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SPECIAL EDITION: EDUCATIONAL OUTCOMES & RESEARCH FROM 1:1 COMPUTING SETTINGS

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After Installation: Ubiquitous Computing and High School Science in Three Experienced, High-Technology Schools

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Special Edition:
Educational Outcomes and Research from 1:1 Computing Settings

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This special issue of the Journal of Technology, Learning, and Assessment focuses on the educational impacts and outcomes of 1:1 computing initiatives and technology-rich K–12 environments. Despite growing interest in and around 1:1 computing, little published research has focused on teaching and learning in these intensive computing environments. This special issue provides a forum for researchers to present empirical evidence on the effectiveness of 1:1 computing models for improving teacher and student outcomes, and to discuss the methodological challenges and solutions for assessing the effectiveness of these emerging technology-rich educational settings.

Complete listing of papers published within the JTLA 1:1 Special Edition

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Bebell, D. & Kay, R. (2010). One to One Computing: A Summary of the Quantitative Results from the Berkshire Wireless Learning Initiative. *Journal of Technology, Learning, and Assessment, 9*(2).

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Shapley, K.S., Sheehan, D., Maloney, C., & Caranikas-Walker, F. (2010). Evaluating the Implementation Fidelity of Technology Immersion and its Relationship with Student Achievement. *Journal of Technology, Learning, and Assessment, 9*(4).

Suhr, K.A., Hernandez, D.A., Grimes, D., & Warschauer, M. (2010). Laptops and Fourth-Grade Literacy: Assisting the Jump over the Fourth-Grade Slump. *Journal of Technology, Learning, and Assessment, 9*(5).

Weston, M.E. & Bain, A. (2010). The End of Techno-Critique: The Naked Truth about 1:1 Laptop Initiatives and Educational Change. *Journal of Technology, Learning, and Assessment, 9*(6).

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Abstract:

There are few studies of the impact of ubiquitous computing on high school science, and the majority of studies of ubiquitous computing report only on the early stages of implementation. The present study presents data on 3 high schools with carefully elaborated ubiquitous computing systems that have gone through at least one "obsolescence cycle" and are therefore several years past first implementation. The data from these schools shows how the elements of a 1:1, wireless environment are being deployed in these science classrooms, and the effects of the environment on science content, data analysis, labs and other uses for visualizations, and classroom interaction. While some positive effects are clearly seen in these classrooms, five years or more into the innovation, problems remain, and school cultural factors seem to play an important role in teacher uptake and integration of the technology. Implications for teacher learning are discussed.

After Installation: Ubiquitous Computing and High School Science in Three Experienced, High-Technology Schools

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TERC, Inc.

Introduction

Over the past decade, policy-makers and educators have advocated a vision for science education that emphasizes a more active student role in data collection, knowledge-representation, reasoning about evidence, communication about science with peers and others, and appropriate use of new scientific instrumentation and tools for data imaging and analysis (AAAS, 1993; Driver, Newton, & Osborne, 2000; Krajcik, Malok, & Hug, 2001; National Research Council, 1996, 2000). This vision has been accompanied by high expectations for how digital technology can transform the science classroom, especially in secondary schools (Osborne & Hennessey, 2003; PCAST, 1997; Fouts, 2000). On the basis of these expectations, there has been an enormous investment in hardware and software (Park & Steresina, 2004). For example, a National Science Foundation report found that "by fall 2001, an estimated 99% of public schools and 87% of instructional rooms had Internet connections" (NSF, 2004, pg. 1–5).

Indeed, many studies have shown that discrete technological interventions show promise for improving science education. In the 1990s, studies showed the value of micro-computer-based laboratories (probeware and software) for students' learning of physics concepts as well as graphic representations (Tinker, 1996). Linn's (2006) work demonstrates student learning benefits derived from knowledge-representation environments, alone or in combination with other tools. The CoVis projects (e.g., Brown & Edelson, 1999; Pea, Gomez, Edelson, Fishman, Gordin, & O'Neill, 1997) combined custom-built collaborative software, carefully planned laboratory activities, and visualization tools for analyzing scientific data sets and provided evidence that these powerful tools could be coordinated to support in-depth student investigations. Studies like those of Beckett and Boohan (1996) and Gilbert (2007) show that dynamic models and visualization tools can help students understand science concepts and argumentation. Weir (1987) found that the introduction of computer microworlds helped mediate learning even for students with severe relational or learning deficits, and also transformed the participant structures of science classrooms. These studies, and many more like them, offered training to participating teachers, and an incentive to explore a particular software or technology, and then examined the effects on their science practices. Such studies establish proof-of-concept evidence, but further research is still needed to validate or modify their results.

Building on these prior strands of development and investigation in educational technology, ubiquitous computing is seen as an important and promising technology configuration for schools (Tinker, Galvis, & Zucker, 2007). Forecasts of trends in educational technology suggest that the number of such implementations is increasing rapidly (Center for Digital Education, 2008). Intranet capabilities can provide additional, community-building, dimensions to peer-to-peer communication and collaboration (Anderson & Dexter, 2003a; Davies, 2004; Hill, Reeves, & Heidemeier, 2000), and permit communications that build or enhance relationships with scientists and other members of the wider scientific community outside the school learning environment (Falk, Lee, & Drayton, 2005). In addition, middle school studies suggest that assessment patterns may change in ubiquitous computing classrooms by enabling more frequent exchanges between student and teacher, and providing more ways of displaying student understanding (Davies, 2004; Hill et al., 2000; Walker, Rockman, & Chessler, 2000; Wallace et al., 2000). However, the shift to 1:1 computing also requires teachers to spend time on technical support in the classroom (Anderson & Dexter, 2003b, Davidson, 2003). In addition, some teachers find that they are drawn into helping individual students navigate since students are each working with their own computer and as a result loose control over the state of the classroom and the general progress of the activity (Hill et al., 2000).

The initial phase of any technology innovation is likely to be fraught with technical and logistical issues; amidst the growing pains, teachers work to evaluate the new tools and incorporate them into their practices (Cuban, 1986: Cuban, 2001a; Zhao et al., 2002). For this reason, the initial phase of implementation (the first 1–3 years) may not give more than a provisional indication of the value of the innovation. Most studies on ubiquitous computing published to date derive from this initial phase: in a review of the literature completed in 2008 (Stroud, 2008), we found that 67% of the studies reported on the pre-implementation phase, or the first two years of implementation of a ubiquitous computing program. Furthermore, the time-scale of the studies tended to be quite short, with 67% of the studies lasting one year or less. Given this backdrop, information from schools that have experience with ubiquitous computing over a longer period of time is of particular value as a source of insight about the innovation over time. A further desideratum for the field is insight into the impact of ubiquitous computing on science teaching and learning at the high school level, where only a few studies have been published (Zucker, 2006; Zucker & Hug, 2008). Research is necessary to address issues raised by skeptics who question whether there is evidence that investment in Wi-Fi contributes to better academic achievement (Cuban, 2006).

This study addresses the need for research on technology use in high-school science, particularly in schools that are past the first phase of implementation. It examines three high schools that have implemented ubiquitous computing for several years, long enough to have passed through at least one obsolescence/replacement cycle. Our paper examines which technological tools are being used, how the use of such tools contributes to high quality science education, and challenges that still need to be addressed (beyond those traditionally studied regarding funds for computers, and installation for wireless).

We report here on our findings with respect to three research questions:

I. **In schools with established, ubiquitous computing environments, what technology tools were employed with what frequency, and what was the perceived value of each?**

Bearing in mind the wide range of apparatus that is available in the science classroom, and the wide range of tasks that are necessary for students and teachers to complete in a science course, we describe which common tools related to the ubiquitous computing environment were in use in these experienced schools. Data for this question are drawn primarily from teachers' logs (described below). These allowed us to establish year-long patterns of technology use for each teacher.

II. How does the technology add value for science education in these schools?

Having established the overall patterns for technology use in these schools, we then explore whether teachers are using (some of) these tools in order to address 4 key areas of “added value” advocated for high quality science education (e.g., NRC, 1996):

A. Additional science content, introduced through the use of software, Web-ware, probeware, and communication tools;

B. Classes and labs enriched or supplemented by simulations, remote instrumentation, models, or 3D visualization tools;

C. Access to scientific data sets, enhanced data analysis, sharing, and knowledge representation;

D. Classroom interaction patterns, and connection to the wider science community.

Because these questions address technical competence, curricular content, and pedagogical considerations, our answers to question II are drawn not only from teacher logs, but also from focus groups, observations, and questionnaires.

III. What challenges did teachers encounter in using their technology suite in their teaching of science?

No complex strand of a school’s activity, such as its use of educational technology, can ever be problem-free. Here we explore what problems seemed most pressing to the teachers in these experienced schools , which were well past the first year or two of implementation. Data for this question are drawn primarily from teacher focus groups and log data (described below).

Methods

Participants

The data reported is derived from a three-year study, funded by the National Science Foundation (NSF/TPC grant #0455795), of schools that have been implementing some version of ubiquitous computing environments for at least five years by the end of the period of data collection (2008). By doing so, we hope to turn the focus on the value that is added when technology is abundantly available rather than discussing the factors related to creating, maintaining, and sustaining a successful ubiquitous computing environment in the study schools (to be treated in a forthcoming paper).

Following are brief descriptions of the three study schools (names of schools and personnel changed to preserve confidentiality). "Urban Tech High" is a public pilot school with approximately 300 students in a racially and economically diverse neighborhood; it graduated its first senior class in 2006. The student body is 53% Black or African American, 29% Hispanic, 9% White, and 8% Asian, and there are twice as many boys as girls. Sixty four percent of students are identified as low income. All classes are equipped with SmartBoards; in contrast to the other two schools in this study, there is no probeware. All students are issued a laptop upon entering 9th grade, and this computer, which is leased, becomes their own upon graduation; thus all laptops are replaced on a 4-year cycle. Laptops are kept in the school building, and do not go home. While in service, the computers are maintained within the school; students are responsible for charging the batteries, and bringing the laptops to the help desk when repairs are needed. A laptop coordinator, network coordinator, and student-based technology consulting company all contribute to the care and maintenance of the hardware infrastructure.

"Rural High" is a public high school that serves 419 students drawn from seven neighboring rural towns, in a new facility completed in 2003. The technology plan was developed as part of the new school's design. The school's population is approximately 98% White; median income is in the lower third for the state, as is the rate of college attendance. The facility has wireless Internet access throughout. Each classroom has a "tower" of 14 laptops, and the district has a program promoting student or family purchase-through-lease of laptops, which can be used in the school, though the small class size means that the class-stationed computers are often enough for one-to-one student use. The school has a technical staff of 3, including the district technology coordinator, plus (during the final year and a half of the study) a technology integration specialist. The district has a 3-year obsolescence plan for its school-owned laptops. All classrooms have interactive whiteboards with projectors, and teachers have laptops.

"Private Academy" serves 360 students of which 80% board. Boarding students come from 33 states and 12 countries. About 20% of their students have learning difficulties of some type and the school has developed a special expertise in working with such students. Private Academy has chosen not to install a wireless network but instead has installed 3,000 Ethernet drops around the campus. Every classroom is arranged so that any and all students can connect simultaneously to the Internet. All students purchase iBooks through the school, but the school tries to arrange for replacement in three years. Classrooms have projectors, connected to the teacher's laptop; some classes have an interactive white board. The school has a full-time technical staff of five.

Technology and the Schools' Visions

In order to understand teachers' practice in the context of their school's policy with respect to the ubiquitous computing innovation, we sought to understand each school's "vision" for the innovation, that is, the goals and purposes which the technology was intended to serve, and the projected benefits to students and teachers. Evidence for schools' vision was drawn from documentary sources, such as technology and obsolescence plans, but also from interviews with school leadership and technology coordinators, in which interviewees were asked to describe the goals and hoped-for impact of ubiquitous computing, especially as it related to science education in the school.

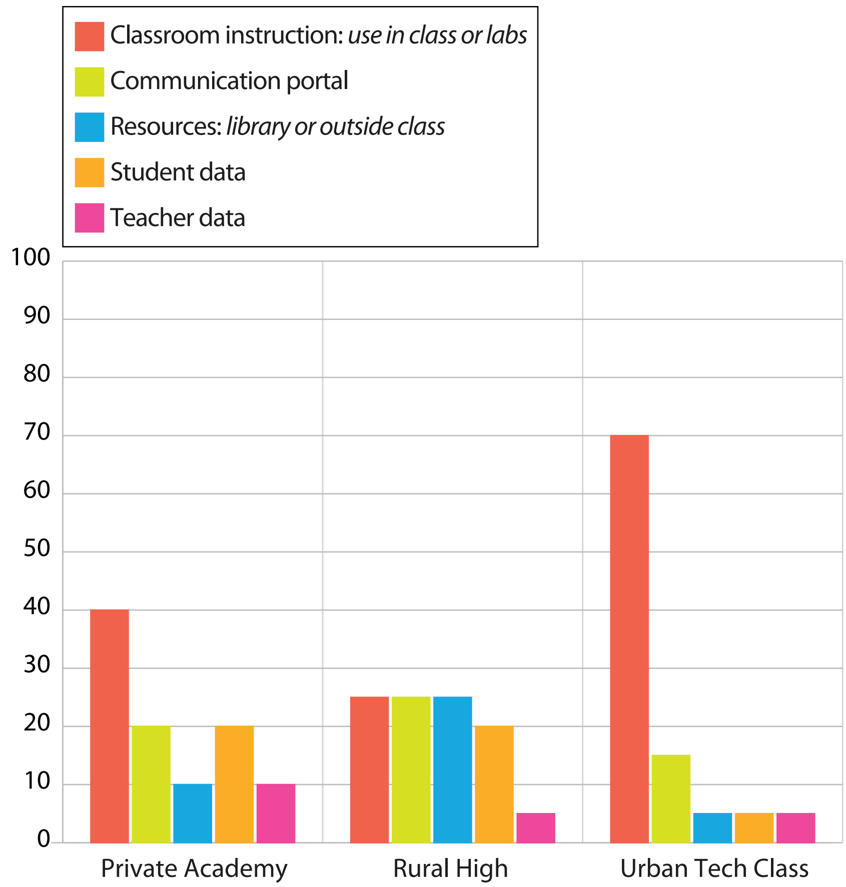
For Urban Tech High, the core goal of technology was to empower students through technological expertise. Administrators at the school felt that changing students' self image and providing them with feeling of mastery would lead to increased student achievement in other academic areas. The majority of the students had previously failed some part of the eighth grade state achievement exam. Offering each student a laptop, and teaching them enough technology to become certified technicians, was combined with a "small school" design which enabled a highly personal approach to nurture the students as learners and citizens of their community. The combination of academic and affective support brought solid academic results. Over 90% of the students passed the 10th grade MCAS exam, and in the school's first graduating class, 59 of 60 seniors were accepted to post-secondary educational institutions.

In Rural High, planning for the ubiquitous environment emphasized increased accountability and transparency for teachers and students, data mining, and other administrative functions, along with impacts in classroom instruction, which focus on meeting the academic requirements of the state graduation exam, and equipping the students with "21st century skills."

Private Academy's pedagogical and technology vision is shaped by two important commitments. Up to 20% of the students have special learning needs, but the school is diverse in other ways as well. The curriculum has been developed, as part of a whole-school reform begun 15 years ago, to reflect this diversity, and indeed to make use of it to spur better education for all students. This relates to the other important commitment, which is to "mastery" — every student demonstrating mastery of at least 80% of the material in each class. As part of this commitment to mastery and differentiated instruction, the school's curriculum, assessment, pedagogy, and administration integrate the technology available. Each classroom contains three groups of students (basic, standard, accelerated) working at a different pace with different expectations. There are times when all students work together, but the technology enables a single teacher to have three different sets of activities going on at any one time. Thus, a school culture of peer learning and sharing influences the way that technology is used within the classroom.

To provide additional insight into the "realized vision" in each school, we asked technology coordinators to estimate the relative proportions of different categories of use in their schools: classroom instruction (either teacher or student use); communications portal (teacher-student, teacher-administrator, teacher-parent); resources (e.g., additional content, drill/practice tools, images, etc.); managing student data (grades and other achievement data); and managing teacher data (lesson plans, teacher portfolios, and similar uses). Figure 1 (next page) displays the results for the three schools analyzed in this paper. These results mirror the priorities for each school outlined above, which were derived from principal interviews and planning documents.

Figure 1: Relative Emphasis on Key Purposes for Technology Implementation



Data Sources and Methodology

Our mixed-methods study reports on quantitative and qualitative data primarily from year three of our project. For this paper, we draw on data taken from 14 high school science teachers, seven from Private Academy, three from Rural High, and four from Urban Tech High. The names of schools and teachers are disguised to protect confidentiality. The majority of these teachers had a moderate amount of teaching experience (three to seven years teaching), while one teacher had nearly 20 years of experience and four others had two or fewer years of experience. Participating teachers were also comfortable with technology. Two teachers considered themselves to be "technology geeks", while the remaining 12 were evenly split between "technologically adventurous" and "technologically comfortable."

Our study collected a wide range of data, including several kinds of teacher reports, student questionnaires, school or district documentation, interviews with principals and other school personnel, and multiple observations of each classroom by project researchers. We asked teachers to identify a specific course and section (e.g., Biology 1), which would be their "case study class" for the year's data collection. Seven teachers selected Biology courses, five chose Chemistry, and two selected Physics.

Teacher Questionnaire

At the beginning of each academic year, all teachers were asked to complete an initial questionnaire about their practice, their use of technology, their curriculum for the year, and their professional development experience. In Year 3, the final year of the study, 13 out of 14 (93%) case study teachers completed the survey, with only one teacher from Rural High failing to do so.

Teacher Logs

In order to collect data on teachers' patterns of technology use across an entire year, we developed teacher logs that teachers completed on the project website. Each teacher completed an online teacher log every two weeks throughout the year, documenting what types of technology they and their students used in their case-study class, the benefits derived from the use, and the issues or challenges that arose. The logs were developed with significant input from the teachers to ensure ease of use, and a high rate of completion, starting from a pilot version in Year 1. The Year 2 log provided teachers with a number of open-response questions about the benefits they saw accruing from the use of various tools, and the challenges that they encountered. These qualitative data were coded by two researchers, and used to develop the questions in the Year 3 log, which were more multiple-choice or structured-response questions. In Year 3, 11 out of 14 (79%) teachers completed the full set of thirteen logs.

Reports of frequency of tool use based on the logs, such as those in the findings for Research Question I below, provide information on occurrences within a two-week reporting period. Thus, if a teacher reported Excel use in 50% of logs, this means that Excel use occurred at least once in half of the 13 reporting periods. If this same teacher told us that the value of Excel was for better graphing and presentation in 10% of their logs, this means that this value of Excel was reported in 5% of the total reporting periods.

In addition, the Year 2 logs enabled us to gather some data on number of days each tool was used within some reporting periods. These samples of daily practice enabled us to characterize in a more fine-grained way the frequency of use of various tools during that study year.

Student Questionnaires

In the third year of the project, students in the teachers' case-study classes were asked to fill in a questionnaire describing the nature and frequency of their technology use at home, in school across all classes, and in science classes. This questionnaire, which was filled out in on-line form, also asked students to describe specific class sessions in which they felt technology was used effectively and ineffectively in science classes. Responses were received from 136 students in 11 out of 14 classrooms (79%), with one teacher from each case study school failing to have their students complete the survey. Answers to open response questions were coded by two researchers.

Focus Groups

Teachers in each school met at the end of each of the 3 years of the study for one-hour focus groups (ranging in size from 3 to 6), which were recorded and transcribed for analysis. Transcripts were coded, and narrative analyses of school focus group sessions were prepared.

Vignettes

Each teacher was asked to write and submit two to four vignettes per year, describing a lesson or sequence of lessons, and reflecting upon the role of technology for themselves and their students in the course of the event described. Half of the teachers submitted three or more vignettes, just under half submitted one or two vignettes, and one teacher from Private Academy did not submit any vignettes.

Teachers' Review

Each teacher was asked to submit, twice a month, on the project website, a description and review of a resource which they had tried. Teachers' critiques of the tools were a valuable source of data about their criteria and needs for resources, especially useful websites.

Observations, Interviews, and Documentation

The data collected by these methods was triangulated with observations of case study classes, conducted by TERC researchers throughout the year, and the additional collection of planning documents, technology plans, and similar information from each school. In Year 2, each teacher was observed 3 times, in Year 3 at least once. Observations, for which a structured observation protocol was used, examined the ways teachers and students made use of technology over the course of a lesson. Individual conversations with teachers, principles, and with technology coordinators, as well as teacher and coordinator focus groups, provided additional depth to our understanding of each teacher's practice within their school's context.

Data Analysis

Basic analyses were conducted for all quantitative data, including portions of the teacher questionnaire, teacher log, student questionnaire, and teacher's review. Analyses included summary statistics by teacher and by school.

Qualitative data, including portions of the teacher log, student questionnaire, focus groups, vignettes, observations, and interviews, was systematically reviewed and coded for content. We took a grounded coding approach (Glaser & Strauss, 1967; Strauss & Corbin, 1998), refining our coding scheme as we iteratively moved through the data until we arrived at a stable system of codes covering the following eight main topics: data, communication, access to science content, participation structures, student skills, learning styles, other student benefits, and other. Of particular importance for the current paper, data from teachers' logs were coded and used to develop individual teacher profiles, in which each teacher's practice and use of technology, with respect to specific tools, and the kinds of value added examined in the study, were described and analyzed. Profiles were written by assigned researchers, and critiqued by other researchers on our team. After discussion of questions or issues, each profile was revised. These profiles were then submitted confidentially to each teacher for verification of accuracy, and for their comments on conclusions drawn.

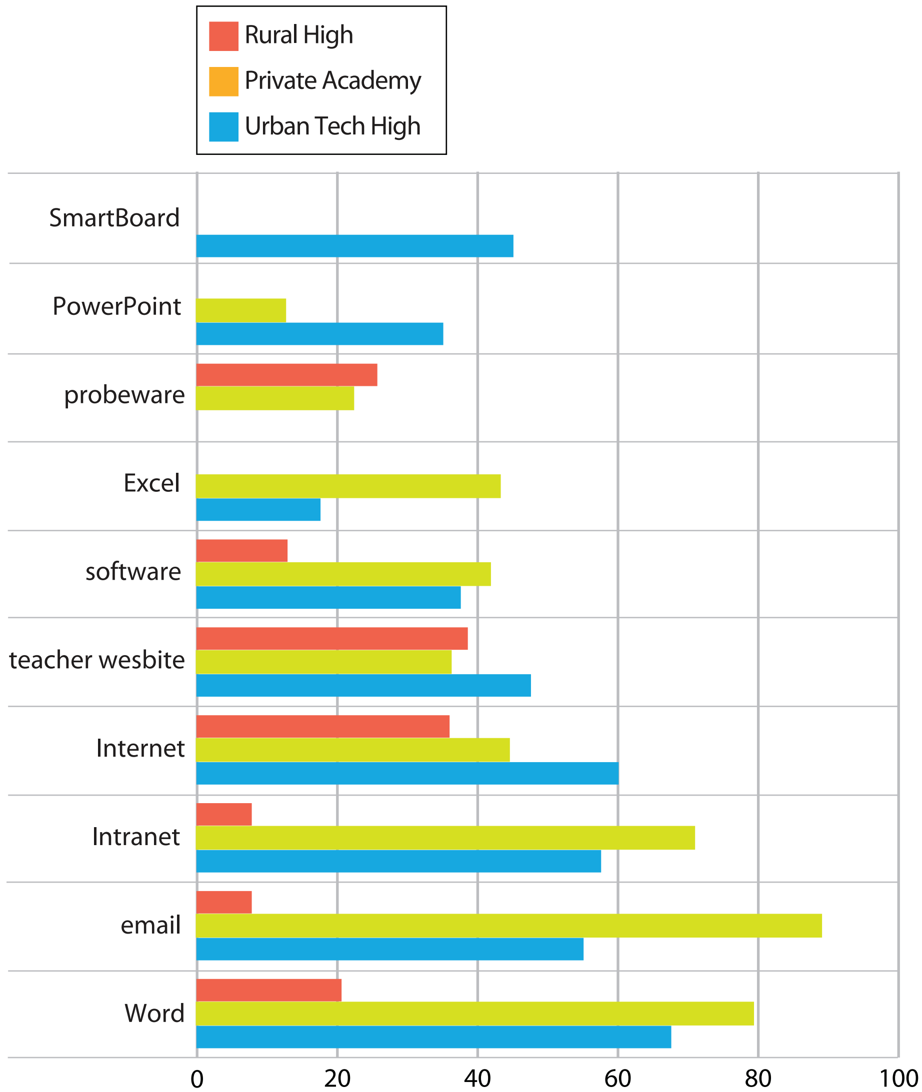
Results

We present results, first with respect to the frequency of tool use in each school, then with respect to the benefits attributed to each tool or category of tools by the teachers in their logs, and finally with respect to the ways that technology contributed added value for science education (as defined in the research questions).

I. In schools with established, ubiquitous computing environments, what technology tools were employed with what frequency, and what was the perceived value of each?

Analysis of teacher logs shows variation both within and between schools in teachers' description of how their students used technology in class and for homework. Variation within the schools is not attributable to variations in technology access, but rather to variation in teacher practice. Variation between schools in some cases reflects the available technology, as described above; for example, Urban Tech High did not have probe-ware at all, while the other two schools did. In other cases it is likely to reflect school culture: Urban Tech High and Private Academy placed more emphasis on the use of the school Intranet than Rural High. Figure 2 (next page) highlights the between-school differences.

Figure 2: Frequency of Students' Technology Use, as Reported in Teacher Logs

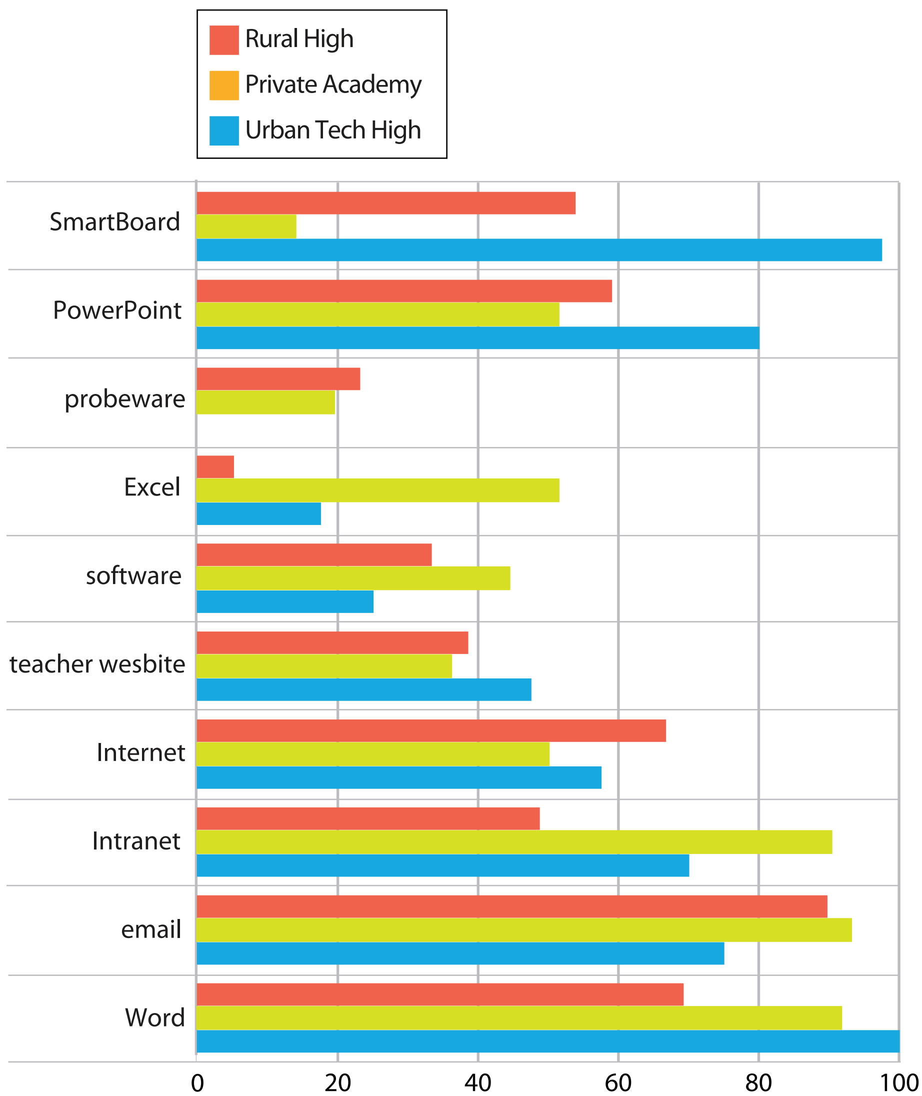


Only in Urban Tech High do students make use of the SmartBoard to present to each other (in Private Academy, where interactive white boards are not installed in all classrooms, students do not use them where they are available, nor do teachers report students using the available projection equipment in other classrooms). Likewise, Urban Tech students use PowerPoint, teacher-created websites, and the Internet/Web more frequently than the other schools. In contrast, Private High shows greater use of software including Excel and Word and greater use of the school's

Intranet and e-mail. On average, Rural High shows the least use of technology of all kinds by students. Frequency of use of probeware is similar for students at Rural High and Private Academy.

We see a somewhat different profile when examining how teachers themselves report using technology within the classroom, to prepare for their classrooms, and for administrative work (Figure 3).

Figure 3: Frequency of Teachers' Use of Technology, as Reported in Teacher Logs



Like their students, teachers in Urban Tech High make heavy use of the SmartBoard and PowerPoint. The classes in Urban Tech High are traditional in that the teacher often stands in the front of the classroom and uses the SmartBoard to direct attention. PowerPoint slides are often used as visual cues to offer increased organizational tools to students. In Private Academy, the lessons are designed to include frequent "jig-saw" sessions, in which small groups work on differing elements of lesson content, to be recombined in subsequent whole-class or other small-group activities. For this reason, less time is directed to the front of the class, which perhaps explains why PowerPoint slides are used with somewhat less frequency than in the other two schools.

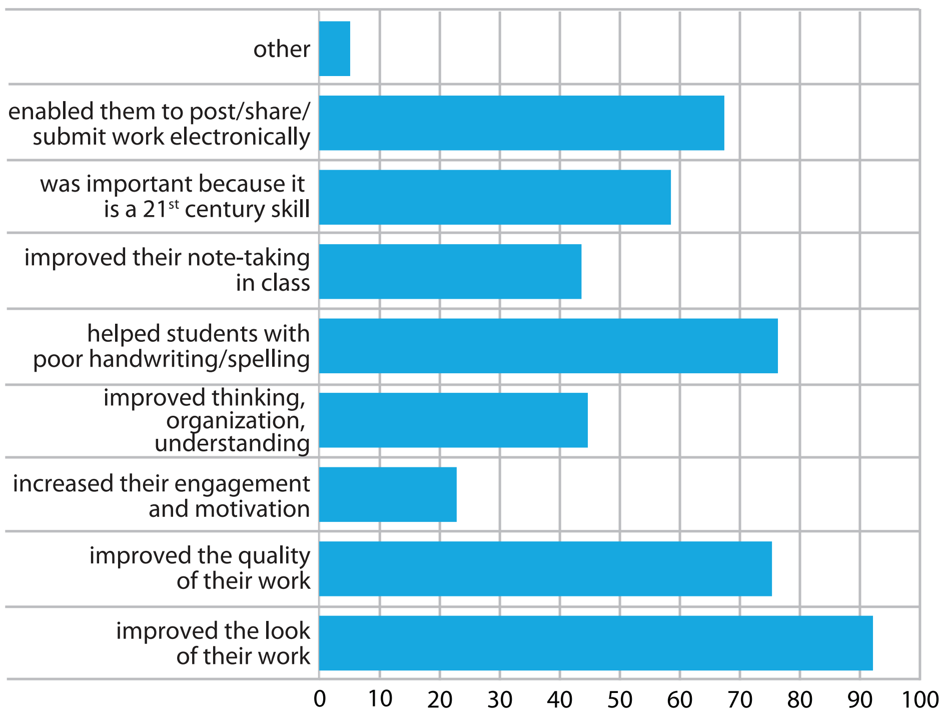
Teachers in Private Academy make most frequent use of Excel for analyzing data with students. They also make most frequent use of their very well developed Intranet by which teachers share lessons and resources, as well as record student grades. Teachers in Rural High make far greater use of the SmartBoard and PowerPoint than their students do. In general technology in Rural High is used by the teachers to demonstrate to the students, rather than by the students themselves.

In this section, we individually examine tool usage and the value that teachers ascribe to their use.

Microsoft Word

As seen in Figures 2 (page 17) and 3 (page 18), Word is used regularly in all schools. When teachers had their students use Word (Figure 4), the benefits that they identified most often were that it improved the look and quality of the work turned in, and in particular that it aided students with poor handwriting and spelling. In nearly 50% of the logs, teachers said that using Word improved students' thinking, organization, or understanding.

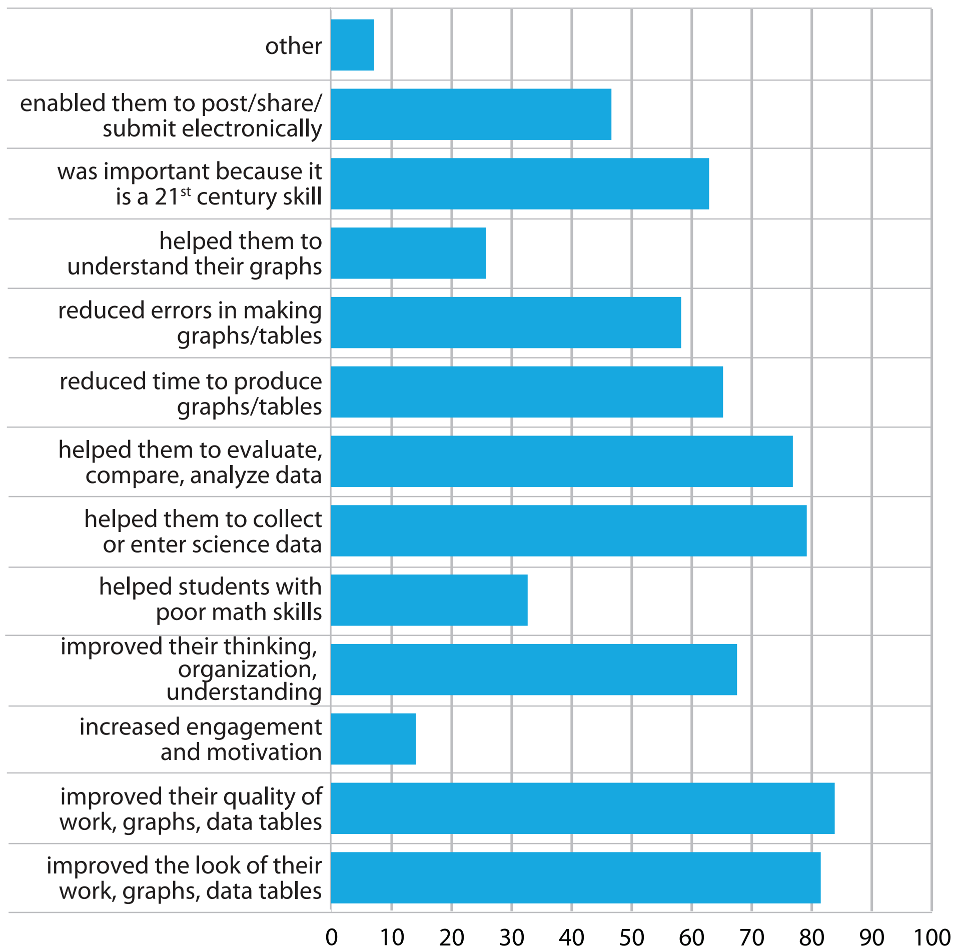
Figure 4: Teachers' Judgment of Benefits of Student Use of Word



Excel

As shown in Figure 2, Excel was used in about 45% of Private Academy classes, and considerably less in the other schools. In addition to its improving the look and quality of student work, teachers felt that Excel improved students' ability to evaluate, compare, and analyze data (77% of logs in which Excel is mentioned) (Figure 5, next page). In more than 70% of the logs, teachers asserted that it made it easier to collect and enter science data, but in only 25% of logs did teachers indicate that Excel helped their students to understand graphs. When asked about spreadsheets' contribution to graphical literacy, teachers agreed that Excel's instantaneous graphing capabilities sometimes handicap students' learning how graphs work, because the software can be used to create graphs quickly and easily, sometimes before the students have reflected on the meaning of the data and presentation. Some teachers who used Excel extensively began by having students create graphs manually before moving towards dependence on Excel or other spreadsheet tools.

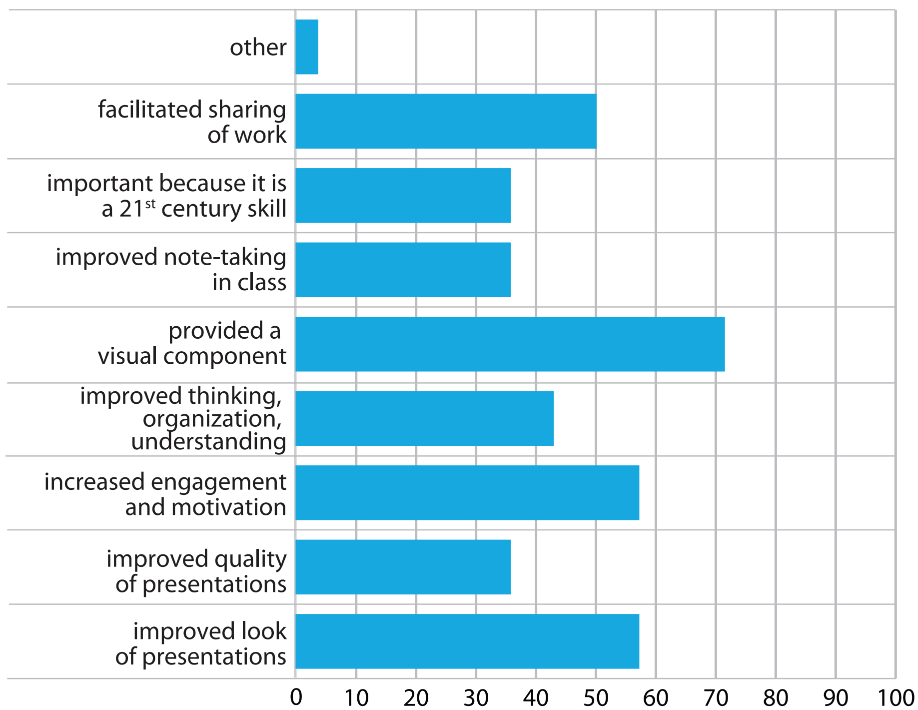
Figure 5: Teachers' Judgment of Benefits of Student Use of Excel



PowerPoint

Teachers felt that their own use of PowerPoint presentations benefited their students by providing a visual component in the classrooms (Figure 6). Especially in Urban Tech High, however, which reported student PowerPoint use in roughly 40% of logs, PowerPoint presentations were used sometimes as an aid for student note-taking. For example, students often produced their own PowerPoint presentations as a review or study aid, and when they did, teachers felt that it was engaging and motivating.

Figure 6: Teachers' Judgment of Benefits of Student Use of PowerPoint

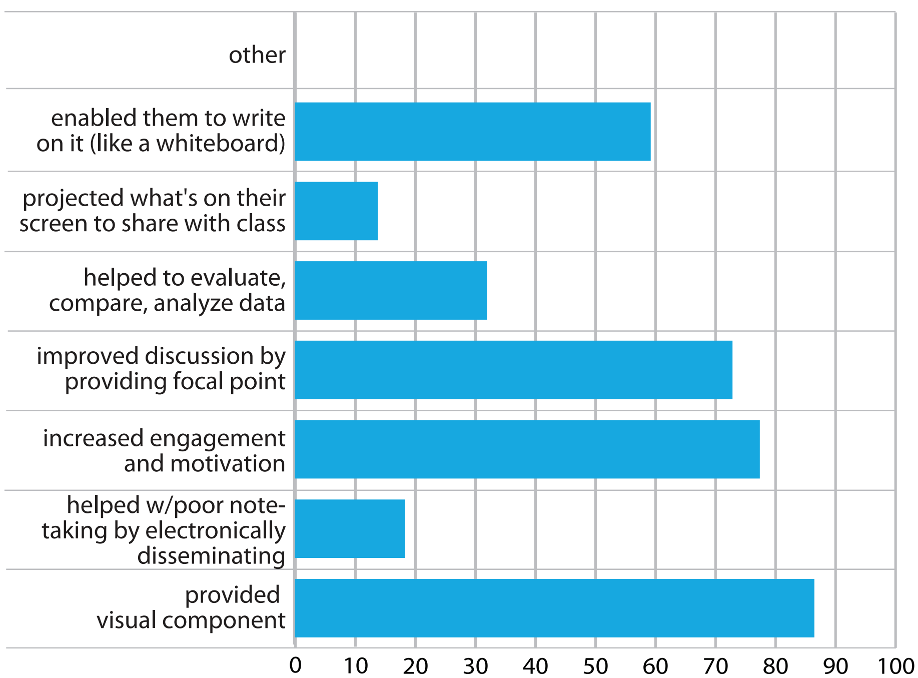


SmartBoard

Interactive whiteboards, such as SmartBoards or ActivBoards were used more frequently by faculty than by students. The benefits most frequently noted by teachers were that it added a visual component to the classroom (87%), but also provided a focal point for discussion (73%), and enhanced students' motivation and engagement (77%) (Figure 7).

One point of interest was the ability of interactive white boards (and tools such as MIMEO, used in Private Academy before the advent of SmartBoards) to capture notes in files which could be posted and shared, and used for student study and review. Teachers reported that students' use of interactive white boards provided benefits with regard to students' note taking in less than 20% of the occasions of use.

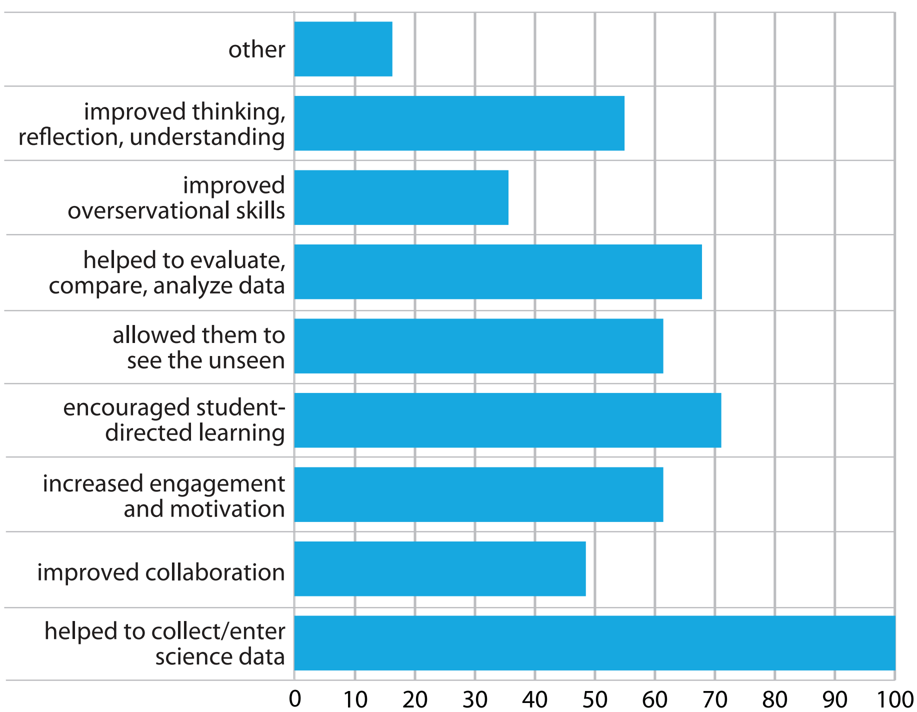
Figure 7: Teachers' Judgment of Benefits of Student Use of SmartBoard



Probeware

Probeware was seen less frequently than expected, reported in less than 25% of logs for Rural High and Private Academy. (Urban Tech High had no probeware during the period of the study.) Probeware use was reported most often in physics classrooms, though it was used occasionally in chemistry and biology classes. Naturally, it was used to collect science data and to evaluate, compare, and analyze it. When used, it was felt to be an effective tool in increasing students' understanding of data — but also to help students get a better insight into scientific phenomena ("seeing the unseen", noted in 61% of logs). Its use was reported to improve thinking, reflection, or understanding in more than half the logs, and to increase engagement, motivation, and student-directed learning (Figure 8).

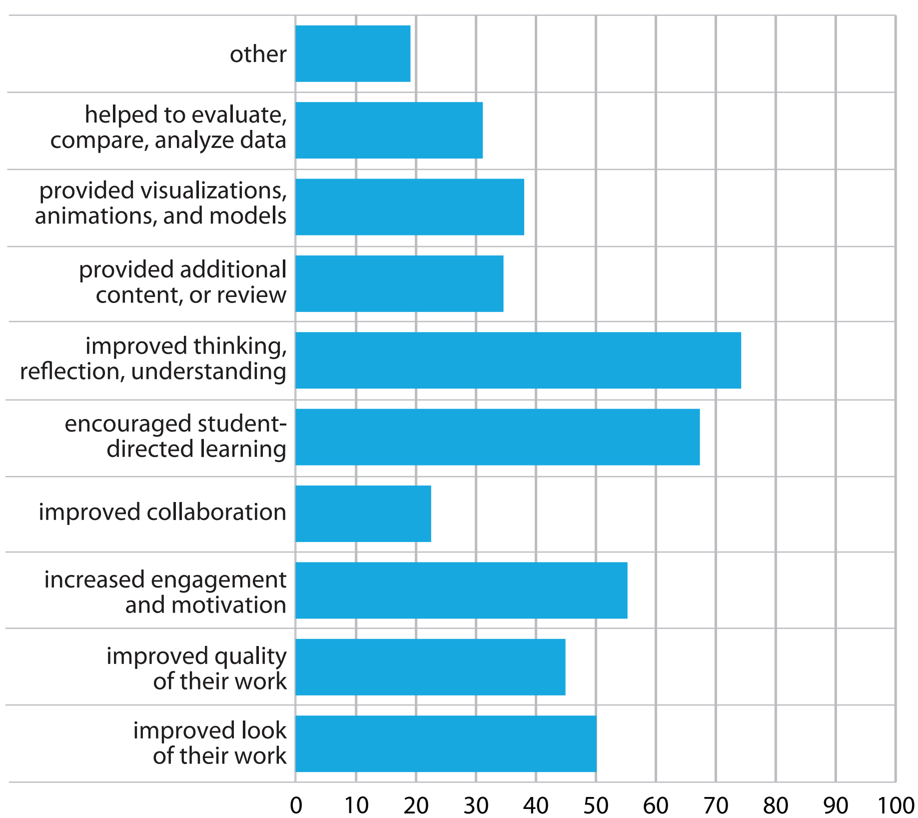
Figure 8: Teachers' Judgment of Benefits of Student Use of Probeware



Science Software

Teachers reported the majority of the time that students' use of science software improved thinking, reflection and understanding, and provided student-directed learning experiences. This general statement reflects teachers' judgments on the value of a wide variety of software ranging from multimedia tools like DreamWeaver or GarageBand to ArcView and Graphical Analysis (Figure 9). This category is complex to report on, because it is an area which reflects individual teachers' exploration, beyond the standard equipment shared with all their colleagues within their school. The common thread, however, is a search for software tools which enhance the learning environment by increasing students' engagement, their investment in investigation of their own questions, and their meaning-making about scientific phenomena. For example, one physics teacher uses a system to capture video of motion, and convert visual data to mathematical expression; another uses pod-casts to push students to strengthen their reasoning about lab data; a biology teacher introduces her students to the use of professional visualization tools for the study of proteins and other complex biomolecules.

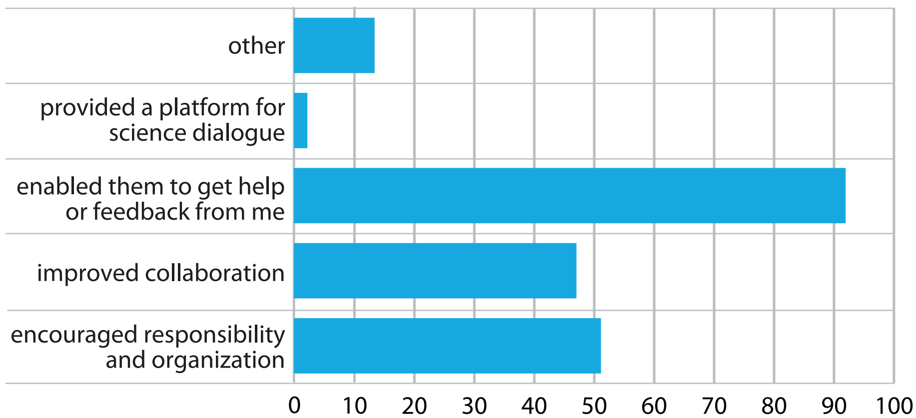
Figure 9: Teachers' Judgment of Benefits of Student Use of Science Software



Email

Students' use of email was reported in a majority of logs to aid in the feedback process (Figure 10). In some cases, teachers in focus groups reported that they felt overwhelmed by students' requests for clarification or help that arrived late into the evening.

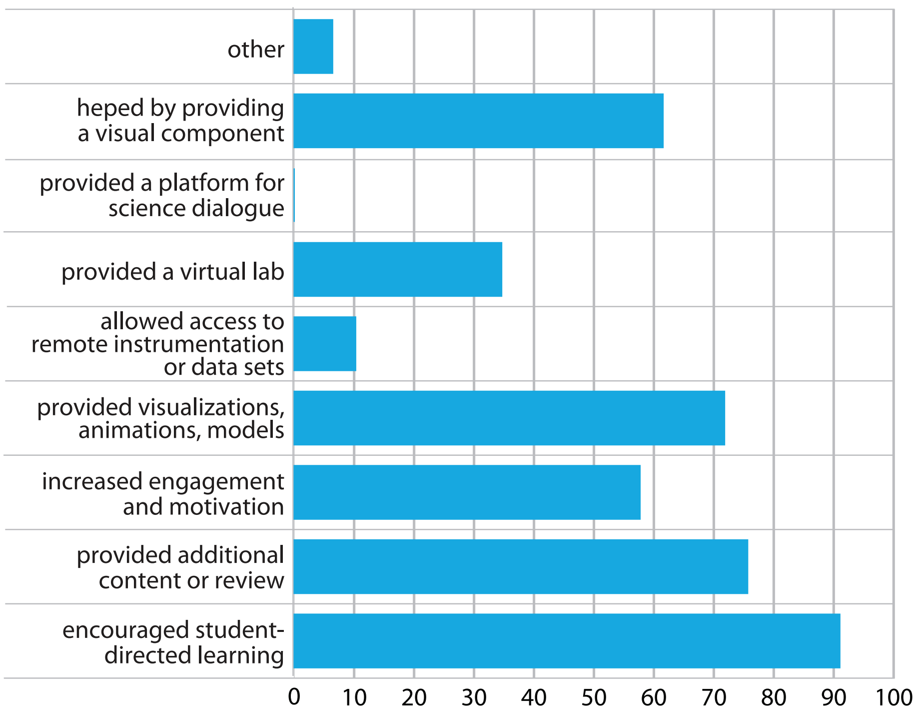
Figure 10: Teachers' Judgment of Benefits of Student Use of Email



Internet (World-wide Web)

Teachers reported many benefits of the Web, but overall they indicated that it offered opportunities for student directed learning, access to additional content, and access to visualizations, animations and models (Figure 11). It was rare that the Web was used to access remote instrumentation or data sets, and use of the Web to converse with outside experts or students in other classrooms was not reported. Note that email was reported in 2% of logs to provide a platform for science dialogue, but this was for conversation among the members of specific classes.

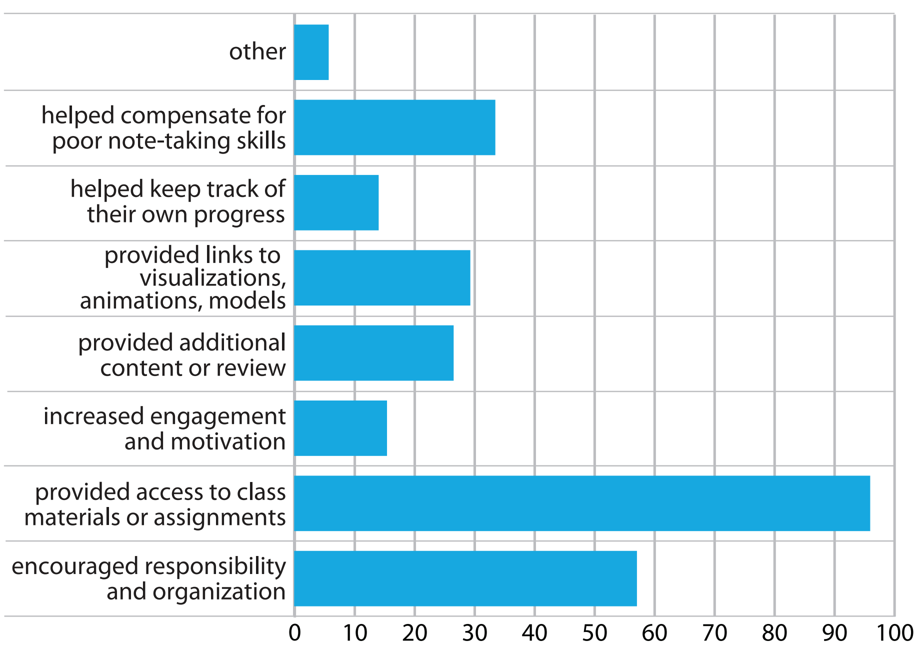
Figure 11: Teachers' Judgment of Benefits of Student Use of the Internet



Teacher Websites

The majority of teachers in the study developed their own websites, which were housed either within the school's Intranet or on the Web. Teachers felt that students had increased access to class material and assignments when they were ill, or needed review (Figure 12). The use of teacher websites also addressed a widely mentioned problem, which is the gathering, evaluating, and updating of collections of curriculum-relevant resources. Teacher websites facilitated this process, which also helps teachers focus students' use of the Web and cut down on the opportunities to wander off to irrelevant or unevaluated sites. By posting on their web sites the URLs of resources to be used in classroom instruction, the teachers could channel students to them directly. Teachers also found that the use of their websites meant that students could no longer complain of "forgetting" an assignment in school. As such they felt that it increased the students' sense of responsibility and organization.

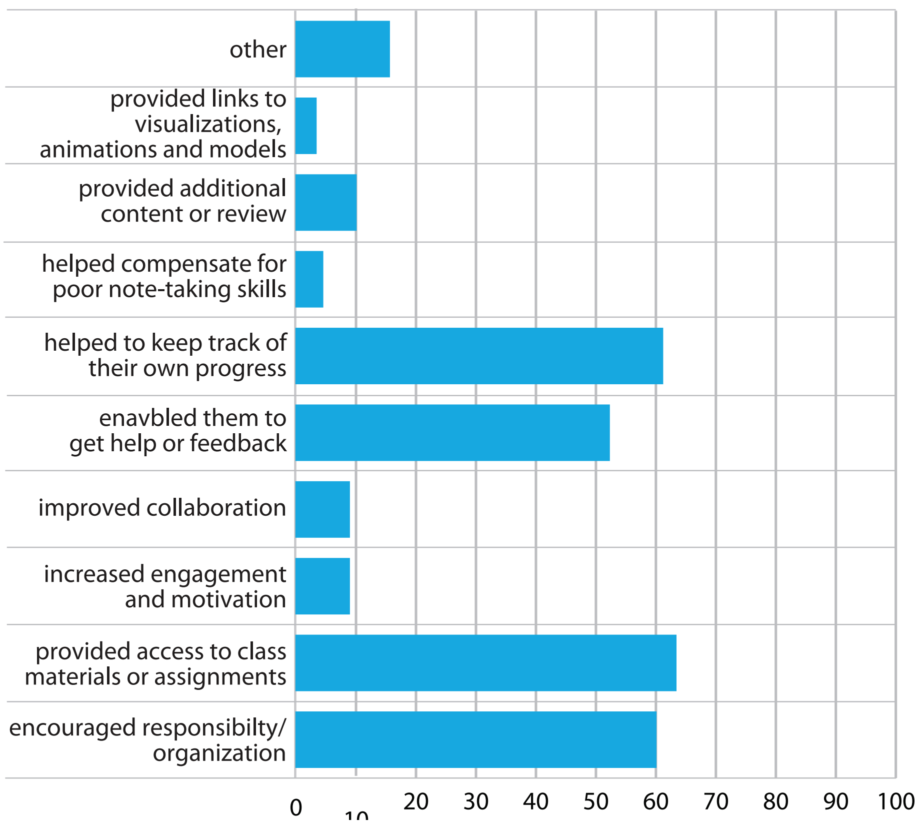
Figure 12: Teachers' Judgment of Benefits of Student Use of Teacher Websites



School Intranets

Teachers most often reported that their students' use of the school Intranets benefited them by giving access to materials (63% of logs) (Figure 13). Nearly as often, however, teachers felt that the Intranet benefited their students by increasing their students' sense of responsibility and organization (60%), and gave them a way to track their own progress (61%). In addition they felt that school Intranets provided a mechanism for students to get feedback (in some cases from other students) (more than 50% of logs).

Figure 13: Teachers' Judgment of Benefits of Student Use of School Intranet



II. How does the technology add value for science education in these schools?

The findings for Question 1 make clear that teachers in these schools are making use of a wide range of technological tools, some (like Excel and probeware) facilitated by the 1:1 computer-student ratio, some made possible by Web access for teacher or student. We had hypothesized, on the basis of the literature on science education, that these tools might make important contributions in the ubiquitous classroom in the following ways:

a. Additional science content, introduced through the use of software, Web-ware, probeware, and communication tools.

b. Classes and labs enriched or supplemented by simulations, remote instrumentation, models, or 3D visualization tools.

c. Access to scientific data sets, enhanced data analysis, sharing, and knowledge representation.

d. Classroom interaction patterns, and connection to the wider science community.

With the background of the quantitative data on frequency of use of specific tools, we explored teachers' views of how ubiquitous computing benefits science learning; data in this section are drawn from teacher logs, analyses of teacher focus groups, teachers' vignettes, and our observations. For each category of "value added," we note the teacher log data about the tools which contributed significantly in the category.

Additional Science Content

The enriched content that we saw derives especially from the ubiquitous accessibility of the Web in these classrooms, either directly, or by way of teacher websites; software was sometimes also a source of such additional content (Table 1). In these schools, 33% of Web use was described as offering the benefit of "additional content"; 11% of software use was described as offering the same benefit, and in 11% of reported uses of the teachers' websites, "additional content" was asserted as a benefit.

Table 1: Principal Sources of Additional Content

Source of Additional Content	% of Logs
Web	33%
Software	11%
Teacher Website	11%

While we saw examples of worksheets downloaded for student use, the most common forms of additional content in these classes were texts (e.g., articles or other text on Web pages), images, and video (see the next section for a discussion of animations and virtual labs). Sometimes students obtained these resources on their laptops, but very often a SmartBoard or PowerPoint mediated the content in the classroom with the teacher presenting the material, or using it as the focal point for classroom discussion.

Teachers in their logs told us that a fairly high proportion (around 90%, in all three schools) of their students' Web use for school supported student-directed learning. To a considerable extent, this Web use involved at least some on-line reading of supplemental material. The most common project activities involved the use of such resources, sometimes with more constraint ("You can't use Wikipedia for a source!!") and sometimes less. This can be to reinforce material presented in class, or to engage students with material the teacher did not have time to incorporate in instruction. This may involve, of course, the use of technology in the construction of a report. For example, an observer notes in one class (Urban Tech High):

> The students need to find a genetic disorder, and use "Publisher" to create a poster, including description, Punnett Square, authorship, resources used. Teacher gives an example of one he did, which the kids feel free to tease him about. "You see how bad mine is, now you can go and make a much better one!" This is a very short assignment, that is, it is due in a couple of days. There's a lot of anxiety about that, a lot of backchat among the students. Teacher suggests Googling genetic disorders to find one. "There are so many

> sites, I want you to find your own resource. You guys are so good at finding music, you can do it." (classroom observation, April 4, 2008)

While all three schools had access to on-line versions of their texts (and in the case of Private Academy, there is no other text than the school curriculum notes developed and enhanced by successive master teachers), we saw little evidence of reading assignments in the online texts; these were used for review. In two cases, the school also had hard copies of the texts; in the third, where no text exists, notes were printed as well as available online.

Images and video were often used, sometimes with live Web access at the time, but often embedded in PowerPoint or other presentation media. While in many ways, this enhancement does not seem fundamentally different from practices common before the Web, the vividness and richness of the Web's "library" of images and video, and the relative ease with which teachers and students can find new resources, has clearly increased the visual quality of presentations in these classrooms, or added elements not possible in texts. The Web enables the teacher to bring in more engaging images than could be made available in a textbook, for example to give students a vivid idea of biomes around the world:

> When we're doing our biome project, the kids can go into the library and they can flip through books. But until they actually are able to go on line and be able to see pictures and in some cases cam movies, Webcam movies of what different places will look like, that can also make so much information about the physical environment, the biological environment, the atmospheric environment so easily accessible — to go back to an encyclopedia is boring. (Private Academy focus group, June 6, 2006)

This teacher makes an important point: the images, especially if they are video clips, are "broad band" in that they can convey an idea of scale and context that is hard to capture in still photos. Thus, some images and video have more informational content than illustrations in a text.

Simulations, Remote Instrumentation, Models, and Visualizations

Animations, applets, and simulations were frequently reported, in as many as 30% of bi-weekly logs, and 20% of class periods. Again, these were primarily accessed through the Web, either directly or by way of the teachers' websites (Table 2, next page). Interestingly, preliminary data suggest that such animations and simulations are more widely used, in these schools, in biology than in chemistry, with physics teachers using them least frequently. However, subject-matter differences are beyond the scope of this paper and will not be analyzed systematically here.

Table 2: Principal Sources of Animations, Visualizations, and Virtual Labs

Source of Animations, Visualizations, and Virtual Labs	% of Logs
Web	35%
Software	11%
Teacher Website	13%

The value here is straightforward: where issues of spatial or temporal scale are important, and processes are very complex, animations and simulations support qualitative understanding of the structure and sequence of events. Students can get a clearer, in-process picture of the components and their interactions, and often can repeat the animation, sometimes with variations. A commonly cited example, mentioned by teachers in all three schools, was the illustration of biochemical processes. A biology teacher from Private Academy said:

> In biology, I think, for anything that is molecularly based, models of how materials move in and out of cells, how some membranes were built, and how they work to facilitate moving the materials in and out— the fact that I can go on line and dig up some animations for that are stellar. (Private Academy focus group, June 6, 2006)

While physics teachers tended to opine that they mostly could make do very well with actual phenomena, there were definitely "unseeable" events for which animations helped students get a qualitative understanding. A teacher from the Urban Tech High talked about a physics example in a focus group session:

> I had difficulties explaining to the kids that, if a bullet were to be fired out of a revolver, and another bullet was dropped, they will hit the ground at the same time. I had difficulty believing myself. So it was kind of tough and challenging to explain it. And we tried the experiment in class with two pennies. And at times, it worked. But at times, it didn't work as we would have hoped. However, there were applets that, okay, [get the point across]. (Urban Tech focus group, June 2006)

Of course, students are acquainted with all kinds of animated and CGI wonders, so that if they are alert, they can be skeptical about such "demonstrations," whatever the heuristic value. This same Urban Tech teacher continued, "Sometimes they're still like, okay, well, you rigged it. You made it work that way. It doesn't work that way." (Urban Tech focus group, June 2006).

In Rural High, an observer watched a virtual lab using a simulation of a manometer, (as part of a gas law unit). The teacher displayed the Web animation on the SmartBoard screen, and had the students take readings from the animated instrument, and then calculate pressures and volumes in two bulbs attached to the manometer. One student complains loudly, while doing her calculations, that “this is NOT like a real lab!” When the class ended, the observer spoke with this girl:

> I talk to the girl who keeps complaining that this is not a real lab. I ask her what the difference is; she says “it’s not hands-on, I like to do hands on.” “Even if you have to repeat a lot, and fuss with the details?” “Yeah, I just like hands on better.” (Rural High classroom observation , December 13, 2006)

Comments like this were heard occasionally in more than one school, though according to the student surveys, most students felt that technology was used neither too much nor too little.

Several teachers told us that their students relate to information and technology in very different ways than they themselves do, and this gives rise to the question, whether the changing culture supports learning in ways that are unfamiliar (to the teacher) and therefore demand new responses and strategies. This has some bearing on the role of visualizations. A teacher from Urban Tech High commented that the visual media are important for the students, because, to a greater degree than was true for the teacher’s generation, the students get information from visual media. She seems to feel that a result of this is that students are less used to creating visualizations for themselves on the basis of other presentations of information:

> They are very tech people … I come from a background of books and using books, but they don’t. I mean, they grew up with the computer, and so this isn’t, like, new to them. It’s what they do. So when we ask them to use books, that would be a learning curve for them. They grew up with TV. Everything was already visualized for them. They are not really used to making visualizations for themselves. (Urban Tech focus group, May 2006)

The complex nature of digital images plays into teachers’ reflections about the use of “virtual labs.” In all three of the schools described here, teachers made very sparing use of these tools. The use of virtual labs is a subject of lively debate in all our study schools, and two important constructive reasons for using them emerged in the focus groups.

First, and very pragmatically, they supplied a need when physical apparatus was not available. The animated manometer referred to above was employed in Rural High because the mercury manometer was banned — the chemistry teacher exhibited it to the students, emptied of its mercury, to establish that the animation they were about to use was based on a real object. In Urban Tech High, an optics lab was done using a Web simulation, because the school had no optics bench.

Sometimes a virtual lab enabled students to quickly get the point of an experiment which in real life requires very exacting laboratory equipment. A biology teacher said, in a focus group at Urban Tech High,

> We spend a lot of time on photosynthesis. There is real lab where you see oxygen being produced, and so forth. However, in those labs, sometimes there are technical issues where it may not have worked out right, and the results did not come out as expected. But there is a particular gizmo that the kids go through. And they have three things they're looking at: concentration of carbon dioxide, the amount of light, and oxygen production. So as they change the concentration of light, and they leave the carbon dioxide at a certain level, they see how much oxygen is being produced. And then they quickly see the relationship. (Urban Tech focus group, June 2006)

Second, some teachers in each school had developed a composite activity, in which the virtual lab was paired with the real lab. In some of these instances the virtual lab component included probes that enabled students to observe phenomena that would be difficult to observe in a "real" lab. In the two cases we observed, the purpose of the virtual lab was to scaffold students' observation of a complicated phenomenon, to prepare them for what they would be seeing in the real lab. For example, in Rural High, one teacher, who was very skeptical in general about the value of virtual labs, found it useful to prepare the students for a dissection lab on sheep's brains by using a virtual dissection which she found on a medical school website. In Private Academy, a ripple tank simulation is the only virtual lab that is regularly used in conjunction with a lab in physics, because it provides such good lessons about signal/noise, and the messiness of experiments in the "real world." The teachers discussed it eagerly in a focus group, and one summed up their judgment:

> I think the ripple tank simulation on line is so far superior in terms of how much understanding they can derive from it. Because I know what to look for in a ripple tank so I see it. But, my students don't know what to look for. (Private Academy focus group, June 2006)

Access to Scientific Data Sets and Enhanced Data Analysis Skills

Engagement with scientific data — collecting, analyzing, and interpreting evidence— is a central value for standards-based high school science education. By making computer resources available to all the students, a school also makes available a range of tools that students can use to work with data. To what extent is technology employed for data work? The two primary tools for this work in the three researched schools are Excel and probeware with its associated data analysis software (e.g., LoggerPro).

Even though these tools have been available for use in schools for decades, their potential is still being explored. For example, in one of our schools, spreadsheets were used rarely, and only in conjunction with probeware. In Rural High, probeware had only recently being purchased. In Urban Tech High there were no probes five years into the life of the school. Although the science teachers said they found probes very desirable, the combination of budgetary constraints and a commitment to maximize appropriate Web use made probe acquisition a lower priority in the administration's eyes. When teachers described how frequently their use of spreadsheets or probeware contributed to work with data, the results (Table 3) stimulated questions about the actual role of data in these science classrooms, and the role of technology in supporting data work.

Table 3: Benefits from Use of Spreadsheets and Probeware for Data Operations

	Data collection	Improved observation skills	Seeing the unseen	Data analysis
Spreadsheet	13%	—	—	15%
Probeware	16%	5%	8%	11%

Excel was the most commonly used data tool, and teachers across the board report being comfortable or very comfortable with its use. Student use of Excel or other spreadsheet software was reported in 20% of the teacher logs, and it was used for data collection on average in 13% of the logs, and for data analysis in 15% of the logs. (Other uses included organizing information and creating study aids.) However, we note that Rural High did not use report using Excel or comparable tools for data work at all (though the teachers used it for record keeping and computation of grades). Probeware was reported in 16% of the logs, and (not surprisingly) its use was almost always for data work.

Thus, in these three schools, technology use for student data collection and analysis is reported in approximately 15% of logs. In focus group discussions, teachers agreed that technology provides important value in data connection and analysis. They asserted that probeware can eliminate errors in recording data, increase accuracy, and make possible more frequent replications of events. Spreadsheets are seen to facilitate computation, reduce the tedium of graphic data sets, and eliminate mathematical errors. Teachers see these tools as being most valuable in data work because they can enable students to concentrate more directly on the scientific concepts being studied. In a focus group at Private Academy, one teacher said,

> I just think going back to a lab where you're plugging in numbers for, like a conservation of energy lab and it takes you a good hour to morph your data into something that could even show you what's happening. I don't want to go back to no spreadsheets … . [That kind of tedium] takes so many kids out of science. That stuff is disheartening. It just takes too damn long to find anything that's even remotely interesting. So [with spreadsheets] you're not wasting your time with algebra. You're like kind of looking like and analyzing and seeing what's going on. I love that. (Private Academy focus group, June 2006)

Her colleague added:

> [Before probeware and spreadsheets] the skills that they had to use were very different. They had to know how to graph. They had to know how to count dots [recording distance traveled per unit time]. But, in reality what I wanted was them to look at the graph and tell me what it showed, and then go back and make some change and make a prediction. And compare that prediction to the actual new graph they're going to get … . You couldn't do that in one period in a physics class. You couldn't get two graphs to produce. So when I started asking the question, why technology in this situation, it's like because the goal here is to get them to interpret motion when you're going fast and going slow. (Private Academy focus group, June 2006)

It is interesting to note, however, that data analysis involving spreadsheets or other digital tools is actually rather rare in these schools. For example, in Urban Tech High, Excel use is reported in 18% of logs, and of those logs, the tool was used for data collection, analysis, or graphing less than 20% of the time. Thus Excel use for data analysis was reported in fewer than 5% of the logs. Rural High reports a somewhat higher frequency of data analysis (their tool is the graphical analysis software that comes with their probes), in 20% of logs; Private Academy reports the highest frequency of students using computer technology for data analysis, in about 35% of logs. In all the focus groups we held with teachers to discuss these findings, teachers agreed that their departments and schools have never discussed what data analysis skills are desirable for their science students. Because Private Academy has a self-developed curriculum, it has established minimal norms for data analysis in science, but the amount of time spent on data analysis varies greatly across classrooms.

Remote scientific resources, such as remote data sets or instrumentation, offer other ways to bring scientific data into the classroom. This link between research science and science education is an important strand in NSF's vision for cyberinfrastructure. Our study schools are well equipped, in terms of teacher capability and technological capacity, to make use of such resources. However, these were reported very rarely (in 6 logs total from across all three schools). The use of remote instrumentation was reported from the practice of one teacher in one school. All the teachers were aware of large scientific data sets relevant to their subjects, and remote instrumentation that might be useful for high school science, but even for teachers who entertained the possibility of using them, logistical difficulties of two kinds created essentially an insurmountable barrier. One teacher summed up these challenges:

> So there are tons of astronomy resources that are out there, like huge databases. But I don't really have the software that runs that. There are some projects that are geared so that they could be done in high school. But I think a lot of the big national databases just really aren't well-suited and well thought out for an educational application. (Private Academy focus group, May 2007)

It was striking that modeling was rarely present in any of these schools, in any subject. In only a few cases did teachers require or challenge their students to derive equations or computational models of phenomena (represented in spreadsheets), which then might be tested against empirical data. In a few other cases, students were asked to use graphical representation software such as Inspiration to create concept maps. We did not see, nor did teachers report, any use of quantitative modeling software or Webware.

Classroom Interaction and the Wider Science Community

Teachers reported no use of email or Web to contact scientists or engage their students with other students, for example, in cross-school data collection projects.

With respect to classroom interaction patterns, our observation data suggest that prevailing pedagogical styles in a school, or even an individual teacher's classroom, will set the interactional patterns into which technology then fits. For example, teacher-led "discussions," in which the teacher interactively conveys content, with student questions and short-responses, is a prominent feature of classes in all these schools (reported in all observations). Sometimes the "discussion" fills less than half of the class period, sometimes more than half — but in Urban Tech High and Rural High, such classes are reported in 50% of observations, while in Private Academy, they are never reported. Students working in small groups are also a consistent feature of these schools, but again the schools vary. In Private Academy, such small group work occupies less than half the class period in about half the observations and more than half the class only 14% of the time. By contrast, in Urban Tech High, small group discussions are not reported in 75% of observations, and in the 25% of observed situations where they do occur, they occupy less than half the class period.

III. What challenges did teachers encounter in using their technology suite in their teaching of science?

Teachers in their focus groups reported on several persistent or emergent problems which affect their uptake and use of the technology for science, including continued technical problems, the time needed to find and evaluate resources and to learn to use the new tools, student attitudes towards technology and the Web, and school cultural issues.

First there is the added demand on teachers to find, assess, and integrate technology, including both tools and resources, in a way that makes sense for the classroom. Given that the Web is constantly evolving, there is never a time when one can stop and say, "Ok, I have all the resources that I need." Also, what is freely available for teachers to use one year, may require a subscription or a fee the next. Too may teachers feel that they are on their own, when it comes to identifying new resources that fit the curriculum.

In all our schools teachers remarked in various ways on the learning curve that the new technology demanded of them. Not only are there new tools to learn, and to integrate into their practice alongside of, or instead of, older apparatus, but there is also the simple challenge of keeping track of resources, and evaluating their actual impact:

> I realized that there are so many silly websites that I use, and there's so much stuff that I go after and pull, and I haven't kept a very good record of what I have. ...If something should happen to a computer of mine, I would lose those favorites. And would I be able to find some of those again if I had to? So that kind of scared me. [The logs we used to report in this study] forced me to think a little bit about whether some of these activities that I was designing or not, or designing with digital or with technology, if they were just to use the stuff and be like a gear weenie, so to speak, or whether they were really effective, you know. (Rural Academy teacher interview, May 2006)

With regard to the challenge of coordination of resources, and putting some boundaries on the boundlessness of the Web, teacher Websites or school Intranets have proven an important resource. The three schools profiled here provide very different levels of support for teacher websites.

Private High has a complex Intranet system, to which parents, administrators, teachers, and students all have access (to varying degrees), and this provides both a place for communication and record keeping, and also a place for the collection and contextualization of Web resources. The school has its own curriculum, which is on-line, and this provides a coherent framework within which to seek and to integrate new resources from the Web — links can be added to the on-line notes either for use in the classroom (e.g. as part of presentations), or for student use.

At Urban Tech High, the internal network is not as elaborate, but each teacher and student has a folder on the server into which resources can be placed and organized. A drawback to this secure system is that it is not accessible from the outside, so students have to email files and resources to their own email account, for retrieval at home. As a solution to this, teachers are creating their own websites outside school to place student resources for use both after school and during class. In Rural High, teachers have been asked to develop websites for themselves, but due to lack of technical help most of them have not been able to do this successfully.

In most of the study schools, technical/logistical challenges persist — even in these highly resourced schools. While the issues are "logistical," they have pedagogical consequences, and in some cases have substantial impact on teachers' attitudes and actions about the innovation. Such issues range from obsolescence of batteries to unreliability of student computers or network problems.

One teacher from Urban Tech High was asked in Year 3 about an issue with the school's Intranet that had surfaced in year 2:

> I think the Intranet has improved. Ironically, [the district] has issued us all Mac Books that run both PC and Mac platforms, that is very unstable and poorly compatible with the current network — so problems persist! (Urban Tech teacher comment on research report, November 30, 2008)

On several occasions, teachers mentioned technology problems that impaired their use of classroom equipment. Their accounts suggest that not all problems are solved by the presences of a strong technical support staff. Perhaps another way to put it is, just as dealing with unconstructive student behavior is a constant part of a teacher's task, so is improvisation around technical glitches. The issues encountered will vary from school to school, as each school's technology setup is different. However, the important point is that such issues are endemic to complex systems.

The problems encountered may be relatively minor (slow Internet connection) or relatively major, as illustrated by comments from an Urban Tech High focus group:

> It's been like hit or miss as far as maybe two thirds of the class will have computers or three quarters of the class will have computers on a day. So I would give them technology assignments, but I wasn't relying on it every day because a lot of them didn't have it. (Urban Tech focus group, June 2006)

In the increasingly complex technological environment in which schools operate, problems which occur anywhere in the system may translate into pedagogical or logistical challenges in the classroom. Some of these are well beyond the school or teacher's control. For example, the links on a Web site that a teacher has found as a resource may not be maintained. A teacher told us, for example, he had found that a site which was valuable for his students, but now was deteriorating, reporting : "It's losing its links. The WebQuests are no longer usable." To the extent such resources have been embedded in the curriculum, the teacher then needs to spend a certain amount of time in maintenance and updating.

Other issues arise in interactions between various parts of the system, inside and outside the school. While these can be easily labeled and dismissed as "compatibility issues," they are in fact symptoms and consequences of the constant changes and fluctuations in an extremely intricate system of systems, which are in effect separate in management, but not in use. The following comments by a teacher on the use of a software system that allows her to synchronize and manage all the computers in the class centrally (for supervision, display, and collaboration) provides a good example of this issue, which plays itself out in various forms depending on the tools being used:

> They couldn't connect Synchronize. And then I couldn't really see by the numbers who was on my screen. I had to walk around the classroom and approach half of my students and make them connect to Synchronize. And it took a lot of time, just with them to connect with Synchronize. It is not really for a wireless environment. It is really for cabled network environment. You can only get like 25 computers going through a router … in the beginning it worked in my classroom. Something happened. (Urban Tech focus group, June 2007)

A lack of time for professional development, especially in the form of teacher collaboration to develop best practices within the school, becomes a barrier to effective integration of computer and Web resources in the classroom. This issue was voiced by teachers in all study schools. Private Academy hosts a 6-week institute for its teachers during the summers, covering technology skills, lesson planning, and technology integration. This program is especially geared towards new teachers. Rural High and Urban Tech High also provide in-service training, both with in-house technology staff, and with external providers. Yet teachers spoke of the need for communication with other teachers, both within the school, and outside. In part, this is because tools are integrated lesson-by-lesson, using trial and error, and other teachers' experiences can provide guidance and short cuts. Teachers valued tips and advice from other teachers and from people outside of their schools, and more and more are seeking such input from various Web resources. Nevertheless, nothing can substitute for focused collaboration in my context — my school culture, with my technology, in relation to the aims that my colleagues and I are seeking to achieve.

We often observed that in wireless classrooms a certain proportion of students were surfing the Web, sending instant messages to their friends, and sometimes also getting onto inappropriate sites that somehow had slipped through the school's filters. Private Academy, by staying with Ethernet cables for student access, avoided much — though not all — of this kind of extracurricular activity (since they could see when students are connected to the Web).

While many teachers and students agree that technology can increase motivation as well as provide students with needed 21st century skills, overuse of technology within a student's day can dramatically decrease the motivational effect. As one teacher in Urban Tech High reported:

> At our school the mantra is, it's to engage the student. Well, since there's nothing unique about anything, the engagement is not there anymore, because it's the same thing in every class. There's only so much you can do with the programs. It's not like one department owns a certain type of program and you only do it in that department. It's like everybody does the same thing, just using different contexts. Everybody does PowerPoint … . There's no push, challenge, "I want to learn this and be challenged." It's, "I know how to do it so let's do it in PowerPoint, it's so much easier. (Urban Tech focus group, June 2008)

Teachers often mentioned in focus groups that student reports look more polished and professional when using technology. Excel creates better graphs, Word creates better looking reports, and visuals can be incorporated into presentations of many kinds. Yet, these issues of presentation do not address teachers' primary concerns about increasing students' abilities to reason, making connections, defending and analyzing their results. In several different focus group sessions, teachers voiced the concern that the ease with which data (text, numbers, images) can be transformed, and transferred between applications, increases the likelihood that students' actual understanding is masked by the power of the technology, whether this happens by the copying (or plagiarizing) of text, or a facile creation of a graph with little understanding of its meaning either mathematical or scientific.

Reasoning about data, which can be scaffolded by graphing tools, probeware, and simulations, is nevertheless constrained by qualitative and quantitative weaknesses that students bring to the classroom. The development of a "culture of scientific argumentation" which is so strongly recommended by science standards and policy documents requires reasoning and inquiry skills which can not be developed through technology alone. Teachers found it important to create environments where computer use does not hamper dialogue, argumentation, and discussion between students. Technology certainly cannot substitute for human classroom interactions.

One teacher described the challenges that students have in relating facts to each other to construct a coherent understanding or narrative about science.

> They can't take this piece of information and this piece of information and put them together, even when we have done it for them. … They still have so much difficulty taking information from two places and relating them. (Urban Tech focus group, June 2007)

The teachers speak of this as having "analytical skills," but their examples seem to provide evidence of the challenge that students have in comprehending complex phenomena, and understanding the way different parts connect to provide coherent sequences, or even explanatory theory — not so much analysis as synthesis. This is of course a major, persistent challenge in science education, and these teachers are clear that this "ground condition" is not changed or obviated by technology.

Finally, we also found that school culture can significantly hinder teacher uptake of the new technologies. In Rural High, for example, the technology initiative was considered to be part of a major move towards student and teacher accountability, as much as for curricular reform (see Figure 1). The result of this emphasis, in the opinion of the teachers, was a period of dysfunction and tension that inhibited some teachers' embracing the new technology for their classrooms.

Furthermore, the superintendent was seen, both by the teachers and the principal, to place a high emphasis on security and discipline, following rules and documenting procedures. For this reason, the issues reported by the teachers are not linked directly to the technology, but rather to management style, as the principal elaborated:

> I think it has to do with ideologies, and it has to do with management styles. It's not fair to blame it on the technology. If there's a rule out there, if the state devises a rule, if the state has a rule for something or there's some sort of a plan that you're supposed to follow, he's going to follow every thing right to the letter, and he's going to make sure that it's documented, and that everything is absolutely in apple pie order, because he wants to make sure he looks great on paper. And it doesn't matter if all of us jump through the hoops to make him get there. (Rural High principal interview, spring 2006)

This sense of extreme guardedness applied to uses of the Web, as well. In addition to other incidents researchers witnessed or had been told about, the teachers spoke on a few occasions of how they were prevented from legitimate uses of the technology because of the security system at the school:

> What the heck's going on? You've got technology and you're going to send your kids out to universities to go and access websites for histology slides and they can't even go there because the filters are blocking everything. (Rural High focus group, spring 2008)

Discussion

The schools in our study have sustained a complex innovation for a significant period of time, to the point that the presence of the "ubiquitous computing" technology has become a reliable element of the school culture. Each school has a relatively stable and experienced science faculty, and unusually high levels of technical support. Informed and consistent administrative policy (Fishman, Gomez, & Soloway, 2002; Zucker & Light, 2009) has helped create the conditions necessary for the maturation of these experiments with ubiquitous computing. In this stable environment, teachers have been able to explore their own values and preferences with respect to the use of technology. Before exploring "lessons learned" from the results provided above, we wish to focus briefly on the learning challenge for teachers, which is an essential ingredient in any classroom reform.

Teachers' evaluation and experimentation in the ubiquitous classroom is vital, since the deployment of particular technologies does not necessarily result in an enrichment of the classroom content, more challenging student engagement with scientific data, or more reflective and inquiry-rich student tasks. Teachers must make choices about how to use these tools, informed by their understanding of instructional content, their students, and their pedagogical/curricular strategy (Rakes, Flowers, Casey, & Santana, 1999; Spillane and Jennings, 1997: Windschitl & Sahl, 2002). Some benefits that come to the wireless classroom derive from the greater availability and mobility of computers, some from better Web access in the classroom, and each of these brings its own questions and challenges, both practical and pedagogical.

It is useful to consider how these tools and technologies relate to the tasks of the teacher. The teacher's ultimate aim is to foster students' growth in understanding and competence about a field of science. To this end, he or she must select, arrange, and represent the "science," create or make possible learning situations for students who bring a variety of motivations and competencies to the classroom, diagnose by a variety of means where students are at vis á vis the curricular goals of the classroom, develop strategies to address issues identified by such diagnoses, and do all in a way that leaves the students' knowledge enriched, but also leaves more or less intact their motivation to learn (Krajcik et al., 2001; Hill et al., 2000; Hoffman, Wu, Krajcik, & Soloway, 2003).

This dense list involves a range of expressive and investigative activities, in which various technologies can play a part. Some of them, like optical aids, have been indispensable for centuries; others, like presentation software, are widely used but still relatively recent. In many cases, one tool might appear to provide the same "service" as another. For example, the combination of a dissecting microscope or hand lens, dissecting probe or forceps, and a flower is a long-standing technological setup for learning about the reproductive structures of angiosperms. Digital photographs, perhaps with commentary, would provide much of the same "content", with (under good conditions) some interesting logistical and pedagogical advantages. Are these so similar in general purport that they are redundant? Are they complementary? Is one superior to the other? (Brown & Edelson, 1999).

The answer in very many cases will depend upon the balance of many considerations. The choice, which is an eminently practical one on many counts, has other implications, however, of which teachers and administrators may not be aware. The choice of tools and media in the classroom represents a way of conceptualizing that area of science, emphasizing the importance of some phenomena over others, establishing the kinds of learning hoped for, and the ways that a teacher might hope to diagnose and assess student learning. A teacher's choice of tools is therefore tactical, strategic, and also epistemological: it shapes the kinds of seeing, knowing, and expressing that students will do, and also the evidence of student learning that will be available to teachers (Linn, 2006).

It is no wonder, then, that Larry Cuban and other researchers find many situations of "high resources, low use" (Cuban, 2001b; Falk et al., 2005; Davies, 2004). Even in the three schools we have described here, where ubiquitous computing has been adopted and supported systematically, and with consistency over time, our teachers have shown that, at least for science teaching, the need for discernment, judgment, experimentation, and change of practice is a continuous challenge. Similarly, maintaining the technology itself is a continuous requirement that is never "complete," because the technology you have wears out, or is rendered obsolete by newer developments. Every such move requires an intellectual and sometimes emotional adjustment by the teachers — and even in a school which is a leader in technology innovation, there is a range of personal response:

some teachers even in high-tech schools are “early adopters” relative to their peers, some are at the opposite end of the spectrum, and most are in-between (Davidson, 2003).

Lessons Learned

With this backdrop, we can reflect on some of the lessons learned by the years of experience in these schools, and exemplified in the findings reported above.

Multiple Innovations

An important point that emerges from our study is that the wireless, 1:1 environment actually involves two major innovations. The first is the availability of laptops for all, and the second is the availability of the Web, and the diversity of resources that can be found there. In the study schools, the implementation of the ubiquitous computing environment has had the important effect of encouraging the use of computer-based tools such as Excel, because they are reliably available. The use of such tools can be both planned and spontaneous, and integrated into the flow of a lesson, uninterrupted by the need to adjourn to a computer lab. Even in these three schools, however, which have worked to develop a high degree of technology integration, the use of a data analysis tool like Excel or LoggerPro was more experimental and less seamlessly a part of teaching and learning.

With the addition of Web resources, the questions about how best to engage with scientific phenomena are complicated further. The Web offers an abundance of photographs and video, and also simulations or animations of almost every phenomenon likely to be addressed in high school science. Yet because these are all representations of phenomena, they challenge the teacher with sometimes conflicting options. The prepared representations have great power in conveying or illustrating concepts. On the other hand, actual phenomena can (in good cases) engage the student in the actual process of investigation, which may include data collection, error analysis, and an understanding of the challenges of empirical work.

Furthermore, both elements of the ubiquitous computing innovation can provide teachers and students complex and powerful representational opportunities for scientific phenomena. In the study schools, teachers used technology based tools for their own presentation. Teachers are still exploring the range of possibilities for student representations, and the implications for formative assessment.

Piecemeal vs. Strategic Implementations, and Attention to Subject-specific Tools and Values

The three schools differ in interesting ways in their integration strategies. Both Private Academy and Rural High provide a very wide range of tools for their teachers' use, including data analysis and visualization tools, multimedia, and "productivity tools" such as Word processing, spreadsheets, etc. Urban Tech High works from a core set of tools that they believe are essential foundational technologies — Word, Excel, PowerPoint, and Access data bases. Additional technologies are used as students' skill and interest grows, but the focus is on mastery and wide application of these core applications.

The contrasts among these schools are instructive. In Urban Tech High, teachers have many different motivations for integrating additional technology or for integrating core technologies in new ways the shaping and implementation of curriculum is in individual teachers' hands. In Rural High, while technical support is easily available, targets for the use of technology are not specified at all, except in the most general terms. (Their technology plan lists: " internet research, word processing, project development, mini-movies, reading and math assignments on line, graphing, drawing, computer assisted drafting, Office training, specialized programs for technology/science projects.") Even more than in Urban Tech High, the teachers are left to develop their technology strategies on their own, or by informal consultation with their colleagues.

In Private Academy, while there is considerable variation from teacher to teacher, the curriculum is a common product, and as it is used, it is critiqued, and improved. Technology integration is one of several factors that are regularly examined. By both informal and formal mechanisms, innovations are tested and shared within the school, and compared with established methods. This integration work has been going on for more than a decade. The example of Private Academy suggests that districts or schools implementing the ubiquitous computing environment require both patience and structured persistence if they wish to transform the science curriculum.

Strategies for Incorporating New Tools

As discussed above, some teachers have found that their teacher website is a key way for them to make their use of the Web and other multimedia resources coherent and targeted. The interactive whiteboard also has this potential, both in conjunction with the Web, and on its own. One of the challenges of 1:1 classrooms is the question of when it is important to work with the class as a whole, and when individual or small group work is more advantageous. Decisions about this question are complicated by the persistence of the "teacher centered classroom" as the fundamental paradigm. In addition, one common tenet of science education reform over the past several decades is the importance of collaboration and discourse in the classroom, which reinforces the traditional use of "lab teams" for practical work (Driver et al., 2000). The 1:1 computer ratio is in tension with this collaborative approach.

Nevertheless, teachers in the study schools have found that the use of the interactive whiteboard can foster substantive classroom discourse. First, the tool enables the teacher to bring a Web site (or sites) to the classroom in a way that is constrained, and prevents student distractions during Web searches. Richer online resources can be used as the basis for richer reasoning and debate. Furthermore, such tools can be used to project student work (data or representations) for classroom discussion, and capture the discussion for future reference by both students and teachers. One teacher from Private Academy wrote:

> I have found that the SmartBoard's number one benefit for me has been to capture the lesson when needed for students to watch again and to review what we did in the class. (Private Academy teacher comment on research report, spring 2009)

Pedagogical Philosophy

There was a striking diversity of approaches to technology integration evident in these high-tech schools, all of whose teachers regarded themselves as comfortable or even adventurous with technology. That is, even in a school like Private Academy, where the integration has involved high-quality equipment, deep and prompt technical support, extensive teacher education, and a highly elaborated, technology-rich curriculum, we see a wide range of teaching styles. Some teachers look like "early adopters," and others like reluctant users, with most falling in between.

Beyond this, however, the uses of technology were clearly shaped by the teachers' understanding of what science education is supposed to be. In the same school, we heard one teacher focusing primarily on information transfer and presentation, while one of his colleagues believed, "In high school, science is all about discovery." Few of the study schools articulated an inquiry-based approach to science, though Urban Tech High emphasized student empowerment and projects and Private Academy included scientific thinking as part of their definition of "mastery." But the school's definitions and goals were trumped by individual teachers' pedagogical stances. Inquiry-oriented teachers deployed the technology to support and expand inquiry; more traditional teachers likewise used the technology according to their values, in conducting a teacher-centered classroom.

School Culture and Teacher Learning

Key aspects of school culture must be considered as part of the 'technology culture' of the school, and will affect teachers' uptake of the new tools — that is, their willing and purposeful exploration of ways to enrich and strengthen the science learning and teaching in their classroom (Maehr & Midgley, 1999; Tinker et al., 2007; Windschitl & Sahl, 2002; Zucker & Light, 2009). While individual teachers will use new tools according to their own professional preferences, it is nevertheless the case that school culture can foster collaborative conversations, and the development of innovations — or hinder them. School culture is a complex compound, reflecting community values as they appear in student and parent attitudes, the rhetoric and espoused values of the school or district, the deployment of resources which either is in support of the espoused values or not, and the way that different priorities within the district are balanced. As we saw above, in Rural High, an administration whose overarching emphasis (as the teachers perceived it) was accountability and security could in effect drive teachers away from experimentation with the rich technological environment that was provided. A mutual adoption of goals is necessary for the explicit balancing of such divergent priorities, to the end of improving the quality of science actually experienced in the classroom by students and teachers.

Professional Development Strategies

Finally, professional development strategies are most appropriate for this new environment when they reflect several key aspects of the teaching situation in the high school science classroom. The high school science classroom tends to be rich in apparatus, most of which has a claim to be effective and add value, depending on whether the aim is qualitative understanding of concepts, model-based reasoning, quantitative competence, science discourse, the ability to use and interpret multiple representations of scientific phenomena, or become acquainted with a range of exemplary systems and experimental approaches. Thus, the tools of the ubiquitous computing classroom take their place alongside much else that is valuable, and teachers will need time and analytical frameworks within which to explore how to best deploy the new resources, to complement and sometimes replace the old.

The diversity of apparatus in part reflects the diversity of operations expected as part of science teaching and learning — presentation and illustration of concepts, acquisition and use of inquiry skills, collection, evaluation, and presentation of data, the growth of scientific discourse, and the various practical skills of measurement, computation, error-analysis, argumentation, and so on. These fundamental operations, which technology can certainly support, exist before and apart from any specific apparatus, and should be part of the professional development program.

The ubiquitous computing innovation is two-fold, or manifold — rich computing resources, rich representational resources, and the abundance of resources available on the Web. Once again, therefore, there is no end-point of integration, because the possibilities for change and improvement are numerous. For this reason, professional development needs to include processes by which teachers regularly discuss their values for science education, the role of experimentation and data analysis, ways of gaining insight into student work, etc., and the roles that technology plays and can play in addressing these questions.

Therefore, the workshop model of professional development is even more inadequate than it has been shown to be hitherto (Darling-Hammond & Sykes, 1999; Cuban, 2001a; Maehr & Midgley, 1996). Teachers within the school need time and helpful structures within which to discuss science content, student work, pedagogy, and technology. Teachers in all study schools expressed a desire for more time to work together to solve the many puzzles their profession sets before them. Furthermore, the wider community of teachers is a powerful resource that some teachers now are able to use effectively, but which may be even more serviceable if the experience of learning community exists within the school as well as beyond its walls (Drayton & Falk 2006; Huberman, 1993).

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