Restructuring Research: Communication Costs and the Democratization of University Innovation

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Abstract

We report evidence indicating that Bitnet adoption facilitated increased research collaboration between US universities. However, not all institutions benefited equally. Using panel data from seven top engineering journals, Bitnet connection records, and a variety of institution ranking data, we find that medium-ranked universities were the primary beneficiaries; they benefited largely by increasing their collaboration with top-ranked schools. Furthermore, we find that the magnitude of this effect is greatest for co-located pairs. These results suggest that the most salient effect of lowering communication costs may have been to facilitate gains from trade through the specialization of research tasks. Thus, the advent of Bitnet – and likely subsequent versions, including the Internet – seems to have increased the role of second-tier universities in the national innovation system as producers of new, high-quality knowledge.

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I. Introduction

We examine the effect of a decrease in collaboration costs resulting from the adoption of Bitnet (an early version of the Internet) on university research collaboration in engineering. Our interest in this question stems not from a concern about either Bitnet or engineering research specifically but rather the broader question of how changes in collaboration costs may affect the process of knowledge production. Exploiting the variation in year of adoption and publication output over time in the 270 universities that published in seven top electrical engineering journals from 1981 to 1991, we find that a Bitnet connection did seem to facilitate a general increase in multi-institutional collaboration (by 40%, on average). At the same time, not all adopters benefited equally. Overall, Bitnet seems to have facilitated a disproportionate increase in the role of second-tier universities, particularly those co-located with top-tier institutions.

The non-uniform effect of Bitnet across university pairs offers insight into the nature of collaborative knowledge production. A researcher deciding whether to add a collaborator to a project will do so if the benefit exceeds the cost such that the returns from collaboration are positive for both parties. Due to the way in which knowledge is produced, a technology shock such as the introduction of Bitnet might affect the returns to collaboration differently depending on characteristics of collaborating pairs, such as the quality of the institutions and the geographic distance between them. Indeed, our finding that certain university pair types benefited disproportionately from Bitnet adoption enables us to make inferences about the relative benefits and costs of collaboration across pair types.

For instance, we examine whether the returns to Bitnet adoption were mediated by pair quality. One might expect that pairs comprised of two top-tier universities would benefit most since, individually, these institutions produced the highest volume of research and thus had the most on which to collaborate. However, we find that top-middle-tier pairs benefited most from adoption. These results suggest that the most salient effect of Bitnet may have been to facilitate gains from trade through the specialization of research tasks.[1]

Why might this be? Consider universities of two research quality types: high and low. The former has a stronger orientation towards research, which is reflected in larger resource allocations to research activities and a broad range of doctoral programs. Researchers at high-quality schools may focus on winning grants, supervising the use of specialized equipment (lasers, robots, simulators, etc.), attending international conferences to present results, and other such high-cost activities. Researchers at lower-quality institutions, who may not have the resources necessary for running certain types of experiments entirely on their own, may have the expertise and equipment necessary for certain steps in the research process. Using Bitnet, data could be transferred to these researchers for data analysis and computing. Indeed, this pattern of activity is consistent with prior descriptive findings that characterize early electronic networks as facilitating a division of labor leading to a greater involvement of researchers at "peripheral" institutions (Hesse et al, 1993; Walsh and Bayma, 1996).

We also examine whether the returns to Bitnet adoption were mediated by the distance between pairs. One might expect that since Bitnet substitutes for other communication mechanisms (phone, fax, travel, etc.) and communication costs increase with distance, Bitnet would have disproportionately benefited pairs that were further apart since such pairs would

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[1] The intuition underlying how the effect of communication costs on collaboration is mediated by quality is similar in spirit to models that examine trade between developed and developing countries (e.g., Dixit and Norman, 1980; Helpman and Krugman, 1985). Many of these models show that the type of trade in equilibrium (i.e., developed-developed or developed-developing) will depend on the nature of the specialization and on the size of the economies. While we focus on specialization to explain our results, we acknowledge it is only one possible mechanism for differences of the observed effect of Bitnet across qualities. Other possibilities include monitoring (Baker and Hubbard, 2003) and heterogeneity in research interests (Rosenblat and Mobius, 2004). The aim of this paper is not to identify the particular mechanism but to empirically measure the impact of Bitnet connection on different types of collaborations.

have enjoyed the greatest cost reduction. However, for top-middle-tier collaborations in particular, our results show that the benefits of Bitnet were greatest for pairs that were close together.

These results suggest that network communication complements other collaborative tools. Since collaborations are predicated on shared ideas, which are often the unplanned output of direct interaction,[2] researchers may benefit significantly from face-to-face communication when they collaborate.[3] Although the cost reduction per collaboration is greater for pairs that are further apart, pairs that are closer together may interact more. Furthermore, electronic communication may be more valuable when paired with face-to-face meetings (Gaspar and Glaeser, 1998).[4]

Overall, we find that second-tier schools significantly increased their collaboration rates with co-located top-tier schools after Bitnet connection. These findings imply that the reduction in collaboration costs further accentuated tendencies for research activity to agglomerate rather than disperse; they are also consistent with the notion that the drop in costs facilitated a more efficiently functioning market for inputs into the production of knowledge, thereby broadening the set of institutions that participated – and continue to participate – in the production of high-quality electrical engineering research.

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[2] See, for example, Merton (1973) and Mairesse and Turner (2005).

[3] This is one of the arguments advanced to explain empirical evidence of agglomeration, particularly in knowledge-intensive industries (Audrestch and Feldman, 1996; Zucker et al, 1998).

[4] A rich theoretical literature has established the ambiguous effect of an improvement in communications technologies on interaction and collaboration across distances (e.g., Gaspar and Glaeser, 1998; Rosenblat and Mobius, 2004). We draw on this literature to interpret our results.

II. A Brief Description of Bitnet

Bitnet was an early leader in network communications for the research and education community. It allowed communication via email, access to remote file archives, use of Listserv, file transfer protocol (FTP), and compatibility with other operating systems such as UNIX.[5] The first Bitnet adopters were the City University of New York and Yale University in May 1981. By the end of the 1980s, Bitnet had become the largest academic network in the world for computer-based communications.[6] Even still, Bitnet did not have all the capabilities of today's Internet. For example, familiar Internet features such as the World Wide Web and the browser were not invented until the end of our study period.

While other networks (e.g., ARPANET, EDUNET, USENET, CSNET) existed at the same time, Bitnet is most suitable for the purposes of our study for a number of reasons. First, rather than being narrowly focused in areas such as defense or computer science like some of the other networks, Bitnet was made available to all scholars; it was consequently adopted more widely than any other network at the time, allowing us to explore how adoption changed collaboration patterns across a diverse set of institutions. Second, Bitnet adoption was carefully documented; data exist on the exact date of adoption for every institution in the network through 1990. This is not the case for other networks. Third, the ability of Bitnet users to exchange data through file transfer protocols as opposed to certain other networks that only allowed bulletin board postings and text messages offers insight into collaboration in fields that particularly benefit from data sharing, such as electrical engineering.

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[5] http://computing.dcu.ie/~humphrys/net.80s.html, Mark Humphrys, *The Internet in the 1980s* (Sept. 15, 2006).

[6] Gurbaxani (1990) provides a detailed account of the diffusion of Bitnet.

III. Data

We use a variety of data sources to examine collaboration between institution-pairs across universities in top electrical engineering journals from 1981 to 1991. We describe each of our main data sources below and provide descriptive statistics in Table 1.

Publication Data Since we are interested in identifying the effect of Bitnet on collaboration, we use publication data from researchers in technical areas that were likely to be early adopters of this communications technology and thus closely reflect the time variation in adoption. Specifically, we collect publication data (16,495 papers) from seven electrical engineering journals over the 11-year period 1981-1991.[7] Each of these journals is considered among the top outlets for research in the specified field. Since we focus only on these seven journals, the total number of publications in our analysis does not change systematically over time.[8] This means that we capture an overall change in multi-institution collaborations relative to single-institution collaborations rather than simply an overall increase in research output.

We extract the unique author-affiliated institution information from each paper and categorize each paper as either single- or multi-institution (i.e., collaborative).[9] We identify 720 unique institutions, of which 270 are US universities – our institution type of interest. These

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[7] The journals are: 1) IEEE Transactions on Aerospace and Electronic Systems, 2) IEEE Transactions on Nuclear Science, 3) IEEE Transactions on Biomedical Engineering, 4) IEEE Journal of Quantum Electronics, 5) IEEE Transactions on Electron Devices, 6) IEEE Transactions on Communications, and 7) IEEE Transactions on Education.

[8] There were a total of 1989 papers published in the first year of observation (1981) and 1401 papers published in the last year (1991). The total number of publications fluctuates from year to year due to the publication of special issues and occasional conference proceedings. The distribution of article quantity across journals also varies.

[9] Papers with multiple authors are still classified as single-institution if all authors are from the same university.

form the basis of our unit of analysis.[10] Thus, our primary data set consists of 36,315 institution-pairs over 11 years, resulting in a balanced panel with 399,465 observations.[11]

Bitnet Connection Data We use an online reference, Cyber Geography Research, for a record of Bitnet connections.[12, 13] Importantly, there is significant variation in these data. Although only three institutions were connected in 1981, there were 66, 183, and 225 connected by 1984, 1987, and 1990, respectively.

Quality Data Since we are interested in the way in which university research orientation (or "quality") mediates the effect of Bitnet adoption on collaboration propensity, we categorize each university as being Tier 1 (high research orientation), Tier 2 (medium research orientation), or Tier 3 (low research orientation). We define institution quality based on ranking by total university-level NSF funding over four years prior to our sample (1977-1980).[14] Thus, we classify the 270 universities in our data into three tiers, with 90 universities in each. We ensure robustness using a number of alternative definitions of institution quality in the appendix.[15]

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[10] We focus on US universities because many of the international institutions and US non-university research labs used networks other than Bitnet. Less than 1% of the connected institutions were for-profit (http://computing.dcu.ie/~humphrys/net.80s.html, Mark Humphrys, *The Internet in the 1980s*, Sept. 15, 2006).

[11] For Table 4, we also construct a single-institution dataset that includes the same 11 years of publishing from the specified journals by the 270 institutions of interest. Therefore, this is a balanced panel dataset of 2970 observations.

[12] http://www.cybergeography.org/atlas/bitnet_topology.txt (Sept. 15, 2006).

[13] We use the year following the technical connection as the first year Bitnet was available at the university. In the journals examined here, six months is a typical publication lag from manuscript submission to publication. All results are robust to using the same year of adoption.

[14] http://www.nsf.gov/awardsearch/tab.do?dispatch=4 (October 2, 2006). In the appendix, we show that the results are robust to including this NSF funding data (from 1981-1991) as a covariate in the regressions.

[15] We use three other definitions: 1) The first uses the 1987 Carnegie Foundation classification report that ranked universities based on their research orientation. Tier 1 is an aggregate of the Carnegie Foundation's categories "Research University 1 and 2." These institutions offer a full range of baccalaureate programs, are committed to graduate education through the doctorate degree, and give high priority to research. From 1983 to 1985, they received at least $12.5 million annually in federal support and awarded at least 50 Ph.D. degrees each year. Tier 2 is an aggregate of the Carnegie Foundation's categories "Doctorate-Granting Universities 1 and 2." These institutions offer a full range of baccalaureate programs, and their missions include at least some commitment to graduate education through the doctorate degree, such that they award annually 20 or more Ph.D. degrees in at least one discipline or 10 or more Ph.D. degrees in three or more disciplines; however, they do not meet the requirements for Tier 1. All other universities are classified as Tier 3. 2) The second definition is based on publications in our seven IEEE journals in the years prior to our study (1972-1979). We split these by quartile and group the bottom two

Distance Data In order to understand how distance between universities mediates the effect of Bitnet adoption on their propensity to collaborate, we calculate the straight-line distance between all possible pairs. We establish the location of each university's primary research campus from its official website and collect latitude and longitude data from the US Geological Survey based on city-state information.[16] We determine the distance between each university pair by employing the great circle method.[17]

IV. Empirical Strategy and Results

A. Did Bitnet facilitate collaboration across institutions?

Our estimation strategy is based on difference-in-differences identification. Using the paired institution data, we examine changes in collaboration between institution-pairs that both adopted Bitnet relative to pairs in which one or both did not adopt. We label the first institution in the pair *i*, the second *j,* and the year *t*.

We run linear regressions on the data using the following equation:

$$(1) \qquad Collaboration_{ijt} = \alpha X_{ijt} + \beta Both\ Have\ Bitnet_{ijt} + \mu_t + \phi_{ij} + \varepsilon_{ijt}$$

where the key explanatory variable, $Both\ Have\ Bitnet_{ijt}$ is a dummy that equals one if both institution *i* and *j* have connected to Bitnet by year *t*.[18] In addition, ϕ_{ij} measures institution-pair fixed effects, μ_t measures year fixed effects, and X_{ijt} is a vector of observable institution-pair-year characteristics. For this linear equation to identify the average effect of Bitnet adoption on

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quartiles together. Those in the top quartile have at least 15 publications over this period. Those in the second quartile have 3 to 14 publications. Those in the remaining two quartiles have two or fewer publications. The bottom two quartiles are grouped together because the total number of publications for these two quartiles over the entire data period (1972 to 1991) is similar. 3) The third definition uses the *1980 Gourman Report,* which ranked the top 50 engineering departments in the US. We define all schools with a top-50 ranking as Tier 1 and all others as Tier 2.

[16] US Geological Survey: http://geonames.usgs.gov/, web query application: http://geonames.usgs.gov/pls/gnis/web_query.gnis_web_query_form (Sept. 15, 2006).

[17] acos(cos(lat1)cos(long1)cos(lat2)cos(long2)+cos(lat1)sin(long1)cos(lat2)sin(long2)+sin(lat1)*sin(lat2))*earthRadius.

[18] We also examine time since Bitnet adoption, the effect of which is most clearly illustrated in Figure 1.

collaboration between two given institutions, we implicitly assume that unobserved institution-pair quality can be decomposed into an additively separable fixed component and a time-varying component that is constant across institution-pairs (Athey and Stern, 2002).

We treat $Collaboration_{ijt}$ as a dummy variable for whether institutions i and j had any collaborations in year t. We estimate equation (1) using a fixed effects linear probability (OLS) regression with the fixed effects differenced out using average values.[19] We treat collaboration as a dummy variable because 78% of all institution-pair-years with at least one collaboration had only one collaboration. Heteroskedasticity-robust standard errors are clustered by institution pair-Bitnet adoption status.

The first column of Table 2 shows our baseline specification. We regress collaboration on both universities in the pair being connected to Bitnet (*Both have Bitnet)*, institution-pair fixed effects, and year fixed effects.[20] Collaborations increased by approximately 50% after both universities in the pair were connected. This represents a significant increase in the propensity to collaborate. However, as we will show in the following sections, Bitnet adoption had an even

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[19] We focus on the linear results for three reasons. First, OLS allows coefficients to be easily compared across models and interpreted. Second, linear regression allows for differencing out the mean fixed effects and using the full data set. Third, while fixed effects logit and poisson regressions also allow differencing of mean effects, nonlinear methods are not necessarily consistent when there is a large number of zeros in the dependent variable (King and Zeng, 2001). The linear probability model is consistent and the estimated errors (with a heteroskedasticity correction) are correct. Wooldridge (2002) argues that the primary concerns about the linear probability model involve extreme values of the independent variables. He further argues that the case for using the linear probability model instead of a nonlinear model is strongest when the variables of interest are discrete, as is the case here. Tables A1 through A8 show robustness to numerous other specifications in modeling (i.e., fixed effects (FE) probit, FE negative binomial, FE zero-inflated poisson, conditional FE poisson, conditional FE logit, and random effects poisson) and covariate choices. The coefficient on *Both Have Bitnet* in the main specification in column (1) is positive and significant with at least 95% confidence in each of these models. Moreover, the additional controls in the regression appear to have boosted the significance of the coefficient of interest.

[20] A potential concern is that error terms are correlated across universities. For instance, if University A collaborates with University B and University B collaborates with University C, then A may be systematically more likely to collaborate with C. This could inflate the standard errors. To address this possibility, we identified all pairs in the data where A collaborates with B at least once and B collaborates with C at least once. This allows us to identify all pairs {A, C} in which the preceding concern may be relevant. We then take the extreme action of dropping all 2916 such pairs from the analysis. Table A9 shows that, if anything, statistical significance increases.

greater effect (more than double) on collaboration between certain types of institutions, namely top tier-middle tier pairs that were co-located.

First though, we provide evidence that our main findings are not likely to be a result of omitted variables or Bitnet adoption endogeneity. For example, perhaps certain universities shifted policy to increase their performance, which resulted in both Bitnet adoption and increased research output. Or maybe certain universities recruited young new faculty who had a taste for both electronic networking and collaboration. Or universities may have adopted Bitnet *because* their collaborations were increasing.

To address these concerns, we first add four covariates that control for observable changes in department quality over time: 1) number of single-authored publications, 2) number of electrical engineering doctorates awarded,[21] 3) number of electrical engineering postdoctoral students,[22] and 4) R&D expenditure in electrical engineering.[23] We lag the latter three covariates by one year to reflect the time between their input into research and publication. The second column of Table 2 shows the results. The coefficient on *Both have Bitnet* is smaller in this regression, indicating that these controls are explaining some of the variation, but the relationship of interest is still statistically significant and economically important; the rate of collaboration increased by approximately 40% if both institutions were connected. We include these four controls in all subsequent specifications.

Second, we add a control to examine whether only one of the schools in the pair adopting Bitnet increased collaboration (Table 2 column 3). If so, this would imply that Bitnet adoption was correlated with some other factor that influenced collaboration since both institutions needed

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[21] NSF Survey of Earned Doctorates

[22] Survey of Graduate Students & Postdoctorates in Science and Engineering

[23] Survey of R&D Expenditures at Universities and Colleges. This variable measures annual spending by electrical engineering departments. Spending from NSF grant money is included in the value.

to be connected to utilize the network as a communication device. However, the coefficient on *One or more has adopted* is not significant and the coefficient on *Both have Bitnet* remains virtually unchanged. This finding is consistent with the assertion that Bitnet facilitated collaboration by lowering communications costs between connected institutions.

We also verify that the measured impact of Bitnet did not begin prior to adoption. If the increase in collaborations is related to Bitnet adoption because second-tier schools were improving in research and also investing in communications technology, then we would expect to observe an increase in collaboration in the years preceding adoption. To explore this possibility, we substitute the *Both have Bitnet* variable for a sequence of dummy variables for the years before and after adoption. Figure 1 shows the predicted collaboration rates by year before and after adoption. There was no significant increase in collaborations in the years preceding Bitnet adoption. Collaboration rates began to rise in the year following adoption and then rose substantially two and three years after adoption. They then remained at a higher rate.

To fully dispel endogeneity concerns underlying the relationship between adoption and collaboration, we would need a strong instrument that is correlated with adoption but not with the propensity to collaborate. Unfortunately, such an instrument is unavailable here. In its absence, we rely on the analyses described above that, in combination, suggest that our results are not driven by spurious correlation. Furthermore, the thrust of our argument is that Bitnet facilitated (rather than caused) an increase in cross-university collaboration. Researchers only collaborate if they want to. Even if the researchers studied here influenced their university's decision to adopt Bitnet so they could collaborate, the network succeeded in facilitating this collaboration.[24]

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[24] Besides endogeneity, another potential concern is the low values for ('within') R^2 in the regressions. Given the large number of observations, the small number of explanatory variables, the linear probability model, and,

B. Does the Bitnet Effect Vary with Institution Quality?

In addition to an overall rise in collaboration, a drop in communication costs might have led to a change in the relative roles of institutions of different qualities in research production. To explore this, we divide the university-pairs in our sample into six quality-type groups as categorized by ranking total NSF grants received by each university over the four years preceding our study: Tier 1-Tier 1, Tier 1-Tier2, Tier 1-Tier 3, Tier 2-Tier 2, Tier 2-Tier 3, and Tier 3-Tier 3. Interestingly, only the coefficients on Tier 1-Tier 2 and Tier 2-Tier 2 pairs are significantly positive (Table 3). Tier 1-Tier 2 pairs in particular showed a substantial increase in collaboration rate after connection. For this sub-sample, both universities in the pair being connected increased the likelihood of collaboration by 133%.[25]

We next seek to better understand who benefits from collaboration between high-medium pairs. We analyze single-institution level data to provide suggestive evidence that it is the medium-ranked institutions that benefited most from top-medium-tier collaboration. These are OLS regressions of total publications on *HasBitnet*, institution-specific covariates, year fixed effects, and institution fixed effects (differenced out).[26] Table 4 shows that Bitnet adoption is

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especially, the differencing out of institution-pair fixed effects, we do not feel this is surprising. As shown in the tables, the pair fixed effects do explain a substantial part of the variation in the data. Despite the low R^2 values, our estimates are statistically significant and economically important. Furthermore, the low R^2 does not mean that researchers choose collaborators randomly. It simply means that it is difficult to predict exactly which year a given pair of institutions will collaborate. In Table A10, we show that we can explain a substantial fraction of the total number of collaborations between pairs in our data set.

[25] Tables A11, A12, and A13 show the robustness of the quality result using the three alternative definitions for quality described above.

[26] The qualitative results of this table do not change if fixed effect poisson regressions are used instead (Table A14). In fact, the significance of the Tier 2 results increases. A linear model is used to be consistent with the rest of the paper. For the regressions in Table 4 to identify the relationship between adoption and research production, we assume that unobserved institution quality can be decomposed into an additively separable fixed component and a time varying component that is constant across institutions. This assumption is questionable if Bitnet adoption is associated with an unobserved quality improvement. For this reason, we are especially cautious in our interpretation of the Table 4 results.

associated with an increase in total research output by middle-tier schools. This is not true of high- and lower-tier schools.

Overall, our results suggest the benefits of Bitnet adoption, measured by an increase in publications, likely accrued primarily to medium-ranked schools (Table 4) due to collaboration with top-ranked schools (Table 3). The reduction in communication costs associated with Bitnet seems to have led to a broadening of the institutions participating in the production of high-quality research, perhaps due to the benefits of specialization and gains from trade through cross-university collaboration.

C. Does the Bitnet Effect Vary with Distance?

If the drop in communication costs did not have a uniform effect over distance on propensity to collaborate, then distance, like quality, may have mediated the effect of Bitnet leading to a change in the spatial distribution of collaboration. To explore this, we employ a spline regression, grouping university pairs by the distance between them. Our results using all institution-pairs (Table 5 column 1) suggest that overall Bitnet adoption was associated with increases in both local and distant collaborations.[27]

Splitting the data by pair quality provides important detail on how distance was related to Bitnet adoption and collaboration. Columns 2 through 7 show that the greatest effect on multi-institutional paper production occurred for co-located high-medium pairs. Medium-tier universities also increased their collaboration with non-co-located top-tier universities, but the

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[27] The coefficient on *under 100km* is not significant, but it is substantially larger in magnitude than all other coefficients. Defining "local" more broadly as 250km leads to a large and significant coefficient (Table A15).

effect of Bitnet was several times greater for those that were co-located.[28] These findings suggest that low-cost electronic communication, while perhaps a substitute for face-to-face interactions under certain conditions, is also an effective complement, reinforcing other factors that lead to agglomeration, including thicker labor markets and equipment indivisibilities.

V. Conclusions

Overall, these findings enhance our understanding of knowledge production. A sharp decrease in collaboration costs amplified the role of middle-tier universities in the production of high-quality research.[29] In effect, Bitnet widened the circle of institutions participating in the national innovation system.[30] These findings offer meaningful insight since knowledge production ("innovation") is central to economic growth (Romer, 1990) and universities are an important component of the innovation system (Nelson and Rosenberg, 1993). Universities, of course, are not all the same; they are endowed with different levels of resources and different specialized expertise. Our results are indicative of a profound shift in the knowledge production system, perhaps because Bitnet facilitated gains from trade through specialization and collaboration.

Due to the nature of our data, however, we are unable to comment on whether Bitnet delivered an overall productivity increase. We have no data on inputs, and our output measure – publications from a fixed set of journals – remains reasonably constant over time. To be clear, what we observe is that Bitnet facilitated a change in the relative roles of certain types of universities with respect to the production of high-quality research.

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[28] Examples of collaborating, co-located, high-medium tier pairs include the Massachusetts Institute of Technology-Northeastern University in Boston/Cambridge and the University of Pennsylvania-Drexel University in Philadelphia.

[29] Our findings are consistent with a vertical specialization of tasks, in contrast to the "O-Ring" theory of production in which workers match with other workers of equal quality (Kremer, 1993).

[30] Ira Fuchs, the founder of Bitnet, responded to these findings by stating that part of the raison d'être of Bitnet was to "democratize connectivity" beyond the defense research community (personal interview, May 25, 2006).

Moreover, institutions other than universities, such as those from the private sector, also became more involved in the collaborative production of knowledge. For example, in 1981, private firms did not contribute to the collaborative research output in our set of journals, whereas they contributed to 7% and 12% of the collaborative papers in 1986 and 1991, respectively. Thus, our findings only provide a partial picture of the evolution of knowledge production.

In terms of the implications of these findings outside electrical engineering, our identified effect is not likely an isolated artifact of the specific fields examined here. For instance, Kim et al (2006) report that in economics, the research productivity effect of being affiliated with an elite institution was significant in the 1970s, weakened in the 1980s, and disappeared in the 1990s; the timing of this research dispersion in economics is consistent with our engineering results.[31] Furthermore, sociologists studying oceanography, mathematics, physics, chemistry, and experimental biology have found that the correlation between high network users and high productivity is greater for "peripheral" scientists (Hesse et al, 1993; Walsh and Bayma, 1996).

The introduction of Bitnet was only one piece of an evolving US research infrastructure in the latter half of the twentieth century. Policy initiatives set in motion by Vannevar Bush (1945) to capitalize on the important role played by collaboration of university scientists in WWII were still evolving during the period of our study. Perhaps of greatest relevance, a report prepared for President Eisenhower (Seaborg, 1960) explicitly called for an increase in research funding, especially for middle-tier research universities. This resulted in a decrease in the fraction of federal funding for the ten largest research institutions, from 37% in 1958 to 20% by

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[31] Hamermesh and Oster (1998) and Gaspar and Glaeser (1998) also examine the field of economics and provide more general results that are consistent with our findings. Hamermesh and Oster show an increase in collaborative research in economics from the 1970s to the 1990s, while Gaspar and Glaeser find a rapid growth in local collaboration in economics since the 1960s.

1990, with the preponderant share going to medium-tier universities (Geiger and Feller, 1995). Still, the specific timing of changes in collaboration patterns identified here are so tightly tied to the adoption of Bitnet that it seems probable the introduction of this communications technology was instrumental in unlocking the potential of middle-tier universities, which may have been nurtured for some time prior through increased funding and other policy initiatives.[32]

Still, this research leaves an important open question: How do researchers choose their collaborators? Effective research collaboration is predicated on familiarity, common knowledge, and trust (Crane, 1965; Merton, 1973). As such, professor-student and student cohort relationships may play a particularly important role in multi-institutional collaborations.[33,34] Thus, Bitnet likely increased the role recruiting and migration patterns played in the architecture of innovation systems. Furthermore, in other national settings where graduate student dispersion patterns or the distribution of capital-intensive research equipment were markedly different, the introduction of electronic networks may not have had the same effect. Alas, our data only set the stage for asking such questions; we leave these puzzles for future research.

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[32] Not only was Bitnet just one feature of the evolving US research infrastructure, it was also just one of many communications-related innovations that gained widespread adoption during the 1980s. For example, TeX (used for digital typography) and personal computers (such as Apple's Macintosh) were other innovations that lowered the cost of collaboration and gained broad adoption during that decade. Once again, though, we note that the specific timing of changes in collaboration patterns identified here are so tightly tied to the adoption year of Bitnet that although other innovations were surely important (and perhaps complementary) in facilitating collaboration, they did not diminish the critical role played by Bitnet.

[33] Based on biographical information for researchers involved in a sub-sample (163) of the collaborations in our study, Table A16 shows a significant fraction involved researchers who were previously at the same institution. Interestingly, the majority of these had professor-student (or professor-post doc) relationships (as opposed to professor-professor, for example) during the time they were at the same institution. Furthermore, although we hesitate to draw any strong conclusions from this small sub-sample, it seems that "institution swapping" is a less important part of the story for co-located collaborations (<100km) than for those separated by a greater distance. Overall, these descriptive data suggest faculty moves and former students play an important role in generating inter-institution collaborations across both quality types and distance.

[34] Professor-student collaborative relationships are particularly salient if research is paradigm shifting. Although his study does not focus on collaborations per se, Weinberg (2006) shows that the interaction of prior geography (having been co-located with an intellectual "leader" of a new paradigm) and vintage (being young in a field, such as a graduate student) are strong predictors for making important contributions early in the life of a scientific revolution.

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Table 1: Descriptive Statistics

Variable (by year)	Mean	Standard deviation	Minimum	Maximum	# of observations
Institution Level					
Total papers	2.779	6.453	0	131	2970
Multi-institution papers	1.587	3.369	0	92	2970
Single-institution papers	1.191	3.546	0	39	2970
R&D in electrical engineering (millions of $, lagged)	1.350	4.752	0	67.613	2970
# of electrical engineering doctorates given (lagged)	2.895	6.864	0	67	2970
# of electrical engineering post-doctoral students present (lagged)	0.652	2.283	0	50	2970
Average year adopting Bitnet*	1985.5	2.018	1981	1990	2970
Has Bitnet	0.400	0.490	0	1	2970
Multi-institution papers if Tier 1	3.819	4.889	0	39	990
Multi-institution papers if Tier 2	0.596	1.107	0	7	990
Multi-institution papers if Tier 3	0.346	1.197	0	13	990
Institution-Pair Level					
# of collaborative papers between the pair	0.00165	0.0521	0	6	399,465
Dummy for pair-years where there is collaboration	0.00134	0.0365	0	1	399,465
Dummy for collaboration if at least one has not adopted Bitnet	0.000724	00269	0	1	298,491
Dummy for collaboration if both have adopted Bitnet	0.00315	0.0560	0	1	100,974
Distance	1767.9	1301.2	0	8293.7	399,465
Sum of # of single-institution papers produced by the pair	2.381	5.025	0	117.0	399,465
Sum of R&D in electrical engineering (millions of $, lagged)	2.700	6.755	0	132.2	399,465
Sum of # of electrical engineering doctorates given (lagged)	5.789	9.765	0	128.0	399,465
Sum of # of electrical engineering post-doctoral students present (lagged)	1.304	3.225	0	62.0	399,465
Dummy if at least one of the pair has adopted Bitnet	0.547	0.498	0	1	399,465
Dummy if both institutions have adopted Bitnet	0.253	0.434	0	1	399,465

*Conditional on adopting Bitnet by the end of 1990

Table 2: Bitnet Adoption and Collaboration Using Institution-Pairs

	(1)	(2)	(3)
Dependent variable is *collaboration*	Main specification without time-varying institution characteristics	Main specification: Linear regression with a dummy for any collaboration as the dependent variable	Includes variable if just one institution has adopted
Both have Bitnet	0.000852	0.000667	0.000673
	(0.000198)**	(0.000199)**	(0.000198)**
One or more has adopted Bitnet			-0.0000652
			(0.000178)
Sum of # of single-institution papers		0.00000277	0.00000271
		(0.0000586)	(0.0000586)
Sum of R&D in electrical engineering (millions of $, lagged)		0.000146	0.000146
		(0.0000330)**	(0.0000330)**
Sum of # of electrical engineering post-doctoral students present (lagged)		0.0000287	0.0000290
		(0.0000480)	(0.0000480)
Sum of # of electrical engineering doctorates given (lagged)		0.0000435	0.0000434
		(0.0000349)	(0.0000349)
# of Observations	399,465	399,465	399,465
# of Groups	36,315	36,315	36,315
R^2	0.001	0.001	0.001
Fraction of variance explained by ϕ_{ij}	0.17	0.17	0.17

**significant at 99% level; *significant at 95% level; +significant at 90% level

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

Table 3: Bitnet Adoption, Collaboration, and Institution-Pair Quality

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable is *collaboration*	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	-0.00164	0.00181	0.0000951	0.000513	0.0000359	-0.000404
	(0.00156)	(0.000451)**	(0.000300)	(0.000278)+	(0.000235)	(0.000225)+
Sum of # of single-institution papers	0.0000117	-0.0000248	0.00000701	0.000390	0.0000531	0.000391
	(0.000165)	(0.0000845)	(0.0000362)	(0.000151)**	(0.000130)	(0.000205)+
Sum of R&D in electrical engineering (millions of $, lagged)	0.000312	0.000124	0.0000560	-0.0000689	-0.0000225	-0.000162
	(0.000103)**	(0.0000575)*	(0.0000216)**	(0.0000486)	(0.0000169)	(0.000226)
Sum of # of electrical engineering post-doctoral students present (lagged)	-0.0000918	0.000103	0.0000674	-0.000106	0.00000113	-0.0000474
	(0.000117)	(0.0000744)	(0.0000618)	(0.0000585)+	(0.0000524)	(0.0000522)
Sum of # of electrical engineering doctorates given (lagged)	0.000154	-0.00000932	-0.0000666	-0.0000602	-0.000135	0.0000691
	(0.000110)	(0.0000409)	(0.0000290)*	(0.0000495)	(0.0000665)*	(0.000133)
# of Observations	44,055	89,100	89,100	44,055	89,100	44,055
# of Groups	4005	8100	8100	4005	8100	4005
R^2	0.002	0.001	0.001	0.001	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.18	0.16	0.16	0.09	0.16	0.08

**significant at 99% level; *significant at 95% level; +significant at 90% level

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

TIER 1, TIER 2, and TIER 3 based on NSF funding from 1977 to 1980

Table 4: Bitnet Adoption and Total Publications, Single-Institution Data

	(1)	(2)	(3)
Dependent variable is *# of publications*	TIER 1	TIER 2	TIER 3
Has Bitnet	-0.0775	0.233	0.0638
	(0.656)	(0.135)+	(0.122)
R&D in electrical engineering (millions of $, lagged)	0.0856	-0.0142	0.611
	(0.0805)	(0.0195)	(0.322)+
# of electrical engineering post-doctoral students present (lagged)	0.0344	0.218	0.0897
	(0.0744)	(0.103)*	(0.179)
# of electrical engineering doctorates given (lagged)	-0.0284	0.0347	-0.116
	(0.0843)	(0.0421)	(0.0998)
# of Observations	990	990	990
# of Groups	90	90	90
R^2	0.06	0.04	0.04
Fraction of Variance explained by ϕ_i	0.78	0.37	0.66

**significant at 99% level; *significant at 95% level; +significant at 90% level

Regressions include year and institution fixed effects

Robust standard errors in parentheses

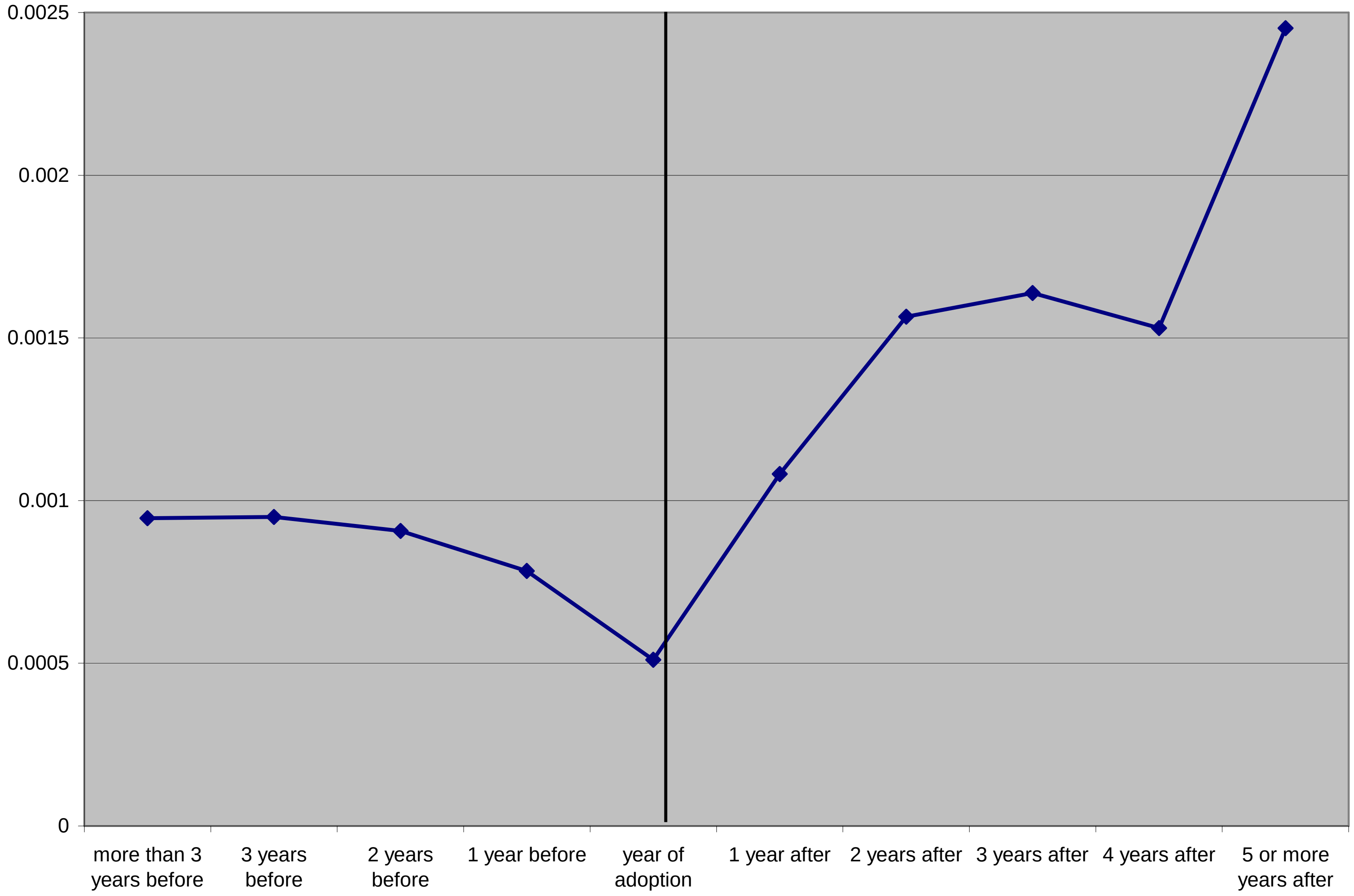
TIER 1, TIER 2, and TIER 3 based on NSF funding from 1977 to 1980

Table 5: Bitnet Adoption, Collaboration, Institution-Pair Quality, and Distance

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *collaboration*	All Data	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Distance is under 100 km and Both Adopted Bitnet	0.00347	-0.0179	0.01424	0.00538	-0.00208	0.00657	-0.000317
	(0.00310)	(0.0143)	(0.00476)**	(0.00511)	(0.00153)	(0.00511)	(0.000250)
Distance is between 100 km and 500 km and Both Adopted Bitnet	0.000380	-0.00347	0.00218	-0.000578	0.00280	-0.00138	-0.000203
	(0.000559)	(0.00277)	(0.000830)**	(0.000872)	(0.00122)*	(0.000767)+	(0.000175)
Distance is between 500 km and 1000 km and Both Adopted Bitnet	0.000133	-0.00411	0.00143	-0.000121	0.000570	0.000135	-0.000148
	(0.000355)	(0.00210)+	(0.000670)*	(0.000331)	(0.000464)	(0.000278)	(0.000166)
Distance is between 1000 km and 3000 km and Both Adopted Bitnet	0.000614	-0.000319	0.00119	0.000264	-0.0000372	0.000313	-0.000607
	(0.000216)**	(0.00166)	(0.000443)**	(0.000378)	(0.000258)	(0.000271)	(0.000324)+
Distance is over 3000 km and Both Adopted Bitnet	0.00131	0.000101	0.00234	-0.000146	0.000660	-0.000238	-0.000320
	(0.000419)**	(0.00178)	(0.000873)**	(0.000526)	(0.000710)	(0.000144)+	(0.000196)
Sum of # of single-institution papers	0.00000348	0.0000110	-0.0000230	0.00000720	0.000388	0.0000534	0.000393
	(0.0000585)	(0.000165)	(0.0000845)	(0.0000362)	(0.000151)*	(0.000130)	(0.000205)+
Sum of R&D in electrical engineering (millions of $, lagged)	0.000145	0.000326	0.000116	0.0000569	-0.0000685	-0.0000224	-0.000163
	(0.0000328)**	(0.000103)**	(0.0000556)*	(0.0000218)**	(0.0000485)	(0.0000167)	(0.000227)
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0000270	-0.0000967	0.0000995	0.0000669	-0.000107	0.00000358	-0.0000471
	(0.0000479)	(0.000117)	(0.0000743)	(0.0000618)	(0.0000590)+	(0.0000531)	(0.0000521)
Sum of # of electrical engineering doctorates given (lagged)	0.0000429	0.000150	-0.00000595	-0.0000674	-0.0000600	-0.000136	0.0000710
	(0.0000350)	(0.000111)	(0.0000411)	(0.0000291)*	(0.0000492)	(0.0000666)*	(0.000134)
# of Observations	399,465	44,055	89,100	89,100	44,055	89,100	44,055
# of Groups	36,315	4005	8100	8100	4005	8100	4005
R^2	0.001	0.002	0.001	0.001	0.001	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.17	0.18	0.16	0.16	0.09	0.16	0.08

**significant at 99% level; *significant at 95% level; +significant at 90% level
Regressions include year and institution-pair fixed effects.
Robust standard errors (clustered by pair-Bitnet status) in parentheses
TIER 1, TIER 2, and TIER 3 based on NSF funding from 1977 to 1980

Figure 1: Predicted Collaboration Rates by Year Before and After Adoption[35]



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[35] See Table A8 column (1) for coefficient estimates.

Appendix

Table A1: Fixed Effects Probit (Fixed effects are estimated, not differenced)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *collaboration*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.228	-0.139	0.800	0.137	0.453	0.0969	Would not converge
	(0.100)*	(0.166)	(0.270)**	(0.251)	(0.506)	(0.531)	
Sum of # of single-institution papers	0.00616	0.00751	0.00817	0.0142	0.701	0.204	
	(0.00386)	(0.00475)	(0.00850)	(0.0178)	(0.178)**	(0.103)*	
Sum of R&D in electrical engineering (millions of $, lagged)	0.01697	0.0146	0.0213	0.145	-0.415	-0.0194	
	(0.00633)**	(0.00713)*	(0.0155)	(0.0492)**	(0.368)	(0.181)	
Sum of # of electrical engineering post-doctoral students present (lagged)	0.00499	-0.00609	0.0274	0.0341	-0.395	0.0235	
	(0.00636)	(0.00753)	(0.0149)+	(0.0184)+	(0.298)	(0.117)	
Sum of # of electrical engineering doctorates given (lagged)	-0.00718	0.000185	-0.0184	-0.0571	-0.290	-0.297	
	(0.00447)	(0.00543)	(0.0116)	(0.0187)**	(0.141)*	(0.100)**	
# of Observations	4213	2200	979	561	153	162	
Log Likelihood	-1437.2	-764.0	-313.1	-179.7	-38.2	-54.9	

Regressions include year and institution-pair fixed effects
Robust standard errors (clustered by pair-Bitnet status) in parentheses
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A2: Fixed Effects Negative Binomial (Fixed effects are estimated, not differenced)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *# of collaborations*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.355	-0.201	1.129	0.180	0.504	0.199	-7.399
	(0.160)*	(0.269)	(0.431)**	(0.377)	(0.751)	(0.748)	(3.88)+
Sum of # of single-institution papers	0.0100	0.0112	0.0118	0.0194	1.027	0.242	6.344
	(0.00529)+	(0.00654)+	(0.0110)	(0.0310)	(0.309)**	(0.122)*	(1.575)**
Sum of R&D in electrical engineering (millions of $, lagged)	0.0224	0.0187	0.0272	0.213	-0.492	-0.0628	-38.545
	(0.00965)*	(0.0108)+	(0.0232)	(0.0766)**	(0.486)	(0.261)	(13.073)**
Sum of # of electrical engineering post-doctoral students present (lagged)	0.00613	-0.00983	0.0363	0.0417	-0.545	0.0595	Dropped
	(0.00948)	(0.0108)	(0.0151)*	(0.0180)*	(0.384)	(0.166)	
Sum of # of electrical engineering doctorates given (lagged)	-0.0112	-0.00130	-0.0239	-0.0868	-0.485	-0.394	-1.791
	(0.00650)+	(0.00752)	(0.0171)	(0.0276)**	(0.303)	(0.157)*	(0.613)**
# of Observations	4213	2200	979	561	187	198	88
Log Likelihood	-1505.8	-805.0	-331.4	-190.2	-42.3	-61.1	-10.1

Regressions include year and institution-pair fixed effects
Robust standard errors (clustered by pair-Bitnet status) in parentheses
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A3: Fixed Effects Zero Inflated Poisson (Fixed effects are estimated, not differenced)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *# of collaborations*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.321	-0.200	1.129	0.223	0.505	0.208	-22.431
	(0.161)*	(0.269)	(0.431)**	(0.382)	(0.751)	(0.689)	(3.883)**
Sum of # of single-institution papers	0.00889	0.0107	0.0118	0.0116	1.027	0.197	6.344
	(0.00542)	(0.00657)	(0.0110)	(0.0353)	(0.309)**	(0.127)	(1.575)**
Sum of R&D in electrical engineering (millions of $, lagged)	0.0213	0.0185	0.0271	0.220	-0.492	-0.0820	-38.547
	(0.00960)*	(0.0108)+	(0.0232)	(0.0762)**	(0.486)	(0.230)	(13.074)**
Sum of # of electrical engineering post-doctoral students present (lagged)	0.00540	-0.0103	0.0363	0.0401	-0.545	0.0247	Dropped
	(0.00965)	(0.010782)	(0.0151)*	(0.0180)*	(0.384)	(0.175)	
Sum of # of electrical engineering doctorates given (lagged)	-0.0119	-0.00145	-0.0239	-0.0873	-0.485	-0.416	-1.791
	(0.00652)+	(0.00753)	(0.0171)	(0.0273)**	(0.303)	(0.164)*	(0.613)**
# of Observations	4213	2200	979	561	187	198	88
Log Likelihood	-1501.9	-805.0	-331.4	-188.3	-42.3	-60.6	-10.1

Regressions include year and institution-pair fixed effects
Robust standard errors (clustered by pair-Bitnet status) in parentheses
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A4: Conditional Fixed Effects Poisson

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *# of collaborations*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.315	-0.147	1.172	0.318	0.640	-0.449	Would not converge
	(0.158)*	(0.251)	(0.422)**	(0.406)	(1.014)	(0.751)	
Sum of # of single-institution papers	0.00635	0.00766	0.00743	0.0252	0.936	0.252	
	(0.00571)	(0.00659)	(0.0124)	(0.0329)	(0.318)**	(0.124)*	
Sum of R&D in electrical engineering (millions of $, lagged)	0.0231	0.0164	0.0386	0.195	-0.664	0.0402	
	(0.0105)*	(0.0125)	(0.0247)	(0.0866)*	(0.763)	(0.372)	
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0252	-0.00609	0.0366	0.0761	-0.554	0.0114	
	(0.00895)**	(0.0133)	(0.0197)+	(0.0192)**	(0.476)	(0.330)	
Sum of # of electrical engineering doctorates given (lagged)	-0.0160	-0.00228	-0.0290	-0.111	-0.336	-0.438	
	(0.00672)*	(0.00773)	(0.0192)	(0.0318)**	(0.237)	(0.189)*	
# of Observations	4213	2200	979	561	187	198	
# of Groups	383	200	89	51	17	18	
Log Likelihood	-1307.6	-689.4	-260.8	-175.7	-27.7	-46.1	

Regressions include year and institution-pair fixed effects

**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A5: Conditional Fixed Effects Logit

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *collaboration*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.396	-0.214	1.277	0.239	0.524	0.111	Would not converge
	(0.185)*	(0.289)	(0.460)**	(0.505)	(1.093)	(0.949)	
Sum of # of single-institution papers	0.0102	0.0119	0.0122	0.0204	1.047	0.309	
	(0.00667)	(0.00811)	(0.0147)	(0.0358)	(0.351)**	(0.152)*	
Sum of R&D in electrical engineering (millions of $, lagged)	0.0260	0.0218	0.0334	0.231	-0.493	-0.0474	
	(0.0116)*	(0.0141)	(0.0260)	(0.0929)*	(0.725)	(0.395)	
Sum of # of electrical engineering post-doctoral students present (lagged)	0.00998	-0.00844	0.0494	0.0518	-0.559	0.0267	
	(0.0121)	(0.0156)	(0.0289)+	(0.0357)	(0.495)	(0.372)	
Sum of # of electrical engineering doctorates given (lagged)	-0.0125	-0.00126	-0.0292	-0.0956	-0.487	-0.467	
	(0.00768)	(0.00914)	(0.0208)	(0.0361)**	(0.276)+	(0.203)*	
# of Observations	4213	2200	979	561	187	198	
# of Groups	383	200	89	51	17	18	
Log Likelihood	-1052.0	-561.7	-225.4	-130.1	-24.7	-38.0	

Regressions include year and institution-pair fixed effects

**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A6: Random Effects Poisson

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *# of collaborations*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.919	0.178	1.734	0.349	0.304	0.455	-16.111
	(0.178)**	(0.322)	(0.450)**	(0.496)	(3.896)	(0.961)	(117.363)
Sum of # of single-institution papers	0.0286	0.0226	0.0206	0.0409	0.575	0.438	1.424
	(0.00685)**	(0.00820)**	(0.0150)	(0.0390)	(0.180)**	(0.211)*	(52.242)
Sum of R&D in electrical engineering (millions of $, lagged)	0.0206	0.0170	0.0268	0.0000264	-0.122	-0.181	-6.871
	(0.00774)**	(0.00679)*	(0.00990)**	(0.0557)	(0.270)	(0.591)	(452.739)
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0535	0.0211	0.0607	0.0834	-0.403	0.210	-13.950
	(0.0124)**	(0.00951)*	(0.0199)**	(0.0307)**	(3.201)	(1.809)	(107.428)
Sum of # of electrical engineering doctorates given (lagged)	0.0226	0.0203	0.0105	-0.0225	-0.0463	-0.00915	0.202
	(0.00577)**	(0.00673)**	(0.0106)	(0.0213)	(0.157)	(0.100)	(50.415)
# of Observations	399,465	44,055	89,100	89,100	44,055	89,100	44,055
# of Groups	36,315	4005	8100	8100	4005	8100	4005
Log Likelihood	-3701.6	-1668.4	-807.5	-557.4	-145.7	-191.9	-73.0

Regressions include year fixed effects and institution-pair random effects
Robust standard errors (clustered by pair-Bitnet status) in parentheses
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A7: Regressions include data on annual NSF grants to the universities

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *collaboration*	All	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	0.000655	-0.00163	0.00180	0.0000940	0.000498	0.0000362	-0.000400
	(0.000201)**	(0.00156)	(0.000452)**	(0.000301)	(0.000272)+	(0.000236)	(0.000222)+
Sum of # of single-institution papers	0.00000346	0.0000108	-0.0000238	0.00000728	0.000392	0.0000530	0.000392
	(0.0000587)	(0.000165)	(0.0000846)	(0.0000363)	(0.000151)**	(0.000130)	(0.000205)+
Sum of R&D in electrical engineering (millions of $, lagged)	0.000146	0.000312	0.000125	0.0000561	-0.0000683	-0.0000225	-0.000126
	(0.0000330)**	(0.000103)**	(0.0000575)*	(0.0000216)**	(0.0000485)	(0.0000169)	(0.000212)
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0000280	-0.0000907	0.000102	0.0000670	-0.000107	0.00000114	-0.0000481
	(0.0000478)	(0.000116)	(0.0000743)	(0.0000618)	(0.0000585)+	(0.0000524)	(0.0000525)
Sum of # of electrical engineering doctorates given (lagged)	0.0000421	0.000155	-0.0000102	-0.0000669	-0.0000603	-0.000135	0.0000750
	(0.0000354)	(0.000111)	(0.0000410)	(0.0000291)*	(0.0000495)	(0.0000667)*	(0.000138)
Sum of NSF Grants awarded to universities (millions of $, lagged)	1.00E-08	-1.61E-08	1.98E-08	5.34E-09	3.60E-08	-1.32E-09	-2.86E-08
	(1.98E-08)	(5.58E-08)	(2.56E-08)	(1.63E-08)	(3.07E-08)	(1.66E-08)	(-2.55E-08)
Log Likelihood	36,315	4005	8100	8100	4005	8100	4005
R^2	0.004	0.007	0.002	0.001	0.001	0.001	0.002
Fraction of Variance explained by ϕ_{ij}	0.17	0.18	0.16	0.16	0.09	0.16	0.08

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A8: Robustness of main result to alternative specifications

	(1)	(2)	(3)
Dependent variable is *collaboration*, unless otherwise stated	Years Before and After Adoption Dummies	Dependent variable is total # of collaborations	Random effects
Both Have Bitnet		0.000854	0.00114
		(0.000289)**	(0.000208)**
3 Years Before Adoption[a]	0.00000408	-0.0000694	0.0000836
	(0.000258)	(0.0000878)	(0.0000301)**
2 Years Before Adoption[a]	-0.0000388	0.000171	0.000122
	(0.000276)	(0.0000408)**	(0.0000286)**
1 Year Before Adoption[a]	-0.000162	0.000155	0.0000979
	(0.000278)	(0.000124)	(0.0000547)+
Actual Year of Adoption[a]	-0.000435	0.0000176	0.000161
	(0.000274)	(0.0000428)	(0.0000457)**
1 Year After Adoption[a]	0.000136		
	(0.000302)		
2 Years After Adoption[a]	0.000620		
	(0.000350)+		
3 Years After Adoption[a]	0.000692		
	(0.000390)+		
4 Years After Adoption[a]	0.000585		
	(0.000446)		
5 or More Years After Adoption[a]	0.00151		
	(0.000505)**		
Sum of # of single-institution papers	0.00000286		
	(0.0000586)		
Sum of R&D in electrical engineering (millions of $, lagged)	0.000140		
	(0.0000328)**		
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0000271		
	(0.0000478)		
Sum of # of electrical engineering doctorates given (lagged)	0.0000345		
	(0.0000348)		
# of Observations	399,465	399,465	399,465
# of Groups	36,315	36,315	36,315
R^2	0.001	0.001	0.005
Fraction of Variance explained by ϕ_{ij}	0.17	0.17	0.10

Unless otherwise specified, regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

[a] Base is more than 3 years before

Table A9: Results where observations with possibly correlated errors are dropped

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable is *collaboration* in columns (1), (2), and (5) and *# of collaborations* otherwise	Linear	FE Probit	FE Negative Binomial	FE ZIP	Conditional FE Logit	Conditional FE Poisson
Both have Bitnet	0.000375	0.493	0.803	0.772	0.844	0.554
	(0.000117)**	(0.167)**	(0.287)**	(0.281)**	(0.379)*	(0.272)*
Sum of # of single-institution papers	0.0000316	0.0226	0.0365	0.0299	0.0379	0.0274
	(0.0000161)+	(0.00873)**	(0.0141)**	(0.0144)*	(0.0244)	(0.0204)
Sum of R&D in electrical engineering (millions of $, lagged)	0.0000577	0.0557	0.0856	0.0807	0.0915	0.0550
	(0.0000182)**	(0.0178)**	(0.0277)**	(0.0269)**	(0.0386)*	(0.0290)+
Sum of # of electrical engineering post-doctoral students present (lagged)	-0.0000295	-0.0101	-0.0127	-0.0128	-0.0168	-0.0112
	(0.0000232)	(0.0158)	(0.0255)	(0.0258)	(0.0342)	(0.0210)
Sum of # of electrical engineering doctorates given (lagged)	-0.0000278	-0.0229	-0.0343	-0.0359	-0.0396	-0.0342
	(0.0000177)	(0.0102)*	(0.0157)*	(0.0156)*	(0.0186)*	(0.0165)*
R^2	0.001	N/A	N/A	N/A	N/A	N/A
Fraction of Variance explained by ϕ_{ij}	0.12	N/A	N/A	N/A	N/A	N/A
LL	N/A	-483.7	-501.5	-497.4	-345.2	-433.3

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A10: Explaining the total collaborations between pairs

	(1)	(2)
Dependent variable: *total # of collaborations* (1981-1991)	Negative binomial	Poisson
Sum of # of papers (1981-1991)	0.00587	0.00542
	(0.000576)**	(0.000475)**
Sum of total R&D in electrical engineering (millions of $, 1981-1991)	-2.90E-06	-3.42E-06
	(-1.08E-06)**	(9.75E-07)**
Sum of total # of electrical engineering post-doctoral students present (1981-1991)	0.0109	0.0120
	(0.00147)**	(0.00112)**
Sum of # of electrical engineering doctorates given (1981-1991)	-0.00158	-0.00111
	(0.000828)+	(0.000702)
Log(distance)	-0.465	-0.442
	(0.0300)**	(0.0224)***
Constant	-2.00	-2.09
	(0.201)**	(0.156)**
# of Observations	36,315	36,315
Pseudo-R^2	0.136	0.202

Table A11: Robustness to 1987 Carnegie Foundation Quality Definitions

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable is *collaboration*	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	-0.0000159	0.00141	0.000494	0.000550	0.000274	-0.000514
	(0.00106)	(0.000449)**	(0.000282)+	(0.000379)	(0.000193)	(0.000204)*
Sum of # of single-institution papers	0.000228	0.0000886	0.0000992	-0.0000963	0.00000180	-0.0000193
	(0.0000780)**	(0.0000585)	(0.0000370)**	(0.0000992)	(0.0000212)	(0.000154)
Sum of R&D in electrical engineering (millions of $, lagged)	0.000132	0.0000544	-0.0000649	-0.0000386	-0.0000367	-0.0000374
	(0.0000905)	(0.0000573)	(0.0000310)*	(0.000101)	(0.0000392)	(0.0000576)
Sum of # of electrical engineering post-doctoral students present (lagged)	-0.0000321	0.000132	0.0000271	-0.000118	0.00000352	0.000101
	(0.000112)	(0.0000733)+	(0.0000547)	(0.0000820)	(0.0000227)	(0.0000949)
Sum of # of electrical engineering doctorates given (lagged)	0.0000908	-0.000100	-0.0000337	0.000175	0.000124	0.000256
	(0.000142)	(0.000108)	(0.0000484)	(0.000105)+	(0.000105)	(0.000193)
# of Observations	58,916	68,640	12,1264	19,470	69,960	61,215
# of Groups	5356	6240	11,024	1770	6360	5565
R^2	0.001	0.001	0.001	0.002	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.17	0.19	0.16	0.08	0.11	0.15

Regressions include year and institution-pair fixed effects
Robust standard errors (clustered by pair-Bitnet status) in parentheses
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A12: Robustness to Quality defined by publication in seven IEEE journals from 1972 to 1979[a]

	(1)	(2)	(3)	(4)	(5)	(6)
Dependent variable is *collaboration*	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Both have Bitnet	-0.00335	0.00139	0.000367	0.000729	0.000743	0.000160
	(0.00249)	(0.000706)*	(0.000257)	(0.000546)	(0.000269)**	(0.000164)
Sum of # of single-institution papers	-0.0000266	0.000107	-0.0000427	0.000186	0.000179	0.0000797
	(0.000206)	(0.0000554)+	(0.0000508)	(0.000127)	(0.000112)	(0.000133)
Sum of R&D in electrical engineering (millions of $, lagged)	0.000386	0.000140	0.0000533	-0.0000174	0.0000150	-0.0000130
	(0.000117)**	(0.0000881)	(0.0000342)	(0.0000908)	(0.0000153)	(0.00000646)*
Sum of # of electrical engineering post-doctoral students present (lagged)	-0.000265	0.000296	0.00000173	0.000282	0.000234	-0.0000267
	(0.000144)+	(0.000113)**	(0.0000326)	(0.000331)	(0.000192)	(0.0000136)+
Sum of # of electrical engineering doctorates given (lagged)	0.000167	0.0000315	-0.0000626	-0.0000511	-0.0000220	-0.0000380
	(0.000139)	(0.0000550)	(0.0000239)**	(0.000102)	(0.0000368)	(0.0000160)*
# of Observations	30,525	54,450	106,425	23,595	93,654	90,816
# of Groups	2775	4950	9675	2145	8514	8256
R^2	0.002	0.002	0.001	0.001	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.17	0.17	0.18	0.11	0.19	0.08

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

[a] Tier 1 includes the top quartile, Tier 2 includes the second quartile, and Tier 3 includes all universities below the median.

Table A13: Robustness to Quality defined by the 1980 *Gourman Report*[a]

	(1)	(2)	(4)
Dependent variable is *collaboration*	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 2 and TIER 2
Both have Bitnet	-0.00637	0.00151	0.000329
	(0.00420)	(0.000415)**	(0.000143)*
Sum of # of single-institution papers	0.000145	-0.0000284	0.000151
	(0.000259)	(0.0000573)	(0.0000665)*
Sum of R&D in electrical engineering (millions of $, lagged)	0.000367	0.000116	-0.0000107
	(0.000146)*	(0.0000424)**	(0.0000220)
Sum of # of electrical engineering post-doctoral students present (lagged)	-0.000286	0.0000432	0.000118
	(0.000213)	(0.0000594)	(0.0000732)
Sum of # of electrical engineering doctorates given (lagged)	0.000419	-0.0000232	-0.000106
	(0.000200)*	(0.0000340)	(0.0000408)**
# of Observations	13,475	121,000	264,990
# of Groups	1225	11,000	24,090
R^2	0.003	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.17	0.18	0.14

Source: Gourman, Jack. 1980. *The Gorman Report*. National Education Standards.

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

[a] Tier 1 includes all universities with electrical engineering departments listed in the top 50. Tier 2 includes all other universities.

Table A14: Robustness of Table 4 to Fixed Effect Poisson specification

	(1)	(2)	(3)
Dependent variable is *# of publications*	TIER 1	TIER 2	TIER 3
Has Bitnet	0.0303	0.454	0.297
	(0.0528)	(0.140)**	(0.179)+
R&D in electrical engineering (millions of $, lagged)	0.0113	-0.0265	0.734
	(0.00370)**	(0.0327)	(0.421)+
# of electrical engineering post-doctoral students present (lagged)	0.00285	0.111	0.257
	(0.00381)	(0.0370)**	(0.260)
# of electrical engineering doctorates given (lagged)	-0.00321	0.00326	-0.101
	(0.00257)	(0.0209)	(0.0542)+
# of Observations	990	990	990
# of Groups	90	90	90
Log Likelihood	-1930.0	-934.9	-549.3

Regressions include year and institution fixed effects
Robust standard errors in parentheses
TIER 1, TIER 2, and TIER 3 based on NSF funding from 1977 to 1980.
**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A15: Distance results using an alternative distance measure

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent variable is *collaboration*	All Data	TIER 1 and TIER 1	TIER 1 and TIER 2	TIER 1 and TIER 3	TIER 2 and TIER 2	TIER 2 and TIER 3	TIER 3 and TIER 3
Distance is under 250 km and Both Adopted Bitnet	0.00212	-0.00565	0.00560	0.000758	0.00586	0.00167	-0.000210
	(0.00114)+	(0.00472)	(0.00181)**	(0.00207)	(0.00261)*	(0.00143)	(0.000187)
Distance is between 250 km and 1000 km and Both Adopted Bitnet	0.0000464	-0.00427	0.00172	-0.000139	0.000395	-0.000590	-0.000174
	(0.000339)	(0.00208)*	(0.000590)**	(0.000400)	(0.000398)	(0.000434)	(0.000169)
Distance is between 1000 km and 3000 km and Both Adopted Bitnet	0.000613	-0.000317	0.00119	0.000263	-0.0000335	0.000311	-0.000607
	(0.000216)**	(0.00166)	(0.000443)**	(0.000378)	(0.000258)	(0.000271)	(0.000324)+
Distance is over 3000 km and Both Adopted Bitnet	0.00131	0.000103	0.00234	-0.000147	0.000664	-0.000240	-0.000321
	(0.000419)**	(0.00178)	(0.000873)**	(0.000526)	(0.000710)	(0.000144)+	(0.000196)
Sum of # of single-institution papers	0.00000336	0.0000121	-0.0000244	0.00000686	0.000397	0.0000532	0.000393
	(0.0000585)	(0.000165)	(0.0000845)	(0.0000362)	(0.000151)**	(0.000130)	(0.000205)+
Sum of R&D in electrical engineering (millions of $, lagged)	0.000146	0.000323	0.000120	0.0000565	-0.0000687	-0.0000227	-0.000162
	(0.0000329)**	(0.000103)**	(0.0000568)*	(0.0000217)**	(0.0000485)	(0.0000168)	(0.000227)
Sum of # of electrical engineering post-doctoral students present (lagged)	0.0000272	-0.0000987	0.000102	0.0000674	-0.000106	0.000000690	-0.0000473
	(0.0000480)	(0.000117)	(0.0000742)	(0.0000619)	(0.0000586)+	(0.0000527)	(0.0000521)
Sum of # of electrical engineering doctorates given (lagged)	0.0000427	0.000151	-0.00000740	-0.0000668	-0.0000581	-0.000136	0.0000709
	(0.0000350)	(0.000110)	(0.0000410)	(0.0000291)*	(0.0000490)	(0.0000667)*	(0.000134)
# of Observations	399,465	44,055	89,100	89,100	44,055	89,100	44,055
# of Groups	36,315	4005	8100	8100	4005	8100	4005
R^2	0.001	0.002	0.001	0.001	0.002	0.001	0.001
Fraction of Variance explained by ϕ_{ij}	0.17	0.18	0.16	0.16	0.09	0.16	0.08

Regressions include year and institution-pair fixed effects

Robust standard errors (clustered by pair-Bitnet status) in parentheses

**significant at 99% level; *significant at 95% level; +significant at 90% level

Table A16: Percentage of collaborations by researchers formerly at the same institution

	By quality type				By distance		
	TIER 1 and TIER 1	TIER 1 and TIER 2	Others		<100km	100 – 1000km	>1000km
% of collaborations by researchers formerly at the same institution	79%	77%	54%		44%	84%	83%
% of above collaborations where researchers had a professor-student (or post doc) relationship when at the same institution	80%	85%	83%		82%	83%	78%
Number of collaborations	102	26	35		39	43	81