THE IMPACT OF INFORMATION AND COMMUNICATION TECHNOLOGIES ON INFORMAL SCHOLARLY SCIENTIFIC COMMUNICATION: A LITERATURE REVIEW

Christina K. Pikas

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University of Maryland College of Information Studies

Abstract

This paper provides a review of the extensive research on the social structure and process of informal scholarly scientific communication and more recent research on the adoption and use of information and communication technologies by scientists for informal scholarly scientific communication. The benefits and uses of the information and communication technologies reported in the literature were examined to determine the influence of the technologies on the prior system. Information and communication technologies have not changed the social structure of science, but have enabled new forms of remote collaboration and slightly higher productivity as measured by number of publications.

1. Introduction

Scientists communicate to brainstorm ideas and be creative, formulate research questions, solve experimental or theoretical problems, disseminate results, and get feedback. Several authors emphasize the importance of communication to science. Garvey (1979) states: "communication is the essence of science." Abelson, an editor of the journal *Science* said, "without communication there would be no science" (1980, quoted in Lacy & Bush, 1983, p. 193). The peer-reviewed journal article – polished, archived, and findable – is only one facet of the scholarly communication process. Science is inherently social and informal scholarly scientific communication forms the backbone that connects scientists and enables scientific progress.

Information and communication technologies have transformed our world in many ways; yet, informal scholarly scientific communication forms a socio-technical interaction network in which communication is influenced by technology but defined by the social structures of scientists and their organizations (Kling, McKim, & King, 2003; Lamb, Sawyer, & Kling, 2000). Researchers know a lot about informal scholarly scientific communication through a rich history of study of the social structure of science and scholarly communication prior to the widespread availability of information and communication technologies such as e-mail, the internet, and instant messaging. The purpose of this paper is review what we know about informal scholarly scientific communication and to examine exactly what influences information and communication technologies have had on the existing structures. An understanding of this interaction of social structure and media effects is important to better support the information seeking and communication of scientists.

This paper views informal scholarly scientific communication (ISSC) before and after the adoption of use of information and communication technologies (ICTs). As will be seen, there is a rich literature from the 1960s through the 1980s that describes the influence of the social structure of science, the channels used, the selection of communication partners, and the relationship of informal communication to the research process. The second half of the paper discusses the media effects research has shown ICTs have on traditional models. The first section of the second half, section 3, defines the term information and communication technologies (ICTs), that describes the adoption by scientists of ICTs for scholarly communication, and presents a literature review of research on ICTs use for informal scholarly scientific communication. Section 4 describes the common research methods used in this interdisciplinary research area. Finally, Section 5 summarizes the findings on informal scholarly scientific communication and suggests interesting research questions stemming from this review.

2. Informal Scholarly Scientific Communication in the Mid 20th Century

2.1 What is Informal Scholarly Scientific Communication?

To fully describe informal scholarly scientific communication, I will decompose the concept into a discussion of the standard models of *scholarly* scientific communication, and what is meant by *formal* and *informal* communication. From these discussions, I will develop a composite definition of ISSC, which will then serve as a baseline for the exploration of its features and conduct.

2.1.1 Scholarly Communication

Scholarly communication, as opposed to popular science communication, is embedded in the context of the scholarly tradition of the discipline and is shaped by the disciplinary rituals and perspectives (Fry, 2006); nevertheless, general models have been developed to describe the general process, players, channels, and message types. Garvey, Griffith, and collaborating researchers in the 1960s and 1970s provided the standard model of the flow of scientific information that still stands as the basis for understanding the timeline and milestones for scientific communication (Garvey & Griffith, 1967; Garvey & Griffith, 1972). Garvey and Griffith trace the communication processes from the initiation of the work through the publication of the polished report in a peer-reviewed journal – a process that can extend up to five years (Garvey, Lin, & Nelson, 1970; Garvey, Lin, Nelson, & Tomita, 1970). The steps in the Garvey-Griffith model are: earliest reports of data, research completed, manuscript started, national meeting, latest report, submission to the journal, journal publication (Garvey & Lin et al., 1970). From the communication point of view, the results of scientific research are presented in increasingly more polished and vetted formats over time, gaining in authority as the information passes peer review and editorial changes, gaining larger audiences who are more distant from the researcher, and losing in immediacy, specificity, and thoroughness (Lievrouw & Carley, 1990; Mikhailov, Chernyi, & Giliarevskii, 1984).

A competing model of scholarly communication is the UNISIST model developed by the United Nations Educational Scientific and Cultural Organization (UNESCO) and the International Council of Scientific Unions (ICSU) published in 1971 (T. J. Allen, 1977; Sondergaard, Andersen, & Hjorland, 2003). While the Garvey-Griffith model emphasizes the timeline for scientific communication, the UNISIST model emphasizes three channels of communication: formal, informal, and tabular (i.e., scientific data rather than text); and three levels of sources: primary, secondary (including library catalogs and abstracting and indexing services), and tertiary sources (such as reviews and encyclopedias) (Sondergaard et al., 2003). These channels and sources connect the information producers with the information users. Datacenters and libraries provide crosswalks between the channels and feedback exists from the users back to the producers (Sondergaard et al., 2003).

2.1.1.1 Formal Scholarly Communication

Formal scholarly communication is published material that has been reviewed by peers, edited by publishers, and is retrievable through various information systems (C. M. Anderson, 1999; Garvey & Griffith, 1972; Garvey & Lin et al., 1970; Sondergaard et al., 2003). In the traditional model it is linear communication with little or no feedback possible created for a broad audience. Scientists rely on published journal articles for recognition, reward, and identity formation (Fry, 2006; Lamb & Davidson, 2005; Price, 1963). These articles are considered reliable and are findable later because they are archived and indexed in secondary sources. The most important of these formal publications will also be reviewed in tertiary resources.

The goal of the formal process is to publish a journal article in a peer-reviewed journal, but much of the content of journal articles has been previously communicated via informal channels, including technical reports and conference presentations (Lin, Garvey, & Nelson, 1970). Formal reports frequently do not provide enough information to reproduce the experiment; journal articles lack details such as equipment settings, lessons learned, and initial missteps or mistakes. A superficial explanation of the need for and use of informal channels is that the review and publication process for journal articles is too lengthy (Hagstrom, 1970). In fact, further study shows that formal and informal communication channels are complementary and that “receipt of a single message is secured by the successive interplay of these two kinds of communications” in a convergence model type of communication (Rogers & Kincaid, 1981; Wolek & Griffith, 1974, p. 412).

2.1.1.2 Informal Scholarly Communication

Informal scholarly communication is anything that does not fit into the definition of formal scholarly communication above; that is, it can take place anytime, anywhere, in any format. Traditionally, researchers have studied communication in the workplace between researchers who are co-located (e.g., T. J. Allen, 1977) or who meet at local or national meetings (e.g., Garvey et al., 1970). Additionally, reviewer notes, letters, telephone calls, and pre- and post-prints are in this category. Besides communicating to get advice, learn about new methods or theories, or hear about new results, scientists communicate informally to collaborate on research, co-author formal publications, and also to gossip and be creative (Kasperson, 1978, cited in R. S. Allen, 1991). Meadows (1974) found that physicists and chemists ranked references from conversations or correspondence very highly as methods of acquiring information.

Wolek and Griffith (1974) found that informal communication by its nature is fortuitous and that there is no certainty that partners will share correct, complete, and the highest quality information available. Ideas diffuse more quickly via informal communication than through journal articles alone as they have champions who can provide subjective details on the innovation (Crane, 1972; Rogers, 1995). Pfaffenberger (1990) finds that informal communication is more effective at providing richness and context to the data and is used to transfer tacit knowledge (know-how) while formal communication transfers facts and descriptions (know-what)(cited in Poland, 1991). Perhaps more importantly, formal communication is generally not interactive and does not support the exploration of new ideas with rapid feedback from a specialized audience who can uniquely address the question and who have pre-established common ground (Cronin, 1982, cited in Gresham, John L., Jr., 1994; Menzel, 1967; Mikhailov et al., 1984). Garvey and Griffith (1972) state it best:

> Information flowing through the informal domain is commonly abstracted, usually colloquial, frequently incomplete, and often vague. The communicator here is not seeking to report a finished scientific work. He often knows, in fact, that the person with whom he is communicating needs only a minimal communication of an idea to understand fully its meaning and importance for their common subject of research. The recipient embodies integrated knowledge; therefore, the message need not, in itself, be integrated. (p.135)

2.1.2 A Composite Definition of ISSC

Based on the above discussion of models of scholarly communication and the description of informal scholarly communication, I propose a composite definition of ISSC. ISSC is the interactive exchange of information between scientists to establish or maintain relationships, exchange scientific information, or work collaboratively. The channel, message features, and social network influence the formulation, transmission, receipt, and understanding of messages; the selection of communication partners; and timing of the communications. The scientist's discipline also influences this system, but I will be looking broadly and generally across the sciences, including social science and mathematics, so will not discuss disciplinary effects separately from the social structure of the research area.[1]

2.2 Social Structure Effects on ISSC

The social structure of the research area depends in part on the existence of "invisible colleges." Price (1963) and Crane (1972) studied the citation structures and formal publication patterns to describe the growth of science and "the informal but specialized social system that produces basic scientific knowledge" (Crane, 1972, p. 1). Crane (1972) found that social circles of researchers form who have similar research interests and are using the same paradigm but are not necessarily co-located. These communications networks, which have split off around a scientific paradigm, are called "invisible colleges" (Crane, 1972).

The social structure and coherence of the invisible college affects informal communications in several ways. Crane (1972) argues that research groups that are well developed and agree on methodologies do not communicate frequently. The members of the group are homophilic and there is less information to transfer (Rogers, 1995). Griffith and Miller (1970) found several types of social structures that impacted informal communication. Low and background levels of communication networking are indicative of low levels of organization into subgroups and may occur where there are competing methods or theories and little agreement (cf.Menzel, 1967). Loose communication networking is characterized by "considerable knowledge of the activities of the other major researchers, and individuals seek out and interact with one another according to current research interests" (Griffith & Miller, 1970, p. 138). Highly coherent groups have a strong leader who may recruit new members and be the innovator in new methodologies. These groups are highly active in intragroup communication but do not communicate frequently outside of the group (Griffith & Miller, 1970).

[1] Earlier reports from Abels, Liebscher, and Denman (1996); Walsh and Roselle (1999); Walsh, Kucker, Maloney, and Gabbay (2000) found that there was a divide between social scientists and physical or life scientists in the use of ICTs; however, in a more recent study, Barjak (2004b) found that the differences were not along the social-natural sciences line but rather among different fields depending on several factors such as proximity to industry.

2.3 Traditional Channels and Methods for Informal Communication

Traditionally, ISSC is carried out in face-to-face meetings, in letters, and in pre-prints. Garvey and Gottfredson (1977) surveyed two thousand scientists and found that the most likely source of research information was face-to-face contact (cited by Lacy & Busch, 1983). Research groups organize lectures, seminars, colloquia, and other informal intellectual social gatherings to encourage information transfer (T. J. Allen, 1966; Fry, 2006). Tracy and Naughton (1994) suggest that information transfer and identity altercasting happen in these informal intellectual discussions via questioning from participants. Scientists establish intellectual identity through explaining and defending research results in scheduled presentations and informal hallway conversations (Garvey et al., 1970).

National professional society meetings provide forums for scientists to meet and establish contact with other scientists who remain geographically dispersed during the rest of the year. Scientists use information gained from these interactions to broaden or redirect current research, learn new techniques to incorporate, or alter the conceptual or theoretical orientation of their work (Garvey et al., 1970). Meeting attendees frequently contact presenters and others they have met at meetings later to exchange news on current projects and research ideas (Garvey et al., 1970). In order to have beneficial conversations at these meetings, attendees must be able to establish common ground. This is done, in part, through shared knowledge of the formal disciplinary literature, a shared language, and in some research areas, shared history and shared methodological approaches learned from a common teacher (Clarke & Brennan, 1993; Crane, 1972; Wolek & Griffith, 1974).

2.4 How Informal Communication Partners Are Selected

Price (1965) demonstrated that social networks existed by examining the citation patterns in science; that is, by examining what articles authors cited in formal communications (cited by Crane, 1972). In other studies, researchers asked scientists to name others whose work they monitor or with whom they discuss their work (e.g., Mullins, 1968). In both cases, the research examined existing relationships, not how relationships formed. The success of informal communication relies in part on knowing whom to ask or where to be to fortuitously encounter information (Erdelez, 1999; Wolek & Griffith, 1974). It is apparent from early studies that for some coherent groups, researchers studied under the same leader in their field and continued to communicate with others using the same methodologies; in other words, during the training process the scientists were recruited into an active group and introduced to information sources by the group leader (Griffith & Miller, 1970). An expectation might be that elite authors or leaders of the coherent groups themselves would be selected more frequently as communication partners; yet Mullins (1968) found that elite authors were no more likely to be reported as members of the social network than other scientists in the group.

National meetings offer many opportunities for scientists to catch up and reestablish ties with members of their invisible college; but, also, of course, to meet members of other social circles within the same larger field. Presenters are the focus of communication at meetings and become centers of contact networks established through discussion of presented results (Garvey et al., 1970). These contacts formed around presentations and the sharing of data, results, and information may be inter-group instead of intra-group and act as bridges between the invisible colleges (Birnholtz & Bietz, 2003; Crane, 1972). Infrequent opportunities for in-person meetings create opportunities for forming common ground through quick interactive exchanges. Participants use particular methods to establish common ground based on least collaborative effort (Clarke & Brennan, 1993). Rogers (1995) generalizes that spatial and social proximity are important features in lowering the collaborative effort required. T. J. Allen (1977) found that the quality of communication also drops off as distance increases.

Crane's (1972) invisible colleges create in-groups and out-groups of scientists. In-group scientists are linked to like-minded scientists, have access to data and early results, and have resources for interpersonal information seeking. Out-group scientists or peripheral scientists, are isolated and do not have access to the same resources. Studies of social networks have added to our knowledge of how colleagues are chosen as resources for informal but purposeful information seeking. Borgatti and Cross (2003) studied the social networks of information scientists and genomic researchers and found three relational characteristics that lead to interpersonal information seeking: "(1) knowing what another person knows, (2) valuing what that other person knows in relation to one's work, and (3) being able to gain timely access to that person's thinking" (p.440). As Wolek and Griffith (1974) found, informal communication relies on knowing whom to ask, knowing what they know, and trusting that they will tell you.

2.5 The Relationship of Informal Communications to the Research Process

Informal communication can be part of a purposeful information seeking process in response to a problem, gap, or information need encountered while formulating the research question, conducting the research, evaluating the data, or documenting the research. On the other hand, while some portion of the informal communication is purposeful, much of it is part of ongoing scanning or monitoring the research environment or being in the right place at the right time to serendipitously make a connection and encounter information (Erdelez, 1999). This section discusses informal communication as part of the research process and then as information encountering behavior.

2.5.1 Informal Communication as part of the research process

The Garvey-Griffith model provides a framework with which researchers can examine how informal communication fits into the traditional overall model of scholarly scientific communication and how informal communication happens at the different stages of the process. In the first stages, scientists actively seek information to formulate the research problem and place the work in context so that it will be novel and useful when complete (Garvey & Griffith, 1972). In this case, informal scientific communication is conducted purposefully to clarify the information need. Lievrouw and Carley (1990) found that local partners were selected for informal hallway communication during the conceptualization phase but that distant partners were consulted during the documentation phase.

Several studies show that scientists follow the Zipf (1949) principle of least effort when seeking information (cited in C. J. Anderson, Glassman, McAfee, & Pinelli, 2001). Specifically, depending on task complexity and purpose for information seeking, scientists choose informal communication with colleagues as the initial channel for seeking project-related information (R. S. Allen, 1991; T. J. Allen, 1966; C. J. Anderson et al., 2001; Orr, 1970). Ellis, Cox, and Hall (1993) found that physicists and chemists seek recommendations from colleagues as the first step in information seeking.

In the days before electronic communication, while the work was underway communications were normally limited to casual conversations with immediate coworkers (Garvey & Griffith, 1972). When the research data was compiled, early results were communicated to non-participants via colloquia at the workplace and also to closely related, if distant, researchers for whom speed was paramount to presentation (Garvey & Griffith, 1972). Researchers who are in close communication with others in their research area do not need to look at the formal paper having understood the implications of the research from early reports received (Price, 1986). Their perceived risk of acting on unreviewed data and interim results is lessened by the trust gained through reading previous work, discussing the ongoing work, and their existing social relationships formed at in-person meetings (Price, 1986).

More polished results are presented at national meetings. The national meetings provide younger researchers, who are not as integrated into the network, access to the information and the presenter. Garvey et al. (1970) found that “the communication behavior at meetings is largely exploratory, the attendee intentionally browsing for sources of potentially interesting information and not wanting to prejudice his selection” (p. 34). The speakers, too, receive valuable feedback which they can then incorporate into their journal article manuscript. However, Garvey et al. (1970) found that less established authors are more likely to incorporate significant changes suggested by meeting attendees. When the manuscript is in preparation, informal pre-prints are forwarded around to the network. While the manuscript is under review at the journal, no further communication occurs on this work until the work is accepted or declined.

2.5.2 Informal Communication Separate from the Research Process

Besides actively searching for information to formulate the research question or get feedback on research recently completed, scientists communicate informally in order to meet future research partners, to keep abreast of their research area, and to facilitate serendipitous discoveries of information. In co-located research groups, Lievrouw and Carley (1990) found that there is a great deal of interpersonal communication, dyadic or small group interaction, hallway chats, and working group meetings between homogeneous and cohesive groups who normally share informal frequent and extensive contact. These chats include hypothetical talk and the trying out of ideas (Lievrouw & Carley, 1990). When work is intensely underway, informal communication outside of immediate coworkers is uncommon (Garvey & Griffith, 1972; Kraut, Egido, & Galegher, 1990).

Informal, occasional communication happens in dispersed invisible colleges, too. Rosenbloom and Wolek (1970) asked 650 scientists to recall a recent instance in which they received work-related information from a colleague who was not a co-worker and found that 33% of the time the information had been volunteered (cited by Lacy & Busch, 1983). Scientists attend local, regional, and national meetings for general awareness even when not presenting. Scientists who are socially integrated into networks of like-minded researchers are better able to keep up with large amounts of information produced independent of their current work (Lingwood, 1969).

The general explosion in the growth of the number of articles and formal resources in the era of "big science" has encouraged informal communication as a method of staying abreast of a field (Price, 1986). Scientists react to this explosion of information by either becoming very specialized and thus monitoring a narrower field or by becoming very generalized and thus reading only review articles and tertiary sources (1969). In either case, scientists may rely on colleagues with other specialties or in other disciplines to act as information filters or gatekeepers to apprise them of new results that impact their work or who are up to date in another subspecialty and can provide information on it (Lacy & Busch, 1983; Menzel, 1967). The "unlooked for" information, as Menzel (1967) calls it, is filtered, provides double exposure to items not attended to on first reading, and allows for revival of older ideas that were not popular when first published.

3. How Have Information and Communication Technologies Changed Informal Communication?

Traditional models of scholarly scientific communication emphasize individual production of knowledge with feedback from colleagues and subsequent exchange of knowledge; in other words, interaction limited to certain stages of the research project, or limited to at least temporarily proximate researchers (Glaser, 2003; Kraut et al., 1990). Early discussions of ICTs in science included optimistic prognostications of increased productivity, the end of peripherality (e.g, Gresham, John L., Jr., 1994), and, in short, the end of the scientific communication structures described by Garvey and Griffith (1972) and the UNISIT model (Sondergaard et al., 2003). Alternatively, some predicted that there would be a balkanization of science in which scientists would only communicate within their social circles and bridging communications between groups would cease (Van Alstyne and Brynjolfsson, 1996, cited in Walsh & Maloney, 2002).

Hurd (1996b) suggested three ways the Garvey-Griffith model could change using alternative versions of how and in what stages computer mediated communication is important. In the first, the electronic journal is the goal, and every communication along the path is conducted electronically. In the second version, the journal is eliminated and the final goal is the publication of the work in a digital library. At an intermediate point, the article is posted for peer review and comment. In the third version, the data is vetted in an online accessible databank, but the published research goes directly into the digital library without review. Likewise, Søndergaard, Andersen, and Hjørland (2003) proposed updating the UNISIT model to add informal electronic communication at each stage and feedback loops between stages and types of communication.

The first half of this article described the social system and structure of science prior to computer mediated communication. Many of the approaches toward understanding ICTs in informal scientific communication have underemphasized the interaction of the social structures of communication with the technologies. Kling, McKim, and King (2003) found that many proposals for new ICTs for science had to be radically restructured after initial trials because they did not take into account the "entrenched and durable scholarly communication practices" (p. 48). They report that scholarly online forums failed to attract participants because designers did not take sociability or cost into account.[2] Many of the studies reviewed here are technology driven; that is, they report on empirical studies of the adoption, use, and impact of specific technologies on the work of one or several groups of scientists (Matzat, 2004). Moreover, recent studies such as Chin, Myers, and Hoyt (2002), report that hyperconnected scientists communicate multimodally; that is, via multiple channels, either channel switching as appropriate to the task or using channels simultaneously to transmit different types of messages. The goal of this half of the review, then, is to relate the body of research on the *social structures* of science to the evidence from more recent literature of how ICTs in general are adopted and used for ISSC.

3.1 What are ICTs?

Lamb and Davidson (2005) provide a useful typology of the use categories of ICTs by scientists: embedded, coordination, and dissemination. Embedded ICTs are communication tools built into scientific tools and experiments such as sensor networks, grid computing, remotely-operated telescopes and observation devices, visualization and virtual reality tools, and telemedicine tools. They are a primary part of collaboratories and make the "big science" research possible (Finholt & Olson, 1997; Kouzes, 2000). Coordination ICTs, such as e-mail, telephone, web pages, instant messaging, chat, wikis, and so forth, constitute the general

[2] See Preece (2000) for more information on designing sociability into online communities.

communication infrastructure that allows scientists to plan, share data and results, write papers, and maintain contacts. Dissemination ICTs, such as electronic journals, popular media, weblogs, and project web sites, transmit the findings to the audience, generally in one way broadcast (R. Lamb & Davidson, 2005). This section will concentrate on the coordination ICTs, how different disciplines and research areas adopt and use various ICTs, and how the ICTs have replaced or enhanced the previous system (Carley & Wendt, 1991, cited in Rojo & Ragsdale, 1997).[3] Changes to productivity, peripherality, and collaboration are discussed in detail.

3.2 The Interaction of the Adoption of ICTs with ISSC

Adoption of an innovation is “the decision to make full use of an innovation as the best course of action available” (Rogers, 2003, p. 21). The diffusion of ICT innovations depends on the Rogers (1995) characteristics of innovations: relative advantage, compatibility, complexity, trialability, and observability; but also, in the case of interactive media, communication-related network effects (*critical mass*) and individual innovation threshold. Critical mass is a system tipping point effect, where there are enough individual adopters that the innovation is self-sustaining (Rogers, 1995). The individual component of critical mass is *threshold*: “some minimum number of other individuals in the system have adopted, and are satisfied with their use of the innovation” (Rogers, 1995, p. 320). I will review how scientists adopted the technologies and what gains have been found as a result of the adoption and then continue by discussing how scientists use and benefit from specific uses of ICTs.

3.2.1 The Adoption of ICTs by Scientists

Although recent large surveys indicate that nearly all scientists who can use e-mail and electronic networks do (Barjak, 2004a), it remains valuable to review the studies of the adoption of various ICTs to understand the influences of individual ICTs on ISSC. Liebscher, Abels, and Denman (1997) studied the use of ICTs in smaller institutions and found that institutional support was an important predictor of use. Technical considerations such as the ability to transmit images or mathematical equations once formed a barrier to communication in biology and mathematics and so may have impeded early adoption in these fields (Walsh & Bayma, 1996b). Walsh and Roselle (1999) compiled comparative rates of e-mail use from various

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[3] For a discussion of how ICTs have impacted *formal* scholarly communication, see Boyce, King, Montgomery, and Tenopir (2004); Correia and Teixeira (2005); Kling and Callahan (2003); Lu, (1998); McCain (2000); Talja and Maula (2003); Tenopir et al., (2003); and Tenopir and King (2001).

scientific fields and found that mathematicians and physicists had been using e-mail since before 1991 and that all areas of science except for ornithology had adopted e-mail by 1997. In 2003, a survey of scientists in research and development organizations in seven European countries found that 99.7 % of scientists reported using e-mail (Barjak, 2004a). Russell (2001) states that scientists in third world countries have been slower to adopt ICTs because of the lack of telecommunications, power, and institutional infrastructure.

E-mail discussion lists have been adopted by some fields and have been adopted and discontinued by others. Whereas e-mail is generally a one-to-one or one-to-few communication, discussion lists are one-to-many; that is, each e-mail is sent to all the participants of the list. R.S. Allen (1991) compares mailing lists to professional society special interest groups (SIGs) that are less exclusive. Arxiv, a popular primarily theoretical physics e-print archive, originated as a discussion list to provide access to preprints more quickly and broadly than mailings from individual scientists (Hurd, 1996a). Arxiv quickly reached critical mass, with more than 20 times the original number of subscribers in the first six months of operation (Hurd, 1996a). In a more recent study, Talja, Savolainen, and Maula (2004) reported that environmental biologists found that discussion lists were good sources of information about meetings, but that high traffic lists with broad focuses were too time consuming to continue to maintain subscriptions. Accordingly, many scientists have discontinued use of mailing lists to try to control information overload.

Instead of social spaces with rich interactions replacing hall conversations at conferences, discussion lists are more commonly used for broadcast messages as mailings were in the past. Rojo and Ragsdale (1997) surveyed participants of 11 lists and found that the majority of the members of the list rarely, if ever, contributed. In addition, Rojo and Ragsdale (1997) report that the “interviewees’ memberships in forums seem fragile and temporary” (p. 327). In other words, the participants may yet refuse to confirm their adoption decision and discontinue use (Rogers, 2003).

As opposed to broad, open mailing lists discussed above, Walsh and Bayma (1996a) found that some lists are only announced to direct contacts or are moderated; this again delineates in- and out-groups. Along these same lines with Fry (2003) found that smaller, project-related mailing lists were heavily used to support close-knit international collaborations (cited inTalja et al., 2004). In any case, Matzat (2004) surveyed academic researchers in the sciences, engineering, and history in the Netherlands and England in 1997-1998 and found that 23.3% were internet discussion group users, 5.1% had previously been internet discussion group users but had discontinued, and 97% of the sample reported that they had access to e-mail.

Both of the above-mentioned categories of ICT are asynchronous and based on e-mail. Very few studies specifically examine the adoption of synchronous ICTs by scientists (not software engineers). Synchronous ICTs include instant messaging (IM), chat, and SMS (short message service). Birnholtz, Finholt, Horn, and Bae (2005) studied the use of chat technology as embedded in the remote control and monitoring equipment for the data gathering stage of a collaboratory experiment. For collaboratory members chat participation, even without active contributions, was required to fully gain the benefits of the experiment; yet, adoption was not universal (Birnholtz et al., 2005). Although several articles report on the addition of instant messaging technologies to collaboratory software (Chin et al., 2002; e.g., Esposito, Mastroserio, Tortone, & Taurino, 2003; Stokes-Rees, Tsaregorodtsev, & Garonne, 2004), reports of adoption and use by collaboratory members are scarce.

3.2.2 Returns on Adoption of ICTs for Informal Communications in Science

Cronin (1982) criticized informal communication as elitist, expensive, and noisy (cited by Gresham, John L., Jr., 1994). Additionally, Garvey and Griffith (1979, p. 158) found that "those who need preprints most – young scientists, workers at small institutions, and researchers in less developed countries – are frequently not the recipients" (cited in Walsh & Bayma, 1996a, p. 356). Have ICTs enabled non-elite or peripheral researchers to have equal access to information? Or, alternatively, is there a digital divide in science where the information rich get richer and the information poor get poorer (Barjak, 2004a; Hesse, Sproull, Kiesler, & Walsh, 1993)?[4] Possible returns on adoption and use of ICTs in science are increased productivity, decreased peripherality, and broader and more geographically dispersed collaborations.

3.2.2.1 Productivity

Defining the productivity of scientists is not trivial. A simple measure is to count the number of journal publications produced; however, this does not take into account the quality of the publications, the individual contributions of co-authors, other venues of publication, funding received, classes taught, students mentored, or theories/methodologies developed (Barjak, 2005).

[4] Merton (1973) calls this the Matthew effect, "those in the research system who are already recognized will cumulatively be more advantaged compared to those who are less recognized" (cited by Matzat, 2004, p. 228).

A proxy used for journal article quality or influence is citedness, or how many times the articles are cited, by whom, and in which forum (Lingwood, 1969). Hesse, Sproull, Kiesler, and Walsh (1993), in an early study of the benefits to oceanographers from using an online network, define scientific productivity in two ways. First, the efficiency premise is that scientists who use networks will spend less time in unproductive activities such as traveling to equipment or labs or using the library (!) to manually look up documents (Hesse et al., 1993). The second premise is that peripheral scientists, that is those who are not in large research institutions or who are otherwise isolated, will have differential benefits from core scientists (Hesse et al., 1993). However, they operationalized these definitions in terms of positive scientific outcomes: number of articles published, professional recognition, contacts among professional oceanographers – not number of trips or library usage. When they completed their study in 1989, they found that productive scientists are more frequent and more powerful users of the network than nonproductive scientists. They could not, however, determine the direction of causality from their study.

Lingwood (1969) also struggled with the concept of productivity. He defined scientific productivity as the “influence the man has on this field: the amount of knowledge he contributes to it, the amount he modifies the general trend of research in the field toward his own theoretical ideas hypothesis, and methodological procedures” (Lingwood, 1969, p. 79). Pelz and Andrews (1966) add patents and others’ view of the influence of the scientist in to their measure of productivity (cited in Lingwood, 1969). In the end, Lingwood (1969) used only book chapters, technical reports, journal articles, and books written by the scientist to measure productivity. His study of educational researchers prior to computer mediated communication found that greater prestige and greater use of informal and formal information sources were predictors of greater productivity (1969).

Kaminer and Braunstein (1998) also use number of publications to measure productivity; however, they add the explanatory variables of classes taught, years since PhD, age at receipt of highest degree, institutional support, and administrative duties. Additionally, they used a ranking system where books received a weight of eight, refereed journal articles received a weight of two, and encyclopedia articles received a weight of 1. Co-authored publications were given a fraction of the total points based on the number of authors. Kaminer and Braunstein (1998) studied faculty members of the University of California Berkeley College of Natural Resources with PhD degrees to determine if internet usage increased productivity. Interestingly, they compared automated system logs from the second half of 1995 with reported use. They found that nearly all of their sample used e-mail, slightly more than 40% reported using the web, and 16% reported using newsgroups (Kaminer & Braunstein, 1998). Kaminer and Braunstein (1998) found that internet use does correlate with higher productivity.

Walsh and Maloney (2002) also mentioned the difficulty in measuring productivity of collaborations and only used group journal publications to measure output. They found that e-mail use had a slightly positive effect on group productivity. A more recent study uses self-reporting of book chapters, journal articles, working papers, and conference papers thereby covering a range from very polished and distant from the research to less formal works in progress (Barjak, 2004b). This study also reported a positive relationship between productivity and computer network use.

3.2.2.2 Peripherality

Literature on informal scholarly communications via traditional channels listed peripherality as a concern and a limitation on the growth of science. Peripheral scientists are socially or geographically distant and thus are not tightly integrated into the invisible college and may miss opportunities for information sharing and social contact (Hesse et al., 1993). Younger scientists, scientists at smaller universities, and scientists in non-Western countries fall into this category. Barjak (2004a) reviewed the results of the Statistical Indicators for Benchmarking the Information Society (SIBIS) survey of 1,400 European scientists in five disciplines and concluded that higher status groups use online information more and are more intensive users of e-mail. In fact, he found that the divide between peripheral and central researchers mentioned in the early literature has conveyed to the “Internet Age” within developed Western countries (Barjak, 2004a).

Young scientists who are more facile with ICTs may communicate more frequently with other young researchers in different disciplines thereby setting up new social circles based on technology, not research area (Lamb & Davidson, 2005; Barley (1990), cited in Walsh & Bayma, 1996a). Yet Covi (2000) found that doctoral students and young researchers were expected to conform to the work practices of their advisors and were not innovative users of ICTs unless the social structure of their field encouraged research method innovations. E-print servers, such as Arxiv, have democratized access to pre-prints in physics (Hurd, 1996a); however, Walsh and

Bayma (Walsh & Bayma, 1996a) reported that there were still barriers because access to the papers is not enough. A theoretical physicist explained,

> "It's different to see a paper and to be there. If you are at the big institutions you have access to the oral information, seminars, you can talk to the person. That's still lacking… At the big institutions… you can get help sorting through it."

Walsh and Roselle (1999) found that researchers trained at research centers, thus already part of the social circle, can more easily maintain ties using ICTs if they move to peripheral institutions. Along the same lines, Walsh and Bayma (1996a, p. 355) quoted a mathematician who said, "if you're sentenced to Podunk, wherever that is, it's not the death sentence it used to be." In other words, peripheral mathematicians can use e-mail to maintain contacts and get news; however, mathematicians still need to travel and to take visiting positions because "mathematical knowledge is transmitted orally and informally, through an enculturation process" and not through the very formal, abstract literature (Sheehan, 1990, cited by Walsh & Bayma, 1996a).

3.2.2.3 Collaboration

In this section, I will discuss the impact of the adoption of ICTs on the frequency and characteristics of collaborations (Section 3.3.1 below discusses how ICTs change informal scholarly scientific communication as part of the collaborative process). In 2003, 20% of all articles indexed in ISI's Web of Science had authors from multiple countries, a dramatic increase from the 8% reported in 1988 (National Science Foundation, Division of Science Resources Statistics, 2006). Additionally, the average number of authors per article grew from 3.06 in 1988 to 4.22 in 2003 (National Science Foundation, Division of Science Resources Statistics, 2006). Research results link some of these increases to ICT adoption and use.

Early articles found that ICTs increased remote collaboration by allowing time shifting of communication; in other words, questions could be posed at the end of the work day in one time zone, received and replied to during the work day in another time zone, with the answer waiting in e-mail when the questioner returned to work (Lievrouw & Carley, 1990). ICTs enabled more collaboration by reducing the cost by replacing some travel and expensive telephone conversations with low-cost ICT communication (Lievrouw & Carley, 1990). Walsh, Kucker, Maloney, and Gabbay (2000) surveyed 333 scientists in four fields and found that increased use of e-mail had a "consistent positive and significant relationship" with reported participation in a collaboration. Also, e-mail use increased the geographical dispersion of participants (Walsh & Maloney, 2002). Walsh and Bayma's (1996a) study participants reported increases in the size of research groups and the increase in remote collaborations with the addition of computer network use.

Collaboratories are a fairly new phenomenon centering around the ability to allow participation in large scientific research projects by geographically dispersed but ICT-connected researchers (Finholt & Olson, 1997). Collaboratories present a social structure fundamentally different from Crane's (1972) invisible college because participants are brought together by common equipment and technology, not necessarily by similar research backgrounds and goals. Consequently, the social structure coordinating communications is different from what is found in invisible colleges. Adoption of ICTs is required to fully participate in the experiment. Birnholtz, Finholt, Horn, and Bae (2005) reported that collaboratory participants who did not participate in the chat channel were less involved in the experiment and did not consider the experiment successful.

3.3 Use of ICTs for ISSC

Just as traditional ISSC occurred in various settings for different purposes, the use of ICTS for ISSC varies with setting and purpose. As discussed above, ICTs have impacted the ability of scientists to collaborate remotely; accordingly, the number and geographic dispersion of collaborations have increased dramatically. Scientists also use ICTs for ISSC outside of ongoing research for information seeking and to maintain social contacts. This section discusses how ICTs are used in and contribute to collaborative work and then how ICTs are used in ISSC outside of collaborative work.

3.3.1 Use of ICTs in Collaborations

In collaborative work, the extent and kind of communication is determined by the nature of the collaboration and the type of work. For example, if the work is ambiguous or non-routine, there will be a need for frequent complex communications (Olson & Olson, 2000). If the work has less dependencies, is more routine, and there is agreement about the process and the goal, less frequent and complex communications will be required (Olson & Olson, 2000). Within collaborations, the different ways the parties work together impact the choice of communication channel. Hara, Solomon, Kim, and Sonnenwald (2003) describe a continuum in the type of collaboration from serial to integrative.

In serial collaborations, each party has a discrete responsibility and the work is passed along to the next contributor. For this type of collaboration, e-mail attachments or electronic file transfer is perfectly adequate. In Walsh and Bayma's (1996b; 1996a) interview study of 67 scientists, participants discussed the serial nature of their collaborative work. Physicists reported a "division of labor" – although the work of each group was highly interdependent, it was conducted separately with e-mail correspondence quickly passing back and forth to coordinate. Biochemists also reported a "division of labor" where part of the work was assigned to each location and the results were compiled at completion.

In integrative collaborations the participants work on the project at the same time and share duties. This is very difficult if the parties are not physically proximate and much richer and frequently synchronous channels are required (Kraut et al., 1990). Chin et al. (2002) discuss the inconvenience of escorting visiting scientists around a lab and the benefits of remote synchronous collaboration for "brainstorming ideas, analyzing results, and debugging error conditions and problems" (p. 92). Similarly, Birnholtz et al. (2005) describe how the chat tool is used while running a collaboratory experiment to give a running commentary and to allow remote participants to participate in the complex running of the equipment.

For both serial and integrative collaborations the point in the research at which informal communications happen has changed with the introduction of ICTs: communication with remote colleagues happens during the actual work and on a continuing basis (Walsh & Roselle, 1999). Prior to the availability of ICTs, summer schools, visiting appointments, and frequent conferences were developed to enable more collaboration (Walsh & Bayma, 1996b). Scientists now meet at meetings or during other in-person sessions, discuss a project, and then return to their geographically distant home institutions and continue the work via ICT (Walsh & Bayma, 1996b).

3.3.2 Use of ICTs Outside of Ongoing Collaborative Work

Scientists use ICTs outside of ongoing collaborative work to seek specific information and to maintain social contacts. Rojo and Ragsdale (1997) characterized participant roles in discussion lists as fishing for information mode, enjoying the debate mode, and social networking mode. They found that some users participate in mailing lists as they would read newsletters: to get information broadcast from active participants, keep abreast of new information, and to learn of upcoming events. Walsh et al. (2000) similarly found that participants perceived increased e-mail use contributed to increased contact with researchers at other institutions, increased information about conferences, and greater awareness of calls for papers. Gresham (1994), Walsh and Bayma (1996b), Talja et al. (2004), and Matzat (2004) each reported that discussion lists worked well to broadcast a request for a citation or information and receive numerous quick and helpful answers.

In Rojo and Ragsdale's (1997) "enjoying the debate mode" we see echoes of the ISSC Garvey et al (1970) reported in conjunction with national meetings. They report that some discussion list members enjoy participating in and occasionally provoking debates about controversies in their field. Conversely, Talja et al. (2004) found that biologists and nursing science researchers had little patience with "conversing" on discussion lists—they viewed the list only as a place for the transmission of information, not as a place for social contact.

In Rojo and Ragsdale's (1997) social networking mode, participants use the discussion list to build and maintain social contacts. They found that this mode was fairly uncommon in the large discussion lists they studied; however, in Carley and Wendt's (1991) study of discussion lists as part of a distributed research group, they found that social messages made up 20% of the total. Kraut et al. (1990) and Chin et al. (2002) both found that ICTs were used to renew lapsed relationships or collaborations.

4. Summary and Conclusion

Glaser (2003) found that ICTs have not changed the production of scientific knowledge or the social networks of scientists; but we have seen that this is not entirely true. The general structure of ISSC as described by Garvey and Griffith remains with some changes due to ICTs. There is agreement in the literature that ICTs increase the individual scientist's efficiency by use of embedded ICTs instead of traveling to the equipment and through use of coordination ICTs to save time in searching for information, contacting larger numbers of colleagues, and getting feedback. This immediate feedback from a large group of peers provides new crosswalks and connections in the UNISIST model. Additionally, the linear flow of communication shown in both the Garvey-Griffith model and the UNISIST model now has information flowing throughout all stages of the process and backwards and forwards to the different nodes. In other words, the messages and the participants have not changed, but channels are faster and more efficient, enabling more connections and more frequent communication.

Numerous studies have found that the size and geographic dispersion of collaborations have increased with the addition of ICTs. Formal communication, whether through online or print channels is still required for common ground formation through training, recognition and reward, authority and reliability outside of the primary research area, and for archiving and refinding information. ICTs have not broken down the structure of science, but have expanded participation by enabling international and interdisciplinary collaborations. In-person meetings are still preferred for knowledge transfer and for getting acquainted but ICTs allow scientists to maintain relationships and contacts previously formed.

4.1 Areas for Further Research

In order for ICTs to replace serendipitous informal communications outside of existing collaborations between researchers who are not physically proximate, there needs to be the capability to have spontaneous, unplanned, inexpensive communication (Kraut et al., 1990). Instant messaging has the ability to serve in this capacity among hyperconnected scientists (Quan-Haase & Wellman, 2005). Quan-Haase and Wellman (2005) studied a high-tech company and found that even when physically proximate, ICTs help manage communication and collaboration. Chin, et al. (2002) indicate that this type of technology might support productive working relationships in science. Further research reviewing the impact of IM presence indicators in co-located scientists and multimodal communication among remotely located scientists would provide insight into how IM works in ISSC.

Real-time backchannel communications are employed at some meetings to move the hall discussion to the conference floor (McCarthy & boyd, 2005). Additionally, real-time blogging of conferences can be a way to meet interested parties and share the conference experience. Communications can distract from presentations but can also add to the richness of informal scientific communications. Further research is needed to discover how these backchannel communications are used and what if any effect they have on benefits received from conference attendance. Likewise, technologies used to locate researchers with similar interests at conferences might be helpful for new entrants to the field.

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