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Patterns of Contact and Communication in Scientific Research Collaboration

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Abstract

In this chapter, we describe the influence of physical proximity on the development of collaborative relationships between scientific researchers and on the execution of their work. Our evidence is drawn from our own studies of scientific collaborators, as well as from observations of research and development activities collected by other investigators. These descriptions provide the foundation for a discussion of the actual and potential role of communications technology in professional work, especially for collaborations carried out a distance.

For many people, the word *scientist* conjures up an image of a white-coated figure, working alone in a laboratory with mysterious instruments and substances. But, as scientists know, science is a fundamentally social process. Examinations of patterns of authorship in the sciences reveal that collaborative research is increasing in many disciplines. In psychology, for example, the mean number of authors per published article rose from 1.5 in 1949 to 2.2 in 1979 (Over, 1982). And, in 1981, over 65% of articles in a sample of six social psychology journals were jointly authored (Mendenhall, Oddou, & Franck, 1984). Nevertheless, there is little research that examines the reasons for the increase in the proportion of research that is published collaboratively, or, more importantly for our purposes, the work processes and problems that differentiate collaborative from solo research.

Yet this evidence of coauthorship means that science is a social activity not only in the sociology of science sense that researchers are connected in networks defined by their intellectual lineage and common interests (cf., Crane, 1976; Garvey & Gottfredson, 1977; Menzel, 1962), but also in the sense that their day-to-day work involves frequent and consequential interaction with other people—colleagues, students, and research assistants. The development of new ideas for scientific research, the execution of research tasks and the preparation of formal research reports have all become processes involving extensive social interaction, accompanied by all the complexity that characterizes other kinds of interpersonal relationships. But, with the notable exceptions of Pelz and Andrews (1966) and Allen (1977), we have little information about the ways in which social processes affect the process of doing science.

This is unfortunate because, in addition to their importance to science itself, research collaborations are an important social and organizational phenomenon. They are somewhat unusual in the realm of work relationships in that they are mainly voluntary and both their duration and their focus are determined by the participants. But this kind of work relationship may be becoming more important outside of academic settings as corporate restructuring minimizes vertical differentiation between employees and as the proportion of "knowledge workers" in the workforce increases. We believe that scientific collaboration provides a model of the way professionals in many fields construct intellectual products. Thus, understanding these relationships is important because they represent a distinctive work process, one that appears to be characteristic of many kinds of professional work.

Finally, to connect our interest in collaboration to the theme of this book, the study of research collaboration may help to specify the technological needs of cooperating work groups, as well as the limits on this technology. So far, improvements in technology do not seem to have caused or even facilitated the increase in the frequency of collaboration that we have reported. With the important exception of improvements in the quality and cost of telecommunications transmission, information technology has not evolved to meet the needs of collaborating research scientists. The trends already noted, however, suggest that opportunities to test and implement technologies supporting collaborative research are proliferating and seem likely to grow more in the years ahead. The premise of this chapter is that understanding the nature of collaborative work relationships can help to make those efforts a success.

Of course, collaborative success is a multidimensional concept; it includes (a) productivity—collaborations that produce an abundance of high-quality research products, (b) longevity—collaborations that last through multiple research projects, and (c) enjoyment—collaborations in which the process of working together is at least minimally pleasant (Hackman, 1987). Moreover, collaborative research relationships differ along at least three important dimensions (Hagstrom, 1965); these variations influence the criteria by which collaborations should be judged and place the observations we present later in context. First, collaborative research may involve a traditional, small-scale project such as an empirical investigation in social psychology or large-scale projects, common for example in particle physics. Second, collaborations differ depending on whether the substance of the research involves a theoretical science, such as mathematics, or an empirical science, such as biology or psychology. The former are characterized by collaborations among equals, with little division of labor, whereas the latter are characterized by more explicit exchange of services and more substantial division of labor. Finally, participants in a collaborative relationship may be peers or near peers, such as university faculty members, or researchers of unequal status, such as faculty members and their graduate students or paid assistants. Although this difference has important implications for many aspects of collaboration, it is not particularly relevant to our interest in technological support; thus, we leave the examination of status influences for a future paper. Here, we present the data we have gathered regarding small, "traditional science" collaborations, primarily in the empirical sciences. The goal of this chapter, then, is to examine some of the factors—especially patterns of contact and communication—that affect the likelihood that a collaborative relationship will develop and that it will be successful and to assess the implications of our findings for the design of technology to support collaborative work.

Our analysis of what brings researchers together and leads them to have successful collaborations draws on several sources of evidence, including data on the research and development process collected by us and by others and extrapolations from relevant literature in social psychology and organizational behavior. Our own data collection consists of three studies: (a) an interview study involving semistructured, hour-long, telephone interviews with one member of each of 90 research collaborations in social psychology, computer science, and management science, in which the respondents provided detailed information about the unfolding of a single collaboration; (b) a survey study in which 66 psychologists described the production and their evaluations of a sample of their published articles; and (c) an archival study in which personal, organizational, and geographic variables were used to predict who would work with whom among 93 members of a large research and development organization. We describe our methods and present portions of our data as they become relevant in the upcoming discussion.

ADVANTAGES AND DISADVANTAGES OF COLLABORATION

Both our own data and the prior literature provide mixed evidence about why researchers work together and the advantages and disadvantages of doing so. We learned from our interviews that researchers become involved in collaborative relationships for a variety of reasons. As Hagstrom (1965) suggested, combining resources to accomplish a project is a major reason.

Our interviews suggest that these resources are both material (e.g., grant money, research assistants, labor, computer time) and intellectual (e.g., substantive knowledge and methodological skills). Moreover, people collaborate because collaboration changes the process of research for them in desirable ways. For many of our respondents, working with another person was simply more fun than working alone. They also believed that working with another improved the quality of the research product, because of the synthesis of ideas it afforded, the feedback they received from each other, and the new skills they learned. In addition to these two major motives, a number of our respondents collaborated primarily to maintain a preestablished personal relationship. In a relationship threatened by physical separation, the collaboration provided a reason for keeping in touch. Finally, some researchers collaborated for self-presentational or political reasons, because they believed that working with a particular person or being in a collaborative relationship per se was valuable for their careers. Of course, these motives are not mutually exclusive, and in most cases respondents cited a combination to explain whey they chose to collaborate.

These professed motivations for collaboration all imply that it has a positive influence on the research process. Through collaboration scientists are able to tackle problems that they are incapable of working on alone because of limitations on their resources, skills, or time. They have more fun doing the work, and their reputations improve in the process. But there is considerable evidence from research on various aspects of group performance that would lead one to be skeptical about claims of unalloyed benefits from research collaboration. In particular, our knowledge of process losses stemming from conformity effects (Janis, 1972), social loafing (Latane, Williams, & Harkins, 1979), and difficulties in coordinating activity (Steiner, 1972), as well as evidence that group problem-solving processes such as brainstorming are not necessarily superior to individual efforts (Dunnette, Campbell, & Jaastad, 1963; Lewis, Sadosky, & Connolly, 1975) cast doubt on this proposition. Direct evidence relevant to these claims is sparse because the prior literature on scientific collaboration has not examined questions of quality; the only relevant study we found is Presser (1980). His analysis of acceptance rates in one social psychology journal for a single year suggests that collaborative articles are better than solo ones; for this journal, articles with multiple authors received higher evaluations from reviewers and higher acceptance and conditional acceptance rates than solo-authored articles.

We attempted to gather additional data about collaborative processes and products by surveying researchers who had moved into or out of jobs at one of the top departments of psychology in the United States between 1980 and 1983. We were able to locate the current mailing addresses of 95 of the 98 psychologists whose names were given to us by 30 university departments, and we sent each of these authors a questionnaire containing titles, publication dates and authorship information about the articles they had published

between 1975 and 1986. These titles, which were drawn from *Psychological Abstracts*, included all of their solo articles and up to two randomly selected collaborative articles for each year during this period. We oversampled solo articles, because about 75% of the articles published by these authors were coauthored. For each article, respondents reported project start and end dates, how far their offices were from that of their principal coauthor, and how frequently they communicated with that coauthor. They also rated their satisfaction with various aspects of the research relationship, with the work process, and with the article itself. Sixty-six (69%) of the authors completed these questionnaires.

The results of our survey lead to a somewhat less favorable view of collaborative research than either Presser's data or the endorsements presented by many of our interviewees. For instance, among the authors in this study, having a collaborative research style did not lead to greater overall productivity. Some authors tended to be productive by writing more—both collaborative and noncollaborative articles (r (total collaborative $\times$ total solo articles) $= .33$; $N = 66$; $p < .01$),—but those who wrote a higher proportion of collaborative articles were no more productive than those who wrote a higher proportion of solo articles (r (proportion collaborative $\times$ total articles) $= .20$; $p > .10$).[1] Thus, the reported claim that one can "get more articles out" by working collaboratively does not seem to be supported by these data.

We also examined respondents' evaluations of solo and collaborative articles and the production process. These questions were presented in an ipsative format (i.e., compared to an author's own corpus) and respondents reported their evaluations on five-point Likert-scales where 1 meant that a particular article was worse than average on a specified dimension for that respondent, a 3 meant that it was typical of the respondent's work, and a 5 meant it was better than average for that respondent. Table 6.1 shows the results of the comparison of these evaluations for 57 respondents who had published at least one solo article ($M = 3.6$) and one collaborative article ($M = 12.7$).

In general, these psychologists rated their solo-authored articles more highly than their collaborative works, both in terms of outcome and process. In particular, they thought manuscripts they wrote alone were better (i.e., clearer, more ingenious and of better quality; $p < .05$) and the work they represented was more important (i.e., more central to the field and of higher theoretical and empirical quality; $p < .10$). They also thought it was easier to

[1]Although these correlations both seem small and similar to each other, they are influenced by outliers. Computing robust correlations by dropping the most extreme respondents raises the correlations between solo authored and collaboratively authored articles, but lowers the correlations between proportion of collaborative articles and total productivity. For example, dropping the most extreme 20% of respondents raises the former correlation to .57, but lowers the latter to .07.

TABLE 6.1
Differences Between Solo and Collaborative Research

Outcome	Solo Mean	Collaborative Mean	t	r
Satisfaction with publication	3.9	3.7	−2.02	−.26**
Satisfaction with research process	3.9	3.7	−1.45	−.19
Perceived importance of work	3.4	3.2	−1.7	−.22*
Ease of scientific & technical tasks	3.2	3.0	−1.54	−.20
Ease of managerial tasks	3.8	3.1	−4.41	−.53***
Years to complete project	1.6	1.7	+.34	+.06
Citations within 3 years	6.3	5.8	−0.61	−.08

*$p < .10$
**$p < .05$
***$p < .01$

handle the managerial work of research (e.g., supervising assistants, handling paperwork, meeting deadlines, coordinating information; $p < .001$) when working alone, and no harder to handle the scientific and technical tasks (i.e., refining hypotheses, devising methods, applying statistics, or expressing ideas; $p < .15$). More objective measures of research quality also fail to show that collaborative articles are superior to solo articles. For example, both solo and collaborative articles took about 19 or 20 months from planning to writing a draft for publication and both garnered about six citations in the *Social Science Citation Index* within three years of their publication. Finally, a stylistic analysis of manuscripts from a different sample of researchers showed no differences in readability between single and multiauthor publications. In sum, we do not find much evidence that collaborative research is more advantageous to either the researcher or science.

Given these outcomes, one might wonder why so many researchers work collaboratively and why the proportion of collaborative scientific research has been increasing. As Beaver and Rosen (1979a,b) argued, both the increased professionalism and the increased empiricism of science is associated with greater collaboration. In psychology the ease or feasibility of working in one way versus the other may depend on the nature of the project. The work involved in executing an empirical project is more amenable to division of labor than the work involved in producing a theoretical article. Thus, we might argue that one reason for the high proportion of collaborative articles in our sample and for the general increase in collaborative psychological work noted earlier is the way psychology has become an increasingly empirical discipline, with current practice differing substantially from say, Freud, William James, and more recently, Piaget.

This apparent relationship between empiricism and collaboration can be seen as part of a larger trend—the increasing sophistication—including

tivity. Over time, science has changed from a lonely, sometimes speculative, intellectual pursuit carried out by individuals such as the isolated, white-coated figure portrayed in the earlier description to a highly professionalized, heavily funded and, in some fields, more rigorous, activity carried out within a highly complex social system. This change is both required by and a determinant of changes in the kinds of research questions scientists undertake.

To understand more about how the institutionalization of science contributes to the occurrence of collaborative research, and, in particular, about how specific collaborative relationships arise, we turn now to an examination of the role of physical proximity as a determinant of who collaborates with whom. We argue that professionalization and institutionalization result in groups of scientists being colocated; this physical proximity, in turn, makes it possible for scientists to find research partners and to carry out their research work in efficient ways. In the following section, we focus on the role of proximity in the process of partner selection among scientific collaborators and describe ways in which proximity aids in the execution of research tasks.

PHYSICAL PROXIMITY: THE FRAMEWORK FOR SCIENTIFIC COLLABORATION

In an earlier work (Kraut, Galegher, & Egido, 1988), we reported that physical proximity helps scientists avoid or minimize many of the problems that arise in the process of conducting research—meeting partners, defining problems, planning projects, supervising coworkers and subordinates—and may influence the probability of repeated collaboration. In this section we treat the role of physical proximity in more detail by examining its effects on the collaborative process and the mechanisms by which it has its effects.

As noted before, the process of selecting a research partner is in many ways analogous to the process of choosing a mate, with combinations of mutual benefit, personal and intellectual compatibility, and ease of contact all influencing whether a pair of potential partners decide to work together. In this process, simple proximity is especially important. As Hagstrom (1965) noted in his study of 96 university faculty and other scientists, "spatial propinquity often leads to collaboration since it is likely to lead to informal communication" (p. 122). In our interview data, this general phenomenon is illustrated by a husband and wife pair who discussed research possibilities in the bathtub and a former pair of housemates whose research plans emerged over the breakfast table. More frequently, researchers in the same academic department decided to work together following informal discussions over lunch or coffee.

systematic effect of propinquity on the likelihood of collaboration. To do so requires a different type of data than either our own or Hagstrom's interview studies provide—data that include information about pairs who did not collaborate as well as those who did. We obtained these data by looking at the relationship between propinquity and collaboration among research scientists and engineers in a large industrial, research, and development laboratory. These data show that within the laboratory, proximity is associated with research collaboration.

The research component of this research and development company consists of approximately 500 PhD and MS-level researchers in the physical, engineering, computer, and behavioral sciences. The organizational structure consists of three hierarchical levels (laboratories, with approximately 125 members each; departments with approximately 30 members each; and groups with approximately 7 members each). The laboratories are located on two campuses, located approximately 40 miles apart. Each building consists of several floors, with several wings per floor. We selected a sample of 93 researchers, all those who had published at least two internal research reports in 1986 and 1987. At least one of these reports had a coauthor, and the other was either a solo-authored report or had a coauthor not included in the first report. For each of the 4,278 unique pairings of the 93 researchers in the sample, we obtained data on four measures:

1. Collaboration: Data on whether that pair published at least one internal research report together were obtained from a company-maintained database of internal publications.

2. Organizational proximity: Proximity on the organizational chart was coded 1 if the pair were in the same group, 2 if they were in the same department, 3 if they were in the same laboratory, and 4 otherwise.

3. Physical proximity: Using the organizational phone book, which listed office addresses with codes for building, floor, and corridor, we computed a rough measure of physical proximity. Offices were coded 1 if they were on the same corridor of the same building, 2 if they were on same floor of the same building, but different corridor, 3 if they were on different floors of the same building, and 4 if they were in different buildings.

4. Research similarity: For each pair, we computed an index of the similarity between the publications of one member and those of the other member on which the first individual was not a coauthor. This index is based on the assumption that authors who share research interests will have written reports containing similar concepts and that abstracts of these reports contain sufficient detail to demonstrate this similarity. The research similarity index is based on information retrieval techniques developed to identify semantic similarity in large text sources (Deerwester, Dumais, Furnas, Landauer, & Harshman, in press). Basically, the similarity of a pair of abstracts is a function of the proximity of the concepts they contain in a semantic space.[2]

TABLE 6.2
Distance Between Offices and Probability of Research Collaboration

Office Location	*Actual Collaborations*	*% of Actual*	*Potential Collaborations*	*% of Potential*
Same corridor	25	46	243	10.3
Same floor	20	36	1038	1.9
Different floors	5	9	1736	.3
Different buildings	5	9	1261	.4

Table 6.2 shows the association of collaboration with distance between potential collaborators' offices, without controlling for any other variables. The data clearly show that pairs whose offices were close to each other were more likely to collaborate (Yules Q for the 2×2 table comparing same corridor and floor to different floor or building = .82; $p < .001$).[3] Eighty two percent of collaborations occurred among researchers with offices on the same floor, even though these constituted only 12% of potential collaborative pairs.

Mechanisms Underlying the Relationship Between Proximity and Collaboration

To explain the association between proximity and the likelihood of research collaboration, we present data from our studies of collaboration and from the more general literature on propinquity in the social science research literature. This evidence is organized around two general explana-

[2]Lynn Streeter and Susan Dumais suggested this approach, and Karen Lochbaum aided us by writing computer programs for this analysis. The analysis starts with a large matrix representing the number of times each of 7,100 terms appears in each of the 4,000 abstracts of research reports from the company. This matrix is reduced to a large number of orthogonal dimensions using singular value decomposition, so that terms that are similar in meaning appear as neighbors in the space. The centroid of the words in each author's abstracts was used to represent his or her work in this multi-dimensional space. In comparing any two researchers, we use only those abstracts in which the other was not a co-author (i.e., solo authored work or collaborative work with other co-authors). The research similarity between two authors is the cosine or product moment correlation between the 100 dimensional vectors representing each author. A cosine of 1.0 (a 0 degree angle) would indicate that the two authors' papers are on top of each other in the space.

[3]Yules Q is a measure of association for 2×2 tables with unequal marginals. It is -1 if the least frequent variable never co-occurs with the more frequent variable. 1 if it always co-occurs, and 0 if there is no relationship between variables.

tions—colocation of similar others and the availability of frequent, high-quality, low-cost communication as a mechanism to facilitate the development of ideas and the execution of collaborative tasks. After dismissing the hypothesis that this relationship is entirely a consequence of the fact that individuals with similar interests are colocated, we discuss the impact of informal communication on both social and mechanical aspects of collaboration.

The Influence of Colocation

One explanation, bordering on artifact, is that researchers who are similar to each other in important ways also have their offices close to each other. It is true that both in academia and in industry researchers whose offices are close together are likely to share common organizational goals and to have research interests in common. In a university, for example, members of an academic department are likely to be colocated, and subspecialities within the same department often have offices on the same floor, corridor, or in the same wing of a building. It is possible that this similarity in research interests, not the fact of proximity, is sufficient to lead to research collaboration. Indeed, in our research and development sample, researcher pairs in the same department were more likely to work together than those in different departments (52% of 294 of the pairs in the same department versus .7% of the 3,984 pairs in different departments; Yule's Q = .88). Moreover, those with similar research interests as defined earlier were more likely to work together (3.3% of pairs in the top quartile of similarity versus .3% of those in the bottom quartile; Yules Q based on a median split of similarity = .74).

But the effects of propinquity on research collaboration cannot be completely explained by organizational proximity and similarities in research interests among those who are close to each other. In a logit analysis holding constant organizational proximity and research similarity, physical proximity has an independent effect on research collaborations. Table 6.3 shows

TABLE 6.3
Numbers of Research Collaborations by Organizational and Physical Proximity

	Organization			
	Same Department		*Different Department*	
Office Location	*Pairs*	*% Collaborating*	*Pairs*	*% Collaborating*
Same floor	271	10.3	909	1.87
Different floors	23	4.3	1708	.29
Different buildings	0	NA	1261	.40

the association of collaboration and physical proximity holding constant the organizational proximity between potential collaborators (i.e., whether they were in the same or different departments). Our sample did not include enough pairs of researchers who were in the same department but sufficiently far apart to analyze the effects of physical distance within a department. We did, however, have enough variation in physical distance among researchers in different departments to examine this relationship. Table 6.3 shows that among researchers in different departments, pairs of researchers who were on the same floor as each other were about six times more likely to enter into research collaboration than pairs on different floors or in different buildings.

Clearly, even among researchers in different departments, having offices on the same hallway increases the likelihood of research collaboration. Instead, what appears to be important is the opportunity for unconstrained interaction provided by proximity.

The Importance of Informal Communication

Most often, naturally occurring, informal contact and communication provide the opportunity for potential collaborators to learn about each other, and also serve as the framework within which collaborative tasks are accomplished. To illustrate the importance of these opportunities, we describe three properties of informal communication and show how these properties affect collaborative work and collaborative relationships.

Communication Frequency. The major mechanism through which proximity has its impact on the likelihood of research collaborations and on their longevity is through its impact on frequency of communication. Even if we consider technologically mediated communication such as telephone (Mayer, 1977) and computer mail usage (Eveland & Bikson, 1987), the frequency of communication between any two people is a strong function of their geographical proximity. What holds true in the world of residential phone service and corporate mail networks holds true in the research world as well. As our interviews and those conducted by Hagstrom indicate, the informal contact that results from frequent opportunities for communication often leads to collaboration. In his sample of industrial research and development engineers, Allen (1977) showed a striking logarithmic decline in communication frequency with distance between potential communicators. For example, in Allen's data, about 25% of engineers whose offices were next door to each other (less than 5 meters apart) talked to each other about technical topics at least once a week; if their offices were 10 meters apart, this figure drops below 10%. After this sharp decline, the curve asymptotes at approximately 30 meters, so that engineers, 30 meters apart and those several miles apart had approximately the same low probability of talking to each other at least once a week.

Our own data show a similar phenomenon even among collaborators already working together. In our survey study of collaboration among psychologists, we asked our respondents to indicate the distance between their own offices and those of the primary coauthor for each of their collaborative articles and to estimate the frequency of their communication with this coauthor when initially planning the project and when planning the journal article itself. Distance was measured on a seven-point, semilogarithmic scale, where a 1 meant that offices were next door, a 4 meant that they were in different floors of the same building, and a 7 meant they were in different states. Communication frequency was measured on a seven-point semilogarithmic scale, where a 1 meant that the collaborators communicated multiple times per day, a 4 meant that they communicated about once per week, and a 7 meant that they communicated less than once a month. Physical proximity was strongly related to frequency of communication during both the planning stage and the writing stage of the research process, as shown in Fig. 6.1. It demonstrates, for example, that researchers who have offices next door to each other have approximately twice as much communication as those whose offices are simply on the same floor.

As a result of this frequent interaction, researchers who are situated near each other are likely to come to like each other more. According to Zajonc (1968), merely being in contact with a person or object increases one's liking

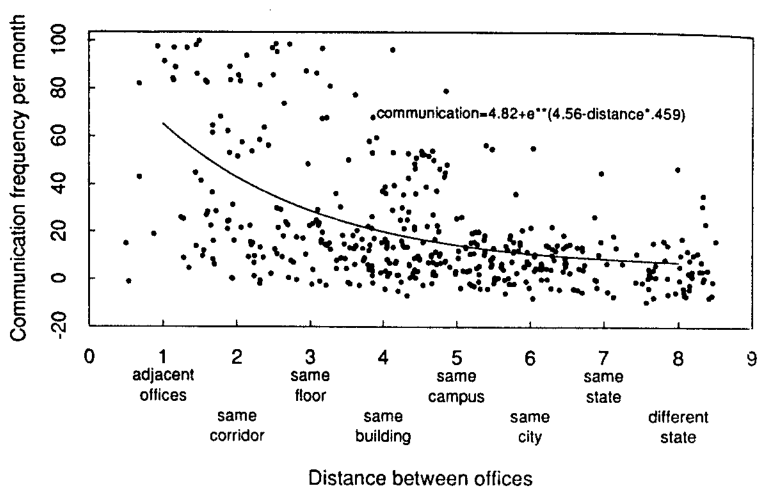

FIG. 6.1. Communication frequency as a function of physical distance.

for it, perhaps by reducing the inherent dislike people have of the unfamiliar. In addition, because one is likely to have to deal with neighbors in the future, the human tendency to like those with whom we anticipate future interaction (Darley & Berscheid, 1967) and to feel in a unit relation with them (Heider, 1958) may also come into play. If, in turn, people are more likely to want to work with people they like, then the opportunity for frequent interaction is likely to have a strong influence on the likelihood of collaboration.

Quality of Communication

In addition to increasing the likelihood of informal communication through increased contact, proximity increases the quality of communication. By high-quality communication, we mean two-way interactions involving more than one sensory channel. The opportunity for interactions of this type is especially important during the initiation and planning stages of a project, when the need for a rich communication modality is strongest.

Our interview data provide evidence of how high-quality informal communication brings researchers with diverse backgrounds and interests together. In the typical situation, a common focus for collaborative projects was constructed from the preexisting interests and expertise of the participants. One example of this sort of relationship is a social psychologist who sought a collaborative relationship with a cognitive psychologist to develop an ill-specified project in social cognition. He said, "the idea was still very fuzzy. We often eat lunch together, so there are many informal opportunities to raise issues and discuss them . . . it was in one of those informal settings, at lunch, or after lunch sometime, I brought up the issue the broad outlines of things, little things meshed and she recommended I read a particular paper." These informal conversations eventually grew into a collaborative project that joined the interests of these two researchers. It seems unlikely that one could have predicted the occurrence of a collaborative relationship between these two individuals, but, in this case, and in many others, the opportunity for high-quality, informal interaction led to a productive relationship. In sum, our data suggest that high-quality informal communication is important because it allows researchers to develop common interests with their neighbors.

Drawing again on our interviews, we learned that discussions of this type tend to merge into more focused conversations about specific projects. According to our respondents, the initial task-level activity in a collaborative relationship usually consists of multiple face-to-face discussions, occurring frequently over the course of days, or, more typically, weeks or even months. Our survey data support this observation; they indicate that when collaborators are most intensively planning their work, they meet almost daily (*M*

= 27 times per month). These discussions are the most intensely interactive aspect of the entire research process and, according to the researchers, the most intellectually exciting and rewarding aspect as well. At a later stage of project development, when collaborators are planning the writing of their research reports, we observed a similar reliance on frequent face-to-face communication. Although actual writing is most often a solitary activity, our survey respondents report meeting 17 times per month while planning these documents. Although frequent, this is significantly less than during initial project planning ($p < .001$).

The intense, highly interactive meetings that characterize planning work generally take place in offices or conference rooms and, typically, the only technologies involved are paper, pencils, and blackboard. Most often, the participants do not prepare for these meetings in any formal sense. There is little reliance on prewritten documents or diagrams as a basis for the discussion; instead, collaborators seem to value the opportunity for spontaneous, informal, and unstructured exchange of ideas. The participants talk, argue, interrupt, write equations, draw sketches, and modify both their own and their partners' work. Participants may take notes in order to have a record of important observations or issues that arise in the conversation or to remind themselves of things to do—articles to read, people to contact, purchases to make—but there is usually no explicit effort to make a formal record of the proceedings. In listening to reports of these conversations, one has the sense of high energy levels and a high level of concentration on the serious, substantive intellectual questions involved. Current communication technology available to most researchers does not allow the intensity of interaction nor the spontaneous exchange of notes and documents that are typical of these face-to-face meetings. Thus, quality problems are likely to arise because research partners are unable to engage in rapid-fire conversation or are unable to obtain the feedback they need to adjust their communications to fit their partners' information needs (Krauss & Weinheimer, 1967; Kraut, Lewis, & Swezey, 1982).

Cost of Communication

A third important feature of communication with one's research partners is cost. Some costs are obvious; if one's research partners are not colocated, the costs of collaboration will have to include the expense of plane tickets and phone calls. More importantly, they are also likely to include the burden of having only intentional, structured interactions via a restricted modality within an already existing relationship. But proximity makes it possible to explore new relationships, and to supervise and sustain progress by providing the low-cost communication necessary to assess compatibility, to catalog what has been done, to alert partners to minor problems, and to enforce guilt.

Being situated near a pool of potential collaborators provides a low-cost opportunity for a researcher to discover the qualities of another that might make him or her a desirable collaborator. This increased awareness of the attributes of one's neighbors allows one to choose partners judiciously, lowering the risk of selecting an inappropriate collaborator. Later on, low-cost communication and the opportunity for quick and easy access to a partner are crucial for collaborators' joint supervision of the project and each other's work. For most of our researchers, project management was extremely informal, with the supervision of subordinates and coordination with peers occurring during casual hallway and lunchroom conversation as often as through formal, scheduled meetings. These "on the fly" interactions are impossible in collaborations over a distance.

Proximity also allows collaborators to share even small decisions. Many of the sticking points in conducting research are minor. They consist of questions like: Should I change the wording of a question in a questionnaire? At what points should we break the program into modules? While working alone, one would simply make a decision. When working with a collaborator, researchers often want to consult with each other on such points, if only to preserve the balance of control they and their partners share in the project. Distance raises the personal costs of communication, so that short messages become uneconomical. As a result, distance cuts down on nags and feedback, which are both crucial to accomplishing collaborative activities. Many interviewees reported frustration at the slowness of working with collaborators who were in different locations. For instance, in describing problems in finishing up projects at a distance, one researcher said, "[This] was the first project that I had done long distance and it certainly made it more time consuming. I was used to being able to walk down the hallway from my office to [my collaborator's] office to talk to him about a problem . . . [In the long distance collaboration] we either relied on the mail going back and forth or even phone conversations and that just wasn't as satisfactory as talking face-to-face . . . It took a long time, and I wasn't used to having that much of a lag for the turn-around . . . I was used to being able to make it much faster."

In sum, having multiple opportunities for high-quality, low-cost interactions makes it possible for potential collaborators to find each other and to manage their work efficiently. Without these opportunities for informal communication, collaborations don't get started, and if the opportunity for informal communication declines, collaborative work typically slows down, becomes more burdensome and, sometimes, comes to an end.

Limits on the Influence of Proximity

Although physical proximity provides people with the opportunities for informal interaction that are important to the initiation of collaboration and managing the work, according to our survey data it does not seem to be associated with either the likelihood of continuing to collaborate with a particular coauthor after an initial project or with the collaborators' satisfaction with their work and the process of producing it—at least not within the normal restricted range of distances from which researchers choose their collaborative partners. However, this null finding may be a function of our methodology, because we do not have estimates of the distance between collaborators after they broke up, and we do have evidence that many collaborations break up if the partners move apart. Our interviews are replete with cases in which a successful collaboration stopped because one partner moved away. For instance, one researcher reported that although he and his former partner often generated ideas for new projects over cocktails at annual conventions, the plans never came to fruition because they never had the opportunity to have the "second conversation" needed to build the idea into a real project (Kraut et al., 1988).

Our survey data indicate that these outcome measures are associated with the pleasantness of the interpersonal relationship between the collaborators, thus we intend to explore the determinants of longevity and satisfaction by discussing collaborative relationships as relationships in a future study. We believe that examining scientific collaboration from this perspective will offer substantial insight into the social psychology of science, a largely unexplored territory. Here, our interest in technology leads us to focus on using the description of collaborative processes that we have already presented as a basis for making recommendations about how technology might make these processes easier and more efficient, especially for collaborators working at a distance. We think it is likely that such technology would also indirectly aid the maintenance of the personal relationships that apparently sustain collaborative work by increasing the opportunities for frequent, high-quality, low-cost communication.

IMPLICATIONS FOR TECHNOLOGY FOR COLLABORATIVE WORK

The previous discussion has natural implications for the design of technology to aid collaborative work. In the following paragraphs we revisit some of the functions that proximity plays in research collaborations and recast them as requirements for group communications technology. We argue that current research in this area concentrates too heavily on the computer support of work-related activities performed once a collaborative effort is underway and directly related to the successful completion of work products. Furthermore, many computer technologies aim to structure these work tasks in ways that fundamentally alter the collaborative process. According to our view, communications technologies that allow more free-form interaction in real-time and time-shifted modes to augment and even to substitute for physical proximity are likely to yield greater benefits. As we discuss later, the aim should be specifically to increase the frequency and quality and to decrease the cost of interactions among potential collaborators who are working across barriers of place and time.

The spate of recent workshops and conferences devoted to the subject reflects the growing interest in refocusing research and development in information technology to address the needs of multiperson work teams, particularly distributed work terms. At least three general classes of tools are needed to support these teams: (a) communication tools to facilitate both planned and unplanned real-time and delayed interactions among collaborators, (b) coordination and management tools to minimize the overhead inherent in multiperson work, and (c) task-oriented tools designed to facilitate the completion and integration of specific work products, whether individually or jointly executed.

Most of the research activity in technologies to support work groups has concentrated on a small part of this range, either on enhancements to formal face-to-face meetings with the explicit goal of structuring interaction or on highly task-specific applications. Thus, technologies such as teleconferencing, group decision support systems (e.g., Kraemer & King, 1986; Vogel & Nunamaker, chap. 19 in this volume), group outlining systems (e.g., Cognoter—Foster, & Stefik, 1986), and group drawing programs (Lakin, chap. 17 in this volume) are designed to facilitate formal meetings among coworkers. Moreover, they often often fix on narrow, albeit important, aspects of these meetings. Tools like collaborative writing systems (Olson & Atkins, chap. 16 in this volume; Fish, Kraut, Leland, & Cohen, 1988) support specific tasks within the total work process. As such they support only a minor portion of the communicative activities that occur in the course of a cooperative work effort.

In the following discussion, we use our knowledge of the functions that proximity serves in research collaborations to define basic requirements that communication technologies must meet to support research collaboration, or for that matter, any cooperative intellectual work that spans months and is at least partially based on a sustained personal relationship among the members of a work group. We believe that these functions translate into two fundamental requirements for communication technology: high quality and low personal cost. Although high quality at low cost is a marketing platitude that has been applied to automobiles, hot dogs, and dishwashers, it applies with special meaning to communications technology. By low cost we mean that the communications medium should be so ubiquitous that a potential user need make no planned effort to use it. That is, the behavioral cost to the actual user would be low, even though the financial cost to users or the organization supporting them may be high. As we said earlier, high quality means that the communication system allows users to transmit all of the information they need to exchange rapidly. Typically, this will mean a two-way (or N-way) communication link involving more than one sensory channel. We expand on these requirements in the following sections.

Low-cost Interactions

As discussed earlier, frequent, informal, and, at times, unplanned contact provides a mechanism for both bringing together potential partners as well as for maintaining existing collaborative relationships. Indeed, we believe the lesson of the J-shaped relationship between distance and communication frequency lies in the fact that much useful communication between research partners is not planned and would not occur if it had to be planned (see Abel, chap. 18 in this volume). During the initiation of a collaboration, proximity allows low-cost contact that provides potential collaborators with the opportunity not only to make contact with each other but to discreetly assess and develop their mutual compatibility before committing to work together. Opportunities for spontaneous communication are especially important in the preplanning stages of a research collaboration, when potential partners are playing with ideas and surreptitiously assessing each others' desirability as a research partner. Once they become committed to working together, frequent communication holds together the threads of a collaborative relationship over time. During the execution of the work, proximity plays a crucial role in project management and mutual supervision between collaborators. The frequent, low-cost communication that proximity permits enables collaborators to provide each other with both subtle prods and status information through casual interactions. Also, quick and easy access to a partner permits sharing of major and even minor decisions and, thus, creates the sense of ownership that keep participants committed to a project. Finally, and perhaps most importantly, throughout the collaborative process as a whole, proximity supports a convivial personal and working relationship by building a consensus of views and interests and maintaining shared knowledge about the project and about the local culture in which it is embedded.

To maintain this level of communication in the absence of proximity requires technology that makes communication cheap, frequent, and spontaneous enough that collaborators can be in touch as easily as if their offices were next door to each other. The technology must allow not only frequent but informal and unplanned interactions as well; many of the interactions that make up this feedback over time are damaged by intentionality and simply would not occur if they must be willfully initiated. This goal of adding a random component to communications is at odds with the traditional goal of communication technology from the courier to the telegraph,

from the telephone to electronic mail, which has been to support intentional, planned communication. In point-to-point communication systems (as opposed to broadcast systems), senders have to have a recipient in mind before they initiate communicative activity. For example, they dial the phone number before they talk.

However, this approach to communication technology is not inevitable. The concept of an electronic hallway or sidewalk where people in different locations can meet spontaneously was raised at least as early as 1975 (Thompson, 1975). The recent experiment at Xerox to provide an omnipresent video connection between two of its research facilities (Goodman & Abel, 1987; Abel, chap. 18 in this volume) is one of the few innovations in the use of communications technology that takes this concept seriously. This pioneering experiment is unique in that it created an environment that encouraged unplanned interactions mediated by technology over considerable geographic distance. Usage data indicated that over 70% of the interpersonal communication between the two sites was casual, drop-in style interaction of less than 5 minutes in duration and that these interactions would likely not have occurred in the absence of a continuous video link. Participants' experiences suggest that having this video link was marginally adequate to promote a shared context and culture that supported joint work across the two locations.

Unfortunately, the communications technology in the Xerox experiment was limited, both by the state-of-the-art in commercial video equipment and by the high financial costs of transmitting the huge amount of information that comprises moving video images. As a result the two locations were linked only by a single channel for slow scan video, two lines for audio connections and an additional one for data. Participants felt that this was inadequate to support crucial aspects of cooperative work, such as project initiation, delicate negotiation, and detailed joint work that required shared graphics (Abel, chap. 18 in this volume). The logistics of switching the limited video resource became burdensome, and in any case, was not sufficient to match the quality of the spontaneous interactions that physical proximity provided within a work site. We deal with some aspects of these deficiencies in the technology in a later section, but can presage the discussion by noting that more sophisticated communications technology may more adequately solve some of the problems solved naturally by proximity.

Although the Xerox experiment attempted to use communications technology to duplicate the effects of physical proximity, one can go beyond mere duplication by using communications technology to create virtual environments that are impossible in the physical world. In the physical world an office can only be surrounded by a few others along a corridor. Even in a better, less linear office arrangement that minimizes average separation among co-workers we are still limited by the two-dimensionality of physical layouts. And in the real world, the inhabitants of those offices are as likely to be there because of accident, seniority, or bureaucratic inertia rather than careful planning.

To overcome the limitations of physical proximity, we can imagine video hallways or other communications technologies that would provide virtual proximity to a larger or more appropriate set of colleagues. Also, unlike physical office arrangements, which are not even as flexible as the organizational structures that support their inhabitants, such electronic hallways are potentially reconfigurable to accomodate organizational changes, changes in personal work interests, or other changes that might affect the collaborative compatibility of a particular set of people.

High-Quality Real-time Interactions

Just as proximity supports low-cost communication, it also supports high-quality interaction. For example, during the idea generation stages that occur at the beginning of a project, when collaborators plan the execution of the work, and later when they plan the documentation of the project, proximity enables the intense, highly interactive, face-to-face sessions that are the cornerstone of the collaborative process.

As our interviews and the Xerox experiment suggest, these intensive meetings require communications tools sophisticated enough to permit high-quality interactions. At a minimum these communication tools must allow participants to exchange whatever information they bring with them to the discussion or create during the course of a meeting itself. Some of this material might be text, on paper or in computer files. Other material might be graphical, ranging from handwritten notes, to figures, photographs, or annotations of already exchanged documents. Currently, commercial video cameras and monitors do not provide sufficient resolution to allow the exchange of this textual and graphical material.

In addition, participants in these meetings must be able to jointly see, point to, and modify these text and graphics objects. Just as one participant in face-to-face meetings might point to headings on a blackboard or paragraphs on a page for the other participants', they must be able to do so in a technology mediated meeting.

Most importantly, however, the technology to support planning and other types of intensely interactive meetings must support the backchannel and other feedback mechanisms that participants in a meeting use to accomodate the informational needs and processing capacities of listeners as well as the dynamic evolution of speakers' conversational goals (Kraut & Higgins, 1984). When people communicate in ways that allow them to assess their partners' view of the world and of their own speech and to use this information to change their conversational tactics, their communication becomes more effective and efficient than it might be when this feedback is lacking (Krauss, Garlock, Bricker, & McMahon, 1977; Kraut, Lewis, & Swezey, 1982; Krauss & Weinheimer, 1966, 1967).

The role of dynamic feedback between communicators in facilitating smooth and efficient exchange of information explains at least in part users' frustration with teleconferencing systems that provide inadequate half-duplex audio (i.e., to reduce audio feedback, only one person can talk at a time) in exchange for the hands-free convenience. Similarly, the lack of real-time feedback may provide a partial explanation for the dissatisfaction with some forms of asynchronous computer communication systems. In a computer conference, for instance, participants enter comments, perhaps about very complex topics, without knowing exactly who they are writing to and without being able to ascertain whether any listener has understood what they are saying. Without the capacity to obtain immediate feedback, authors may find it difficult to tailor their communications so that they are readily understandable to other readers. If readers do not understand a particular entry, they may be unlikely to follow it up or to respond in a way that seems directly relevant; this process of inadequate encoding and unresponsiveness may then produce the frustration about lack of responses described by Tombaugh (1984). Given this dynamic, it is easy to see why it has proven to be difficult to get people to use computer conferences on a regular basis (Johansen, 1987).

Conclusions

In this section we did not attempt to exhaustively catalogue technology that would support research collaborations nor even to list all of the available communication technology. Rather, we have focused our attention on the two major functions currently fulfilled by physical proximity. We drew implications from these functions about two styles of communications technology that we believe could provide the foundation for technologies supporting cooperative work. Omnipresent video might provide the low-cost and therefore frequent and spontaneous interactions crucial to initiating collaborations, monitoring and coordinating the project, and maintaining a smooth personal relationship. Multimedia meeting tools might provide the high-quality communication to support planning and review. Although many other specific tools have been proposed and could be built to support particular tasks that occur frequently, most are likely to build from these two foundations.

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