Science teachers have been innovators and leaders in the use of technology for many decades. They have used technology in labs and physical experiments; hands-on activities; field trips; and data collection. Science teachers pioneered the use of hand-held devices in schools in the 1980's, using probes and micro-computer-based labs to collect data. Yet even today, in 2002, there is evidence that many science teachers are not making effective use of the digital technologies now available in classrooms and schools. In some cases, teachers do not have adequate access to technology or adequate support to be able to use it effectively. Teachers themselves report that they are not well prepared to use new technologies even when they have access and support (Becker, Ravitz, & Wong, 1999).

What do they need to know to use technology – and particularly computers and the Internet – in ways that promote meaningful learning? The argument of this paper is that what is missing is knowledge at the intersection pedagogy and technology, and that the missing knowledge is not what one might expect. Teachers need knowledge in two broad categories. First, they need to be able to identify and develop technologies into tools for meaningful science learning, and this means knowing what technology offers for
such learning and what effective use looks like in practice. Second, they need a useful portfolio of technologies that engage students in meaningful learning, and this means knowing about specific tools and resources that they can use in their teaching. Rather than more technical knowledge – about emerging technologies, or networking, or hardware – what teachers need is knowledge of curriculum-based technologies that work with both the ways teachers teach and what students need to learn.

**Lessons from the classroom**

Teachers themselves provide evidence that what they need is not technological expertise, but rather a useful portfolio of technology resources. From observations of science teachers using computers in their classrooms, five important lessons about teaching with technology stand out:

1. Knowing how to use computers is not the same as knowing how to teach with computers. A teacher can be an early adopter or a "techie" and a good science teacher and yet not teach effectively with technology. There are many versions of this:
   - An early adopter can be so enamored of the technology that she teaches technology rather than science.
   - A competent computer user may know the tools for his own work (e.g., word processing and email), but not the cognitive tools for teaching his subject matter.
   - A teacher with a lot of "training" may know technologies to which she does not have access; for example, knowing how to make computer models with STELLA but not having the software on the school's computers.

2. Technology is specific: grade level, subject, computer configuration, and computer availability are among the variables that completely change what is desirable
and what is possible in a particular classroom. Thus, it is difficult to provide "generic" education for teaching with technology. Teachers need to know how to use specific software for specific purposes – general knowledge of technology is not adequate. Even if teachers have general knowledge of technology, they still need to convert that knowledge into specific ways to use specific technologies in their classrooms. Being an expert with Excel, and being an expert social studies teacher, does not automatically endow a teacher with knowledge of how to use Excel to teach social studies.

3. Teachers do not need to know it all – they need a repertoire of technologies they can teach with – software, Web sites, data sources, plus computers, printers, and other devices like cameras and scanners. They do not need it all – just a selection of those items that fit with their curriculum and that are available in their school or classroom. Not every teacher needs to use every technology.

4. Teaching with technology is time-consuming, hard work for a teacher. It is not sufficient to set up a lesson, turn on the computers, and let the students go to work. To gain the benefits of technology, teachers need to help students engage with the complex ideas and processes that technology makes possible. In most cases, technology does not "teach" on its own. It requires interaction among students and between students and teacher to make sense of what the technology offers. This requires subject matter knowledge, pedagogical knowledge, and technology knowledge as well as extensive planning. Teachers need to know not only what the technology will do, but also what students are likely to do with the technology. They need to anticipate problems with technology and with pedagogy, and be able to respond to those problems in the moment. In essence, they need to rehearse their teaching with technology ahead of time, the way
that expert teachers develop mental models of teaching routines and activities to rehearse other kinds of teaching. But most teachers have not had the opportunity to develop those kinds of mental models, or engage in rehearsals for teaching with technology. Technology is new, and because it changes so rapidly, it tends to stay new year after year.

5. Computers change too fast to worry about what you are not doing: teachers and administrators need to focus on doing what can be done with the technologies available, not on pushing the envelope. Technology currently available in schools offers enormous possibilities for meaningful learning in science. Even if the technology continues to change as rapidly as it has in the past decade, the only way teachers can use it effectively is to create relatively stable repertoires of technology uses that serve important curricular ends and that can be sustained over time.

All of these factors imply that teachers should not be expected to be technology experts. First, given the variability of the contexts in which teachers teach, it is hard to imagine general technological knowledge that has wide application across settings. Second, given the rate of change of technology, it is unrealistic that teachers could keep up with the latest and truly be experts. Finally, the demands on time for knowing any particular technology in any meaningful way are huge. Teachers have more valuable ways to spend their time than understanding the new features in the latest system software, or trying out new software packages released for science education. Some teachers will do these kinds of things, but it will continue to be the exception, not the rule, that a teacher is or becomes a technical expert.

What do teachers need to know? The argument that follows proposes three areas of knowledge important for effective teaching with technology: 1) knowing what
technology offers for meaningful science teaching and learning; 2) knowing what effective use looks like in practice; and 3) knowing a portfolio of technologies that can be used in meaningful science learning. These three areas are addressed in the sections that follow.

1. What do teachers need to learn about what technology can offer?

There are two broad categories to describe what teachers need to learn about what technology offers: what it offers for student learning, and what it offers for teaching. A convenient way to talk about what technology offers is to use the idea of affordances (Gibson, 1977). An affordance is something that is made possible, although not necessarily required, by an object such as a technology. So, for example, a chair affords sitting, and so does a flat rock high on a mountain. Affordance will be used here to indicate such characteristics of technology – possibilities that may or may not be realized in practice. Proposed here are four affordances for learning, and five affordances for teaching, as shown in Table 1. The following sections explain these affordances and what they mean for teacher learning.

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Table 1: Affordances of Technology for Teaching and Learning
Affordances for Learning

Technology for science education can afford opportunities for students to engage in meaningful learning in four categories:

- **Representation**: Providing representations of ideas and processes that are difficult or impossible to represent without technology
- **Information**: Providing access to data and content
- **Transformation**: Changing the nature of tasks in which students engage
- **Collaboration**: Facilitating communication and collaboration with peers and experts

None of these is an automatic result of using technology, but they are affordances that describe what technology can offer, and why there is so much enthusiasm for technology in the science education community.

1. **REPRESENTATION**: Providing representations of ideas and processes that are difficult or impossible to represent without technology.

For example, technology can be used to speed up time through simulations of processes that would ordinarily take place in real time. Using modeling and simulation programs such as ModelIt, or StarLogo, students can build models of complex systems such as stream ecology or a predator-prey system. Doing this work can help students understand important concepts in the topical area (e.g., the food chain in a predator-prey model) as well as important processes of scientific investigation (e.g., dependent and independent variables or using graphs to represent data).

Another example is probeware. With handheld devices like calculators or personal digital assistants (PDA's) connected to digital probes, students can measure and
record data such as the PH, temperature, and oxygen content of water in a nearby stream. In a laboratory setting, probes connected to computers can be used to record temperature change or other variables, yielding real-time output of graphs. Clearly, doing these activities is only worthwhile in the context of units of work that provide students opportunities to make sense of the data collected and the ideas and processes entailed by these activities. But certainly, these technologies make it possible to avoid some of the pitfalls of activities that depend on data collection – time-consuming and inaccurate data collection and graphing, for example.

Simulated dissections provide another example of representational technology for science learning. Scientifically accurate simulations of dissections of frogs, cow eyes, sheep brains, and fetal pigs can be found online, and others are available on CD ROMS. Although dissections can be done without computers, there is often controversy surrounding use of real animals, and there is also some evidence that students learn a great deal from the simulated dissections, especially when used in conjunction with real dissections (Cavanaugh, 2002).

2. INFORMATION: Providing access to data and content.

Using the Internet, students can have access to data that was previously impossible to use in classrooms. For example, up-to-the minute weather data, images from the most recent NASA missions, and current earthquake data from around the world are readily available on the Web. Students can find content about topics that would have been very difficult to study prior to the Internet – for example, information about zebra mussels in the Great Lakes or reports on the predicted water levels and snow cover in Lake Superior. Access to information is important in at least two ways: first, it makes
it possible to study things that are interesting and motivating to students. Second, it provides content for schools that are resource-poor, perhaps dependent on old and outdated textbooks.

3. **TRANSFORMATION**: Changing the nature of tasks in which students engage.

Doing lab work in science classes has historically been a matter of following recipes for getting through a specific series of steps and reaching a known conclusion. Authentic processes of science – particularly experimentation and data collection and analysis – have played only a small role in science classrooms, in part because of the time they require. Technology has made it possible for students to engage in these processes by speeding up time and automating data collection. As described above, tools like ModelIt, handheld devices, and probeware radically change what students can do, and what they can learn, in science classes – they are not merely doing the same things better, they are doing things they could not do before. They can do what scientists do – collect and analyze data, test hypotheses, design experiments, draw conclusions – because of tools that reduce some of the constraints of the classroom, and of the developmental barriers to such work. For example, technology can let students use the ideas and processes of calculus well before they have the mathematical knowledge to do and understand calculus (Roschelle, Kaput, & Stroup, 2000).

4. **COLLABORATION**: Facilitating collaboration with peers and experts.

Some of the earliest uses of technology in science education were collaborative data collection activities – NGS KidsNet connected kids around the world through activities in which students collected and shared data such as acidity measurements of
local rainfall.\textsuperscript{8} Today, such activities continue through NGS and other projects, including Kids as Global Scientists\textsuperscript{9} and project GLOBE.\textsuperscript{10} A favorite site for collaborative projects is Journey North, a Web site where teachers can sign up to participate in observations of migratory populations, sharing data with students across the country and world.\textsuperscript{11} Another example of this affordance is the Jason project, in which classes participate virtually in scientific explorations, including, for example, the journey to Mars.\textsuperscript{12} In these journeys, students can communicate with scientists in the field, ask questions, make suggestions, and "watch" as the explorations unfold. It is by participating in collaborative scientific activities that students learn that science itself is a collaborative, human effort to make sense of all that is in our world and in the universe.

These four affordances – representation, information, transformation, and collaboration – explain the impetus for using technology in science education. With technology, students can do things that were previously impossible and learn science that was inaccessible to previous generations of science students. What teachers need to know is what each particular technology – a software program or Web site, for example – affords for student learning. That is, teachers need to be able to apply this list to a technology as part of evaluating its usefulness for science learning and then planning for its use.

Another aspect of understanding what technology offers is considering how it supports teaching. That is taken up in the next section.

**Affordances for Teaching**

The second category of affordances of technology relate to teaching. One could create a list of ways that technology might improve the work of a teacher – for example,
automating student records, facilitating communication with parents, or keeping track of lesson plans. General management and organizational affordances are not the focus here. The question here is, in what ways can technology support the work of teaching for meaningful science learning? For example, thinking for a moment of traditional resources as technologies, textbooks support teaching by providing a map of the content to be covered along with an authoritative version of that content. The chalkboard supports teaching by providing a persistent, stable place to record ideas. It is proposed here that technology, from pencils to computer software, can support teaching across five dimensions:

1. **Boundaries**: What are the topics the technology supports and where will students work on them?

2. **Stability**: To what extent, and at what pace, will the technology change over time?

3. **Authority**: To what extent does the technology provide authoritative content?

4. **Pedagogical context**: To what extent, and with what tools, does the technology support managing, monitoring, and evaluating student work?

5. **Disciplinary context**: To what extent and in what ways does the technology provide a coherent flow of ideas in the domain or structure the development of skills or processes?

Not all technologies provide supports in all dimensions, and it is not suggested that more is better. Instead, these affordances represent tradeoffs: In the abstract, technologies that provide *none* of these supports make the work of teaching more
difficult, with more demands on the teacher. Technologies that provide all of these supports could make meaningful science learning, and particularly learning through inquiry, less likely by over-structuring the environment. What teachers need to know is what to look for when they are deciding when and how to use a particular technology, and what might be needed to adapt it to their classroom culture. This list of dimensions is one way of thinking about the affordances of technologies for supporting the work of teaching. Teachers can consider these affordances as they evaluate and adapt technologies to their classrooms.

1. **Boundaries: What are the topics the technology supports and where will students work on them?**

For a technology to be useful, it must fit somewhere into the curriculum. Most technologies, including chalk and the Internet, neither specify how they fit into a particular curriculum nor match well with any specific curriculum. Someone (often the teacher) has to make the match. Using the Internet as an example, one common use in classrooms is to have students “do research.” This activity can mean having students work in a relatively unbounded domain and in an unbounded “space” where they can encounter content from A to Z. These two kinds of boundaries – the intellectual boundary around topics and the spatial boundary around the location of student work – can be more or less open-ended depending on the technology and how it is incorporated into the classroom. A worksheet is highly bounded in both respects, for example, while the Internet does not necessarily provide either (although some Web sites provide both.)

A technology can be clearly aimed at a particular niche in the curriculum, focus on a particular topic, and provide a workspace where students interact. On the other
hand, a technology can lack boundaries. A dataset on the Internet, an open-ended research assignment, or a visual representation tool are examples of technologies that lack one or more kind of boundary. The presence or absence of technology-created boundaries suggest different work for teacher. For example, to use a visual representation tool effectively, the teacher must fit it into particular places in the curriculum, making it useful for a specific purpose by putting it into a bounded use. Some technologies provide very clear boundaries. WISE (the Web-based Inquiry Science Environment)\textsuperscript{13} and Journey North, for example, give teachers support by bounding the work students are expected to do and the location where they do it. Yet both provide opportunities for open-ended inquiry. ModelIt does not bound the topic – it can be used to model any process, including social processes. But it does bound the location and nature of student work. There is no “best” version of boundaries to support teaching, but it is a dimension that should be considered when designing activities for meaningful science learning.

2. Stability: To what extent, and at what pace, will the technology change over time?

Conventional materials do not change much, and they do not change rapidly. Teachers can count on them year after year, and thus can invest time and effort to develop effective uses. Technology can be just the opposite, especially Web-based technology, changing from day to day, and certainly not to be relied on for years in the future. Other technologies change or disappear when a company changes hands – many wonderful programs from MECC (Minnesota Educational Computing Consortium), for example, never made the transition to the company that bought MECC in 1995. Some of the best technologies for science education are very stable and relatively long-lived.
ModelIt from Hi-ce, StarLogo from the MIT Media Lab, and Project Globe are examples of technologies that a teacher can count on. Teachers need to know, and consider the implications of, the stability of technologies they decide to use. If they choose technologies that are likely to disappear, it means finding something different the next year.

3. Authority: To what extent does the technology provide authoritative content?

Whether something is true or false, reliable or unreliable, relevant or irrelevant is not a routine issue in classrooms using conventional materials. Even though there is evidence that science textbooks often contain incorrect information, teachers are free, or even encouraged, to count on textbooks as authoritative. Technology turns this upside down. Information obtained on the Internet can be anything whatsoever. Information created through the use of technology – e.g., a student-created model – may not be a valid representation of science. Teachers need to know a lot of science to deal with the issue of authority, whether they determine for themselves or help students learn to determine what is scientifically valid. While this may be good – e.g., by altering students' and teachers' views of the nature of science – it requires different knowledge, skills, and allocations of time on the part of the teacher. Some technologies provide support in this area. For example, data from NASA, the American Meteorological Society Web site,14 or the One Sky Many Voices project provide authoritative, reliable information for science education. This is a dimension that a teacher needs to consider when using a technology: is it authoritative? If it is not, how will the issue of scientific accuracy be dealt with?
4. Pedagogical Context: To what extent, and with what tools, does the technology support managing, monitoring, and evaluating student work?

One of the most difficult things about teaching with technology is the pedagogy. How does the teacher manage this teaching? Keeping track of student work, figuring out what students are doing, responding to questions are all made more complex when some kinds of technologies are in use. For example, if students are working on computers, and if they are doing open-ended activities in which they work at their own pace or on their own topic or model, the teacher may have few ways of assessing what the student is doing, or how she is doing. Some technologies and materials provide many more supports for teachers. In a well-known study, Carter found that expert teachers could draw accurate conclusions about classroom activities from pictures of classrooms (Carter, Cushing, Sabers, Pamela, & Berliner, 1988). Teachers rely on seeing what is on the students' desks, how it is configured, who is working together, what page in the book is open, and more. In a virtual environment, many of these clues are not present, or are in such abbreviated form (e.g., one screen at a time) that they are difficult to interpret. Yet some technologies provide such clues for teachers. For example, in ModelIt with which students develop a model over time, the software provides a current version of student work and the teacher can tell by looking (albeit expert looking) what kinds of thinking the student has been doing. Technologies that support teachers in this category are those that both make student thinking visible and capture a record of student thinking. Many technologies, especially Web-based technologies, make it difficult for the teacher to gather data about student work through observation and interaction. For example, using a Web-based data set, each student may be looking at entirely different data, the teacher
may have only a single screen with no apparent history of what the student has done before, and the data may be unfamiliar to the teacher, especially if it is a large data set. In such a case, the teacher needs to anticipate the desirability of using supplementary materials (structured notebooks or question sheets, for example) for students to record and track their work.

5. Disciplinary Context: To what extent and in what ways does the technology provide a coherent flow of ideas in the domain or structure the development of skills or processes?

Disciplinary context refers to the coordination of the technology with the curriculum and the discipline, including developmental appropriateness, coherence of topics, and relevance and accuracy with respect to the domain. At their best, textbooks and conventional curriculum materials pay attention to the order and flow of topics, to the age- and developmental appropriateness of content and activities, and to current understandings in the discipline. Schwab describes the process of creating curriculum as "discovering in scholarly materials curricular potentials which serve the purposes which have been envisaged in the light of detected student needs; then, assessment of the probable advantages of one potential against others as a means toward educational benefits," (Schwab, 1978, p.380). He and many others who have studied curriculum development describe this as complex, knowledge-intensive work. Yet, when teachers use the Internet and other technological resources, they may find themselves in the position of doing this work on their own, with little support from the tool itself or from outside the classroom. This places great demands on teachers' subject matter knowledge. Some technologies provide more support for the disciplinary context than others. For
example, Web sites like Journey North or Project Globe have extensive resources for teachers to help them place these activities in context. Tools like the units in WISE or One Sky Many Voices address particular topics in the curriculum and make well-developed connections to the discipline.

Although there is no best configuration for technology with respect to these affordances, having none of them is a recipe for chaos rather than deep learning. At the extreme, a lesson with no boundaries on topic or location of student work, with materials that may change before the hour ends, with no authoritative sources of information, no support for pedagogy, and no support for disciplinary coherence sounds like a free-for-all. And yet, that is a real possibility for some uses of the Internet, and perhaps other technologies as well. At the other extreme, prescriptive technologies, whether “drill and kill” software or programmed texts, provide little opportunity for meaningful science learning. What is needed with respect to these affordances is balance: enough support for teaching through one or more of these dimensions to make the teaching feasible, but not so much that learning is prescribed. Some technologies provide superb support for teaching by making student thinking visible, providing a record of student work, and at the same time, supporting inquiry-based, open-ended activities. Teachers who learn to look for and recognize these affordances in technologies they consider for classroom use will be better able to adapt technologies in ways that make them work for meaningful science learning.
2. What do teachers need to learn about what effective use looks like in practice?

The ideas above suggest some of the opportunities made possible by technology through representation, information, transformation, and collaboration, and some of the ways technology can support the work of teaching. However, none of these affordances can or will happen without the mediation of a knowledgeable teacher. In the end, use of technology in practice – not a list of affordances for teaching and learning – is what determines effectiveness. Technology alone does not teach – or, worse, if it teaches, what it teaches may not be what we want it to teach. Students certainly learn from television, from computer games, and from Internet browsing and chatting. But, in schools, we want students to learn particular kinds of things, and in some cases, specific things. This coordination of teacher intention and student learning requires teaching – the mediation and intervention of a knowledgeable other. Teachers teach, and they are an essential part of the sense-making process that must go on for students to learn science in meaningful ways. What do teachers do to teach effectively with technology? Effective teachers pay attention to six critical elements for teaching with technology: affordances, integration, content, appropriateness, effort, and time. Effective uses of technology can be recognized by the presence of these elements. This section details these elements that contribute to effective use of technology in classrooms.

a. AFFORDANCES. Effective uses of technology do things that are uniquely possible with, or enhanced by, technology.

Effective use of technology is not about doing the same things but making them look better by using technology. It is about taking advantage of what technology can do –
the four affordances for student learning outlined above. Effective teaching with
technology makes use of these affordances to do the impossible. For example, it is not
enough to have computers in use for word processing, surfing the net, or checking email.
Although these may be important functions that students need to be able to do with
computers, they do not necessarily advance the cause of teaching science for meaningful
learning. The first question that should be asked about any use of technology in a science
classroom is, what are students learning from or with this tool that is better learned with
the tool than without it? If the answer does not include a serious objective for learning
science, the use of technology should be called into question.

   b. INTEGRATION. Effective uses of technology do things that address
specific curricular needs – the uses are INTEGRAL, not PERIPHERAL.

   Integral uses of technology do things that are central to the curriculum and
include all students. Adding a research project on astronomy for the sole purpose of
letting students gain some experience with looking for images on the Web is peripheral.
Incorporating images from NASA into a unit investigating the properties of light – as in
the WISE unit "How far does light go?" – is integral for a teacher whose curriculum
includes light. Using a modeling or simulation tool to "play" with a model of a predator-
prey relationship as a reward for early completion of work is peripheral. Although it may
benefit the few students who get to do it (or it may not, depending on how it is used) it
could not be a fundamental part of the course or it would be used to engage all students.
On the other hand, having all students work on models of the local watershed using
ModelIt, as part of a unit on water quality, is an integral element of the curriculum.
c. CONTENT. Effective uses of technology focus on content, not on technology.

It is easy to get sidetracked by technology, in part because computers and networks are so unreliable and fragile. When computers crash or the network goes down, or one of the 15 computers has different settings than the others, or the software configuration is different on each computer, a teacher is practically required to deal with technology problems. Enough of these issues can send even the most dedicated and well-intentioned science teacher over the edge between teaching science and teaching technology. If students need help using the technology every minute, it does not take long for a teacher to either give up on the technology altogether and return to conventional tools, or give in to the need to be the technical support and deal with all the problems.

Another reason that teachers teach technology rather than subject matter is that the content can be so messy and hard to manage in technology-based activities. This has to do with affordances of the technology (e.g., the affordances for teaching and learning described above) and design of the activity, but it is a pitfall hard to avoid. For example, one affordance of technology is access to information. But, without extensive structuring of what information is used, how it is accessed, and what it is used for, an activity that lets students find and use information can be so hard to manage that a teacher may reasonably resort to helping students with technical issues rather than substantive ones. In this case, the teacher begins to teach how to refine searches, or what search engines to use, rather than trying to figure out how to help each student substantively with the content he encounters. These are perhaps important things for students to learn, but not if the goal of the class is to learn about the properties of light.
d. APPROPRIATENESS. Effective uses of technology are not necessarily high-tech – the tool matches the learning goal.

Technology can mean a lot of different things, but in educational settings, it is perhaps best thought of as tools and techniques for improving teaching and learning. The best technology for a given purpose may not be a computer or the Internet. It may be a graphing calculator, or a set of blocks, or a video. It may even be a blackboard and chalk. A good example of a relatively low-tech tool for teaching very complex ideas is JASPER. (Cognition and Technology Group at Vanderbilt CTGV, 1997) It consists of a set of videos (originally video disks, currently CD’s) that provide stories in which complex problems are embedded. The videos are professionally produced and give a real life setting, or anchor, for problems that could actually occur in the real world. The technology gives a representation of problems that would be hard to create in the classroom and it provides guidance for the teacher in the form of extension activities and suggestions for use. It also makes it functionally simple for teacher or student to "rewind" to a specific point in the video to find data or parameters needed for problem solving. The work of teaching and learning with JASPER, and the real determinant of its success, comes from what teacher and students do together to engage with the ideas and problems presented in the video, not from whether it is the latest in technology advances.

e. EFFORT. Effective uses of technology entail hard work and engagement by teacher and students.

Technology does not teach; teachers teach. More accurately, technology does not necessarily teach what we mean for it to teach. It has been shown time and time again that what students learn when left to their own devices with a technology – from
television to books to manipulatives to computers – is unpredictable, uneven, and often
erroneous (Ball, 1992; Erlwanger, 1973; Salomon, 1984). The work of the teacher is to
help students learn the important ideas that are afforded by the technology. The only way
to do this is through dialog, listening to what students say, watching what they do, giving
them opportunities to talk about their thinking, and giving them feedback. The teacher
nudges them in the right direction, helps them understand difficult concepts, and keeps
them focused on the relevant data and ideas.

What do teachers need to do to teach with technology? They need to engage with
students in making sense of the science they are working on. Although that sounds easy
and straightforward, in practice it is not so simple. When computers or other digital
technologies are involved, it is extremely complex and often both physically and
intellectually exhausting. Imagine 30 kids, 15 computers, an activity engaging students in
analyzing current weather data from the Web (for description of such a case, see Wallace,
2002). Students are learning to read weather maps, to understand major factors in weather
forecasting, and to make simple predictions. What happens in reality is that the teacher is
in constant motion, helping one student after another, answering the same question in 15
different ways, keeping track of who is confused and what they are confused about,
making mental notes of what needs to be explained or clarified to the whole class,
making decisions about what to do next for each student and for the class as a whole
(Lampert, 1995). Compare that to taking the whole class through a demonstration and
explanation of map reading and forecasting, with the teacher standing in front of the
room projecting a map on a screen or monitor, and talking. And compare that to letting
the kids use the maps on the Web, but with the teacher grading papers at her desk. All
three of these scenarios entail using the Web to teach weather, but their impact on both teacher and students is vastly different.

**f. TIME. Effective uses of technology take time.**

Alan Kay, one of the early innovators in educational technology, talks about "hard fun" and it is a notion worth repeating (Kay, 1998). Teachers and students have come to expect technology to be fun and even easy – if you can't figure out how to use a piece of software in a few minutes, it is too hard. This comes in part from experiences with the Internet – using a Web browser is so simple and can yield such interesting results that it has created a disincentive for doing hard work to use technology. But, in fact, some of the most beneficial technologies in science education are what Kay calls "hard fun." It takes a lot of initial effort, but the payoff is huge. Kay's example is the pipe organ, which could be seen as the interface from the devil. It takes a big investment of time and effort to learn to use it, but the results are stupendous, two hands and two feet controlling hundreds of remotely located pipes to play truly inspired music. In today's climate, the pipe organ might be rejected as not intuitive or easy enough. Similarly, tools like ModelIt, WISE, JASPER, and nearly every significant technology for science education require an investment of effort on the part of teacher and students to yield the meaningful learning the tools can support. Even searching the Web, although easy to do at a basic level, takes time, effort, and knowledge if it is to lead to meaningful learning (Wallace, Kupperman, Krajcik, & Soloway, 2000). In schools and classrooms where the time pressure is immense, it is difficult to use such tools effectively. If we expect teachers to make meaningful use of technology in science education, they need time, and they need to know that it takes time.
3. What do teachers need to learn in order to develop a portfolio of technologies for their own teaching?

Knowing what technology offers for teaching and learning and what effective use looks like in practice is not enough. Teachers still need to be able to translate that knowledge into actual uses of technology in their own classrooms. This means developing a portfolio of technologies that actually work in their unique contexts. What do teachers need to know to be able to collect this portfolio? At one level, they need to apply the knowledge outlined above to evaluate technologies that are available to them. This is easier said than done. For example, if a teacher has the Internet in his classroom, the number of possibilities can be overwhelming, making it hard even to begin a process of selecting and evaluating. At another level, teachers need some way to bring technologies into view – to decide what to consider for evaluation. Probably the best way to make these decisions is by relying on others – school district curriculum personnel or professional colleagues or publications that point to resources others have found useful. Another approach is to look for technologies that solve particular pedagogical problems (e.g., children’s ongoing misconceptions about heat and temperature) or fit into particular places in the curriculum. The main point is that teachers cannot know or evaluate every possible technology that might be useful, but they need to learn strategies for choosing and evaluating a few technologies until they develop a portfolio that infuses their teaching with appropriate tools. Evaluation strategies are not difficult – a starting point is the affordances described in this paper. What is hard is winnowing down the vast and complex array of things that might be considered and coming up with a few good ideas to evaluate and then adopt. One of the issues is that these decisions are inherently local. As
outlined above in the section on Lessons from the Classroom, what works for one teacher may be impossible for another. Thus, the work of finding feasible technologies may best be done in local, collaborative groups of teachers who teach in the same school or district, at the same grade level, and with similar access to and support for technology.

Once a teacher identifies a technology for her portfolio, she then has the opportunity to develop it through experience into a tool for meaningful science learning. The teacher learns how students respond to activities that use the technology, what activities are most effective, what strategies and routines are most beneficial, and a host of other complex knowledge about how the technology works in her classroom. This knowledge cannot be learned in general about technology: it is specific to a particular technology in a particular classroom. This is where, and when, the teacher really learns to teach with technology for meaningful science learning.

**Summary: What do teachers need to know?**

The argument above suggests that teachers need to know about how technology intersects with meaningful science teaching and learning, and they need a portfolio of technologies that can be used in such learning. On the face of it, it seems straightforward that if teachers know how to evaluate technology, know how to fit it into teaching and learning, and have access to a portfolio of technologies, effective use will follow. However, using technology effectively for meaningful science learning has proven to be hard at best, and more often elusive. Research suggests that although there is ample technology available to teachers and students, it is often used ineffectively or not used at all (Becker & Anderson, 1999; Cuban, Kirkpatrick, & Peck, 2001). Some have blamed this on teachers or administrators, attributing to them a weak commitment to innovation
or a kind of techno-phobia. Others have blamed it on teacher knowledge, arguing that teachers do not know enough about technology. These do not seem like adequate explanations. Teachers, administrators, and parents, along with policy makers and the general public, have expressed an unprecedented enthusiasm for the value of computers and networked technologies in schools (Schofield, Davidson, Stocks, & Futoran, 1997). And districts along with individual teachers have invested time and money in professional development for teaching with technology. So, what are the barriers to effective use?

One problem is the unreliability and fragility of technology. Until and unless teachers can count on technology to be usable, rationality dictates that they not depend on it. If they cannot depend on it, it cannot be an integral part of their work. A second problem is access. Even though the numbers have improved – the student to computer ratio in the United States is down to about 6:1 (National Center for Education Statistics, 2000) – there is much evidence that teachers cannot plan to use computers when they want to in the configurations that make the most sense. For example, they may have to sign up months in advance to get to use the lab, and then only have it for a few of days. Or, they may have two computers in their classroom to serve 30 students, with other computers in teacher workrooms and the library. Neither of these scenarios lends itself readily to the kinds of technology-based science activities that lead to meaningful student learning.

Another problem is the overwhelming amount of technology now available, with so many choices and so much information that the best technologies for education are buried. Free tools like some of those mentioned above, superb Web-based activities, and
important data sets are lost in the quagmire of advertising, propaganda, personal Web sites, and just plain junk on the Internet. Teachers may also receive advertising from commercial publishers selling stand-alone software or programs that supplement adopted textbooks. Teachers have limited time to find and evaluate technology, and trying out new things is always risky in classrooms. A final problem is professional development: although there has been a huge investment in professional development for teaching with technology, the focus may have been on the wrong kinds of knowledge. Learning to use productivity tools (electronic grade books or email, for example) may be important for some aspects of teaching, but such knowledge does not lead in any straightforward way to effective science teaching. Learning to use a great science tool that is not available is also ineffectual. Professional development needs to focus on the kinds of knowledge outlined above, including the final step of supporting teachers as they develop a suitable portfolio of technologies for meaningful science teaching and learning.

**Conclusions**

Teachers need a different kind of knowledge than the technology knowledge a banker or a lawyer or a computer programmer might need. They need knowledge that is directly related to teaching science in the classroom. This entails knowing what a technology can offer for student learning, and knowing how technology can support teaching. It also entails knowing specific technologies that fit into their classroom. To obtain the latter, they need time with their own colleagues, in local collaborations to figure out how to use specific technologies in ways that work in their classrooms and schools. Effective uses of technology are specific – there are few if any generic uses of technology that provide meaningful opportunities for students to learn. Teachers need
time to identify resources or technologies; to learn to use them and learn how they fit in the curriculum; to develop activities that lead to meaningful learning; to interact with students as they engage in meaningful learning; and to reflect on their teaching.

Unfortunately, in many schools, technology knowledge per se -- knowledge of hardware and infrastructure -- is still a big issue because the technology is so fragile and unreliable that teachers who want to use it must be able to fix it when it breaks. Until and unless technology becomes more reliable and better supported, many teachers will, and should, make the rational choice not to use it as an integral part of their teaching. Instead of expecting teachers to have technical knowledge of the sort that can restart a network or troubleshoot a disk crash, we should expect teachers to be developing meaningful uses of technologies for their curriculum.

In the end, what science teachers need is a repertoire of "learning technologies" -- each a combination of devices, software, and curriculum -- that they use in their teaching, in a setting where those technologies are stable, reliable, and well-supported. In the past, a teacher's repertoire has consisted of school-provided curricula, lab materials, and supplementary materials the teacher has collected. In the future, this repertoire should include technologies that fit learning goals by addressing ideas and topics specific to this classroom. Teachers cannot know everything, and they cannot be expected to evaluate every new device or program that comes along. What they can do is accumulate, over time, a portfolio of stable technologies that work, supplementing and replacing them through a rational, collaborative process, aided by district and state resources, for identifying and evaluating new resources.
1 STELLA is a product of High Performance Systems, Inc. Information is available at their Web site, http://www.hps-inc.com/

2 ModelIt is a product of hi-ce at the University of Michigan. Information is available at http://hi-ce.eecs.umich.edu/scienc/laboratory/modelit/

3 Information about StarLogo can be found at http://www.media.mit.edu/starlogo/

4 For examples and software, see the hi-ce Web site at http://www.handheld.hice-dev.org

5 Some examples of simulated dissections can be found at http://www.froguts.com and http://www.exploratorium.edu/learning_studio/cow_eye/

6 One NASA Web site particularly useful for science teaching is http://spaceflight.nasa.gov/

7 The Great Lakes Environmental Research Laboratory Web site is useful for finding data about the Great Lakes, http://www.glerl.noaa.gov/data

8 KidsNet was developed by TERC (http://www.terc.edu).

9 The Kids as Global Scientists is part of the One Sky Many Voices project, http://www.onesky.umich.edu/site/projects/projects.html

10 The GLOBE Web site is http://archive.globe.gov/

11 Journey North can be found at http://www.learner.org/jnorth

12 The Jason Project Web site is http://www.jasonproject.org/

13 WISE activities are available at http://wise.berkeley.edu/

14 The AMS Web site for educators is http://www.ametsoc.org/dstreme/
References


