

1

Founding Vision of Network Science:

The 1980s was a heady decade for the development of technology. The decade began with the word *computer* assuming a whole new meaning. Until then, a computer was a large and expensive machine designed for computation and organization of data—a machine that needed to be programmed by highly trained experts. These units would be called *mainframes* today. However, the invention of the Apple II computer in 1977 and the IBM PC in 1981 effectively redefined the word. These new machines, initially called *desktop computers*, were then available relatively inexpensively to individuals. In short order, word processing replaced typing and spreadsheets became an indispensable tool for budgeting and accounting. The development of the modem and computer networks allowed information to be exchanged via telecommunications, and e-mail grew rapidly in popularity among the university community and later among businesses and individuals.

Some pioneering educators began exploring how these new technologies could improve teaching and learning. Network science—an innovative model of curriculum designed to foster inquiry-based teaching and learning—was one of the early applications of telecommunications technologies to education. The first section of this chapter reviews the development of network science, focusing on the ideas that shaped the model. Because much of this development was done at TERC, a research and development (R&D) organization in Cambridge, Massachusetts, the work of TERC figures

prominently. TERC's efforts were not done in isolation, but reflected ideas unfolding at the same time in other parts of the country. The second section of the chapter traces these ideas—the roots of network science: science educators' belief that science is best taught through inquiry, the Science-Technology-Society movement, contemporary ideas about technology in education, and the newly emerging push toward school reform. In the third and final section, we offer an assessment of the founding vision of network science. Through our research, we have learned that some difficulties, which are typical of current network science practice in classrooms, stem from shortcomings in the original vision. We describe these shortcomings and make recommendations about how to remedy them. In subsequent chapters, we elaborate on these recommendations.

THE FOUNDING VISION

Network science began with the simple idea of creating communication links among classrooms to share e-mail and data. Proposed as KIDNET and later renamed National Geographic Kids Network, the idea was developed through a collaboration of TERC and the National Geographic Society. Funded in 1986 by the National Science Foundation, NGS Kids Network made use of multiple new technologies—desktop computers, graphical user interfaces, modems, and computer networks—to enable the rapid exchange of messages between distant sites via telecommunications.

By 1986, the use of an electronic network to support writing in classrooms had already been pioneered in the QUILL project, Computer Chronicles News Network and InterCultural Learning Network, and FrEdMail. By giving students the ability to exchange text messages, these projects fostered collaboration among distant schools. Network science projects sought to go further than these pioneering electronic networks, giving students the ability to exchange data they had collected, thereby opening up the possibilities for cross-classroom collaborations to include shared data-rich inquiries. Some educators believed that, once these impressive new technologies were fully developed and in place, they would at last have the tools needed to make far-ranging improvements in science teaching and learning. Through network science curricula, they aimed to revitalize science teaching and learning from elementary school to the end of high school.

The group at TERC that developed Kids Network—Robert Tinker, Cecilia Lenk, and Candace Julyan, among others—documented their early ideas in a proposal submitted to the National Science Foundation in 1986 (TERC, 1986) and in articles published frequently over the next few years.¹ From their writings, we can construct the set of ideas that motivated NGS Kids Network. These ideas were developed further in subsequent network science efforts at TERC—most notably, the Star Schools project, Global Lab, Alice/Collaborative Inquiry Testbed, Testbed for Telecollaboration, and Kids Network: Leveraging Learning. Groups in other parts of the country were influenced by and, in turn, contributed to the development of these ideas, including the Beacon Project (Maine State Systemic Initiative), Classroom BirdWatch (Cornell Lab of Ornithology), Community Science Connection (Arnold Arboretum, Boston), EnergyNet (Illinois), EstuaryNet (Wells Estuarine Reserve, Maine), Global Thinking Project (Georgia State University), and the Nebraska Department of Education (Wetlands and Amphibians as Bioindicators curricula, jointly sponsored with the U.S. Environmental Protection Agency).

We refer to these ideas collectively as the *founding vision of network science*. Clearly, there was some evolution of the ideas over the last decade, but key ideas that have emerged across all the projects were firmly rooted in the early work of the group at TERC. Descriptions of these ideas follow (see Table 1.1 for summary).

Fundamentally, network science aimed to expand the classroom to a community of classrooms linked through telecommunications. This linking of classrooms had important implications for teaching and learning.

Telecommunications expands the boundaries of the classroom, bringing together people with different perspectives, promoting collaboration. Students can explore relevant problems . . . from geographically dispersed classes. For teachers, telecommunications can be an important way to decrease isolation and build support with other educators. (Lenk, 1989, p. 1)

For many network science curricula, this community of classrooms aspired to become a global community—one including students and teachers from all continents. The word *global* became a part of the names of many network science projects. A Pilot

TABLE 1.1
THEMES OF NETWORK SCIENCE PROJECTS

Investigation of “real science” problems

- Students focus on real and compelling problems that are relevant to their lives.

Students-as-scientists

- Students investigate problems not yet studied by scientists.
- Students learn scientific processes: framing investigable questions, conducting experiments, analyzing data, sharing results, etc.
- Student work is taken seriously by the scientific community because scientists have an investment in the outcomes.
- Students work within a cross-classroom community of practice.

The role of data is critical

- Investigations require substantial data and the efforts of many investigators.
- Students learn to frame empirical questions related to these problems and answer them with the data.

Constructivist learning

- Pedagogy represents a departure from traditional vocabulary-based, transmission model of teaching.
- Students learn by constructing their own understandings.

Societal implications of science (Science-Technology-Society)

- Students need to be discerning about the ways in which science and society interact.
- Students advocate actions on the basis of what they have learned.

Global learning community

- Students learn about different cultures and different environments through telecommunications and collaboration with peers.

Pedagogical change

- Because the answers are not already known, the teacher must give up the role as the content expert with answers and serve instead as the expert on how-to-know.
- The teacher facilitates student investigations, acting more as coach than stage director.

TABLE 1.1 (continued)

Collaborative/cooperative learning

- Investigations inculcate the idea that science is a cooperative venture and emulate communities of practice in which scientists work.
- Collaborations in-class and online give students experience with collaborative work.

The affordances of the technologies are critical

- They promote collaboration and data sharing.
- They provide access to up-to-date information.
- They expand the boundaries of the classroom and decrease isolation.

Network for Global Education was first proposed by TERC in 1989, which became the Global Lab Curriculum.

Students, through network science curricula, would investigate relevant problems chosen by curriculum developers, project organizers, or students and their teachers. These problems would be authentic—that is, real problems, not yet solved by scientists, that students could study by analyzing data collected from dozens or even hundreds of classrooms. Their data would have scientific significance that data collected by one classroom, in one geographic area, could not have. For example, in the NGS Kids Network Acid Rain unit (1990, 1997), students collect data about acid rain in their own communities, submit these data to the central database, and retrieve the full set of data collected by hundreds of schools. When examined by students, the full set of data may reveal patterns of acidity in rainfall that no individual class is able to discover by itself based on its own data. Over time, the grid of student measurements would have the potential to be much more finely grained than anything available to scientists, and this would become a potential resource for scientists to use.

Students were able to become scientific colleagues and collaborators; they were expected to submit data and make interpretations of the data, elaborate on the ideas of other students, offer critiques or challenges to these ideas, and question the meaning of terms. This approach was developed most intensively in the Global Lab Curriculum—an environmental science program designed to build research skills of students in Grades 8 to 10.

During the field testing of Global Lab, discussion forums (“Global Lab Voices”) were set up for students and teachers to participate as colleagues across classrooms. Reflecting this new role, the original research of students and teachers was published in their own magazine, *The Planet: The Journal of the Global Laboratory Community*.

Network science also encouraged students and teachers to act on “the social implications of the scientific results” (TERC, 1986, p. B-2). The NGS Kids Network Acid Rain unit culminates with students looking for causes of acid rain in the pattern of industrial pollution and deciding what actions might be taken to decrease the acidity of rain and make rivers and lakes more habitable for fish and plants.

Network science advocates saw in new technologies a key to realizing this vision of authentic, inquiry-based science learning. Modem-based telecommunications opened up the potential for cross-classroom collaborations. Also important was creation of software that would support students and teachers in analyzing data. Inexpensive data analysis software was not available to schools, and what was available (spreadsheets) was limited in its functions and not appropriate for the kinds of inquiries being organized. The *Alice Network Software* (the prototype for *NGS Works*, 1997) was designed to give classrooms access to an inexpensive cross-platform software package—“an integrated suite of tools for word processing, graphing, mapping, and telecommunications” (Feldman & McWilliams, 1995), to support cross-classroom collaboration. With this software, students could exchange messages, create shared sets of data, and analyze these data (including graphing and display of data on simple maps). To work hand in hand with the *Alice* software, network science developers created server-based, automated, data-sharing software to handle the processes of data submission, consolidation, and retrieval.

The technical progress over this decade has been notable. In 1986, the Acid Rain pilot test utilized a scientist at the hub of network activity. This expert read and responded to e-mail, received data from individual classes, and sent out a consolidated set of data. Many TERC-supported projects in the early 1990s used the *Alice Network Software*, which adapted e-mail messages for purposes of data exchange. The system was cumbersome, however, and left students and teachers waiting to know whether their data submission

had been successfully added to the consolidated data set. By late 1994, TERC began moving these projects to the emerging World Wide Web where there was potential for immediate feedback from the server and therefore better interaction by participants. TERC designed and built server functionality specifically to serve network science projects. This new web technology greatly simplified the submission of data, and students could submit data and then immediately view the data set consolidated from the data of multiple classes, including their own data. Students could also view and retrieve selected data subsets. In addition, the server enabled web-based discussions, which were designed to support teachers and students in solving technical or curriculum problems and to encourage an exchange of ideas about project-related content. These discussion groups served to give project staff greater interaction with participants and participants easier communication with one another. Finally, the server was a shared resource for all classes, giving up-to-date information on events and key dates as well as providing a library of shared documents and links to related resources.

The founding vision of network science was a bold one. Perhaps the most striking aspect of the vision, viewed from our vantage point a decade later, is not the global community of classrooms or the emphasis on relevant problems, but the role assigned to students in this curriculum model. No longer just learners, students were assigned the role of student as scientist. In the original proposal for Kids Network (TERC, 1986), the approach was referred to as a departure from both text-based instruction and contemporary thinking about inquiry learning:

Student-as-scientist is even more motivating than guided-inquiry instruction. The answer for most inquiry investigations is known. . . . KIDNET experiments, by contrast, have been chosen so that the answers are not known. (p. II-1)

Julyan (1991), former project director at TERC for Kids Network, wrote about her experience with network science, similarly emphasizing communications among classrooms and with scientists:

The basic premise behind these curricula is that students can and should be scientists, that they can and should converse with real scientists about their work, and that computers can enhance this enterprise. Students conduct experiments, analyze data, and share results with

their colleagues using a computer-based telecommunications network. This collecting and making sense of data gives students the opportunity to experience the excitement of science that scientists feel. (p. 5)

Later still, Feldman and Nyland (1994) represented the vision of student as scientist this way:

While collaborators may be geographically remote, they are tied together by a common problem or agenda. They may all be investigating the effects of ozone through a single approach (use of Global Lab's Total Column Ozonometer); or sites may be designing related experiments and requesting data from each other. The work of students in one classroom is fit into a larger effort of others, mirroring how scientists work. (p. 2)

In this model, the problems selected are real and engaging—ones for which scientists have yet to develop solutions. The curriculum aims to “connect elementary science with the real world outside the school,” and content is “clearly related to real-life science issues” (TERC, 1986, p. A-7). Moreover, student work is taken seriously because the scientific community has an investment in its outcomes.

ROOTS OF NETWORK SCIENCE

The original vision of network science, developed in the 1980s, was shaped by the availability of new technologies—principally the advent of inexpensive desktop computers and networked environments. The network science vision, however, also has roots in inquiry-based teaching and learning; the Science-Technology-Society movement, which was prominent in the 1980s; national reports urging a reform of U.S. education; and the new directions in researchers' thinking about the role of technology in learning and teaching (see Table 1.2). In this section, we summarize the influence of these intellectual threads on network science.

TABLE 1.2
ROOTS OF NETWORK SCIENCE MODEL

- Inquiry-based teaching and learning
- Science-Technology-Society movement
- National reports urging a reform of U.S. education
- New thinking about the role of technology in learning and teaching

Inquiry-Based Teaching and Learning

The influence of the inquiry model of teaching and learning on network science is seen clearly in the original Kids Network goals. The first three of the goals stated:

- Let children do science through exploration, discovery, and testing.
- Make science challenging with age-appropriate activities that involve children in projects based in the world outside the classroom.
- Help children develop a flexible, problem-solving attitude toward experience. (TERC, 1986, p. A-1)

These goals represent a rejection of traditional vocabulary-based transmission pedagogies. The vision of network science builds on the understanding (developed most notably by Jean Piaget, Jerome Bruner, and, more recently, Seymour Papert) that students learn through constructing their own knowledge. The goals also acknowledge the importance that Dewey (1910, 1929, 1938) placed on problem solving and reflective inquiry as mechanisms of learning. In the spirit of the project method of the Progressive Movement, these goals also recognized that students should be solving problems of genuine interest and relevance to them, using concrete materials “in a purposeful activity in a natural setting” (Kilpatrick, 1918).

Network science is also indebted to the innovative science curriculum reforms of the late 1950s and 1960s.² Like the reforms of the progressives before them, these projects aimed to exploit students’ natural interests and curiosity. The goals of these projects were to model scientific inquiry and develop problem-solving skills. These projects emphasized hands-on activities and open-ended questioning as a means to develop the process of discovery learning—that is, observing, questioning, comparing, collecting data, and building theories.

Network science modified the practice of inquiry in the classroom by adding the new goal of student as scientist, which had one clearly differentiating quality:

The answer for most inquiry investigations is known, and learning happens when students “puzzle out” the answer. KIDNET experiments, by contrast, have been chosen so that the answers are not known. (TERC, 1986, p. A-1)

In network science, students would be investigating areas that scientists are still exploring.

Science-Technology-Society Movement

Another influence on the network science vision of school science was the Science-Technology-Society (STS) movement, which was a major force within science education in the 1980s. Within the STS framework,

Science education is defined, then, as the discipline concerned with the study of the interaction of science and society, i.e., the study of the impact of science upon society as well as the impact of society upon science. Their interdependence becomes a reality and the interlocking concept for the discipline. (Yager, 1984; cited in Bybee, 1987, p. 668)

In this view, exemplary science programs should focus on social problems and issues and emphasize student decision making, local and community relevance, and cooperative work on real problems (Yager, 1984).

These ideas are reflected in many network science projects. A focus on environmental problems is common; it provides a context for students to do research about their own communities using the immediate environment as the laboratory. Students investigate real problems that affect their own communities and the planet, and can submit recommendations to policymakers. In this way, students learn to understand their role as stewards of the environment and its natural resources.

National Reports Urging a Reform of U.S. Education

In the early 1980s, the National Commission on Excellence in Education (1983) told Americans,

Our Nation is at risk. Our once unchallenged preeminence in commerce, industry, science, and technological innovation is being overtaken by competitors throughout the world . . . the educational foundations of our society are presently being eroded by a rising tide of mediocrity. . . . If an unfriendly foreign power had attempted to impose on America the mediocre educational performance that exists today, we might well have viewed it as an act of war . . . unthinking, unilateral educational disarmament. (p. 1)

The political hegemony that the U.S. wielded in the post-World War II era had eroded, and Americans began to see themselves as vulnerable to economic competition.

With this report, the nation embarked on a series of efforts to examine and resolve the perceived weaknesses of the educational system. The dire prognosis of U.S. education and the need to make fundamental changes helped set the stage for the development of network science as a new curriculum model. In addition, two early themes of the school reform movement prepared the way for network science. First, the school reform movement called for the use of just-emerging computer technology throughout the curriculum (although how was left altogether vague). Second, the movement advocated not only the use of new curriculum materials but also new approaches to learning. Network science curricula clearly responded to both these themes.

New Thinking About the Role of Technology in Learning and Teaching

Network science was developed in the context of a changing understanding of the role technology would play in school teaching and learning.

Many early educational uses of computers involved computer-assisted instruction (CAI). The model of learning was fundamentally a behaviorist one, relying on predetermined sequencing and repetition for learning. During the late 1980s, many school districts made significant investments in a variant of CAI, often called *interactive learning systems*. Subsequent research studies on this use of technology found little value compared with traditional modes of instruction (Collins, 1996). Drill-and-practice software is a contemporary descendant of this genre of educational technology and makes use of the same basic ideas about student learning.

Koschmann (1996) looked at the history of educational technology over the last two decades and subdivided the innovations into two distinct paradigms. The first, which he called *Logo-as-Latin*, marks an important break with the earlier theories of *what* and *how* students should learn, and it builds on a constructivist set of understandings. Rather than computers teaching a set body of knowledge to students, Papert created the *Logo* language (1980) to enable students to control the computer through mastering a

simple programming interface. A similar emphasis on students' learning through their own actions characterizes microcomputer-based laboratories, games such as *Logical Journey of the Zoombinis* (Broderbund, 1996), and simulations such as *SimCity* (Maxis, 1994) and its successors.

The second paradigm, Computer-Supported Collaborative Learning (CSCL), builds on the constructivism of the first paradigm and adds a focus on the social context of learning. In this paradigm, students are viewed as members of communities with common goals, and technology supports the work of the community. Early work in this genre would include e-mail exchanges such as QUILL (Bruce & Rubin, 1993), Computer Chronicles News Network and InterCultural Learning Network (Mehan, 1985, 1989; Riel, 1985), and FrEdMail (Levin, Rogers, Waugh, & Smith, 1989). The development of the Internet has allowed for the development of much more advanced CSCL environments than these earlier programs. Besides network science projects, more recent examples of CSCL environments include multiuser virtual environments (MUSEs and MUDs; e.g., MicroMUSE at GTE/BBN), CSILE (Scardamalia & Bereiter, 1996), as well as network science curricula.

There is significant overlap between many of the qualities of these two paradigms. Collins (1996) used the term *interactive learning environment* to encompass both of them, and he listed the following capabilities of such environments (1996): realistic situations, simulation, animation (i.e., ability to see processes that are otherwise not observable), expert advice (presented just when the learner needs it), video, diverse knowledge sources, multiple representations, testing hypotheses through modeling, scaffolding, and reflection. These capabilities enable interactive learning environments to "support learning in ways that schools [elsewhere: human teachers] cannot easily provide" (see Table 1.3).

Because these learning environments support a constructivist and collaborative approach toward learning and teaching, it is not surprising that many of these elements are evident in the network science projects. Of the elements of these learning environments, network science projects typically make use of realistic situations, expert advice, diverse knowledge sources, multiple representations, testing hypotheses through modeling, scaffolding, and reflection. These elements are seen in the case studies presented in chapter 2.

TABLE 1.3
CAPABILITIES OF INTERACTIVE LEARNING ENVIRONMENTS

- Realistic situations *
- Simulation
- Animation
- Expert advice (presented just when the learner needs it) *
- Video
- Diverse knowledge sources *
- Multiple representations *
- Testing hypotheses through modeling *
- Scaffolding *
- Reflection *

* indicates elements typical of network science projects

Note: Adapted from Collins, 1996.

ASSESSING NETWORK SCIENCE

As bold and inspiring as the founding vision was, the shortcomings of this vision have become more and more evident. As difficulties in network science projects were identified, project organizers and researchers initially attributed them to inadequate technology or teachers' and students' lack of understanding of the technology. Even after technological problems were ameliorated, however, many of these difficulties persisted. Therefore, with the benefit of hindsight—and a decade of experience—we have come to understand that some of these difficulties stem from weaknesses in the original vision.

Several sources highlight these issues. Based on the work of the Alice/Collaborative Inquiry Testbed at TERC with its partner projects, Feldman and Nyland (1994) reported problems that were apparent across a number of network science curricula. This study represented a broad look across programs; a second study (Karlán, Huberman, & Middlebrooks, 1997) provided a detailed account of the use of one curriculum, NGS Kids Network, in 11 classrooms at seven schools over 9 months.

Many of the issues outlined by these research studies were echoed by project organizers, curriculum writers, and teachers at the Network Science Conference (which the Testbed staff convened in November 1997) and in the evaluator's report on the work of Testbed for Telecollaboration (Goodman Research Group, 1998).³ They were additionally substantiated by the authors' observations in classrooms and informal conversations with teachers participating in a number of network science curricula. In the last year, outside evaluations of network science curricula have become available and point to some of these same issues (e.g., SRI's evaluation of Global Lab Curriculum—Young, Haertel, Ringstaff, & Means, 1998).

The more we know, the more we are enlightened by the subtleties affecting the effective use of technology in support of inquiry-based teaching and learning. The development of productive models for educational technologies demands that we learn from our initial attempts and look carefully at the complex realities of supporting students and teachers in the hard work of learning.

In the remaining section of this chapter, we point to four aspects of the network science vision that have proved difficult in practice over the last decade. These problems include:

- Supporting teachers
- Identifying the community of learners
- Making data meaningful
- Engaging students in productive inquiry

Our discussion includes recommendations as to how to approach each of these problems. We elaborate on these recommendations in subsequent chapters.

Supporting Teachers

Although the network science vision attempted to build on the work of an earlier generation of educators advocating guided inquiry, its proponents did not adopt all of the ideas put forth. Most significantly, the role of the teacher was not given much consideration in the founding vision of network science. Curriculum materials often assumed an unrealistically high level of pedagogical experience and knowledge on the part of teachers, and they offered inadequate support for teachers who were just starting to use network science curricula.

It is only the teacher who can set the stage in the classroom for students to engage the ideas of others and thereby fosters the kind of thoughtful, reflective discussion that characterizes learning; through questioning, the teacher helps students develop their own understandings further. The experience of network science projects points to this crucial role that the teacher must play in supporting student inquiry and the importance of greater support for teachers. Network science projects have only recently begun to give the required attention to these new roles for teachers. By contrast, developers of an earlier generation of guided inquiry curricula elaborated the crucial role of the teacher from the start. Their role was described extensively by Elementary Science Study developers Jerome Bruner (1962, 1971) and David Hawkins (1965a, 1965b, 1974).

In chapter 4, we discuss the problem of providing better support for teachers in the context of providing support for reflective discourse.

Identifying the Community of Learners

Having the technological capability for widespread telecollaboration is not enough to ensure that it will happen. Just because a class can share resources and expertise with other classes does not mean that cross-classroom collaborations will develop and that the databases constructed will be used for question generating, analysis, and interpretation. In fact, participants in network science projects typically do not achieve a high level of cross-classroom collaboration.

We believe that the problem lies in the relative emphasis placed on telecollaboration in contrast to the natural community of learners based in the classroom. Network science holds out the promise that a learning community can be constructed online—as the virtual community formed by all the classes working together—and that this community will have greater potential to encourage learning than the classroom. We now believe that it is critical to identify the classroom as the primary community of learners in which the dialogue among students takes place. In this setting, students have the ongoing day-to-day and face-to-face interaction with peers and a teacher through which the norms and skills of inquiry can be learned and continually supported.

We believe there is a powerful role for the virtual community: It is best utilized as a way to enrich the primary, classroom-based community—that is, to provide new and contrasting contexts in which to understand experiences. These ideas are pursued in greater depth in chapter 4.

Making Data Meaningful

Network science focuses on the use of student-collected data to study topics that are considered relevant to students' lives. However, the data collected are often too complex for students to comprehend. Because these data tend to be cumbersome, abstract, noisy, or inaccurate, the data sets are difficult for students and teachers—even experts—to analyze. As a consequence, when classes successfully collect the required data, we see little use of the data for analysis and few contributions to online discussions about the data.

Data sets need to be simple in design, and the purpose of cross-classroom sharing and consolidation must be clearer than it has been in many network science curricula. Archival data sets should be used to supplement data collected by students. (These archival sets can be based on data collected by students in previous years, but they must be cleaned up before distribution.) Most of all, teachers and students need support in learning that data analysis is more than generating graphs. At its heart, data analysis is a process of creating hypotheses and using data to test or reformulate hypotheses, creating and structuring data that test these hypotheses, searching the data for insights, and making and critiquing arguments based on the data. Network science projects have not yet incorporated this perspective on data analysis and thus fall short of their goal of students analyzing data. These ideas are elaborated on in chapter 5.

Engaging Students in Productive Inquiry

Many network science projects have not lived up to their potential to involve students in productive inquiry. First, the network science model of curriculum typically constrains classrooms by imposing rigid schedules for data submission and exchanges. The low level of completion for many network science projects—which, according to Karlan et al. (1997) was less than 50% of classes in

one project submitting data—may reflect teachers' inability to fit the real lives of their classrooms, punctuated by school events and holidays and snowstorms, into the schedule demands of many network science projects.

The consequence of a rigid schedule, however, is even more significant than a low level of completion. Karlan et al. (1997) pointed out that the data-sharing model in use by NGS Kids Network, shaped by the goal of collecting and exchanging data across large numbers of classrooms, is not consistent with often-stated characteristics of inquiry practices. The program requires a single pace of activities for participation. For many classes, this required pace allows little time for students to reflect, revise their work or personal theories, and probe other students' thinking, or for classes to explore divergent but relevant inquiries. This finding about NGS Kids Network is typical of other network science curricula.

Aiming to coordinate work among classes, many network science projects are constrained by centralized schedules. To refocus science learning on inquiry, teachers and students need flexible schedules to allow questions to be pursued in greater depth. Without such flexibility, the potential of the curriculum to support student inquiry is greatly diminished.

(Karlan et al.'s study of the strengths and weaknesses of this curriculum inspired the current revision of the NGS Kids Network curriculum. This evolution of NGS Kids Network curricula is the basis of a case study outlined in chap. 2.)

Second, network science encourages the use of real scientific and social problems to spark learning, focusing on the importance of investigating questions for which the answer is not known. However, this emphasis on questions for which the answer is not known and the questions (and data) are of genuine interest to scientists excludes the possibility of students investigating concepts that may be well known to scientists but no longer of interest to them. Because such concepts are still unknown to students and potentially of great interest, they offer a scientific excursion through which students can reliably have successful and powerful learning experiences. For example, students might investigate phenomena as simple as why some objects float—a topic that is unlikely to be of any interest to scientists.

Linn (1995), participating in an informal review of network science curricula, described this problem from a cognitive perspective:

If . . . we focus too much on problems of concern primarily to research scientists we run the risk of teaching students concepts and principles that they lack opportunity to practice and are therefore prone to forget.

Julyan (1988) experienced the difficulty in creating activities under such constraints when she was directing the development of NGS Kids Network:

While a number of activities make terrific inquiry-type classroom experiments, a large percentage of those activities are not suitable for a national network of classrooms or are not of use to scientists. The challenge in our curriculum is to find the delicate balance of educationally significant experiments that will be successful in both a classroom and a national network and that are of interest to the scientific community. (p. 6)

Looking across some of the projects inspired by the network science vision, we fear that the balance has been struck on the side of real science to the detriment of “terrific inquiry-type” experiences for students.

Finally, the challenge of engaging students in productive inquiry is complicated by the thinking encouraged in the shorthand metaphor of student as scientist. The phrase has power and utility in emphasizing the constructivist perspective that students should not be treated as the proverbial empty vessels to be filled, but rather as curious beings interested in the ways the world works, able to learn from one another, and capable of helping to shape their own learning.

However, this metaphor falls short of capturing the complex reality. It does not take into account the stages by which students grow into the complex intellectual and social roles of a scientist. The metaphor of student as scientist has encouraged network science projects to overlook some crucial questions of students’ developmental levels (e.g., what behaviors of scientists can students productively model at each level as they grow in their intellectual understanding of science concepts and in their ability to assume social roles?).

The National Science Teachers Association has dealt with this issue in its various standards publications. For example:

Although all students have the capacity to inquire, that capacity changes and becomes more sophisticated as students mature and gain

experience. Younger adolescents explore questions with trial-and-error experiences and experiments, and they are introduced to testing by learning about variables and establishing controls. As adolescents develop cognitively, they become capable of using more formal thinking skills, such as the manipulation of several variables and using abstract thinking. (National Science Teachers Association, 1998, p. 7)

For example, 10-year-olds are immensely curious and eager to talk about how they see the world—qualities that might be labeled as those of a scientist. Unlike scientists, however, they have little experience with the concept of *acid* beyond (at best) some familiarity with the word. Any curriculum that concerns acids would need to present at length the experiences from which some aspects of the concept of acid might be developed, such as the interaction of acids and metals or acids and living systems. However, the curriculum would not be able to present the underlying chemical structures of acids for which the 10-year-old is not at all prepared. Furthermore, despite the readiness of 10-year-olds to learn to respect evidence and struggle with fair testing, they still lack the ability to define a hypothesis or control variables in an experiment by themselves. These skills require careful structuring of curriculum and support from the teacher (see, for example, Driver, Guesne, & Tiberghien, 1985).

The documents that capture the founding vision of network science provide scant reference to developmental issues in students' learning. The vision draws deeply on the constructivism inherent in thinkers like Piaget, but gives much less attention to Piaget's equally compelling evidence for developmental learning stages. Network science projects have sometimes struggled to identify content appropriate to students at a given level, and too often have chosen content and modes of learning that are overly sophisticated for these students. As a result, too much reinterpretation of the curriculum has been left to the teacher.

The lessons learned by network science projects over the last decade, described in chapter 3, define the role of technology in engaging students in productive inquiry.

Technology has inspired for many the compelling idea of students transcending the limits of their classrooms and schools. The ear-

liest version was that teaching machines (CAI) would replace teachers. A more recent version, part of the founding vision of network science, was that communities and resources on the Internet would create entirely new learning contexts.

The example of network science urges greater caution. Too often the developers of network science have relied on technological answers to the design problems that arose. Moving from undifferentiated e-mail to web-based threaded discussions was one such change, and creating better tools for data analysis was another. However, the technology was not able to solve the problems of how to give teachers the skills and time needed to participate productively in online discussions or how to support teachers and students in learning the requisite skills to make use of the improved data tools. Technology will no doubt have a role in solving these problems, but the role will be only as one component of a broad-based plan for improving teaching and learning. No curriculum can effect meaningful change without the presence of a broader context to support these changes. This statement is especially true with programs like network science curricula where teachers are widely dispersed and therefore not able to benefit from ongoing, face-to-face support.

The importance of a strong local context for implementing substantial educational change is made by Young et al. (1998):

However, as yet, technology does not provide the same intensity as having a mentor come to one's classroom, discuss the learning objectives and approach for a lesson, observe the lesson, and provide critical feedback on what went well and what could be improved. Although one could imagine a way of using technology to accomplish this . . . such communities are very difficult to build and sustain. . . . (p. 95)

The experience of other technology-rich educational innovations is instructive. Fitzpatrick (1997) summarized the experience to date of researchers looking at the integration of the geographic information systems (GIS) software into classrooms.

However, our experience shows that there are two characteristics that, far above all else, predict a teacher's ability to use the tool effectively: the teacher's willingness to engage in his/her own unpredictable exploration and the willingness to allow students this same opportunity. Far more influential than even the presence or absence of

powerful hardware, the teacher's modeling of "a lifelong learner and thinking explorer" predicts whether certain students will get the chance to use GIS. Thousands upon thousands of children are in schools that are technologically rich but explorationally poor, while some fortunate scores of their brethren, even in sites with just one computer, are encouraged to be thinking explorers, following the model of their teacher . . . sometimes even ahead of their teacher in exploring new territory. (p. 33)

Technology has a vital role of supporting inquiry-based teaching and learning. However, our experience with network science curricula over the last decade points to the importance of technology being carefully and thoughtfully implemented within a broader context that supports these same changes, including revised curricular goals for students and significantly greater opportunities for teacher professional development. Technology, after all, is only one component in fostering a "teacher's willingness to engage in his/her own unpredictable exploration and the willingness to allow students this same opportunity."