Has Distance Died with Networks? - An Empirical Study of Scholarly Citations and Genealogy in Knowledge Spillovers*

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February 25, 2014

Abstract

Using new data on citations to mathematics papers, genealogy of mathematicians, and highly disaggregated distance data for the world top 1000 institutions, we study how distance and networks affect knowledge spillovers among scholars. We measure scholarly networks through co-authorship, advisor-advisee relationship, academic siblings (sharing the same PhD advisor), employment connections (working in the same institution at the same year or in different years), and Alma Mater relationship (obtaining PhD from the institution where another scholar is affiliated). There are three key findings. First, network factors significantly facilitate knowledge spillovers, given geographic barriers such as distance and borders. The most important network factors include co-authors, advisees citing advisors, and colleagues. Second, the persistent negative effect of distance on knowledge spillovers is significantly dampened by networks, and in some specifications we observe that distance effect completely vanishes and border effects also disappear, once appropriately controlling for networks. Third, networks are more important for scholars who reside more spatially relative to each other. These findings are robust to various econometric specifications and sampling strategies regarding different control groups using the matching methodology.

Keywords: network, distance, border, geography, knowledge spillovers, paper citations, genealogy, matching

*The authors thank the Mathematics Genealogy Project (MGP) for providing data from its database for use in this research and Mitch Keller's assistance in obtaining genealogy data from MGP. Yao Amber Li gratefully acknowledges financial support from the Research Grants Council of Hong Kong, China (General Research Funds Project no. 643311), and Asier Minondo from the Spanish Ministry of Economy and Competitiveness (MINECO ECO2011-27619, co-financed with FEDER) and the Basque Government Department of Education, Language policy and Culture. We also thank Bronwyn Hall, Wolfgang Keller, Anthony J. Venables, Quoc-Anh Do, Jim MacGee, and Edwin Lai for helpful discussions. Finally, we thank Ho Yin Tsoi, Bo Jiang, Yiye Cui, and Song Liu for excellent research assistance during this project. All errors are our own.

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1 Introduction

More than a century ago, Marshall (1896) pointed out that knowledge spillovers were a justification for industries to concentrate geographically. Spillovers will face geographic boundaries and, hence justify concentration, if knowledge encompasses a large component of tacit information. If new ideas are transmitted through conversations, informal meetings or other types of personal interactions, physical proximity will play a key role in the transmission of knowledge. Empirical studies do, in fact, find that knowledge spillovers are highly geographically localised (Jaffe et al., 1993; Peri, 2005; Belenzon and Schankerman, 2013, among others).

Though there is plenty of empirical evidence to support the persistent effect of geography in knowledge spillovers, the channel through which it affects knowledge spillovers is still contentious. There have been different hypotheses. Head and Mayer (2013) propose (tacit) information that is hard to obtain remotely as a unified explanation for distance effects. This relates to the Grossman's hypothesis of the role of familiarity in high distance and border effects in international economics (Grossman, 1998). For example, a patent inventor will cite the prior work she is familiar with. If this familiarity or information story is correct, we would expect that knowledge flows between more closely connected, familiar persons become much easier. If we are able to find appropriate measures to control for "connections", we would expect the diminishing effect of distance or even the death of distance in the spread of knowledge when people are well connected.

The aim of this paper is to confirm this hypothesis. Previous studies have used patent citation information to analyze the geographical concentration of knowledge. Instead of patent citation data we use paper citation data to test the hypothesis. For our analysis, papers have properties that are shared by patents. On the one hand, papers, as patents, are published (granted) in prestigious journals as long as they push the knowledge frontier. Second, papers, as patents, build upon and cite previous papers (patents). The paper citation records indicate who benefits from the efforts of whom. Therefore, cross-paper citations trace out the direction and the intensity of knowledge flows among scholars.

We use new data on citations to mathematics papers, genealogy of mathematicians, and highly disaggregated distance data for the world top institutions to study how distance and networks affect knowledge spillovers among scholars. First, we track all articles published in all mathematic journals that are listed in the ISI Web of Science (WOS) to extract citations data. We choose mathematics because mathematics is basic science and the transmission of mathematics knowledge, compared with other social sciences, is less affected by cultural, language, historical, or other social and country-wise factors. For example, in the case of economics some journals might be focused on country-level issues. In these cases citations to other papers that also analyze country-level issues is not determined by the friction imposed by distance, but due to preferences. Moreover, in the case of mathematics a common language is used by scholars. Thus, mathematic citations provide a good setup for us to isolate the effect of geography and networks.

Second, to capture "connections", we construct networks variables based on data from Mathematics Genealogy Project. Those scholarly networks include co-authorship, advisor-advisee relationship, academic siblings (sharing the same PhD advisor or obtaining PhD from the same institution), employment connections (working in the same institution in different years or in the same year), and Alma Mater relationship (obtaining PhD from the institution where another scholar is affiliated). To our knowledge, this is the first time those networks data are used to analyze the effect of distance in knowledge spillovers.

Third, we use highly disaggregated geographic distance data extracted from Google Maps to precisely measure distance between any two institutions for the world top 1000 institutions in mathematics. Our distance data goes to even 1 or 2 miles within a city that allows us to trace out the detailed knowledge flows in very nearby geographic area.

To evaluate the effect of geography and networks in paper citations, we follow the matching methodology of Jaffe et al. (1993) and Belenzon and Schankerman (2013) and compare the characteristics of our sample with the characteristics of a control group. Our main control group is constructed by the following criteria: for each citation received by a paper we randomly select another observation that does not cite the paper but is published in the same journal and the same year as the original citing paper. The union of the original sample and the control group constitutes the sample that is used in the econometric analysis. As a robustness check we also build an additional control group where the control observation shares, at least, a keyword with the original article, to tease out any impact of within-field specialization.

We use linear probability models (LPM) as baseline regressions to accommodate a large number and high dimensions of fixed effects. There are three key findings. First, network factors significantly facilitate knowledge spillovers, given geographic barriers such as distance and borders. Second, the persistent negative effect of distance on knowledge spillovers is significantly dampened by networks, and in some specifications we observe that distance effect completely vanishes once controlling for network effect. Third, networks are more important for scholars who reside more spatially relative to each other. These findings are robust to various econometric specifications and sampling strategies including different control groups and the subsample of top 100 journals.

This paper makes at least three contributions. First, it investigates the effect of geography and networks simultaneously in knowledge spillovers and contributes to the large literature of the causes of knowledge localization, most often through patent citations. The patent citation literature starts from the seminal work by Jaffe et al. (1993) and is then followed by many studies, for example, Peri (2005) Thompson and Fox-Kean (2005), Thompson (2006), Li (2012), Singh and Marx (2013). But all these previous studies only analyzed the effect of geography in knowledge spillovers, and did not study the effect of networks. Second, this paper contributes to the study of networks by providing the compelling empirical evidence to show the importance of networks in knowledge transmission. The prior studies of networks in international economics usually focus on business networks rather than scholarly networks. For example, Huang (2007) estimates that countries that are more averse to uncertainty have larger distance effects on their exports; Hortaçsu et al. (2009) suggest that different levels of trust may underlie the distance effect. Last, and perhaps most important, this paper contributes to the vast literature in international economics on the persistent distance and border effects by showing that distance effect can be effectively attenuated or even completely suppressed with appropriate controlling for networks.[1]

[1]See Disdier and Head (2008) and Head and Mayer (2013) for comprehensive reviews on persistent distance effect in

The remainder of the paper is organized as follows. Section 2 describes the data. Section 3 presents econometric specifications and measurement. Section 4 reports main findings and Section 5 presents robustness checks. The last section concludes.

2 Data Description

2.1 Data Sources

Our data combines three main sources: the Thomson Reuters' ISI Web of Science (WOS), the Mathematics Genealogy Project, and the highly disaggregate geographic distance data from Google Maps.

Citation Data

WOS provides a record per each article published in the journals covered in the database. The record provides data on the tittle of the article, the journal in which it was published, the authors, the affiliation of the authors, and the cited articles. The cited article is identified by the first author, the journal in which it was published, the year of publication, volume and first page.

From WOS we select the all the journals, 255, included in the category "Mathematics" in 2009. Our database covers all the articles published in these journals in the period 1975-2009. However, for a large number of journals abstracting and indexing of articles started later than 1975. With these limitations, the database contains information about 367,405 articles.[2] A shortcoming of WOS is that it does not provide the affiliation for a substantial number of authors. In particular, for 578,065 author + article combinations included in our database, we have the affiliation for 71% of combinations. To complete the missing affiliation information we follow the approximate structural equivalence methodology developed by Tang and Walsh (2010) as implemented in Agrawal et al. (2013). For each record without authors affiliation we check whether there is another record with the same author name (full surname and name or full surname and initials) with an affiliation. We assign this latter affiliation to the missing record as long as both articles cite, at least, two articles that are not highly cited. The low citation benchmark is set at less than 50 citations. Applying this procedure we increase the author + article combinations with full affiliation information from 71% to 79%. After this missing information filling procedure we end up with 302,258 articles with author affiliation.

This latter set of articles cites 1,367,310 different articles (including self-citations). The ISI Web of Knowledge only identifies the first author of the cited articles. To identify the affiliation of the first author, and the identity and affiliation of the rest of co-authors (if there are), we matched the cited articles with our original database. As our database only includes the journals included in Mathematics category, we can only identify the authors and co-authors of the cited articles belonging to this set. After this matching, and removing self-citations, we end-up with 232,626 citing articles (63% of the initial number) and 170,001 cited articles (12% of the initial number).

In this latter sample there are 15,706 different affiliations for the citing authors and 11,899 different affiliations for the cited authors. We select the 1000 affiliations with the highest number of citing

international economics.

[2] Annex 1 presents the journals included in the database, the number of articles per journal and the earliest article of the journal included in the database.

articles.[3] The top 1000 affiliations account for 82% of the sample after all previous cleaning steps: 189,710 citing articles and 164,252 cited articles.

Genealogy Data

The second main database used by this paper is the Mathematics Genealogy Project (MGP). The MGP records the doctoral degrees awarded in mathematics since the 14th century. The MGP provides the name of the PhD student that got the degree, the names of the advisors, the year in which the PhD was completed and the school where the degree was obtained. We merged these data with the citing authors and cited authors in our database. We were able to match the records by author for around 46% of records.

Distance Data

We developed a specialized software that extract the detailed latitude and longitude information for all top 1000 institutions from Google Maps (http://maps.google.com) so that we construct highly disaggregated distance data between institution pairs. This is a substantial improvement from existing studies on the effect of distance on knowledge spillovers. To our knowledge, the previous studies usually track the location only to the city level. That implies that within the same city all institutions share either zero distance or a common internal distance calculated by the area of the city. In our data, we can track distance up to highly disaggregated level. For example, there are multiple universities located in Boston, U.S., and the distance between Harvard and MIT is only 1.84 miles approximately. Having disaggregated distance data is particularly useful when analyzing the localization and the transmission of knowledge.

2.2 Descriptive Statistics

We provide some descriptive statistics of our database in this section. First, we analyze the evolution of the number of articles, authors, institutions to which authors are affiliated and countries where those institutions are located in 1975-2009. Our sample contains world top 1000 institutions. As shown in Figure 1, there has been a notable increase in the number of articles and authors per year; moreover, the rate of increase seems to have accelerated from the late 1990s onwards. The number of articles published in 1975 was 220, written by 214 different authors. The number of articles published in 2009 was 15,278, written by 16,048 different authors. A share of the increase in the number of articles and authors is explained by the new journals that are incorporated to our database during the period of analysis. To control for new journals, we also calculate the evolution of articles per year and authors per year for the journals that were already publishing in 1975. We also observe a substantial increase in the number of articles and the number of authors. Figures 2a presents the same analysis for the number of institutions authors are affiliated to and the number of countries where these institutions are located. We can see that there is also a sharp increase in the per year number of institutions and countries. Figure 2b performs the same analysis for the journals that were already publishing in 1975. The pattern is very similar. Hence, during the period 1975-2009 there was a large increase in the production of articles on mathematics, a similar increase in the scholars participating in the production of this new knowledge, and a broadening of the set of institutions and countries

[3] When there is more than one author, the article is divided by the number of authors.

that participate in this production.

Second, we analyze the evolution of the number of citations per article.[4] As shown in Figure 3, there was a notable increase in the number of citations per article between 1975 (16 citations per article) and 1980 (23 citations per article). Afterwards, there is a mild rate of increase in the number of citations per article, reaching a figure of 28 citations per article in 2009. The article which is most cited in our final database is Positive solutions of nonlinear elliptic equations involving critical sobolev exponents, written by Haim Brezis and Louis Nirenberg and published in Communications on Pure and Applied Mathematics, Volume 33, Issue 4 in the year 1983. The author which is most cited is Shing-Tung Yau, Professor at Harvard University, with 1986 citations to his articles.

To analyze the flows of citations between institutions, we use a network display where institutions are nodes and citations are directed edges (Figure 4). The size of the node is correlated with the number of articles produced by the institution. In order not to blur the graph with too many nodes and edges, we have selected the top 50 institutions, based on the average of citations made and citations received. The institution with the highest number of articles (the largest node) is Moscow State University, with 1,968 articles, followed by Berkeley (1,586), Russian Academy of Sciences (1,543), Princeton (1,454) and MIT (1,442). The institution that receives the highest number of citations is Princeton, with 9,554 citations, followed by Berkeley (9,346), MIT (9,319), New York University (5,639) and Harvard University (5,623). The institutions that cite more are Moscow State University, with 4,472 citations, followed by Berkeley (4,324), Kyoto University (4,220), MIT (4,166) and University of Paris 11 (4,147).

Excluding citations to the same institutions, the strongest edges are Russian Academy of Science citing Moscow State University (142 citations), University of California at Los Angeles citing Berkeley (142 citations), MIT citing Harvard (136 citations), Rutgers State citing Princeton (136 citations) and Kyoto University citing University of Tokyo (136 citations). The density of the top 50 institutions network is very large, reaching almost the 100% figure; this means that all institutions cite all other institutions. The density is much lower in the top 1000 institutions' network: 22%.

In Figure 5 we analyze the evolution of the average distance of a citation during the period 1975-2009. The figure shows a logarithmic shape, denoting that the average distance rose notably during the first years of the period, and afterwards it continued to rise but at a lower rate. Looking to the start and the end of the period, we can see that the average distance of a citation has more than double, from 1,570 km. in the year 1975 to 3,772 km. in the year 2009.

Third, we provide some descriptive analyses on the network variables. We start analyzing the evolution of the number of authors per article during the period 1975-2009. Using data from the whole sample, we see that there is a steady rise in the number of authors per article (Figure 6). In 1975 the average number of authors per article was 1.24, whereas in 2009 it raised to 1.88. This trend is similar in other scientific areas, such as evolutionary biology (Agrawal et al., 2013) or economics (Hamermesh, 2013). Nevertheless, it is important to stress that the average number of authors in mathematics is lower than in other sciences. For example, the average number of authors in evolutionary biology articles was four in 2005 (Agrawal et al., 2013), 3.75 authors per article in biomedical research during the period 1961-2000, 2.5 authors per article in physics in the period 1991-2000, 2.22 authors per article in computer science in the period 1991-2000 (Newmen, 2004), and 2.19 authors per article in

[4]For this analysis we use the whole sample, instead of the sample of top 1000 institutions.

economics in 2011 (Hamermesh, 2013).[5]

We also analyze the probability that a citation is related to the existence of a network link (Figures 7a-7c). In Panel A we analyze the variables co-authors, coincided in the same institution and year (coincided), and worked in the same institution (worked). We can observe that the percentage of citations where the citing scholar and the cited scholar coincided or worked in the same institution was very high at the beginning of the period. Then, there is a reduction in the percentage for both variables, and later the variable worked remains constant at 45% and the variable coincided remains constant at 30%. In contrast, during the first part of the period, we observe a rise in the percentage of citations where the citing scholar was co-author of the cited scholar. Then, this rise moderates, reaching a 32% figure in the year 2009. In panels B and C we analyze the network variables derived from the Mathematics Genealogy Project (MGP) database. Note that the number of observations we can match with MGP is much lower. Percentages are calculated over the citations we can match with MGP; this might lead to very high percentages for some network variables. In Panel B we analyze PhD same school and PhD same advisor. Note that the correlation between both variables is very high (0.89), meaning that when a scholar cites another scholar who got her PhD in the same institution, it is very likely that they had the same PhD advisor. We can see that there has been a large reduction in the percentage of citations where citing and cited scholars shared PhD school and advisor. At the beginning of the period in 60% of citations the citing scholar and the cited scholar did the PhD in the same school and had the same PhD advisor. Despite an increase in the percentages for the period 1997-2001, there is a declining trend in the percentage, reaching a figure below 20 in the year 2009. In Panel C we analyze the network variables advisor citing, advisor cited, affiliation citing and affiliation cited. The highest percentage of citations is linked to affiliation cited, that is, when the citing scholar cites another scholar of the institution where she obtained her PhD. We can see that, as expected, the percentage of citations in which the advisee cites the adviser is larger than the opposite. We observe, as well, that the percentages for all network variables do not change substantially during the period of analysis.

As alternative way to show that networks contribute to the probability of citing, we build the network of citations for the most cited author in our database: Shing-Tung Yau. In Figures 8a-8c, this author is represented by a node and is located in the middle of the network, with a light green color. The rest of nodes are the 1376 authors that have cited, at least once, Shing-Tung Yau. We use the force atlas algorithm to layout authors according to the number of citations to Shing-Tung Yao articles. The authors that have cited Shing-Tung Yao more are located in the inner rings and the authors that have cited Shing-Tung Yao less are located in the outward rings. In Figure 8a we color Shing-Tung Yao co-authors in blue and the non-coauthors in red. We can see that the highest concentration of blue nodes happens in the proximity of Shing-Tung Yao. This means that co-authors have a higher probability to cite Shing-Tung Yao that non co-authors. In Panel B we analyze whether coinciding in the same institution and year is related to number of citations. We also observe that the highest concentration of blue nodes (scholars that have coincided with Shing-Tung Yao in the same institution and year) have cited more the work of this author. In Panel C we present the data for worked in the same institution. In this case, although the highest concentration of blue nodes is still

[5]For example, two of the most important achievements in mathematics in the last two decades, the proof of Fermat's Last Theorem and the resolution of Poincaré's conjecture were achieved by scholars working alone.

located in the inner circles, we also observe a substantial proportion of blue nodes in outward rings. This points outs that having worked in the same institution rises the probability of citation, but less than the previous network links.

3 Econometric Specification and Measurement

To evaluate the factors that influence paper citations, we follow the empirical methodology of Jaffe et al. (1993) and Belenzon and Schankerman (2013) and compare the characteristics of our sample with the characteristics of a control group. The control group is constructed as follows: for each citation received by a paper we randomly select another observation that does not cite the paper. However, the randomly selected paper should be published in the same journal and the same year as the original citing paper. The union of the original sample and the control group constitutes the sample that is used in the econometric analysis. As a robustness check we also build an additional control group where the control observation shares, at least, a keyword with the original article, to tease out any impact of within-field specialization.

We use linear probability models (LPM) as baseline regressions because it is computationally much easier to accommodate a large number and high dimensions of fixed effects. Since our main control group is matched on the journal of the paper and its publication year, the methodology automatically controls for these factors in the regressions.[6] The main empirical specification is

$$C_{i(u)j(u')t} = k + \alpha' \mathbf{G}_{ij} + \beta' \mathbf{N}_{ijt} + \varphi_t + \varphi_j + \varphi_{uu'} + \varepsilon_{ij} \quad (1)$$

where $C_{i(u)j(u')t}$ is a dummy variable equal to 1 if article i (with its corresponding author located in institution u) cites article j (with its corresponding author from institution u'), and zero otherwise. Here u and u' refer to citing instruction (the affiliation of the corresponding author of the citing article) and cited institution (the affiliation of the corresponding author of the cited article), respectively. $\mathbf{G}$ is a vector of geography-related variables, including distance and borders. The distance between article i and article j is defined as the minimum distance between the institutions to which citing authors are located and the institutions to which cited authors are located. Borders include a national border dummy and a subnational border dummy: the former takes the value of 1 if all of the authors of the citing article i are affiliated to institutions which are located in the different country of all of the authors of article j, and zero otherwise;[7] the latter is defined as 1 if all of the authors of the citing article i are affiliated to institutions which are located in the different city of all of the authors of article j, and zero otherwise. $\mathbf{N}$ is a vector of network related variables to capture the connection between authors of article i and article j. The variables φ_j and $\varphi_{uu'}$ are cited article and citing-cited-institutions fixed effects, and k is a constant term. We also experiment with various fixed effects terms, including citing and cited article fixed effects, citing and cited institutions fixed effects separately, and so on. We compute standard errors clustered at the level of the cited article, which allows the error

[6] Though the methodology automatically controls for the citing year, we still include the citing year fixed effects in our regressions.

[7] In other words, if any of the authors of article i is affiliated to an institution which is located in the same country of any of the authors of article j, the national border dummy is zero.

term to be correlated across citing articles for the same cited article.

Measurement of Network

The first variable included in this network vector **N** is "coauthors", which takes the value of one if any of the authors of the citing article was a co-author of the any of the authors of the cited article, and zero otherwise. The second variable is "coincided", which takes the value of 1 if any of the authors of the citing article coincided with any of the authors of the cited article in the same institution and year, and zero otherwise. The third variable is "work in the same institution", which takes the value of 1 if any of the authors of the citing article worked in the same institution of any of the authors of the cited article, and zero otherwise. The fourth variable is "PhD in the same institution", which takes the value of 1 if any of the authors of the citing article got the PhD in the same institution as any of the authors of the cited article, and zero otherwise. The fifth variable is "Advisor", which takes the value of 1 if any of the authors of the citing article was the PhD advisor of any of the authors of the cited article, and zero otherwise. The sixth variable is "Advisee", which takes the value of 1 if any of the authors of the citing article was the advisee of any of the authors of the cited article, and zero otherwise. The seventh variable is "same PhD advisor", which takes the value of 1 if any of the authors of the citing article had the same PhD advisor as any of the authors of the cited article, and zero otherwise. The eight variable is "affiliation citing", which takes the value of 1 if any of the authors of the citing articles is affiliated to the institution where any of the authors of the cited article got her PhD, and zero otherwise. Finally, the ninth variable is "affiliation cited", which takes the value of 1 if any of the authors of the citing articles got her PhD in an institution where any of the authors of the cited article is affiliated, and zero otherwise.

4 Results

This section presents the main results regarding the effect of geography and network as well as their interaction effects in knowledge spillovers. There are two key findings. First, the effect of distance and borders is substantially weakened once network factors are taken into account. Second, some key network factors such as co-authorship and advisor-advisee relationship show significantly stronger effect among scholars whose locations are more distance from each other. In other words, network becomes increasingly important with the extension of physical distance. The evidence to support these two findings are presented as follows.

Table 1 reports the result of baseline regressions. Panels (a), (b), and (c) include different fixed effects terms: panel (a) uses cited article fixed effects only; panel (b) adopts cited institution fixed effects only; panel (c) includes both cited article and citing-cited institution pair fixed effects as in equation (3). Each panel contains three specifications. The first specification only regresses the citation dummy on log distance and borders. The second specification adds the first set of network variables, namely, "coauthors", "coincided", and "work in the same institution". The third specification further adds on more network variables such as "PhD in the same institution", "Advisor", and "Advisee" etc. from genealogy analysis. Hereafter we use specifications 1, 2, and 3 refer to these three specifications, respectively, in different econometric estimations that are presented by different panels.

Specification 1 always presents significantly negative coefficients on distance and borders, suggesting that physical distance and borders indeed impede the knowledge spillovers, which is consistent with the findings in the existing literature. The most interesting and novel finding is that network helps to attenuate and even kill the persistent negative effect of distance (and borders). Incorporating network variables substantially dampens the effect of distance and borders: in all three panels, distance effects reduce by more than 60% once controlling for network effect. In some specifications both distance and border effects even disappear (e.g., column 3c).

[Insert Table 1 here]

It is also interesting to analyze the effect of network itself in knowledge spillovers. Table 1 shows that, after controlling for geography factors, almost all network variables significantly positively affect citation probability among scholars, except for "PhD in the same institution" which is insignificant. For example, co-authorship relation increases the citation probability by 23.3%-40.1%. Working in the same institution at the same year and sharing the same PhD advisor also increase the citation probability by 16.3%-27.7% and 10.4%-13.2%, respectively. Advisees more likely cite their advisor's papers: if any of the authors of article j is advisor of any of the authors of article i, that increases the probability that article i cites article j by 17.2%-20.4%. Advisors also like to cite their advisees' articles and the citation probability is increased by 12.8%-17.3%. Overall, the most important network factors include co-authors, advisees (citing advisors), and colleagues. The significantly positive effect of network variables in citations suggests that network plays an important role in overcoming the geographic impediment and facilitating knowledge spillovers among scholars.

Table 2 presents the baseline linear probability regressions with the dummy variables for different distance intervals. Panels (a), (b), and (c) incorporates the same combinations of fixed effects as in Table 1. The results in specification 1 in different panels (see column a1, b1, and c1) show that geography sharply constraints knowledge spillovers without incorporating network factors: all coefficients on borders and distance intervals are significantly negative. This is consistent with the previous literature. In contrast, once we incorporate network variables in specifications 2 and 3, all distance intervals (together with borders) substantially reduce both the magnitude and the significance of their effects. In particular, in specification 3 with the full set of network variables, the effect of most distance intervals vanishes. This confirms our previous finding that network attenuates the effect of distance and borders.

[Insert Table 2 here]

Table 3 presents the interaction effect between network and distance. Panels (a), (b), and (c) are adopted as in Table 1. We focus on specifications 2 and 3 where both distance and network variables are included in Table 3 and we further add interactions between distance and each network variable. The sign of coefficients on those interaction terms are of our interest. We expect to see positive signs for key network variables because a positive sign indicates that the effect of network is increasing with distance. In other words, network may not be that important for geographically nearby scholars but network becomes increasingly important once distance increases. The results in Table 3 confirm this hypothesis. Those key network variables that capture the direct relationship between scholars, such as co-authorship and advisor-advisee relationship, show significantly positive interactions with distance.

This suggests that those direct personal connections of scientific network such as co-authorship and advisor-advisee relationship are particularly important in facilitating knowledge spillovers for scholars whose locations are more distant from each other. A scholar who is located in a remote institution may have difficulty in attending seminars and conferences so that her work is less likely to be cited by other scholars, but those who are within her network (either her coauthors or her advisors/advisees) can effectively and timely learn her new development through personal connection and thus generate citations to her work.

[Insert Table 3 here]

5 Robustness

To verify the robustness of our findings, we experiment with various econometric specifications including different combinations of fixed effects terms in linear probability models and Probit estimations. We also test our baseline regressions with different samples including the control group constructed by keyword and the sample of top 100 journals. Our findings are robust to those exercises.

First, the finding that network reduces distance effect is robust to different econometric specifications. Table 4 reports results of baseline regressions with alternative specifications: panels (a), (b), (c), and (d) incorporate cited article and citing article fixed effects, cited institution and citing institution fixed effects, citing-and-cited institution pair fixed effects, and cited article and cited institution fixed effects, respectively. Table 5 reports results of Probit estimation where each panel corresponds to a different sampling strategy: panel (a) uses the whole sample of 255 journals with our main control group constructed by the same year and the same citing journal; panel (b) is based on the whole sample of 255 journals with control group where the control observation shares, at least, a keyword with the original article; panel (c) uses the top 100 journals sample with the main control group; and panel (d) is based on the top 100 journals sample with the control group constructed by keyword. Each panel in Tables 4 and 5 contains three specifications as in Table 1. All findings in Table 1 remains robust that the effect of distance and border is significantly dampens once taking into account network variables. Also network factors in general show significant positive effect in facilitating citations.

[Insert Tables 4 and 5 here]

Second, the main finding that distance effect is weakened by network is robust to different sampling strategies. We replicate the baseline regressions of Table 1 to different samples, including the whole sample with control group constructed by keywords (see Table 6) and the top 100 journal sample with the main control group (see Table 7). Again, the results in Table 1 remains robust.

[Insert Tables 6 and 7 here]

Third, the finding that network effect increases with distance is also robust to alternative econometric specifications. Panels (a), (b), and (c) correspond to the specifications with cited article and citing article fixed effects, cited institution and citing institution fixed effects, and citing-cited institution pair fixed effects, respectively. Similar as in Table 3, the key network variables such as co-authorship and advisor-advisee relationship show significantly positive interactions with distance, suggesting that those network variables are particularly important when distance is large.

[Insert Table 8 here]

6 Conclusion

Based on new data on citations to mathematics papers, genealogy of mathematicians, and highly disaggregated distance data for the world top institutions, we study how distance and networks affect knowledge spillovers among scholars. We find that network factors significantly facilitate knowledge spillovers, given geographic barriers such as distance and borders. However, the persistent negative effect of distance on knowledge spillovers is significantly dampened by networks, and in some specifications we even observe that distance effect completely vanishes once controlling for network effect. Moreover, networks are more important for scholars who reside more spatially relative to each other. These findings are robust to various econometric specifications and sampling strategies. To our knowledge, this paper provide the first compelling evidence on the interactions between distance and networks in scholarly knowledge flows and contributes to the vast literature on knowledge localization, networks effect, and the distance effect in international economics.

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A Tables

Table 1: Baseline Regressions

	Panel (a)			Panel (b)			Panel (c)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)
Geography:									
ln(distance)	-0.0227***	-0.00833***	-0.00682***	-0.0198***	-0.00707***	-0.00611***	-0.0106***	-0.00373***	0.0000599
	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
national border	-0.0759***	-0.0202***	-0.000984	-0.0669***	-0.0177***	-0.00508	-0.0156***	-0.00458	0.00175
	(0.003)	(0.002)	(0.006)	(0.002)	(0.002)	(0.004)	(0.003)	(0.003)	(0.008)
city border	-0.305***	-0.0459***	0.00963	-0.252***	-0.0411***	0.00150	-0.0793***	-0.00921*	-0.00546
	(0.005)	(0.005)	(0.013)	(0.004)	(0.004)	(0.009)	(0.006)	(0.006)	(0.017)
Network:									
co_authors		0.401***	0.319***		0.335***	0.257***		0.317***	0.233***
		(0.002)	(0.006)		(0.002)	(0.004)		(0.002)	(0.007)
coincided_year		0.277***	0.224***		0.235***	0.184***		0.203***	0.163***
		(0.003)	(0.007)		(0.002)	(0.005)		(0.002)	(0.007)
worked_same_institution		0.224***	0.199***		0.194***	0.170***		0.161***	0.138***
		(0.002)	(0.006)		(0.002)	(0.004)		(0.002)	(0.006)
phd_same_school			0.0139			0.0191**			-0.00486
			(0.011)			(0.008)			(0.010)
phd_same_advisor			0.132***			0.119***			0.104***
			(0.006)			(0.004)			(0.007)
advisor_citing			0.173***			0.128***			0.134***
			(0.014)			(0.007)			(0.018)
advisor_cited			0.204***			0.172***			0.179***
			(0.009)			(0.006)			(0.011)
affciting_sccited			0.0207**			0.0134***			0.0210**
			(0.008)			(0.005)			(0.009)
affcited_scciting			0.0674***			0.0469***			0.0526***
			(0.007)			(0.004)			(0.007)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	yes	no	no	no	yes	yes	yes
Cited institution fixed effects	no	no	no	yes	yes	yes	no	no	no
Citing-cited institution fixed effects	no	no	no	no	no	no	yes	yes	yes
No. of observations (ij,t)	1184209	1184209	158709	1184209	1184209	158709	1184209	1184209	158709
F-statistics	2508	10220	940	3599	12946	1903	1.89	2.17	2.28
R^2	.133	.241	.412	.0843	.179	.249	.515	.548	.814

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Table 2: Estimation with Discrete Distance

	Panel (a)			Panel (b)			Panel (c)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)
Geography:									
national border	-0.0917***	-0.0248***	-0.00426	-0.0797***	-0.0217***	-0.00900**	-0.0262***	-0.00828***	0.00226
	(0.003)	(0.002)	(0.006)	(0.002)	(0.002)	(0.004)	(0.003)	(0.003)	(0.009)
city border	-0.255***	-0.0413***	0.00281	-0.208***	-0.0329***	-0.0112	-0.0738***	-0.0114	-0.0305
	(0.009)	(0.007)	(0.020)	(0.007)	(0.006)	(0.014)	(0.009)	(0.008)	(0.023)
25≤ distance <50	-0.0826***	-0.0313***	-0.0262	-0.0657***	-0.0262***	-0.0167	-0.0330***	-0.0121	0.0328
	(0.012)	(0.010)	(0.027)	(0.010)	(0.008)	(0.019)	(0.011)	(0.011)	(0.030)
50≤ distance <150	-0.109***	-0.0135	-0.0217	-0.0934***	-0.0138*	-0.00500	-0.0457***	-0.00995	0.0298
	(0.010)	(0.008)	(0.022)	(0.008)	(0.007)	(0.016)	(0.010)	(0.009)	(0.026)
150≤ distance <500	-0.170***	-0.0419***	-0.0212	-0.150***	-0.0398***	-0.0139	-0.0647***	-0.0168**	0.0367
	(0.009)	(0.008)	(0.020)	(0.007)	(0.006)	(0.015)	(0.009)	(0.009)	(0.024)
500≤ distance <1000	-0.218***	-0.0719***	-0.0464**	-0.192***	-0.0674***	-0.0340**	-0.0763***	-0.0222***	0.0282
	(0.009)	(0.008)	(0.021)	(0.007)	(0.006)	(0.015)	(0.009)	(0.009)	(0.024)
1000≤ distance <1500	-0.230***	-0.0701***	-0.0492**	-0.201***	-0.0631***	-0.0346**	-0.0830***	-0.0211**	0.0225
	(0.009)	(0.008)	(0.022)	(0.008)	(0.007)	(0.016)	(0.009)	(0.009)	(0.026)
1500≤ distance <2500	-0.233***	-0.0803***	-0.0463**	-0.205***	-0.0736***	-0.0366**	-0.0940***	-0.0344***	0.0144
	(0.009)	(0.008)	(0.021)	(0.007)	(0.007)	(0.015)	(0.009)	(0.009)	(0.024)
distance >2500	-0.219***	-0.0685***	-0.0479**	-0.193***	-0.0622***	-0.0348**	-0.0808***	-0.0246***	0.0258
	(0.009)	(0.008)	(0.021)	(0.007)	(0.007)	(0.015)	(0.009)	(0.009)	(0.024)
Network:									
co_authors		0.401***	0.322***		0.335***	0.261***		0.317***	0.238***
		(0.002)	(0.006)		(0.002)	(0.004)		(0.002)	(0.007)
coincided_year		0.276***	0.223***		0.234***	0.182***		0.203***	0.162***
		(0.003)	(0.007)		(0.002)	(0.005)		(0.002)	(0.007)
worked_same_institution		0.223***	0.198***		0.193***	0.169***		0.161***	0.136***
		(0.002)	(0.006)		(0.002)	(0.004)		(0.002)	(0.006)
phd_same_advisor			0.130***			0.115***			0.106***
			(0.006)			(0.004)			(0.007)
advisor_citing			0.172***			0.128***			0.143***
			(0.013)			(0.007)			(0.018)
advisor_cited			0.204***			0.173***			0.183***
			(0.009)			(0.006)			(0.011)
affciting_sccited			0.0229***			0.0163***			0.0229***
			(0.008)			(0.005)			(0.009)
affcited_scciting			0.0654***			0.0464***			0.0486***
			(0.007)			(0.004)			(0.007)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	yes	no	no	no	yes	yes	yes
Cited institution fixed effects	no	no	no	yes	yes	yes	no	no	no
Citing-cited institution fixed effects	no	no	no	no	no	no	yes	yes	yes
No. of observations (ij,t)	1184209	1184209	165690	1184209	1184209	165690	1184209	1184209	165690
F-statistics	2180	8914	903	3115	11257	1777	1.89	2.17	2.26
R^2	.134	.241	.405	.085	.18	.246	.515	.548	.809

Notes: ***, **, and * indicate significance at the 0.1%, 1%, and 5% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Table 3: Interaction between Distance and Network

	Panel (a)		Panel (b)		Panel (c)	
Specification:	(a2)	(a3)	(b2)	(b3)	(c2)	(c3)
Geography:						
ln(distance)	-0.0101***	-0.0111***	-0.00868***	-0.00990***	-0.00775***	-0.00750***
	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.003)
national border	-0.0192***	-0.00108	-0.0166***	-0.00581	-0.00578**	0.00241
	(0.002)	(0.006)	(0.002)	(0.004)	(0.003)	(0.008)
city border	-0.0902***	-0.0609***	-0.0825***	-0.0690***	-0.0428***	-0.0431**
	(0.005)	(0.015)	(0.004)	(0.010)	(0.006)	(0.018)
Network:						
co_authors	0.237***	0.160***	0.179***	0.0993***	0.210***	0.152***
	(0.003)	(0.009)	(0.002)	(0.005)	(0.003)	(0.010)
co_authors×distance	0.0330***	0.0305***	0.0319***	0.0313***	0.0225***	0.0174***
	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)	(0.002)
coincided_year	0.317***	0.256***	0.275***	0.223***	0.211***	0.155***
	(0.007)	(0.019)	(0.005)	(0.013)	(0.006)	(0.020)
coincided_year×distance	-0.00946***	-0.0109***	-0.00957***	-0.0124***	-0.00312***	-0.00260
	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)	(0.003)
worked_same_institution	0.274***	0.196***	0.250***	0.185***	0.186***	0.118***
	(0.007)	(0.020)	(0.006)	(0.014)	(0.006)	(0.020)
worked_same_institution×distance	-0.00982***	-0.00180	-0.0108***	-0.00455**	-0.00541***	0.00109
	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)	(0.003)
phd_same_advisor		0.121***		0.102***		0.104***
		(0.007)		(0.004)		(0.010)
phd_same_advisor×distance		0.00294**		0.00364***		0.00178
		(0.001)		(0.001)		(0.002)
advisor_citing		0.147***		0.104***		0.110***
		(0.016)		(0.008)		(0.024)
advisor_citing×distance		0.00766**		0.00791***		0.00878*
		(0.003)		(0.002)		(0.005)
advisor_cited		0.157***		0.118***		0.157***
		(0.012)		(0.007)		(0.015)
advisor_cited×distance		0.0120***		0.0141***		0.00756***
		(0.002)		(0.001)		(0.003)
affciting_sccited		0.0122		0.00840		0.0105
		(0.011)		(0.006)		(0.013)
affciting_sccited×distance		0.00297		0.00244*		0.00269
		(0.002)		(0.001)		(0.002)
affcited_scciting		0.0235**		0.0110*		0.0108
		(0.010)		(0.006)		(0.011)
affcited_scciting×distance		0.00810***		0.00710***		0.00734***
		(0.002)		(0.001)		(0.002)
Year fixed effects	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	no	no	yes	yes
Cited institution fixed effects	no	no	yes	yes	no	no
Citing-cited institution fixed effects	no	no	no	no	yes	yes
No. of observations (ij,t)	1184209	165690	1184209	165690	1184209	165690
R^2	.244	.409	.184	.251	.55	.809

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Table 4: Alternative Specifications

	Panel (a)			Panel (b)			Panel (c)			Panel (d)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)	(d1)	(d2)	(d3)
Geography:												
ln(distance)	-0.0243***	-0.00616***	-0.00645***	-0.0200***	-0.00651***	-0.00520***	-0.00918***	-0.00332***	-0.00107	-0.0228***	-0.00835***	-0.00675***
	(0.001)	(0.001)	(0.002)	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)
national border	-0.110***	-0.0447***	-0.0134**	-0.0843***	-0.0368***	-0.0194***	-0.0157***	-0.00608**	-0.00175	-0.0758***	-0.0201***	-0.00170
	(0.002)	(0.002)	(0.006)	(0.002)	(0.002)	(0.004)	(0.003)	(0.003)	(0.008)	(0.002)	(0.002)	(0.004)
city border	-0.318***	-0.0251***	0.0351***	-0.240***	-0.0309***	0.00395	-0.0605***	-0.00765	0.00129	-0.305***	-0.0458***	0.00873
	(0.005)	(0.004)	(0.014)	(0.004)	(0.003)	(0.009)	(0.006)	(0.005)	(0.015)	(0.004)	(0.004)	(0.010)
Network:												
co_authors		0.483***	0.429***		0.339***	0.268***		0.263***	0.191***		0.401***	0.322***
		(0.002)	(0.007)		(0.002)	(0.004)		(0.002)	(0.006)		(0.002)	(0.005)
coincided_year		0.324***	0.263***		0.239***	0.185***		0.179***	0.151***		0.277***	0.223***
		(0.002)	(0.008)		(0.002)	(0.005)		(0.002)	(0.008)		(0.002)	(0.006)
worked_same_institution		0.267***	0.234***		0.198***	0.174***		0.146***	0.131***		0.224***	0.199***
		(0.002)	(0.006)		(0.001)	(0.004)		(0.002)	(0.007)		(0.002)	(0.004)
phd_same_advisor			0.139***			0.112***			0.0947***			0.130***
			(0.008)			(0.005)			(0.005)			(0.006)
advisor_citing			0.187***			0.131***			0.104***			0.172***
			(0.020)			(0.012)			(0.010)			(0.015)
advisor_cited			0.189***			0.171***			0.146***			0.204***
			(0.013)			(0.008)			(0.008)			(0.009)
affciting_sccited			0.0342***			0.0200***			0.0146**			0.0232***
			(0.010)			(0.006)			(0.007)			(0.007)
affcited_scciting			0.0730***			0.0463***			0.0373***			0.0655***
			(0.008)			(0.005)			(0.006)			(0.006)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	yes	no	no	no	no	no	no	yes	yes	yes
Citing article fixed effects	yes	yes	yes	no	no	no	no	no	no	no	no	no
Cited institution fixed effects	no	no	no	yes	yes	yes	no	no	no	yes	yes	yes
Citing institution fixed effects	no	no	no	yes	yes	yes	no	no	no	no	no	no
Citing-cited institution fixed effects	no	no	no	no	no	no	yes	yes	yes	no	no	no
No. of observations (ij,t)	1184209	1184209	165690	1184209	1184209	165690	1184209	1184209	165690	1184209	1184209	165690
R^2	.248	.36	.643	.0902	.186	.262	.459	.491	.708	.133	.241	.405

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Table 5: Probit Estimation

	Panel (a)			Panel (b)			Panel (c)			Panel (d)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)	(d1)	(d2)	(d3)
Geography:												
ln(distance)	-0.0419***	-0.0142***	-0.00852**	-0.0287***	-0.00672***	-0.00280	-0.0446***	-0.0190***	-0.00993**	-0.0298***	-0.00944**	-0.0100
	(0.001)	(0.002)	(0.004)	(0.002)	(0.002)	(0.007)	(0.002)	(0.002)	(0.005)	(0.004)	(0.004)	(0.012)
national border	-0.185***	-0.0770***	-0.0494***	-0.229***	-0.144***	-0.106***	-0.171***	-0.0667***	-0.0444***	-0.220***	-0.130***	-0.0814**
	(0.004)	(0.005)	(0.012)	(0.007)	(0.008)	(0.020)	(0.005)	(0.006)	(0.014)	(0.012)	(0.013)	(0.037)
city border	-0.258***	-0.0599***	0.0164	-0.169***	-0.00412	0.194**	-0.325***	-0.113***	0.0550	-0.179***	-0.0146	0.0977
	(0.017)	(0.019)	(0.056)	(0.027)	(0.028)	(0.082)	(0.022)	(0.025)	(0.076)	(0.044)	(0.047)	(0.151)
Network:												
co_authors		1.635***	1.441***		0.724***	0.602***		1.653***	1.487***		0.786***	0.633***
		(0.010)	(0.024)		(0.011)	(0.028)		(0.013)	(0.032)		(0.019)	(0.051)
coincided_year		0.241***	0.0384*		0.0112	-0.0505		0.225***	0.0122		0.0101	-0.0197
		(0.009)	(0.023)		(0.013)	(0.034)		(0.012)	(0.029)		(0.022)	(0.063)
worked_same_institution		0.434***	0.349***		0.306***	0.237***		0.402***	0.311***		0.277***	0.154***
		(0.005)	(0.013)		(0.008)	(0.022)		(0.007)	(0.016)		(0.014)	(0.039)
phd_same_advisor			1.047***			0.0562			1.051***			0.131*
			(0.039)			(0.038)			(0.050)			(0.069)
advisor_citing			1.088***			0.268**			1.323***			0.278
			(0.139)			(0.113)			(0.194)			(0.190)
advisor_cited			1.334***			0.190***			1.294***			0.224**
			(0.072)			(0.059)			(0.092)			(0.110)
affciting_sccited			0.115***			0.0738			0.178***			0.0683
			(0.033)			(0.047)			(0.040)			(0.088)
affcited_scciting			0.337***			0.258***			0.308***			0.305***
			(0.028)			(0.037)			(0.034)			(0.067)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
No. of observations (ij,t)	1072644	1072644	146967	303013	303013	38203	572167	572167	83706	97665	97665	11277
Pseudo R^2	0.008	0.101	0.179	0.009	0.045	0.080	0.009	0.103	0.188	0.011	0.047	0.109

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Table 6: Baseline Regressions for Control Group by Keyword

	Panel (a)			Panel (b)			Panel (c)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)
Geography:									
ln(distance)	-0.0159***	-0.00417***	-0.00259	-0.0130***	-0.00337***	-0.00167	-0.0173***	-0.00551***	-0.00180
	(0.001)	(0.001)	(0.005)	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.004)
national border	-0.109***	-0.0609***	-0.0339**	-0.0907***	-0.0519***	-0.0299***	-0.115***	-0.0690***	-0.0441***
	(0.005)	(0.005)	(0.015)	(0.003)	(0.003)	(0.008)	(0.004)	(0.004)	(0.014)
city border	-0.198***	-0.0285***	0.0195	-0.141***	-0.0157**	-0.000914	-0.178***	-0.0121	0.0205
	(0.010)	(0.009)	(0.033)	(0.007)	(0.007)	(0.018)	(0.009)	(0.009)	(0.028)
Network:									
co_authors		0.298***	0.240***		0.225***	0.193***		0.300***	0.236***
		(0.004)	(0.017)		(0.003)	(0.008)		(0.004)	(0.014)
coincided_year		0.192***	0.148***		0.141***	0.103***		0.191***	0.144***
		(0.005)	(0.019)		(0.004)	(0.009)		(0.005)	(0.015)
worked_same_institution		0.173***	0.129***		0.137***	0.106***		0.171***	0.127***
		(0.004)	(0.015)		(0.003)	(0.008)		(0.004)	(0.012)
phd_same_advisor			-0.00412			0.000873			-0.00617
			(0.018)			(0.008)			(0.015)
advisor_citing			0.0645			0.0710***			0.0743*
			(0.047)			(0.020)			(0.043)
advisor_cited			0.0842***			0.0475***			0.0946***
			(0.025)			(0.013)			(0.022)
affciting_sccited			0.00574			0.00586			0.00579
			(0.022)			(0.010)			(0.019)
affcited_scciting			0.0945***			0.0694***			0.0903***
			(0.018)			(0.009)			(0.016)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	yes	no	no	no	yes	yes	yes
Cited institution fixed effects	no	no	no	yes	yes	yes	no	no	no
Citing-cited institution fixed effects	no	no	no	no	no	no	yes	yes	yes
No. of observations (ij,t)	336753	336753	43417	336753	336753	43417	336753	336753	43417
R^2	.137	.189	.463	.0514	.0945	.147	.158	.208	.508

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term. Using discrete distance dummies yield the similar pattern as in this table.

Table 7: Baseline Regressions for Top 100 Journals Citations

	Panel (a)			Panel (b)			Panel (c)		
Specification:	(a1)	(a2)	(a3)	(b1)	(b2)	(b3)	(c1)	(c2)	(c3)
Geography:									
ln(distance)	-0.0240***	-0.00977***	-0.00765***	-0.0205***	-0.00823***	-0.00588***	-0.00931***	-0.00301**	0.00204
	(0.001)	(0.001)	(0.003)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)	(0.003)
national border	-0.0758***	-0.0190***	-0.00111	-0.0657***	-0.0176***	-0.00821	-0.0125***	-0.00248	-0.0131
	(0.003)	(0.003)	(0.008)	(0.003)	(0.002)	(0.005)	(0.004)	(0.004)	(0.011)
city border	-0.298***	-0.0331***	0.00818	-0.243***	-0.0297***	0.00272	-0.0910***	-0.0170**	-0.0211
	(0.007)	(0.006)	(0.017)	(0.005)	(0.005)	(0.011)	(0.008)	(0.008)	(0.023)
Network:									
co_authors		0.432***	0.340***		0.355***	0.273***		0.348***	0.256***
		(0.003)	(0.008)		(0.002)	(0.005)		(0.003)	(0.010)
coincided_year		0.0541***	0.0179*		0.0391***	0.00607		0.0437***	0.0286***
		(0.003)	(0.010)		(0.003)	(0.007)		(0.003)	(0.011)
worked_same_institution		0.212***	0.186***		0.178***	0.154***		0.147***	0.120***
		(0.003)	(0.008)		(0.002)	(0.006)		(0.002)	(0.008)
phd_same_school			-0.00731			0.00459			-0.0116
			(0.014)			(0.009)			(0.014)
phd_same_advisor			0.159***			0.124***			0.142***
			(0.015)			(0.009)			(0.016)
advisor_citing			0.227***			0.154***			0.166***
			(0.020)			(0.010)			(0.028)
advisor_cited			0.223***			0.190***			0.214***
			(0.014)			(0.008)			(0.016)
affciting_sccited			0.0343***			0.0234***			0.0440***
			(0.012)			(0.007)			(0.013)
affcited_scciting			0.0605***			0.0416***			0.0369***
			(0.010)			(0.006)			(0.011)
Year fixed effects	yes	yes	yes	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	yes	no	no	no	yes	yes	yes
Cited institution fixed effects	no	no	no	yes	yes	yes	no	no	no
Citing-cited institution fixed effects	no	no	no	no	no	no	yes	yes	yes
No. of observations (ij,t)	626357	626357	89285	626357	626357	89285	626357	626357	89285
F-statistics	2,508	10,220	938	3,599	12,946	1,883	1.89	2.17	2.27
R^2	.129	.243	.433	.0781	.177	.252	.568	.601	.842

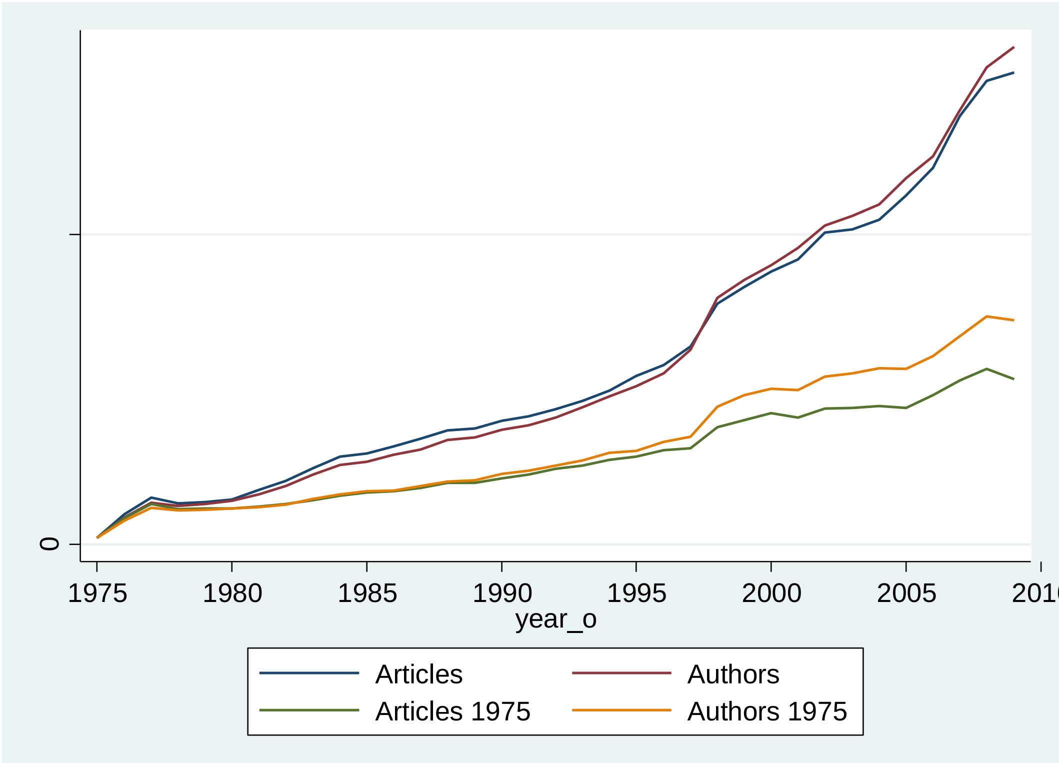
Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term. Using discrete distance dummies yield the similar pattern as in this table.

Table 8: Alternative Specifications: Interaction between Distance and Network

	Panel (a)		Panel (b)		Panel (c)	
Specification:	(a2)	(a3)	(b2)	(b3)	(c2)	(c3)
Geography:						
ln(distance)	-0.00959***	-0.0108***	-0.00889***	-0.0101***	-0.00832***	-0.00923***
	(0.001)	(0.002)	(0.001)	(0.001)	(0.001)	(0.003)
national border	-0.0433***	-0.0147**	-0.0353***	-0.0196***	-0.00757***	-0.00436
	(0.002)	(0.007)	(0.002)	(0.004)	(0.003)	(0.008)
city border	-0.0901***	-0.0372**	-0.0797***	-0.0737***	-0.0462***	-0.0533***
	(0.005)	(0.018)	(0.004)	(0.011)	(0.006)	(0.017)
Network:						
co_authors	0.310***	0.284***	0.181***	0.103***	0.154***	0.0880***
	(0.004)	(0.014)	(0.003)	(0.007)	(0.003)	(0.007)
co_authors×distance	0.0336***	0.0252***	0.0322***	0.0314***	0.0242***	0.0221***
	(0.001)	(0.002)	(0.000)	(0.001)	(0.000)	(0.001)
coincided_year	0.0538***	0.0694***	0.0263***	0.0344***	0.0110***	0.0215
	(0.005)	(0.018)	(0.004)	(0.011)	(0.004)	(0.014)
coincided_year×distance	-0.000678	-0.00845***	0.000878	-0.00729***	0.00292***	-0.00280
	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)	(0.002)
worked_same_institution	0.282***	0.214***	0.240***	0.181***	0.170***	0.123***
	(0.006)	(0.022)	(0.005)	(0.014)	(0.007)	(0.023)
worked_same_institution×distance	-0.00459***	0.00121	-0.00876***	-0.00336*	-0.00564***	-0.000714
	(0.001)	(0.003)	(0.001)	(0.002)	(0.001)	(0.003)
phd_same_school		-0.0258		-0.0148		-0.0186
		(0.021)		(0.012)		(0.014)
phd_same_school×distance		0.00395		0.00307		0.00135
		(0.003)		(0.002)		(0.003)
phd_same_advisor		0.157***		0.111***		0.102***
		(0.022)		(0.013)		(0.014)
phd_same_advisor×distance		-0.00181		0.000883		0.00163
		(0.003)		(0.002)		(0.003)
advisor_citing		0.154***		0.109***		0.0768***
		(0.030)		(0.016)		(0.011)
advisor_citing×distance		0.00925*		0.00747**		0.00888***
		(0.005)		(0.003)		(0.003)
advisor_cited		0.150***		0.117***		0.102***
		(0.020)		(0.012)		(0.010)
advisor_cited×distance		0.0107***		0.0143***		0.0124***
		(0.004)		(0.002)		(0.002)
affciting_sccited		0.0170		0.00886		0.00634
		(0.016)		(0.009)		(0.009)
affciting_sccited×distance		0.00393		0.00300*		0.00229
		(0.003)		(0.002)		(0.002)
affcited_scciting		0.0281*		0.0123		0.0153*
		(0.015)		(0.008)		(0.008)
affcited_scciting×distance		0.00950***		0.00688***		0.00495***
		(0.002)		(0.001)		(0.002)
Year fixed effects	yes	yes	yes	yes	yes	yes
Cited article fixed effects	yes	yes	no	no	yes	yes
Cited institution fixed effects	no	no	yes	yes	no	no
Citing-cited institution fixed effects	no	no	no	no	yes	yes
No. of observations (ij,t)	1184209	158198	1184209	158198	1184209	158198
R^2	.362	.652	.19	.269	.493	.714

Notes: ***, **, and * indicate significance at the 1%, 5%, and 10% level. Robust standard errors (clustered at the level of cited article) in parentheses. All regressions include a constant term.

Figure 1. Articles and authors per year, 1975-2009



Source: elaborated by authors using data from the Web of Science database.

Figure 2a. Number of institutions and countries that participate in the production of mathematics' articles per year, 1975-2009

Source: elaborated by authors using data from the Web of Science database.

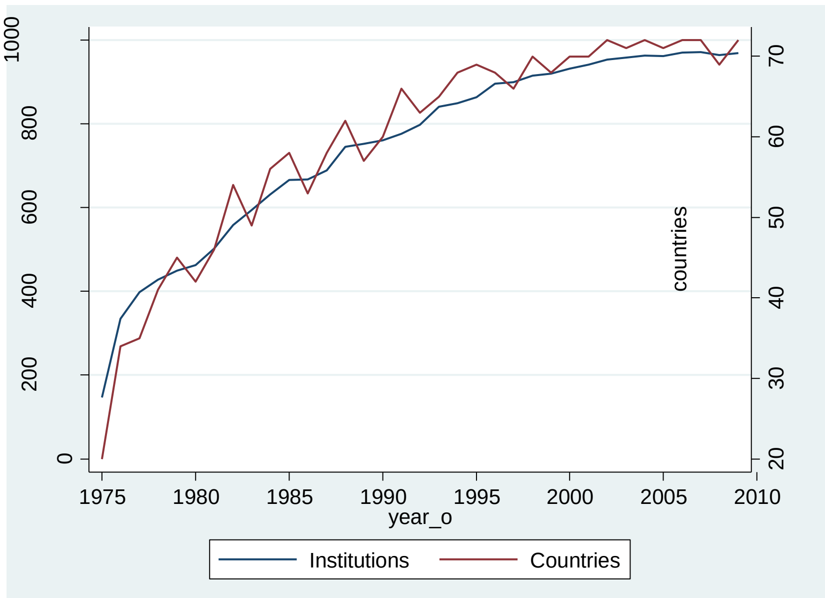
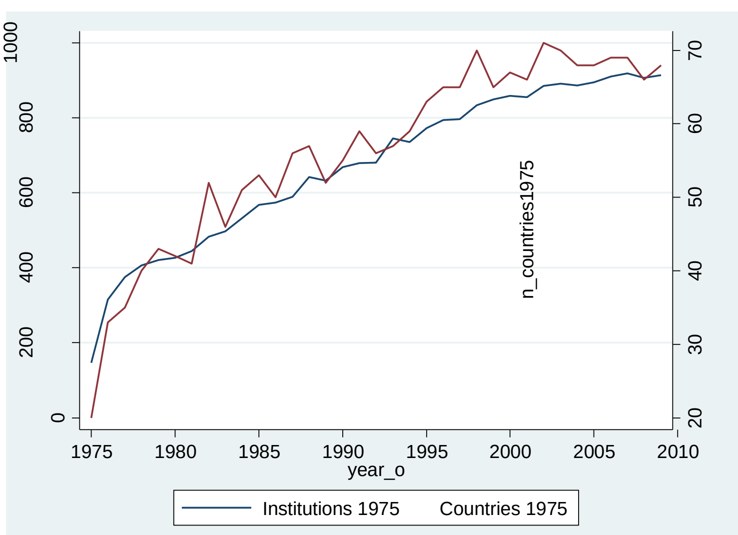
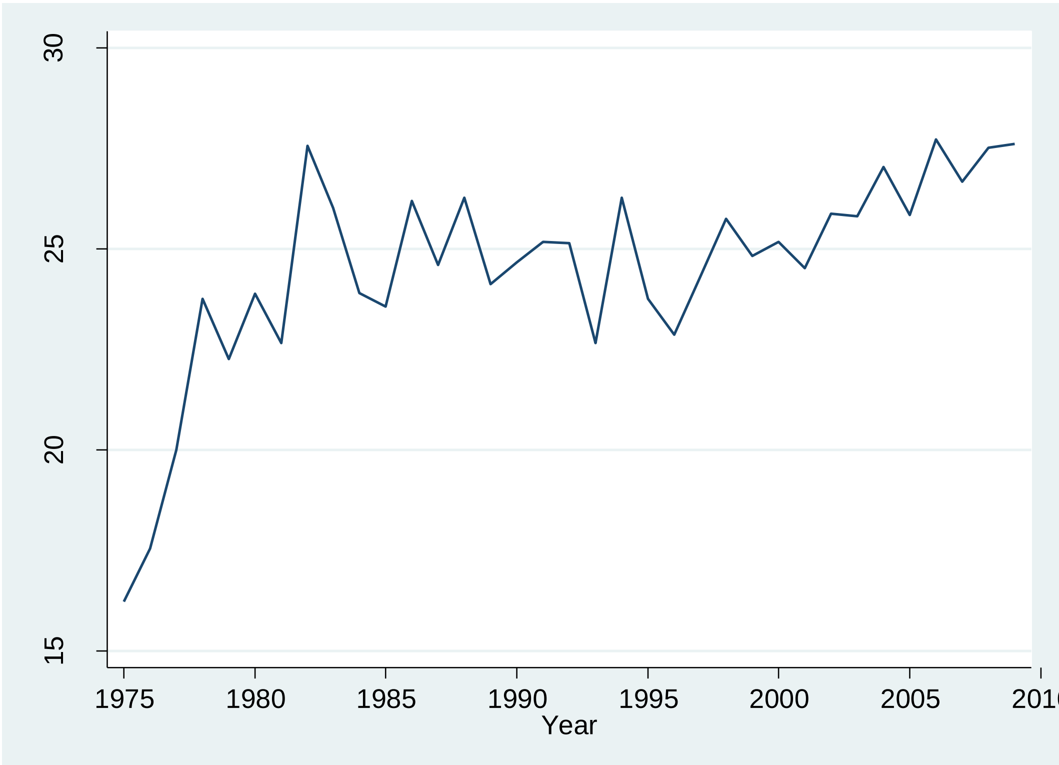


Figure 2b. Number of institutions and countries that participate in the production of mathematics' articles per year, 1975-2009 (Only journals publishing in 1975)



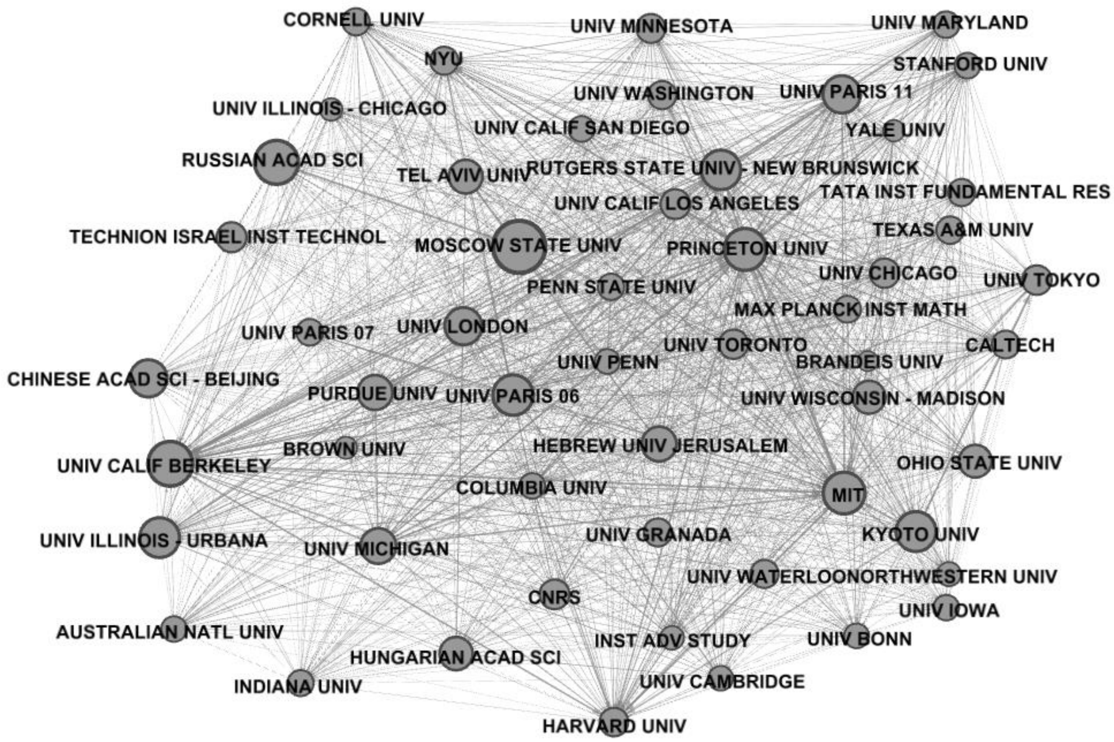
Source: elaborated by authors using data from the Web of Science database.

Figure 3. Average citations per article, 1975-2009



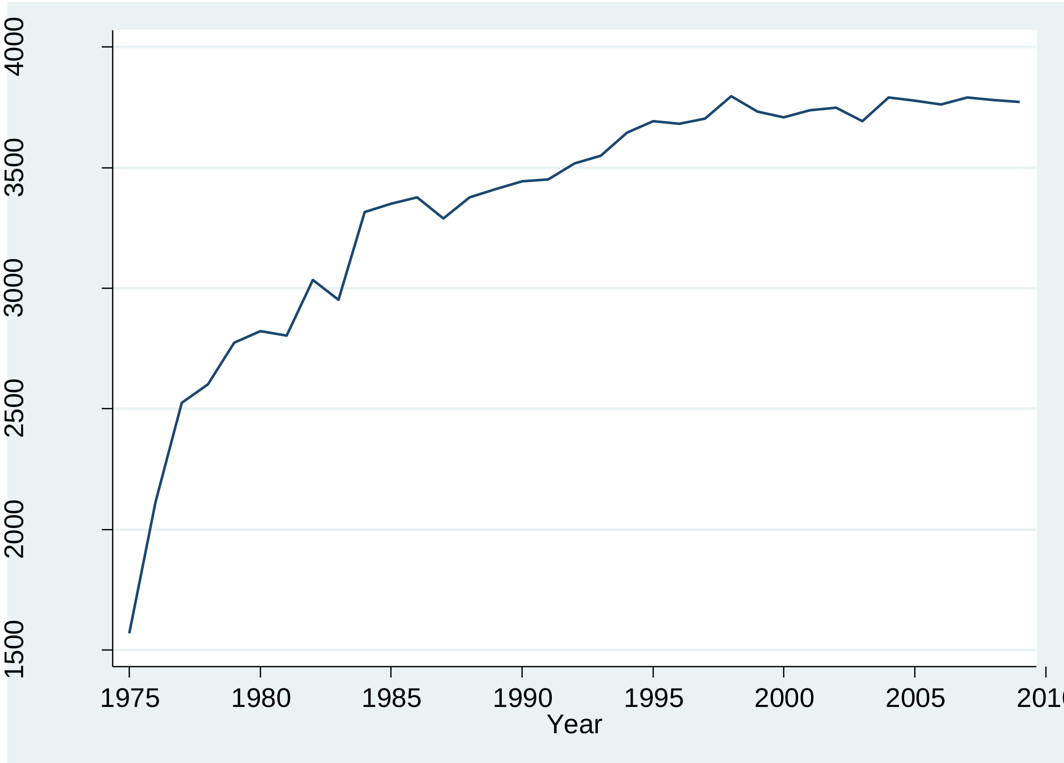
Source: elaborated by authors using data from the Web of Science database.

Figure 4. The network of citations (Top 50 institutions)



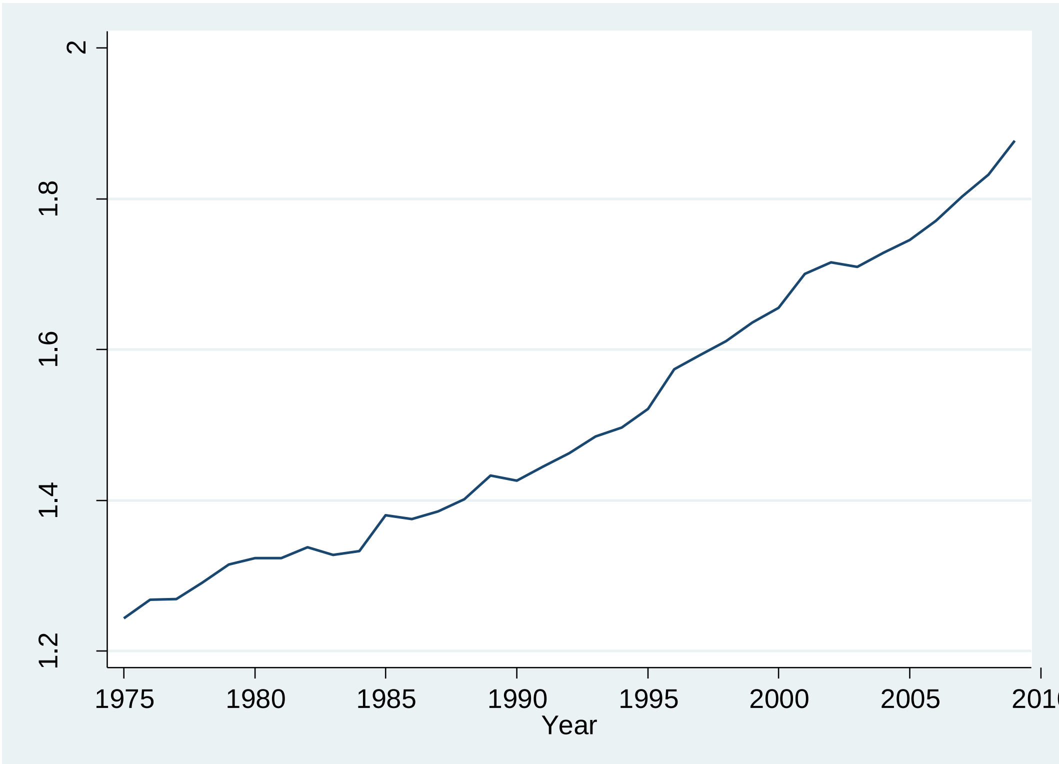
Source: elaborated by authors using data from the Web of Science database.

Figure 5. Average distance of a citation, 1975-2009 (km.)



Source: elaborated by authors using data from the Web of Science database.

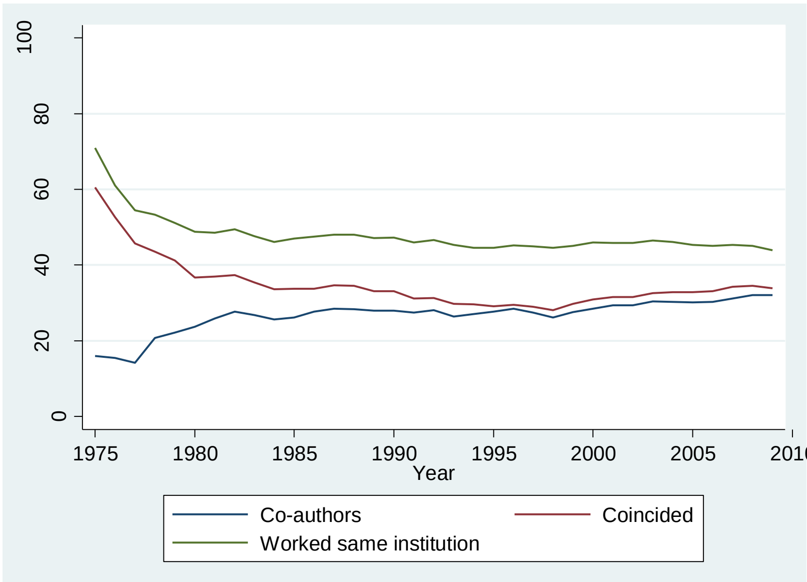
Figure 6. Average number of authors per article, 1975-2009



Source: elaborated by authors using data from the Web of Science database.

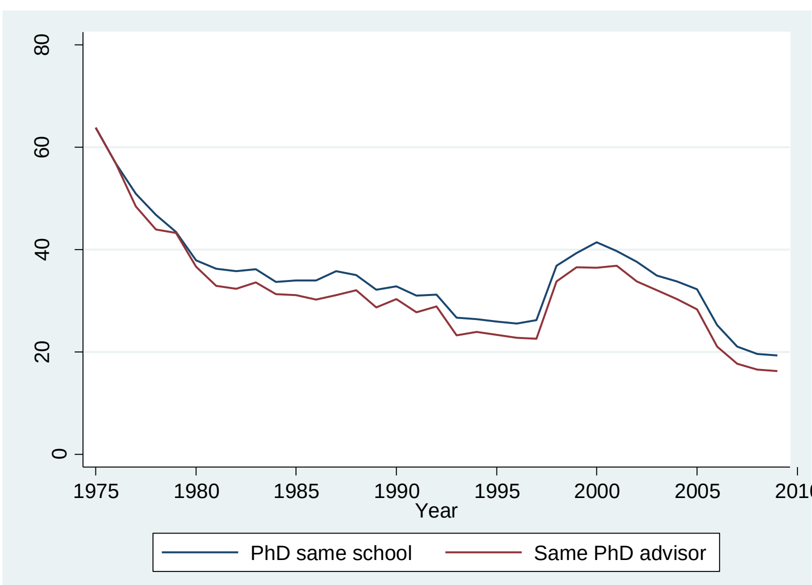
Figure 7. Percentage of citations where a network link is present, 1979-2009

A. Co-authors; coincided in the same institution and year; worked same institution



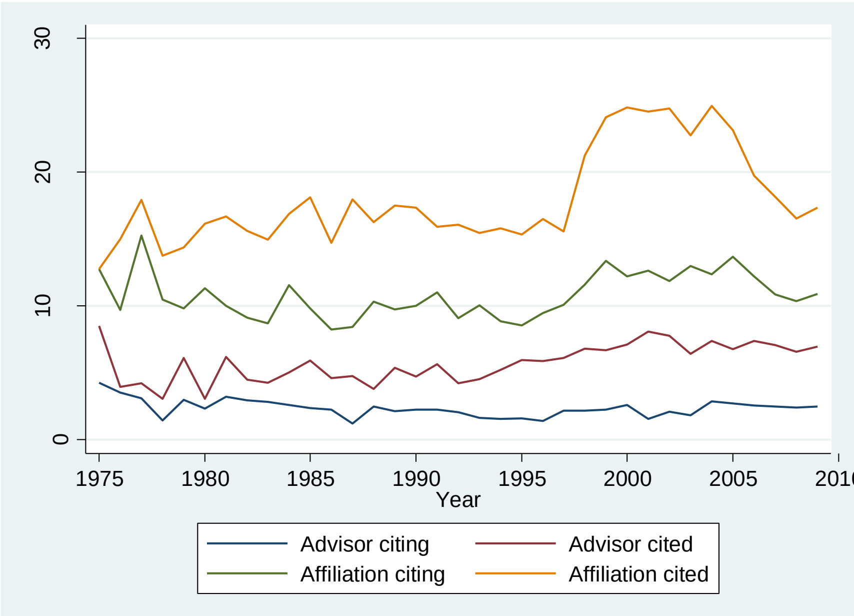
Source: elaborated by authors using data from the Web of Science database.

B. Phd same institution; same PhD advisor



Source: elaborated by authors using data from the Web of Science database and the MGP database.

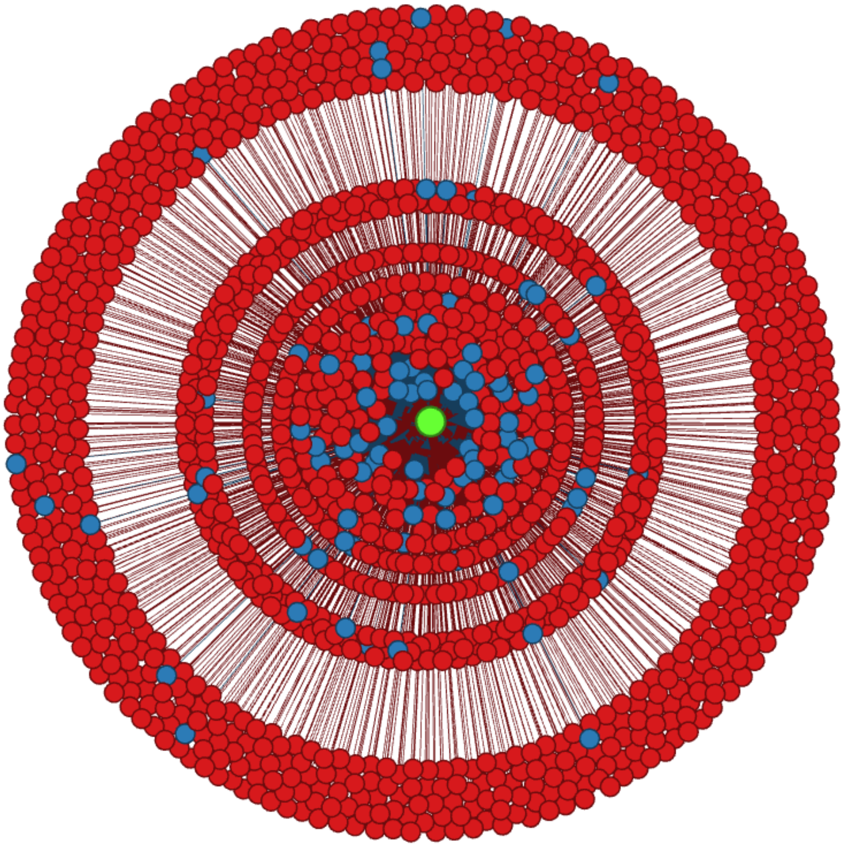
C. Advisor citing; advisee citing; affiliation citing; affiliation cited



Source: elaborated by authors using data from the Web of Science database and the MGP database.

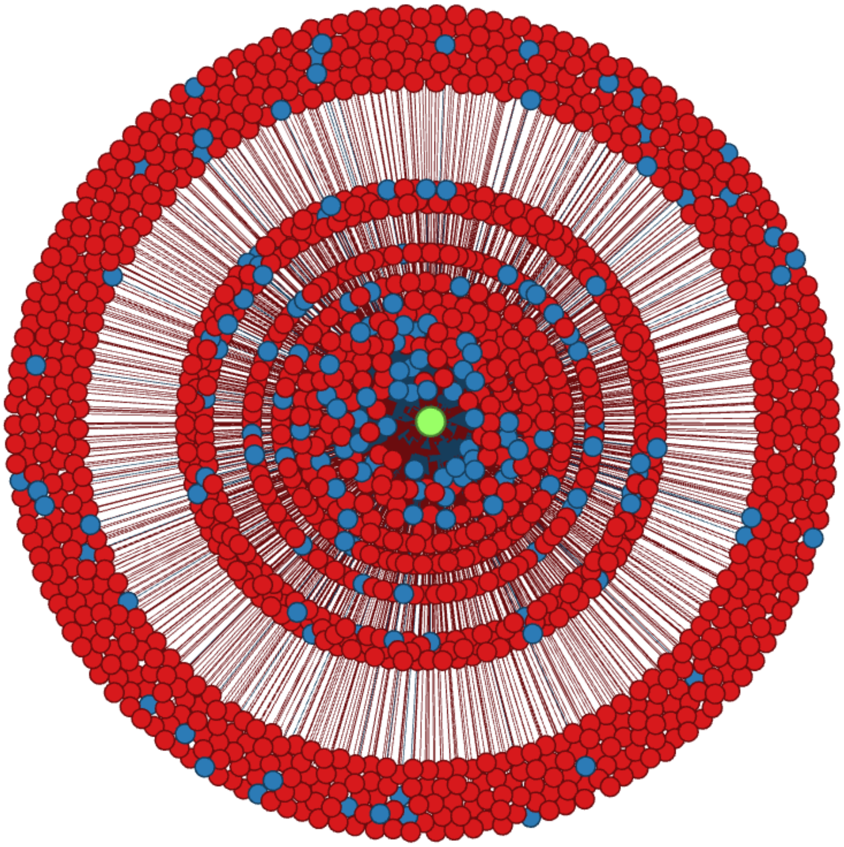
Figure 8. The citation network of Shing-Tung Yao

A. Co-authors



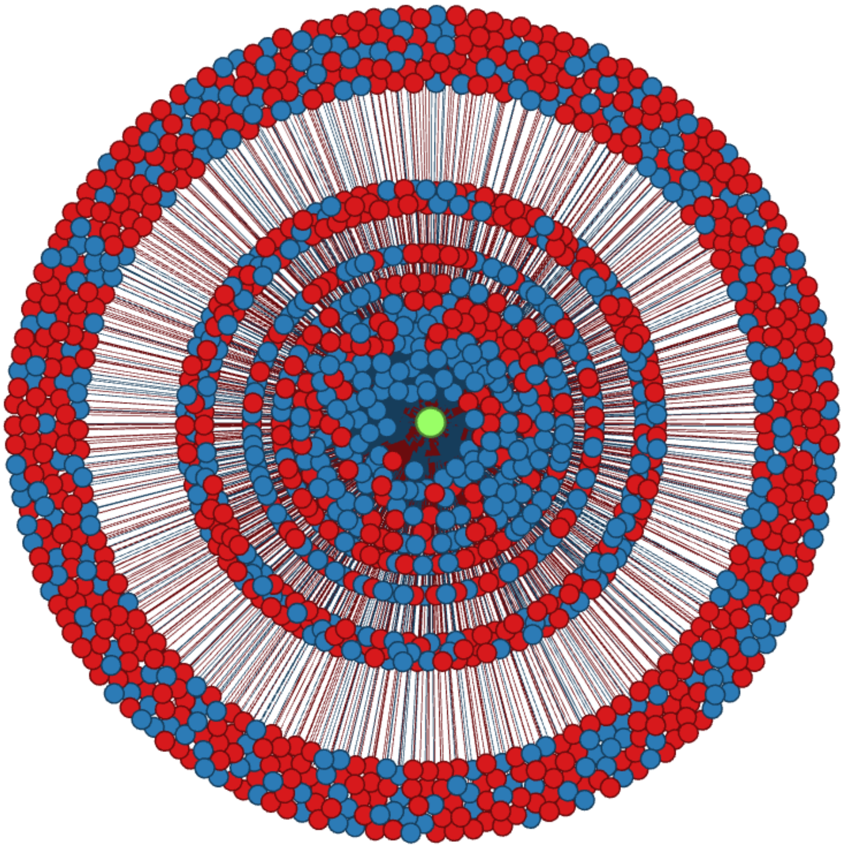
Note: nodes (authors) located closer to the center of the circle have cited more the work of Shing-Tung Yao. Blue nodes are co-authors of Shing-Tung Yao; red nodes are not co-authors.
Source: elaborated by authors using data from the Web of Science database.

B. Coincided in the same institution and year



Note: nodes (authors) located closer to the center of the circle have cited more the work of Shing-Tung Yao. Blue nodes have coincided with Shing-Tung Yao in the same institution and year; red nodes have not.
Source: elaborated by authors using data from the Web of Science database.

C. Worked in the same institution



Note: nodes (authors) located closer to the center of the circle have cited more the work of Shing-Tung Yao. Blue nodes have worked in the same institution as Shing-Tung Yao; red nodes have not.
Source: elaborated by authors using data from the Web of Science database.

Annex 1. Journals included in the database (1975-2009)

Journal Name	Nº of art.	Earliest year
ABHANDLUNGEN AUS DEM MATHEMATISCHEN SEMINAR DER UNIVERSITAT HAMBURG	612	1981
ABSTRACT AND APPLIED ANALYSIS	272	2005
ACTA ARITHMETICA	2623	1981
ACTA MATHEMATICA	542	1975
ACTA MATHEMATICA HUNGARICA	2528	1983
ACTA MATHEMATICA SCIENTIA	1640	1983
ACTA MATHEMATICA SINICA-ENGLISH SERIES	1198	1999
ADVANCED NONLINEAR STUDIES	252	2002
ADVANCES IN DIFFERENCE EQUATIONS	201	2005
ADVANCES IN GEOMETRY	291	2001
ADVANCES IN MATHEMATICS	2735	1975
ALGEBRA AND LOGIC	103	2007
ALGEBRA COLLOQUIUM	669	1997
ALGEBRA UNIVERSALIS	1654	1981
ALGEBRAIC AND GEOMETRIC TOPOLOGY	411	2005
ALGEBRAS AND REPRESENTATION THEORY	264	2001
AMERICAN JOURNAL OF MATHEMATICS	1751	1975
AMERICAN MATHEMATICAL MONTHLY	3872	1975
ANALYSIS AND APPLICATIONS	60	2007
ANNALES ACADEMIAE SCIENTIARUM FENNICAE-MATHEMATICA	344	1982
ANNALES DE L INSTITUT FOURIER	1782	1975
ANNALES POLONICI MATHEMATICI	149	2007
ANNALES SCIENTIFIQUES DE L ECOLE NORMALE SUPERIEURE	831	1975
ANNALI DELLA SCUOLA NORMALE SUPERIORE DI PISA-CLASSE DI SCIENZE	228	2002
ANNALI DI MATEMATICA PURA ED APPLICATA	242	1984
ANNALS OF GLOBAL ANALYSIS AND GEOMETRY	552	1995
ANNALS OF MATHEMATICS	1567	1975
ANNALS OF PURE AND APPLIED LOGIC	1572	1983
APPLIED CATEGORICAL STRUCTURES	469	1995
ARCHIV DER MATHEMATIK	5390	1975
ARCHIVE FOR MATHEMATICAL LOGIC	314	1996
ARKIV FOR MATEMATIK	737	1975
ARS COMBINATORIA	2351	1985
ASIAN JOURNAL OF MATHEMATICS	154	2005
ASTERISQUE	1402	1981
BALKAN JOURNAL OF GEOMETRY AND ITS APPLICATIONS	147	2005
BANACH JOURNAL OF MATHEMATICAL ANALYSIS	88	2007
BOUNDARY VALUE PROBLEMS	166	2005
BULLETIN DE LA SOCIETE MATHEMATIQUE DE FRANCE	934	1975
BULLETIN MATHEMATIQUE DE LA SOCIETE DES SCIENCES MATHEMATIQUES DE ROUMANIE	93	2007

BULLETIN OF SYMBOLIC LOGIC	198	1997
BULLETIN OF THE AMERICAN MATHEMATICAL SOCIETY	1636	1975
BULLETIN OF THE AUSTRALIAN MATHEMATICAL SOCIETY	2830	1981
BULLETIN OF THE BELGIAN MATHEMATICAL SOCIETY-SIMON STEVIN	800	1997
BULLETIN OF THE BRAZILIAN MATHEMATICAL SOCIETY	152	2002
BULLETIN OF THE IRANIAN MATHEMATICAL SOCIETY	66	2007
BULLETIN OF THE KOREAN MATHEMATICAL SOCIETY	272	2007
BULLETIN OF THE LONDON MATHEMATICAL SOCIETY	2310	1981
BULLETIN OF THE MALAYSIAN MATHEMATICAL SCIENCES SOCIETY	77	2007
CALCOLO	153	1999
CALCULUS OF VARIATIONS AND PARTIAL DIFFERENTIAL EQUATIONS	756	1993
CANADIAN JOURNAL OF MATHEMATICS-JOURNAL CANADIEN DE MATHEMATIQUES	2649	1975
CANADIAN MATHEMATICAL BULLETIN-BULLETIN CANADIEN DE MATHEMATIQUES	2102	1975
CENTRAL EUROPEAN JOURNAL OF MATHEMATICS	165	2007
CHINESE ANNALS OF MATHEMATICS SERIES B	1519	1981
COLLECTANEA MATHEMATICA	102	2005
COMBINATORICA	1142	1981
COMBINATORICS PROBABILITY & COMPUTING	569	1998
COMMENTARII MATHEMATICI HELVETICI	1295	1975
COMMUNICATIONS IN ALGEBRA	7932	1975
COMMUNICATIONS IN ANALYSIS AND GEOMETRY	402	1998
COMMUNICATIONS IN CONTEMPORARY MATHEMATICS	356	1999
COMMUNICATIONS IN PARTIAL DIFFERENTIAL EQUATIONS	1914	1982
COMMUNICATIONS ON PURE AND APPLIED ANALYSIS	492	2002
COMMUNICATIONS ON PURE AND APPLIED MATHEMATICS	1457	1975
COMPLEX ANALYSIS AND OPERATOR THEORY	93	2007
COMPOSITIO MATHEMATICA	2154	1975
COMPTES RENDUS MATHEMATIQUE	2652	2002
COMPUTATIONAL COMPLEXITY	197	1995
COMPUTATIONAL GEOMETRY-THEORY AND APPLICATIONS	685	1993
CONSTRUCTIVE APPROXIMATION	746	1985
CZECHOSLOVAK MATHEMATICAL JOURNAL	2185	1975
DIFFERENTIAL EQUATIONS	6164	1980
DIFFERENTIAL GEOMETRY AND ITS APPLICATIONS	686	1993
DISCRETE & COMPUTATIONAL GEOMETRY	1438	1986
DISCRETE AND CONTINUOUS DYNAMICAL SYSTEMS	1239	1995
DISCRETE MATHEMATICS	10356	1975
DISCRETE MATHEMATICS AND THEORETICAL COMPUTER SCIENCE	170	2002
DISSERTATIONES MATHEMATICAE	27	2007
DOCUMENTA MATHEMATICA	109	2005
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