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Frequency and Structure of Long Distance Scholarly Collaborations in a Physics Community

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The authors present results from a real-world study depicting remote collaboration trends of a community of more than 87,000 scientists over 30 years. They utilize publication records of more than 200,000 scholarly journal articles, together with affiliations of the authors to infer distance collaborations. The longevity of their study is of interest because it covers several years before and after the birth of the Internet and computer-supported collaborative work (CSCW) technologies. Thus, they provide one lens through which the impact of computer-assisted collaborative work technologies can be viewed. Their results show that there has been a steady and constant growth in the frequency of both interinstitute and cross-country collaborations in a particular physics domain, regardless of the introduction of these technologies. This suggests that we are witnessing an evolution, rather than a revolution, with respect to long-distance collaborative behavior. An interdisciplinary approach, combining numerical statistics, graph visualizations, and social network measurements, facilitates their remarks on the changes in the size and structure of these collaborations over this period of history.

Introduction

Research is a social process involving the dissemination and review of documents, the exchange of ideas and expertise, the shared viewing and interpretation of events, and other collaborative information intensive activities. It is clear that recent technologies provide alternate avenues for participating in these social activities remotely, evident by e-print archives for disseminating articles rapidly and widely, virtual collaboratories for exchanging ideas, video conferencing, and other computer-mediated communication (CMC) technologies. To best design related tools for the future, it is important to understand the evolution of collaborative behavior. Did the availability of the Internet or tools for virtual collaboration change the frequency or structure of remote collaborations? Our motivation for this work began with an intuition that these tools impacted the frequency of long-distance research collaborations considerably. In this work, we test that intuition by utilizing publication records together with institute affiliations of authors to infer distance collaborations among a community of physicists. Our approach is to study the frequency and structure of remote collaborations before and after the emergence of the Internet and computer-supported collaborative work (CSCW) and CMC related technologies. We include and interpret our findings, revealing a constant and steady increase in the number of collaborations throughout the entire 30-year period. Rather than having a revolutionary effect, which may be witnessed by a change in the evolutionary trend, CSCW and the Internet appear to have enabled the evolution to continue smoothly, as is the case when new technology is created to meet an existing need. For our purposes, we treat the birth years of CSCW, the Internet, and the World Wide Web (WWW) as 1984, 1989, and 1992, respectively, which we base on the history of CSCW by Grudin (1994), and the history of the Internet at CERN (Segal, 1995). Although these dates are approximate, they can be used to make general comparisons over a 30-year span.

Received February 4, 2006; revised October 29, 2006, December 3, 2006; accepted December 4, 2006

 • Published online 13 June 2007 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/asi.20638

Background and Related Work

The origin of scientific collaboration extends back to the 17th and 18th centuries, and according to Beaver and Rosen (1978), has grown because of the professionalization of science. Wray (2002) also argued that its growth can be attributed to the need of abundant resources in contemporary research, and Price and Beaver (1966) discussed the impact that an elite group of collaborators can have on research. Although the benefits of collaboration are vast, collaborative works have been shown to have greater epistemic value or authority than individual works, as witnessed, in part, by citation history (Beaver, 2004; Wray, 2002). For example, Beaver (2004) found that the citation lifetime for publications with multiple authors was significantly higher than that for single-authored works, at 16.8 versus 11.1 years on average.

It is thus not surprising, then, that the nature and structure of scientific collaboration has received a great deal of attention. The predominant way in which the structure of collaboration has been studied in the sciences is via inference from co-authorship. Co-authorship networks are social networks constructed by connecting two authors, or nodes, if they have co-authored an article together. Co-authorship surely is not the only form of collaboration in the sciences (see also, Katz & Martin, 1997) and acknowledgements, for example, are a less visible, but notable form of contribution (Cronin, Shaw, & La Barre, 2003; Giles & Councill, 2004). In some fields, such as experimental high-energy physics, author lists can reach hundreds or even thousands of people (Birnholtz, 2006; Newman, 2001). In these cases, it is unlikely that two given authors will have directly worked together (Newman, 2004b). In our study, we restrict our definition of collaboration to co-authorship, and exclude experimental articles to avoid this disparity between the theoretical and experimental subcommunities.

Using co-authorship as a measure of collaboration, collaboration in the sciences in general has been reported to have been increasing since at least 1950, in fields such as psychology, biology, economics, and social science (Kraut, Galegher, & Egido, 1988; Laband & Tollison, 2004; Moody, 2004; Over, 1982). In the domain of physics, where this study is focused, Newman (2001, 2004a, 2004b) has made significant contributions in understanding basic, structural, and evolutional properties of co-authorship networks. Newman reported the mean number of authors for papers in theoretical high energy physics as 1.99 based on data between 1995 and 1999 from the arXiv, an e-print repository (Ginsparg, 1994, 2000). He also compared related properties to other subfields and domains, including biology and mathematics, also studied by Barabasi (2002). In addition to these sciences, many other domains have been studied using co-authorship networks, including younger fields such as CSCW (Horn, Finholt, Birnholtz, Motwani, & Jayaraman, 2004) and digital libraries (Liu, Bollen, Nelson, & Van de Sompel, 2005).

One differentiating feature of our work from the above research is that we focus specifically on remote co-authorship as opposed to co-authorship in general. Instead of constructing the co-authorship network as described above, we replace authors in the network with their respective institutes, and in this way approximate remote collaboration. Our longitudinal study allows us to examine the impact of the Internet and CSCW technologies on remote collaboration.

Multinational collaboration (an even stricter definition of remote collaboration) is another type of collaboration that we consider in our work. The National Science Board (2006) reported that "in 2003, 20% of all articles had at least one foreign author, up from 8% in 1988." Wagner (2005) examined six cases of international collaboration across six fields as evidenced by co-authorship networks, and found that international collaboration was increasing at a faster rate than collaboration overall. She reported on the number of countries that were represented in each field, and on the percentage of articles that had multiple countries. Luukkonen, Persson, & Sivertsen (1992) also witnessed growth in international collaboration. Our work looks at multinational collaboration in the high-energy physics domain over a period of 30 years, far longer than any other study we have encountered.

Time-motivated studies of scientific research also include the work of Chen (2005), who used betweenness centrality (Freeman, 1997) to capture pivotal points in a field's history influenced by its citation networks, and the work of Morris, Yen, Wu, and Asnake (2003), who visualized evolution of keywords to discover emerging research fronts. Through these and other studies, much has been discovered about behaviors and behavioral trends, research topics and trends, as well as about the tools or informetrics for discerning such properties. Our work likewise relies on metrics from social network analysis, including betweenness centrality and strongly connected components.

In addition to using quantitative metrics, we also deployed animated visualizations of the remote collaboration networks to observe their evolution, and found that each method supported the other. Work by Börner, Penumarthy, Meiss, and Ke (2006) included the use of visualizations to study information diffusion over nearly 20 years in the United States. Interestingly, their work found that the Internet did not impact the distance over which information diffuses as measured by citation links. Their result was consistent with our result for remote collaboration.

Understanding the nature of remote collaboration and the impact of the Internet, or other CSCW technologies, is not only important to the scientists, but also to designers of these technologies. Brush, Wang, Turner, and Smith (2005) argue, for example, that designers of online communities ought to incorporate social network metrics into their sites. Although we did not attempt to study the specific media used for the collaborations, we refer the reader to work by Haythornthwaite and Wellman (1998), which relates media usage to collaborative relationships, and Hara, Solomon, Kim, and Sonnenwald (2003), who studied multidisciplinary collaboration through surveys, interviews, and observations.

Methodology

We obtained journal publication data from the SPIRES-HEP database. SPIRES-HEP is a widely accessed database of high-energy physics (HEP) related articles that began in the late 1960s. It is run by the Stanford Linear Accelerator Center (SLAC) together with DESY, FNAL, and others across the HEP community.

Prior to extracting collaborations from the publication archive, we participated in several dialogues and exchanges with high-energy physicists at SLAC about their domain and the intentions of our study, coming to the following formulation. First, only articles with five or fewer authors were extracted to remove corruption due to experimental articles, which are of a highly collaborative different nature, and often have more than 100 co-authors (Horn, Finholt, Birnholtz, Motwani, & Jayaraman, 2004). The importance of the distinction between collaboration and "teamwork," the latter having a greater number of participants, has also been noted by Beaver (2001). The number of articles with five or fewer authors in the collection was also verified to be increasing at a constant rate, representative of other theoretical scientific subfields, including mathematics, whose number of authors has been reported to be increasing at a constant rate for 60 years (Grossman & Ion, 1995). Hence, our resulting collection attempted to best represent collaboration in the theoretical high-energy physics community and spanned 87,592 authors, 202,597 journal articles, 4,264 institutes, and 138 countries over the 30-year period from 1975 to 2004 inclusive. The robustness and longevity of the SLAC-SPIRES collection provided us with the tools we needed to draw conclusions about the impact of CSCW technologies on this community's collaboration behaviors. Furthermore, the conclusions we draw may not apply to hyperauthored collaborative works, which can have hundreds of authors and may be evolving differently.

Second, for each article in this collection, we quantified its number of remote collaborations from the number of distinct institutes of its co-authors. If two institutes were represented in an article, then that article was declared to have one remote collaboration. Note that although authors move and affiliations change, the institute of the author at the time of submission of the article for each article was captured. It is also the case that authors may have joint appointments, and may record both institute affiliations at the time of article submissions. Because this was a nontrivial percentage of cases (10–13% in most years), we decided to include each of the authors' recorded institutes rather than discarding or truncating the affiliation list arbitrarily. Last, affiliations in our data set are distinguished by specific departments. Because global positioning system (GPS) coordinates were not available for all institutions, we defined any collaboration between them as remote. For example, collaboration between a physics department and computer science department at the same university will be noted as remote.

Using the same formulation as above, we mapped the affiliations to their respective countries, thus constructing cross-country collaboration representations, for comparing the impact of CSCW technologies on potentially more widespread and culturally diverse collaborations.

Numerical statistics, graph visualizations, and social network measurements were performed to interpret the changes in both the size and structure of the remote collaborations over this period of history. Pajek (Pajek, n.d.), a network analysis tool, and Graphael (Forrester, Koourov, Navabi, Wampler, & Yee, 2005), a network visualization tool, were used in part.

Results

The results of our analysis show that there have been steady and constant trends with respect to the frequency and structure of both interinstitute and cross-country collaborations in our domain, unaltered in the dates surrounding the introduction of CSCW and Internet technologies.

Frequency, Breadth, and Strength of Remote Collaborations

Figure 1 shows the percentage of publications for which there was an interinstitute collaboration, calculated independently for each year. Although we witness an increase in this percentage, reaching nearly 60%, the rate of that increase remains constant for the entire 30 years, both before and after the addition of new technologies. A revolutionary impact of these technologies might have been apparent if there was an increase in the slope or a change in the line shape midway in the time interval. Instead, in 30 years, the percentage of interinstitute articles has increased at a constant rate, roughly equating to a steady 1% increase per year, regardless of technological innovations, or other influences. The constant rate of increase was, however, enabled to continue.

Also represented in Figure 1 are the collaborations across countries. We observe a similar and mostly constant trend from roughly 10% to nearly 40% of publications being affiliated with multiple countries over the 30 years. This rate of growth is rather consistent with the findings of the National Science Board (2006) reported above, which reported a 12% increase in the percentage of articles with at least one foreign author over 15 years, and with the findings of Wagner and Leydesdorff (2005), which showed a 7% increase in 10 years. From the graph, we can predict the frequency will continue to increase steadily, as the number of papers in total is also increasing.

Besides frequency, we also observe a steady increase in the breadth of distance collaborations, as measured by the average number of remote collaborators per institute, as shown in Figure 2. Specifically, the number of institutes with which an institute collaborates with in a given year has increased steadily for 30 years at a constant rate of one additional

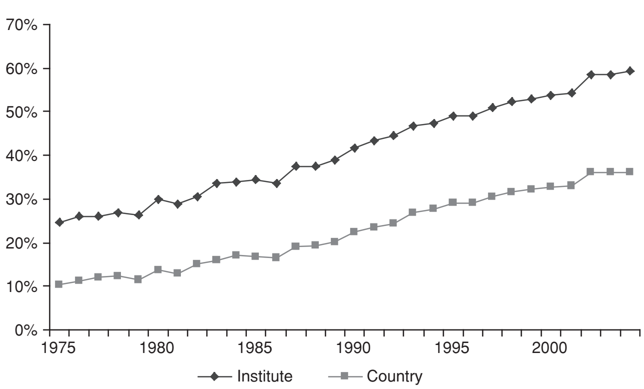

FIG. 1. Percentage of papers with interinstitute and cross-country collaborations.

DOI: 10.1002/asi

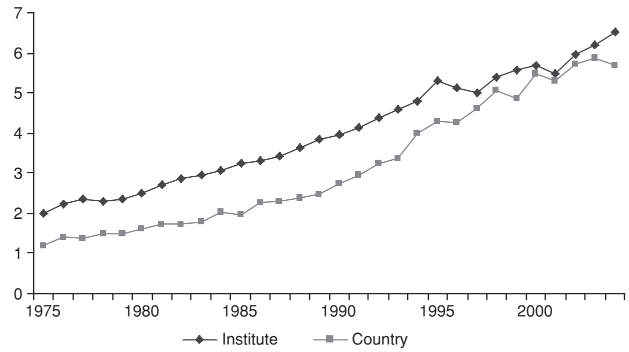

FIG. 2. Breadth of interinstitute and cross-country collaborations.

institute every 2 years. The analogous information for the number of ties that countries have per year shows a somewhat constant growth, with possibly a more rapid growth between 1989 and 1995.

In social networks, strong ties correlate with frequent interactions or exchanges. Likewise, we captured the strength of collaborations, as measured by the quantity of articles remotely collaborated on over each pair of collaborating institutes. What we again found however, is a steady increase, with considerable predictive power, but without evidence of trend-based changes after the years of interest. The seemingly predictive nature of these behaviors is of notable interest.

Structure and Evolution of Remote Collaboration Networks

To achieve a more robust understanding of the evolution of these networks, we constructed remote collaboration visualizations via weighted graphs and animated them over time. Two institutes (or countries) are connected in a given year if there is a collaborative relationship between them, as captured by the publication of an article that year by authors at the respective locations. The weights of the edges represent the number of articles on which the two nodes collaborated in that year. Weighting helps to visualize the strength of ties also quantified above, for example, by allowing display of thicker lines for strong ties. Figure 3 shows two series of four snapshots in time for each of the institute and country graphs; in practice, we played an animation including the graphs for each of the 30 years to better detect trends.

The first time sequence shows the evolution of the collaborations between institutes. The collaboration network shows a slow and steady increase in the density of collaboration, beginning as early as 1975, again showing no peak that could be attributed to CSCW. One interesting trend is the movement of one large node from a central position to an outside role. This node represents CERN, a high-energy physics powerhorse, and its size is correlated with its number of connections. By watching the graph evolve, it is clear that as new institutes slowly joined and built ties, the "physical" centrality of this institute moved outward. The graph layout algorithm attempts to minimize crossing links, so nodes in the center are often nodes that serve to connect other nodes, or that appear between other nodes on their paths. This role is not unlike the notion of betweenness centrality (Freeman, 1997) in social network analysis, which describes the influence of an actor in a network, by how frequently it is "between" other actors as measured by shortest paths between them. We computed betweenness scores for the institutions, which confirmed that this score was steadily decreasing for CERN throughout the entire period (with a score of nearly .5 in 1975 and .1 in 2004). This change was again constant throughout time with no visible changes after the births of CSCW and the Internet.

Another common metric in social network analysis is the percentage of actors in a community who are in the largest strongly connected component (SCC). A large SCC, or the presence of relatively few disconnected nodes is evidence of stability of a field, and predicted longevity, both properties that technology may serve. The intuition is that technology may have changed the shape of the community and served to join disconnected smaller subgroups. Both the visual graph and independent calculations concurred that the percentage of nodes in the SCC increased steadily over time. This value

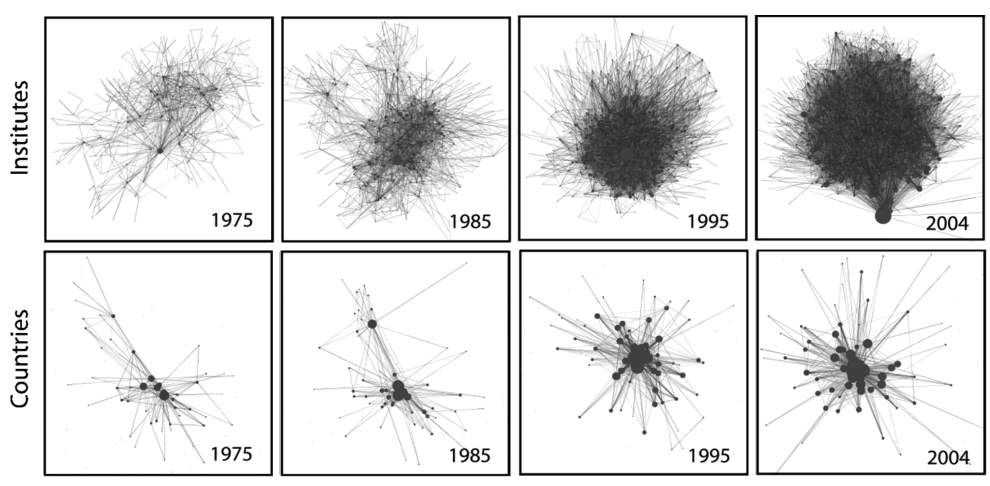

FIG. 3. Snapshots of institute and country collaboration graphs.

DOI: 10.1002/asi

started at nearly 80% in 1975 and reached just under 100% 10 years later, which is where it has stayed for the last 20 years, showing a thriving community. Again, there were no noticeable differences in the structural behaviors from the mid-1980s to the mid-1990s. Instead, its connectivity has been maintained.

The second time sequence in Figure 3 shows the evolution of the collaborations between countries and, as before, shows quite gradual and constant changes over each year. We observed one trend blatantly in the animated playback beginning around 1983, which concerns the movement of the noticeable node (which happens to be Russia) in the upper left corner of the two graphs into the very center of the latter two graphs. Over these years, Russia, appeared to first gain ties while remaining somewhat removed from the most central cluster, then continually moved towards the center, reaching it in 1989. The changes in betweenness scores for Russia, depicted by a rise and fall, coincide with this movement, but do not appear to coincide with the birth of these new technologies.

The percentage of nodes in the largest SCC of the country graph also grew steadily over time, and there were never any components, or groups other than the largest and only SCC. The steady growth rate before and after the birth of the Internet again suggests that CSCW technologies did not alter the general shape of the community.

Conclusion

We have presented a study of the frequency and structure of remote collaborations of a scholarly community over 30 years, with the purpose of looking for trends that may coincide with the introduction of the Internet and CSCW related technologies. Our choice of collaboration networks (both institute- and country-based) and the size and longevity of our data allowed us to test our hypothesis as to whether or not the Internet had an impact on the frequency of remote collaboration, in our chosen domain. Rather than examining ties between authors (or articles in the case of citation analysis), as in earlier work, we extracted ties between author affiliations and countries to present the structure and evolution of remote collaborations in the high-energy physics community. We find that the change in relative frequency of remote collaborations is precisely constant with respect to the number of papers throughout our 30-year period, so that this growth cannot be attributed to the impact of these technologies, as we first anticipated. Instead, these technologies more likely may have enabled an existing trend to continue.

Of particular interest to us were the steady rates of increase in long distance collaborations, both by institute and by country. Reflecting on this observation, virtual communication innovations may simply have been perpetual throughout time, and the trends may have been driven by inherent or social needs for outreach and communication. Regardless, our findings suggest that we are witnessing an evolution, rather than a revolution with respect to remote collaborative behavior and the Internet. And the characteristics of this evolution are of interest themselves.

In this article, we have tried to represent remote collaboration for the theoretical high-energy physics community by studying collaboration across institutes and across countries. It was noted that our definition of collaboration is limited to the co-authorship of a journal article as described above, and our findings limited to our chosen domain. Interestingly, however, physicists have been recognized as lead users (von Hippel, 1989) of communication technologies, argued by von Hippel as invaluable when designing novel products. Physicists' forward-reaching innovation helped lead to the World Wide Web we have today; in fact, the SPIRES-HEP literature database that we use in this work was the first Web site in North America. And, physicists also developed the first e-print open-access archive (Ginsparg, 1994) for communicating research.

We conclude that at least for the domain that we studied and for our limited definition of long-distance collaboration, we could not find evidence of significant changes in collaboration structure and frequency after the introduction of the Internet and CSCW related technologies. Instead, we found stable trends and healthy community structure, likely enabled to continue by such inventions. This lack of visible influence of the Internet on remote collaboration is consistent with work on information diffusion in the United States by Börner et al. (2006), described above.

Finally, we do no claim in this work to have studied the determinants of remote collaboration; clearly there are many nontechnical influences including social and political influences. Instead, we have used both quantitative and visualization methods to depict behavior over time. These methods corroborated steady and constant frequency and structural changes for our chosen community.

Acknowledgments

The authors wish to graciously thank Heath O'Connell for his work in providing us with publication data and Travis Brooks and Michael Sullivan, also from the SPIRES database team for their assistance. We are grateful for the assistance and input of our colleagues Gilly Leshad, Sadat Shami, and David Williamson, and for the valuable comments of our anonymous reviewers.

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DOI: 10.1002/asi

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DOI: 10.1002/asi