroom discourse space, which is augmented by information exchanges). In contrast, archetypal CSCL most often concentrates attention on spaces that are wholly contained within the bounds of the computer screen.

This potential power of augmentation may be understood by analogy to microworlds. Piaget, the intellectual spirit behind Papert's concept of microworlds, theorized that facility with abstract representations, which are more advanced than concrete representations, arrives later developmentally. Developers of microworlds invert this theory with the design principle that transforming abstract ideas into a manipulative, exploratory concrete form makes the abstraction more learnable. But microworlds only took the abstractions as far back as concretely realized sign systems (even if they initially began with a physical robotic "turtle" in the early implementations of Logo). Participatory

Simulations and Probeware reconnect abstractions with embodied, physical, spatial explorations that precede concrete sign systems. This may make the learners' experience of abstract concepts yet more visceral and meaningful (Colella et al., 1998; Colella, 2000).

2. Leveraging topological space, of two distinct kinds

Lemke (1999) makes a compelling distinction between typological and topological representations, suggesting the interplay of language-based, taxonomic, categorical representations ("typological") and spatially based, visual, continuously varying representations ("topological"). Lemke argues that much of the history of mathematics revolves around the fruitful interplay of these representations.

The WILD applications noticeably leverage topological space, capturing information based on spatial proximity and preserving for reflection that which is simultaneously topological and typological. For example, the ImageMap assessment represents degrees of student understanding through a direct spatial mapping of individual contributions to an aggregate representation. Even the more rudimentary ClassTalk — in the first instance a multiple-choice/typological system — emphasizes topological representations by presenting: (a) results as an easily interpreted histogram, rather than as tables of numeric data, and (b) students with stimuli that are choices among multiple visual representations. Likewise, Participatory Simulations exchange information based on inter-student proximity in the virus role-play to examine the dynamics of disease transmission. SimCalc representations are editable graphs that are topological in nature, and in Probeware, the placement of a probe in a data source (a spatial act) results primarily in a graph (a spatial representation). The museum scenarios focus on image capture and proximity to an exhibit (or outdoor landscape element) as key drivers of the information exchange. While we have highlighted 2-D representations in the ImageMap assessment characterizations, we can foresee 3-D and 4-D image-based assessment activities as well. An example of a 4-D image assessment task item (time is the fourth dimension), would be a digital video record of a classroom teaching interaction that requires a group of pre-service teachers to each highlight, with graphical and text annotations, specific problems with the instructional strategies used by the video recorded teacher at different moments in time. Aggregate representations of the pre-service teachers' responses could bring to light different perceptions of the issues that the video recorded teacher faced in his or her instruction, and help guide a reflective learning discussion among the faculty member and pre-service teachers.

This emphasis on computer use to bring more topological representations into the classroom continues an overall trend to balance topological (e.g., graphs) and typological (e.g., algebra) representations that has been an important part of past CSCL research. But beyond that, WILD classrooms have new affordances that make topological representations even more powerful, and typological representations less so. The *stylus* used with handheld computers as a pointing and inscriptional device makes it especially easy to correlate user control with spatial representations, even more so than with a mouse. Further, directional beaming and probe placement connects information exchanges to simple physical gestures, whereas most conventional CSCL exchanges must use icons or labels to represent logical destinations and sources of information flows. Conversely, it is intriguing that Palm OS devices, the trendsetter in user interfaces for handhelds, have dramatically simplified their design vis-à-vis desktop computers in part by simplifying typological representations from hierarchies to flat categorical lists: on a Palm OS handheld, one cannot organize folders of folders of folders of files; only a single level of categorization is allowed. And although a portable keyboard makes writing easier, Palm OS devices are not good for reading or writing large amounts of text.

We make an important distinction between two kinds of topological representations that we designate as "*geo*spatial" and "*semio*spatial." Geospatial representations (geo = "of the world") are defined by formally specifiable mapping functions from measurable spatial parameters of the physical world (distance and direction, as in terms of height, depth, width) and their representational system counterparts (i.e., inscriptions: such as 2D and 3D maps, drawings, pictures). In contrast, semiospatial representations are those in which the spatial attributes of the topological representation are *not* mappable to spatial attributes of the physical world (except to those of the inscription itself). Semiospatial representations include Cartesian and other graphs, concept maps, flowcharts, and non-geo-gridded information visualizations generally. More technically, semiospatial representations are those for which, if one were to ask a geospatial question about aspects of a specific representation—such as "*How many meters away is the concept 'President' from 'Vice President' in an organizational chart for the U. S. government?" — one would be committing what Gilbert Ryle (1949) would have called a "category mistake," from which various logical fallacies and conceptual conundrums may follow. Semiospatial representations are useful for supporting reasoning, argumentation, and deictic functions that are important for establishing co-reference and attentional alignment in collaborative learning.

The following scenario illustrates the power of topological features of semiospatial representations for learning. A teacher creates a diagram on a whiteboard, captures it with a digital camera, and then distributes it to the students' handheld computers in the classroom. These handhelds allow pointing with a stylus to spaces on that diagram so as to answer her question: "Which link in this concept map did you find most difficult?" An instructional discourse then ensues when the class and teacher see the aggregated results of their link selections depicted on the computer-projected display of the diagram with data superimposed. The semiospatial representation provided by this technological augmentation of the physical whiteboard space, in the diagram's depiction on each student's handheld display, provides the common spatial framework for CSCL.

Lemke's typological/topological distinction and our geospatial/semiospatial distinction can be viewed as part of an overall educational technology interest in understanding the cognitive value and educational use of multiple representations (Kaput, 1992; Kozma et al., 1996; Shafrir, 1999). For handhelds, such multiple representations are likely to be distributed across multiple devices. In NetCalc classrooms, we observed students aligning multiple devices so they could compare multiple representations. In the Datagotchi scenarios developed as a CILT seed project (http://www.cilt.org/images/DataGotchi.pdf), we suggested that students would naturally line up their WILD handhelds to form larger spaces along which representations could be compared (in the manner of Rekimoto, 1998).

3. Aggregating coherently across all students participating individually

Another interesting characteristic of three of the WILD applications is that they aggregate information generated by *all* the *individual* students in the classroom. This is most salient in the ClassTalk and ImageMap applications, where each student contributes an answer, and all answers are rapidly aggregated into a single representation. In planned extensions to the ImageMap, we take this strategy further so that an exploration can occur simultaneously with all students participating. The idea is that an unknown shape (perhaps a phase plot of a chaotic motion) can be generated by having many students each exploring different portions of the parameter space. As the plot fills in with different contributions, students can start to see regions that haven't been explored, and ones where something interesting might be happening. This intermediate representation can then direct their continued exploration, as they see what

they are building together (Pea, 1994). Aggregation across everyone also features prominently in Participatory Simulations. Many NetCalc/HubCalc scenarios involve students contributing individual mathematical objects to an overall aggregate representation that includes the whole class. Not only are all the students' responses aggregated, but they are also aggregated in a coherent representation that can be read and understood as a whole fairly easily. They are thus akin at a within-classroom level to the aggregate scientific visualizations in student-scientist partnership projects such as GLOBE, Global Lab, and KidsNet, in which students from disparate sites collect local data defined by scientific protocols that are then aggregated at a remote server and reflected back for interpretative discussions at local sites (Cohen, 1997). In contrast, in archetypal CSCL it is far more common for only 2 or 3 students to contribute to a shared representation (e.g., Single Display GroupWare). Or in cases with large numbers of contributors (e.g., Knowledge Forum), the aggregation emerges slowly and asynchronously and may not produce a cohesively readable overall representation.

Aggregating coherently across all students is particularly important because it enables quick formative assessments that can allow the teacher to "take the pulse" of learning progress for the classroom as a whole. Further, because all students have individual devices, the teacher can ensure that all students are participating individually. And because every student has a role in the aggregate representation, they may take a more active role in discussions; they are literally *represented in* the information structure that supports the instructional discourse, rather than *outside of it* as an information consumer. By contrast, in conventional CSCL, with multiple students crowded around one machine, freeloading is a common phenomenon and the teacher must visit each group of students to track progress.

4. Conducting classroom performances

It has become fairly common to describe the positive changes in the teacher's role brought about by CSCL as a move from "sage-on-the-stage" (teacher-centered instruction) to "guide-by-the-side" (teacher as coach, or guide to small group or individual learners working with educational technologies), an arrangement in which more attention can be given to understanding students' thinking and reasoning than with lecture-centric instruction. The move to "guide-by-the-side," however, is at least partially an artifact of desktop technology; there is literally nowhere else for the teacher to go when 2 to 4 students are crowded around a single monitor. In a WILD classroom, this physical constraint does not

apply, and it is not at all clear from our examples that the teacher will only be a "guide-by-the-side," as more interesting and powerful roles are possible. What then will be the apt metaphor for the role of the teacher in a WILD classroom?

The WILD applications above have in common a teacher role much more like the "conductor-of-performances" for an orchestra: students in a WILD classroom are contributing to an overall performance. In the ImageMap application (and especially the extended version described above), they generate an overall aggregate representation, with a coherent visual gestalt. In Participatory Simulations, they participate in a simulation run (like an emergently-choreographed performance). In SimCalc/NetCalc, they contribute to an overall animation. For all three cases, students contribute to a joint performance, verbally and with input technology. The teacher attends primarily to group performance, not to each individual student. Moreover, the teacher, like the conductor, has responsibility for choosing and sequencing the material to be performed (the curricular activities), interpreting the performance, and guiding it toward its desired forms. As in rehearsal, the conductor might direct groups of students to practice something alone, or in small groups. During performance, the teacher will work to ensure that all parts are heard, that everyone gives their best performance—directing attention towards the students who need the most encouragement while keeping the overall performance moving forward.

WILD technology provides a radical shift because, unlike personal desktop computers, it creates the communication and computational conditions that make collective performance with representations both possible and meaningful in the aggregate. In some ways, such collective performances share key elements of the sage-on-the-stage, but are more dialogic by design. Full group participation contexts will be featured more fully, and teacher-led discussion around the contributions of an individual or group will become more prominent. But unlike sage-on-the-stage, the teacher need not bear primary responsibility for filling in the turns of the representational and conversational space. WILD technology will readily facilitate contributions from students and groups that can create transformative learning conversations as the norm (Pea, 1994; Polman & Pea, in press), rather than those of information transmission. Moreover, like the conductor, the WILD paradigm puts the teacher naturally in a position to notice whether and how much each participant is contributing, and thus can help the teacher work on having all the students continuously working towards the classroom performance.

5. Act becomes artifact

The final application affordance we draw attention to is that WILD applications have the potential to *instrument the learning space* to collect summaries of messaging patterns and messaging content over longer timespans and over multiple sets of classroom participants to enable multi-level analyses of patterns of interactions and outcomes. Instant messaging (also called "texting" or SMS) is hugely popular among teens in countries where SMS is universally available on cell phones. We expect that messaging of text, representations, and data will become much more frequent in WILD learning spaces, and that the overall patterns of messaging, as well as message contents might be productively analyzed. Of our sample applications, this potential is most clear in the Exploratorium/museum examples; by giving individual visitors devices for interacting with exhibits, interesting use histories can be collected across a large set of visitors. Each visitor's exhibit interaction becomes a captured artifact; the database of interactions can be data-mined, analyzed, and reflected upon. (Earlier prototypes and policy issues raised by such "history-enriched digital objects" are outlined in Hill & Hollan, 1994). A teacher will be able to request an aggregate data set on what her students did with a particular exhibit. The class could then reflect back in the classroom on different phenomena they noticed in the exhibit. Researchers and designers may reflect on these results (with appropriate permissions concerning privacy of data), looking at the history of when the exhibit was used, how it was used, and what different classes of visitors did with it.

This possibility to mine the data generated in the "act becomes artifact" cycle is nascent in the other sample WILD applications. But it will become more prominent as classrooms become "persistently WILD." Since classrooms will spend much more time with personal, ready-at-hand WILD applications than they currently do with computers in labs, far more of the students' interactions will be captured on devices (and servers that aggregate the information). Further, the classroom communications networks can be instrumented to track information exchanges, so that patterns of exchanges can be examined. All electronically-mediated or "e-interactions" could be tagged with values for a broad range of parameters, including facts like time-stamp, user identity, institutional demographics, and response characteristics, but also user profile characteristics explicitly defined or tacitly inferred. The value of those "e-transactions" can be mined as to their properties in context and concomitant results. Once the WILD conversational acts are captured and indexed in the

flow of networked message transactions, the teacher and learners themselves may reflect on the patterns of their interactions.

Finally, the actual "workflows" required by a CSCL activity, such as a jigsaw classroom, can be directly enacted on the devices, so that the topology of the network and devices matches the conceptual topology of problem-solving roles and knowledge exchanges (thus an artifact, the curriculum, becomes more directly enactable).

These "act becomes artifact" possibilities will create significantly new CSCL research opportunities for applying computational data-mining methodologies (such as those used in bio-informatics, Witten & Frank, 2000), to unearth patterns of relationships between instructional transactions and learning outcomes. With conventional textbook curricula, researchers make a distinction between the bought curriculum (textbook), the teacher's planned curriculum, the taught curriculum (what is enacted in the classroom), and the learned curriculum. It is now very hard to get statistical data on more than the bought curricula, because of the difficulty of tracking what actually happens in the classroom; it is even harder to track what students learn in a fine-grained way. If WILD applications make CSCL activities more directly enactable in an instrumented networked classroom, it will become much more possible to track the taught curriculum. Further, if ClassTalk/ImageMap formative assessment techniques are easy to give as quick, take-the-pulse quizzes, information will be generated about the learned curriculum. Mining the correlations among the bought, planned, taught, and learned curriculum could create a very powerful research process for curriculum improvement. Yet these prospects have "big brother" like overtones of continuous surveillance. Much nuanced work will be necessary on privacy and security policies and safeguards so mining of the act-becomes-artifact cycle is devoted to services that help learners.

Augmented activity spaces emerge

We have suggested five WILD application affordances already illustrated by early handheld CSCL applications: (1) augmenting physical space; (2) leveraging topological space, of two distinct kinds; (3) aggregating coherently across all students' individual contributions; (4) conducting classroom performances; and (5) "act becomes artifact." Looking for the larger pattern in these directions, we see WILD-based CSCL leading to considerably different CSCL application types than those of the desktop: those more grounded in physical

space, about spatial relationships, simultaneously engaging whole classrooms, and encouraging a "conductor" metaphor for teaching more than one of "guide-on-the-side." Overall WILD-based CSCL seems headed towards augmented activity spaces.

These are early impressions, of course, and as WILD applications develop, new directions may become evident. In any event, the major point of our argument holds — the differing physical capabilities of personal, palm-sized computers and either wireless local-area networks or mobile ad-hoc networks create differing application-level affordances, which creates quite different potentials for CSCL. (For more on mobile ad-hoc networks, see http://www.ietf.org/html.charters/manet-charter.html.) Moreover, given how compelling handhelds are likely to be in the next few years, compared to bulky, expensive, complex desktop computers, we can expect that these differing application affordances will become very significant for the majority of innovators exploring K-12 learning situations. Today's archetypal CSCL applications include:

- *Distance Learning*: participation in a shared, possibly immersive, virtual space that mimics some characteristics of real learning spaces, e.g., a virtual campus and offices for teacher professional development organizations and participants using MOO technology (TAPPED IN: Schank et al.,1999).
- *Single Display GroupWare*: Side by side use of a shared, large display by a group of 2–4 students and (intermittently) a teacher (e.g., Dynagrams: Pea, 1992; Stewart et al., 1998).
- *Knowledge Spaces*: contribution to a shared conceptual space that organizes individual knowledge elements, such as OISE's CSILE (Scardamalia & Bereiter, 1994).
- *Messaging*: writing notes or messages to a partner or discussion forum (e.g., Honey et al., 1994).

Distance learning will still be a significant issue for universities seeking to broaden their audience to students who cannot readily come to class. But for the largely local and classroom-based K-12 audiences, "virtual spaces" inside tiny palmtop screens will not be compelling compared to the augmented physical spaces they will inhabit. Distance learning will still be interesting in the "act becomes artifact" sense, emphasizing comparative analyses across data from different sites, but not in the "communicating with a distant partner" sense.

However, assuming these devices spread popular instant messaging capabilities, and that these capabilities are active on the devices when students are on the bus, in the café, or at home, a new kind of "distance learning" may

emerge. After they leave class, teams of students may be able to coordinate ongoing groupwork more closely: they may engage in coordinating schedules, sending each other updated information, asking spontaneous questions of each other, all from various locations in their neighborhood. A common story from European countries is of groups of teenagers talking about messages coming in on cell phones as they sit in a café together. New and interesting patterns of CSCL may emerge where "groupwork" engages additional outsiders as a school-based group member is messaged while sitting among a non-school-based group. Thus, we speculate that analyses of messaging patterns, uses, and practices (presently a smallish specialty within CSCL) may grow in interest and importance. There are also intriguing prospects in this context for the WILD educational applications of COINs (community of interest networks), network services used in the business world to bring together individuals or organizations with common interests, concerns and/or values.

The CSCL thread that studies shared knowledge generated around shared screens (e.g., Dillenbourg & Traum, 1999) will change with WILD. Large shared screens will be less common than small personal screens, though a few large, public displays (such as in the ClassTalk application) will likely be very important. Suthers (2001) highlights the problem of following the "same" conceptual object as it moves around different displays. This problem will, we expect, become more prominent: how will students track "their" contribution as it gets beamed around to different displays, with differing representational characteristics, and amid derivative works? Further, among CSCL issues, it may be that the maintenance of *shared attention* will be more problematic with smaller screens, while the problems of negotiating control of a single mouse may be less problematic. In general, CSCL issues concerning how shared knowledge arises in a classroom with multiple representational devices with different technical characteristics and different user capabilities are likely to be rich.

Finally, we believe the creation of "knowledge spaces" within and across classrooms will have a very distinctive flavor with WILD classrooms. WILD lends itself more to creating knowledge spaces through peer-to-peer and multicast "synchronization" of contributions to the same semantic category than it does to client-server "construction" of contributions in complex, integrated, server-based systems. Frankly, we do not yet know about what peer to peer knowledge sharing systems for CSCL will be like, but chances are they will be more ad hoc, more diverse, more fragmentary, and more decentralized than today's client-server knowledge spaces. Creating appropriate synchronization capabilities among handhelds for classrooms (which we at SRI term

"ClassSync" in contrast to the PalmOS "HotSync": see Brecht, Chung, & Pea, 2002), such that knowledge spaces thrive, will be an interesting research area.

Speculations on new research directions

In closing, we envision research directions for CSCL in a future WILD age. Koschmann (1996) notes that educational technologies have evolved through the paradigms of CAI, ITS, Logo-as-Latin, and CSCL. The paradigms can be organized as two dialectic pairs of forces. Early debates focused on the relationship of student to computer: computer-controlling-student (CAI) vs. student-controlling-computer (Logo). This split was recast as the choice of computer as tutor (CAI), tutee (Logo), or tool (Taylor, 1980). Later, the debate split on the role of cognitive representations in educational technology (Lajoie & Derry, 1993) with an ITS camp emphasizing *information-processing-model-based interventions* to trace student cognition and compare it to normative models, another emphasizing computer-based models and their representations as a *semiotic intervention* mediating CSCL discourse among students and teachers, emphasizing contributions of socio-cultural theories of learning (e.g., Vygotsky, Leont'ev, and Rogoff).

We find that the *control* (tutor, tutee, tool) and *representational issues* (modeling the learner vs. mediating learner conversations) are insufficiently rich to organize the interesting R&D debates. We speculate that an interesting debate will form around the kinds of *system couplings* (Morrison & Goldberg, 1996) among the information in different distributed devices, and critical theory discourse around power relationships in schooling contexts (Apple, 1992; Segal, 1996). Overly tight coupling, where every information exchange among personal devices is centrally controllable and tracked, may be too close to Orwellian scenarios. Overly loose coupling, where each Palm is an information island, will not lead to interesting shared knowledge spaces and activity artifacts. The kinds of coupling needed may also diversify with different pedagogical strategies and activity designs. Some CSCL researchers have been turning to Activity Theory as fertile ground for design theory (e.g., Gifford & Enyedy, 1999), an approach that has attracted attention for CHI design generally (Bodker, 1991; Nardi, 1996). In an activity theoretic perspective, activity occurs within the framework of an objective and a community of other users, in which rules and roles affect participants' behaviors, and in which the outcome can become another activity or artifact. While not necessarily committing to the

different aspects of the social theory that guides such work, we find it useful for articulating different kinds of systemic coupling that may become important for CSCL. Activity Theory is a methodological framework with a core representation being the diagram displayed below (Figure 1, adapted from Nardi, 1996).
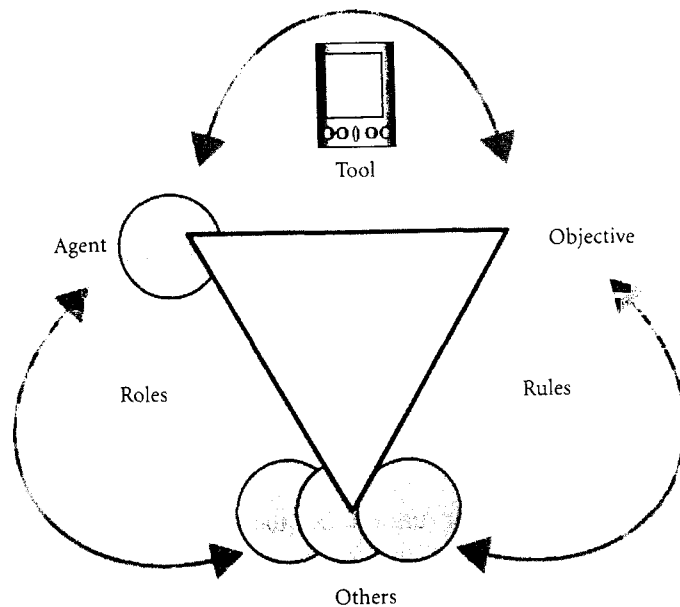

Figure 1. Activity Theory (adapted from Nardi, 1996)

The tutor, tutee, tool debate, as well as the representation debate, have largely focused on the topmost agent-tool-objective relationship of the diagram.

Tutor: Computer is the agent, student problem-solving behavior is the objective (goal), model tracing is the tool

Tutee: Student is the agent, a computer program written by the student is the objective, microworlds are the tools

Tool: Student is the agent, computer is the semiotic tool, shared knowledge is the object

With WILD, other parts of the framework become important system couplings. For example, "rules" and "roles" become important categories of coupling in the distributed system, especially rules that protect privacy, but also privilege-like rules about "roles" that define capabilities one is enabled to have with one's

device in specific situations, such as rules about who can make or take what kind of contribution to or from a knowledge synchronization system. This generative nesting is fertile for inventing new pedagogical activities in WILD settings; the coupling of the output of one activity to the next sequential activity, or within a hierarchical framework of activity becomes interesting. Further, "division of labor" becomes an interesting category of coupling, as students may choose to divide up multiple representations among multiple devices, to provide a larger overall screen space. Thus rules and roles interact.

In the past, debates focused on the *control issue* (tutor, tool, or tutee) or the *representation issue* (model tracing inventions vs. semiotic inventions). Whereas these clashes may continue in educational technology now, as far as WILD classrooms go, only the tool and semiotic perspectives make a good fit. We see little evidence that students want to be "tutored" by their personal devices, and while they may tweak parameters in simulations, or do constructionist activities with them, it is unlikely that Logo-as-Latin will be the primary paradigm, with students spending most of their time WILD programming. Moreover, while there will be many interesting uses of intelligent modeling in the data mining/ act-becomes-artifact sense, the low power of palmtops makes embedded intelligent model tracing unlikely. WILD is a much better fit for semiotic intervention with new forms of modeling and representation.

Going beyond these historical clashes over control and uses of representation, WILD will differ from traditional CSCL applications by creating a more distributed systems peer-to-peer network topology. The kinds of coupling and regulation of those couplings in such a system should be fertile ground for future innovation and controversy. Finally, Lemke's distinction between topological/typological representational systems will find new purchase in WILD activities, and there is much to explore in the prospects of geospatial and semiospatial representational systems for augmenting the physical spaces in which learning, teaching, and communication more broadly occur.

Notes

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1. "A SmartProbe combines a sensor, analog-to-digital conversion, a microcontroller, memory for saving its calibration, serial communication, and power-management circuitry all into one small, convenient package." (http://concord.org/themes/probeware.html)

References

Abrahamson, L., A. Davidian & A. Lippai (2000). *Wireless calculator networks: Why they work, where they came from, and where they're going.* Presented at the 13th Annual International Conference on Technology in Collegiate Mathematics, Atlanta, Georgia, November 16–19, 2000.

Apple, M. (1992). Computers in schools: Salvation or social disease? *The Education Digest,* 57(2), 47–52.

Bannasch, S. (1999, Fall). The electronic curator: Using a handheld computer at the Exploratorium. Concord *Consortium Newsletter.* (http://www.concord.org/library/1999fall/electronic-curator.html)

Bannasch, S. (2000, Fall). *Beam Me Up, Scottie!* Handheld computers extend the range of wireless communication in schools. *Concord Consortium Newsletter,* 4(3). (http://www.concord.org/library/2000fall/beam.html)

Bannasch, S. (2001, Spring). Wireless Computers and Probeware Support a New Science Curriculum: Using iPAQ Pocket PCs to study science fundamentals. *Concord Consortium Newsletter,* 5(1). (http://www.concord.org/library/2001spring/newscience.html)

Becker, H., & M. Reil (1999). Teacher and teacher-directed student use of computers and software. Irvine, CA: Center for Research on Information Technology and Organizations, University of California.

Bødker, S. (1991). *Through the interface: A human activity approach to user interface design.* Hillsdale, NJ, Lawrence Erlbaum Associates.

Brecht, J., M. Chung, & R. Pea (2002, January 7–11). CML — The ClassSync Modeling Language. *Proceedings of the 4th International Conference on Computer Supported Collaborative Learning.* Boulder, Colorado.

Cattagni, A., & E. Ferris (2001, May). *Internet Access in U.S. Public Schools and Classrooms: 1994–2000.* National Center for Education Statistics (NCES 2001–07).

CILT [Center for Innovative Learning Technologies] (1998). *Datagotchi deep dive: Imagineering a low-cost handheld mathematical tool for collaborative learning.* (http://www.cilt.org/images/DataGotchi.pdf)

Cohen, K.C. (1997). (Ed.). *Internet links for science education* (pp. 189–220). New York, NY: Plenum Press.

Colella, V., R. Borovoy & M. Resnick (1998). Participatory Simulations: Using computational objects to learn about dynamic systems. In *Proceedings of CHI '98,* Summary, (pp. 9–10), (Los Angeles CA, April 1998).

Colella, V. (2000). Participatory Simulations: Building Collaborative Understanding through Immersive Dynamic Modeling. *Journal of the Learning Sciences, 9(4),* (471–500).

Crawford, K., & C. Staudt (1999, Fall). A computer in the palm of their hands. *Concord Consortium Newsletter* (http://www.concord.org/library/1999fall/palm-computer.html).

Crawford, V., & P. Vahey (2002, March). *Palm Education Pioneers Program March 2002 Evaluation Report.* Available at http://www.palmgrants.sri.com.

Dillenbourg, P. J. & D. Traum (1999). Does a shared screen make a shared solution. In C. M. Hoadley & J. Roschelle (Eds.), *Proceedings of the Computer Support for Collaborative Learning (CSCL) 1999 Conference (pp. 127–135).* Palo Alto, CA: Stanford University [Available from Erlbaum Associates, Mahwah, NJ].

Dufresne, R. J., W. J. Gerace (1996). Classtalk: A classroom communication system for active learning, *J. Comput. in Higher Education, 7,* (pp. 3–47).

Engelbart, D. C. (1962, October). *Augmenting human intellect: A conceptual framework* (Summary Report, AFOSR-3233). Menlo Park, CA: SRI International. (http://sloan.stanford.edu/mousesite/EngelbartPapers/B5_F18_ConceptFrameworkInd.html)

Exploratorium (2001). *Electronic Guidebook Forum: Issues and Questions about Wireless Handheld Computers in Exhibition Spaces.* Report from the Exploratorium Workshop, San Francisco, CA, October 11 and 12, 2001 (http://www.exploratorium.edu/guidebook/forum/).

Gay, G., R. Reiger, T. Bennington (2001) Using mobile computing to enhance field study. In N. Miyake, R. Hall, & T. Koschmann (Eds.). *Carrying the conversation forward.* Mahwah, NJ: Erlbaum

Gifford, B. R. & N. D. Enyedy (1999). Activity-centered design: Towards a Theoretical Framework for CSCL. In C.M. Hoadley and J. Roschelle (Eds.), *Proceedings of the Computer Support for Collaborative Learning (CSCL) 1999 Conference (pp. 189–196).* Palo Alto, CA: Stanford University [Available from Erlbaum Associates, Mahwah, NJ].

Hill, W. C., & J. D. Hollan (1994). History-enriched digital objects: Prototypes and policy issues. *The Information Society, 10* (2), 139–145.

Honey, M., D. Bennett, N. Hupert, B. Kanze, T. Meade, E. M. Panush, K. Powell, R. Spielvogel, B. Dubitzky, M. Cohen, H. Melnick & L. Peterson (1994). The mathematics learning forum online: Using telecommunications as a tool for reflective practice. *Machine-Mediated Learning,* 4(2&3), 163–176.

Hutchins, E. (1996). *Cognition in the wild.* Cambridge, MA: MIT Press.

Kaput, J. (1992). Technology and mathematics education. In D. Grouws, (Ed.), *Handbook of research on mathematics teaching and learning (pp. 515–556).* New York: Macmillan Co.

Kaput, J., & S. Hegedus (submitted). *Exploiting classroom connectivity by aggregating student constructions to create new learning opportunities.* Paper submitted for presentation at the 26th Conference of the International Group for the Psychology of Mathematics Education, July 21–26, 2002, Norwich, UK.

Koschmann, T. (1996). Paradigm shifts and instructional technology: An introduction. In T. Koschmann (Ed.), *CSCL: Theory and practice of an emerging paradigm (pp. 1–23).* Mahwah, NJ: Lawrence Erlbaum Associates.

Kozma, R. B., J. Russell, T. Jones, N. Marx & J. Davis (1996). The use of multiple, linked representations to facilitate science understanding. In S. Vosniadou, R. Glaser, E. De Corte, & H. Mandel (Eds.), *International perspective on the psychological foundations of technology-based learning environments (pp. 41–60).* Hillsdale, NJ: Erlbaum.

Ledbetter, J. (2001, June 17). Wireless secrets and lies. *The Industry Standard* (http://www.thestandard.com/article/0,1902,27206,00.html?nl=int)

Lajoie, S. P. & S. J. Derry (1993). *Computers as cognitive tools.* Hillsdale, NJ: Erlbaum Associates.

Lemke, J. (1999). Typological and Topological Meaning in Diagnostic Discourse. *Discourse Processes, 27(2),* 173–185.

Mazur, E. (1997). *Peer Instruction — A User's Manual.* Princeton, NJ: Prentice Hall, Inc.

Morrison, D. & B. Goldberg (1996). New actors, new connections: The role of local information infrastructures in school reform. In T. Koschmann (Ed.), *CSCL: Theory and practice of an emerging paradigm (pp. 125–145).* Mahwah, NJ: Lawrence Erlbaum Associates.

Nardi, B., (Ed.) (1996). *Context and Consciousness: Activity Theory and Human-Computer Interaction.* Cambridge, MA, MIT Press.

Norman, D. A. (1994). *Things that make us smart: Defending human attributes in the age of the machine.* Perseus Press.

Pea, R. D. (1992). Augmenting the discourse of learning with computer-based learning environments. In E. de Corte, M. Linn, & L. Verschaffel (Eds.), *Computer-based learning environments and problem-solving* (NATO Series, subseries F: Computer and System Sciences) (pp.313–343). New York: Springer-Verlag GmbH.

Pea, R. D. (1993). Practices of distributed intelligence and designs for education. In G. Salomon (Ed.). *Distributed cognitions* (pp.47–87). New York: Cambridge University Press.

Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *Journal of the Learning Sciences, 3(3),* 283–298.

Pea, R. D., & L. Gomez (1992). Distributed multimedia learning environments: Why and how? *Interactive Learning Environments,* 2(2), 73–109.

Polman, J.L., & R.D. Pea (in press). Transformative communication as a cultural tool for guiding inquiry science. *Science Education.*

Rekimoto, J. (1998). A multiple device approach for supporting whiteboard-based interactions. In *Proceedings SIGCHI'98: Human Factors in Computing Systems (pp. 344–351).* Los Angeles, CA.

Ryle, G. (1949). *The concept of mind.* Oxford: Basil Blackwell.

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

Schank, P., J. Fenton, M. Schlager & J. Fusco (1999). From MOO to MEOW: Domesticating technology for online communities. In C. M. Hoadley and J. Roschelle (Eds.), *Proceedings of the Computer Support for Collaborative Learning (CSCL) 1999 Conference (pp. 518–526).* Palo Alto, CA: Stanford University [Available from Lawrence Erlbaum Associates, Mahwah, NJ].

Segal, H. P. (1996). The American ideology of technological progress: Historical perspectives. In S. T. Kerr (Ed.), *Technology and the future of schools.* Chicago: The National Society for the Study of Education, (pp. 28–48).

Shafrir, U. (1999). Representational Competence. In I. E. Sigel (Ed.), *Theoretical Perspecitives in the Development of Representational Thought.* New Jersey: Lawrence Erlbaum Associates.

Soloway, E., C. Norris, P. Blumenfeld, B. Fishman, J. Krajcik & R. Marx (2001, June). Log On Education: Handheld Devices are Ready-at-Hand. *Communications of the ACM,* 44(6), 15–20.

Soloway E., W. Grant, R. Tinker, J. Roschelle, M. Mills, M. Resnick, R. Berg & M. Eisenberg (1999). Science in the Palms of Their Hands. *Communications of the ACM, 42(8),* 21–27.

Staudt, C. (1999, Fall). Probing untested ground: Young children learn to use handheld computers. *Concord Consortium Newsletter* (http://www.concord.org/library/1999fall/untested-ground.html)

Staudt, C. & S. Hsi (1999, Spring). Synergy projects and pocket computers. *Concord Consortium Newsletter.* (http://www.concord.org/library/1999spring/synergyproj.html).

Stewart, J., E. Raybourn, B. Bederson & A. Druin (1998). When two Hands are better than one: Enhancing collaboration using single display Groupware. In *Adjunct Proceedings of SIGCHI'98: Human Factors in Computer Systems (pp. 287–288).* Los Ange. ... ...

Suthers, D. D. (2001, to appear). Towards a systematic study of representational guidance for collaborative learning discourse. *J. Universal Computer Science,* 7(3). (http://lilt.ics.hawaii.edu/lilt/papers/2001/)

Taylor, R. (1980) Introduction. In R. Taylor (Ed.) *The computer in the school: Tutor, tool, and tutee (pp. 1–11).* New York: Teachers College Press.

Thornton, R. K. (1997). Learning physics concepts in the introductory course: microcomputer-based labs and interactive lecture demonstrations. In J. Wilson (Ed.), *Conference of the Introductory Physics Course (pp. 69–86).* NewYork: Wiley & Sons.

Tinker, R. (1997, July 7). *The whole world in their hands.* Concord Consortium (http://www.concord.org/library/ pdf/future.pdf).

Tinker, R. & J. Krajcik (2001). (Eds.), *Portable technologies: Science learning in context.* New York: Kluwer Academic/Plenum Publishers.

Wilensky, U. & W. Stroup (1999). Learning through Participatory Simulations: Network-Based Design for Systems Learning in Classrooms Computer Supported Collaborative Learning. In C. Hoadley, Ed., *Proceedings of the 3rd International Conference on Computer Supported Collaborative Learning, CSCL '99.* Stanford, CA: Stanford University: December 12–15, 1999.

Wilensky, U., & W.M. Stroup (2000, June 14–17). Networked Gridlock: Students Enacting Complex Dynamic Phenomena with the HubNet Architecture. In B. Fishman & S. O'Connor-Divelbiss (Eds.), *Fourth International Conference of the Learning Sciences (pp. 282–289).* Mahwah, NJ: Lawrence Erlbaum Associates.

Witten, I. & E. Frank (2000). *Data Mining.* New York: Morgan Kaufman.

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