

Collaboratories

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Introduction

Science is an inherently collaborative enterprise. This trend has accelerated over the past few decades. The Internet, in particular, has created new possibilities for the organization of joint scientific work, specifically among geographically separated collaborators. A notable instance of Internet-mediated science is the collaboratory, or laboratory without walls, in which scientists are connected to each other, to instruments, and to data, independent of time and location. This chapter explores past and current laboratory efforts to identify factors that predict success and failure. The chapter concludes with an assessment of directions for future collaboratory development.

Historically, joint intellectual activity has depended on physical proximity. For example, the probability of person-to-person communication under traditional circumstances is strongly constrained by distance; diminishing to zero beyond thirty meters (Allen, 1977; Kraut, Egido, & Galegher, 1990). In terms of a particularly important kind of group intellectual activity, scientific collaboration, proximity has a direct effect on the quality and frequency of collaboration (Katz, 1994). Further, convenient access to scarce instruments provides an additional imperative for co-location in science (Hagstrom, 1965). In the high

energy physics community, for instance, research activity is confined to a handful of labs worldwide (Traweek, 1992). Other scientific communities face similar limitations. The conventional response to these limitations has historically been residency, either permanent or temporary, at an instrument site. Therefore, in terms of the performance of joint intellectual work, sharing a common work setting has evolved as a critical tool to support both frequent interaction among collaborators and the use of unique facilities.

Despite the benefits of co-location, there are important individual and collective costs. Individual costs involve lost productivity associated with dislocation from a familiar environment, as when a scientist travels to a remote facility. On a collective scale, co-location inevitably involves exclusion and isolation from those who are located elsewhere. Some mechanisms, such as conferences and workshops, can attenuate this effect. For the most part, however, a shared physical space comes to define a shared intellectual space in which collaboration with those nearby is much more likely than with those who are distant, even after controlling for disciplinary differences (Kraut et al., 1990). Focusing on science, there are additional collective costs of co-location. Specifically, to the extent that co-location plays into competitive rivalries among research sites, cooperation may be undermined. For example, lack of cooperation can lead to redundant capacity, such as supporting several independent and underutilized instruments, rather than a single shared and fully utilized instrument. More important, barriers to interaction across sites may slow the integration of knowledge required to resolve research questions that exceed the capacity of single sites, or even single disciplines. The global AIDS epidemic, for example, is often cited as the kind of large research problem that requires unprecedented levels of cooperation from communities that have, in the past, worked independently (e.g., clinicians, bench scientists, activists, and policy makers).

Trends in the Organization of Scientific Work

The greatest transformation in the organization of scientific work has been the increased orientation toward large-scale projects, or “big science” (Weinberg, 1961). As noted in Price’s (1963) landmark analysis,

greater size and complexity of research tasks are reflected in a higher need for collaboration, at least when measured as the number of authors on publications. This trend toward collaboration is increasing and appears to be independent of discipline, as shown in recent analyses of authorship in biology (Zhang, 1997), information science (Lipetz, 1999), social science (Endersby, 1996), and political science (Fisher, Cobane, Vander Ven, & Cullen, 1998). Collaboration in science has become so well accepted that in 1997, the then chair of the National Science Board, Richard Zare, wrote in a *Science* editorial that future research progress would demand mechanisms to support mega-collaborations of the type required to solve critical global problems such as AIDS (Zare, 1997). In Zare's formulation, research activity would be organized as a form of "distributed intelligence" in which experience and knowledge held by scientists at one location could be easily shared and utilized by scientists elsewhere. Specifically, Zare (1997, p. 1047) described an era where "knowledge is available to anyone, located anywhere, at any time; and in which power, information, and control are moving from centralized systems to individuals." This model suggests a dramatic revision of the historical organization of science, away from "invisible colleges," where the bulk of new knowledge is created by a small core of elite researchers working among themselves (Crane, 1972; Price & Beaver, 1966)—such that 16 percent of practicing scientists account for about 50 percent of all publications (Price, 1986). By contrast, the notion of distributed intelligence suggests a mobilization of scientific effort—and a corresponding increase in research output and capacity—so that a larger fraction of the scientific workforce participates in the creation of new knowledge.

The notion of science as distributed intelligence relies heavily on information technology to overcome barriers of time and space. Specifically, studies of scientists and engineers at work suggest that the amount and quality of interaction with colleagues, particularly spontaneous and informal conversations, is an important predictor of productivity (Allen, 1977; Fox, 1983; Hagstrom, 1965; Kraut, et al., 1988; Kraut, et al., 1990; Menzel, 1962; Pelz & Andrews, 1966). Scientists who are remote from communities of elite and active researchers, then, are at a disadvantage in terms of initiating contact with leading investigators that can lead to deeper collaborations. Therefore, the introduction of tools, such as electronic mail, that facilitate easier communication

between scientists at nonelite institutions and those at elite institutions could produce increased involvement by nonelite scientists in cutting-edge research. This outcome is one possibility predicted by the "peripherality hypothesis" (Sproull & Kiesler, 1991, p. 95). According to this hypothesis, the introduction of electronic communication may produce universal benefits, differential benefits for those who are relatively advantaged, or differential benefits for those who are relatively disadvantaged (as in the previous scenario comparing nonelite and elite scientists). For example, a number of studies in business settings have shown how employees of global firms use computer-mediated communication to overcome barriers of remote geographic location (Constant, Sproull, & Kiesler, 1996; Finholt, Sproull, & Kiesler, in press; Kraut & Attewell, 1997). In these cases, electronic mail, bulletin boards, and mailing lists allowed peripheral employees to have the same access to important activities and information flows as centrally located employees, such as those at headquarters sites.

Evidence from a small number of studies appears to support the idea that electronic mail and other computer-mediated communications do enhance scientific productivity (Bishop, 1994; Bruce, 1994; Cohen, 1996; Hesse, Sproull, Kiesler, & Walsh, 1993; Walsh & Roselle, 1999), and that computer networks seem to support larger and more dispersed collaborations (Orlikowski & Yates, 1994; Raefeli, Sudweeks, Konstan, & Mabry, 1998; Walsh & Roselle, 1999). However, there is weaker evidence with respect to differential benefits for nonelite scientists. For example, in a survey study of 399 scientists in experimental biology, mathematics, physics, and sociology, Walsh and Maloney (in press) found slight evidence that electronic mail use was differentially benefiting peripheral scientists relative to core scientists. That is, e-mail use was universally associated with higher productivity, but not in a way that changed the status of peripheral scientists compared to core scientists. Similarly, Cohen (1996) found little support for the equalizing effect of e-mail use among a sample of academic researchers.

One speculation with respect to the absence of a peripherality effect revolves around features of the Internet that grant people discretion regarding selection of communication partners. That is, proponents of the distributed intelligence concept believe that mechanisms like the Internet will break down barriers among disciplines and institutions by

allowing people to act on preferences to associate with others who are different. However, Van Alstyne and Brynjolfsson (1996) argue that if preferences run counter to this expectation, people may choose to associate and communicate mostly with similar others (i.e., because this requires less effort). In this case, then, use of the Internet will produce increased balkanization rather than increased diversification. Under the balkanization scenario, scientists will interact and collaborate more with geographically distributed scientists, but these distant collaborators will be highly similar on critical dimensions (e.g., status, training, methodology preference).

The Collaboratory Concept

Studies cited in the preceding section suggest that, at least on preliminary examination, electronic communication alone may not be enough to enable a broader range of collaboration in science. This broader collaboration refers both to increased interaction independent of location, as well as the reduction of status barriers, such that distinctions between elite and nonelite scientists become less significant. However, electronic communication, combined with better access to critical instruments and data, may produce differential benefits. That is, while communication is unquestionably important in fostering and sustaining successful scientific collaborations, joint research work also requires access to specialized equipment and unique data sets. This suggests that a true test of the peripherality hypothesis in science requires elaboration of additional network capabilities; particularly applications that enhance sharing of data and data visualizations, and applications that allow remote use of important instruments and facilities.

One mechanism to achieve enhanced access to data and instruments is the “collaboratory.” First proposed by visionary scientists and computer scientists in the late eighties, a collaboratory is “a center without walls, in which researchers can perform their research without regard to physical location—interacting with colleagues, accessing instrumentation, sharing data and computational resources, and accessing information in digital libraries” (Wulf, 1989, p. 19). The term “collaboratory” is a hybrid of collaborate and laboratory. Hence, elaborations of the collaboratory concept stress the simultaneous need to solve problems of control and operation of instrumentation over the Internet, of access and distribution of data

sets, and of convenient and flexible interaction with colleagues. Development of computing technology to support collaboratories has not been guided by a grand plan. Rather, systems have emerged through a combination of prodding by visionaries, appropriation of technology designed for other purposes, and the availability of low-cost, high-performance personal computers.

Early proponents of scientific computing anticipated some of the functions of the collaboratory. For example, Vannevar Bush (1945) explored how computers might be used to help scientists keep pace with the explosion of scientific knowledge. He imagined a machine, called the “memex,” that would allow scientists to access and retrieve data and results from a vast array of scientific publications. Pioneers such as Douglas Engelbart wrote in the sixties about the use of computing to support intellectual work, and built prototype systems for computer-supported meetings (Engelbart, 1963). The initial practical step on the path to collaboratories occurred with the opening of the first wide area computer network in 1969, called the ARPAnet after the Advanced Research Projects Agency of the U.S. Department of Defense, which sponsored the development of the network. Although originally designed to share scarce computing resources, the most important function of the ARPAnet, ultimately, was its support for electronic mail between researchers in computer science and artificial intelligence (Newell & Sproull, 1982). Throughout the seventies and eighties, networking technologies developed further, culminating in the creation of the Internet in 1985; thus creating the first worldwide community of online users (Lynch & Preston, 1990).

The collaboratory idea appeared as scientists recognized the potential represented by expanding national and international computer networks. The first explicit discussion of collaboratories occurred at a National Science Foundation (NSF)-sponsored workshop in 1989 convened by Joshua Lederberg and Keith Uncapher. This workshop gave the collaboratory concept visibility within the NSF and other relevant national scientific communities. The report of the workshop outlined a number of specific research priorities, including enabling infrastructure to support collaboratories; construction of collaboratory test beds in various scientific disciplines; and studies of the process of collaboration and the use of these test beds by scientists (Lederberg & Uncapher, 1989). One outcome of the 1989 workshop was a series of further workshops in

1993 sponsored by the Computer Science and Telecommunications Board of the National Research Council (NRC) to explore the feasibility and utility of collaboratories for three disciplines: molecular biology, physical oceanography, and space physics. These fields were chosen for their heterogeneity in size, style of research, technical sophistication, and traditional sources of support. An important result of this activity was the NRC's report *National Collaboratories: Applying Information Technology for Scientific Research* (National Research Council, 1993). The report called for substantial support to develop, refine, and evaluate the collaboratory concept in realistic settings. The impact of these, and other prototype collaboratories, is discussed at length later in this chapter.

Four broad changes since the earliest days of the ARPAnet have created conditions conducive to collaboratory development. First, when the ARPAnet appeared, its bandwidth was limited and network use was restricted to institutions with ARPA projects. Today, even the smallest institutions and the most peripheral scientists can have network connections. Second, in the early days, network connections were scarce. Today, through the proliferation of personal computing and local area networks, network connections are ubiquitous. Third, early user applications had command line interfaces. Today, most software products have intuitive, graphical interfaces that allow users to perform sophisticated actions without learning obscure command sequences. Finally, while early network use was confined to a small community of computer scientists, contemporary users represent a broad spectrum of scientific disciplines as well as a mass audience from business and the general public.

At a more specific level, nearly two decades of technology evolution have led to a rich variety of computer and network tools for the support of collaborative work. Combinations of these existing tools, with elaboration of some new tools, form the core capabilities that constitute a collaboratory. As shown in Figure 2.1, derived from Atkins (1993), these capabilities can be defined as technology to link people with people, technology to link people with information, and technology to link people with facilities. Examples of people-to-people technologies include familiar applications, such as electronic mail, and tools for data conferencing, such as Microsoft NetMeeting. Technologies to link people with information, including the World Wide Web and digital libraries, have recently experienced tremendous growth in sophistication and use (for a

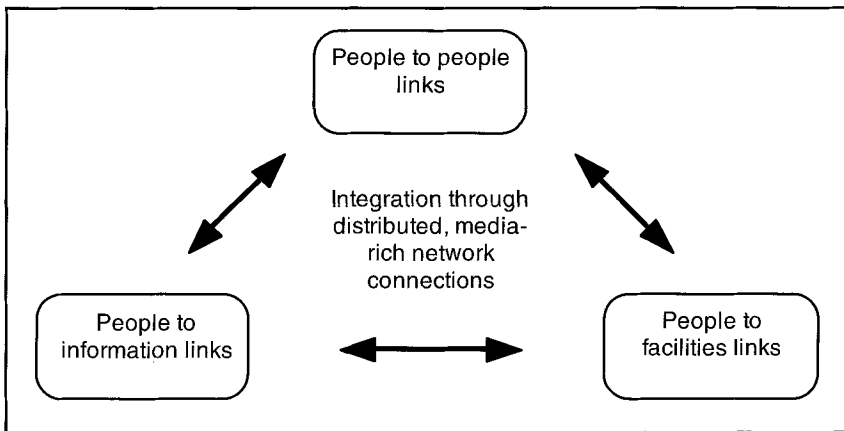


Figure 2.1 The collaborative concept: Using distributed, media-rich network connections to link people to each other, to facilities, and to information

more detailed survey of digital libraries see the chapter by Edward Fox and Shalini Urs in this volume as well as the special issue of *Communications of the ACM*, April 1995, edited by Fox, Akscyn, Furuta, and Leggett). Finally, technologies to link people to facilities include data viewers that display the current modes and status of remote instruments as well as services that provide scientifically critical data. An early effort along these lines was the MOS Implementation System, which allowed very large scale integrated chip designers to access remote fabrication facilities (Lewicki, Cohen, Losleben, & Trotter, 1984).

Collaboratory Experiences

The previous sections have described broad scientific and technological trends that have led to collaboratory development. This section offers a chronological description of notable operational collaboratories, covering the period from 1980 to 2000. The focus here is on those collaboratory efforts that have been or are in use by practicing scientists and that have produced accounts of this use. Table 2.1 summarizes key features of the collaboratory efforts described below.

*SCIENCE*net, 1980s

SCIENCEnet was a proprietary network service initiated in 1980 to meet the unique information and communication needs of the

Table 2.1 Descriptive characteristics of U.S. collaboratory efforts, 1992–2000

Project Title	Start Date	Sponsor	Total Budget	Target Community	Peak use	Total Use	Relevant Studies
Worm Community System	1990	NSF	\$1,741,141	<i>c. elegans</i> researchers	NA	NA	Star94
UARC	1992	NSF	\$4,455,329	Space physicists	54	163	Finholt97
CoVis	1992	NSF	\$4,794,633	K-12 students	NA	NA	Fishmann00
CMDA	1994	NSF/NIH	\$2,273,321	Electron Microscopy	NA	NA	Hadida-Hassan99
Remote Experimental Environment	1995	DOE	NA	Fusion researchers	NA	NA	Caspar98
EMSL Collaboratory	1995	DOE	NA	NMR users	5	17	Bair99
Chickscope	1996	U. of Ill.	NA	Microscopy, K-12 students	30	900	Bruce97
MMC Collaboratory	1997	DOE/NIST	\$10,890,000	Electron Microscopy	NA	NA	Zaluzec98
Diesel Combustion Collaboratory	1997	DOE	\$7,155,000	Diesel combustion	NA	NA	Pancerella99
Great Lakes Regional CFAR	1998	NIH	\$814,088	AIDS researchers	25	86	Teasley01
SPARC	1998	NSF	\$2,440,000	Space physicists	34	215	Olson00
BioCoRE	1998	NIH	\$1,225,000	Structural biologists	NA	NA	Bhandarkar99
Nano-Manipulator	1998	NIH	\$1,225,000	Remote use of AFM	NA	NA	Sonnenwald01
Bugscope	1999	NSF	\$447,751	Microscopy, K-16 students	30	1500	Potter00

oceanography community. In return for a monthly fee, SCIENCEnet subscribers obtained access to colleagues and to data. For example, SCIENCEnet supported project-oriented mailing lists used to coordinate activity among scientists in multiple locations. In addition, SCIENCEnet provided infrastructure for the storage and transport of large data sets. A critical feature of SCIENCEnet was its global coverage, which permitted logins from forty-five countries and the Antarctic, as well as via satellite link from research vessels. SCIENCEnet was particularly well suited to the needs of oceanographers, who frequently collaborate to coordinate data gathering across remote locations, or who monitor arrays of automatic sensors, such as buoys moored in the ocean or sensors installed on polar ice caps.

Hesse et al. (1993) conducted a systematic analysis of SCIENCEnet use and the relationship of usage to scientific outcomes. Data came from a 1988 survey of 338 SCIENCEnet users. Respondents were stratified by category of use, where frequent users had greater than median levels of use and infrequent users had below median levels of use. Scientists were also classified according to location (inland versus coastal), seniority, and disciplinary affiliation (physical oceanography—the target audience for SCIENCEnet—versus other). Outcomes included scientific productivity, measured as publications; professional recognition; and social integration, measured as the extent of each respondent's social network. Results showed that frequent SCIENCEnet users were more active, productive scientists. As compared with infrequent users, they worked at more prestigious institutions, received more professional recognition, published more, and knew more oceanographers. Controlling for category of use, network usage was still positively related to publications, recognition, and social integration. Further, for inland scientists, use of SCIENCEnet helped to overcome the disadvantage of a noncoastal location, at least in terms of publications. Perhaps the most interesting observation from Hesse et al.'s study was the finding that SCIENCEnet users reported that SCIENCEnet's operators were very sensitive to the special needs of oceanographers—and therefore worked hard to make the system as useful and invisible as possible, in order to allow users to maximize their focus on conducting research.

Worm Community System, 1990–1996

The Worm Community System (WCS) was initiated by Bruce Schatz (1991) and others in 1990 to meet the needs of biologists studying *c. elegans*, a tiny nematode with desirable scientific properties, such as transparent skin and the ability to be frozen and unfrozen for shipping between labs. At the time WCS was built, the community of scientists studying *c. elegans* included 1,400 researchers at over 100 labs. The WCS consisted of a set of hypertext-linked resources, which was a novel architecture at a time before widespread use of the World Wide Web. The WCS included graphics of the *c. elegans* physical structure; a genetic map; formal and informal research notes (including a newsletter called the *Worm Breeder's Gazette*); directory services; a thesaurus; and a database called *acedb*. Star and Ruhleder (1994) described use of the WCS, based on

observations of and interviews with over 100 researchers at twenty-five labs over a three-year period, 1991–1994. They found that, while respondents described WCS as easy to use and relevant to *c. elegans* research, “most have not signed on; many have chosen instead to use Gopher [an Internet-based document search and retrieval protocol developed by Alberti, Anklesaria, Lindner, McCahill, & Torrey (1992)] and other simpler net utilities with less technical functionality” (Star & Ruhleder, 1994, pp. 254–255). This finding was disappointing for the WCS developers, particularly given the efforts by the WCS team to ensure adequate feedback from the user community during the development of WCS.

Star and Ruhleder identified several factors in the nonuse of the WCS. At a high level, a key problem was that the target audience of biologists had to master relatively complex system installations (e.g., choosing the proper X-windows version) within alien computing environments (e.g., Unix workstations). Lower-level problems included information barriers (“where do I download the WCS system from?”), unforeseen consequences (e.g., the difficulty of maintaining a unique operating system, such as Unix, among mostly Macintosh computers), and political/cultural issues (“What is the appropriate trade-off between private and public information?”). Specifically, in terms of political/cultural factors, many post-docs were reluctant to share ideas or data via WCS, or similar mechanisms, for fear of being anticipated, or scooped, by others. Star and Ruhleder summarized researchers’ experience with the WCS in terms of Bateson’s (1972) “double bind” concept—whereby actions, with respect to the WCS, were often contradictory. For example, users were torn between the power of the WCS versus the inconvenience of learning new systems and leaving familiar work environments (i.e., most work was performed from a desktop machine, while WCS-related work had to be done from a special workstation).

Upper Atmospheric Research Collaboratory, 1992–1999

The Upper Atmospheric Research Collaboratory (UARC) was initiated in 1993 to serve the needs of a distributed community of space physicists who were users of instruments located at a National Science Foundation-funded observatory located above the Arctic Circle on the west coast of

Greenland. Space physics focuses on the interaction between the Earth's atmosphere and magnetosphere and the sun. The best-known phenomena studied by space physicists are the northern and southern lights, or the photon emissions associated with charged particles in the ionosphere. The goal of UARC was to provide real-time control of remote instruments used to study these and other upper atmospheric events. In addition, UARC was intended to support communication among geographically distributed colleagues about shared real-time data and to provide access to archived data. Finally, UARC was intended to demonstrate the utility of "user-centered" design, in which the system evolved through rich interactions between computer scientists, space physicists, and behavioral scientists—with the latter playing a critical role in determining system requirements and evaluating the system in use (Finholt & Olson, 1997; McDaniel, Olson, & Olson, 1994). The original UARC implementation, which was operational from 1992 to 1998, was built in NeXTStep, and required either a NeXT workstation or a workstation configured with the NeXTStep operating system. A later version, based on Java applets, was operational from 1995 to 1998, and could be run on any operating system with a Java-compatible Web browser.

Olson et al. (1998) provide a summary of experiences with the UARC system. During the NeXTStep era, UARC succeeded in providing real-time output from instruments in Greenland, notably an incoherent scatter radar, to a small number of users in Europe and in North America. For the most part, during this early period, UARC was used as a tool for the collective viewing of live data and for discussion of the data. Typically, scientists would organize activity in small groups around focal observing intervals, called "campaigns," much as they did pre-UARC—except that UARC eliminated the need to travel to the Greenland observatory. A key finding related to early UARC use was the observation that the collaboratory expanded the pool of participants in data gathering sessions, compared with traditional sessions, but the additional participants tended to be relatively passive (McDaniel, Olson, & Magee, 1996). That is, in the collaboratory setting, greater ease of access to research activity provided an opportunity for more people to watch—and to increase their level of participation as needed. Finholt, Lewis, & Mott (1995) found that this feature of UARC supported educational use, to the extent that novice space physicists could "lurk" in the collaboratory and

observe experienced scientists at work, much as Lave and Wenger (1991) have described novice workers doing in shared physical settings.

Increased use of the World Wide Web within the space physics community, starting around 1994, influenced a redesign of UARC. The second generation system abandoned the NeXTStep environment, which, because it required a separate workstation or special modifications to existing workstations, had become a barrier to adoption. The second generation version of UARC also introduced a more scalable data distribution approach. These changes enabled dramatic new kinds of collaborative use. First, interest in global-scale phenomena forced expansion from the original Greenland site to the entire chain of incoherent scatter radars—now including observatories in Norway, Massachusetts, Puerto Rico, and Peru. Scientists also demanded output from spacecraft, including imaging satellites in polar orbit as well as satellites monitoring the solar wind and the surface of the sun. Second, scientists who focused on computational models of the upper atmosphere wanted to view their simulated data side-by-side with observational data—and to discuss differences in real time with experts in interpretation of the observational data. Finally, scientists discovered that tools developed for real-time data gathering and visualization could be easily adapted for viewing archival data. This produced a need for “retrospective” campaigns in which the collaboratory was used to view a significant data interval (e.g., a solar sub-storm) from several corroborating instruments (e.g., radar, satellite, computational models, and so forth). Later UARC campaigns, as a result of these changes, had a different character and involved many more scientists and institutions. For example, in April 1997, more than fifty scientists from twenty labs logged into UARC over a four-day period coinciding with a coronal mass ejection.

While the evolution from the NeXTStep-based system to a Java-based system did result in the new kinds of use described above, there were still many problems. The goal of the redesign was to produce a UARC system that would be free of the orphaned NeXTStep environment and would run on the heterogeneous mix of machines and operating systems used in the space physics community. The reality was that the change to Java coincided with rapid evolution of the Java language, such that the initial Java applet version of UARC ran on beta versions of a limited set of Web browsers—and then on only some operating systems. Users were

forced to download updated browsers frequently; in some cases the UARC choice was not the main browser in use at a site (e.g., Sun's HotJava browser versus more popular programs). The cost in extra effort for users severely undermined confidence in the UARC system and tarnished otherwise successful efforts to increase the scale and scope of the collaboratory.

Environmental Molecular Sciences Laboratory Collaboratory, 1993–Present

The Environmental Molecular Sciences Laboratory (EMSL) Collaboratory was initiated in 1993 at the Pacific Northwest National Laboratory (Bair, 1999; Kouzes, Myers, & Wulf, 1996). The collaboratory capability was developed in parallel with creation of the EMSL's physical facility—a collection of instruments and expertise focused on environmental molecular science. Environmental molecular science, in this case, refers to a molecular-level understanding of the physical, chemical, and biological processes that underlie remediation of contaminated soils and groundwater, processing and disposal of stored waste materials, and human health and ecological effects of exposure to pollutants. The EMSL facility consists of data resources (notably a 20 terabyte robotic tape archive), magnetic resonance instruments, and mass spectrometers. Key elements of the collaboratory include applications to support remote operation of the magnetic resonance and mass spectrometer instruments, as well as an electronic notebook for instrument users to record and retrieve data. In addition, collaboratory users have access to a set of generic collaboration tools, including whiteboards, chat rooms, audio and video conferencing, and application sharing (i.e., remote viewing of a shared screen image). As of 1999, the EMSL Collaboratory had gone through three generations of development, with the current system implemented as a Java application.

Schur et al. (1998) summarize user experiences in the EMSL Collaboratory. Schur et al. focused on the 200 researchers targeted as potential users of the collaboratory. They conducted interviews with scientists prior to collaboratory use and then observed collaboratory use by a geographically dispersed research team. Researchers contrasted their current practices with a desired ideal, using a standard paradigm of two

to five researchers engaged with an eight-hour experimental run. Respondents said that under current practices, disproportionate amounts of time and attention were sunk into preparation for experiments and reporting of experimental results. Collaboration with colleagues occurred mostly around transitions, such as moving from experimental preparation to actually conducting an experiment, and not when needed the most. By contrast, researchers wished to devote the bulk of their time and attention to analysis and interpretation of experimental results, while streamlining preparation and reporting activities. Throughout all experimental activities, they wanted continuous access to colleagues for consultation and discussion, but on an as-needed basis.

Observations of scientists in the collaboratory concentrated on a team conducting a protein structure analysis using a Nuclear Magnetic Resonance (NMR) spectrometer and on a team of intelligence analysts working on detection of nuclear material for purposes of detecting non-proliferation treaty violations. The observational studies produced a number of key findings. First, scientists co-located with research instruments worried that the collaboratory would reduce them to instrument technicians—doing the bidding of remote scientists at the expense of their own work. In fact, collaboratory use produced sufficient efficiencies such that the local scientists actually had more time to pursue their own projects. Second, much as scientists wished, collaboratory use did allow them to focus more on analysis and less on details of data collection and transmission (e.g., faxes, file transfers, and e-mail). Third, with experience, collaboratory users moved from using collaborative tools in traditional ways, such as one person presenting to others as in a telelecture, to novel techniques focused more on application sharing and data conferencing (even forgoing video-mediated interaction in favor of data conferencing). Finally, audio and shared cursor movements, such as with telepointers, proved much more important and useful than video in the collaboratory for signaling the beginning and end of tasks, and for avoiding interruptions and talking over others when speaking.

K-12 Collaboratories

A significant potential use of collaboratories is to introduce elementary and secondary school students to authentic research practices, such as the CoVis project's efforts (1992–1998) to build electronic notebooks to

support access and analysis by student teams to the same kinds of data used by practicing scientists (Edelson, Pea, & Gomez, 1996; Fishman, 2000), or through access to previously exotic research instruments. Good examples of this latter strategy include classroom use of electron microscopes at the Argonne National Laboratory (Zaluzec, 1998) and the nanoManipulator at the University of North Carolina described in detail with the other National Institutes of Health laboratories, below (Jones, Superfine, & Taylor, 1999); undergraduate access to nuclear magnetic resonance spectrometers at the Pacific Northwest National Laboratory (Myers, Chonacky, Dunning, & Leber, 1997); and two prototypes that emerged from the World Wide Laboratory (WWL) project at the University of Illinois. The overall goal of the WWL effort has been to provide remote and automated access to imaging instrumentation, such as electron microscopes and nuclear magnetic resonance imaging (MRI) spectrometers, for teams of geographically distributed researchers (Carragher & Potter, 1999). The project has produced a number of Web-based applications for controlling instruments and viewing data displays, aimed at research scientists. An interesting consequence of the Web-based tool development, however, was the realization that with these new tools, access to various high-powered imaging instruments was now available to anyone with an Internet connection and a Web browser.

This realization led to a proposal to use WWL tools in a prototype effort to allow students in kindergarten through high school classrooms to remotely track the development of a chicken embryo using MRI facilities at the University of Illinois' Beckman Institute. This experiment, called Chickscope (1995–1998), involved students from ten classrooms, their teachers, and instrument operators at the University of Illinois during the spring of 1996 (Bruce et al., 1997). Eight of the classrooms were in Champaign-Urbana, one was in a nearby rural county, and one was in South Carolina. The project had two goals: (a) determine the impact of Internet access to high-powered scientific instrumentation for science instruction in the K-12 environment; and (b) test interactive control of the MRI instrument under diverse and adverse conditions (e.g., low bandwidth connections). In addition to remote control of the MRI instrument, Chickscope users also had an archive of images, a chat room, and a special chat area for input from MRI experts. Over the course of the twenty-one-day incubation period, each classroom was

granted two twenty-minute observation sessions per week. At the end of the experiment, students and teachers reported that access to the MRI was useful—but required some effort to learn how to interpret the MRI images. Everyone was excited to have an additional modality for learning about chicken embryonic development. Finally, teachers reported that the use of Chickscope had a number of beneficial learning outcomes, including increased ability to compare and contrast data, and improved 3-D spatial reasoning (e.g., required to make sense of the planar sections captured by the MRI field of view as it “sliced” through the egg).

Bugscope (1999–present), a successor project to Chickscope, builds on the earlier project’s success by reducing costs, such as instrument time and operator effort, while expanding participation (Potter et al., 2000). The focus of Bugscope is the use of an environmental scanning electron microscope (ESEM) to view insects. An ESEM is a special kind of electron microscope that allows specimens to be viewed in their natural state, i.e., without a conductive coating. Classrooms submit proposals for studies they wish to perform, and approved projects are given microscope time to analyze their samples. In contrast to Chickscope, classrooms receive only one hour of viewing time, but multiple classrooms can participate in a session. As of February, 2000, thirty classrooms involving 1,000 students all over the country had used Bugscope. This expansion was achieved while also reducing costs and demands on instrument time. Bugscope users have been enthusiastic in their support for the facility and there are currently over 100 proposals for new Bugscope projects.

DOE 2000 Collaboratories

The EMSL Collaboratory, described above, is one of several collaboratory test beds funded by the Department of Energy under the DOE 2000 initiative. Other projects include the Diesel Combustion Collaboratory (1997–2000) (Pancerella, Rahn, & Yang, 1999); the Materials Microcharacterization Collaboratory (MCC, 1997–2000) (Zaluzec, 1997, 1998); and the Remote Experiment Environment (REE, 1994–1997), a collaboratory to support observation and participation in magnetic fusion energy research involving the DIII-D tokamak experiment (Caspar et al., 1998; McHarg, Caspar, Davis, & Greenwood, 1999). A tokamak is a machine for creating a toroidally shaped magnetic confinement field used

to contain the plasma, or very high-temperature gases, required to achieve a fusion reaction. Fusion is a kind of nuclear reaction in which two light atomic nuclei combine to form another element with the release of energy. The DIII-D tokamak experiment refers to a specific machine, the largest tokamak in the U.S., located at General Atomics in San Diego, California. REE merits extra attention because of the effort to document users' experiences in this laboratory.

Because operation of the DIII-D tokamak is expensive, scientists must work together in the planning and operation of experimental runs. Within the REE, remote scientists can view data, interact with colleagues at the tokamak site and elsewhere, and observe—via video and audio—activity at the experiment control center. A test use of the REE involved a number of experiments controlled from Lawrence Livermore National Laboratory, in Livermore, California, using the DIII-D tokamak (Bly, Keith, & Henline, 1997). Over the course of the experimental runs, scientists at the two locations were able to coordinate their efforts to accomplish a successful experiment. Reactions to the laboratory-style experiment varied. Remote participants were enthusiastic about their increased access to activity at the DIII-D tokamak, while local participants sometimes resented the intrusion of the “outsiders.” Remote participants also felt excluded from key cues—such as warning lights and alarms—that were available to local participants.

Engineering Collaboratories

Many of the early collaboratory projects, summarized above, had to produce applications from scratch. Recently, software producers have identified a market for collaboration tools, such as application sharing and presence awareness, and have released a number of products—some of which have become immediately successful; for example, Mirabilis' ICQ (Mirabilis was acquired by America Online, or AOL), AOL's Instant Messenger, and Microsoft's NetMeeting. The cost of these tools, free for download in many cases, combined with their ease of use, has led to wide experimentation in business settings. The most pressing need for collaborative technology is often in engineering contexts in which engineers must confer over drawings and other visual data. While use of tools like NetMeeting, which allows data conferencing over images and output from applications, has grown dramatically, there are very few systematic

studies of NetMeeting use. Two exceptions include recent analyses of NetMeeting use in aerospace engineering (Mark, Grudin, & Poltrock, 1999) and in software engineering (Finholt, Rocco, Bree, Jain, & Herbsleb, 1998).

Both studies focused on use with geographically distributed teams of engineers, where NetMeeting was used along with conventional telephone-based audio conferencing. In the aerospace case, principal findings included overdependence on a small number of technically savvy users; awkward organization of conversational turn taking; high overhead associated with initiating data conferences; restrictive models of use (e.g., only broadcasting briefing slides and not collaborating over joint work); multitasking by data conference participants; and problems of awareness (e.g., not knowing who was who, and not knowing who was present at remote locations). For the software engineers, principal findings included observation of difficulties reconciling different screen resolutions when sharing screens; awkward organization of turn taking—particularly when transferring control over a shared application; the importance of highly motivated NetMeeting “champions” in getting groups over initial learning curves; and the need to run NetMeeting in the background to allow spontaneous data conferencing sessions.

National Institutes of Health Collaboratories

The National Institutes of Health (NIH) have recently launched two significant collaboratory initiatives. The National Center for Research Resources (NCRR) made a series of collaboratory supplement awards to research resource awardees during the period 1998–2002. These supplements were designed to take existing, shared resources, such as instruments and supercomputer simulations, and enhance access to these resources via the addition of network-based collaboration tools. NCRR collaboratory awards included support for work on structural biology via the BioCoRE, or Biological Collaborative Research Environment (Bhandarkar et al., 1999); advanced microscopy via the CMDA, or Collaboratory for Microscopic Digital Anatomy (Hadida-Hassan et al., 1999; Young et al., 1996); and the “nanoManipulator,” a mechanism for remotely steering the head of an atomic force microscope (AFM)—allowing direct manipulation of nanoscale materials (Sonnenwald, Bergquist, Maglaughlin, Kupstats-Soo, & Whitton, 2001; Jones, et al., 1999).

In a parallel effort, the National Cancer Institute is funding a virtual Center for AIDS Research (CFAR) spanning four midwestern universities: Northwestern, Minnesota, Wisconsin, and Michigan. The Great Lakes Regional Center for AIDS Research (GLRCFAR, 1998–2002) combines complementary expertise across the sites in a way that none of the sites, alone, could match. Further, the GLRCFAR is notable because it represents the first attempt to build a collaboratory employing only off-the-shelf components. While the GLRCFAR was initiated in 1998, collaboratory use has already become routinized (Teasley, 2001; Teasley & Jain, 2000). For example, CFAR participants log in twice a month for a collaboratory-based seminar series, using PlaceWare. PlaceWare is a Web-based tool that simulates a virtual lecture hall, based loosely on the LambdaMOO system developed at Xerox Palo Alto Research Center (Curtis, 1997). MOOs (multi-user dungeon [MUD] object-oriented) were originally conceived as a virtual space used for text-based adventure games (derived from Dungeons and Dragons, hence the dungeon reference) but since expanded to cover implementations like PlaceWare, and also other scientific MUDs and MOOS (e.g., Churchill & Bly, 1999; Glusman, 1995; Van Buren, Curtis, Nichols, & Brundage, 1994). In addition to PlaceWare lectures, GLRCFAR scientists regularly confer via NetMeeting, both to write clinical protocols and proposals, and also to view live output from remote instruments (e.g., electron microscope images of patient tissues). Finally, the GLRCFAR is the virtual home for documents and data relevant to joint work across the four-member institutions.

Space Physics and Aeronomy Research Collaboratory, 1998–2001

The Space Physics and Aeronomy Research Collaboratory (SPARC) is a successor project to UARC. As a follow-on effort, SPARC has been able to focus on expanding and improving UARC. From an implementation perspective, SPARC is designed as a “thin client” application. This means that users access all features of the collaboratory through a conventional Web browser, rather than through specialized software, as in both generations of UARC. For example, in UARC, the initial NeXTStep system was a barrier to use because the technology was exotic and the subsequent Java applet system was too unstable to win user confidence. With

SPARC, the interface is familiar—anyone who uses a Web browser can get started—and demands on local workstations involve only display of conventional Web elements, such as standard graphics formats (e.g., JPEG or GIF). A critical operational difference between UARC and SPARC is that SPARC facilities are available continuously, while UARC's were available only during campaign intervals. Finally, SPARC represents a reorientation of the collaboratory to post-hoc data exploration and analysis, termed an electronic workshop, as opposed to real-time data collection, which was the main emphasis in UARC. SPARC still supports real-time data gathering, but scientists found a greater need for retrospective, group investigation of data and visualizations from intervals of known value and interest.

The Collaboratory Challenge

In 1993, William Wulf wrote about the “collaboratory opportunity.” He noted that the configuration of technologies, needs, and practices were then coming into alignment to make virtual labs possible. In some ways, developments since the early nineties have exceeded Wulf's projections. For example, the explosion in Internet use, driven by the World Wide Web, has had an impact on science just as it has on other spheres of human activity. Yet, by comparison with the breakout success of the Web (Schatz & Hardin, 1994), collaboratory use has been confined to a much smaller number of users. Even within the space of scientific applications on the Web, collaboratories have been dwarfed by digital libraries and knowledge bases, such as the Los Alamos preprint server (Ginsparg, 1994), GenBank (Ouellette, 1998), and the Protein Data Bank (PDB) (Berman, et al., 2000). For example, considering only the PDB, this resource receives an average of between 60,000 and 100,000 hits per day and currently stores 12,592 different structures (Research Collaboratory for Structural Bioinformatics, 2000). It is important to consider whether the relatively modest size and growth of collaboratories, compared to systems like the PDB, reflect a failure of the original collaboratory vision. Rather than failure, the experience with collaboratories, to date, indicates the enormous difficulties of supporting complex group work in virtual settings. Overcoming these difficulties represents the great challenge for the next stage of collaboratory development and use. Meeting

this challenge involves both extracting lessons learned from previous collaborative efforts and solving a number of critical problems at the tricky intersection of technology with individual and group behavior.

Meeting the Challenge: Lessons Learned

A number of tentative conclusions can be drawn from observation of collaboratories in use. It is helpful to start by examining the impact of collaborative use on the organization and output of work, specifically the work of scientists—since most collaboratories have been targeted at scientific applications. Across the examples described earlier, it is clear that collaboratories have changed the number and type of participants in scientific work. For example, from the UARC and SPARC cases, relaxing of the constraints on travel to Greenland and other remote observatory sites has expanded the number of potential participants in research tasks, such as data collection. In addition, participants are more diverse, both in terms of experience and expertise. The earlier examples also suggest that collaboratories can increase the pace and efficiency of some scientific tasks. For instance, in the case of the Great Lakes Regional Center for AIDS Research, scientists reported that the use of collaborative tools dramatically reduced the time required to produce a clinical protocol from weeks to hours. Similarly, among space physicists, monitoring conditions via SPARC has allowed them to use scarce instrument time more effectively by activating instruments only under optimal conditions, and not according to a predetermined schedule.

It is less clear that collaboratories have qualitatively changed scientific work, but there is some suggestive evidence. Specifically, use of collaborative tools forces reflection on resources, such as data, which may have previously been unshared, that become shared. In one community of brain researchers, this realization produced a formal covenant, signed by scientists as a condition of use of the collaboratory, that specified how community data were to be used. This covenant paid particular attention to protecting the interests of younger researchers to prevent senior researchers from anticipating, or “scooping,” their results. Along the same lines, space physicists using UARC and SPARC articulated “rules of the road” describing how public data were to be used, including rights of first publication and mechanisms for sharing credit, such as to instrument owners. In terms of scientific output, collaboratories seem to produce at

least two kinds of changes. First, it becomes much easier to combine theoretical visualizations with visualizations of observational data. This helps bridge the gulf that exists in many fields between theoreticians and experimentalists. The capacity to blur the distinction between computational and physical simulations, for example, is a centerpiece of the National Science Foundation's George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES). Within NEES, collaborative tools will allow researchers to combine distributed physical simulation facilities, such as shaking tables and centrifuges, with computational simulations to produce complex real-time models of entire structures, or even entire built complexes such as cities. Second, collaboratories seem to produce a larger field of view. Among space physicists, for example, the ability to view hundreds of instruments worldwide encourages a more global orientation.

To summarize, experience to date with collaboratories suggests:

1. use does not need to be constant to provide value (general purpose tool vs. specialized instrument analogy);
2. systems that are easily integrated into existing work environments are more readily adopted (stand-alone application vs. browser accessible);
3. some domains of activity are more naturally inclined toward collaboration (data collection vs. contemplation and idea formation);
4. long-distance collaboration creates new expectations for participants, including altered roles (e.g., operators who must be more responsive, students who guide faculty, senior investigators who must accommodate less experienced participants).

Meeting the Challenge: Solving Critical Problems

Perhaps the most significant barrier to both the design and use of collaboratories is that most group practices and routines assume a shared space. For example, studies of distributed cognition show that people inventively exploit features of the social and physical world as resources for accomplishing tasks, and thereby reduce their reliance on mental

symbolic manipulations (Hutchins, 1995; Pea, 1993). An illustration of this phenomenon is the use, by naval navigators, of the “three-scale nomogram,” or a predrawn chart where the multiplication, addition, and division required to compute speed from distance traveled per unit time are represented as complementary logarithmic scales (Hutchins, 1990, p. 201). Changing the circumstances for collaboration, as in laboratories, may undermine the effectiveness of the collaborative process by introducing new demands due to loss of a common physical setting. One critical new demand in the virtual context is that workers must be explicit about information that is normally tacit when co-located.

For example, scientists seated together at a workstation can unambiguously reference features in a data visualization simply by pointing. In a virtual setting, the same scientists must first ensure that they have each produced the same visualization and then ensure that a specific feature referenced by one is the same feature viewed by the other (e.g., through a specific coordinate system or through reference to unmistakable landmarks). In this scenario, the loss of tacit cues in the virtual setting may mean a greater risk of losing common ground (Clark & Brennan, 1991), where common ground is the shared cognitive understanding that allows collaborators to successfully coordinate their effort to accomplish joint work. At a minimum, then, collaboratory collaborations may require more effort, in terms of communicating the additional information required to achieve common ground. A challenge for collaboratory developers is producing tools and applications that compensate for the absence of a shared setting, such as through so-called WISIWYS (What I See Is What You See) interfaces. For instance, in both UARC and SPARC, research has focused on mechanisms for data display and data transport to ensure that what one scientist sees can be seen by other scientists (Hall, Mathur, Jahanian, Prakash, & Rasmussen, 1996; Lee, Prakash, Jaeger, & Wu, 1996).

Given the significance of co-location, and more importantly, the long development of human practices and behaviors contingent on co-location, it is not surprising that attempts to organize activity in virtual settings have proven difficult. This is the main point Olson and Olson (2001) make in arguing that “distance matters.” Based on laboratory experiments and empirical observations in the field, Olson and Teasley (1996) conclude that for some tasks, co-location is still essential. Specifically, when tasks are

tightly coupled; that is, dependent on frequent interaction and feedback among collaborators, contemporary communication technologies—such as e-mail, video and audio conferencing, and groupware (e.g., Lotus Notes)—do not provide an adequate substitute for co-location. In part, this failure is attributed to inadequate design and poor infrastructure. For example, accurate gaze detection is a key way that humans impute additional meaning in conversations. Yet, most video conferencing applications offer weak support for this kind of fine-grained detail.

Overcoming the difficulties inherent in virtual interaction, then, is partially a matter of elaborating designs and technologies that make virtual settings more like physical settings. Yet, even if successful designs and technologies are identified, there remain critical barriers to successful virtual collaboration. Olson, Finholt, & Teasley (2000) characterize these additional barriers in terms of collaboration readiness and collaboration technology readiness (see also Olson & Olson, 2001; Sonnenwald, 2000; Sonnenwald & Pierce, 1995). Collaboration readiness refers to the extent that potential collaborators are motivated to work with each other. In terms of collaboratory introduction, success seems to require a positive orientation toward collaboration, either as a result of incentives or as a result of normative practice. For example, in the Great Lakes Regional CFAR case, funding from the CFAR was directly tied to willingness to collaborate, as measured by acceptance and use of collaboration tools. This coercive approach worked to bring otherwise reluctant scientists to use PlaceWare, NetMeeting, and so forth, resulting in sufficient critical mass to motivate continued use of these tools. In the case of UARC, initial participants in the collaboratory were selected based on pre-existing collaborations. Additionally, space physics, as a field, has a history of highly collaborative research.

Collaboration technology readiness refers both to the presence of sufficient technology infrastructure, and to the availability of local technology expertise, both explicit and implicit. For example, Olson et al. (2000, p. 12) describe a progression from applications that require minimum training, such as e-mail, to technologies that require greater investment, such as data conferencing tools. Attempts to leapfrog steps in this progression can produce frustration and resistance. Similarly, attempts to implement sophisticated applications, such as desktop video conferencing, will have a higher probability of success when

underlying infrastructure is adequate—in this case, access to high bandwidth network connections. In terms of collaboratory development, important lessons can be drawn from the difficulties described earlier with respect to the evolution of UARC from a NeXTStep-based system to a Java-based system. That is, apparent technological advantages, such as the purported universality of Java code, needed to be weighed against the equally important factors of familiarity and reliability.

Future Collaboratory Development

Laboratories emerged as physical settings designed to house rare and expensive instruments, as well as the scientists using the instruments. The forms of social organization that grew out of this arrangement depended heavily on co-location. Today, the evolution of information technology suggests a form of collaboration without proximity. Specifically, the goal of collaboratory development is the creation of “laboratories without walls.” This concluding section explores the consequences for scientific practice and for scientific communities when collaboration becomes independent of physical location.

As noted earlier, in discussion of the peripherality hypothesis, a hope for collaboratory elaboration and use is that improved access to important but scarce instruments and data, combined with easy communication among researchers will diminish the barriers of status, time, and space that hamper scientific progress. However, it is important to note that powerful forces will continue to exist that will move collaboratories in the direction of exclusivity and selection that have characterized the historic organization of science. First, the availability of a means for contact between two scientists does not guarantee that contact will occur. For instance, science in the virtual realm may be just as likely as traditional science to be typified by strict enforcement of boundaries defining invisible colleges. In an examination of an early system that supported network-mediated communication among scientists, Hiltz and Turoff (1993) found that elite scientists using the system were more likely to receive messages than nonelite scientists, but that elite scientists were more likely to ignore the messages they received, particularly when those messages were sent by nonelite scientists. Second, economic considerations dictate that some scientific data and results will always be

secured from widespread access. In chemistry, the bulk of practicing chemists are employed in private firms. These firms have proprietary interests in the products of their employees, specifically intellectual property such as patentable compounds and processes. As a result, chemists as a group use public computer networks less than other scientific disciplines that are dominated by academic practitioners (Walsh & Bayma, 1996). Third, scientific collaborations appear to require face-to-face contact, at least initially, suggesting that conferences and invited meetings will continue to function as critical filters on scientific participation. In a study of interpersonal communication networks among computer scientists, Carley and Wendt (1991) found that face-to-face contact was critical in starting a scientific relationship. While the computer scientists used e-mail to maintain existing collaborations, none of the identified collaborative relationships started via e-mail.

Collaboratory advocates envision the ultimate withering away of physical laboratories. However, it seems more realistic to suggest that collaboratory use will augment, but not replace, proximity as a tool for fostering scientific collaboration. Further, the benefits of collaboratory use may differ depending upon the status and experience of collaboratory users. Opportunities and gains seem most obvious for graduate and undergraduate students and nonelite scientists, since these are often the members of the scientific community least able to travel and meet other scientists. Collaboratories may represent a mechanism for accelerating students' immersion into important networks. For example, through UARC, space physics graduate students were able to participate in experiments during their first year, while in the past this did not occur until the third or fourth year. For elite scientists, collaboratories may offer more imposition than benefit. Specifically, if collaboratory sessions become opportunities for nonelite scientists and students to bombard these senior investigators with questions or demands, the senior scientists may respond by withdrawing their participation (and rely on traditional means for continuing collaborations). Finally, for nonelite scientists, collaboratories may provide broader access to some resources, such as instrument time, and may deliver access to elite scientists (although still at the discretion of the elite scientists). Most importantly, nonelites may use collaboratories to foster links with one another, which could be both valuable and damaging (*viz.*, the balkanization outcome

described by Van Alstyne and Brynjolfsson [1996]—in which the Internet may reinforce connections among those who are similar vs. creation of more diverse links). From the perspective of creating an intellectual community, the collaboratory may fill a critical niche, particularly for scientists at smaller institutions where they may have few local colleagues. However, if the concentration of nonelites is taken as an indication of the secondary status of a community, collaboratories may become the home for scientists who are marginalized in their larger, more traditional scientific communities. An instance of this may be the phenomenon of “e-journals,” which are numerous on the Web (Odlyzko, 1999), yet continue to have a clearly inferior status relative to traditional journals.

In summary, the emergence of collaboratories represents an important convergence of computing technology with scientific practice. Collaboratories, by themselves, will not produce changes in science. However, at this early stage in their development, it may be possible to anticipate openings for change afforded by collaboratories and be prepared to exploit these openings. This means that those in the scientific community, and beyond, should actively explore how collaboratories can be used to expand participation in science, rather than accepting collaboratories and other new technologies as extensions of the status quo.

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