The Small World of Material Handling Research

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***Abstract*—Using data from 88 journals over an 8 year period, we investigate the relationships among researchers in material handling. We apply social network analysis to measure many attributes of the network, including papers published each year, papers published per author, number of collaborators per author, strength of collaboration between authors, and how influential an author is in the network. We observe that collaboration patterns in material handling follow a scale-free structure in the presence of some hub-like researchers. According to social network theory, these hub researchers facilitate rapid dissemination of knowledge in the network. We conclude that the scientific community in material handling indeed forms a "small world," yet the level of connectedness is lower than in other scientific networks. We hope these findings will inspire new and increasing levels of collaboration in the discipline.**

***Index Terms*—logistics, material handling, social networks, scientific collaboration**

I. Introduction

Collaboration among scientists is increasing in both volume and importance [1], which makes understanding the term "research collaboration" important. Katz and Martin [2] define the term to mean working together to achieve the common goal of producing new scientific knowledge. Collaborators might contribute in one or more ways to the research, including analysis, writing, and raising funds for the project [2], [3].

Katz and Martin [2] list benefits and costs of research collaboration. Benefits include sharing and transferring knowledge, the "clash of views," or differences of opinion that help produce robust results, intellectual companionship, and increased visibility of the work. Costs of collaboration include the time and cost of travel and extra time required to manage the collaboration. Despite these disadvantages, most of the literature [4]–[8] agrees that research collaboration is beneficial.

It is generally accepted that collaborators publish papers from their studies [9]–[11]. To understand patterns of collaboration, numerous studies have been conducted based on bibliographic information such as co-author networks, citation analysis, co-citation, impact factor, h-index, and so on. Studying communication and interaction patterns of research collaborators using social network analysis is a fairly new research area [5]. Price [12] introduced the idea of networks to bibliographic studies such as co-authorship and co-citation networks. In a co-authorship network, vertices represent authors, and two authors are connected by an edge if they have co-authored one or more papers. The co-authorship network can reveals very interesting collaborative patterns in academic communities [13].

The Erdös Number Project is an early example of using a co-authorship network, in this case among mathematicians [4]–[6]. Paul Erdös (1913–1996) was an influential Hungarian mathematician who wrote more than 1,400 papers with more than 500 colleagues [14]. An author who published a paper with Erdös has Erdös number 1; an author publishing with an author who has Erdös number 1 has Erdös number 2; and so on. Though the idea of Erdös number was originally a tribute to Paul Erdös, it later became a tool to study how mathematicians cooperate to find answers to unsolved problems.

Milgram [15] conducted the famous "small world" empirical study on social networks. Milgram asked participants from Omaha and Wichita to send an information packet to a person in Boston. If the participants knew the person in Boston by first name (meaning closely connected), then they would send the packet directly, otherwise they had to send the packet through their friends. From this experiment, Milgram found that it took 6 links on average for the packet to reach its destination. Based on this experiment, the "small world" or "six degrees of separation" hypothesis was developed, which states that most pairs of people in a population can be connected by only a short chain of intermediate acquaintances, even when the population is very large. In the case of research, this small world facilitates spreading information of new knowledge [16].

Newman [4] studied the structure of collaboration networks in biology, medicine, physics and computer science. He collected information from different databases (MEDLINE, NC-STRL, and Los Alamos e-Print from 1995 to 1999) and found that the "small world" also exists among scientists. He also observed that networks are highly clustered—two scientists are more likely to collaborate if they have another collaborator in common. In his later publications, he introduced quantitative concepts such as betweenness, funneling, and the significance of statistical differences in bibliometric studies [17]–[19]. Later, numerous authors studied dynamics and the evolution of co-authorship networks [6]–[8], [20]. It is now well established that the application of social network analysis to collaborative networks reveals interesting information regarding a scientific community. In this study, we explore the network of material handling researchers using social network analysis.

TABLE I: Journals with the highest proportion of papers in material handling.

International Journal of Production Research	21.3%
European Journal of Operational Research	10.0%
Computers & Industrial Engineering	6.3%
International Journal of Advanced Manufacturing Technology	6.1%
IIE Transactions	5.8%
International Journal of Production Economics	5.8%

II. Data Collection

Collecting data from prominent journals in the research field is a widely accepted strategy to build a collaboration network [5]. We gathered data from ten databases: Elsevier, Emerald Insight, Institute of Electrical and Electronics Engineers (IEEE), Inderscience, Institute for Operations Research and the Management Sciences (INFORMS), Production and Operations Management Society (POMS), Sage, Springer, Taylor & Francis, and Wiley. We collected papers on material handling from these databases from 2010 to 2017.

To identify whether a paper addresses material handling, we searched the following keywords within the search fields of each of the ten databases: material handling, warehouse design, order picking, Automated Guided Vehicles (AGV), automated storage and retrieval system (AS/RS), warehouse management system (WMS), picker routing, warehouse design, puzzle-based storage, order fulfillment, pallets, and slotting.[1] The keyword search returned both papers that listed the term as an explicit keyword and those that contained it in its text.

The search revealed 751 authors from 428 papers contained in 88 journals. Journals with the most research papers are in Table I. We found that counting the number of authors is tedious work, because even the name of an author is an unresolved issue in bibliometrics [21]. For example, in our initial database we had three authors named M. B. M. De Koster, René de Koster, and René B.M. de Koster, whom we know to be the one and only René de Koster. Because our database has a relatively small number of authors, we tried to minimize such confusion by manual checking.

III. Observations

A. Community Insights

Before discussing the network (Figure 1), we should emphasize that it represents only papers published during the period 2010–2017, and only papers on material handling as defined by our choice of keywords. Some of the most influential authors in our field are absent entirely, either because they retired before this period, because they have moved into other areas of inquiry, or because their papers fell outside our choice of keywords. Some very productive authors will in this graph appear not very productive only because they publish much of their work in other subjects. We should also emphasize that, despite our great efforts to the contrary, it is almost certain that we missed some important papers and authors. We beg the reader's indulgence, and ask that he or she kindly inform us of missing data.

We begin with some observations about the productivity of the community as a whole. The average number of authors per paper has increased in almost all the scientific fields [5], [6], [18], and this is true of the material handling community as well. Figure 2 shows a gradual increase in the average number of authors per paper in the years between 2010 and 2017, from about 2.7 to about 3.3 authors. The number of papers published per year has risen dramatically, from 32 in 2011 to 85 in 2017. The number of authors publishing in material handling has seen a corresponding increase. The number of papers at a rate of 17 percent each year and number of authors at a rate of 15 percent each year. These data suggest that the material handling field is growing, and that the degree of collaboration is increasing.

B. Papers and Collaborators

Lotka [22] established a hypothesis now called "Lotka's law of scientific productivity," which states that the distribution of the number of papers published per author follows a power law with exponent -2. Following Lotka, we found that $p(k)$ fraction of authors with k publications follows a power law $p(k) = 303.83k^{-1.965}$ with $R^2 = 0.9065$ (Figure 3a). In the material handling community, René de Koster has published the most papers in the last 8 years (Table II).

The average number of collaborators per author in material handling is around 3. The distribution of author collaboration, also known as "Degree Distribution" (Figure 3b), also follows a power law $p(k) = 490.73k^{-1.928}$ with $R^2 = 0.797$. René de Koster has the highest number of collaborators (Table II).

TABLE II: Authors with highest number of papers and highest number of collaborators.

Author	Papers	Author	Collaborators
René de Koster	33	René de Koster	37
Nils Boysen	17	Debjit Roy	15
Sunderesh Heragu	14	Mauro Gamberi	14
Debjit Roy	13	Nils Boysen	14
Yugang Yu	13	Yeming Gong	14
Christoph H. Glock	12	Kevin R. Gue	13
Eric H. Grosse	12	Yugang Yu	13
Russell D. Meller	12	Jun Ota	12
Charles J. Malmborg	10	K.L. Choy	12
Kevin R. Gue	9	Riccardo Manzini	12

According to Barabási [23], scale-free networks exhibit a power-law degree distribution $P(k) \sim k^{-\gamma}$ with $\gamma < 3$, and therefore is characterized by "hub nodes" of increasing degree. The scale-free property is important in forming a small world [5]. Hubs are crucial to the network in two ways. First, if vertices with lower connectivity are removed from the network, the presence of hub nodes means that relatively few nodes would be disconnected entirely. Second, the presence

[1] Presentation of this paper at the International Material Handling Research Colloquium in July, 2018 made clear that our choice of keywords was more important than we realized: for the purposes of this paper, the choice essentially defines the field of material handling. We believe that any future study of collaboration should choose these terms more scientifically, perhaps by surveying members of the community.

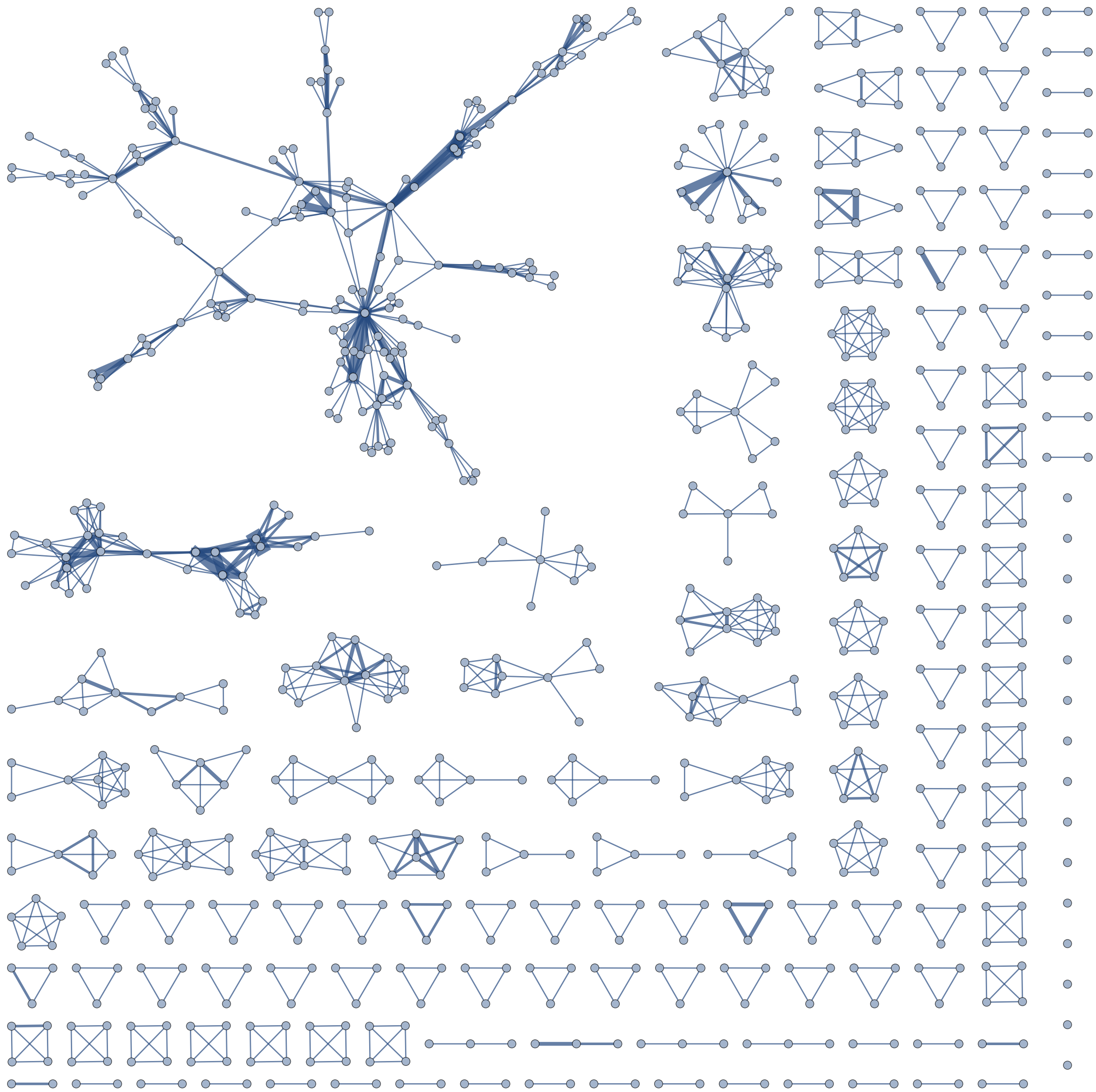
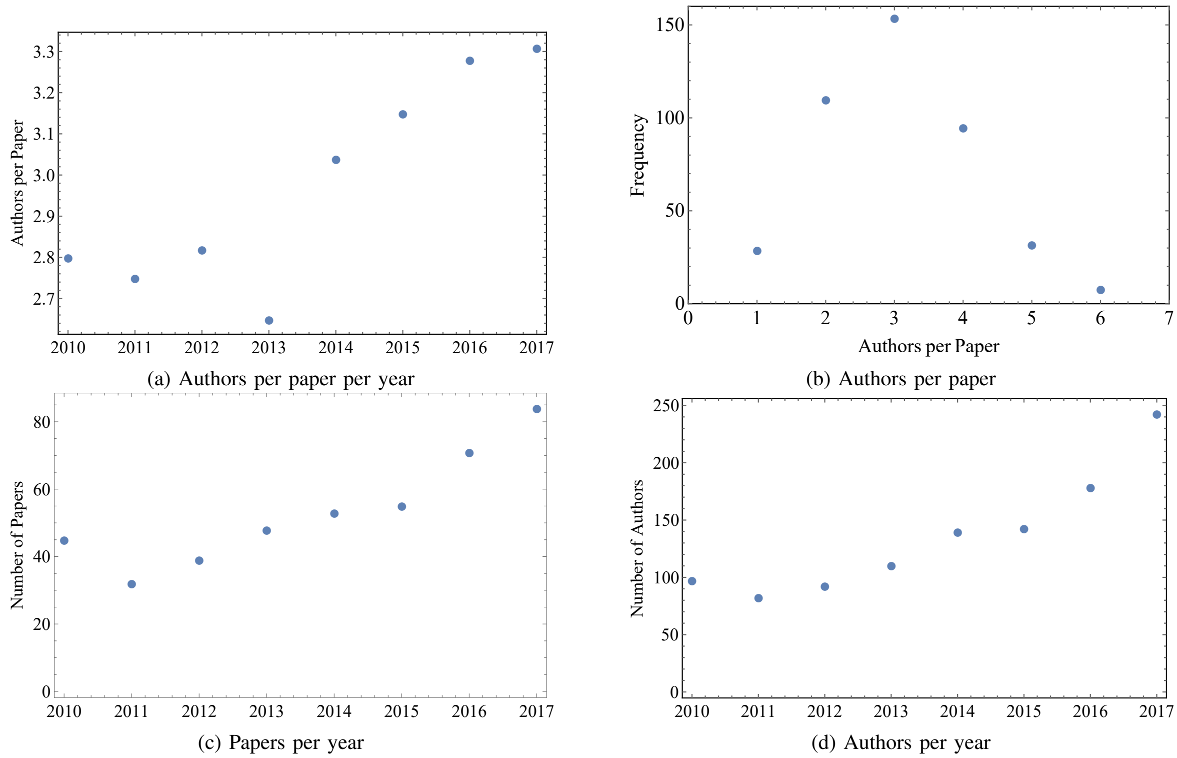


Fig. 1: The collaboration network of material handling researchers. Vertices represent authors; links represent collaboration on a paper. Thickness of an edge represents the number of co-authored papers.

of hubs makes passing information through the network very easy, in the same way that hub airports facilitate transportation between far flung cities. In the context of a collaboration network, the scale-free property means the loss of a relatively disconnected colleague, due perhaps to pursuit of another discipline, has little effect on the connectivity of the network. Also, hub-like researchers make possible more rapid sharing of important discoveries.

C. The Giant Component, Degree Separation, and Clustering Coefficient

A *giant component* is the largest connected component of a social network. The giant component typically indicates the core research topics of the scientific community [24]. In the material handling network, the giant component comprises 20 percent of the authors (149 of 751). According to Kumar [5], the size of the giant component of all the major disciplines exceeds 50 percent. Table III shows relevant statistics from other scientific disciplines—Physics, Neuro Science (NS), Library and Information Science (LIS) and Digital Library (DL). We



(a) Authors per paper per year (b) Authors per paper (c) Papers per year (d) Authors per year

Fig. 2: Data on the material handling community as a whole.

observe that the size of giant component in material handling is very low compared to these disciplines. It is possible that the relatively smaller number of authors in material handling explains this phenomenon.

The average degree separation of the giant component in material handling is 4.38, which means it takes on average this number of researchers to reach a randomly selected researcher from any other. Because our giant component is small, the average degree separation is also smaller than in other scientific disciplines. The *clustering coefficient* of the material handling network is 0.547, which means two authors are this likely to collaborate if they have a common third author. In this category, we are comparable to other disciplines.

D. Collaboration Strength

Granovetter [26] studied "tie strength" in social networks, which he defines as "a (probably linear) combination of the amount of time, the emotional intensity, the intimacy (mutual confiding), and the reciprocal services which characterize the tie." Granovetter concluded that strong ties are developed among similar categories of people but weak ties bridge communities. However, this pattern is opposite in scientific networks, where weak ties develop communities and strong ties connect communities [27], [28]. Usually, weak ties are short-term collaborations between, for example, students and advisors, and strong ties are long-term collaborations between researchers and research groups [28]. Therefore, stronger links are important to the overall connectivity of the network for knowledge transfer and creation [27], [29]. Table IV lists the top collaborating pairs in material handling research.

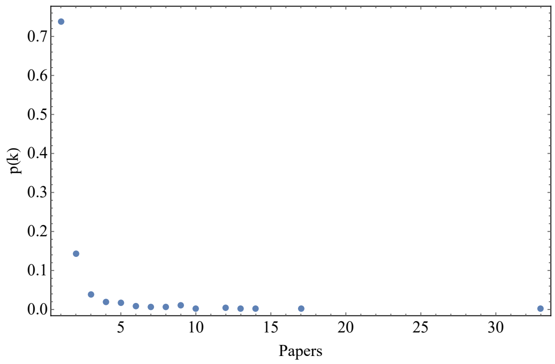
E. Centrality Measures

In social network analysis, centrality measures identify the important vertices in the network. Important vertices promote faster dissemination of information, help to stop epidemics and help to protect the network from breaking [30]. Degree centrality, betweenness centrality and closeness centrality are three popular centrality measures. We applied these measures to the giant component (Table V and Figure 4).

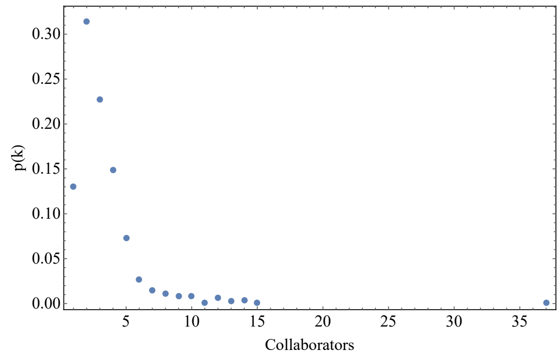
The *degree centrality* of a vertex is the number of edges to which it is connected. A node with higher degree centrality might have more influence, more access to information, or more prestige than those with fewer connections [31]. Table V shows that René de Koster has the highest degree centrality among researchers in material handling.

The *betweenness centrality* of a node i is the total number of shortest paths in the network that pass through i. This metric is an indicator of the most influential researchers in the network [4]. We list betweenness centrality in the second column of Table V. Again, René de Koster is the most influential researcher according to this metric.

Closeness centrality gives high centralities to vertices that are at a short average distance to every other reachable vertex. Vertices with higher closeness centrality might have better access to information at other vertices or more direct influence on other vertices [31]. Column 3 of Table V shows closeness



(a) Paper Distribution



(b) Degree Distribution

Fig. 3: Paper and Collaborator Distribution

TABLE III: Summary statistics for Physics, Neuro Science (NS), Library and Information Science (LIS), Digital Library (DL) and Material Handling (MH) coauthorship networks.

	Physics	NS	LIS	DL	MH
Authors	52,909	209,293	11,067	1597	751
Papers	98,502	210,750	-	639	428
Degree Separation	5.9	8	8.84	6.6	4.38
Giant Component	85%	80%	49%	38%	20%
Clustering Coefficient	0.43	0.75	0.425	0.89	0.547
Time Period of Study	1995–1999	1991–1998	2002–2007	1995–2003	2010–2017
Source	[13]	[6]	[7]	[25]	

TABLE IV: Top collaborating pairs

Authors	Papers
Christoph H. Glock / Eric H. Grosse	12
René de Koster / Yugang Yu	10
Ananth Krishnamurthy / Sunderesh Heragu	9
Ananth Krishnamurthy / Charles J. Malmborg	9
Charles J. Malmborg / Sunderesh Heragu	9
Alessandro Persona / Fabio Sgarbossa	8
Alessandro Persona / Daria Battini	7
Daria Battini / Fabio Sgarbossa	7
Riccardo Manzini / Riccardo Accorsi	7
Nils Boysen / Simon Emde	7

centrality of the material handling scientists. Here again, René de Koster is the researcher closest to others in the network.

IV. Conclusion

The collaboration network we develop here covers only research papers in the past eight years and 88 journals, but we believe it is complete enough to give a good picture of the state of collaboration and productivity in the field of material handling research. The increasing number of researchers and papers over this period is a positive sign, as is the small world structure of the giant component, which indicates that researchers are on average within six connections of one another.

Traditionally, the idea of a small world is important to the transmission of information, but is this true in the age of the internet? And what role do conferences such as the International Material Handling Research Colloquium play in this transmission? Newman [4] argued that although written communication through published papers is important, the majority of the scientists communicate privately using email or phone calls to share scientific findings or to share databases, but this study is now dated (2001). We do not have scientific answers to these questions, but we would suggest based on our own experience that collaboration via co-authorship does establish a continuing bond that results in "knowing what others are doing" in a way that promotes new ideas and better research.

One cause for concern is the relatively small portion of the community that comprises the giant component (about 20 percent). Simply including, via some new collaboration, the second and third largest components would increase this proportion to 26 percent. Of course, writing a paper only to increase the size of the giant component in a social network is ridiculous, but meaningful collaborations among these groups could improve the health and future prosperity of the community. We challenge the authors in these and other components to reach out and make it so.

Acknowledgment

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TABLE V: Authors with the highest degrees of centrality, betweenness, and closeness.

Author	Degree	Author	Betweenness	Author	Closeness
René de Koster	37	René de Koster	6445	René de Koster	0.3864
Debjit Roy	15	Debjit Roy	4093	Debjit Roy	0.3663
Yeming Gong	14	Jennifer A. Pazour	2326	Akash Gupta	0.3259
Yugang Yu	13	Kees Jan Roodbergen	2294	Andrew L. Johnson	0.3245
Kevin R. Gue	13	Russell D. Meller	2069	Kees Jan Roodbergen	0.3231
Xianhao Xu	12	Kevin R. Gue	1670	Marco Melacini	0.3162
Russell D. Meller	11	Andrew L. Johnson	1657	Jennifer A. Pazour	0.3135
Tone Lerher	10	Banu Y. Ekren	1634	Elena Tappia	0.3109
Sunderesh Heragu	10	Sunderesh Heragu	1221	T. Lamballais	0.3051
Kees Jan Roodbergen	10	Don Taylor	1157	Yeming Gong	0.2965

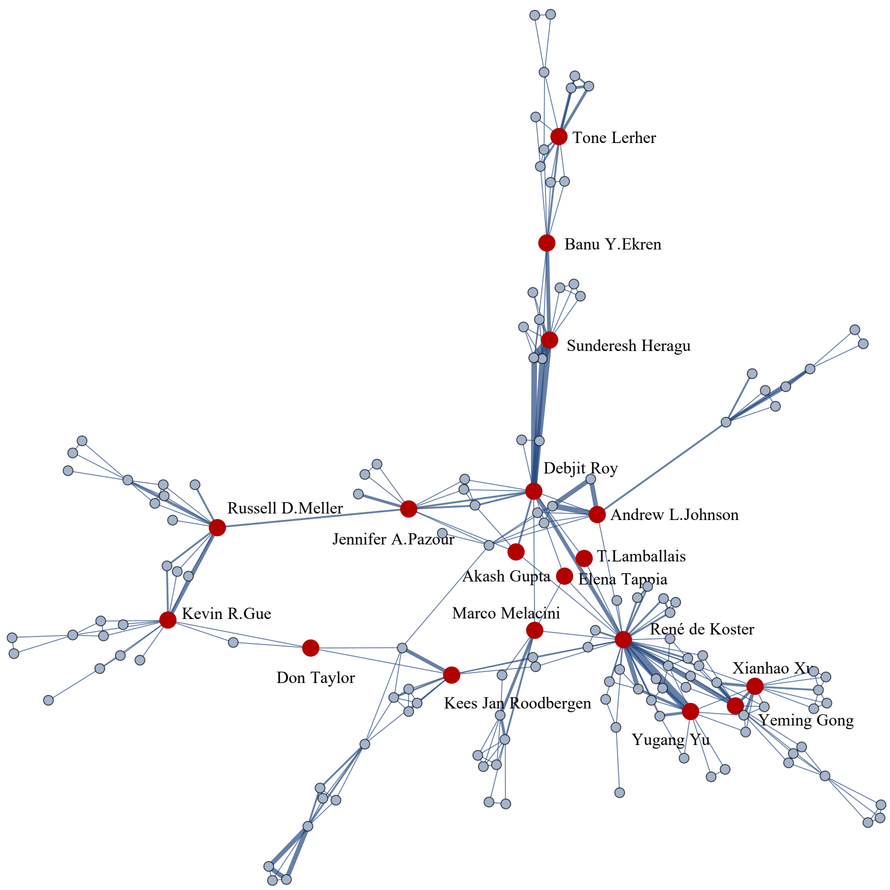

Fig. 4: The giant component with vertices of highest centrality.

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