Effective Integration of Dynamic Representations and Collaboration to Enhance Mathematics and Science Learning

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Abstract

The vision to transform school education through the use of information and communication technologies has existed for more than two decades. Successful models of small-scale implementation of that vision in a few classrooms or schools have been evident for almost as long, but few of them have achieved widespread success. The trajectory of most learning technology innovations starts with an exciting vision of transformative potential, peaks with a demonstration in a few model sites, and then, sadly … nothing. Given the failure rate, it makes a lot of sense to pay attention to innovations that achieve widespread positive results. What can we learn?

I examine two technologies that have been effectively integrated into schools, achieved impressive scale and produced large learning gains and transformations in pedagogical practice. The first is the graphing calculator. Graphing tools have been integrated into middle and high school classrooms in many states and countries, including Australia. In the United States, at least half of all high school students have and use a graphing calculator. The results of America's National Assessment of Educational Progress as well as sophisticated analyses of multiple research studies show the strong positive impact of graphing calculators on learning, particularly in engaging students in learning advanced mathematical concepts.

The second technology is that of handheld collaboration tools, which are being rapidly adopted worldwide, across multiple subjects and grade levels. These tools span a range from very simple 'clickers' (a device similar to a remote control that allows students to 'vote' on the best answer and allows teachers to aggregate student responses) to wireless handhelds, such as Palm or PocketPCs, which can be used to organise students according to successful patterns of collaborative learning. Such tools build on what we know about how people learn, including research on the effectiveness of peer learning and formative assessment. Teachers who use the innovations repeatedly describe a transformed classroom experience.

I suggest a few key factors underlying the classroom success of both technologies. Obviously, they are relatively simple, robust and cheap (and also remarkably free from techno-speak buzzwords). More importantly, in each case there is a deep scientific linkage between the capabilities of the technology and how people learn. Without these two factors, there is no point in pursuing effective integration. I emphasise two further, less obvious factors. In both cases, the adoption of these innovations has been led by practising teachers, who function as the key champions and influencers in a professional community. As well, both innovations begin with little or no expectation of a changed classroom but provide a context that can support a long, steady trajectory of continuous improvement. I suggest that future pathways for continuous improvement could begin with fairly simple technologies and end with fairly dramatic transformations of classroom learning.

Introduction

Handheld devices are growing in importance in education, largely because their affordability and accessibility create an opportunity for educators to make the 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, yet 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?

I begin by discussing a simple but important factor: network handhelds can allow a 1:1 ratio of student to device 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, I 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. 2000). Further, successful technologies must be integrated into the social practices of schools, which in turn requires 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 organised around knowledge work and innovation, both of which depend mightily on the quality of learning in school. Without incorporating 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 responded to this challenge, most recently calling itself the 'learning sciences' (Sawyer 2006). To introduce readers to the broad scope of research that relates to networked, handheld computers and that falls under the rubric of the Learning Sciences, I take the following approach. First, I 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. I next review two historical examples of success with high levels of access to handheld and/or networked technology. From this review, I draw the conclusion that handhelds are already making a huge difference in student learning. In addition, I observe that handhelds are not simply smaller personal computers. Indeed, the truly successful examples of technology-enhanced learning draw upon properties of networked handhelds that are not particularly like 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.

I conclude this paper by considering factors necessary for effective integration of information and communication technologies (ICT) into the life of schools and students. The handhelds in the historical examples are relatively simple, robust and cheap (and also remarkably free from techno-speak buzzwords). More importantly, in each case there is a deep scientific linkage between the capabilities of the technology and how people learn. Without these two factors, there is no point in pursuing effective integration. I emphasise two additional, less obvious factors. First, in both cases, the adoption of these innovations has been led by practising teachers, who function as the key champions and influencers in a professional community. Second, both innovations begin with little or no expectation of a changed classroom but provide a context that can support a long, steady trajectory of continuous improvement. I suggest that future pathways for continuous improvement could begin with fairly simple technologies and end with fairly dramatic transformations of classroom learning.

The value of ready-to-hand access

Traditional desktop technology is expensive, and as a result, limited computer resources must be shared among many teachers and students. Today the typical student to computer ratio is 5:1, and computers are most often located in special computer labs rather than in ordinary classrooms (Cattagni & Farris 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 a 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. 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 student. 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 have done. Approximately 40 per cent of high school mathematics classrooms use graphing calculators, whereas only 11 per cent of mathematics classrooms use computers. Finally, because handhelds can be used much more frequently than can computers in traditional computer labs, they dramatically increase the potential of computational technologies to positively influence 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, noninvasive support to group learning. 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 animations can enable Year 8 students to learn concepts normally encountered only in a high school calculus class (Vahey et al. 2004). Early evaluations suggest teachers and students respond to handhelds favourably. In a study of 100 Palm-equipped classrooms, 90 per cent of teachers reported that handhelds were effective instructional tools that had the potential to affect student learning positively across curricular topics and instructional activities (Vahey & Crawford 2002).

Graphing calculators

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

Pedagogical affordances of graphing calculators

Like other handheld 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 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 (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 (for example, modeling)
- 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 labouring 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 $ax^2 + bx + c$, which can be quite tedious when 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 (Goldenberg 1995; Kaput 1992). 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 visualisation aids, fostering further conceptual understanding.

Research on graphing calculators

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

In the United States, the National Assessment of Education Progress (NAEP) samples Year 4 and Year 8 students across 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 Year 8 level (but not at Year 4 level) is associated with greater mathematics achievement:

> 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. 141).

A study by Heller et al (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 within the theme of ‘Dynamic algebra’. This study shows that daily use of graphing calculators is generally more effective than infrequent use, and establishes that those teachers and students who used graphing calculators most frequently were those who learnt 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 & Thomas 2000). The study compared pre-test and post-test 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 mathematical 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 summarise the results of a large body of experimental studies, which yields a robust estimate of true effectiveness. A meta-analysis by Ellington (2003) summarised 54 classroom experiments, of which 80 per cent 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. Ellington’s analysis shows a positive effect on student achievement of interventions based on use of graphing calculators. 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 during 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 et al. 2005). This report screened available research using stringent quality-control criteria published by the United States 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 mathematics 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 practising teachers who function as the key champions and influencers in a professional community (Ferrio et al. 1997). Secondly, 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. 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 mathematics.

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

A second effective handheld learning technology is the networked response system. The first notably successful classroom response system, Classtalk, was patented in 1989. Similar product concepts have since been re-implemented many times. A major benefit of these classroom networks is that they enhance classroom communication between the teacher and the students. Employing a combination of networking hardware and software, classroom networks 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.

Importantly, this technology accommodates common teaching practices while also offering new enhancements for classroom teaching. While effective teacher implementation of classroom communication practices is a critical component of improved student performance, network technology can be a key enabler by facilitating rapid cycles of assigning, collecting, interpreting and discussing student work.

Instructional processes using classroom networks

From a technological viewpoint, a classroom network can be thought of as a tool to augment the interaction loop between teacher and students. The concept of interaction loops builds upon Weiner's pioneering work in cybernetics (Weiner 1948). As illustrated in Figure 1, 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.

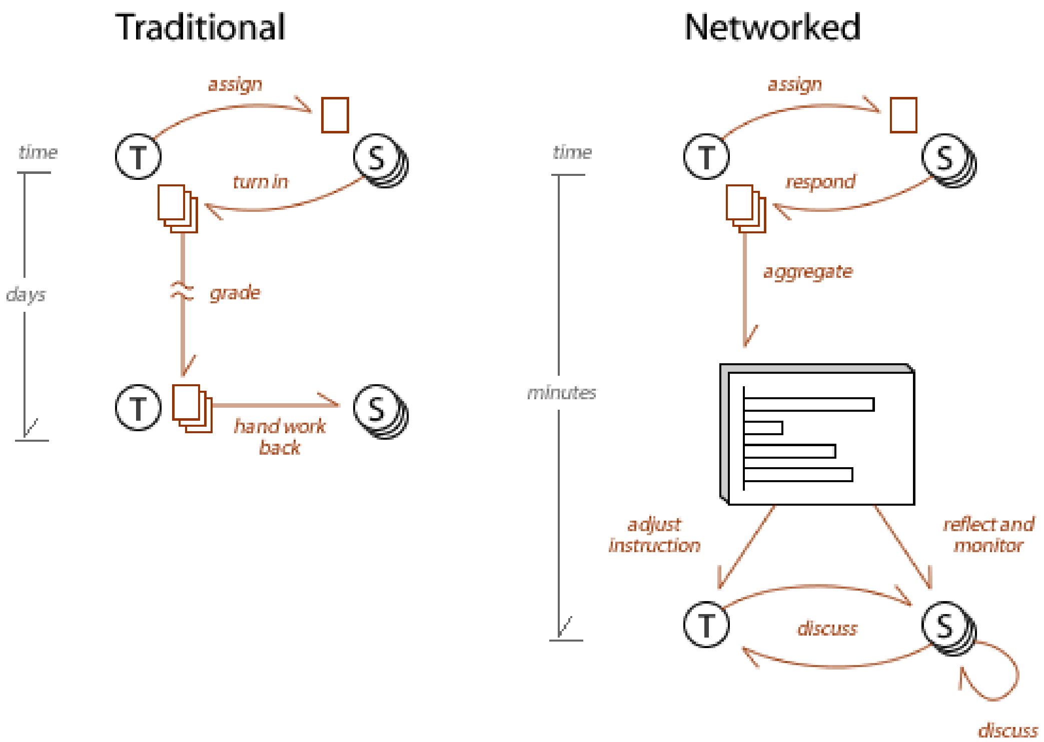

Figure 1: Traditional vs networked classroom interaction loop

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. The networked loop of Figure 1 shows a histogram of students' responses to a question.

Pedagogical affordances of classroom networks

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 learnt and to engage in discussion of 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 classroom networks to date, students engage in a participatory simulation. 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 uses of classroom networks 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 catalyse class discussions of complex concepts. Harvard's Eric Mazur, an early leader in developing the pedagogical use of classroom networks, calls this approach 'peer instruction' (Mazur 1997), 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 classroom networks 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 (Davis 2003; Stroup 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 recognise that they are not alone. It is important to note that the overall impact of the lesson need not be at all test-like. Students' 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 classroom 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 visualisation that enhances mutual pattern recognition. But non-technological social processes, such as asking questions, explaining, clarifying and summarising, still carry much of the burden of teaching and learning.

The most recent and thorough examinations of this technology (using Texas Instruments graphing calculators and a pre-release networking product) emphasise a virtuous cycle of changes that results in a classroom that uses the system (Davis, 2003; Owens et al., 2002). The cycle is characterised by the four factors of successful classrooms identified in a groundbreaking summary of learning science research (Bransford et al. 2000; National Research Council 1999). The classroom becomes more learner-centred, assessment-centred, knowledge-centred and community-centred. These are powerful and apparently robust effects of a fairly simple use of 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 & Hegedus 2002). Many more kinds of classroom response aggregations are possible. Clearly, pedagogical applications for classroom response systems deserve much more research attention in the coming years.

Research on classroom response systems

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 of 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 would adapt his subsequent instruction by moving on to the next topic or by spending more time on the subject until mastery was achieved. For questions that uncovered lots of misconceptions, Mazur would facilitate discussion of the topic, encouraging students to explain and debate their understandings. The resulting discussions could focus on understanding the correct conceptual structure because, while questions were superficially simple, they were laser-like in their ability to demarcate misconceptions and stimulate valid reasoning.

The process of discussing possible responses, misconceptions and conceptual understandings among peers, through ConcepTests and classroom 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 emphasises 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 (FCI) shifted markedly between pre-test and post-test, suggesting that his new approach was effective (1997). Impressively, the post-test showed that only 4 per cent of students were below the threshold of mastery as defined by the FCI. There was 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 a 1991 class by giving them the same final exam. He found that the scores shifted upwards about 10 per cent and manifested a much narrower distribution, showing that he had achieved important progress in 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). Broader reviews of research on 'peer instruction' have also found impressive outcomes (Crouch & Mazur 2001; Fagen et al. 2002).

Why have classroom response systems been so successful?

A number of key features contributes to the success of classroom response systems in bolstering science and mathematics learning. Like graphing calculators, classroom response systems are relatively simple, robust and cheap; they are also remarkably free of much of the complexity that accompanies the use of technology in computer labs. More importantly, there is a deep scientific linkage between the capabilities of the technology and how people learn. Students learn best when classrooms are learner-centred, knowledge-centred, assessment-centred and community-centred – qualities than can be enhanced when teachers use classroom networks for formative assessment, adapting instruction and encouraging peer learning.

Another parallel with the case of graphing calculators is that the use and adoption of classroom response technology has been led by practising teachers who function as the key champions and influencers in a professional community (for example, Eric Mazur, whose book is enormously popular, spends a great deal of time travelling to promote his method). It is noteworthy, too, that classroom response technology has a low threshold for adoption. Initially, teachers do not have to change much of what they do to adopt this technology; all teachers ask questions and expect students to respond. The big initial difference with this technology is that it makes the thinking of *all students in the group* visible, not just the answer of one individual student. Further the responses are *anonymous,* which can decrease students' academic anxiety. Over time, however, teachers who frequently use classroom response systems report major changes in their practice. Teachers are often surprised that students did not learn despite their clear explanations and discover that they must engage students in discussion to draw out misconceptions and construct more robust understandings. Teachers find they can adapt instruction, moving more quickly over topics that students understand and spending more time on difficult topics. Over time, students become more focused on helping each other learn and the classroom climate improves.

Emerging representational and collaborative tools

The representational capabilities of graphing calculators can now be found in a variety of devices, including Palm and Pocket PC PDAs, handheld gaming devices and mobile phones. Indeed, the capabilities of devices to calculate and represent mathematic and scientific concepts will rapidly expand over the coming years. Simultaneously, the wireless networks required for classroom communications are also becoming increasingly ubiquitous. Whereas the original Classtalk used a wired network and later a custom infrared network, today handheld technologies can join ubiquitous 802.11 wireless networks and allow students to participate in classroom communities. These converging capabilities are leading to a variety of powerful new applications of representational and collaborative tools for learning. A few of these emerging applications are described below.

Networked calculators

The SimCalc algebra classroom uses increasingly robust and inexpensive handheld devices, enabled with motion and connectivity, to create a new learning environment for students. 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)

A glimpse at a Year 8 algebra lesson designed by Hegedus and Kaput shows why these investigators are enthusiastic. In class, the teacher asks each student to 'count off' and then poses a mathematical challenge that varies according to their count-off number – so that each student is working on their own, slightly different, challenge. In this case, the challenge is to make a function whose graph starts at your number and goes through the point (6, 12). Using a calculator, the students each specify mathematical functions. Then, using the classroom network, the teacher rapidly 'harvests' every student's unique solution for display on an overhead panel. The students now see their work on a shared screen, leading to passionate engagement in talk about the mathematics they created. In addition, the teacher can guide them to investigate new structure that appears in the aggregated set of lines, for example, how do their slopes vary? Furthermore, the graphed functions can also control a motion animation on both the students' units and the classroom display. Each student's function thus becomes part of a mathematical model of a race, dance or parade! (See http://www.simcalc.umassd.edu for more information.)

Teachers can take advantage of networked capabilities by assigning both individual tasks and group tasks so that the individual tasks contribute to the larger group solutions. This set-up allows students to collaborate with peers and to see the interaction between different elements of a larger mathematical concept. As students complete the task at hand, they can electronically 'submit' their solutions to the teacher's device. The teacher's device can instantly aggregate responses and display simple graphs of, for example, student response patterns. This rapid accumulation of student work allows teachers to assess individual and overall student understanding immediately and precisely. In turn, teachers can adjust instruction, provide feedback and require students to revise their work as needed. Pedagogically, teachers can display student work so as to strategically direct student attention to certain concepts and underlying mathematical structures. Finally, classroom networks facilitate a blend of public anonymity and individual accountability that can reduce academic anxiety, while still encouraging all students to work hard.

By facilitating motion, connectivity and collaboration, networked handheld devices are creating a transformation in mathematics classrooms. In transformed classrooms, technology is not merely a medium for individual practice with mathematics content, but rather, technology is 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 dramatically 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, organised and displayed for discussion in the public workspace’ (Hegedus & Kaput 2003).

Mediated computer-supported collaborative learning

Miguel Nussbaum and colleagues in Chile (Zurita & Nussbaum 2004) have developed a series of activities that use wirelessly connected Pocket PC handhelds to foster collaborative learning. They seek to enhance learning of subject matter and also to encourage students to develop better social skills and attitudes, thereby enhancing their ability to participate in teamwork and innovation.

A typical classroom in Chile has 40 students and very few resources. Compared to a classroom in the United States, the walls are rather bare and teachers typically have only a blackboard and textbooks with which to share content with students. Even power outlets for plugging in computers are hard to find in the Chilean classrooms I visited. Thus a handheld, battery-powered solution is necessary. In the classroom I visited, the teacher gave a short lecture and then proceeded to give students the handhelds from a charger-case that recharges the batteries between classes. Students quickly assembled into groups of three and began to work together to answer questions.

Nussbaum has designed several activities, but the simplest uses a familiar multiple-choice question format – with a twist. Instead of telling students whether they are right or wrong, the software tells the students only if they agree or disagree. If they disagree, then they must discuss their answers to resolve their differences of opinion. While simple, this functionality drives the students to engage each other in peer learning. In more sophisticated activities, students may exchange pieces of a solution to find matching representations. Or they may be asked to design and sketch solutions to a challenge with a requirement that they discuss and agree upon the best design in their small groups before submitting the best design to the teacher. In the most complex activities, students jointly control a mobile robot.

Nussbaum’s designs build upon powerful cooperative learning principles (Johnson & Johnson 1989), particularly the principle that every student should be individually accountable but should be rewarded for group success. As is the case with early classroom response systems, Nussbaum builds upon a simple activity that happens everyday in classrooms – question answering – but transforms this activity into a much more powerful form through the use of wireless handheld technology.

HyperCard for classroom collaboration

At SRI International, my colleagues and I have been addressing the challenge of creating a general-purpose medium for collaboration in classrooms where each student has a wirelessly connected handheld device with stylus or ink input. For example, many classrooms are now adopting Tablet PCs. In addition, classrooms sometimes now have electronic whiteboards on which the teacher can draw with a marker or finger. Unfortunately, there is little educational software available to take advantage of the unique new affordances of ink in a shared graphical environment.

GroupScribbles enables collaborative improvement of ideas based upon individual effort and social sharing of notes in graphical and textual form (‘scribbles’). An analogy to Apple’s HyperCard puts GroupScribbles in context. When Apple produced the Macintosh operating system in the 1980s, it had wonderful new educational capabilities, such as multimedia and hypertext. However, educators could not yet realise the potential because only programmers could access the capabilities. When HyperCard was released, educators responded with a surge of creativity. With HyperCard, educators were able to make everything from grade books to frog dissections without hiring a programmer. By analogy, today’s classroom has new capabilities of wireless connectivity among handheld or tablet devices for every student. However, educators cannot tap these capabilities without a programmer and hence little innovation is occurring. With GroupScribbles, SRI introduces a way for educators to rapidly design new collaborative and group-learning activities without the need for additional programming. The only limit is the educator’s creativity.

The GroupScribbles user interface presents each user with a two-paned window. The lower pane is the user’s personal work area, or ‘private board’, with a virtual pad of fresh ‘scribble sheets’ on which the user can draw or type. A scribble can be shared by dragging and dropping it on the public board in the upper pane. When this happens, a tuple representing the scribble is written to a tuple space corresponding to that public board. Other participating clients monitor the space for such activity and update the client’s display. Users may interact with public scribbles in a variety of ways, such as browsing their content, repositioning them, or moving one from the public board into their private space. New public boards can be created to support multiple activities or spaces for small groups to work.

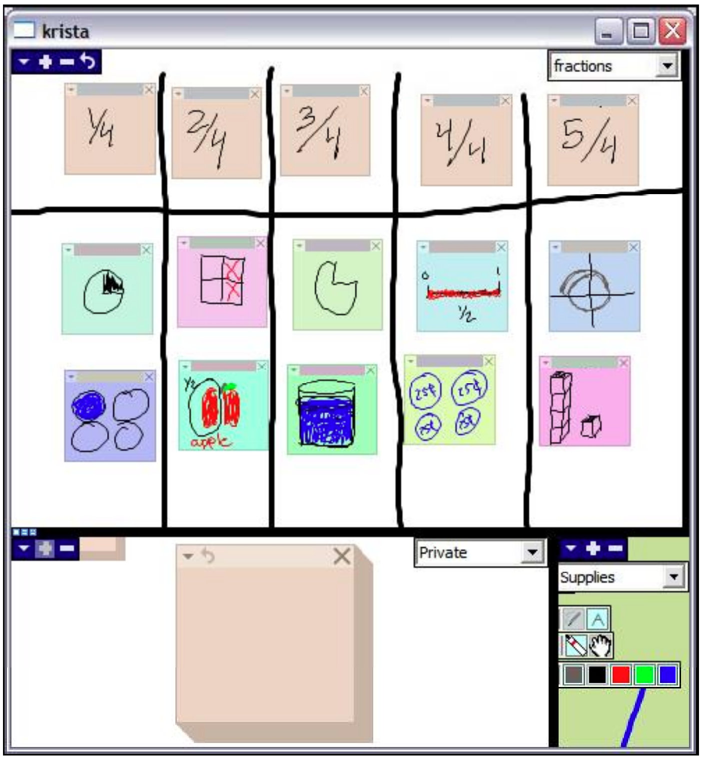

Figure 2: A GroupScribbles activity in which students represent fractions in different ways

We have found that GroupScribbles allows teachers to improvise a wide variety of interesting group activities in suitably equipped classrooms. For example, Figure 2 shows the teacher's view of an activity with fractions. In this activity, each student first suggests a different fraction. Students write their fractions as scribbles and drag them to the public board, resulting in the top row. The teacher can then challenge the students to come up with different representations of the fractions. Students then create these representations and drag them underneath the matching fraction. The teacher can then lead a rich classroom discussion about the resulting display, which has a variety of fractions and representations present.

Conclusion: Efficiency and innovation

Effective integration of technology into classroom learning is a difficult challenge. Many technologies have been proposed and tested in classrooms, but few succeed in lasting. Wireless handheld devices offer many advantages in cost, simplicity and capabilities, but will they be effectively integrated? In reflecting upon historical examples of effective integration of handheld and classroom network technologies, I have come to the conclusion that *simplicity* is an absolutely essential feature of all technologies that succeed at scale in transforming classrooms. Education is a complicated institution and teachers have busy and difficult jobs. The classroom is no place for complex, fragile, unstable technology.

A second key characteristic of effective integration is that it requires the participation of teachers. Indeed, teachers significantly co-invented both graphing calculators and classroom response systems. In the case of graphing calculators, teachers initially invented the pedagogies and new curricular approaches required to take advantage of the technology – but over time the leading companies came to rely upon advice from the teacher networks to design new features (Ferrio et al. 1997). Today's graphing calculator embodies significant contributions from both technical and teacher contributors. Classroom response systems followed the same trajectory, with significant involvement in the design and use of the systems by action researchers such as Eric Mazur. In the world of business, it is common that leading products draw their innovations in part from vendors and in part from users (von Hippel 2005). But this practice is surprisingly lacking in education research, where many technologies are invented by researchers and then transferred into the classroom. The resulting technologies are often too complex and too rigid to fit into classroom practices. Our field needs more focus on simple technologies that are open to teachers' adaptation and improvement.

Simplicity and adaptability, however, is not enough. Many technologies could be simple but not result in meaningful enhancements to learning. Many technologies could be adaptable but not productive. To characterise the requirements for effective integration, I have become increasingly drawn to a framework that comes from groundbreaking work in rethinking learning and transfer (Bransford & Schwartz 1999). Bransford and Schwartz posit that learning has two dimensions. Ordinarily, schools focus on an 'efficiency' dimension: how quickly can students solve a collection of routine multiple-choice questions with the accuracy required for a high test score? This can result in fragile knowledge, because when students are asked to solve a slightly different type of problem they often lack the more general knowledge needed to do it. The second dimension corresponds to 'adaptability' or 'innovativeness' and describes the deep knowledge the students need in order to adapt what they know to new situations. The ultimate goal of learning is to become an 'adaptive expert' who can do routine things very efficiently and also solve novel problems with brilliant insights. For present purposes, the most important point is that the path to adaptive expertise does not start with efficiency or dwell only on the construction of innovative approaches (as in the more overblown forms of constructivism). Rather, learners iterate between efficiency and innovation on their pathway to adaptive expertise (see Figure 3).

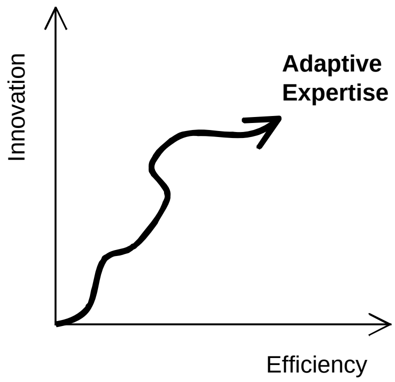

Figure 3: The path to adaptive expertise

Likewise, I argue that effective integration of technology requires thinking about efficiency, innovation and a pathway to adaptive expertise. Many technologies fail in schools because they actually make teachers' lives more complex. This cannot work; effective integration requires technologies that make teachers lives easier. Yet, while they do so, the technologies must also enable significant innovation. For example, in the case of graphing calculators, teachers gain speedy calculation and the possibility for students to check their own work (efficiency) and *also* have access to multiple representations and can build mathematical understanding on the basis of both graphic and symbolic representations of algebra (innovation). With practice, teachers can organise their classrooms to be more efficient and *also* transform their pedagogy to take advantage of graphical representations.

A few teachers are rapid innovators, but the majority of teachers (like the majority of people in any profession) need time to become more innovative and efficient. This brings forth the notion of a pathway to adaptive expertise. No technology can suddenly transform a teachers' level of adaptive expertise. But well-designed technology can provide a pathway for growth, whereby as teachers use the technology they can gradually transform to become more adaptive and more expert in helping their students learn.

Classroom response systems are a great example of just such a technology. At first, teachers who use classroom response systems change very little. The technology merely allows them to collect student responses more quickly (efficiency) but also to give feedback more systematically and anonymously (innovation). However, over time, teachers who pay attention to the group thinking that is made visible by the technology can identify weaknesses in their own teaching. These teachers become more adaptive and more efficient. They adapt their lesson plans to what they see, while they are teaching, about the qualities of students' understanding. They become more efficient by adjusting the pace of instruction to move more rapidly over things that students learn quickly and to cover in more depth those concepts that students struggle with. Although there is no single moment at which a teacher becomes an adaptive expert, the technology of classroom networks is their partner as they develop their adaptive expertise.

In conclusion, I recommend greater attention to *simple, inexpensive* technologies for the classroom; those without buzzwords and with hardware that is cheap and robust. The most powerful technologies will be quite open to teachers' innovation and adaptations; and the most successful technology companies will develop strong relationships with practising teachers who are innovators and build better products from innovations that occur both within and outside their company. Finally, the most transformative products will work by creating a pathway along which teachers can develop adaptive expertise in supporting student learning. These transformative products will balance the twin concerns of making classrooms more efficient and making them more innovative.

References

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

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

Bransford, JD, Brophy, S & Williams, S 2000, 'When computer technologies meet the learning sciences: Issues and opportunities', *Journal of Applied Developmental Psychology,* vol. 21, no. 1, pp. 59–84.

Bransford, JD & Schwartz, DL 1999, 'Rethinking transfer: A simple proposal with multiple implications', in A Iran-Nejad & PD Pearson (eds), *Review of research in education,* vol. 24, pp. 61–100. American Educational Research Association, Washington DC.

Burrill, G, Allison, J, Breaux, G, Kastberg, S, Leatham, K & Sanchez, W 2002, *Handheld graphing technology in secondary mathematics: Research findings and implications for classroom practice*, Texas Instruments, Dallas TX.

Cattagni, A & Farris, E 2001, 'Internet access in United States public schools and classrooms: 1994– 2000', retrieved 15 July 2006, from http://www.usdla.org/html/journal/JUN01_Issue/article04.html

Chan, TW, Roschelle, J, Hsi, S, Kinshuk, Sharples, M, Brown, T et al. 2006, 'One-to-one technology-enhanced learning: An opportunity for global research collaboration', *Research and Practice in Technology-Enhanced Learning,* vol.1, no. 1, pp. 3–29.

Consortium for School Networking 2004, *A guide to handheld computing in K–12 schools*, Consortium for School Networking, Washington DC.

Crouch, CH & Mazur, E 2001, 'Peer instruction: Ten years of experience and results', *The Physics Teacher,* vol. 69, no. 9, pp. 970–7.

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

Davis, S 2003, 'Observations in classrooms using a network of handheld devices', *Journal of Computer Assisted Learning,* vol. 19, no. 3, pp. 298–307.

Ellington, AJ 2003, 'A meta-analysis of the effects of calculators on students' achievement and attitude levels in precollege mathematics classes', *Journal for Research in Mathematics Education,* vol. 34, no. 5, pp. 433–63.

Fagen, AP, Crouch, CH & Mazur, E 2002, 'Peer instruction: Results from a range of classrooms', *The Physics Teacher,* vol. 40, no. 4, pp. 206–7.

Ferrio, T, Phipps, A & Schaar, R 1997, 'Building a breakthrough business concept', *TI Technical Journal*, pp. 26-32.

Goldenberg, P 1995, 'Multiple representations: A vehicle for understanding understandings', in DN Perkins, JL Schwartz, MM West & MS Wiske (eds), *Software goes to school*, Oxford University Press, New York, NY, pp. 155–71.

Graham, AT & Thomas, MOJ 2000, 'Building a versatile understanding of algebraic variables with a graphic calculator', *Educational Studies in Mathematics*, vol. 41, no. 3, pp. 265–82.

Hegedus, SJ & Kaput, J 2003, 'The effect of a SimCalc connected classroom on students' algebraic thinking', paper presented at the Psychology in Mathematics Education conference, Honolulu, HI, July.

Heller, JL, Curtis, DA, Jaffe, R & Verboncoeur, CJ 2005, *Impact of handheld graphing calculator use on student achievement in Algebra 1*, Heller Research Associates, Oakland CA.

Johnson, DW & Johnson, RT 1989, *Cooperation and competition: Theory and research*, Interaction Book Company, Edina, MN.

Kaput, J. 1992, 'Technology and mathematics education', in D Grouws (ed.), *A handbook of research on mathematics teaching and learning*, Macmillan, New York.

Kaput, J & Hegedus, SJ 2002, 'Exploiting classroom connectivity by aggregating student constructions to create new learning opportunities', paper presented at the 26th conference of the International Group for the Psychology of Mathematics Education, Norwich, UK.

Khoju, M, Jaciw, A & Miller, GI 2005, *Effectiveness of graphing calculators in K–12 mathematics achievement: A systematic review,* Empirical Education, Palo Alto, CA.

Mazur, E 1997, *Peer instruction: A user's manual*, Prentice Hall, Englewood Cliffs, NJ.

National Center for Education Statistics 2001, *The nation's report card: Mathematics 2000* (NCES 2001-571), United States Department of Education, Washington DC.

National Research Council 1999, *How people learn: Brain, mind, experience, and school*. National Academy Press, Washington, DC.

Owens, DT, Demana, F, Abrahamson, AL, Meagher, M & Herman, M 2002, *Developing pedagogy for wireless calculator networks: Report on grants ESI 01-23391 & ESI 01-23284* (also presented at SITE, Albuquerque, NM, March 2003), Ohio State University Research Foundation, Columbus, OH.

Roschelle, J & Pea, R 2002, 'A walk on the wild side: How wireless handhelds may change computer-supported collaborative learning', *International Journal of Cognition and Technology*, vol. 1, no. 1), pp. 145–68.

Roschelle, J, Pea, R, Hoadley, C, Gordin, D & Means, B 2000, 'Changing how and what children learn in school with computer-based technologies', *The Future of Children*, vol. 10, no. 2, pp. 76-101.

Sawyer, K (ed.) 2006, *The Cambridge handbook of the learning sciences*, Cambridge University Press, New York.

Seeley, C 2006, 'Technology is a tool: President's message', *NCTM News Bulletin*, vol. 42, no. 7, p. 3.

Soloway, E, Norris, C, Blumenfeld, P, Fishman, BJK & Marx, R 2001, 'Devices are ready-at-hand', *Communications of the ACM*, vol. 44, no. 6, pp. 15–20.

Stroup, WM, Kaput, J, Ares, N, Wilensky, U, Hegedus, SJ, Roschelle, J et al. 2002, 'The nature and future of classroom connectivity: The dialectics of mathematics in the social space', paper presented at the Psychology and Mathematics Education North America conference, Athens, GA.

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

Vahey, P & Crawford, V 2002, *Palm education pioneers program: Final evaluation report*, SRI International, Menlo Park, CA.

Vahey, P, Tatar, D & Roschelle, J 2004, 'Leveraging handhelds to increase student learning: Engaging middle school students with the mathematics of change', paper presented at the 2004 International Conference of the Learning Science, Santa Monica, CA.

von Hippel, E 2005, *Democratizing innovation*, MIT Press, Cambridge, MA.

Weiner, N 1948, *Cybernetics, or control and communication in the animal and the machine*, MIT Press, Cambridge, MA.

Wilensky, U & Stroup, W 2000, 'Networked gridlock: Students enacting complex dynamic phenomena with the hubnet architecture', paper presented at the the fourth annual International Conference of the Learning Sciences, Ann Arbor, MI.

Zurita, G & Nussbaum, M 2004, 'A constructivist mobile learning environment supported by a wireless handheld network', *Journal of Computer Assisted Learning*, vol. 20, pp. 235–43.