Designing Networked Handheld Devices to Enhance School Learning

Jeremy Roschelle

Charles Patton

Deborah Tatar

DRAFT – Not for citation

Please see the published version of the chapter:

Roschelle, J., Patton, C, Tatar, D. (2007). Designing networked handheld devices to enhance school learning. In M. Zelkowitz (Ed.) *Advances in Computers* Vol 70., 1-60.

Abstract

Handheld devices, especially networked handheld devices, are growing in importance in education, largely because their affordability and accessibility create an opportunity for educators to transition from occasional, supplemental use of computers, to frequent and integral use of portable computational technology. Why and how might these new devices enhance school learning? We begin by discussing a simple but important factor: networked handhelds can allow a 1:1 student:device ratio for the first time, enabling ready-at-hand access to technology throughout the school day and throughout the learner's personal life. We argue that designers need to understand the capabilities of the new generation of handheld computers and wireless networks that are most relevant for learning. We follow this with a discussion of Learning Science theories that connect those capabilities to enhanced learning. The capabilities and features feed into design practices. We describe a set of example applications that are arising from the capabilities, theories and design practices previously described. Finally, we close with a discussion of the challenge of scale.

Designing Networked Handheld Devices to Enhance School Learning

Jeremy Roschelle, SRI International
Charles Patton, SRI International
Deborah Tatar, Virginia Tech

I. Introduction

Handheld devices, especially networked handheld devices, are growing in importance in education, largely because their affordability and accessibility create an opportunity for educators to transition from occasional, supplemental use of computers, to frequent and integral use of portable computational technology (Soloway et al., 2001; Tinker & Krajcik, 2001). Yet educators have been excited about many waves of technology, from film projectors to audio tapes to personal computers and most waves of technology have failed to make a substantial impact in school learning (Cuban, 2003). Given the disappointing history of technology in education, why should we expect networked, handheld devices to be different?

We begin by discussing a simple but important factor: networked handhelds can allow a 1:1 student:device ratio for the first time, enabling ready-at-hand access to technology throughout the school day and throughout the learner's personal life (Chan et al., 2006). However, we will argue that merely increasing access to technology in schools and in students' lives is not enough. Time and time again, educational studies have shown that those technologies that make an impact in learning do so by changing how and what students learn (Roschelle et al., 2001). Further, successful technologies must be integrated into the social practices of schools, which require integration with teaching practices, curricula, assessments and school leadership. This is a difficult but very important challenge. It is difficult because schools are complex institutions with a dynamic of technology adoption that is quite different from enterprise or consumer markets. It is very important because 21st century societies are increasingly organized around knowledge work and innovation, both of which depend mightily on the high quality of school learning. Without utilizing technology in learning, it is hard to imagine how societies might produce sufficient gains in student learning to continue on successful paths of innovation and improvement in quality of life.

A rather large community of research has grown around this challenge, most recently calling itself the "Learning Sciences." (Sawyer, 2006). While networked handhelds present opportunities for learners of all ages, we focus here on the experiences, opportunities, and challenges of using handheld technology in K-12 education. To introduce readers to the broad scope of research relating to networked, handheld computers in K-12 education and falling under the rubric of the Learning Sciences, our article takes the following approach. First, we describe how a new generation of networked handheld technology is enabling students to have greater access to technology in their everyday lives, including school learning. We next review three historical examples of learning success utilizing high levels of access to handheld and/or networked technology. From this review, we draw the conclusion that handhelds can (and actually are already) making a huge difference in student learning. In addition, we observe that handhelds are not simply smaller personal computers. Indeed, these successful examples of technology-enhanced learning drew upon properties of networked handhelds that do not particularly characterize personal computers. Further, the historical success stories drew upon rich integration with social practices, suggesting that successful designers must think about more than the technology—they must understand how people learn and how schools work.

Having set this stage, our logic flows as follows. We argue that designers need to understand the capabilities of the new generation of handheld computers and wireless networks that are most relevant for learning. We follow this with a discussion of Learning Science theories that connect those capabilities to enhanced learning. The capabilities and features feed into design practices. We describe a set of example applications that are arising from the capabilities, theories and design practices previously described. Finally, we close with a discussion of the challenge of scale. Can new designs for technology-enhanced learning surpass the level of success already experienced with the three historical cases?

Increased Access Enables Frequent, Integral Use

Traditional desktop technology is expensive, and as a result, limited computer resources must be shared amongst many teachers and students. Today the typical student-computer ratio is 5:1, and computers are most often located in special computer labs rather than in ordinary classrooms (Cattagni & Ferris, 2001). The logistics of scheduling class time at the lab—and the time required to move students between rooms—greatly interferes with teachers' abilities to integrate computers into regular learning practices (Becker, 1999). Thus, despite school's enormous effort to acquire computer resources, there is often a gap between a school's advertised computational facilities and those that a teacher can realistically access [3]. This situation supports occasional, supplemental computer use at best and presents a challenge to integrating technology with other learning materials and activities in the classroom. Further, perfunctory use of technology limits the overall possible impact of computing in education: if an instructional resource is used infrequently, it is unlikely to have a large effect.

In contrast to traditional desktop computers, handheld devices are relatively inexpensive, allowing for each student to own a device or for teachers to have a classroom set with enough for every child. In addition, handhelds are mobile and flexible, allowing for easy use in and across classrooms, field sites, and home environments. Because of these unique characteristics, handhelds hold the promise of enabling many more students to experience integral uses of learning technologies. Indeed, graphing calculators—which are a well-established and effective handheld device—have reached far more K-12 learners than computers. Approximately 40% of high school mathematics classrooms use graphing calculators, whereas only 11% of mathematics classrooms use computers (NCES, 2001). Finally, because handhelds can be used much more frequently than traditional computer labs, they drastically increase the potential of computational technologies to positively impact the learning process (Consortium for School Networking, 2004).

Importantly, two qualities that have been most associated with successful learning through technology are frequency of use and integration of the technology into the classroom teaching experience. Wirelessly interconnected handhelds provide a unique opportunity to create a learning environment where technology is a transparent, non-invasive support to group learning (Cortez et al. 2005). Use of technology in the classroom should ideally extend beyond productivity tools and web browsing, to tools that allow more learners to master difficult concepts as they explore and interact with data and ideas. For example, computer simulations can enable 6th grade students to master Newtonian physics concepts at level that surpasses ordinary 12th graders (White, 1993). Early evaluations suggest teachers and students respond to handhelds favourably. In a study of 100 Palm-equipped classrooms, 90% of teachers reported that handhelds were effective instructional tools with the potential to impact student learning positively across curricular topics and instructional activities (Crawford & Vahey, 2002; Vahey & Crawford, 2002)

Researchers have used a variety of synonymous terms in referring to the use of digital technologies to support human learning. Terms used in the literature include: computer-assisted instruction, educational technology, educational computing, information and communication technology in education, and more recently, e-learning, distributed learning, asynchronous learning, and networked learning. In this chapter, we use the term technology-enhanced learning (TEL), where technology refers specifically to digital technology with graphic displays and keyboards, styluses, buttons or other affordances for hands-on input.

The notion of one-to-one computing (a ratio of at least one computing device for each student) was coined by Elliot Soloway and Cathie Norris. In their keynotes addressed in the IEEE International Workshop on Wireless and Mobile Technologies in Education (WMTE2002) and International Conference on Intelligent Tutoring Systems (ITS2004), they argued that today's "personal computer" is not personal to students at school, since students most often have to share with others at a computer lab. The researchers also pointed out that the process of learning changed when all students were able to afford a pencil and again when all students obtained their own books (Papert, 1980). A similar change can happen if everyone owns and regularly uses a personal computing device as an integral aspect of their learning experience.

Over next 10 years, we anticipate that personal, portable, wirelessly-networked technologies will become ubiquitous and pervasive in the lives of learners, both in and out of school. The rapid advancement of these technologies is already changing the lives of students outside of school (Dede, 2005; Tapscott, 1998; Howe & Strauss, 2000; Kasesniemi & Rautiainen, 2002; Oblinger, 2003; Rheingold, 2002). Indeed, in many countries, devices like mobile phones or graphing calculators already have a high adoption rate among school-aged children.

As these devices become affordable for the majority of parents and college students, mobile, connected, and personal devices will increasingly come to the attention of educational institutions. For example, the Massachusetts Institute of Technology (MIT) has proposed that $100 laptop computers be purchased for school-aged children by states (MIT, 2005). At the same time, wireless services and Internet access in many countries will become available in most schools and universities and in public areas, from coffee shops to libraries. For example, Google has offered to bring free wireless access to the entire city of San Francisco (Peterson, 2005).

While the expanded presence of mobile technologies is widely accepted, the specific form of personal, educational computing that will become most available to students is still controversial. Educators today talk about everything from mobile phones and notebook computers to Tablet PCs and personal digital assistants (PDAs). In addition to these general-purpose computing devices, many researchers advocate specialized designed-for-learning devices. For example, graphing calculators are commonly used in high schools in North America and many European countries. Electronic English dictionaries are commonly used throughout Asia (upgraded with wireless communication capability). With growing interest in the relationships between gaming and learning, students will also be able to use portable gaming devices for learning (Gee, 2003; Steinkuehler, 2004). In the near future, we can expect to see new types of devices emerging as well. The prices of these computing devices and network access will drop, according to Moore's Law and its corollaries (Moore, 1965).

As students increasingly use personal devices for learning outside of school, a new pressure in the adoption of learning devices in schools will emerge. Will students who come to expect mobile, connected, personal devices outside of school demand to use them within school? How will learning in classrooms and everyday life be transformed?

II. Historical Large Scale Successes

It is always difficult to predict how an emerging technology will take shape in a new area of application. Prediction is especially difficult without a sense of history. The biggest misconception about handheld, networked technologies in education is that they are new. To the contrary, at least three handheld and/or networked technologies are already in successful, widespread use. To design for the future, we ought to begin by understanding the past. Hence, we begin with a review of three historical successes: graphing calculators, classroom networks, and probeware.

Graphing Calculators

Graphing calculators have become one of the most widely adopted handheld technologies in education. In the United States, for example, about 40% of high school students own graphing calculators, and even higher percentages use school-owned devices in the classroom (NCES 2001). Graphing products are now integrated with national and state standards (e.g., National Council of Teachers of Mathematics, 2000) and they are supported in some curricula. Furthermore, best practices of instruction are well-documented (Burrill et al., 2002; Seeley, 2006) and teacher professional development offerings are widely available.

Pedagogical Affordances of Graphing Calculators

Like other hand-held instructional technologies, graphing calculators are inexpensive, mobile, and readily adaptable to existing classroom practices. These qualities—combined with the instructional affordances of the technology itself—mean that graphing calculators have a powerful potential to help students master important concepts in mathematics. Employed as an instructional technology, graphing calculators can enable teachers to foster a problem solving approach to mathematics and help students to reason mathematically. The unique contributions of graphing calculators to problem solving and reasoning include:

Increasing attention to conceptual understanding and problem solving strategies by offloading laborious computations;

- Examining the related meanings of a concept through the display of multiple representations, such as exploring rate of change (i.e. slope) in a graph and table;
- Engaging students with interactive explorations, real world data collection, and more authentic data sets;
- Giving students more responsibility for checking their work and justifying their solutions.
- Introducing topics that were previously too difficult for many students (e.g. modeling); and
- Providing a supportive context for productive mathematical thinking.

Students with calculators can take on traditional tasks in new ways and also tackle new topics that would otherwise be inaccessible. Rather than laboring over tedious calculations, classes that use calculators can devote more time to developing students' mathematical understanding, their number sense, and their ability to evaluate the reasonableness of proposed solutions. Students can also use calculators to explore concepts and data sets that would otherwise be too complex or cumbersome. For example, students can easily investigate the effects of changing a, b, and c on the graph of ax2 + bx + c, which can be quite tedious using paper and pencil graphing techniques.

Research has also shown that students can often reason best when they experience mathematics through related representations, such as equations, tables, and graphs (Ellington, 2003; Khoju, Jaciw, and Miller, 2005). Graphing calculators can make constructing and using multiple representations easier, allowing students to spend more of their time and intellectual energy exploring the underlying concepts. In addition, technology can link the representations, enabling students to make conceptual connections, such as understanding how a change in an equation links to a change in a graph. Standard mathematical representations can also be linked to other visualization aids, fostering further conceptual understanding.

Research has also shown that students using graphing calculators change their approaches to problem solving: they explore more and their attempted solution strategies are more flexible (Ellington, 2003; Khoju, Jaciw, and Miller, 2005). In general, students who use calculators better understand variables and functions and are better able to solve algebra problems in applied contexts than students who do not use calculators. Similarly, students who use calculators use graphs more often and interpret graphs better than students who do not regularly use the technology. Finally, students who use calculators are better able to move among varied representations—that is from graphs to table to equations—than students who do not have access to the technology. Clearly, students who regularly use calculators have an advantage over those who do not. Moreover, those who use calculators most frequently see the greatest gains.

Research on Graphing Calculators

When it comes to instructional technologies, educators and policymakers want more to do more than merely identify potentially beneficial tools. In addition, they want concrete guidance on how to achieve an effective implementation and confidence that large-scale implementations will also be successful. Fortunately, strong graphing calculator research is available to address these concerns.

In the United States, the National Assessment of Education Progress (NAEP) samples both 4th and 8th graders throughout the country and measures how many students perform at proficient and advanced levels in mathematics. This research has consistently shown that frequent use of calculators at the eighth grade level (but not at the fourth grade level) is associated with greater mathematics achievement, stating:

Eighth-graders whose teachers reported that calculators were used almost every day scored highest. Weekly use was also associated with higher average scores than less frequent use. In addition, teachers who permitted unrestricted use of calculators and those who permitted calculator use on tests had eighth-graders with higher average scores than did teachers who did not indicate such use of calculators in their classrooms. The association between frequent graphing calculator use and high achievement holds for both richer and poorer students, for both girls and boys, for varied students with varied race and ethnicity, and across states with varied policies and curricula (National Center for Education Statistics, 2001, p. 144).

A study by Heller (2005) corroborates the NAEP findings. Heller examined a model implementation, which included a new textbook, teacher professional development, and assessment tools—all aligned with the graphing technology by the theme of Dynamic Algebra. This study shows that daily use of graphing calculators is generally more effective than infrequent use, and establishes that the teachers and students who used graphing calculators most frequently learned the most.

An Example from New Zealand

Researchers in different settings have investigated the effectiveness of graphing calculators in relation to students, teachers, and schools with diverse characteristics. Alan Graham and Michael Thomas, for example, examined the effectiveness of graphing calculators in algebra classrooms in New Zealand (Graham and Thomas, 2000). The study compared pretest and posttest scores for students in treatment and control group classrooms in two schools. In all of the classrooms, the regular classroom teacher taught the "Tapping into Algebra" curriculum module. In treatment group classrooms, each of the students received a graphing calculator to use throughout the module; in control group classrooms, students did not use graphing calculators. Students in all classrooms had similar background characteristics and math abilities. Graham and Thomas found that students in the treatment groups performed significantly better than students in the control groups on the post-test examination.

Meta-Analyses show the effectiveness of graphing calculators

Meta-analysis is a technique that enables researchers to statistically summarize the results of a large body of experimental studies, yielding a robust estimate of true effectiveness. A meta-analysis by Ellington (2003) summarized 54 classroom experiments, of which 80% employed some form of random assignment of students to experimental groups (using calculators) and control groups (not using calculators). Random assignment is a key component of true experimental studies, as it allows social scientists to make strong causal inferences with the fewest threats to experimental validity (Cook & Shadish, 1986). Ellington's analysis shows a positive effect of graphing calculator-based interventions on student achievement. The effects are substantial, often increasing an average student's achievement by 10 to 20 percentile points (Ellington, 2003). In addition, the studies suggest that when graphing calculators are allowed on tests, gains extend from calculations and operations to conceptual understanding and problem solving. Ellington's summary includes a wide variety of grade levels, socio-economic backgrounds, geographic locations, and mathematical topics, suggesting that the effectiveness of calculators holds true in a variety of contexts.

A second meta-analysis looked specifically at Algebra. Khoju, Jaciw, and Miller (2005) screened available research using stringent quality-control criteria published by the U.S. Department of Education's What Works Clearinghouse. They found four suitable studies that examined the impact of graphing calculators on Algebra learning. Across a wide variety of student populations and teaching conditions, use of graphing calculators with aligned instructional materials was shown to have a strong, positive effect on Algebra achievement.

Why have calculators been so successful?

A number of key features contribute to the success of graphing calculators in bolstering math learning. Graphing calculators are relatively simple, robust and cheap; they are also remarkably free of much of the complexity that accompanies full-featured computers. More importantly, there is a deep scientific linkage between the capabilities of the technology and how people learn. Students learn best with increased learning time, scaffolding, formative assessment, and opportunities for reflection and revision—qualities that can be achieved with graphing technology.

Two less readily obvious factors also contribute to the success of graphing calculators. First, the adoption of the technology has been led by practicing teachers, who function as the key champions and influencers in a professional community (Ferrio, 2004). Second, efforts to integrate graphing calculators into classrooms did not begin with the expectation of a rapidly transformed classroom, but rather provided a context to support a long, steady trajectory of continuous improvement (Demana and Waits, 1997). In this way, teachers can begin with one or two relatively simple applications of the technology, and gradually increase the depth and breadth of their calculator integration as they grow more comfortable with the technology. At each stage, graphing calculators can provide concrete enhancements for teaching and learning math.

In summary, the evidence for the impact of calculator use on student achievement is robust and consistent. Graphing calculators are inexpensive and can align with curricula, instructional practices, and assessments. In addition, teacher professional development for integrating graphing calculators into classroom practices is widely available. Collectively, the combination of curricula, pedagogy, assessment, and technology—aligned through professional development—creates the circumstances for sustained improvement in deep conceptual learning.

Classroom Response Systems (Feedback)

A second effective handheld learning technology is the networked response system. The first notably successful classroom response system, Classtalk, was patented in 1989 (Abrahamson et al., 1989), and similar product concepts have since been re-implemented many times*. A major benefit of these networked response systems is that they have enhanced classroom communication between the teacher and the students. Employing a combination of networking hardware and software, networked response systems provide displays that reveal what students are doing, thinking, and understanding. Teachers can use the information provided through classroom networks to augment the natural communication flow of the classroom.

Instructional Processes Using Networked Response Systems

From a technological viewpoint, a classroom network can be thought of as a tool

---

* Eleven current commercial products have been identified. Examples include:
eInstruction (http://www.eInstruction.com),
TI-Navigator (http://education.ti.com/us/product/tech/navigator/features/features.html), and
Discourse (http://www.ets.org/discourse/)

to augment the interaction loop between teacher and students. The concept of interaction loops builds upon Weiner's pioneering work in cybernetics (Weiner, 1948). A traditional loop opens when the teacher assigns an activity to a student and continues when the student turns in the assigned work to the teacher. The loop is completed days later when the teacher returns the graded assignment to the student. In this model, only a few students are involved in the process of sharing their work, there is very little discussion after a question has been answered, and for the majority of students there is a long delay before they receive any response from the teacher.

In contrast, the networked loop demonstrates classroom interaction occurring much more rapidly and with a smaller-sized task. In this context, an activity might be a request to answer a question, solve a problem, state a position, write an equation, or give a reason. Students provide their responses as input into a personal computing device, such as a graphing calculator, palm-sized computer, laptop, or even a special-purpose device similar to a TV remote. Then, the teacher's desktop machine collects and aggregates the student work, and presents it in a meaningful graphic that teachers and students can interpret quickly.

Pedagogical Affordances of Networked Response Systems

Teachers and researchers have found that the ability to harvest students' work immediately has a range of applications. In the simplest case, a teacher poses a multiple-choice question, and the classroom network rapidly produces a histogram showing the distribution of responses in the classroom. Seeing the histogram makes it easier for both teachers and students to focus on what needs to be learned and to engage in discussion around those topics. In slightly more sophisticated cases, students mark a point on an image or show the line they graphed. These points, lines, or even motions can be aggregated instantly to reveal higher-order patterns (Hegedus & Kaput, 2003). In some of the most advanced uses of networked response systems to date, students engage in a participatory simulation ("part-sim".) For example, each student controls a traffic light in a classroom simulation of traffic patterns shown on the public display. Then the class collaborates to identify some of the principles of operation that would allow traffic to flow smoothly (Wilensky & Stroup, 2000).

Even the most basic usages of networked response systems can profoundly impact teaching and learning in the classroom setting. Teachers and students can use the readily interpretable data generated by the network to observe patterns and differences among student responses. By revealing how students are thinking, the response comparisons also enable teachers to drive all students to explain their thought processes more thoroughly. The shared points of reference provided by the system, in conjunction with inquiries from the teacher, can in turn catalyze class discussions of complex concepts. Harvard's Eric Mazur, an early leader in developing the pedagogical use of networked response systems, calls this approach "Peer Instruction" (1997b), suggesting that the real heart of the learning occurs when students engage with each other conversationally on the basis of the dissonances revealed by the shared display.

In spite of the fact that networked response systems execute a fairly simple function, early adopters have consistently described the technology as a catalyst for a significant, powerful shift in the classroom climate, pedagogy and resulting learning (Abrahamson et al., 2000; Davis, 2003; Dufresne et al., 1996; Owens et al., 2002). Formative assessment is known to be a very powerful intervention (Black & Wiliam, 1998) and these systems enable students to receive much more feedback than normal. In addition, students can see where classmates share their misunderstandings and recognize that they are not alone. It is important to note that the overall impact of the lesson need not be at all test-like. Student work can be displayed anonymously, so that embarrassment is essentially eliminated (Owens et al., 2002). Finally, real-time information about students' comprehension enables teachers to modify instruction to meet the needs of learners.

The above discussion suggests that effective implementation of networked response systems requires integrated roles for the teacher and the technology, as well as a combination of pedagogical technique and computational capability. The role of the technology in transforming classroom learning is small but extremely valuable. In particular, the technology provides anonymity, speed of response collection, and the ability to produce a shared visualization that enhances mutual pattern recognition. But non-technological social processes still carry much of the burden of teaching and learning: asking questions, explaining, clarifying, summarizing, etc.

The most recent and thorough examinations of this technology (using Texas Instruments graphing calculators and a supplementary networking product) emphasize a virtuous cycle of changes that result in a classroom that uses the system (Davis, 2003; Owens et al., 2002). The cycle maps onto the four factors of successful classrooms identified in a groundbreaking summary of learning science research (Donovan et al., 1999). The classroom becomes more learner-centered, assessment-centered, knowledge-centered, and community-centered. These are powerful and apparently robust effects from a fairly simple use of networked response technology. Further they do not appear to be limited by subject matter, and can be significantly extended beyond the range of multiple choice and short answer questioning. For example, 'image map assessments' have been proposed in which students' marks on images are aggregated (Roschelle & Pea, 2002). Others are working at Cartesian aggregation spaces of contributed mathematical functions (Kaput, 2002). Many more kinds of classroom response aggregation are possible. Clearly, pedagogical application underlying networked response systems deserves much more research attention in the coming years.

Mazur's Peer Instruction

In an effort to improve his students' gains-scores on an introductory physics assessment, Mazur pioneered a new style of classroom practice that relied on augmented teacher-student communication and increased classroom discussion around important concepts. Mazur's new practice began with what he termed a "ConcepTest"—a challenging question designed to foster thinking and discussion that gets at the heart of the target concept. Mazur would pose a ConcepTest to his students, allow them to ponder the answer, and have them submit a response via the classroom network. Based on the percentage of students who answered correctly, Mazur adapted his subsequent instruction by moving on to the next topic, or by spending more time on the subject until mastery was achieved. If a question uncovered lots of misconceptions, Mazur would facilitate discussion, encouraging students to explain and debate their understandings. These kinds of discussions focus on understanding the correct conceptual structure because, while questions are superficially simple, they are laser-like in their ability to demarcate misconceptions and stimulate valid reasoning.

The process of discussing possible responses, misconceptions, and conceptual understandings amongst peers, through ConcepTests and networked response technology, lies at the crux of Mazur's pedagogical approach. He calls this process Peer Instruction. In his written work on this topic, Mazur emphasizes the strategic planning and classroom practice that are required for a teacher to implement Peer Instruction. As with other instructional technologies, classroom networks can provide critical enablers for enhanced teaching and learning, but it is pedagogical talents that make the innovation successful.

Mazur shows that in the year he first implemented his Peer Instruction methods, the distribution of scores on the Force Concept Inventory (a standard assessment of student understanding in Physics) shifted markedly from pretest to posttest, suggesting that his new approach was effective (1997a). Impressively, after the posttest only 4% of students were below the threshold of mastery as defined by the Force Concept Inventory (FCI). There is a steady improvement in scores in each subsequent year over a decade, even though students' incoming scores did not change (Crouch & Mazur, 2001). Mazur also compared the scores of his 1985 class with those of the 1991 class by giving them the same final exam. He found that the scores shifted upwards about 10% and manifested a much narrower distribution, showing that he had achieved an important impact on many of his students' conceptual understanding (Mazur, 1997). He also examined students' responses to more conventional physics problems (stressing mathematical manipulations) versus conceptual problems and argued that while conceptual understanding improved, students' ability to solve the more conventional problems was not compromised (Mazur, 1997).

A review of the effects of networked response systems

The following table illustrates the primary impacts of networked response systems, with the most frequent findings listed first. As the table indicates, the two most commonly reported effects are increased student engagement and improved conceptual understanding. More than half of the studies reported that students were more engaged—as evidenced by their attention and attendance in class—in classes where CATAALYST was used. Another eight studies reported increased student interest and enjoyment in these classes, which in turn probably contributed to higher levels of engagement. Just under half of the studies also reported gains on learning outcomes, as measured by end-of-course objective tests and standardized achievement tests. Although few of these studies used any comparison group and none placed statistical controls on comparison groups, increased student understanding of complex subject matter was widely reported. Other commonly reported outcomes included increased "interactivity" and group discussion, as well as increased awareness among teachers and students of the difficulties students faced in mastering subject matter. In addition to the impacts highlighted in this chart, a handful of studies also reported "more pressure on students to think" (Abrahamson, 2000), students coming to class more often (Mazur 1997; Davis, 2002), and reduction in student anxiety (Davis, 2002).

Table 1: Reported Benefits of Networked Response Systems

Claimed Benefit	Research Studies Citing Benefit
Promotes greater student engagement (16)	(Boyle & Nicol, 2002) (Burnstein & Lederman, 2001) (Crouch & Mazur, 2001) (Cue, 1998) (Dufresne et al., 1996) (Fagen, Crouch, & Mazur, 2002) (Kaput & Hegedus, 2002) (Horowitz, 1988) (MacDonald (1999) (Poulis et al., 1998) (Ratto et al., 2002) (Robinson, 2002) (Scheele, Mauve, & Effelsberg, 2002) (Webking, 1998) (Foundation, no date) (Woods & Chiu, in press)
Increases understanding of complex subject matter (11)	(Abrahamson, 1998) (Boyle & Nicol, 2002) (Crouch & Mazur, 2001)

	(Fagen, Crouch, & Mazur, 2002) (Hake, 1998b) (Hartline, 1997) (Kaput & Hegedus, 2002) (Poulis et al., 1998) (Sokoloff & Thornton, 1997) (Wilder Foundation, n.d.) Woods & Chiu (in press)
Increases interest and enjoyment of class (7)	(Abrahamson, 1998) (Boyle, 1999) (Boyle &Nicol, 2002) (Burnstein & Lederman, 2001) (Cue,1998) (Dufresne et al., 1996) (Woods & Chiu, in press)
Promotes discussion and interactivity (6)	(Boyle & Nicol, 2002) (MacDonald, 1999) (Robinson, 2002) (Scheele, Mauve, & Effelsberg, 2002) (VanDeGrift, Wolfman, Yasuhara, & Anderson, 2000) (Woods & Chiu, in press)
Helps students gauge their own level of understanding (5)	(Dufresne et al.,1996) (Ganger & Jackson, 2003) (Piazza, 2002) (Robinson, 2002) (Webking, 1998)
Teachers have better awareness of student difficulties (4)	(Abrahamson, 1998) (MacDonald, 1999) (McNairy, 2002) (Robinson, 2002)
Extending material can be covered beyond class time (2)	(Ratto, Shapiro, Truong, & Griswold, 2002) (Truong et al., 2002)
Students do more thinking in classrooms (2)	(Boyle & Nicol, 2002) (Cue, 1998)
Improves quality of questions asked (1)	(Ratto et al., 2002)
Overcomes shyness (1)	(Truong et al., 2002)
Saves time (1)	(Boyle, 1999)
Simplifies record keeping (1)	(Webking, 1998)

Why Have Networked Response Systems been so Successful?

A number of key features contribute to the success of networked response systems in bolstering learning. Importantly, classroom response technology accommodates common teaching practices while also offering new enhancements for classroom teaching. Like graphing calculators, response systems are also relatively simple, robust, and cheap, and there are purposeful linkages between the technology and insights from the learning sciences. In addition, response systems address a specific classroom need—namely, enhanced communication and feedback among teacher and students. Of course, effective teacher implementation of classroom communication practices is a critical component of improved student performance. Yet network technology can be a key enabler of this improved communication and feedback by facilitating rapid cycles of assigning, collecting, interpreting, and discussing student work.

Probeware

Of all the instructional technologies for science classes, the technology with the longest track record is that of electronic probes and sensors and associated software (hereafter, "probeware"). Used in classrooms, probes instantaneously gather and graph data from live experiments (Mokros & Tinker, 1987; Nachmias & Linn, 1987). It is hard to overstate how important this is in classroom learning. Before probes were readily available, students typically gathered data in class, graphed it at night, and analyzed it the next day. An enormous "gulf of evaluation" (Norman, Design of Everyday Things) thus lay between collecting the data and making sense of it. By the time students were interpreting data, they often could barely remember what it was about. Further, students are often careless in collecting data, leading to a 'garbage in, garbage out' problem. Because of the pace of school, teachers must often ignore these bad data sets and simply move on to the next topic. This sends students a very poor message about the nature of scientific inquiry. Consequently, the ability to collect, graph, and analyze a whole series of experiments in one class period is a radical innovation. By closing the gulf of evaluation, probes support the long-term pedagogical drive towards 'inquiry-centred' science classrooms (Tinker & Krajcik, 2001).

Teachers can now purchase a variety of kits that enable students to collect data from experiments using a computer or graphing calculator with attached probes or sensors. Probeware can be used in all areas of science: pH sensors in Biology, pressure probes in Chemistry, and motion recorders in Physics. They can be used in the classroom, but are also commonly used in the field. A very popular scenario for using handheld probes is water quality evaluation (Vahey & Crawford, 2002). Students take their handhelds and probes to a nearby stream and each student takes measurements at different points along the streambed. The students combine their data by beaming or aggregating onto a common teacher machine. Back in the classroom, students use their handhelds to graph and analyze the combined data set.

In a conventional lab experience, students gather their data during class, graph the data that night at home, and discuss it the next day in class. Unfortunately, if students collect inaccurate data, they might not discover it until they get home, when it is too late. Even if they have accurate data, by the time they graph it, they may forget what it means. By the time they discuss the data in class, 24 hours have elapsed and students have likely forgotten the questions and ideas that were elicited by the lab experience.
Probeware addresses all these problems. The major benefits of using probeware are:

- Ease of collecting and recording accurate data
- Ability to collect time series data
- Use of the computer or calculator for instant graphing and analysis of data
- Possibility of exchanging or pooling data sets among students

Probeware, used well, can open avenues of exploration for students as they use it to experiment with phenomena of their choosing. Students using probeware experience less tedium in setting up their experiments and focus more on the research questions and the data. This can focus students on the science meaning behind the data instead of the rote procedures for collecting data in a valid way. Students can also collect more observations than manual methods allow, permitting more comparisons and hence, better generalizations. Through the immediacy of data collection and data display, probeware directly connects observation in the real world to abstract representations and allows for the investigation, variation, and play that provide better understanding of important scientific concepts.

Probeware has also been shown to support data collection by students for scientific research at a world-wide scale. The GLOBE environmental monitoring program teams scientific researchers studying local, regional, or global questions with students and community groups who provide on-the-ground data collection in a scientifically valid way. Data is reported to a central database and can be analyzed by both students and scientists for their own investigations.

Studies (Tinker and Krajcik, 2001) indicate that students who learn with curricula that include probeware take a more active role in their learning and are taught to use skills of observation. Collaborative learning is naturally supported by the ability to share displays of data and integrate others' findings. Finally, students who learn with these manipulatives show better retention of concepts that those taught in a lecture format.

Research

While there has been a significant volume of research showing that probeware can help students learn to do inquiry, there has been much less research documenting the impact of probeware on science content learning. In their study of a probeware-supported inquiry unit on water-quality, Krajick and Starr (in Tinker and Krajick, eds., 2001) aimed to examine the impact of project-based learning and probeware on science content learning. The water-quality unit was taught by two science teachers, to about seventy 7th grade students in four classes at Greenhills Middle School. The Greenhills School devotes ample attention to integrating innovative teaching methods, through professional development, technology and curricula—thus making them distinct from other schools and teachers. As a result, the researchers decided that control classrooms, either outside the school or with different teachers at the same school, would not provide a valid comparison group for the study. Instead, the researchers used assessments aligned with national standards in order to show that an innovative learning environment employing project-based learning and probeware technology can result in important learning outcomes for students (Tinker & Krajick, p.105).

In order to get an understanding of student learning, the researchers used three tools to assess students' content knowledge and their ability to apply target concepts to new and unique situations. The first tool was a test consisting of multiple-choice, short-answer, and extended-answer items which students took before and after the unit. Students were also required to draw pre- and post-unit 'concept maps' illustrating their understanding of the factors and linkages related to water-quality. Finally, students created booklets, which they added to at each of three visits to the field. The extended-answer questions, as well as the concept maps and science booklets, were evaluated using precisely defined assessment rubrics.

Statistical analyses comparing the pre- and post-test results for each of the various types of assessments revealed that students made significant gains in both basic content knowledge and deeper conceptual and analytic understandings of water quality (Tinker and Krajick, 2001). Furthermore, large effect sizes associated with the mean-score increase from pre- to post- measure indicate that the scores were not only statistically different from one another, but that the gains themselves were substantial. Because students were not concurrently participating in other related science interventions, it can be surmised that the project-based, probe-ware program was responsible for the student gains.

The two teachers who implemented this science curriculum wrote about their perspectives on the benefits to students of using probe-ware in a project-based learning environment. First of all, teachers felt that students' relationship with the technology improved over time: students learned to trouble-shoot problems on their own; they began to understand instrument calibration; and they learned to properly care for and maintain their tools. In addition, use of the technology benefited students' attitude toward science learning. Because the project was rooted in students' real-world environment, they viewed the process and the data as meaningful. In turn, students felt ownership in their own work, were excited to interpret their data, and were intent on finding ways to support their research and findings. Finally, teachers felt that the experience also had a positive impact on students' in-depth understanding of water quality, and on their thinking and learning skills in general. Teachers found that students improved in their ability to analyze and synthesize data, to understand the implications of data, to create more comprehensive pictures of the situation under investigation, to make connections between data and key environmental factors, to identify patterns and trends in data, and to understand relationships in the field (in Tinker and Krajick, Eds., 2001).

Discussion

The three historical examples presented above are important, in part, because they demonstrate that networked handhelds have produced worthwhile improvements in school learning. In the case of graphing calculators, the improvements have occurred at scale seldom seen in educational technology: around 40% of high school students have a graphing calculator and the data from numerous studies is consistent and positive. We see graphing calculators as representational tools; they allow students to engage with mathematics in both linguistic (e.g. algebraic symbols) and graphic ways. Research shows that providing students with multiple, linked representations—and especially a combination of linguistic and graphical representations—can produce powerful learning gains. Networked response systems, on the other hand, work through a different mechanism. They are participatory and feedback tools, which in the presence of a capable teacher can transform classroom dynamics to increase student engagement in learning. Probeware incorporates elements of representation (instantly graphing data) and feedback (students can quickly see if they are getting bad data) but also change how students experience physical place—students can more easily measure and quantify their world and can thus more readily engage in scientific inquiry. In the sections that follow, we will continue to build upon these aspects of historical success.

We draw a second important set of conclusions from these examples as well—namely, that our imagination of the meaning of networked handheld devices should not be overly constrained by a vision of anytime/anywhere access to school information or a vision of handhelds as small computers. Some researchers are drawn to thinking about how school information could be made available anywhere. They imagine how learning might be improved if students could see their class schedules online, review their grades, retrieve homework, submit assignments, ask questions of their instructor, and so on . . . all with a personal, low-cost, mobile, wireless handheld device. There are two problems with this vision. First, it relies on placing an interface to instructional management and learning tools on a small screen with limited input possibilities. Second, access to administrative information is unlikely to have an impact on how students learn.

Other researchers imagine handhelds as small, inexpensive computers. They seek to package all of the complexity found in computer applications into a handheld format. It is important to note, however, that the most successful historical examples involve rich social practices built around rather simple (but uniquely functional and reliable) technology. A number of important lessons emerge from the realization that instructional technologies tend to be most effective when simple and efficient technologies are combined with sound pedagogical techniques (Carroll, 1998). This finding indicates, for instance, that restraint is a valuable quality when designing instructional technologies. Rather than trying to create an all-encompassing system, we utilize technology for specific, targeted affordances for tasks that are not well served with the process and pattern already in place in the classroom. Talking and passing out papers are integral parts of handheld-based activity. Students should not struggle to read instructions about an activity on the same tiny screen on which they are conducting the activity when paper-based or white-board based instructions work very well. Furthermore, teachers we have studied prefer students handing in work on paper, for later grading in their easy chair.

The examples of graphing calculators, networked response systems, and probeware emphasize this direction towards simple, well-honed technology and rich, pedagogically developed social practices. In each case, the technology performs a small, precisely-defined function uniquely well, but much of the rest of teaching and learning is left to social practice. Probeware excels at collecting and sharing data, and little else. Yet it supports a transition from routine, unexamined scientific practice to inquiry-based practice in the classroom. In networked response systems, the questions are often authored and posed to the class offline, and the technology performs only the essential functions of gathering responses anonymously and instantly summarizing them in a publicly displayed histogram. Yet the system promotes critical thinking as students and teachers compare, elaborate, explain, critique, and debate about the patterns of response.

The participatory simulation variants of networked response systems excel at exchanging small, extremely simple data messages among spatial neighbors. Yet students can readily become socially involved in designing experiments. For example, they can try to slow the spread of disease by quickly assigning those infected to quarantine, or by having fewer social partners. As evidenced in all of these examples, the technology serves to enable new types of instruction, yet much of the actual learning occurs in lesson-design and debriefing phases that are not mediated directly by the technology.

This fairly weak coupling of informatics and social practice results in many seemingly ironic outcomes. For example, the essential pattern of the classroom can become one of 'peer learning' despite a technology that has no peer-to-peer communication capabilities (such as Classtalk). The sense of community in the classroom can evolve rapidly, despite the lack of any 'online community' tools. Students become more involved in designing and interpreting controlled experiments, despite software that has no sense of variation in parameters. (To perform an experiment with participatory simulations, students only change their spatial movement; the software has no knowledge that it is involved in a 'different' experiment. The parameters are embodied by the students and are not explicit constructs in the software.) Students can perceive receiving much more individualized assessment feedback, despite the fact that all they ever see is a shared, anonymous public representation of the group's thinking. As these apparent ironies indicate, the causal arrow from technology affordances to social practice is often quite crooked. Consequently, *research attention should be directed at identifying those learning niches in which simple technology could fit in extremely and uniquely well and to understanding the social practices by which those new affordances become powerful*.

III. Technology context for learning applications

The world of new hardware and networking capabilities deployed beyond the classroom is constantly expanding. With each new capability the realm of potential learning opportunities also widens. New computational functions, graphs, animations, and other representational capabilities can potentially augment the ways in which information can be presented to students, thereby creating opportunities for more students to grasp complex concepts in math and science. Similarly, these new representational and networking functions can potentially expand the variety of ways in which students can express, share, and demonstrate their knowledge. Together, these capabilities could potentially increase opportunity for peer-to-peer learning, and improve teachers' capacity to assess their students' understanding and tailor instruction accordingly. To better understand these prospects we examine some important technology developments from the perspective of their potential fit with classroom practice and their potential uses to improve learning.

As we move into this future of new capabilities and new opportunities, a number of important realities and choices will shape the potential for learning devices to make a difference in education. First, the success or failure of particular classes of devices to attain market dominance may affect viable choices for the classroom. Second, details of the physical network infrastructure and of the communication protocols enforced between machines have huge implications for classroom potential. Third, the stance that designers take about the relationship between systems affordances and the Internet has implications for the complexity, or "weight," of the system, and therefore its flexibility and how often it gets used. Finally, in spite of efforts to use inexpensive devices such as cell phones, or to create inexpensive versions of more pricey devices (as with the $100 laptop), the cost of technology is still a significant hurdle for many schools. As technological innovation and learning-science insights create momentum and a strong rational for the use of educational technology in schools, cost remains as a social brake on technology adoption in education.

Market Dominance

The question of general versus specific functionality will be paramount in the evolution of educational technologies. Until recently, it has been taken for granted that handheld devices and computers are the same, learning-wise, and that therefore general-purpose functionality would be most useful. Yet the body of research on specific-use devices (like graphing calculators) paints a drastically different picture. Experience has shown that devices with specific, targeted applications can integrate smoothly with existing classroom practices and effectively enhance classroom learning. We have argued that this capacity is crucial for use and success in the classroom. The question remains, though, of whether design-intensive point products can prosper or even survive in the new economic environment. In the larger market for small devices, for example, there is a movement towards internetworking. *Internetworking* is when the functional usages and adaptations of devices are inter-related and inter-dependent, for example, when a PDA is also a cell phone. The fit of seamlessly inter-networked devices into classroom practice is, at best, unclear at this time. Thus, on one hand, we have products that have demonstrated educational effectiveness, but may not have broad market viability. On the other, while there is great hope for general multi-purpose devices, the educational effectiveness of such general-purpose devices has yet to be documented.

Physical Networks

One arena in which these larger economic issues will play out and overlap with technical and design issues is in the infrastructure and topology of the network—characteristics that are fundamental in determining how easily and effectively networked handhelds can be used in classrooms. A major choice is between infrared (IR) based beaming and radio-frequency (RF) connectivity. Our primary work has been with machines that use infrared (IR) beaming, affording spatially-directed, point-to-point communication.

Infrared technology has some strong advantages in classrooms. First, IR requires no fixed infrastructure and no configuration, which allows teachers to adopt the technology without becoming or employing network administrators. It avoids dependencies on the uptime of other network components.

Second, IR simplifies the designation of communication targets: users spatially specify to whom they are beaming, and thus do not need to pick user names from lists. The appropriateness and timing of a particular beam is negotiated in the social realm with little technical overhead.

Indeed, IR fits ad hoc ensembles of students that frequently occur in classrooms: Teachers expect to be able to say "Everyone who is done, come to the front of the class and bring your Handhelds" and then create pairs from the students who are ready for the next task. Teachers may design tasks for pairs, but when there are an uneven number of students in the class, they expect the students to form trios. Finally, students do not lose communication functionality when on a field trip.

Furthermore, because of its punctuated nature, IR does not create as substantial a need for power as does radio-frequency communication. Special purpose devices provide far more opportunities than general purpose ones to optimize power consumption without compromising performance.

These issues that promote infrared connectivity turn out to be very important in practice in the classroom. However, radio-frequency communication is coming to dominate the market and it too has advantages. It can, in theory, create simple mechanisms for a teacher to get everyone's device to a particular state, or to collect work from all students simultaneously. It can support in a straightforward fashion the powerful image map assessment and aggregation activities we listed above. It can support access to the Internet. Hence, we predict great interest in radio-frequency networking in classrooms in the future.

Connections to the Internet

However, radio-frequency connectivity is not itself a full classroom solution. In practice, wireless Internet use on small handheld screens has been problematic. Despite intensive design and strong hype, Wireless Application Protocol (WAP) has been a spectacular failure (Kiili, 2002). Equally surprising, Short Messaging System (SMS) has succeeded beyond anyone's expectations (Rheingold, 2002). However, even common Internet applications can be quite problematic in classrooms. Schools, for example, have been tempted to ban instant messaging because it enables cheating and disruptive behavior (Pownell & Bailey, 2001). Further, attention is a teacher's most precious commodity, and no teacher wants her students' attention focused on messaging with friends outside of class (Schwartz, 2003).

There are other reasons we may not want the most general form of radio-frequency Internet connectivity as currently conceived for classroom-based applications. For moderately loaded shared media networks, contention-based access to the medium by individual nodes is typically most efficient. In systems where collisions can be detected by the sender (such as in wired Ethernet) this efficiency holds up even to highly loaded situations. However, in wireless networks, nodes cannot both send and receive simultaneously. Consequently, collisions between senders can't be directly detected. Connectivity may degrade disastrously as more users attempt to share the medium. The sudden and apparently unpredictable loss of connectivity due, perhaps, to users in a neighboring classroom beginning to access their own wireless access point, creates a lack of trust in the reliability of wireless and consequently less than full-scale adoption.

In classrooms and other situations where proximal social interaction is a key component of communication, wireless range beyond perhaps a decameter ceases to be a benefit and is, instead, a liability. In addition, physical proximity to other users and to network resources such as access points provides an opportunity to greatly simplify the usually daunting process of configuring. Combining the use of point-to-point communications for selection ("this is the access point I want to connect with") and automated configuration, with the use of short-range, high-bandwidth radio communications would appear to provide much higher reliability as well as greater ease of use in classroom-like situations.

In other words, the notions of RF communication, and "connection to the Internet" turn out to need much more definition and elaboration as a concept in order to be useful in a classroom context. Any design wants the benefits of all choices and the costs of none. What makes this more challenging is that many features that are clear benefits in non-educational situations are not really benefits in the classroom.

In this section, we have discussed background properties of existing handheld connected technologies that condition the design of learning activities. A great deal of research, as mentioned in Table 2, has attempted to utilize different aspects and properties of these systems. In the next few sections, we will present some examples of the many kinds of promising connected classroom work that are currently under investigation. Although some are currently downloadable, each should be taken as an indicator of what may come in the future rather than a plan, as none of them rise to the level of influence attained by our earlier examples. We will then use these examples to return to the importance of guidance from the learning sciences in creating handheld, wirelessly connected classrooms and discuss some of the implications of this on-going work for designers of the future.

Table 2: A partial list of handheld projects classified by classroom functionality and technological status. Citations may be found at http://www.manleyhopkins.cs.vt.edu/handheldlist.pdf (Reprinted from Kim and Tatar, 2006)

	Personal / Background Tools	**Central Representation Devices**	**Controllers of Other Devices**	**Communicators**	**Teacher Management Devices**
Clicker Systems	Boomerang (Tatar et al., 2003)	ClassTalk (Dufresne et al., 1996)	PUC, CPoF (Myers et al., 2004)	I-Guides (Hsi, 2002)	EduClick (Liu et al., 2003)
Graphing Calculators	PIGMI (Hennessy, 1999)	Gridlock (Wilensky & Stroup, 2000)	LabWorks (Morgan & Amend, 1998)	Match-My-Graph, Slot Machine (Tatar et al., 2003)	HubNet (Wilensky & Stroup, 2000)
PartSims	Cooties (Soloway et al., 2001)	Chemation (Bobrowsky et al., 2004)	Thinking Tags (Colella et al., 1998)	HEARTS (Jipping et al., 2001), Geney (Danesh et al., 2001)	MathWorlds (Hegedus & Kaput, 2002)
System Sims	CritterVille (Soloway et al., 2001)	NetCalc (Tatar et al., 2003)	MRSCL (Mitnik et al., 2004)	Sketchy (Bobrowsky et al., 2004)	Environmental Detectiv

	al., 2001)		al., 2004)	al., 2004)	es (Klopfer et al., 2002)
Awareness Devices	StudySpace (Schnase et al., 1995)	Data Doers (Tatar et al., 2003)	Symbiotic Environment (Raghunath et al., 2003)	Awarenex (Tang et al., 2001)	Information Aware System (Wang et al., 2003)
Focused Practice	VeGame (Belloti et al., 2003)	Who's who? (Moher et al., 2003)	Probeware (Tinker & Krajcik, 2001)	Electronic Guidebook (Bannasch, 1999)	Code It! (Goldman et al., 2004)
Active Document Exchangers	FreeWrite (Bobrowsky et al., 2004)	Plantations Pathfinder (Rieger & Gay, 1997)	Campus Mobile (Demeure et al., 2005)	NERTS (Jipping et al., 2001)	Quizzler (Penuel & Yarnall, 2005)
Formative Assessment	WHIRL project (Roschelle et al., 2004)	Palm sheets (Soloway et al., 2001)	SLiC project (Soloway et al., 1999)	ImageMap (Roschelle & Pea, 2002)	Gradebook (Penuel & Yarnall, 2005)
Information Delivery / Storage	Fling-It (Soloway et al., 2001)	MCSCL (Zurita & Nussbaum, 2004)	Cornucopia (Rieger & Gay, 1997)	PiCoMap (Luchini, 2002)	NotePals (Davis et al., 1999)

Emergent Classroom Connectivity

SimCalc: Connectivity and Dynamic Representation

The SimCalc project is investigating new applications for graphing technology that will enable more students to develop a conceptual understanding of key concepts in the math of change and variation. SimCalc builds on the strengths of graphing calculators by using robust and inexpensive handheld devices, enabled with connectivity and animation. However, compared to the normal use of graphing calculators, SimCalc substantially increases the student's interaction with multiple, linked, dynamic representations. That is, the student's focus is brought to bear on the relationship between behavior in the simulated world of cars, elevators, or dots, and of the position or velocity graphs that describe their motion as the different representations are animated. Networking capabilities allow teachers to deepen math content and increase student participation in their classrooms by permitting the focused and mathematically relevant contrast between what individual students see on their own screens and the aggregated behaviours on the large screen at the front of the classroom. Thus, students might "count off" so that each student has a unique ordered pair of his/her table and individual number, then create a "car ride" that reflects those parameters (e.g. the student from Table 1, Position 4 would create a car ride in which y=1x + 4; the student from Table 4, position 1, would create y=4x + 1), then aggregate the "rides" at the front of the room. Visible patterns emerge. SimCalc researchers Hegedus and Kaput are excited about more than test scores: "classrooms that integrate dynamic software environments with connectivity can dramatically enhance students' engagement with core mathematics beyond what we thought possible…." (Hegedus & Kaput, 2003, p. 54)

Under these conditions, technology becomes a pervasive medium in which teaching and learning take place in the social space of the classroom. Thus, as more work happens through collaborative interaction, learning increasingly occurs in the social space (Stroup et al, 2002). This collaborative learning drastically augments the learning that occurs through individual interaction with technology devices. With careful pedagogical guidance by teachers, students can progress through a trajectory of understanding in which their focus advances "from static, inert representations, to dynamic personally indexed constructions in the SimCalc environment on their own device, to parametrically defined aggregations of functions, organized and displayed for discussion in the public workspace" (Hegedus and Kaput, 2004, p.135).

ImageMap: Aggregating and Presenting Student Responses to Enhance Learning

ImageMap is an assessment feedback system for supporting media-rich learning conversations. In a classroom lesson using ImageMap, an image (e.g. graph, map, photo) is distributed to each student with a handheld, networked device; the teacher poses a question about the representation; each student annotates the image with a response; next, a server receives the responses from the pool of students; aggregates the responses by superimposing the student annotations on the image that was distributed and projects the aggregated responses on a public display, allowing students and teachers to see the distribution pattern of different answers. Thus, students might mark the Confederate States during the Civil War on a map of the United States. Many might choose Alabama or Georgia, but fewer would hazard guesses about Delaware or Maryland. In this way, the ImageMap assessment represents degrees of student understanding through a direct spatial mapping of individual contributions to an aggregate representation.

In planned extensions to the ImageMap, developers are extending the strategy of aggregating individual responses 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 students' continued exploration, as they see what they are building together (Pea, 1994).

As is the case with a number of networked handheld applications, the teacher role during ImageMap engagements is like that of a "conductor of performances" for an orchestra, with the students contributing to an overall performance. In the ImageMap application (and especially the extended version described above), students contribute to a joint performance, verbally and with input technology, generating an overall aggregate representation, with a coherent visual gestalt. 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 and that everyone gives their best performance—directing attention towards the students who need the most encouragement while keeping the overall performance moving forward.

Classroom Presenter: Flexible Presentations using Digital Ink

In moving from manual presentation systems (such as overhead projectors) to computer-based presentation systems (such as power-point slides), instructors saw some benefits and some losses. Computer based systems offer many conveniences: instructors can easily prepare their lectures in advances, switch back and forth between the presentation and other computer-based tools (including web applications), and save, re-use, and share their classroom materials. The trade-off, however, was a drastic loss of flexibility, as instructors could no longer annotate their presentations in writing to correspond with real-time events throughout lecture and discussion. Classroom Presenter is a tablet-PC-based application that combines the advantages of computer based presentation tools with the flexibility afforded by traditional systems. By using tablet-PCs as a platform for lecture presentations, teachers can use digital ink to write directly on their slides. In addition, Classroom Presenter supports multiple separate—but linked—views of the presentation: the teacher view, the projector view, and the students' views. This structure enables all students to have access to the instructors notes, enables students to beam their markings to the teacher and/or the projector, and also provides "private" annotation space for both students and the instructor on their own respective devices.

The affordances of the Classroom Presenter system support active and collaborative learning, student engagement, real-time feedback for the instructor of students' understanding, and the integration of student materials into classroom discussions. Thus far, reactions to the system have been highly positive: in a survey of students from over 200 science and engineering courses in which the instructor used

Classroom Presenter, 55% of students said that the use of the system positively impacted their understanding of lecture material, and 69% of students would encourage other professors to use the system as well.

Boomerang: Capturing Student Generated Questions

Often when we approach learning, we think about teachers quizzing or asking questions of students. This activity orients students and teachers towards the body of knowledge for which the student is accountable. Student generated questions are also valuable for learning. However, standard classroom practice may permit only a small number of student questions, students with good questions often feel discouraged because other people's questions are so different from theirs and students often are discouraged by teachers who do not recognize the importance of question asking.

Boomerang is a tool designed to support students asking questions. It allows all students to submit questions privately which can then be posted and discussed by the group as a whole. When students ask questions in their own words, they reveal gaps in understanding that may not be elicited by the teachers' use of standard terminology and phrases. By asking questions, students not only fill in gaps in their knowledge base, but they also open up possibilities for wonderment.

Match My Graph: Language Games for Math Learning

One reasons that graphing calculators and SimCalc is so important is that middle school math students typically have difficulty remembering the meaning represented by a graph. Indeed, students may interpret a position graph that shows a line with an upward slope (see Figure 1) as a representation of a car going up a hill. Another SimCalc variant, Match-My-Graph, targets the meaning of the graph by asking students to put it into words. Students work in pairs. One student, the grapher, draws a function over a domain. Only they can see their graph and its relationship to the motion of the car. The other student, the matcher, has the job of creating the same function over the same domain, by making successive guesses and interpreting hints. The matcher must use math language with sufficient care to convey precise meaning to the grapher. Over multiple rounds, each student takes turns as grapher and matcher. Several metrics of student engagement—including impermeability to distraction—confirm that students involved in Match My Graph activities are very focused on the task at hand.

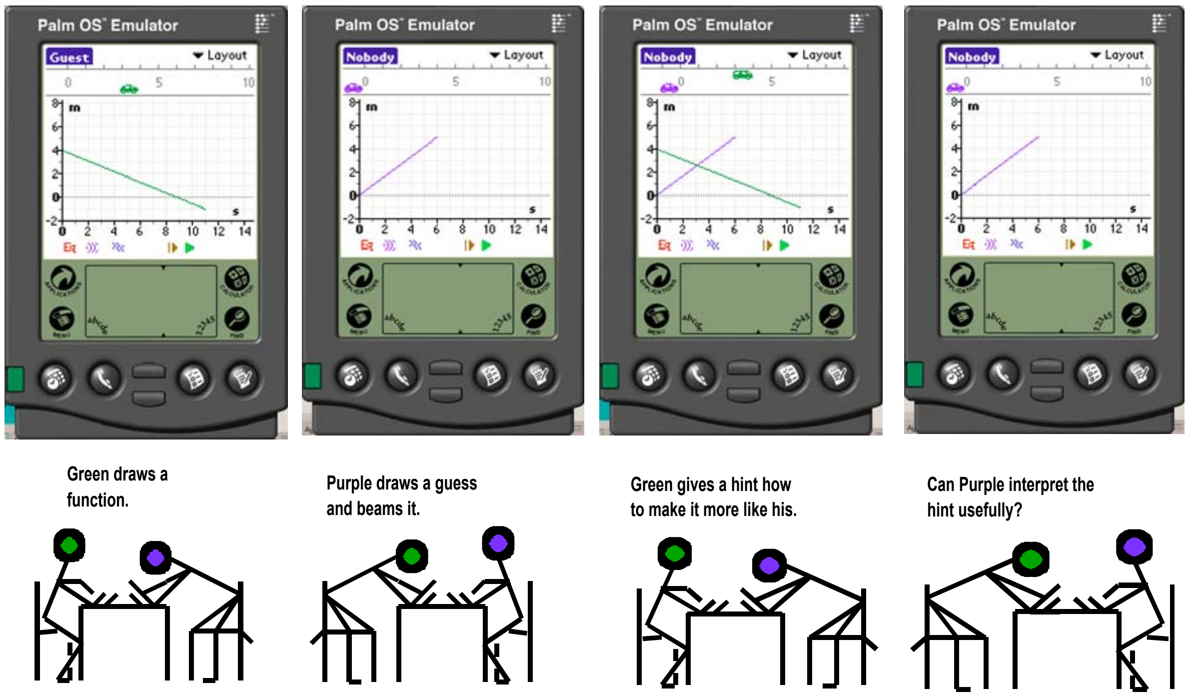

Figure 1: Activity Sequence in Match-My-Graph (reprinted from Tatar et al., 2004)

An important part of Match-My-Graph is running the animation to understand whether a steeper graph represents a faster or slower car. What does an increase in the slope of the line mean for the animation? Four variations of this task stress the student's ability to create and interpret mathematical language. In the most complex version, a student looking at two velocity functions and no representation of the car motion must give hints to a student looking at a position graph.

Note that the teacher in this case is "untethered", roaming the classroom. She often observes groups and makes a decision whether to engage with them more actively. Yet a challenge to this is her lack of direct access to the screen states of the participants. Sometimes students fail to realize what is important about their own activity, and therefore give accounts that ignore important phenomena. To support the teacher's observation, in the context of untethered teaching, work has been done exploring the parameters of sharing necessary to support a networked functionality "Look" which allows the teacher to gain a lightweight snapshot of a student's screen. In contrast to much work in CSCW on the importance of shared screens, this work asks "how little knowledge of the visual workspace can still be useful to resolve differences?"

Data-Doers: Helping students to be "minds-on" during hands-on science activities

In science classes, students face a number of difficulties in grasping scientific concepts and understanding hands-on demonstrations. Data-doers is a tool that aims to facilitate science learning by supporting students in being "minds-on when they are hands-on". Even though many teachers have near miraculous powers of knowing what's going on behind their heads, they cannot be everywhere in the classroom at once. Consequently, students engaged in hands-on work may sometimes become distracted or confused about the tasks at hand and their relationship to the larger point of the lab experience. "What were those numbers?" "What was I supposed to do with them?" "What are we doing anyway?" Their confusion may last only a few minutes, and yet in the fast-paced world of the classroom, those few minutes can put them at a disadvantage.

Data Doers allows teachers to create handheld-based worksheets for labs or demonstrations to help students with data collection activities. Students can then work individually or in small groups, preparing materials that may eventually be shared in a class discussion. Data Doers reminds students to think about what they are doing in two *direct* ways:

(1) Based on teacher-set upper and lower bounds for measurements, it gives students feedback about when a result that they report is not plausible and needs to be reconsidered and possibly re-measured.

(2) It allows students to beam to their data, thus enabling them to make comparisons and contrasts more quickly.

It also provides more occasions for student thought in a three *indirect* ways:

(1) Teachers can collect student values and respond in a more timely fashion.

(2) Students will not be copying over data tables during class discussion, because they will either take the Handhelds home or take printouts home.

(3) Teachers can use the presentation of the Data Doers spreadsheet for a lab as a means of "pre-flecting", creating classroom discussion about the lab and its goals before it starts.

eXspot: Using RFID Technology to Enhance and Extend Museum-based Learning

Although the learning that takes places at science museums is typically highly motivating, it is also unstructured and unsystematic, and occurs in short spurts of engagement. Studies have shown that at museums such as the Exploratorium—an interactive, hands-on museum in San Francisco with over 100 exhibits covering a wide variety of topics—visitors typically spend only about 30 seconds at any given exhibit (Hsi & Fait, 2005). The key challenge for museum educators, then, is to find ways to deepen visitors' learning and extend their experiences, without shattering the motivation that comes from un-structured, self-directed exploration.

Researchers at the Exploratorium have been working on a new application called eXspot that uses RFID technology to support, record, and extend exhibit-based informal science-learning experiences. The eXspot system is supported by a wireless network linking stationary RFID readers to portable, individual RF tags. Visitors to a museum each receive an RF tag, which they first register (using an ID number and email address) at a registration kiosk. As visitors progress through the museum, RFID readers stationed at each exhibit read RF tags that come within a certain range. Visitors can then use their ID information at museum kiosks or on home computers to login to personalized web-pages that capture their museum experience. Each visitor's museum trajectory, as well as photographs taken at various exhibits and links to additional resources and activities, appears on the personalized sites.

A bonus application of the eXspot system is that it can serve as an embedded evaluation tool for museum research. Information captured from RF tags as the visitors progress through a museum can provide valuable information regarding exhibit interaction patterns, use of RFID-supported exhibits, preferences for online content and learning activities, and repeat-visit information. All of this data serves to inform museum strategies and strengthen the learning value of community science museums.

Crickets

Crickets are tiny programmable devices that students can embed in their own physical creations. Using sensors and actuators, students can write simple programs telling Crickets how to behave. In this way, Crickets make it possible for students to control both the physical design for the structures and mechanisms of a creation as well as the computational design of behaviors (Resnik, 2006). In particular, they build on the notion of physical design (with blocks, tiles, Lego© parts, etc.) as a learning domain in which the consequences of design decisions and explorations are immediate and transparent. They then add to that context the ability to explore behavioral design in a similarly transparent fashion (Resnick et al., 2000)

Discussion: Capabilities, Tensions, Potential Resolutions

Certain features emerge from this discussion: *a local messaging topology* among participants in mostly face-to-face settings; variations in *teacher control* and expectations for teacher behavior; the potential of *spatially directed communications,* for example, in beaming in Match-My-Graph, in the placement of probes in particular spatial locations in the stream and implicitly by posting a mark in a certain place in image map assessment; in the predominance of *short, asynchronous structured data* over long general purpose text messages (such as in email) or long-term conversations (such as telnet or Napster); and in *aggregation* of data and experience by student and teacher. Finally, a *shared public display* is often important in making these aggregates available for discussion. We ask next how best to think about the status of each of these. What factors, if any, should be treated as design principles? What factors are necessary for learning success and success in the world?

IV. Overarching Ideas from the Learning Sciences

In discussing historical successes, we noted that successful applications of learning technology do not insert technology into schools in isolation from other factors. To the contrary, behind every successful learning technology we described an integration of simple, focused technologies and transformed teaching practices. We next considered emergent technological capabilities and applications. Describing the technology features of these examples is not enough because the designs have been informed by dual technological and learning perspectives. Readers would be unlikely to be able to generalize to powerful new designs of their own without also understanding the learning theories that informed each design. Therefore, in this section, we discuss recent advances in learning theory that have been most closely associated with design of networked, handheld learning technologies.

Recall from the historical examples that they drew upon the capabilities of networked computers to *represent* scientific and mathematical ideas in profoundly new ways, to provide enhanced *feedback* to teachers and students, and to enable students to engage in *inquiry* that is more aligned with scientific practice. The field of empirical research and theory that has been most closely associated with representational, feedback and inquiry approaches is called the "Learning Sciences." Although researchers have been active in this field for 20 years, they have only recently pulled together to form a society (the International Society of the Learning Sciences, http://www.isls.org) with two journals (*Journal of the Learning Sciences*, *International Journal of Computer-Supported Collaborative Learning*), and two important reference works (*How People Learn* and *The Cambridge Handbook of the Learning Sciences).*

In this section, we selectively highlight aspects of the Learning Sciences that we have found to be most relevant to the issue at hand: the design of handheld and wireless learning technologies to enhance school learning. We approach this task in three stages. First, we describe two overarching perspectives in the Learning Sciences, one that emphasizes cognitive augmentation and the other that emphasizes social participation. Many successful projects draw upon the tensions that lie between these perspectives. Second, we discuss a set of design factors link with Learning Science theories and cut across many example applications. Third, we note that the Learning Sciences has been concerned not only with theory and results, but also with the practice of design. Hence our third section discusses the technology design practices emerging in this field.

Perspectives

Cognitive Augmentation

Inspired by Vannevar Bush's classic essay, "As We May Think"[1], Douglas Englebart defined a program of research that linked advances in computing to a vision of augmenting human intelligence (Englebart, 1962). Englebart's innovations—including the mouse, the use of graphical user interfaces to communicate ideas, and collaboration across a network—have become commonplace affordances of personal computing technology over the past 30 years. The power of cognitive augmentation is so strong that many of us would feel unable to work without our accustomed computational tools.

Englebart's innovations also occurred in the midst of a cognitive revolution in psychology, which moved beyond earlier stimulus-response theories to focus on human problem solving as mediated by representations (Newell & Simon, GPS). These mediating representations could be both knowledge within the mind and cultural symbol systems outside the mind, such as notations, diagrams, and visualizations. Computers turned out to be good both for testing theories of cognition (e.g. the field of Artificial Intelligence) and for creating novel symbol systems that could better mediate human problem solving performance.

The joint onset of the augmentive and cognitive revolutions had powerful effects on theories of learning. Before this time, learning was largely seen as a matter of applying effort to forming the right stimulus-response bonds (a theory called "behaviorism"). A student had learned something when they could quickly answer a question correctly. Many applications of computer technology in learning still build upon this old way of looking at things; these applications try to motivate students to put more effort into question-answering by making it more fun (e.g. by introducing a game-like

[1] http://www.theatlantic.com/doc/194507/bush

reward structure). Applications of computer technology learning also reflect this old way of looking at learning when they see "interactivity" as a stimulus-response cycle: the student does something and the computer responds (or visa versa).

After the cognitive revolution, learning was seen as a process of transformation of a students' knowledge that is highly related to problem solving. A student now had use knowledge in solving a complex problem to demonstrate learning. Further, "interactivity" now was described in reference to an extended problem solving process: how could "interacting" with a computer-based model or simulation (that itself was a dynamic system of symbols) be a powerful resource for a student to re-think their ideas about physics, for example? Computers now were seen as tools that could augment learning and problem solving processes by providing conceptual tools that were more appropriate to the learner's challenge (Lajoie & Derry, 1993).

Arising within this history, key innovations in the learning sciences were cognitive tools that augmented the learning process. The programming language Logo provided "gears for the mind" (Papert, 1980 which could make abstract geometric ideas more concrete (as instructions to a "turtle" to draw graphics) and help students learn new ways of thinking mathematically (such as recursion). At Xerox PARC (an institution that hired many people from Englebart's lab), Alan Kay imagined a "Dynabook" which would enable students to manipulate scientific models and instantly see the consequences. Knowledge Forum, a collaborative learning tool for science classrooms, helped students to visualize and improve the structure of their ideas about a scientific phenomena. This transformed science classrooms from being more about memorizing facts (per earlier behaviorist theories) to being about scientific inquiry. Similarly, "The Adventures of Jasper Woodbury"—an early expression of Learning Science theories in multimedia format provided an extended context in which students could learn mathematical concepts while using those concepts to solve realistic problems.

As the cognitive revolution continued, much more was learned about representation. Of particular importance to learning is the transition from emphasizing general problem solving abilities to discovering that expertise depended on domain-specific knowledge and skills. Hence, a mathematician does not solve problems using the same representations or approaches as a biologist. Each field of inquiry has its own cultural tools and problem solving approaches that are particularly tuned to its subject matter. In Learning Sciences, this insight led to a search for ways of using computers to produce new ways of representing knowledge so that students might learn more easily. Many of the representations took advantage of the graphical, manipulable and dynamic aspects of modern computer technology, resulting in modeling, simulation, and visualization tools appropriate for learning a range of topics in mathematics, science and other subjects.

This history underlies the cases of handheld learning technology we have drawn out for consideration in this review. Graphing calculators, for example, provide students with a visual representation of functions that makes mathematical reasoning more fruitful for most students. A "killer application" of graphing calculators occurs in a typical calculus sequence when students need to understand that functions appear locally linear. By zooming in progressively closer in the graph of a function, students can experience local linearity in a way to that leads to great understanding of this fundamental idea within calculus. Simultaneously, graphing calculators offload laborious calculations, thus enabling teachers and students to allocate their cognitive resources to the more important aspects of the mathematics at hand. Within the newer applications we discussed, we also see a focus on handheld devices as representational tools that augment students' capabilities as they learn.

Table 3: Precognitive and Cognitive Perspectives on Learning Technology

	Precognitive Perspective	**Cognitive Perspective**
View of learning	Acquiring correct associations between a stimulus and a response	Transforming prior knowledge to be able to be able to solve authentic problems in a domain of expertise
View of interactivity	Receiving quick and informative responses to each action can accelerate students' acquisition of appropriate associations	Interacting with a dynamic notation or simulation model during problem solving can lead students to transform their knowledge
Role of technology	Motivating students to apply more time and effort to learning through entertaining reward structures	Providing representations that are especially conducive to building a conceptual model of a particular area of mathematical or scientific investigation.

Key features of technology	Allows designers to create a controlled sequence of interactions that optimizes formation of correct associations and motivation to apply effort to learning.	Allows designers to create new forms of representation, using dynamic, manipulable graphic notations and models
Prototypical handheld example	Flashcards on a handheld allow students to practice associations anytime and anywhere.	Graphing calculators enable students to explore local linearity of a function

Although we have been drawing a somewhat strict line between precognitive and cognitive approaches (see Table 3 for a summary), we should acknowledge that this is an oversimplification. The view of learning as embedded in problem solving and the role of technology as supplying cognitive tools for inquiry also goes back to seminal 20th century thinkers such as Dewey, Piaget, and Vygotsky – and these thinkers have figured large in the Learning Science approach to supporting learning through cognitive augmentation. Dewey, for instance, offers a clear philosophical account of what problem solving looks like. His account is helpful in distinguishing superficial problem solving (e.g. where a multiple choice test question is termed a "problem" if it contains a framing story) from inquiry-oriented problem solving. Dewey described the inquiry as being rooted in students' feelings of confusion and frustration with an inability to make something work, involving the application of both conceptual and physical tools over time to transform the students relationship to the situation, with a resulting cathartic realization of a new approach to the situation that removes the confusion and results in ability to work effectively in a range of similar situations. Hickman (1990) gives a compelling account of Dewey as having foreseen the cognitive augmentation view of cultural tools. In learning, one role of cognitive tools is to extend the time and intensity with which teachers and students are able to engage with complex and extended problem solving before frustration or confusion blocks progress.

Piaget also figures large in the cognitive augmentation view of tools for learning. In Piaget's theory, one important line of child development is from more embodied to more concrete to more abstract ways of solving problems. Learning technologists often look at this not as a fixed sequence but instead as a map of children's resources for learning; children have relatively few and fragile resources for learning through a purely abstract modality but relatively robust resources for learning through embodied and concrete experiences. Hence, one way to enable children to work more productively with abstract ideas (such as mathematical or scientific concepts) is provide a range of well-designed concrete embodiments that bridge to the abstractions. The historical success of probeware, for example, can be seen as enabling students to participate in scientific inquiry by connecting to their ability to engage in embodied sensory exploration of the world. Likewise, cognitive tools running on handhelds (such as mathematical models) give students an opportunity to interact with a more concrete realization of abstract theoretical concepts.

We also note can note continuity from precognitive to cognitive perspectives. For example, our introduction emphasized the importance of frequent and integral access to technology. The theoretical roots of this concern reside in the concept of "time on task." Students learn more when they spend more time learning; Learning Scientists agree that arranging for teachers and students to spend more time engaged in learning is really important. Indeed, one of the drivers towards simpler technology is a desire to avoid introducing complexities (and logistic problems like running out of batteries) that steal precious minutes from engaged learning. Another area of continuity regards the importance of feedback. Both precognitive learning and cognitive augmentation perspectives highlight the importance of giving students timely and supportive feedback as they learn. The main difference, as would be expected, is whether the feedback is on the correctness of associations or related to a more extended problem solving process. In a learning sciences approach, "formative assessment" (the technical term for feedback) is often directed at helping students understand how experts judge the quality of explanations and problem solutions and give guidance to students on the fruitfulness of particular problem solving approaches.

Social Mediation of Participation

Like all revolutions, the cognitive revolution also had its excesses. Approximately midway in our timeline running from Englebart's 1968 demonstration to the present, scholarly concern with the excesses of the cognitive revolution culminated in a counter-revolution that stressed a more social and contextual view of learning. Some of the excesses that scholars raised included:

- A emphasis on problem solving in overly logical situations, like playing chess, rather than more common but fuzzy practical situations, like doubling a recipe.
- A tendency to treat context as yet more information to be represented, rather than a more phenomenological, embodied, situated account of context as cultural, historical and physical.
- A neglect of the social and collaborative dimensions of learning and an overemphasis on learners as isolated individuals.

In one way of viewing this history, the cognitive revolution supplied a thesis (the problem solving view of learning), which was then countered with an antithesis (a more social, cultural and situated view of problem solving). One can see the field of the Learning Sciences as the emerging synthesis which brought together these tensions, especially as applied to the design of learning technology. Therefore our narrative below explores the consequences of a social participation view of learning for the design of networked handheld applications.

One early and important center in which the social participation view of learning technology developed a particularly full theoretical and practical realization was the Laboratory of Comparative Human Cognition at the University of California, San Diego. Here, in work that started in 1972, Mike Cole and colleagues began attending to the problems students had learning school subjects in particular cultural settings, such the problems Liberian students experienced in learning mathematics. But rather than developing a "deficit" view that emphasized cultural impoverishment, the social participation view often undertook anthropological studies to understand how children (or adult workers) in cultural settings develop powerful mathematical competence. This led to a long-term experiment in the development of after-school settings in which students use technology in support of learning, called the "Fifth Dimension." In parallel with the development of this technology-enriched setting, researchers developed a cultural-historical view of learning that drew upon Dewey, developmental psychology and especially the work of Russian psychologists such as Vygotsky. Below we describe some key features of the Fifth Dimension design and theory, especially as these features contrast with the cognitive augmentation perspective and lead to a broader Learning Sciences perspective (Fifth Dimension Clearinghouse website).

The Fifth Dimension was designed as an after-school setting for learning within community centers such as Boys' and Girls' Clubs, YMCAs, recreation centers, libraries, and public schools. A central element of the design was play; whereas most school settings beyond Kindergarten contain learning in a very formal structure, the Fifth Dimension uses play as a primary activity system for developing mastery of a subject.

The heart of the Fifth Dimension is a wooden Maze divided into twenty rooms. Each room provides access to two kinds of activities, computer and non-computer. About seventy-five percent of the activities utilize educational software and computer games. Included are telecommunications activities for searching the Internet, tools for computer-mediated, and video-mediated conferencing. The remaining activities are non-electronic and include board games and arts and crafts. The software represents the curricular content of the Fifth Dimension. Subject matter includes social development, communications, reading, writing, math, geography, social studies, health, technology, language, and problem solving. In all, the Maze contains over 120 educational and computer games and non-electronic activities (from http://www.education.miami.edu/blantonw/5dClhse/childs.html).

In addition to play, another critical aspect of the design was a sense of place. While the Fifth Dimension did not design for learning in formal school settings, it also did not design for learning in complete ad hoc settings either (as some researchers in handheld and networked learning do when they emphasize learning "on the bus" or "in the park.") The cultural and historical location of their design in places that were organized and designed for learning is critical to their successful design. Below we draw out three additional aspects of the Fifth Dimension that are central to the social participation perspective on the design of learning technology.

First, the Fifth Dimension was conceptualized as a set of activities in which students participate. This may seem superficial but is actually a deep point. The cognitive augmentation perspective often did not question the school-like nature of many of the tasks students were asked to do, and how that artificiality of school-like tasks prevents students from gaining a deeper appreciation and understanding of a subject. The point is theoretically deep because activity is a central construct in Russian psychology and a hinge-point in linking that theory to design. Activities are theorized as the minimal unit of meaningful engagement in a cultural practice, and include an analysis of goals, mediating tools, roles, involvement of a community. Likewise, when Learning Scientists design applications of technology to learning, they don't merely design cognitive tools, but rather design coherent activities in which those technologies are used in social practice.

Second, the Fifth Dimension conceptualized a new role for a leader often called "the Wizard.' In an allusion to the Wizard of Oz, the wizard only appears through the technology (and is a role often played by a group of people in a backroom). The wizard may act as a knowledge expert but may also be a prankster or curmudgeon who prods students' development forward. Theoretically, the wizard relates cultural prototypes of adults who guide and support learning but not merely through the narrow role that teachers often take, the role of a "sage on the stage." Likewise, in many designs for the use of networked handheld in learning, the teacher is no longer expected to simply be the expert who delivers correct knowledge, nor is the device seen as an anytime/anyplace gateway to authoritative knowledge. In many successful designs of networked handhelds for learning, teachers are expected to prod students into more active roles in learning and the network enables students and teachers to enact rich social forms of participation in learning that go far beyond to accessing "learning objects" on the web.

This brings us to a third point: the Fifth Dimension emphasized social participation of learners in activities. In particular, learners were expected to establish goals and strategies for their own participation, to collaborate in small groups, to reflect and communicate their emerging understandings, and to transition from roles as novices to roles as masters of their environment who could help others. Peer interaction was considered especially critical. Theoretically, this relates to the perspective that learning involves a transformation of participation in a community of practice. Complementing a knowledge-centered view, this view sees learners progress from "legitimate peripheral participation" in a cultural practice (such as making scientific arguments) to become more central participants in the real work of science and eventually to becoming masters who organize the learning environment for new students to sustain and grow the practice.

Drawing upon the work of Vygotsky, Learning Science researchers and technology designers often build on the idea that learners often first enact complex new practices in a social group and only later internalize the social performance as a cognitive capacity. In comparison to the cognitive view, in which cultural symbol systems primarily mediate thinking within an individual mind, the Vygotskian view sees the same cultural symbol systems as primarily mediating social practices of thinking—by allowing practitioners to think together more effectively. With respect to learners, Vygotsky conceptualized a "zone of proximal development" that was the conceptual area that lay between what a child could do individually and what they could do in a social group. Researchers could design mediating tools for the zone of proximal development to extend and deepen this zone to enable more fruitful social interaction around complex problems. Through social use of powerful mediating symbol systems, students could come to internalize expert use of those symbol systems and move along the trajectory toward expertise.

The contrast between the cognitive augmentation and social participation views of learning technology can clearly be seen in work around a modeling tool called the Envisioning Machine (Roschelle, 1991). The Envisioning Machine provided an simulation environment in which students could learn Physics concepts by manipulating objects in a "Newtonian World" to match the motion of a ball in an "Observable World." Students used a mouse to drag velocity and acceleration vectors in the Newtonian World; when they started the simulation, the corresponding motion would be produced including a display of the changing velocity vector over time. As a tool for cognitive augmentation, the Envisioning Machine was carefully designed to suggest and constrain students' thinking towards a vector addition model of kinematics—a powerful symbol system for reasoning about motion that is abstract and non-intuitive for most students. However, the eventual analysis of how students learned with the Envisioning Machine came to emphasize a social participation perspective. Students found the Envisioning Machine engaging because it encouraged a playful engagement with a core physics challenge—modeling the real world with theoretical concepts. As students participated in this activity, they initially could not see the symbol systems of the Newtonian World in the way an expert physicist does. However, the symbols mediated their use of language and enabled them to use available metaphors such as "pulling" to gradually construct a shared understanding of how the Newtonian World worked. This understanding was not identical to an expert view but constituted progress from very peripheral understanding of what physicists do and how they think towards a greater ability to participate in conversations with scientists about motion. One can see the Envisioning Machine not just as augmented cognition but also as mediating students' collaborative participation in scientific modeling practices—enabling them to engage in scientific modeling for a longer time period than they might have without the mediating tool and without each other.

Within the historical examples of networked handhelds introduced earlier, the case of networked response systems is the best fit to a social mediation perspective (Penuel, Abrahamson, & Roschelle, forthcoming). One can look at these systems merely in terms of providing more feedback to teachers and students. However, doing so misses a great deal of the action in successful classroom implementations. Students and teachers both report that the use of these systems changes how they participate in class. On the good side, students report less anxiety in sharing ideas in class; on the bad side, some students resent that their participation in class can now be measured by the teacher and adopt positions of resistance. Either way, these systems evoke strong feelings from the students about participation.

Penuel and his colleagues propose that concepts from the sociocultural theory of learning can explain how, when, and why audience response systems effectively transform and enhance learning (Penuel et al., in preparation). First, the sociocultural perspective of learning posits that people learn when they practice using the tools of a given discipline, with the guidance of an expert. As people become more comfortable with these tools, their participation within the community of learning transforms, resulting in a transformation, too, of the interpersonal and group interactions that take place within the community of learners. Second, the sociocultural perspective argues that actions are mediated by discourse and symbolic representations. Extended practice at using the discourse of a discipline and at conceptualizing and communicating answers to open-ended questions aids students in developing deeper understandings of science concepts. This emphasis on the importance of discourse provides an understanding of how and why the discussions resulting from the use of audience response systems are so influential in fostering increased conceptual understanding among students. Finally, a sociocultural perspective on student interest, motivation, and identity illuminates the ways in which audience response systems—and the features of the tasks and classroom dynamics associated with their use—might influence student engagement and student participation. Taken together, ideas from the sociocultural perspective of learning shed light on the mechanics of change taking place in classrooms that implement audience response systems.

A Learning Sciences Synthesis

Both the cognitive augmentation and social mediation moved beyond to the view of learning as mastery of a simple association of stimulus with response and the view of motivation as a simple impetus to put in enough effort to master the associations. Between stimulus and response, the cognitive revolution inserted mental representations. The social mediation view instead inserted cultural tools. While the theoretical differences between these moves is huge, the resulting learning technologies can look quite similar: a representational tool for augmenting mathematical cognition looks pretty much the same as a mediational tool for social participation in mathematical practices. Hence rapprochement and synthesis is achievable.

Table 4: Comparison of Perspectives on Learning

Cognitive Augmentation Perspective	Social Mediation Perspective	Learning Sciences Perspective
Formal learning	Informal Learning	Linking Formal and Informal Learning
Symbolic tools (representations) mediate mental operations	Symbolic tools (representations) mediate social practice	Symbolic tools (representations) can fruitfully link cognitive and social dimensions of learning
Symbolic systems as the unit of design	Activities as the unit of design	Activities with symbolic systems as the unit of design
Successful learners are able to solve complex problems and undertake scientific inquiries	Successful learners are able to participate in disciplinary community of practice	Successful learners can participate in collaborative inquiry in a domain.

As one simple starting point, we can synthesize across settings. Researchers in the cognitive augmentation perspective have been more attuned to design tools for formal learning settings. Researchers in the social mediation perspective have been more attuned to the use of learning technology outside the formal school day. With the advent of handheld and networked technology, there seems to be little reason to make a sharp distinction between these two settings. Students will be able to carry their handhelds between formal classroom settings and settings in clubs, museums, and homes. In place of sharp distinctions, networked handhelds will likely encourage a sense of "seamless learning spaces" (Chan et al., 2006) that enable learning to move among and across different settings.

A synthesis can start with the view that the purpose of technologies in learning is provide symbolic tools that enable students to engage effectively in extended episodes of thinking, communicating, and reflecting – not simply to make the master of simple associations more fun. A more cognitive view is often helpful in analyzing the relationship of a proposed tool to disciplinary knowledge: how does this tool embody or distort the ways in which mathematicians think about mathematics? A more mediational view is often helpful in analyzing the relationship of a proposed tool to disciplinary practices: how does this tool enable or block students from participating in social practices which successively approximate the practices of real scientists?

When designing a learning tool, designers working from a cognitive augmentation point of view often start by thinking about the symbol system that expert mathematicians or scientists use to solve problems. How could abstractions in the mind of experts become more tangible and concrete in the hands of learners? How could the abstract concepts be represented in a way that directs and constrains student thinking towards the ways in which experts think about the concepts? How could students attention be focused on the really important parts aspects of thinking in this domain, offloading less important, distracting parts to automation?

Designers working from a social mediation point of view start by thinking about designing an activity system that engages students in an approximation of the social practices of actual scientists and mathematicians. Designers think about appropriate goals for the activity and how technology can mediate students' involvement in it. What roles and rules will be necessary to structure playful engagement so as to enhance the learning potential of the activity? What new roles will teachers and other adults take? How does this activity fit as a transition between the cultural practices of childhood and the cultural practices of a specific discipline? How will it build children's affiliation with each other and enable them to see themselves moving along a trajectory towards greater participation in a community of practice?

In the Learning Sciences, these two design points of view come together by thinking about activities with domain-specific symbol systems as the fundamental unit of design. This synthesis balances the need to think about how technology can make an expert's abstract operations on symbols more tangible for learners and with the recognition that the smallest meaningful chunk of social practice that can be designed is an activity.

Finally, each perspective offers a slightly different view of what success looks like. In the cognitive augmentation perspective, researchers celebrate success when students can solve complex problems or undertake scientific inquiries that reflect deep understandings of a particular domain of expertise. In the social mediation perspective, researchers see success more in terms of increasing ability to participate in the core practices of a professional community. A Learning Sciences synergy suggests seeing successful learning as an ability to participate in collaborative inquiry in a particular mathematical or scientific domain.

V. Design of Instructional Technologies

Design Factors

When discussing themes in the creation of historical and new handheld, connected activities, we identified local messaging, teacher-control, spatially-directed communication, short, asynchronous data messages and aggregation as factors. The crucial issue for computer scientists to bear in mind when designing handheld-based, wirelessly connected systems for learning is that, ultimately, nothing is more important than the learning. As in medicine, failure is a tragedy in the context of education, a waste of society's resources in general but a loss to every child who fails to learn what he or she ought. And the key to success in education is maintaining the primacy of the meaning of the experience to the learner in the classroom over the design principle.

If we re-examine the technological features that we drew out as important before in the light of the knowledge of the Learning Sciences just presented, we see that four themes provide underlying causes for those features to attain importance: shared attention, rich representation, the role of public and private work, and the importance of control. Importantly, for example, local messaging is not significant in itself but rather because of the situation it creates in the design context. Local messaging is an important technique to consider insofar as it helps maintain shared attention among relevant participants and therefore promotes deeper interaction between peers or between student and teacher.

Design Practices

In designing handheld-based, wirelessly connected activities for the classroom, we must balance the considerations of producing an entire system, emphasizing user or user group experience (Tatar et al., 2006). Stroup and Petrosino (in preparation) characterize the classroom as an eco-system, and they rightly emphasize the limitation on and inter-dependence of resources.

Our goals as engineers must be not to set immediate boundaries nor to simplify the problem at all costs, but rather provide a "space of relevance," that is, a framework in which to think about the tradeoffs. Earlier, in discussing the technological context, we talked about the relationship between RF, IR, the market place, power usage, teacher control, connections to the internet, and aspects of network performance at small scales. These are fundamentally incommensurate considerations. There may develop a societal consensus about how to handle them, but that consensus will just be another factor to take into account in the decision process than any project goes through.

This kind of design calls for a new paradigm for proceeding, a design tensions paradigm (Tatar et al., 2006). Like design rationale (Carroll; McLean) or scenario based design (Carroll and Rosson), design tensions focuses on reflection. However, unlike these paradigms, it does not carry the weight of capturing reflection in a form of interest to all subsequent designers. It attempts to assess the issues for the current design in situ. Our goals guide us through the design of handheld-based wirelessly connected system, but we may not fully understand our goals until they run into conflict during the process of design. Thus we might hazard a guess that most designers have the twin goals of producing something useful in learning and having it adopted widely. Both of these goals might appear to converge on the choice of a particular platform for delivery because of its potential for widespread frequent integral use. However, if it turns out that the devices cannot be recharged in time to use in class after class, suddenly the creators must choose or find a third option. This approach to design differs from the usual engineering problem solving in two small but highly significant ways. First, it emphasizes the integration rather than the separation of design decisions, suggesting that design decisions must be revisited during the design and building process in the light of subsequent discoveries. Second, as called for in the Value Sensitive Design movement (Friedman and Kahn, 2000; Friedman et al., 2002), it focuses us on the values inherent in the design decision. The design of learning technologies is high stakes, value laden enterprise.

One useful way of categorizing classroom systems is via the dichotomy of vertical vs. horizontal technology (Table 5, adapted from Stroup and Petrosino): tightly focused use (vertical) or general purpose use (horizontal). Other characteristics that appear to be tightly clustered with this characterization include whether it is designed primarily in reference to a teacher's pedagogical needs (vertical) or a student's personal needs (horizontal), whether it is designed to be a fixture of a classroom (vertical) or travel with the student from class to class (horizontal).

Table 5: Categorization of Classroom Technologies

Characteristic	Horizontal Technology	Vertical Technology
Designed for whom	Student	Teacher
Focus of functionality	Just-in-case	Just-enough
Physical movement between contexts	Portable across physical contexts	Fixed within use context (e.g. math classes
Inter-device communication	Peer-to-peer / neighbor	Networked / flexible group
Content domain interaction	Interdisciplinary by nature	Domain-focused

However, while this table characterizes some portion of a state of affairs in the world, note that it does describe potential for new designs to solve the problem of what "good" is in the context of a particular project. Yet we have argued that values are central to the design process. Let us return to the examples of connected SimCalc and

Match-My-Graph/NetCalc to illustrate how a designer might think about the different levels of decisions and goals in the system within the same project. Both the connected SimCalc and the Match-my-graph projects started with desktop SimCalc and its benefits. Indeed, they were funded by the same grant. As summarized in Table 5, in other words, the projects had deep and broad agreement at the vision level. Project personnel agreed that the current state-of-affairs in the world was that desktop SimCalc was highly successful, that it could promote both excellence and equity in math knowledge by giving students a better grasp of the math of change and variation. They also agreed, at the vision level, that it ought to be cheaply available in a form that would get it to more students. The project approach, also agreed upon, was to utilize inexpensive networked, handheld computers, building on the example of graphing calculators. Furthermore, they agreed in their pedagogical commitment to designing for learning through supporting the use of multiple, linked representations and through promoting participation and feedback. These agreements have considerable consequence. For example, they suggest that there might be a minimum capacity for the display of representations. Cell phones, for example, fall under the "inexpensive" and "wide spread" criteria, but not perhaps the strong representation. I-pods (which were not yet known quantities) may have sufficient representational power, but not sufficient manipulation.

However, when it came to the level of project tensions, of what goals really to support, the project agreed to diverge. One portion of the project chose to emphasize an approach that maximized the installed base of particular technology (graphing calculators) over its display and manipulation capacities. The other portion chose to emphasize the display and manipulation capacities over the installed base by choosing PDA's. Both attempted to have some elements of the others. That it, the graphing calculator based portion of the project choose to work with high-end calculators not currently possessed by every student. The PDA based portion of the project chose to go with low end IR PDA's, the least expensive on the market. While the power utilization of graphing calculators can't be beat, the Palm IIIc used less power and lasted longer (more than 90 minutes of active use) than many of the alternatives.

Ultimately, both ends of the project were successful in developing usable learning systems. Neither was a waste of time nor bad. Both advanced the field. However, they were different in ways that must be anticipated and understood during the design process.

Working with SimCalc on a graphing calculator, with its small, low-resolution screen and repurposed buttons, presents on-going usability challenges. In part for reasons of pedagogical commitment by Hegedus and Kaput, in part because of the kinds of classrooms in which the graphing calculator version of SimCalc has been used, and in part because of these UI drawbacks, the graphing calculator version of SimCalc has emphasized the relationship between the individual and whole class activities. At the same time, the capacity to continue the research and for it to spread spontaneously by teacher downloading is a substantial advantage.

Working with PDA's led to the exploration of more forms of networked connectivity, of which Match-my-graph is one example. It led to a more attractive and more usable interface. It led to a focus on peer-learning, and to a different image of student-teacher relationships, the "untethered" teacher model. It also led to subsequent on-going research on the architecture of connectivity (Lin et al., 2006; Chaudhury, 2006) and may in the long run feed back into the push into the classroom of devises that are more user friendly than graphing calculators.

Table 6: Divergent Approaches to SimCalc Resulting from Project Tensions

Vision	Is: "SimCalc, when used well, teaches the math of change and variation, in a way that promotes both excellence and equity in math knowledge "	Ought: "It ought to be cheaply available to more students"
Approach	Project drivers: The state of cheap handheld devices; the prevalence of graphing calculators in schools	Values: Pedagogical commitments to multiple, linked representations; participatory and feedback

	already.	tools; HCI commitments to graphical-user-interfaces (GUI's).
Project Tensions	Use PDA's with their larger screens and flexible input devices vs. use graphing calculators with their wide-spread prevalence.	
As Created Dilemmas	On-going usability challenges vs. a longer lead-time to demonstrations of effectiveness. Tailoring of success to teacher controlled vs. student-controlled classrooms.	

VI. Looking Forward

In this section, we examine some examples of devices that are not yet widely and effectively integrated into classroom learning. With respect to both meshing well with current practice and incorporating key lessons from the Learning Sciences, we consider the potential for new constellations of technology-enhanced learning to meet or surpass the level of success already experienced with the three historical cases.

I-Pods

Apple Computer's iPod digital music player, though it is early in its evolutionary sequence, illustrates the way in which changes in the technology ecosystem open niches for new species of technology. If the PalmPilot enables users to "break off a piece of their personal computer and take it with them in a very usable form", then the iPod enables users to "break off a piece of the Internet and take it with them in very usable form". In this case, the piece of the Internet in question is access to digital audio resources, such as mp3 files. The iPod is typically characterized as a personal device, and can be said to be very special purpose (in that its core function is centered on doing one thing: playing media). However, the fact that media are domain context neutral (an iPod plays pop music and recorded lectures on quantum physics equally well) opens the possibility that the iPod may expand to be a much more general purpose device than originally imagined.

Viewed with an eye toward its potential integration with existing practice in such a way as to incorporate learning science principles, there are a number of intriguing potential iPod applications to explore. In particular, modelling inquiry at the point of instruction both meshes well with current practice and has the potential of transforming practice through incorporating a rich, shared representation. For example, providing video snippets illustrating data collection procedures and issues *in situ* at the field site of a water quality experiment may be as convenient as providing written or oral directions but may also be far more effective in focusing discussion on the key inquiry issues of the experimental process.

Gaming Devices

In contrast to the I-pod trajectory, gaming devices such as Gameboy, PlayStation, Nintendo, Xbox, etc. are continuing to evolve toward extreme specialization. Many of these devices have hardware facilities that far exceed those of typical "horizontal" devices (such as laptops or personal computers), facilities that could, in principle, be employed in a much more general purpose way. However, the well-defined, but very large, niche these devices occupy (and battle for dominance in) tends to preclude trading off any aspect of gameplay performance for either adaptation to current practice or incorporation of learning science results.

Mobile Phones

The evolution of mobile (cellular) phones is greatly complicated by the regulatory and infrastructure constraints of their ecosystem. Though they are clearly personal devices and could, in principle, be useful in a broad range of contexts, the supporting service model militates against their evolution toward utility in classrooms and other face-to-face contexts (since those uses would, sensibly, skip the trip to the cell tower and the back.) But especially, the current inability of local institutions (such as schools) to control their usage in any kind of fine-grained way (the most common current control is to outlaw their use in classrooms) militates against any integration with current practice. The emergence of Wi-Fi-based mobile phones, for which the local wireless network infrastructure can be used as an alternative to carrier-provided infrastructure, could significantly alter this situation. Given that many of the applications described here might provide as much or more utility when implemented on mobile phones as on other classes of handheld devices, and that mobile phones are rapidly becoming the most ubiquitous of networked handheld devices, the emergence of locally controllable mobile phones could occasion a broad class of new, widely deployed, learning applications.

Projectors, SmartBoards, and other Large Format Displays

In the context of technology for teaching and learning, a very interesting emerging genus of devices comprises stationary, shared, interactive displays such as projectors, SmartBoards, and wall-mounted display panels. In classrooms today, the image source for these displays is typically a laptop or personal computer and they are used as the shared focus of attention for the entire class. In this sense, they become a general purpose, hybrid system with a classroom, rather than personal, focus. Clearly, this breed of technology is not simply adapting to a pre-existing niche but also altering the ecosystem in a way that may allow novel hybrids to flourish (personal special-purpose devices sourcing the displays in aggregate; special purpose functionality like graphing built into the displays; etc.)

Laptops and Tablet PCs

Laptop computers and their Tablet PC variants provide an illuminating contrast with the other networked handheld devices considered here. In contrast to the vertical, special-purpose nature of the devices described above, laptops and tablets are archetypical general purpose, “horizontal” devices. In addition, rather than the device application evolving to meet a learning need, current educational practice is evolving in response to the inclusion of laptops in the classroom context (“now that every student has a laptop, what do we do with them?”)

Except for the specific instance of enabling more, and more frequent, re-writing and re-visioning (for which there are successful, more “vertical” alternatives such as the popular AlphaSmart devices), effective learning applications of such general-purpose devices are not as well established as effective learning applications of more specific-use devices. That said, the direct and natural interaction through stylus drawing provided by Tablet PCs strongly suggests a rich realm for exploration of potential linkages with powerful learning experiences and careful meshing with current – and emerging – practice.

The $100 Laptop

The $100 laptop, devised by Nicholas Negroponte and his colleagues at MIT, is a response to concerns that technology is too often prohibitively expensive for wide-spread use in schools. Because it is still fundamentally a general-purpose, horizontal device, the $100 laptop fills a niche in the learning and technology ecosystem similar to that of regular laptops and tablet PCs. However, some important differences derive from the relative low-cost and enhanced durability of the $100 laptop. In particular, $100 laptops make it possible for students to not only work with technology on a 1 to 1 basis, but also to be in sole possession of the device, keeping the laptop with them at all times, both at school and at home. As a result, the $100 laptop has the potential to drive a rapid evolution of practices that capitalize on a strengthened home/school connection and a new bridge between informal and formal learning.

VII. Conclusion

Handheld devices, especially networked handheld devices, are growing in importance in education, largely because their affordability and accessibility create an opportunity for educators to transition from occasional, supplemental use of computers, to frequent and integral use of portable computational technology. We have offered a view on this trend that is grounded in historical examples of success, learning theory, an analysis of design tradeoffs and a discussion of design practices.

Our historical review highlighted three examples of handheld and wireless technologies that already have made a significant impact in school learning: graphing calculators, classroom response systems, and probes for collecting scientific data. Each of these has amassed a research literature providing evidence of a positive impact in education and detail on the factors contributing to implementation success.

The review and synthesis of learning theory highlighted two perspectives that can guide successful design of transformed classrooms, a cognitive augmentation perspective and a social participation perspective. We suggested that transformative uses of networked handheld devices will link in-school and out-of-school uses of technology for learning. Transformative uses will position the devices as a symbolic tool that fruitfully links social and cognitive dimensions of learning. To realize this potential, educators will design new forms of learning activity in which learners use symbol systems to participate in collaborative inquiry in a particular academic discipline.

Our analysis of tradeoffs argued that education has different requirements from consumer or enterprise markets and thus technologies that are successful in consumer or enterprise markets may not be a good fit to school markets. We note that all three historical examples of success were not consumer or enterprise products, but rather were specifically designed for the education market. Therefore, innovators should not think of educational handhelds as scaled-down computers but rather as specific appliances designed for a unique ecological niche. We called for designs of new ICT infrastructures that fit the needs of school. Some of these needs include: a local messaging topology among participants in mostly face-to-face settings; variations in teacher control and expectations for teacher behavior; the desirability of spatially directed communications,; in the predominance of short, asynchronous structured data over long general purpose text messages or long-term conversations; and in aggregation of data and experience by student and teacher. A shared public display is often important in making these aggregates available for discussion. As there are no easy solutions, we suggested that a design tensions framework will be useful as designers work to realize the potential of new devices in enhancing the classroom experience.

We now conclude with a few comments on the challenge of scale. In nearly every country, improving the quality of education is seen as deeply linked to improving economic growth and the quality of life. Education, however, is a large-scale system which is slow and difficult to change. Furthermore, the history of attempts to use technology in the service of improving education is not a happy one. Simply put, most technologies have failed to make a noticeable impact in educational quality. Yet, a few handheld technologies, such as the graphing calculator, are making a positive impact at scale (as affirmed by the correlation between graphing calculator use and mathematics achievement on the National Assessment of Educational Progress). We can make a difference with technology but it is never easy.

Here are a few ways in which handheld and networked technology could fail to enhance education. Wireless networks could prove too complex for schools to maintain or could fail to perform gracefully in conditions where 30 students suddenly ask for the same piece of data. New handheld devices could usher in a new age of incompatible operating systems (how will that iPod interoperate with that PDA and that graphing calculator) leading to a nightmare of system incompatibilities. The antisocial affordances of new technologies – allowing cheating, disruptive behavior, increasing student inattention to school tasks, or access to illicit materials – could outweigh the benefits in the eyes of parents, administrators and other school stakeholders. Purchasers could fail to demand integration of curriculum, assessment and teacher professional development with new technologies, and thus ignore the most important lesson of the past: that no technology improves learning in schools without substantial attention to these complementary components. Case studies could ignore the unusual extra resources made available in a school testbed and attempts to replicate and scale could fall apart in new locations that do not have these unique or extra resources.

We believe that networked handheld technology can overcome these potential downsides, but only if innovators keep the challenges of scale in mind as they design new technologies, activities, and school improvement plans. For a technology to work at scale, it must be quite simple and robust; it must tap complementary technical and social forces in learning; it must integrate with other drivers of school improvement (such as curriculum, assessment, and teacher professional development), it must make low demands on already over-taxed school resources and be effective despite variability among schools, teachers, and students. Interdisciplinary teams will be crucial to overcoming these obstacles and thus we invite technologists to join hands with educators and learning scientists in the quest for applications of handheld and networked technologies that can have a positive impact at necessary scale to improve the lives of children and teachers throughout our vast educational systems.

Acknowledgements

Special thanks to Corinne Singleton for her tremendous support in writing this article. This material is based in part upon work supported by the National Science Foundation under Grant Numbers #0205625 and #0427783. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

Abrahamson, L. A., F. Hantline, et al. (1989). Electronic classroom system enabling interactive self-paced learning [patent #5002491]. Patent and Trademark Office. United States of America.

Abrahamson, L. A., A. Davidian, et al. (2000). Wireless calculator networks: Where they came from, why they work, and where they're going. 13th Annual International Conference on Technology in Collegiate Mathematics, Atlanta, GA.

Becker, H. J. (1999). Internet use by teachers: Conditions of professional use and teacher-directed student use. Irvine, CA, Center for Research on Information Technology and Organizations.

Becker, H. J. and M. Riel (1999). Teacher professionalism & the emergence of constructivist-compatible pedagogies. Irvine, CA, Center for Research on Information Technology and Organizations, University of California.

Black, P. and D. Wiliam (1998). Inside the black box: Raising standards through classroom assessment. London, King's College London.

Burrill, G., J. Allison, et al. (2002). Handheld Graphing Technology in Secondary Mathematics: Research Findings and Implications for Classroom Practice. Dallas, TX, Texas Instruments.

Burnstein, R. A. and L. M. Lederman (2001). "Using wireless keypads in lecture classes." The Physics Teacher.

Carroll, J. M., Ed. (1998). Minimalism Beyond the Nurnberg Funnel. Cambridge, MA, MIT Press.

Chan, T., Roschelle, J., Hsi, S., Kinshuk, Sharples, M., Brown, T., Patton, C., Cherniavsky, J., Pea, R., Norris, C., Soloway, E., Balacheff, N., Scardamalia, M., Dillenbourg, P., Looi, C., Milrad, M., & Hoppe, U. (2006). One-to-one technology-enhanced learning: An opportunity for global research collaboration. Research and Practice in Technology Enhanced Learning, 1(1), 3-29.

Consortium for School Networking (2004). A guide to handheld computing in K-12 schools. Washington DC, Consortium for School Networking.

Cook, T. D. & Shadish, W. R. (1986). Program evaluation: The worldly science. Annual Review of Psychology, 37, 193-232.

Crawford, V. and P. Vahey (2002). Palm Education Pioneers Program: March 2002 Evaluation Report. Menlo Park CA, SRI International.

Crouch, C. H. and E. Mazur (2001). "Peer instruction: Ten years of experience and results." The Physics Teacher 69(9): 970-977.

Cuban, L. (2003). Oversold and underused: Computers in the classroom. Cambridge, MA, Harvard University Press.

Davis, S. (2002). Research to industry: Four years of observations in classrooms Using a network of handheld devices. IEEE International Workshop on Wireless and Mobile Technologies in Education, Växjö, Sweden, IEEE Computer Society.

Davis, S. (2003). "Observations in classrooms using a network of handheld devices." Journal of Computer Assisted Learning 19(3): 298-307.

Dufresne, R. J., W. J. Gerace, et al. (1996). "Classtalk: A classroom communication system for active learning." Journal of Computing in Higher Education 7: 3-47.

Ellington, A. J. (2003). "A meta-analysis of the effects of calculators on students' achievement and attitude levels in pre-college mathematics classes." Journal for Research in Mathematics Education 34(5): 433-463.

Engelbart, D. C. (1962). A conceptual framework for augmenting human intellect. Menlo Park, CA, SRI International.

The Evolution of Instructional Use of Hand Held Technology. What we wanted? What we got! Franklin Demana and Bert K. Waits To appear in the Proceedings of the October, 1997 Technology Transitions Calculus Conference.

Fagen, A. P., C. H. Crouch, et al. (2002). "Peer instruction: Results from a range of classrooms." The Physics Teacher 40(4): 206-207.

Ferrio, T. (2004). What year did the graphing calculator get to scale? (email correspondance).

Friedman, B., & Kahn, P. H., Jr. (2000). New directions: A value-sensitive design approach to augmented reality. Paper presented at the DARE 2000.

Friedman, B., Kahn, P., & Borning, A. (2002). Value sensitive design: Theory and Method. Seattle, WA: University of Washington.

Graham, A. T. and M. O. J. Thomas (2000). "Building a versatile understanding of algebraic variables with a graphic calculator." Educational Studies in Mathematics 41(3): 265-282.

Hake, R. R. (1998). "Interactive-engagement vs. traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses." American Journal of Physics 66: 64-74.

Hegedus, S. J. and J. Kaput. (2002). "Exciting new opportunities to make mathematics an expressive classroom activity using newly emerging connectivity technology."

Hegedus, S. J. and J. Kaput. (2003). The effect of a SimCalc connected classroom on students' algebraic thinking. Psychology in Mathematics Education conference, Honolulu, HI.

Hegedus, S.J. and J. Kaput. (2004). An Introduction to the Profound Potential of Connected Algebra Activities: Issues of Representation, Engagement and Pedagogy. Proceedings of the 28th Conference of the International Group for the Psychology of Mathematics Education. Vol. 3. pp. 129-136.

Heller, J. L., D. A. Curtis, et al. (2005). Impact of handheld graphing calculator use on student achievement in algebra 1. Oakland CA, Heller Research Associates.

Hickman, L. A. (1990). John Dewey's pragmatic technology. Indianapolis, IN, Indiana University Press.

Kaput, J. (2002). Implications of the shift from isolated, expensive technology to connected, inexpensive, diverse and ubiquitous technologies. Representations and mathematical visualization. F. Hitt. Mexico, Departmento de Matematica Educativa del Cinvestav - IPN.

Kaput, J. and S. J. Hegedus (2002). Exploiting classroom connectivity by aggregating student constructions to create new learning opportunities. 26th Conference of the International Group for the Psychology of Mathematics Education, Norwich, UK.

Khoju, M., A. Jaciw, et al. (2005). Effectiveness of graphing calculators in K-12 mathematics achievement: A systematic review. Palo Alto, CA, Empirical Education, Inc.

Kiili, K. (2002). Evaluating WAP Usability: What Usability? IEEE International Workshop on Wireless and Mobile Technologies in Education, Växjö, Sweden, IEEE Computer Society.

Lajoie, S. P. and S. J. Derry, Eds. (1993). Computers as cognitive tools. Hillsdale, NJ, Lawrence Erlbaum Associates.

Liu, T.-C., H.-Y. Wang, et al. (2003). "Embedding Wireless and Mobile Technologies in Classroom to Enhance Learning and Instruction." Journal of Computer Assisted Learning(this issue).

Mazur, E. (1997). Peer Instruction: A user's manual. Englewood Cliffs, NJ, Prentice Hall.

Mokros, J. R. and R. F. Tinker (1987). "The impact of microcomputer-based labs on children's ability to interpret graphs." Journal of Research in Science Teaching 24(5): 369-383.

Nachmias, R. and M. Linn (1987). "Evaluations of science laboratory data: The role of computer-presented information." Journal of Research in Science Teaching 24: 491-506.

National Center for Education Statistics (2001). The nation's report card: Mathematics 2000. Washington DC, U.S. Department of Education.

Owens, D. T., F. Demana, et al. (2002). Developing Pedagogy for Wireless Calculator Networks: Report on Grants ESI 01-23391 & ESI 01-23284. Columbus, OH, The Ohio State University Research Foundation. (2002), Developing Pedagogy for Wireless Calculator Networks, The National Science Foundation, 4201 Wilson Blvd., Arlington, Virginia 22230.

Papert, S. (1980). Mindstorms: Computers, children, and powerful ideas. New York, Basic Books.

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.

Penuel, W. R., Abrahamson, A. L., & Roschelle, J. (forthcoming). Theorizing the transformed classroom: A sociocultural interpretation of the effects of audience response systems in higher education. In D. Banks (Ed.), *Audience response systems in higher education: Applications and cases*.

Pownell, D. and G. D. Bailey (2001). Getting a handle on handhelds: What to consider before you introduce handhelds into your schools. Electronic School.com.

Resnick, M., Berg, R., and M. Eisenberg (2000). Beyond Black Boxes: Bringing Transparency and Aesthetics Back to Scientific Investigation. Journal of the Learning Sciences, Vol. 9, No. 1, Pages 7-30.

Resnick, M. (2006). Computer as paint brush: Technology, play, and the creative society. To be published in: D. Singer, R. Golikoff & K. Hirsh-Pasek (Eds.), Play = Learning: How play motivates and enhances children's cognitive and social-emotional growth. Oxford University Press.

Rheingold, H. (2002). Smart Mobs: The Next Social Revolution. Cambridge MA, Perseus Book Group.

Robinson, S. (2002). Discourse: Decades of achievement results. Princeton, NJ, Educational Testing Service.

Roschelle, J. (1991). Microanalysis of qualitative physics: Opening the black box. Annual Meeting of the American Educational Research Association, Chicago, IL, AERA.

Roschelle, J. (1991). Students' construction of qualitative physics knowledge: Learning about velocity and acceleration in a computer microworld. Berkeley, CA, University of California, Berkeley.

Roschelle, J., Pea, R., Hoadley, C., Gordin, D., Means, B. (2001). Changing How and What Children Learn in School with Computer-Based Technologies. The Future of Children, 10(2). Los Altos, CA: Packard Foundation. 76-101."

Roschelle, J. and R. Pea (2002). "A walk on the WILD side: How wireless handhelds may change computer-supported collaborative learning." International Journal of Cognition and Technology 1(1): 145-168.

Roschelle, J., W. R. Penuel, et al. (2004). "The networked classroom." Educational Leadership 61(5): 50-54.

Roschelle, J., W. R. Penuel, et al. (2004). Handheld tools that "informate" assessment of student learning in science: A requirements analysis. IEEE Wireless and Mobile Technologies in Education, Taiwan, IEEE Press.

Sawyer, K., Ed. (2006). The Cambridge Handbook of the Learning Sciences. New York, Cambridge University Press.

Scheele, N., M. Mauve, et al. (2002). "The interactive lecture: A new teaching paradigm based upon ubiquitous computing."

Schwartz, J. (2003). Professors Vie With Web for Class's Attention. New York Times. New York.

Seeley, C. (2006). "Technology is a tool: President's message." NCTM News Bulletin 42(7): 3.

Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). Experimental and quasi-experimental designs for generalized causal analysis. New York: Houghton Mifflin.

Shadish, W., T. Cook and L. Levison (1991) Foundations of Program Evaluation. Newbury Park, CA: Sage.

Soloway, E., C. Norris, et al. (2001). "Devices are ready-at-hand." Communications of the ACM 44(6): 15-20.

Stroup, W. M., J. Kaput, et al. (2002). The nature and future of classroom connectivity: The dialectics of mathematics in the social space. Psychology and Mathematics Education North America conference, Athens, GA, Educational Resources Infomration Center (ERIC).

Stroup, W. M. and A. J. Petrosino (in preparation). "An Analysis of Horizontal and Vertical Device Design for School-Related Learning." Journal of Technology Education.

Tatar, D., V. Michalchik, et al. (2003). Beaming, teaming & talk: Handheld wireless math meets middle school sociality. NCTM Research Presession, San Antonio, TX.

Tatar, D., Vahey, P. and Roschelle, J. (2006) Design Tensions in the Creation of a Handheld, Networked Application for Teaching Math. Submitted, *Journal of Human-Computer Interaction*.

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

Vahey, P. and V. Crawford (2002). Palm Education Pioneers Program: Final Evaluation Report. Menlo Park, CA, SRI International.

The Virtual Fifth Dimension Clearinghouse and Propagation Center Website. Accessed June 2006. http://www.education.miami.edu/blantonw/5dclhse/kidsactivities/main_ki.html.

Weiner, N. (1948). Cybernetics, or control and communication in the Animal and the machine. Cambridge, MA, MIT Press.

White, B. (1993). "ThinkerTools: Causal models, conceptual change, and science education." Cognition and Instruction 10(1): 1-100.

Wilensky, U. and W. Stroup (2000). Networked Gridlock: Students Enacting Complex Dynamic Phenomena with the HubNet Architecture. The Fourth Annual International Conference of the Learning Sciences, Ann Arbor, MI.

Woods, H. A. and C. Chiu "Wireless response systems in college classrooms."

Zurita, G. and M. Nussbaum (2004). "A constructivist mobile learning environment supported by a wireless handheld network." Journal of Computer Assisted Learning 20: 235-243.