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From laboratories to collaboratories: A new organizational form for scientific collaboration

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Abstract

This paper explores the potential impact of collaboratories on psychology. A collaboratory is a computer-supported system that allows scientists to work with each other, facilities, and databases without regard to geographical location. Collaboratory impact is discussed in terms of changes in the organization and practice of scientific work as this work moves from physical to virtual settings. Examination of prototype collaboratories in the physical sciences shows that collaboratory use produces changes through improved access to scarce resources, support for joint work among distant colleagues, and opportunities for broader participation in research by students. Similar results of collaboratory use in psychology are predicted if psychologists exploit collaboratory capabilities to design new ways of conducting research, rather than adopting collaboratory technology as an extension of the status quo.

From laboratories to collaboratories: A new organizational form for scientific collaboration

Science is a collaborative enterprise and the traditional environment for scientific collaboration is the laboratory. From the primitive facilities constructed by learned societies in the early nineteenth century, to the massive national laboratories of the present day, laboratories have fostered collaboration in two ways. First, as physical settings, laboratories provide access among scientists to each other and to rare or expensive instruments (Kraut, Egido, & Galegher, 1990; Allen, 1977; Hagstrom, 1965; Pelz & Andrews, 1966). Second, as social organizations, laboratories certify and disseminate knowledge, train future generations of scientists, and produce agreement about scientific practices and beliefs (Latour, 1987; Latour & Woolgar, 1979; Knorr-Cetina, 1981; Lynch, 1985; Traweek, 1988). Recent developments in the evolution of information technology suggest that laboratories as physical settings may be less essential for scientific collaboration then was formerly the case. This paper outlines these emerging technologies and explores the consequences for scientific practice, with a specific focus on psychology, when collaboration is not as contingent on physical location.

Throughout the modern era of scientific research, laboratories as social organizations have been intertwined with laboratories as physical settings. For example, to speak of Wundt's laboratory at Leipzig at the end of the nineteenth century means both the physical location of Wundt's apparatus and his idea of a particular kind of experimental psychology. Similarly, among chemists, to refer to Humphrey Davy's laboratory means both the facilities constructed for him by the Royal Institution at the turn of the nineteenth century and the legacy of Davy's work there, including his discoveries and his collaboration with Michael Faraday (Fullmer, 1989). Even today there is a strong association between physical location and schools of thought. That is, ideas are linked with specific individuals, periods and places. For example, in psychology, “behaviorism” is tied to Skinner’s lab and research group at Harvard in the 1950s.

The overlap between laboratories as places and laboratories as organizations reflects three factors. First, the conduct of scientific research often requires costly or scarce resources. Concentration of equipment at specific locations is one way to maximize investments in expensive apparatus and this leads to concentration of scientists at these locations. For example, the huge accelerators required to do high energy physics have made CERN and FermiLab key research centers for particle physicists (Westfall, 1989; Krige, 1989). Second, much of the work of scientific research involves tacit knowledge about practice that is difficult to convey (Knorr-Cetina, 1981; Latour & Woolgar, 1979). Specifically, tacit knowledge often isn’t recordable in easily transferred forms, such as documents. Therefore, subtleties of how work should be done are frequently conveyed only through demonstration and observation. For instance, in a study of molecular biologists, Cambrosio and Keating (1988) found that critical techniques for producing monoclonal antibodies were not reported in journals, but were passed from scientist to scientist at the lab bench. Finally, as scientists and research groups at a laboratory begin to produce a respected body of work the reputation of this work attracts other scientists. Therefore, scientists seek proximity because it will enhance the quality and frequency of their communication with a target person or research group (Kraut et al. 1990; Allen, 1977). For example, during J.J. Thomson’s tenure at Cambridge’s Cavendish Laboratory (1871-1909) his discoveries, particularly the identification of the electron in 1897, attracted scientists from all over the world (Falconer, 1989).

The Cavendish example illustrates how laboratories are embedded within larger social networks. Specifically, associations created within laboratories form the basis for lifelong affiliations among scientists. These “invisible colleges” can have important consequences in terms of career opportunities, reputation, and dissemination of results

(Crane, 1972). Until recently, network associations developed as they did in Thomson's era: by movements of scientists from lab to lab. Now, however, alternative mechanisms exist for making and maintaining links with other scientists. In particular, the evolution of computer-mediated communication makes it possible for scientists to do some forms of joint work without traveling to distant sites. For example, mathematics is a discipline characterized by frequent visiting among collaborating colleagues. Today, it is possible for mathematicians to reduce some of these travel demands through the use of electronic mail to discuss ongoing research (Walsh & Bayma, 1993). Similarly, much of the programming language Common LISP was written by computer scientists at remote sites who coordinated their activities via electronic mailing lists (Steele, 1990). Yet, despite these advances, computer networks have not afforded the access to colleagues and the access to equipment possible at a physical building or campus. The sections that follow show how this situation is rapidly changing. Desktop video conferencing, remote control of distant instruments, shared data viewers, and graphical database interfaces are making it possible for geographically distributed scientists to reproduce characteristics of a shared physical setting without co-location. One model for the integration of these systems to support group scientific work is the "collaboratory" concept.

A new paradigm for scientific collaboration

A collaboratory is the "...combination of technology, tools and infrastructure that allow scientists to work with remote facilities and each other as if they were co-located." (Lederberg & Uncapher, 1989, p. 6) A National Research Council (1993) report defines a collaboratory as a "...center without walls, in which the nation's researchers can perform their research without regard to geographical location -- interacting with colleagues, accessing instrumentation, sharing data and computational resources [and] accessing information in digital libraries." (National Research Council, 1993, p. 7) A simplified form of these definitions describes a collaboratory as the use of computing and communication technology to achieve the enhanced access to colleagues and instruments provided by a shared physical location, but in a domain where potential collaborations are not constrained by temporal or geographic barriers.

Development of computing technology to support scientific collaboration has not been guided by a grand plan. Rather, systems have emerged through a combination of prodding by visionary thinkers, appropriation of technology designed for other purposes, and the marketing 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 global database system that would allow scientists anywhere to access and retrieve scientific publications. Pioneers such as Doug 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 national data network in 1969, called the ARPAnet after the Advanced Research Projects Agency of the 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 became its support for electronic mail between computer science and artificial intelligence researchers (Newell & Sproull, 1982). Throughout the seventies and eighties networking technologies developed further, culminating in the creation of the Internet in 1985, which created the first worldwide community of on-line users. Today, the U.S. government is leading an initiative to upgrade the national information infrastructure to meet growing network demands through the construction of the so-called "information superhighway."

The collaboratory idea appeared as scientists recognized the potential represented by expanding national and international computer networks. The first explicit discussion of collaboratories was at an 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: enabling infrastructure to support collaboratories, construction of collaboratory testbeds in various scientific disciplines, and studies of the process of collaboration and the use of these testbeds 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 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 outcome of this activity was the NRC’s (1993) report *National Collaboratories: Applying Information Technology for Scientific Research*. The report called for substantial support to develop, refine, and evaluate the collaboratory concept in realistic settings.

Although not of the scope called for in the NRC report, at present there are numerous collaboratory-like facilities, mostly started after 1992. Many of these efforts have been funded in full or partially by grants from the High Performance Computing and Communication initiative; a $3 billion effort to produce the National Research and Education Network. Table 1 summarizes the current state of collaboratory development in the United States and elsewhere, organized by scientific discipline. The most mature projects are in atmospheric and space science (Clauer et al. 1994; Pea & Gomez, 1992; Pea, 1993), and in biology (Schatz, 1991; Glusman, 1995). The concentration of collaboratory efforts in medicine reflects recent funding from the National Library of Medicine, while the concentration of systems in the physical sciences reflects recent funding from the Department of Energy (U.S. Department of Energy, 1995; Kouzes, Myers, Devaney, Dunning, & Wise, 1993; Kouzes, 1995; Elvins, Young, & Mercurio, 1992). A summary of these projects and pointers to relevant locations in the World Wide Web (WWW) is in the Appendix.

Technologies to support collaboratories

Four broad changes since the earliest days of the ARPAnet have created conditions conducive for collaboratory development. First, when the ARPAnet appeared its bandwidth was limited and network use was restricted to those institutions with ARPA projects. Today, even the smallest institutions and the most peripheral scientists 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 arcane 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.

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 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 technology include familiar applications such as electronic mail for exchanging messages, file transfer software for exchanging documents and data, and bulletin boards or newsgroups for broadcasting information. New people-to-people technologies include more exotic applications. For example, a variety of programs now support desktop video conferencing (e.g., CU-SeeMe from Cornell University, ProShare from Intel, Vistium from AT&T, ShowMe from Sun), where users can simulate face-to-face conversations by transmitting video and audio between computers at remote locations. Group Decision Support Systems such as TeamFocus (Nunamaker, Dennis, Valacich, Vogel & George, 1991) and SAMM (DeSanctis, G.L., Poole, M.S., Lewis, H., & Desharnais, G., 1992) provide groups with a suite of tools to engage in structured decision making. Programs now exist that support joint work via network connections that allow people to communicate remotely about a common document or picture. Some of these joint work tools are synchronous, such as ShrEdit (Olson, Olson, Storrøsten & Carter, 1993), DistEdit (Knister & Prakash, 1990), and Aspects. Other joint work systems are asynchronous, such as PREP (Neuwirth, Kaufer, Chandhok, & Morris, 1990) and Lotus Notes. Finally, a class of applications called “awareness tools” has emerged to reproduce in a distributed network environment the social cues and information that are normally available only in a shared physical setting, such as closed office doors that indicate an occupant is busy or unavailable. Cruiser (Root, 1988), RAVE (Gaver, Moran, MacLean, Lovstrand, Dourish, Carter & Buxton, 1992), Portholes (Dourish & Bly, 1992), and Montage (Tang, Isaacs & Rua, 1994) are all examples of awareness tools.

Technologies to link people with information have recently experienced tremendous growth in sophistication and use. Traditionally, information in computers was stored locally in databases and accessed through awkward text-based interfaces (e.g., library catalog programs). Today, the contents of millions of datafiles throughout the Internet have been linked via the World Wide Web, an ad hoc system for classifying data on individual machines that makes this information searchable and retrievable by users on other machines. Graphically oriented applications for searching the WWW, called “browsers,” have gained broad acceptance, and several, such as Mosaic and Netscape Navigator, have become among the most popular computer applications ever written (Schatz & Hardin, 1994). The power of the Web was demonstrated during the Comet Shoemaker-Levy 9 collision with Jupiter in July, 1994, when hundreds of thousands of users downloaded up-to-the-minute images using browser software. Efforts to produce more formal on-line collections of information have taken the form of digital libraries, where network access provides users with copies of books, journals, reference materials, and rare documents (see special issue of Communications of the ACM, April 1995, for a series of articles on digital library projects).

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) Users that need to synchronize their activities with a universal time standard can do so via the Internet by querying the U.S. official time kept on cesium clocks at the Naval Observatory. More examples of technology to link people with facilities are presented below in the description of the Upper Atmospheric Research Collaboratory (UARC).

A working collaboratory

A number of recent projects have attempted to create working collaboratories. For example, Schatz (1991) focuses primarily on the people-to-information link in his development of the Worm Community System, a distributed database that biologists use to share information about the *C. elegans* gene sequence. Pea and Gomez (1992) address people-to-people, people-to-information, and people-to-facilities links in the Collaborative Visualization project for elementary and secondary school students studying earth science. Finally, perhaps the most evolved application of the collaboratory idea is Clauer et al.'s (1994) Upper Atmospheric Research Collaboratory (UARC). UARC supports a distributed community of space physicists by providing them with real-time control of instruments in Greenland, the ability to communicate with their colleagues about shared real-time data, and access to archived data. In UARC, a half dozen instruments transmit data over the Internet to specially designed display programs. Scientists at ten sites around the world can view these displays by running the data viewing programs on local machines. A simple text-based "chat" window allows the scientists to share reactions with each other about the phenomena they are observing and to send instructions to the site crew in Greenland. Simple collaboration support such as the ability to mark notable data, share views of data streams, and point to data features are also provided to assist the real-time interactions.

As the preceding summary suggests, the most mature example of collaboratory development is concentrated in space physics. However, while existing collaboratories do not yet explicitly support psychological research, many of the collaboratory features useful to physical scientists are likely to be important for psychologists as well. Specifically, the desire to communicate remotely about data displays or to use distant instruments is not unique to biologists and space physicists. Further, apart from offering insights about beneficial aspects of collaboratory design for conducting psychological research, operational collaboratories are interesting as the focus of psychological research. For example, Finholt, Mackie-Lewis, and Mott (1995) examined UARC to understand how experienced scientists used the collaboratory to tutor novice scientists, such as graduate students. The UARC chat window created a running log of conversations between scientists and students that Finholt et al. used to analyze question-asking strategies employed by the students. Comparable classroom studies often involve extensive video recording and transcribing. Activity within UARC, however, was saved automatically to computer files which eliminated many of the time-consuming steps typically required to analyze tutoring discourse.

The impact of collaboratories

Collaboratories represent a potential transformation of the laboratory idea. Parallels to this transformation exist in other domains where different organizational forms are emerging through new technologies, such as: virtual corporations in place of physical corporations (Davidow & Malone, 1992); a global workplace instead of national or local workplaces (O'Hara-Devereaux & Johansen; 1994); and "cyberspace universities" instead of physical campuses (Duderstadt, 1994). It should not be assumed that these transformations necessarily represent progress. That is, collaboratories may not make scientific collaborations better or easier. However, it is reasonable to assume that collaboratories will make scientific collaborations qualitatively different and that use of collaboratories will introduce a new set of tradeoffs and constraints in scientific work.

Understanding the impact of collaboratories, then, should be an important goal for psychologists interested in the cognitive and organizational aspects of science. First, examination of the transformation of scientific collaboration caused by collaboratories is likely to produce general insights about the process of cognition that occurs among groups of individuals engaged in common and sustained intellectual tasks, such as scientific collaborations. Second, from a methodological perspective, instrumented collaboratories provide an unprecedented opportunity to collect data on the full range of behavior and activity among collaborating scientists. Finally, collaboratories are of interest for the conduct of psychology. As psychology becomes more collaborative, understanding the use of collaboratories can shape the design of technology to assist collaboration among psychologists.

Collaboratories and scientific collaboration

Collaboratories introduce one kind of change in scientific work by divorcing collaboration from physical locations. However, Hutchins (1995) has observed that use of the physical setting in which work occurs is a key to successful coordination of joint intellectual activity. That is, collaborators have a tacit dependence on physical proximity based on long experience collaborating with co-located others. Changing the circumstances for collaboration, as in collaboratories, may undermine the effectiveness of the collaborative process by introducing new demands due to loss of physical setting.

In a physical setting collaborators do not need to communicate about information that is tacitly shared. For example, co-located scientists using UARC do not need to tell one another which display is being viewed or the parameters of this display. However, remote UARC users must state this information explicitly. Similarly, co-located scientists using UARC know which scientists are participating in an experiment by monitoring who is working at the local workstation. By contrast, UARC users spread across many time zones have a reduced sense of who is actively engaged with an experiment, because they can't easily track the arrival and departure of remote colleagues. In each of these scenarios the loss of tacit cues in the computer-mediated setting may mean that collaboratory users are at greater risk of losing common ground (Clark & Brennan, 1991) with other participants in the collaboratory . At a minimum collaboratory collaborations may require more effortful communication to establish adequate accounts of common ground. Failure to communicate common ground information explicitly may lead to misunderstandings that complicate the nature of collaborative activity.

Collaboratories and methodological innovation

Science is an example of a human cognitive activity in which individual and collective processes overlap. However, the psychology of science up to now has focused on individual cognition, in part because this has been the focus of mainstream cognitive psychology, but also because data on collective processes are difficult to gather. For example, much of the collective scientific activity in natural settings is embodied in the conversations and interactions among scientists. Capturing this activity through ethnographic methods requires highly skilled participant observers who are able to: live in an environment for long periods of time; keep careful notes; and synthesize and interpret these notes after the fact. Capturing naturally occurring scientific activity through video taping requires extensive and often costly off-line analysis (e.g., Olson, Olson, Carter & Storrøsten, 1992). Collaboratories offer an interesting alternative.

Much of the behavior by collaboratory users is mediated by communication and computing technology. Therefore, it becomes possible for observers of collaboratories to capture such behavior in time-stamped log files for which at least some automatic processing can be done. The methodological advantages of this approach make collaboratories an appealing arena for studying the ways in which people jointly construct scientific knowledge and how this process shapes the organizational forms that are used to carry out the dependent individual and collective goals of understanding natural phenomena. Of course, exploiting these methodological advantages will require special sensitivity to issues of computer privacy. Also, at least in initial studies of collaboratories, collaboratory behavior will need to be contrasted with behavior in a control setting, such as traditional laboratories.

Collaboratories and psychology

The initial impact of collaboratories on the practice of psychology will occur in two domains. First, research that depends on access to rare and expensive equipment will benefit from collaboratory technology. For example, recent work in cognitive neuroscience has focused on brain images obtained via Positron Emission Tomography (PET) scanners (e.g., Jonides, Smith, Koeppe, & Awh, 1993). But, a PET scanner is a costly and complex machine and many researchers do not have one nearby. A collaboratory represents a potential solution to this problem by distributing PET images via computer network where local and distant scientists can view, manipulate, and discuss the images. A second domain that may benefit from collaboratories is research that focuses on parallel phenomena happening in separate locations. For instance, in cross-cultural research the geographic dispersion of investigators and study participants is essential. However, this dispersion complicates communication, particularly when coordinating activity across time zones. Again, a collaboratory represents a potential solution by storing information or documents from tasks-in-progress so collaborators can do joint work asynchronously.

Broader use of collaboratories may focus on three areas. First, collaboratories are potentially important educational tools. The capabilities that allow remote scientists to interact with one another also allow a guest scientist to interact with a distant classroom, or a student to participate in a distant experiment. Further, the ability to capture and record collaboratory activity means that sessions involving experienced scientists can be re-played and analyzed by graduate and undergraduate students. Second, collaboratories are potentially important for organizing and accessing archived data. A frequent concern in psychological research is the lack of power in many studies (Cohen, 1988; Rosenthal & Rosnow, 1991). Meta-analysis offers one solution to this problem by combining similar studies to obtain larger sample sizes (Rosenthal, 1991; Rosenthal & Rubin, 1989). However, the burden of locating studies to conduct a meta-analysis typically limits the use of this technique. Broad and reliable access to published results and to raw datafiles, through a collaboratory, offers one way to reduce the effort required to aggregate and analyze existing data. Finally, collaboratories are potentially important as experimental apparatus. For instance, in organizational research on decision making, university students are often used as proxies for real members of organizations, such as managers. Or, managers are studied outside of their work context, as is the case for participants in executive education courses. A collaboratory offers a means to capture the behavior of actual managers as they make real decisions.

Conclusions

Laboratories emerged as physical settings designed to house rare and expensive equipment. 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.

Much of the rhetoric surrounding calls for the creation of collaboratories stresses the leveling potential of this technology. For example, from Figure 1, the people-to-facilities aspect of collaboratory use is anticipated to enhance utilization of scarce scientific resources, by expanding access to these resources. The people-to-people aspect of collaboratory use is anticipated to make remote scientists more visible to one another, and therefore, allow them to recognize common interests and concerns that can form the basis for future collaborations. Finally, the people-to-information aspect of collaboratory use is anticipated to provide faster and less-restricted availability of data and results. Findings from previous studies and cases suggest that these hoped-for effects are not unrealistic. For instance, Hesse, Sproull, and Kiesler (1994) found that land-locked physical oceanographers used scientific computer networks to overcome some of the liabilities of their location to maintain contact with scientists at elite coastal research centers. Similarly, Walsh and Bayma (1993) found that collaborating mathematicians relied on email contact to sustain and advance joint work between visits to colleagues' institutions. Finally, among physicists, on-line archives of pre-print papers at Los Alamos, accessed via the Web and through anonymous ftp, have proven to be an effective way of sharing results outside of the formal journal process (Taubes, 1993).

Despite the promise of collaboratories to democratize science, important forces exist that will tend to move collaboratories in the direction of exclusivity and selection that have characterized conventional laboratories. 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 is 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 mediated communication among scientists, Hiltz and Turoff (1993) found that elite scientists using the system were more likely to receive messages than non-elite scientists, but that elite scientists were more likely to ignore the messages they received, particularly when those messages were sent by non-elite 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, 1993). 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 network study of computer scientists Carley and Wendt (1991) found that face-to-face contact was critical in starting a scientific relationship. While the computer scientists used email to maintain existing collaborations, none of the identified collaborative relationships started via email.

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 by the status and experience of collaboratory users. Opportunities and gains seem most obvious for graduate and undergraduate students and non-elite 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 non-elite 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 non-elite 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 important, non-elites may use collaboratories to foster links among one another, which could be both valuable and damaging. 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 non-elites 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.

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 the scientific community, and psychologists in particular, 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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Table 1

Developers, focus and URLs of existing collaboratories

Name and discipline	Developer/s	Focus	URL
Atmospheric/space science			
Collaborative Visualization Project	Northwestern University	scientific visualization for K-12 students studying the earth's atmosphere	http://www.covis.nwu.edu
Upper Atmospheric Research Collaboratory	University of Michigan, SRI International, Danish Meteorological Institute, Lockheed Palo Alto Research Laboratory, University of Maryland	ground-based observation of ionospheric phenomena using the Sondrestrom Upper Atmospheric Research Facility	http://www.si.umich.edu/UARC/HomePage.html
Biology			
BioMOO	Weizmann Institute	on-line discussions about biology	http://bioinformatics.weizmann.ac.il/BioMOO/

Collaboratory for Microscopic Digital Anatomy	University of California-San Diego	digital acquisition of three dimensional data from biological specimens	http://www-ncmir.ucsd.edu/CMDA.html
Worm Community System	University of Illinois	data about the *C. Elegans* genome	http://csl.ncsa.uiuc.edu/CSLWWW/WCS.html

Table 1 (continued)

Developers and focus of existing collaboratories

Name and discipline	Developer/s	Focus	URL
Chemistry			
Collaboratory for Environmental and Molecular Sciences	Baetelle Pacific Northwest Laboratory	remote access to Nuclear Magnetic Resonance spectrometers	http://www.emsl.pnl.gov:2080/docs/collab/CollabHome.html
Spectro-Microsocopy Collaboratory	Lawrence Berkeley Laboratory University of Wisconsin-Milwaukee	remote access to the Advanced Light Source at Lawrence Berkeley Lab to obtain spatially resolved chemical information	http://www-itg.lbl.gov/BL7Collab.html
Humanities			
Collaboratory for the Humanities	University of Michigan	annotated electronic editions of sixteenth century manuscripts	http://www.hti.umich.edu/cgi-bin/imagemap/index?71,162
Medicine			

ARTEMIS	West Virginia University	telemedicine system for rural West Virginia	http://www.cerc.wvu.edu/nlm/nlm.html
Distributed Health Care Imaging	Lawrence Berkeley Laboratory, Kaiser Permanente	distribution of coronary angiograms from Kaiser Permanente's Cardiac Catheterization Laboratory in San Francisco to six Bay Area Kaiser Permanente hospitals	http://george.lbl.gov:80/Kaiser/LBL.CRADA.NII.html
InterMED Triad Collaboratory	Stanford University, Columbia University, Harvard University	dictionaries for disease description	http://www.cpmc.columbia.edu/intermed_proj.html http://camis.stanford.edu/projects/intermed-web http://dsg.harvard.edu/public/intermed/InterMed_Collab.html

Medical Collaboratory	University of Michigan	synchronous and asynchronous remote consultation about radiographs and ultrasound videos	http://www.si.umich.edu/~weymouth/Medical-Collab/index.html

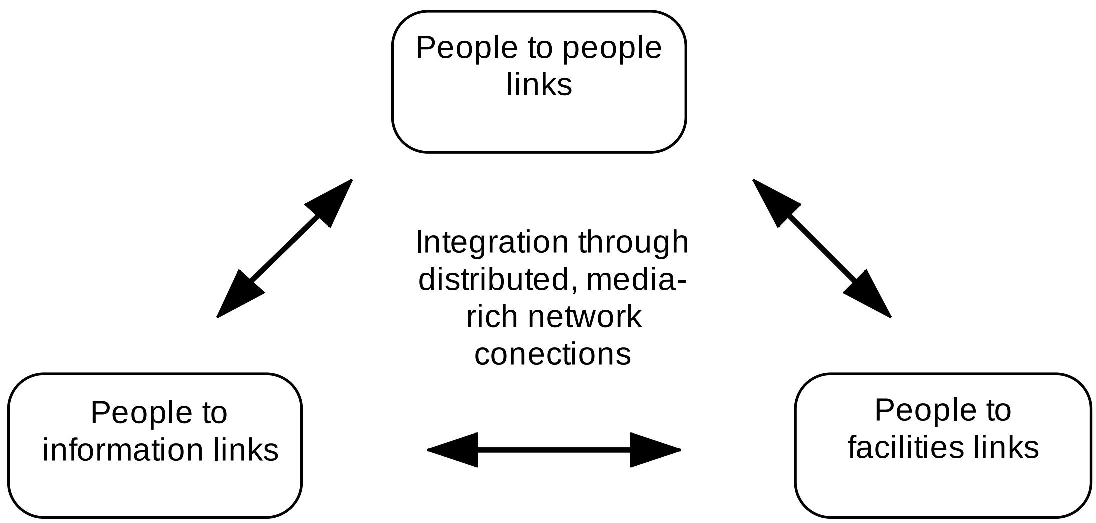
Table 1 (continued)

Developers and focus of existing collaboratories

Name and discipline	Developer/s	Focus	URL
Physics			
Remote Experimental Environment	Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Princeton Plasma Physics Laboratory, General Atomics	real-time participation in experiments conducted at the D-IIID tokamak fusion reactor at General Atomics	http://www.nersc.gov/Projects/REE/

Figure captions

Figure 1. The collaboratory concept: Using distributed, media-rich network connections to link people to each other, to facilities, and to information


People to people links
Integration through distributed, media-rich network conections
People to information links
People to facilities links