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Social Networks in the Virtual Science Laboratory

Communicating scientists' behavior, as well as their ideas, computer-supported cooperative work technology fosters virtual social networks of far-flung collaborators pursuing mutual interests and experiments.

Located at the Pacific Northwest National Laboratory in Richland, WA, the High Field Magnetic Resonance Facility houses 11 nuclear magnetic resonance (NMR) spectrometers. The Virtual Nuclear Magnetic Resonance Facility provides online Internet access to these spectrometers [4]. The VNMRF and its suite of tools for computer-supported cooperative work allow researchers to collaboratively set the controls of the spectrometers, execute NMR experiments, acquire data, analyze results,and communicate with other researchers, all without leaving their home institutions or offices (see Figure 1).

Virtual science laboratories like VNMRF represent a compelling vision [3, 6]. They are consistent with a notion laid out by William A. Wulf, former chairman of the Computer Science and Telecommunications Board of the National Research Council, of a "collaboratory," or virtual science laboratory, as a "center without walls, in which the nation's researchers can perform their research without regard to geographical location" [7]. Such laboratories strive to be open research environments in which scientists from various disciplines collaborate on advanced research using leading-edge instruments and tools while reducing the physical, organizational, and political boundaries that might otherwise inhibit them from fully using their collective skills, abilities, and brainpower to solve the world's most challenging scientific problems.

Here, we describe the social networks that have emerged from the VNMRF and the effects and influences computer-supported cooperative work, or CSCW, technology has on these networks. Their development depends on a number of factors, including personal and professional objectives, work functions, organizational roles, and collaborative capabilities. Our results over the past three years serve as a useful point of comparison when analyzing social networks and CSCW in scientific contexts, as well as in other collaborative settings, including those in business and education.

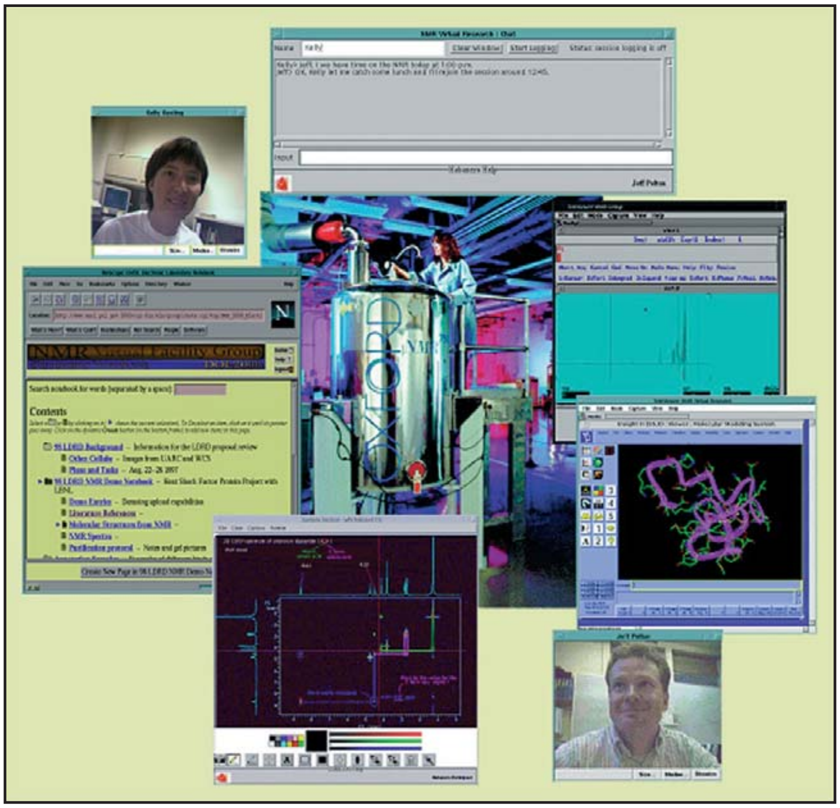

Figure 1. Instrument control, data analysis, and CSCW tools of the Virtual Nuclear Magnetic Resonance Facility at Pacific Northwest National Laboratory.

The NMR research community is unlike the communities that traditionally evolve around specific scientific disciplines, such as chemistry, biology, and physics, or more specific fields, such as inorganic chemistry, biochemistry, and structural biology. Whereas in these other communities, members are pulled together based on mutual scientific background, skills, and interests [5], the relationships among members in an NMR research community are tied to a specific complex scientific instrument—in this case, the NMR spectrometer. Like other kinds of instrumentation, such as electron microscopes, x-ray crystallography facilities, and light sources, NMR spectrometers are useful across many disciplines and fields. However, they and their associated experiments are sufficiently complex that a community of specialists has also developed around them.

NMR spectroscopists are typically educated and trained in specific scientific fields and thus belong to both the NMR spectroscopy and their domain science communities (see Figure 2). Looking across several scientific domains further illustrates how various scientific communities intersect with NMR spectroscopy. Figure 2 positions the field as a collaborative, unifying space for multidisciplinary research. Leveraging this view, the HFMRF provides an open environment in which multidisciplinary researchers share ideas, resources, and abilities, collaborating on cutting-edge research. However, left to their own devices, HFMRF users rarely initiate contact with other researchers. Rather, they come to the HFMRF with fixed agendas and schedules, focusing solely on them in designated areas of the physical laboratory.

In the HFMRF, consultants support and guide collaborating scientists in the use of the spectrometers. The consultants have therefore observed many experiments with varying samples, parameters, data sets, and results while serving as gatekeepers of practical knowledge. Their experience and knowledge facilitate development of research groups in a couple of ways: as conduits among HFMRF users, providing referrals to other scientists conducting similar or related research; and as sources of experience and knowledge useful to visiting scientists beyond instrument support.

Scientific Research Groups

The emergence of active research relationships in the VNMRF is important because it shows how

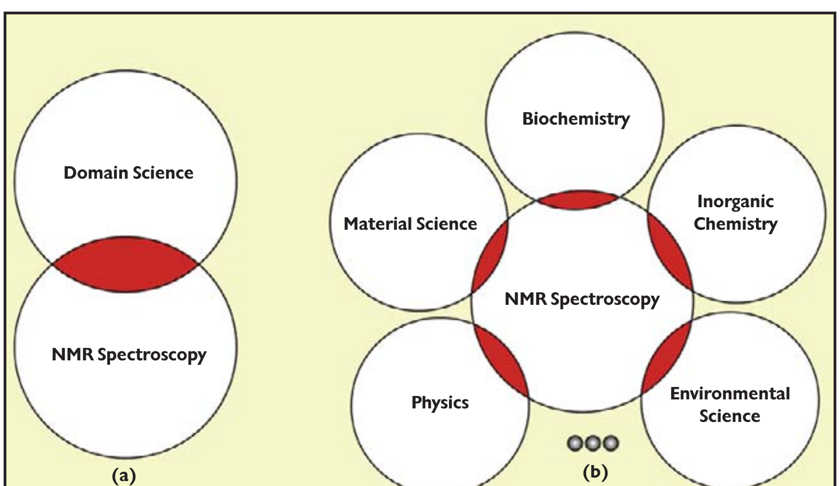

Figure 2. (a) An NMR spectroscopist's research communities; (b) multidisciplinary research communities intersecting with NMR spectroscopy.

strong collaborations evolve in an instrument-based science laboratory. To better understand the evolution of research groups, we've explored the transition of roles, duties, and expectations of VNMRF collaborators over time, observing five general phases of scientific research group formation:

Associative. Scientists build extensive research networks of contacts. They accumulate them through encounters and referrals at formal gatherings, such as meetings and conferences, and in virtual gatherings, such as newsgroups and mailing lists. With each one, a scientist has at least surface-level awareness of a contact's research, interests, skills, expertise, and available resources. Taking an egocentric view [2], Figure 3(a) identifies a representative set of contacts (by location) of a specific HFMRF consultant whose research network illustrates the proximal sprawl of potential collaborators and points up the need for distance collaboration.

Formative. Researchers enter into formal working relationships with the consultants. The duties and expectations of both user and consultant are based on their defined roles. For instance, users commonly request access to instruments, send samples, receive guidance on spectrometer operation, then operate the spectrometer directly. Consultants grant access to instruments, receive and insert samples, provide guidance on spectrometer operation, then monitor the use of the instrument. The interaction between users and consultants is aimed at the specific operation of the spectrometers and is narrow and prescribed.

Explorative. Working together, users and consultants gradually reveal their experience, knowledge, skills, and personalities to one another. Their relationships allow them to mutually explore one another's interests, skills, and expertise, identifying potential commonalities and complements, brainstorming theories and ideas, designing the experiment, and analyzing results. Mutual exploration also allows collaborators to assess their social compatibility.

Active. The working relationships between users and consultants fosters mutual trust, familiarity, comfort, commitment, and sense of ownership. Along with social compatibility, these characteristics are also the basis for more active scientific collaborations in which participants become peer researchers in an investigation. As such, they share day-to-day control of the experiment, as well as its direction. They mutually expect to be deeply involved in the research and share in its recognition.

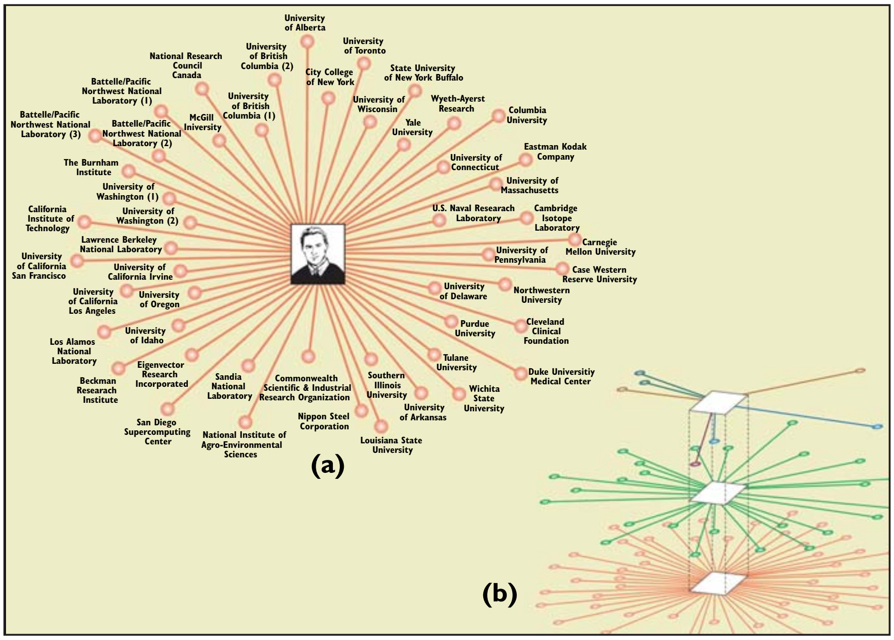

Figure 3. (a) An HFMRF consultant's research network; (b) mappings among the consultant's research network (bottom layer), assigned user group (middle layer), and active research collaborations (top layer).

Dormant. Active collaborations sometimes fall into a state in which the research becomes indefinitely suspended. A dormant collaboration may result from the loss of mutual trust, comfort, commitment, or sense of ownership among researchers. Alternatively, an active collaboration may fall dormant if it lacks the intellectual curiosity to keep it alive. Moreover, researchers may become preoccupied with new work activities, pushing aside earlier collaborations and projects. In other circumstances, there may be a breakdown in hypotheses or theories, the emergence of inconclusive experimental results, or the breaching of physical or theoretical limits of the instrumentation or resources. In many cases, the research collaboration moves back and forth between active and dormant states—as researcher interest, trust, comfort, commitment, and sense of ownership fluctuate, and available hypotheses, ideas, and instrument capabilities evolve.

Table 1 outlines the transition of roles and attributes across the five research-group-formation phases; it also covers the various artifacts shared among collaborators during each phase. For example, during the associative phase, collaborators share references and contact information. During the formative phase, they share access to and operation of the spectrometers, along with the laboratory environment in which they are located. Collaborators also share terminology and meaning as to the use of the spectrometers. As they enter into expanded working relationships in the explorative and active collaboration phases, collaborators share more abstract artifacts, including experiments, theories, ideas, and analyses.

Figure 3(b) outlines a specific HFMRF consultant's shifting groups and relationships. The bottom layer represents the consultant's initial research network of contacts; the middle layer the set of users the consultant supports; and the top layer four active research collaborations (identified by different colors) involving the consultant and specific users. Only a few active research collaborations emerge from the research network of contacts and the working relationships among consultants and users. From bottom to top, each layer also identifies the roles of a collaborator, from scientist-contact, to user-consultant, to peer researcher. Implicit is the increasing dynamism and intensity in the relationships, as communication and interaction become richer, roles more multifaceted, and tasks more collaborative.

Phase	Roles	Attributes	Shared Artifacts
Associative	Scientist-Contact	• Awareness of research work • Awareness of resources • Awareness of interests • Awareness of skills and expertise	• References • Contact information
Formative	User-Consultant	• Stereotypical interactions • Predefined roles • Limited expectations	• Access to resources • Operation of resources • Work context • Narrow vocabulary • Narrow meaning
Explorative	User-Consultant/ Peer Researchers	• Similar or complementary research interests • Similar or complementary research skills and expertise • Analytical interaction • Extended roles • Extended expectations • Social compatibility	• Theories • Experiment • Analysis • Richer vocabulary • Richer meaning
Active	Peer Researchers	• Mutual trust • Mutual familiarity • Mutual comfort • Mutual commitment • Mutual sense of ownership • Perseverance (maintenance of collaboration)	• Theories • Experiment • Analysis • Richer vocabulary • Richer meaning
Dormant	Peer Researchers	• Loss of mutual trust • Loss of mutual familiarity • Loss of mutual comfort • Loss of mutual commitment • Loss of sense of ownership • Loss of perseverance • Irreconcilable impasse	

Table 1. Phases of scientific research group formation.

Social Networks

The existence of both the VNMRF and HFMRF provides an ideal opportunity to compare virtual and physical science laboratories. Each kind of laboratory directly affects the evolution of the related scientific research groups. Here, we elaborate on several important collaborative features emerging from our comparative analysis, eliciting the effects, advantages, and disadvantages of the virtual over the traditional laboratory in the development of social networks. Table 2 summarizes our results, comparing collaborative attributes across the phases of scientific research group formation.

Extending research networks. Scientists also extend their personal research networks in traditional ways. They may encounter interesting research work at meetings and conferences and in publications, then initiate contact with the appropriate researchers. Contacts are also initiated through referrals; for example, HFMRF consultants commonly refer their users to past users and other PNNL scientists who may have similar research interests and experiences. Some referrals arise from serendipitous encounters; for example, one consultant described how simply walking past a researcher's office with a user could trigger an incidental connection between researcher and user. Once the connection is made, the consultant follows up with formal introductions.

Virtual science laboratories like the VNMRF extend research networks through the Internet. Scientists surf the Web for information, articles, and contact information relevant to their research interests. For instance, many VNMRF users initially discovered the facility through www.emsl.pnl.gov:2080/hfmrf/index.html. Research networks are also extended through other Internet-based mechanisms, including newsgroups and mailing lists.

Functional space for collaboration. To maintain a persistent collaboration space, researchers often invoke control, analysis, and CSCW tools on a specific computer and leave them running over several days. They return periodically to monitor the experiment and coordinate with their collaborators through the various communication channels. In a way, this virtual collaboration space is analogous to a physical labora-

Phase	Physical Science Laboratory	Virtual Science Laboratory
Associative	Researchers extend research networks via meetings, conferences, publications, and referrals.	Researchers extend research networks via mailing lists and newsgroups.
	Site visits to physical laboratory allow visitors to meet more members of host organization.	Widespread access to virtual collaboration spaces allows consultants to meet more researchers.
Formative	Required site visits to physical laboratory limit number of user-consultant collaborations.	Widespread access to virtual collaboration spaces provides unlimited number of user-consultant collaborations.
Explorative	Required site visits to physical laboratory limit contact among collaborators.	Instantaneous access to virtual collaboration spaces provides unlimited contact among collaborators.
	Limited communication (telephone, email) confines conveyance of ideas and expressions of thought.	Multimodal communication facilitates conveyance of complex ideas and rich expressions of thought.
	Physical laboratories hold researchers captive in a live, synchronous environment.	Synchronous and asynchronous interactions allow research to be partitioned and move forward in a natural, productive manner.
	Collaborators' interests, skills, expertise, and social compatibility are fully exposed in a physical laboratory.	Withheld interaction limits collaborators' abilities to assess each other's interests, skills, expertise, and social compatibility.
Active	Required site visits to physical laboratory limit amount of active research.	Instantaneous access to virtual collaboration spaces sustains active research.
	Limited communication (telephone, email) confines conveyance of ideas and expressions of thought.	Multimodal communication facilitates conveyance of complex ideas and rich expressions of thought.
	Physical laboratories hold researchers captive in a synchronous environment.	Synchronous and asynchronous interactions allow research to be partitioned and move forward in a natural, productive manner.
	Collaborators' actions and behaviors are fully exposed in a physical laboratory.	Withheld interaction reduces quality and viability of collaboration.
Dormant	Required site visits to physical laboratory pose barriers to reactivation of dormant collaborations.	Instantaneous access to virtual collaboration spaces facilitates the resumption of dormant collaborations.
	Site visits to physical laboratory uproot researchers from work environment and lessen competing interests.	Collaboration may turn dormant if the daily routine consists of many competing interests.

Table 2. Physical and virtual science laboratory effects on the phases of scientific research group formation.

tory in which researchers meet to set instrument controls, execute experiments, and analyze resultant experimental data. Unlike physical spaces, however, virtual collaboration spaces are portable, accessible from anywhere the user might be located.

The significance of a virtual collaboration space is that it provides widespread and instantaneous access to an experiment. Widespread access allows HFMRF consultants to meet more researchers (extending their personal research networks), thus entering into more user-consultant relationships, presumably yielding opportunities to form new research collaborations. However, the virtual collaboration space also reduces opportunities for the user to meet other researchers at the consultant's organization to whom they otherwise would have been exposed in a physical laboratory. On the other hand, instantaneous access to a virtual collaboration space provides collaborators unlimited opportunity to work together. For dormant collaborations, virtual collaboration spaces are readily available for the resumption of research activities. In contrast, having to return to a physical laboratory to restart research activities may be a limiting factor preventing dormant collaborations from ever reactivating themselves.

Multimodal communications. John Gabarro, an organizational behavior researcher at Harvard Business School, found that collaborators in mature and stable working relationships commonly employ many different forms of communication, liberally substituting among communication forms, because the "considerable mutual knowledge and experience" characteristic of these relationships require "a shared repertoire of meanings and ways of expressing those meanings" [1]. We have found that researchers share more complex ideas, abstract artifacts, and richer meaning and vocabulary as a scientific collaboration advances. As in Table 1, the artifacts they share become increasingly varied, intricate, and multifaceted in a working relationship.

In the traditional physical laboratory, remote scientists are constrained to only a few communications media like the telephone and email. Virtual science laboratories provide additional options, including text chat, audio/videoconferencing, electronic whiteboards, and electronic laboratory notebooks. These tools support not only the conveyance of rich meaning but serve to convey human behavior. In the VNMRF, remote researchers share spectra or data plots on the whiteboard, notes and messages in the text chat, structured results in the notebook, gestures and expressions through the video cameras, and conversation and speech inflections through the audio channel. Using the various communication media, remote collaborators convey complex ideas and rich expressions of thought—critical capabilities for the explorative and active phases of scientific research group formation where they pursue deeper, more analytical research activities.

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Synchronous and asynchronous research work. To some scientists, the physical laboratory represents a form of captivity; visiting researchers are held in designated areas while consultants feel obliged to accompany their guests. In a sense, virtual science laboratories liberate researchers, and collaborators are free to plan and schedule their interactions throughout the day. As a result, VNMRF users typically partition research tasks among themselves, perform them independently, then meet to coordinate results and future activities. Collaborators also meet at times when synchronous collaborative effort is essential, such as when brainstorming ideas, analyzing results, and debugging error conditions and problems. VNMRF's collaborative tools are well suited for the dual modes of mutual and independent work, providing real-time communication tools for synchronous interaction (such as audio/videoconferencing) and persistent record tools for asynchronous interaction (such as electronic laboratory notebooks and text chat). Support for both synchronous and asynchronous interaction allows exploratory and active collaborations to proceed naturally and productively.

Unlike a situation in which a collaborator physically looks over other collaborators' shoulders scrutinizing their every move and behavior, individual scientists may turn collaboration off and on through the VNMRF's CSCW tools. This capability is useful in a collaboration to help limit the amount of extraneous information passed among collaborators but may also be detrimental if used to hide critical actions or shut off potentially constructive interaction. For example, some consultants have used it to limit interaction with certain users they find difficult or to avoid having to explain the details of actions to inquiring users. In an explorative collaboration, the withholding of interaction may lessen the opportunity for collaborators to assess one another's interests, skills, expertise, and social compatibility, thus stalling a more active collaboration. In active collaborations, withholding interaction can diminish the quality of the collaborations and ultimately their viability.

Conclusion

Physical and virtual science laboratories are social spaces in which scientists interact, organize into groups, develop relationships, and share opinions, ideas, resources, and work. We've explored these spaces in the context of evolving scientific social networks, seeking to understand the positive and negative effects of CSCW technology on them and on their scientific research. We've found that the consultant is a central figure in the development of research collaborations and the control of collaborative capital. The collaborations and roles in the science laboratory can be described in terms of progressive phases. CSCW technology provides a number of benefits and challenges in forming scientific research groups; researchers can and do learn to adjust their processes to emphasize the benefits. Our analyses can inform development of CSCW tools and collaborative scientific research environments, yielding improvements in how scientists conduct research and, at the level of communities, scientific progress. **C**

References

1. Gabarro, J. The development of working relationships. In *Intellectual Teamwork: Social and Technological Foundations of Cooperative Work,* J. Galegher, R. Kraut, and C. Egido, Eds. Lawrence Erlbaum Associates, Hillsdale, NJ, 1990, 79–110.
2. Garton, L., Haythornthwaite, C., and Wellman, B. Studying online social networks. In *Doing Internet Research,* S. Jones, Ed. Sage, Thousand Oaks, CA, 1999, 75–105.
3. Goldberg, K., Ed. *The Robot in the Garden: Telerobotics and Telepistemology in the Age of the Internet.* MIT Press, Cambridge, MA, 2000.
4. Keating, K., Myers, J., Pelton, J., Bair, R., Wemmer, D., and Ellis, P. NMR facility. *J. Magnet. Reson. 145,* 2 (Aug. 2000), 262–275.
5. Kraut, R. and Galegher, J. Patterns of contact and communication in scientific research collaboration. In *Intellectual Teamwork: Social and Technological Foundations of Cooperative Work,* J. Galegher, R. Kraut, and C. Egido, Eds. Lawrence Erlbaum Associates, Hillsdale, NJ, 1990, 149–172.
6. Parvin, B., Taylor, J., Crowley, B., Wu, L., Johnston, W., Owen, D., O'Keefe, M., and Dahmen, U. Telepresence for in situ microscopy. In *Proceedings of the International Conference on Multimedia Systems and Computing* (Hiroshima, Japan, June 17–23). IEEE Computer Society Press, Los Alamitos, CA, 1996, 481–487.
7. Wulf, W. The collaboratory opportunity. *Sci. 261,* 5121 (Aug. 13, 1993), 854–855.

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