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Social network analysis as a field of invasions: bibliographic approach to study SNA development

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Abstract
In this paper, the results of a study on the development of social network analysis (SNA) and its evolution over time, using the analysis of bibliographic networks are presented. The dataset consists of articles from the Web of Science Clarivate Analytics database obtained by searching for the keyword "social network*" and those published in the main journals in the field (in total 70,000+ publications). From the data, we constructed several networks. In this paper, the focus is on the analysis of the citation network. Analyzing the obtained network, we evaluated the SNA field's growth and identified the most cited works. Using the normalized Search path count weights, we extracted the main path, key-route paths, and link islands in the citation network. Based on the probabilistic flow node values, we also identified the most important articles. Our results show that the number of published papers almost doubles each 3 years. We confirmed the finding that the authors from the social sciences, who were most active through the whole history of the field development, experienced the "invasion" of physicists from the 2000s. However, starting from the 2010s, a new very active group of animal social network analysts took the leading position.

Keywords Development of scientific fields · Social network analysis · Citation network · Search path count · Probabilistic flow · Web of science

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Introduction

Social network analysis (SNA) is a rapidly developing scientific field that has appeared and grown significantly over the past 50 years. In the 1970s, the field was highly fragmented and could be represented by a set of individual scientific groups unrelated to each other. Due to the significant efforts of some individuals and institutions, during 1970-80s it was organized around the newly appeared *International Network for Social Network Analysis*, *Sunbelt* conference, and specialized journals *Connections* and *Social Networks*. In the beginning of 1990s, the representatives of SNA had already formed an "invisible college" and the field itself achieved the status of a "normal science" (Freeman 2004; Hummon and Carley 1993). From that point, the field of SNA has grown significantly, both in the number of scientific publications and different disciplines involved (Otte and Rousseau 2002; Borgatti and Foster 2003). To a large extent, the substantial increase in interest in this topic was due to the emergence of the Internet in 1990s and online social networks during the 2000s. However, if until the 2000s the field was mostly developed inside different branches of social sciences, starting from the new century it received significant attention from the researchers of the natural sciences. The so-called *"invasion of the physicists"* (Bonachich 2004) resulted in development of Network Science, whose representatives sometimes reinvented and rediscovered the issues that had been developing in the social sciences for quite some time (Freeman 2004, 2011).

To study scientific disciplines and their development through time, various tools of bibliometric analysis have been proposed and extensively used over the last decades. There is an extensive set of studies in the literature devoted to different scientific fields and their comparison on various levels—national, multinational, and international. The data for analysis are usually obtained from particular journals, thematic sets of literature, or databases of bibliographic information. The development of SNA was also studied by means of the bibliometric analysis of publications, authors, and journals involved in the field. Several authors studied citation structures of works and journals (Hummon and Carley 1993; Leydesdorff et al. 2008; Batagelj et al. 2014), collaboration and co-authorship structures (Otte and Rousseau 2002; Leydesdorff et al. 2008; Batagelj et al. 2014), structures of co-citations between works, authors, and journals (Brandes and Pich 2011), topical structures and keyword co-occurence networks (Leydesdorff et al. 2008; Groenewegen et al. 2015). Attention was also given to different subfields and topics (Hummon et al. 1990; Kejžar et al. 2010; Batagelj et al. 2014, 2019) and subdisciplines within the field (Otte and Rousseau 2002; Borgatti and Foster 2003; Lazer et al. 2009; Varga and Nemeslaki 2012).

While providing very important results for the understanding of the field, these studies fail to show the overall picture of its current development. The results of the research done in the area are partial, as they usually (1) highlight specific topics and answer certain questions concerning communication, collaboration, or citation (in different combinations), (2) study *various* bibliometric units—works, authors, journals, or keywords (in different combinations, so the results are difficult to compare), (3) focus on some specific sets of data (certain journals or specific data bases), (4) more often analyze selected subfields and subtopics, but not the whole SNA field, (5) cover time periods which are no longer up-to-date. The extensive growth of the field's disciplinary borders in last several years underlines the importance of detailed and contemporary research of SNA.

Our study implements a comprehensive approach for the identification of the main trends in the development of SNA, with a representation of various disciplinary areas, groups of scientists, and topics. The study is based on the analysis of networks of articles from the *Web of Science (WoS)* database and works published in the main journals in the field. The applied approach to bibliometric analysis has already shown its productivity in a set of studies of different scientific fields and topics (Kejžar et al. 2010; Batagelj et al. 2014, 2017). In the current paper, we observe the trends in field's development using only the analysis of citation network of publications, which allows us to identify key works, main topics and scientific ideas in the field, connections between them and their evolution through time.

"Social network analysis: a review of previous studies" section presents previous studies in the SNA field, focusing on the field's development and using similar analytical procedures. "Data" section describes the dataset and some issues of network construction. "Results" section provides the statistical properties of the citation network, and the groups of key publications extracted using Main path, Key-routes, Islands and Probabilistic flow approaches, which are explained in the corresponding subsections. The article is supplemented with Appendices describing some of the implemented procedures and the list of the main publications in the field of SNA.

Social network analysis: a review of previous studies

One of the most comprehensive overview of the history of the development of SNA was presented by Freeman in *'The Development of Social Network Analysis'* (Freeman 2004). Using a methodology from the sociology of science, Freeman patterned the links among the people who were involved in the development of the field, pointed out the main historical events, and presented *"the history of social network analysis written from a social network perspective"*. This qualitative study was also supported by a survey of early social network analysts (founding fathers and mothers) on their introductions to structural thinking—the scientific antecedents—and their most important works.

According to Freeman, the birth of the social network thinking can be attributed to the beginning of the twentieth century. However, the first more or less consistent period is the 1940–60s, which is associated with the emergence of a large number of scientific schools, most of which were not aware of each other and were potentially competing. That is why, by the 1970s the field was highly fragmented: according to the results of the survey, the field's intellectual antecedents formed different groups—sociologists, on the one side (though, loosely connected to each other) and anthropologists, geographers, social psychologists, communication scientists, political scientists, historians, and mathematicians (who showed more agreement about the patterns of influence)—on the other side.

Starting from the 1970s, a number of attempts were made to unify many separate strands of SNA by a number of individuals and institutions. Among these attempts, Freeman points out the organization of the *International Network for Social Network Analysis (INSNA)* in 1977, the creation of *Social Networks* journal in 1979, the conferences and the regular meetings that brought separate groups together (including those connected by an early version of Internet), the appearance of computer programs standardizing analysis of social network data, educational programs at the universities, and "bridging" positions of some scholars travelling around different institutions. All these attempts led to the institutionalization of the field in the 1980s, when *'the representatives of each of these network "schools" [...] all joined together and organized themselves into a single coherent field'* (Freeman 2004, p. 135).

The findings of Freeman on the unification of the field are supported by the results of one of the first quantitative study on the development of the SNA field conducted by Hummon and Carley (1993), which was based on the citation analysis of the works published in the first 12 volumes of *Social Networks* and important articles that were cited by their authors. Adding some historiographic data to the results of the network analysis, the authors came to the conclusion that by the 1990s the members of the SNA community met the requirements for being an invisible college. This notion means that until that time there had been a core active group of scientists (INSNA members), having a shared paradigm, defining important problems, promoting common methods of analysis, and working in core substantive areas and incrementally developing the ideas. They had a primary professional outlet (*Social Networks*) and regular face-to-face interaction (through conferences). The main paths going through the citation network were few in number, densely connected, extensive, and continuous. Hummon and Carley concluded that the SNA not only acceded the status of a discipline, but also that the type of science engaged in within the social network field was what Kuhn had labeled a "normal science".

Based on the number of works related to the SNA field in databases of sociological, psychological and biomedical publications 1974–1999, Otte and Rousseau (2002) came to the conclusion that *'it was only in the early 1980s that SNA started its career'*. While the fast growth of the number of publications was mostly seen in sociology, the biomedical and psychological literature showed a modest increase as well, which *'proves that other fields, besides Sociology, have used the term and the techniques'* of SNA.

The studies of the development of SNA within different disciplines follows the same trends. In their review of Network analysis usage in management and organizational research, Borgatti and Foster (2003) also showed the exponential growth of publications in the field indexed by *Sociological Abstracts* and containing "social network" in the abstract or title 1970–2000s. Analyzing organizational network studies by means of bibliographic coupling and citation network analysis, Varga and Nemeslaki (2012) found a strong connection to economics, management and business science, and sociology. Otte and Rousseau (2002), being interested in the social information discipline, found the presence of SNA there as well: some of the most active information science authors also published articles in journals close to SNA (such as *Scientometrics, JASIS(T), Journal of Classification*).

However, in the beginning of the 21st century, the field faced some challenges—an "invasion of physicists" into the field of SNA (Bonachich 2004), which caused a confrontation between the traditional social network analysts and the physicists, discovering the network approach and *"reinventing existing tools and rediscovering established empirical results"* (Freeman 2004). A detailed description of the physicists' appearance in the field and their tension with social scientists was shown by Freeman (2011). These expert evaluations were supported by studies of several branches of the SNA field on the topics of centrality measures (Batagelj et al. 2014), clustering and classification (Kejžar et al. 2010), and blockmodeling (Batagelj et al. 2019). The findings of these studies confirmed the "invasion of the field" by other disciplines: while previously the SNA field had developed in different branches of social sciences, starting from the 2000s, the key works in the field belong to the authors from physics (mostly), computer science, neurosciences, and medicine.

These "invasions" are supported in the studies of other bibliographic units (authors, journals, keywords) with different ways of analysis (co-authorship, citation, co-citation and bibliographic coupling networks). Using the dataset **SN5** (Batagelj 2008) presented by Batagelj et al. (2014) (*WoS*, descriptions of articles on social networks before 2007) Brandes and Pich (2011) implemented the procedure of bibliographic coupling (based on the closeness of nodes according to their citing patterns) to different sets of bibliographic entities, including authors. The analysis revealed the same patterns that were observed in previous studies: the distinction between different groups of authors—social network scientists and the representatives of Network science—with the latter forming the most cohesive groups according to the similarity of citation patterns. Lazer, Mergel, and Friedman Lazer et al. (2009) studied the development of SNA within sociology—*"which has served as the primary home of social network analysis over the last several decades"*. Looking at the co-citation patterns of papers on social networks published in two leading general sociological journals, *the American Sociological Review* and *the American Journal of Sociology*, at three periods—1990–1992, 2000, and 2005,—they delineated different "canons" typical for times and the associated authors in each. Being especially interested in the impact that works written within physics had on the study of social networks within sociology, they found the *'rapid entry of the physicists into the canon between 2000 and 2005, and a possible centralization of the field around small-world networks related research'*. Leydesdorf, Schank, Scharnhorst, and De Nooy (2008) based on the analysis of the *Social Networks* journal's citation structures, constructed from aggregated journal-journal citation data from the *Journal Citations Reports* of the *Science Citation Index* (1994–2006), found a strong connection with other sociological journals, and weaker connections with journals from psychology, organization, and management studies. They showed that in some years the journal was also cited in a larger citation environment including journals in physics and applied mathematics. However, *'in spite of the fact that the citation impact of Social Networks in recent years has increased, this has not changed its disciplinary identity'*: it still *'can be considered as a representative of sociology journals'*, rather then an interdisciplinary journal (Leydesdorff et al. 2008).

The previous studies done in the field of SNA development show that the institutionalization of the field reflected in the rapid increase of the yearly number of articles related to it, which has been constantly growing since 1970–80s. According to Freeman, already by the 2000s the study of social networks had become one of the major areas of social science research (Freeman 2004). On the other hand, even though the initial involvement in SNA was interdisciplinary (Hummon and Carley 1993), recently the field has faced some challenges, with *the physicists' invasion* being one of the most important (Lazer et al. 2009; Brandes and Pich 2011; Batagelj et al. 2014; Freeman 2011).

Based on these findings, this paper evaluates the main changes that the field has undergone and highlights the current trends in its development. We focus on the following questions: (1) is the field still growing in sense of the number of published works, (2) what are the most important and influential works in the field and how are they connected to each other, (3) what are the disciplines actively involved in the SNA field—are there still physicists "invading" the field, or has another wave of "invaders" from other disciplines come?

Data

Data collection and cleaning

The source of data for our research was the *WoS*, Clarivate Analytics's multidisciplinary databases of bibliographic information. Some comments should be given concerning the choice of this database. Even though for a long time *WoS* had a monopoly in the abstraction and evaluation of scientific work, other sources of bibliometric data appeared—such as *Scopus, Google Scholar*, special citation resources and scientific social media (*SciFinder,* *Mendeley*, etc.). Previous comparisons of different databases have shown that they vary significantly according to their coverage of certain scientific disciplines, and have their pros and cons. For example, *Google Scholar* provides broad coverage for most disciplines, while *Scopus* and *WoS* have fewer publications and a weaker representation of the works in the social sciences and the humanities. The number of works for all disciplines, especially for engineering, was found to be higher in *Scopus*, than in the *WoS* (Hilbert et al. 2015; Harzing and Alakangas 2016; Martín-Martín et al. 2018). The *WoS* contains mainly publications from the journals with a certain impact factor, while *Google Scholar* contains different types of sources, including journals, conference papers, books, theses and reports. This can be important for the representativeness of those disciplines where journals are not the only prestige sources for sharing scientific knowledge (but also conference proceedings, reports, etc.), and publications are not the only type of scientific contributions (but also software, data, patents, etc.) (Franceschet 2009). We expect that this can lead to a certain under-representation of some fields in our dataset, where SNA is developing—for example, computer science. At the same time, an important feature of *WoS* is that it provides coverage back to 1900 with descriptions including references (CR field); for other databases, the information on citations is included in the descriptions of publications only from 1970 (*Scopus*), or not included at all (*Google Scholar*) (Elsevier 2019; WoS 2019). Together with lower consistency and less accuracy of the data in *Google Scholar*, it makes the choice of the *WoS* most appropriate for the current study. However, it should be noted that its results are inevitably relative to the available data.

Figure 1 presents an example of a record describing an article as obtained from WoS. Such articles with full description are called *hits*. The works, which appear only in the WoS CR fields as references, do not have full descriptions in the collected dataset, and are called *terminal* works. We had to limit our search to the WoS Core Collection because for other databases in WoS the CR fields, which contain citation information, could not be exported.

The dataset has two parts. It is based on the SN5 data collected for the Viszards session at the Sunbelt 2008 (Batagelj et al. 2014), and contains all the records obtained for the query `"social network*"` and articles from the journal *Social Networks*, until

Fig. 1 WoS record

```
PT J
AU GRANOVET.MS
TI STRENGTH OF WEAK TIES
SO AMERICAN JOURNAL OF SOCIOLOGY
LA English
DT Article
C1 JOHNS HOPKINS UNIV, BALTIMORE, MD 21218 USA.
CR BARNES JA, 1969, SOCIAL NETWORKS URBA
   BECKER MH, 1970, AM SOCIOL REV, V35, P267
   BERSCHEID E, 1969, INTERPERSONAL ATTRAC
   BOISSEVAIN J, 1968, MAN, V3, P542
   BOTT E, 1957, FAMILY SOCIAL NETWOR
NR 61
TC 2156
PU UNIV CHICAGO PRESS
PI CHICAGO
PA 5720 S WOODLAWN AVE, CHICAGO, IL 60637
SN 0002-9602
J9 AMER J SOCIOL
JI Am. J. Sociol.
PY 1973
VL 78
IS 6
BP 1360
EP 1380
PG 21
SC Sociology
GA P7726
UT ISI:A1973P772600003
ER
```

2007. We additionally searched for the works without full descriptions which were most frequently cited and papers on SNA of around 100 social networkers. The final version of SN5 contained 7950 works with a full description (hits), 193,376 works (hits and cited only), 75,930 authors, 14,651 journals, and 29,267 keywords. The SN5 data were extended in June 2018 using the same search scheme. Starting from 2007, 576 articles from *Social Networks* journal were added. Additionally, in 2018, all the articles from the network-related journals contained in the WoS were included—such as *Network Science*, *Social Network Analysis and Mining*, *Journal of Complex Networks* (in total, 431 article). Other network-related journals—such as *Computational Social Networks*, *Applied Network Science*, *Online Social Networks and Media*, *Journal of Social Structure*, and *Connections*—were considered, but were not included since they are not abstracted in WoS.

As terminal (cited only) works can be highly cited and in this sense important, we additionally collected full descriptions for works with high (at least 150) citation frequencies using WoS. If a description of a work was not available in WoS, we constructed a corresponding description without CR data, searching for the work in Google Scholar (exporting it in the RIS bibliographic format and converting it into the WoS format). We also included manual descriptions of important works without the CR field from the dataset **BM** on blockmodeling (Batagelj et al. 2019). We should note that additional influential papers, usually published earlier, could be overlooked by our search queries because they do not use the contemporary terminology. Finally, our dataset included 70,792 WoS records with complete descriptions.

Basic network construction

Using **WoS2Pajek 1.5** (Batagelj 2007), we transformed our data into a collection of networks: one-mode citation network **Cite** on works (from the field CR of the WoS record) and two-mode networks—the authorship network **WA** on works × authors (from the field AU), the journal network **WJ** on works × journals (from the field CR or J9), and the keyword network **WK** on works × keywords (from the fields ID, DE or TI). An important property of all these networks is that they share the same first node set—the set of works (papers, reports, books, etc.)—which means that they are *linked* and can be easily combined using network multiplication into new *derived* networks (Batagelj et al. 2014).

Works that appear in descriptions can be of two types: those which have full descriptions (*hits*), and those which were only cited (terminal works listed in the CR fields). This information was stored in a partition **DC**, where $DC[w] = 1$ if a work w has the WoS description, and $DC[w] = 0$ otherwise. The partition **year** contains the work's publication year from the fields PY or CR. This information is essential for the construction of temporal networks. WoS2Pajek also builds a CSV file **titles** with main data about hits (short name, WoS data file line, first author, title, journal, year), which can be used to list the results, and the vector **NP**, where $NP[w]$ = number of pages in a work w.

The usual *ISI name* of a work (its description in the field CR) has the following structure:

```
AU + ', ' + PY + ', ' + SO[:20] + ', V' + VL+ ', P' + BP
```

(first author's surname, initials, year of publication, title of the journal, volume and the number of the starting page; + denotes concatenation), which results in such descriptions as

```
GRANOVETTER M, 1985, AM J SOCIOL, V91, P481
```

(all the elements are in the upper case). As in the WoS the same work can have different ISI names, WoS2Pajek supports also *short names* (similar to the names used in HistCite software output), which has the following format:

```
LastNm[:8] + '_' + FirstNm[0] + '(' + PY+ ')' + VL + ':'
+ BP.
```

For example, for the mentioned work its short name is `GRANOVET_M(1985)91:481`. For last names with prefixes `VAN`, `DE`,...the spaces are deleted, and unusual names start with characters `*` or `$`.

However, some problems with data can still exist even with this approach as the information in CR field can include typos in publication year, volume and page numbers, etc. That is why some additional cleaning on the highly cited nodes was implemented (see "Appendix A" for details).

After all iterations of cleaning, we finally constructed the dataset used for the further analysis. From 70,792 hits (data with full description, $DC = 1$) we produced networks with sets of the following sizes: works $|W| = 1,297,133$, authors $|A| = 395,971$, journals $|J| = 69,146$, key words $|K| = 32,409$. We also removed multiple links and loops from the networks and labeled the obtained *basic* networks **CiteN**, **WAn**, **WJn**, and **WKn** (Table 1). In this paper, we analyze only the citation network. Other networks were used for more detailed analysis of other bibliographic entities.

As explained, for the cited only works ($DC = 0$) only partial descriptions are provided: we have information about the *first* author, the journal and the publication year, and we have no information on the keywords (as there are no titles in ISI names of terminal works). That is why for further analysis we constructed networks which contain only works with a complete description ($DC = 1$). All the link weights in the obtained networks were set to 1. We labeled these *reduced networks* **CiteR**, **WAr**, **WJr**, and **WKr**. In these networks, the sizes of sets are as follows: works $|W| = 70,792$, authors $|A| = 93,011$, journals $|J| = 8,943$, key words $|K| = 32,409$ (remained the same) (Table 1).

Table 1 Sizes of basic and reduced networks

	# Nodes (sum)	# Mode 1	# Mode 2	# Arcs
CiteN	1,297,133			2,753,633
CiteR	70,792			398,199
WAn	1,693,104	1,297,133	395,971	1,442,240
WAr	163,803	70,792	93,011	215,901
WKn	1,329,542	1,297,133	32,409	1,167,666
WKr	103,201	70,792	32,409	1,167,666
WJn	1,366,279	1,297,133	69,146	720,044
WJr	79,735	70,792	8943	61,741

Results

Distribution of works and main publications in citation network

In Fig. 2, the distributions of the number of works per year are presented. The picture on the left side shows how many works from the set of hits are published per year. The data show constant and fast growth in the number of articles on SNA topics starting from 2007, when there were 1576 articles published. In 2012, the amount of hits overcomes the level of 5000, and grows by more than 1000 articles per year. In 2015 and 2016, there were 9285 and 9693 articles published, respectively. On average, the number of publications increased by 1.2 times every year, with the largest growth in 2007, when it increased by 1.7 times. Such growth can be explained by the general interest of researchers in networks (including online), which also manifested itself in the increase in number of journals on these topics. For 2017 and 2018, there are fewer works in our dataset (9042 and 2618)—due to the incompleteness of the WoS database for recent years (the values for these years are not considered in the distribution). The distribution till 2016 fits the *exponential model*.

$c \cdot a^{year-1965}$, where $a = 1.2338$, and $c = 0.2526$.

The obtained values show that the number of works almost doubles in every 3 years ($\log(2)/\log(1.2338) = 3.299148$).

The right side of Fig. 2 shows the publication years for the terminal works which are cited only. The majority of works which are cited were published recently: there are 13,202 works published in 1990, 33,185 in 2000, and 67,343 in 2010. The amount of cited works published after 2014 is decreasing, which simply means that works published very recently could not yet get the large amount of citations. However, the presence of the newest works shows that they are already seen and cited by representatives of the field. There are citations of works published in the first part of 20th century and even earlier—from the 14th century (41 works), 15th (20), 16th (45), 17th (245), 18th (528), and 19th (2,151 works). The distribution of works from 1900 to 2018 fits the *log normal distribution*.

$c \cdot \text{dlnorm}\,(2018 - year, a, b)$, where $a = 1.501$, $b = 0.9587$, and $c = 7.110\ 10^4$.

Such result was already obtained in other studies of citation networks (Batagelj et al. 2014, p. 119–121).

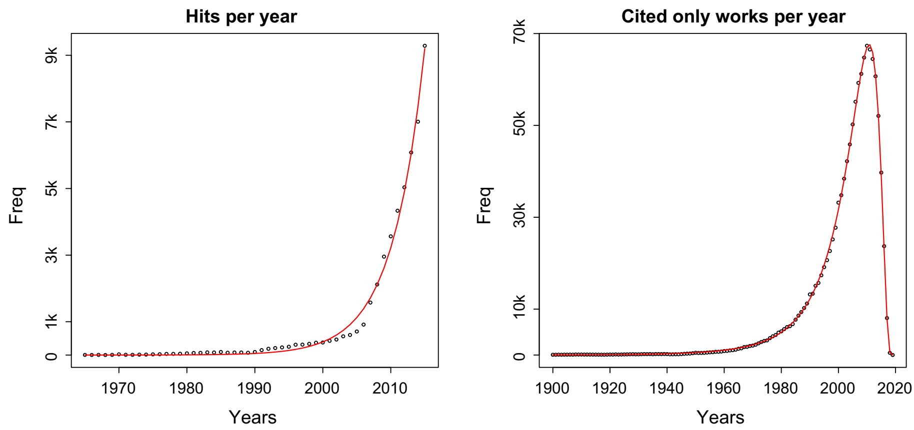

Fig. 2 CiteN: Distribution of hits (left) and terminal works (right) by years

In Fig. 3, the indegree distributions in **CiteN**—complementary cumulative and density—in double-logarithmic scale are shown. The density fits the *power law* distribution $f = c \cdot n^{-\alpha}$, with fitted $\alpha = 2.3007$ and $c = 749338$. This means that a small number of works attracts a large number of citations, and a large number of works attracts only small number of citations. Works with the largest indegrees are the most cited papers. The complementary cumulative distribution confirms the scale-free nature of the indegree distribution.

Table 2 presents the 60 most cited works (indegree in **CiteN**). Almost half (28) of these works were published before 2000, and quarter of them (15) are books (their label ends with a colon ":"). The most cited works are the book of Wasserman and Faust published in 1994, and the article of Granovetter on the strength of weak ties.

Other highly cited books are from social sciences (marked in boldface in table). Some of these works are devoted to the general issues of SNA methodology and theory, such as Scott's *Social Network Analysis*, 2000 (1192 citations); Coleman's *Foundations of Social Theory*, 1990 (1093); Hanneman and Riddle's *Introduction to social network methods*, 2005 (854). There is also set of works on the social capital—Burt's *Structural Holes*, 1992 (2330) and *Brokerage and closure*, 2005 (565), and Lin's *Social capital*, 2001 (800). Also there are several well-known books on broader topics: Putnam's *Bowling alone*, 2000 (1510) and *Making democracy work* (jointly with Leonardi and Nanetti), and Fischer's *To dwell among friends*, 1982 (539). Rogers' *Diffusion of innovations* appears twice - in 1995 (555) and 2003 (628), as well as the book *Ucinet for Windows: Software for Social Network Analysis*, 2002, attributed to Everett (1171) and Borgatti (999) as the first author.

Highly cited articles of the social scientists include works of McPherson and Smith-Lovin (homophily), Freeman (centrality, betweenness), Burt (structural holes), Coleman, Portes, Adler and Kwon (social capital), Granovetter, Uzzi (embeddedness), and Milgram (small world).

The table also includes the names of physicists working within the Network science (marked by *). The most highly rated articles are of Watts and Strogatz on *Collective dynamics of 'small-world' networks*, published in Nature in 1998 (2906), and of Barabási and Albert on the *Emergence of scaling in random networks*, appeared in Science in 1999 (2614). Other works are of such authors as Newman, Albert, Girvan, Fortunato, Blondel

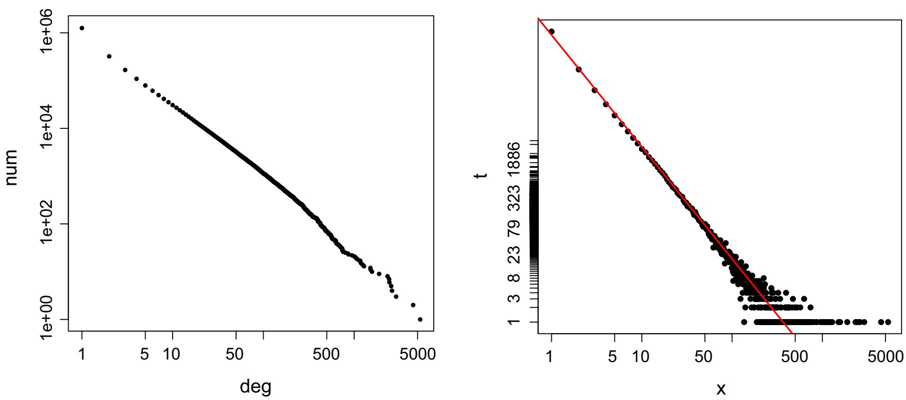

Fig. 3 CiteN: Indegree distribution—complementary cumulative (left) and density (right) in double-logarithmic scale

Table 2 CiteN: The most cited works—indegree

i	Freq	id	i	Freq	id
1	5348	**WASSERMA_S(1994):**	31	734	*NEWMAN_M(2001)98:404
2	4471	**GRANOVET_M(1973)78:1360**	32	719	*NEWMAN_M(2010):
3	2906	*WATTS_D(1998)393:440	33	701	PORTES_A(1998)24:1
4	2614	*BARABÁSI_A(1999)286:509	34	687	BLEI_D(2003)3:993
5	2561	**FREEMAN_L(1979)1:215**	35	670	**BURT_R(2004)110:349**
6	2447	BOYD_D(2007)13:210	36	654	HANSEN_M(1999)44:82
7	2429	**MCPHERSO_M(2001)27:415**	37	639	*PALLA_G(2005)435:814
8	2330	**BURT_R(1992):**	38	634	*CLAUSET_A(2004)70:066111
9	1886	**COLEMAN_J(1988)94:95**	39	629	*BONACICH_P(1987)92:1170
10	1572	*NEWMAN_M(2003)45:167	40	628	ERDOS_P(1959)6:290
11	1520	*GIRVAN_M(2002)99:7821	41	628	**UZZI_B(1997)42:35**
12	1510	**PUTNAM_R(2000):**	42	628	**ROGERS_E(2003):**
13	1285	*ALBERT_R(2002)74:47	43	613	**PUTNAM_R(1993):**
14	1240	**GRANOVET_M(1985)91:481**	44	593	BERKMAN_L(1979)109:186
15	1192	**SCOTT_J(2000):**	45	583	**ZACHARY_W(1977)33:452**
16	1171	**EVERETT_M(2002):**	46	572	**BORGATTI_S(2009)323:892**
17	1166	*NEWMAN_M(2004)69:026113	47	569	*NEWMAN_M(2001)64:025102
18	1093	**COLEMAN_J(1990):**	48	565	**BURT_R(2005):**
19	1058	STEINFIE_C(2007)12:1143	49	561	ADLER_P(2002)27:17
20	1034	*FORTUNAT_S(2010)486:75	50	559	**CHRISTAK_N(2008)358:2249**
21	999	**BORGATTI_S(2002):**	51	555	**ROGERS_E(1995):**
22	945	**CHRISTAK_N(2007)357:370**	52	554	MILGRAM_S(1967)1:61
23	867	**FREEMAN_L(1977)40:35**	53	553	BARON_R(1986)51:1173
24	854	**HANNEMAN_R(2005):**	54	550	**GRANOVET_M(1978)83:1420**
25	800	**LIN_N(2001):**	55	539	**FISCHER_C(1982):**
26	757	KAPLAN_A(2010)53:59	56	537	BRIN_S(1998)30:107
27	756	*BLONDEL_V(2008):P10008	57	524	**MARSDEN_P(1990)16:435**
28	742	NAHAPIET_J(1998)23:242	58	523	KEMP_D(2003):137
29	740	FORNELL_C(1981)18:39	59	523	KLEINBER_J(1999)46:604
30	740	*NEWMAN_M(2006)103:8577	60	517	*BOCCALET_S(2006)424:175

Bold is for social scientists, * for physicists

(with Guillaume, Lambiotte, Lefebvre), Clauset, Moore on large and complex networks, community detection and clustering. A famous work of mathematicians Erdős and Rényi *On random graphs* published in 1959 is also on the list.

There are also some representatives of other disciplines, in topics such as social network sites and social media (including the highly cited article of Boyd D. and Ellison *Social network sites: Definition, history, and scholarship*, published in 2007 and having 2447 citations); medicine, and management.

Works with the largest outdegree in **CiteN** are the most citing works. These works are books, introductory chapters of books, and review articles. Most of these works belong to the field of social sciences, they include education, human relationships, archaeology, migration, internet studies, and social media, but not exactly the topic of SNA. However, some works published in the journals in physics and computer science do address the issues of network analysis (Boccaletti, Latora, Moreno, Chavez and Hwang, and Costa and others on complex networks, Castellano, Fortunato, and Loreto on social physics of social dynamics, Brandes on methodological foundations of network analysis), as well as works representing—quite surprisingly—the field of animal social networks.

Boundary problem and transformation of citation network

The original **CiteN** network has 1,297,133 nodes. Considering the indegree distribution in this network we found the following counts for the lowest number of received citations: 0 (41,954 works), 1 (933,315), 2 (154,895), 3 (58,141), and 4 (29,885), which all together cover 94% of all works. Thus, most of the works were hits with indegree equal to 0 or were referenced only once or twice (terminal works with indegree equal to 1 or 2). The works that recieved only few citations can be considered as not important, therefore they should not be included into the final network (*boundary problem* (Batagelj et al. 2014, p. 126–128)). To obtain the richer network, we removed all the cited only nodes with indegree smaller then 3 ($DC = 0$ and indegree < 3). We also removed all the nodes with labels starting with string `[ANON`. This resulted in a subnetwork **CiteB** with 222,086 nodes and 1,521,434 arcs.

For the citation network analysis, we used *Search path count (SPC)* algorithm (Batagelj et al. 2014; Batagelj 2014), which determines for each arc the weight which is equal to the probability that a random path through the network passes through this arc. This algorithm requires the network to be acyclic. A citation network is (almost) acyclic, however, it can include some small cyclic parts which can be identified as nontrivial (with the minimum size 2) strong components of the network. First we searched for the nontrivial strong components (see "Appendix B" for details). To get an acyclic network, we applied the *preprint transformation* to **CiteB**. The preprint transformation replaces each work u from a strong component with a pair of nodes—a published work u and its preprint version u'. In Pajek the node u' is labeled with node u preceded by a character "=". A published work can only cite preprints. Each strong component was replaced by a corresponding complete bipartite graph on pairs (Batagelj et al. 2014, p. 82–84). The resulting network **CiteT** has 222,189 nodes and 1,521,658 arcs.

We computed the SPC weights on **CiteT** network arcs. We identified the main paths (CPM main path and Key-route paths) in this network. To find the most "important" parts of this network, we also used the Islands approach (link and node islands) and the Probabilistic flow. So, we applied five different procedures to validate the obtained most important works in SNA. These results are described below. The full information on each paper (first author, title, journal, year of publication) obtained by different procedures is presented in Table 3 in "Appendix C". In this table, the second column (code) describes in which analysis the work appears: 1—Key-routes, 2—CPM main path, 3—ink island 5, 4—Link island 4, 5—Node island, 6—Probabilistic flow tops.

Citations between years in bounded network

It is interesting to observe how many citations are made per year. We combined **CiteB** network with the partition on the year of publication and constructed a network of citations between years, where the values are equal to the number of times that all works published in 1 year were cited in all works published in another year (the network is directed, only later years can cite previous years). Figure 4 presents the distribution of citations between years in

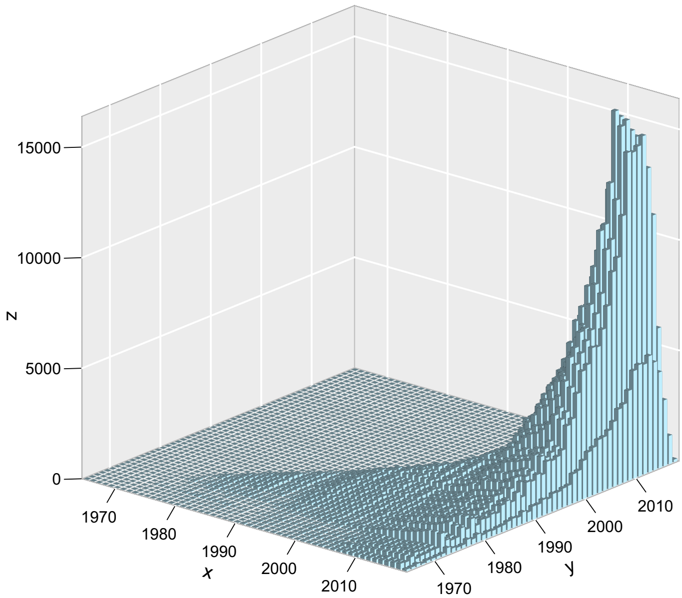

Fig. 4 Citations between years

a three-dimensional space. The majority of citations in recent works are made to recent works as well. The years having the largest amount of citations from other years are 2007 (80,129), 2008 (77,595), 2009 (82,294), 2010 (88,840), 2011 (79,843). No year before 1996 is in the list of the 20 most cited years. The largest number of citations are from 2015 and 2016 to 2010 (16,384 and 15,755, respectively) and 2011 (16,026 and 15,944).

Figure 5 presents the curves of values of citations per year in the period 1985–2018 (54 years in total), which were normalized in the following way:

$$\mathbf{P_i} = \frac{f_i}{\sum_i f_i}$$

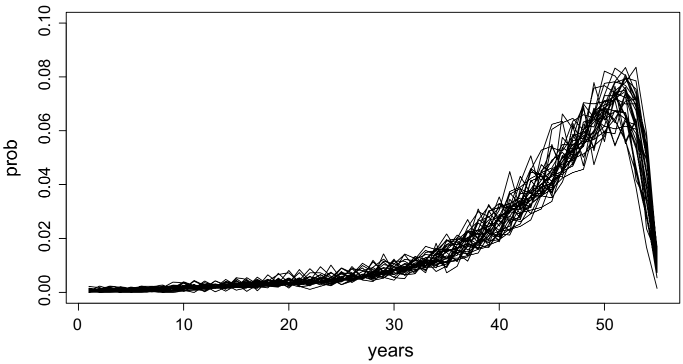

Fig. 5 Citations between years—normalized

where f_i is a frequency of the values, and $\mathbf{P_i}$ is a probability that the paper of the proper age (from 1 to 54) is cited by papers of other years. The result shows that the yearly citation patterns do not vary significantly from year to year—there are always noticeably more citations made of recent works, than of works published previously. This effect was already observed in the analysis of large bibliographic datasets from the WoS (Šubelj and Fiala 2017).

Main path and key-routes

The *Main path* (MP) in a weighted network is obtained by starting with the (*seed*) arc with the largest SPC weight as the initial MP segment of the path. Then it is extended recursively in both directions by appending the incoming/outgoing arc with the largest weight to its ends. The CPM main path is obtained by the *Critical Path Method* (CPM), borrowed from Operations research, which determines the path with the largest sum of weights. Usually both methods give the same or very similar results. For details see (Batagelj et al. 2014, p. 135–139).

Figure 6 displays the CPM main path through the SNA literature (the same to the one obtained with the MP procedure), which includes 59 nodes. We divided this CPM main path into three parts, according to the discipline of the works that are presented.

The first group, composed of the works published 1944–1996, presents the works of network scientists from the social sciences. These works appeared (see “Appendix C”) in

Fig. 6 SPC net: Main path by fragments—sociology, physics, biology. (2nd and 3rd parts start with two works from the previous group)

the journals *Social networks, Administrative Science Quarterly, Annual Review of Sociology, American Sociological Review, Social Forces, Sociological Methods & Research, Journal of Mathematical Psychology, Psychological Review, The Journal of Psychology*, recalling the formation of SNA. In this part of the network, 6 out of the 20 works belong to Burt.

Since 1999, the initiative in the field has moved to the physicists, whose works appear in the journals *Physical Review E, Journal of Statistical Physics, Reviews of Modern Physics, European Physical Journal B, Physics Reports, Nature*, and *SIAM Review*. In the part of the network (1999–2007), 9 out of the 14 works belong to Newman.

The third part of the network, which contains works from 2008 to 2018, is devoted to completely another topic—animal social networks. The works appear in the journals *Animal Behaviour, American Journal of Primatology, Primates, Journal of Evolutionary Biology, Journal of Animal Ecology, Journal of Evolutionary Biology, Trends in Ecology & Evolution*, and others. Note that this group started from behavior-oriented journals, and lately turned to the journals from the fields of ecology and evolution. The most active author in this group is Farine, who has 6 works out of the 25 works. While the *invasion of physics* into SNA has been already shown in other studies (Lazer et al. 2009; Brandes and Pich 2011), the appearance of the third group in the main path is surprising. For the centrality literature, it was shown that the trend goes from physics to neuroscience (Batagelj et al. 2014), and for the network clustering literature, the main path consisted only of the social and physical parts (Batagelj et al. 2019).

The *Key-route method* (Liu and Lu 2012) is a variant of the MP method in which we select a set of seed nodes and construct a subnetwork of corresponding main paths. The same approach can also be used for CPM main paths. Using the Key-route method, we produced a more nuanced image of the most important paths in the SNA literature, as it contains some deviations from the structure of the network identified with the CPM method (Fig. 7). The Key-route paths contain 127 nodes, with 57 nodes intersecting with the main path. We still get the division into three previously mentioned periods.

The publications belonging to the first period (1944–1999) include 50 works on SNA written by social scientists. It starts with two works of Heider on his theory of social perception and cognitive organization (1944, 1946), which form the basis for the work of Cartwright and Harary (1956) on structural balance. Later, two works of Holland and Leinhardt on structural models follow, published in 1970–1971. Next comes the classical paper of Granovetter on the strength of weak ties (1973), which is a basis for the works of Breiger, Boorman, Arabie on clustering relational data, White, Boorman and Breiger on role structures in multiple networks, and Alba and Kadushin on the measures based on social proximity, all published in 1975–76. Then there are the 6 works of Burt on positions in multiple networks (stratification and prestige), structural equivalence and networks subgoups, published from 1977 to 1981 (the one of 1981 is in co-authorship with Bittner), which have links to the works of Holland and Leinhardt on social structure as a network process, Breiger and Pattison; Lauman, Galaskiewicz and Marsden; and Wellman on community structures, published at about the same time, as well as later published works of Breiger and Pattison on social roles, and Faust and Romney on commenting Burt's article on structural equivalences. This group of works deals with network and community structures, positions, structural equivalence, and blockmodels.

These are followed by works on the measurement and different network metrics: Romney and Faust, Bernard, Killworth and Sailer (1982) on recalled data for network construction, and Stephenson and Zelen on centrality (1989). The last work is also linked to the works of Mizruchi on measures of influence, Bonacich on power and

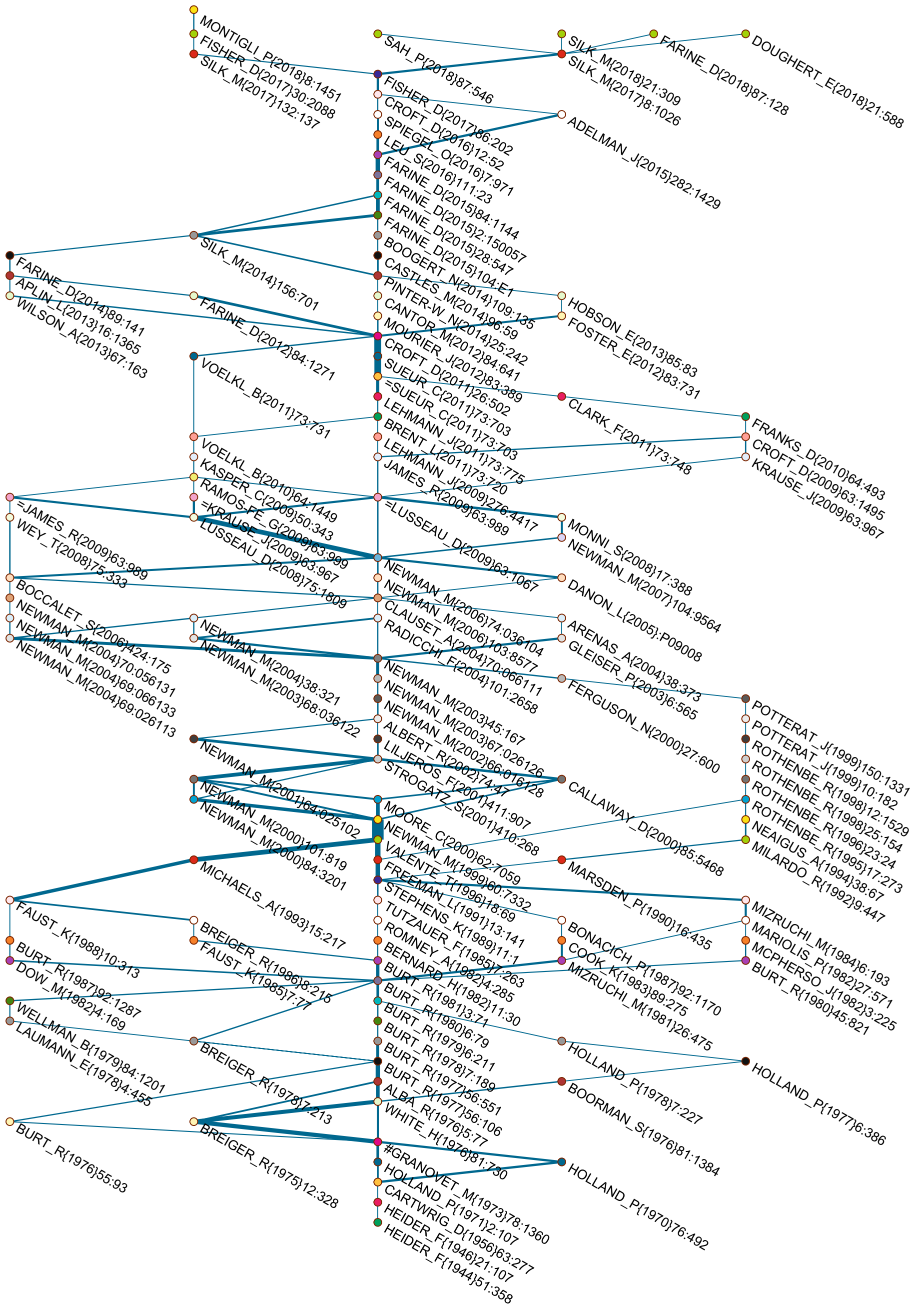

Fig. 7 SPC net: key routes

centrality measures, and Burt, Christman, Kilburn; Mariolis and Jones; Mizruchi on interlocking networks. This is followed by the work of Stephenson and Zelen; and then Freeman, Borgatti, and White on the measures of centrality, published in 1991. The last article is very strongly linked to the work of Valente on social network thresholds in the diffusion of innovations (1996). Another strong link of Valente is the previous work of Michaelson (1993) on the development of a scientific specialty as a diffusion through social relations, which is in turn based on the work of Faust on structural and general equivalences in positional analysis (1988).

The work of Valente is the one bridging the first group of scientists from the social science with the group of physicists, which includes 28 works from the Network science discipline published in the second period (1999–2008). Valente was cited by Newman and Watts in the work on the small-world network model, which appeared in 1999. This work was followed by others on the same topic (small-world networks), written by Newman, also jointly with Moore, as well as by the work of Callaway, Newman, Strogatz, and Watts on random graphs (2000). Then both directions meet at the work of Strogatz on complex networks. This topic continues, including clustering and preferential attachment in growing networks and the spread of epidemic diseases on networks (Newman, 2001, 2002). From 2003 to 2006, this topic redirected to the community detection in large networks.

We should note, however, that there is also an epidemiological branch in the observed network, which starts from the works of Stephenson and Zelen and Freeman, followed by Milardo on personal networks, Neaigus and others, and Rothenberg and others in the works on the disease transmission (1992–1998), Potterat, Rothenberg and Muth, and Potterat and orthers on infection transmission (1999). These works are cited by Ferguson and Garnett (disease transmission), and then the route comes back to the main path—to Newman's work on the structure and function of complex networks (2003).

Since that time, the topics on the obtained Key-routes network have changed significantly. The work of Newman on community structures is strongly linked to the work of Lusseau and Conradt (2009) on animal social networks, which starts the third period (2008–2018) of the SNA literature with 49 works of behavioural ecologists. Lusseau's work was followed by many others, on the same topic: Krause et al. (2009) with general works on animal SNA, and Ramos-Fernandez, Boyer, Aureli, and Vick; Kasper and Voelkl; Voel and Noë; Lehmann and Dunbar; Lehmann and Ross; Brent, Lehmann, and Ramos-Fernández; Sueur and others (2009–2011), working with social networks of Nonhuman Primates. Many of the works in this part are published in special issues "Social Networks: new perspectives" (edited by Krause, Lusseau and James) in *Behavioral Ecology and Sociobiology* journal, and special issue "Social Networks in Primates" in *American Journal of Primatology*. These works are followed by Croft, Madden, Franks, and James (2011), which represents a practical guide to hypothesis testing in animal social networks. This work is cited by others presenting research on mixed-species groups (Farine, Garroway, and Sheldon), killer whales (Foster and others), sharks (Mourier, Vercelloni and Planes), dolphins (Cantor and others), all published in 2012, and birds (Silk, Croft, Tregenza and Bearhop) and starlings (Boogert, Nightingale, Hoppitt and Laland), both published in 2014. There are also works on methodological issues: by Hobson, Avery and Wright (*An analytical framework for quantifying and testing patterns of temporal dynamics in social networks*), Castels and others (*Social networks created with different techniques are not comparable*), and Pinter-Wollman and others (*The dynamics of animal social networks: analytical, conceptual, and theoretical advances*), published in 2013–2014. These works were followed by four works of Farine (jointly with Whitehead, Sheldon, Firth, Aplin, Crates, Culina, Garroway, Radersma and others) published in 2015, on the methodological issues on constructing, conducting and interpreting animal SNA, and study of wild bird territory acquisition. Some of these works cite the article of Silk, Croft, Tregenza and Bearhop (2014) studying social group dynamics in birds. We should also note that there are some works connected to the main path, which represent social personality and phenotype (Wilson, Krause S., Dingemanse, Krause, J.; Alpin and others; Farine), published in 2013–2014.

The upper part of the network contains works published in 2016–2018. It presents studies on disease transmission (Adelman, Moyers, Farine, Hawley; Sah, Mann, Bansal; Silk and others; Dougherty, Seidel, Carlson, Spiegel and Getz), and the studies of animal path tracking (Leu, Farine, Wey, Sih, Bull; Spiegel, Leu, Sih and Bull). Also it contains works on theoretical issues (*Current directions in animal social networks* by Croft, Darden and Wey *Social traits, social networks and evolutionary biology* by Fisher and McAdam) and the implementation of different models of network analysis to animal behaviour research: exponential random graph models and statistical network models (Silk and Fisher), the potential of stochastic actor-oriented models (Fisher, Ilany, Silk and Tregenza), dynamic vs. static SNA (Farine).

A detailed information on the papers (with the information on the first author only) included into the Main path and Key-route paths is presented in Table 3 in "Appendix C".

Link islands

Islands are a very general and efficient approach to determine the "important" subnetworks in a given network. For a given weight on links, a *link island* is a connected subnetwork having higher internal cohesion than the links to its neighbors—it contains a spanning tree in which the smallest weight is larger than the largest weight on links linking the island to its neighbors. Similarly, for a given node property/attribute, a *node island* is a connected subnetwork having a property value on all its nodes higher than on the neighboring nodes. Usually the search is implemented for maximal islands of size (number of nodes) in a given interval [k, K]. For details see (Batagelj et al. 2014, p.54–57).

Using the Islands approach, we searched for SPC link islands with the number of nodes between 10 and 200, and found 5 islands of 138, 65, 13, 12, and 11 nodes. The maximum CPM weights of the islands provide informatin on their importance. The cut-values for the islands are 0.0230 for the island of 138 nodes, 0.0236 for 65 nodes, 0.0008 for 13 nodes. For the islands of 12 and 11 nodes the values are very small—3.51610^{-7} and 2.65210^{-21}, respectively—which shows that they are not so important in comparison to other obtained groups.

The largest, Island 4, with 138 nodes is presented in Fig. 8. Its structure is similar to the structure of the Key-route paths—there are 89 overlapping nodes in two networks. The majority of the works presented in this island (from 1944 to the work of Valente, published in 1996) belong to the social network scientists, whose works were discussed in the previous subsection. In comparison to the Key-routes, this island includes a clearer group of works on blockmodeling—by Faust and Wasserman; Doreian, Batagelj, Ferligoj, Mrvar, and Batagelj, publishing 1992 – 1997. In the physicists part (from Newman, 1999 to Newman, 2006 on the main route) the topic of evolving networks is also presented (Bianconi and Barabási; Yook, Jeong, Barabási, Tu, 2001; Jeong, Néda, Barabási, 2003). The third, behavioural ecologists' subnetwork, is short and finishes with the works on animal social networks published in 2010.

However, this group is fully presented in Island 5, which contains 65 nodes (Fig. 9). It has 39 overlapping nodes with the Key-routes subnetwork. "New" works in the island also belong to the topics on animal social networks described above. However, there are some works devoted to methodological issues of network analysis—reconstructing animal social networks from independent small-group observations (by Perreault,

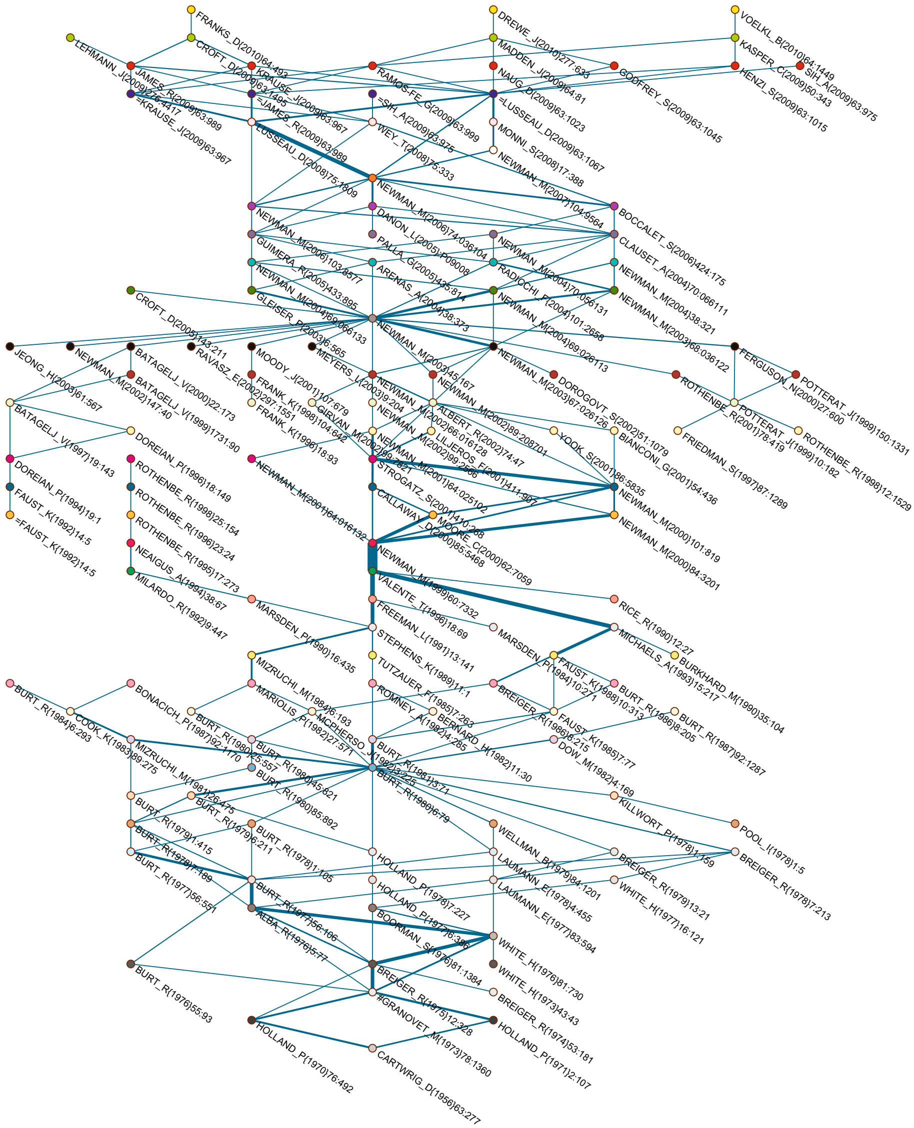

Fig. 8 SPC net: Island 4

published 2010), temporal dynamics and network analysis (by Blonder et al., published 2012), the mining of animal social systems (by Krause et al., published 2013), animal social network inference and permutations for ecologists in R (by Farine, published 2013), estimating the uncertainty and reliability of social network data using Bayesian inference (by Farine and Strandburg-Peshkin, published 2015). It is interesting that this group forms a separate subnetwork, even though it is connected to the upper part of Island 4 by topic. This may mean that the works included in this subnetwork are more connected to each other, while social animal network papers in Island 4 are more strongly connected to the previous works of the physicists.

Other islands are presented in Fig. 10. For the purpose of better visibility, the weights of the links inside of them were multiplied by 100. The left, Island 2, consists of 12 works in the field of social networks in education, including issues of leadership, teacher and student communication and collaboration. Another very coherent group is presented in the same figure on the bottom right. These are 11 works on neuropsychiatry. The upper right island presents 13 works of physicists with the strongest links between the work of Boccaletti and others (2014) on the structure and dynamics of multilayer networks, and others, on the topics of complex, multilayer, dynamic, and temporal networks, as well as the spreading processes in these networks.

Using the Node islands approach, we searched for the node islands in the SPC network of size [10, 200], and found one island of size 200. The works in that island in large part overlap with the works from Islands 4 and 5. This result will be interpreted in “Discussion” section. The obtained works are listed with the code 5 in Table 3.

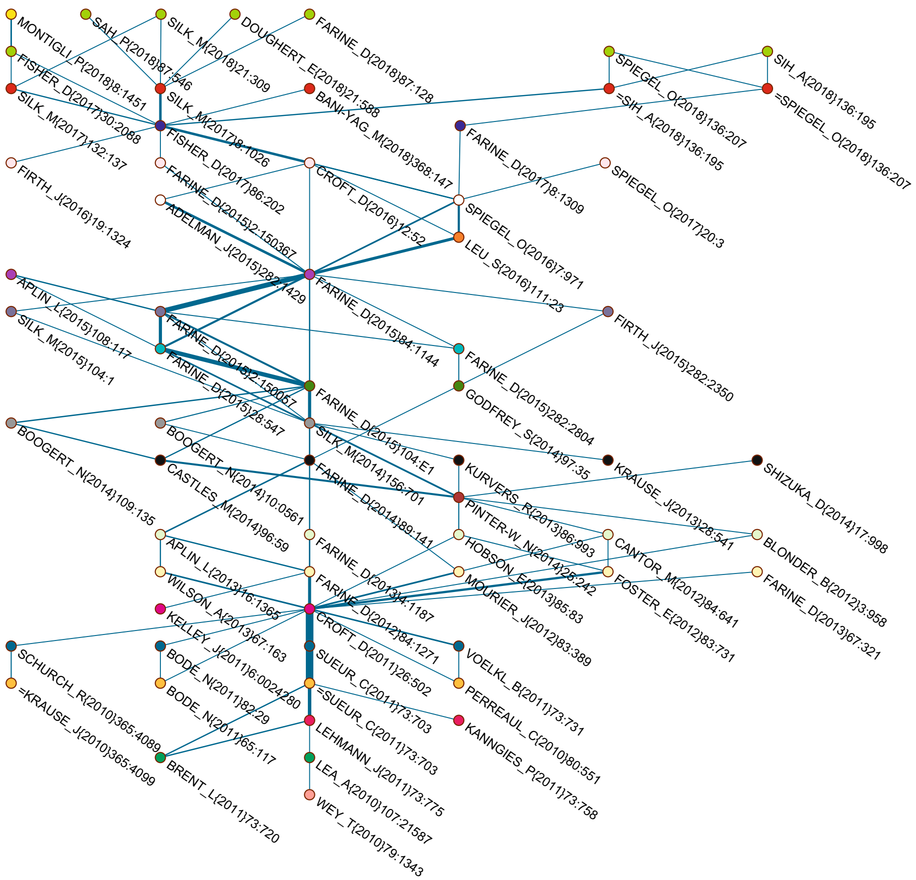

Fig. 9 SPC net: Island 5

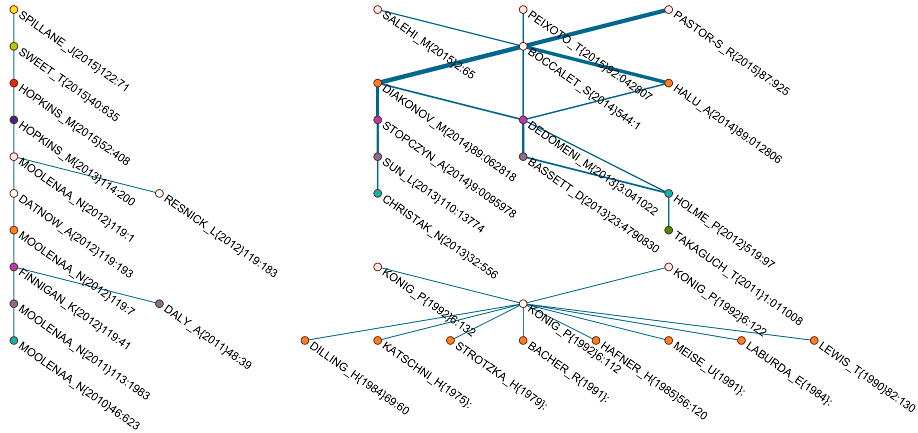

Fig. 10 SPC net: Islands 1–3

Probabilistic flow

The *Probabilistic flow* algorithm (Batagelj et al. 2014, p. 81–82) determines the node index (and the link weight), where the node value is equal to the probability that a random path starting in some initial node reaches this node. While evaluating the importance of an arc/node the SPC method considers the complete citation history, the Probabilistic flow method considers only the recent history. We computed the Probabilistic flow on the **CiteT** network, and determined 200 nodes with the largest values of the probabilistic flow index (with Islands approach). They are presented in Table 3.

The works with largest probability indexes match the list of most cited works (largest indegree values of CiteN network): out of 60 works from Table 2 only 8 works are not present in Table 3. Thus, most of the publications with the largest values of probabilistic flow are already described as the most cited: works of Wasserman and Faust (1994), Watts and Strogatz (1998), Granovetter (1973), Boyd and Ellison (2007), Barabási and Albert (1991), Freeman (1979), Burt (1992), Milgram (1967). Except listed, there are other works of physicists at the top of this distribution: Barabási and Albert (1999), Girvan and Newman (2002), Newman (2003), Albert and Barabási (2002). Works that appeared in the list of 60 top works according to the probabilistic flow weight, which are not in the list of the most cited works, are works of physicists (Strogatz, Watts, Albert, Jeong, Barabási, Redner), computer scientists (Brin, Page, Motwani, Winograd), mathematicians (Bollobás, Thomason), and social scientists (Katz, Mitchell, Glaser).

By contrast, the obtained set of works is quite different from the lists of the most "important" works obtained with the SPC algorithm (main path and key-routes) and the Islands approach. However, there are still some intersections of the works from the Probabilistic flow list with the works from the subnetworks of main path, key-routes, and islands 4 and 5 (see Table 3, "Appendix C").

Discussion

In this article, we used several procedures to extract the most important nodes and parts of the Citation network, obtained from the bibliographic dataset of the SNA literature. Counting the indegree distribution of the Citation network, we listed the 60 most cited works, written mostly by social scientists or physicists. The most cited works from this list belong to Wasserman and Faust, and Granovetter, followed by Watts, Barabási, and Freeman.

Then we used the SPC algorithm to calculate the weights of arcs in the Citation network. On the obtained weighted network, we used different methods for the identification of the main works and groups of works. Using the CPM main path, we obtained a subgroup of 59 works, representing three periods in SNA development: (1) the early and classic period up to the end of the 1990s represented by the works of social scientists on the issues of network structures, positions and blockmodels, measurement and various network metrics; (2) the period of the "physicist invasion" up to the late 2000s, resulting in the Network science, mainly on the topics of small-world and complex networks, and community detection; (3) the period of the "behavioral biologist invasion", studying animal social networks. The works in this group study animal communities, but also the issues of the implementation of general SNA methodological, analytical and theoretical developments, including the temporal and statistical network models, ERGM, SAOM, etc. Key-routes created a subgroup of 127 nodes, having large intersection to the Main path subgroup and following the same divisions to the periods. However, in this subnetwork the group of epidemiological studies on disease transmission is better represented.

In the same weighted SPC network, we searched for link islands – subgroups of nodes having a higher internal cohesion (based on link weights) to each other than to their neighbors. The size of these groups was limited to between 10 and 200 nodes, and we extracted 5 islands of 138 (Island 4), 65 (Island 5), 13, 12 and 11 (Islands 1–3) nodes. The structures of the two largest islands correspond with the subnetwork obtained by the Key-routes algorithm: there are 89 and 39 nodes, respectively, overlapping with the nodes of the Key-routes. Interestingly, Island 4 contains mainly the works of social scientists and physicists, and just a few works of animal SNA, published up to 2010. However, behavioral biologists are fully represented in Island 5. This can give as an idea that there are only a few works in the field of animal networks, which are strongly connected to physicists based on their citations. However, the Main path algorithm forced the nodes to be connected in the network, even if the line weight between some of them is quite low—and this is how we get the main island with the representatives of three scientific fields. Unlike this approach, the Islands approach identifies locally important parts of the network, which should be *distinct* from their neighbourhood. Using this approach, we also found more works on blockmodeling in Island 4, and also found several extra subgroups on the topics of education, neuropsychology, and physics.

Searching for the node islands of the same size [10, 200] – subgroups of nodes having the node SPC weights on all their nodes higher than on the neighboring nodes—we extracted one island of 200 nodes. The works in this island in large part overlapped with the works from the two largest link islands. We suppose that the Island approach was not able to extract subgroups on some topics, as these works did not form separate islands due to their embeddedness in the main island.

Using a Probabilistic flow approach on the SPC weighted network, we identified 200 nodes with the largest values of the probabilistic flow index. The 60 works with the largest index overlap with the list of most cited works. The works with the highest indices, not presented in the most cited works list, come from the fields of physics, computer science, mathematics, and social science.

Overall, there are 14 works appearing in all subnetworks, which belong to several social scientists—Granovetter (1973) on the strength of weak ties, White, Boorman and Breiger (1976) on the blockmodels of roles and positions, and Cartwright and Harary (1956) on structural balance and the generalization of Heider theory, – while the majority of works belong to physicists: Newman, Girvan, Albert, Barabási, Strogatz, Clauset, Moore, Boccaletti (jointly with Latora, Moreno, Chavez, Hwang) on complex networks and community detection. These works can be regarded as the most central works in the SNA literature.

Conclusions

Our study uses the bibliometric approach for studying SNA. We presented only the analysis of the citation network—the distribution of the number of works and citations by years, the most important and influential works and their groups—to answer the questions posed at the beginning.

Is the field still growing? The results show that starting from its institutionalization in the 1980–90s, SNA has grown significantly, both in terms of the number of publications and the number of disciplines involved in the research using the SNA approach. The number of publications shows exponential growth, and on average it doubles every 3 years.

What are the disciplines involved? The analysis confirmed the previous studies on SNA development using citation network analysis. Up to the middle of 1990s the most "important" works belong to social sciences, and starting from the 2000s the field experienced the "invasion of the physicists" leading to the establishment of Network science. To our surprise, from the 2010s both groups experience the "invasion" of scientists from a completely different field—animal SNA. This does not mean that either social scientists or physicists are no longer presented in the field—it means that the new group is more active both in the number of publications and citations of each other.

What are the most important and influential works? In spite of the "invasions", the most cited works still belong to the social scientists—with Wasserman, Faust, and Granovetter on the top. Other highly cited works are from social scientists (Freeman, McPherson, Burt, Coleman, Putnam, Scott, Everett and Borgatti, and others), physicists (Newman, Watts, Barabási, Albert, Girvan, and others), and computer scientists (Boyd, Kleinberg, Blei). The works of physicists are cited by the newly established group of the animal SNA. The reason for this requires further research.

A possible explanation for the appearance of new groups could be due to the algorithms used to identify the main subgroups of the networks. The Main path algorithm *forces* nodes to connect in the network, even if the arc weight between some of them is quite low. The Islands approach identifies locally important parts of the network, which are *distinct* from their neighbourhood. The works on some topics could not form a separate island due to their embeddedness (as a bulge without a peak) in the main island. The further analysis of derived networks (e.g. networks of co-authorship and co-citation between journals and authors) and their temporal analysis should provide a more detailed explanation of the appearance and coexistence of different groups in SNA.

Once again, we should emphasize that for the results of bibliographic network analysis the coverage of the bibliographic databases used in the research is extremely important. An interesting option for the future analysis is a combination of bibliographic data from different databases (such as WoS, Scopus, Google Scholar, and others). The main challenge in this approach is the entity resolution (synonymy/homonyms: works, authors, journals, keywords). This problem would be simplified by the standardization of information stored in bibliographic databases (ORCID, DOI, ISSN, ISBN, etc.).

As the attention of this study is given to the field of SNA, we can register its evolution through time. However, the results clearly show that the idea of network analysis is spreading around different disciplines, as more and more scientists from various scientific fields use the methodology in their research. We can see a shift from *social network analysis* to the *network analysis* in general, where networks being analyzed come from different disciplines. The emergence of the *network science* discipline in natural sciences is a part of this process. However, the studies register a "tension" between social and natural branches of network analysis, that is why we propose that the joint efforts from different directions should be done to merge the separate branches of studies into the whole multidisciplinary field. It can be profitable for all the scientists working with networks to discuss the field's development not in a discourse of "invasions", but in terms of common collaboration and awareness of each other's work.

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A Appendix: Synonymic referencing

Some problems associated with name recognition can occur in the database, when the same work is referred to by different short names. For example, the short names `BOYD_D(2007)13` and `BOYD_D(2008) 13:210` reference the same work of Danah Boyd, originally published in 2007, but in many cases it is referenced as being published in 2008. There were also cases when the short names were different due to discrepancies in the descriptions—such as `GRANOVET_M(1973)78:1360` and `GRANOVET_M(1973)78:6`, or `COLEMAN_J(1988)94:95` and `COLEMAN_J(1988)94:S95`. The names of some authors were presented in a different way—for example, `GRANOVET_M` and `GRANOVET_`. We identified these cases for all works with large indegree frequencies in the Cite network.

To resolve these problems, we have to correct the data. There are two possibilities: (1) to make corrections in the local copy of original data (WoS file) or (2) to make an equivalence partition of nodes and shrink the set of works accordingly in all obtained networks. We used the second option (Batagelj et al. 2014, p.395–399). For the works with large frequencies we prepared lists of possible equivalents and manually determined equivalence classes. With a function in R we produced a Pajek's partition of equivalent work names representing the same work. We used this partition to shrink the networks **Cite**, **WA**, **WJ**, and **WK**. The partitions **year**, **DC** and the vector **NP** were also shrunk.

B Appendix: Strong components

The citation network **CiteB** has 41 nontrivial strong components of different sizes, which are presented in Fig. 11. Different strong components are indicated by node colors. Edges (reciprocal, bidirectional links) are colored in blue, while arcs (directed

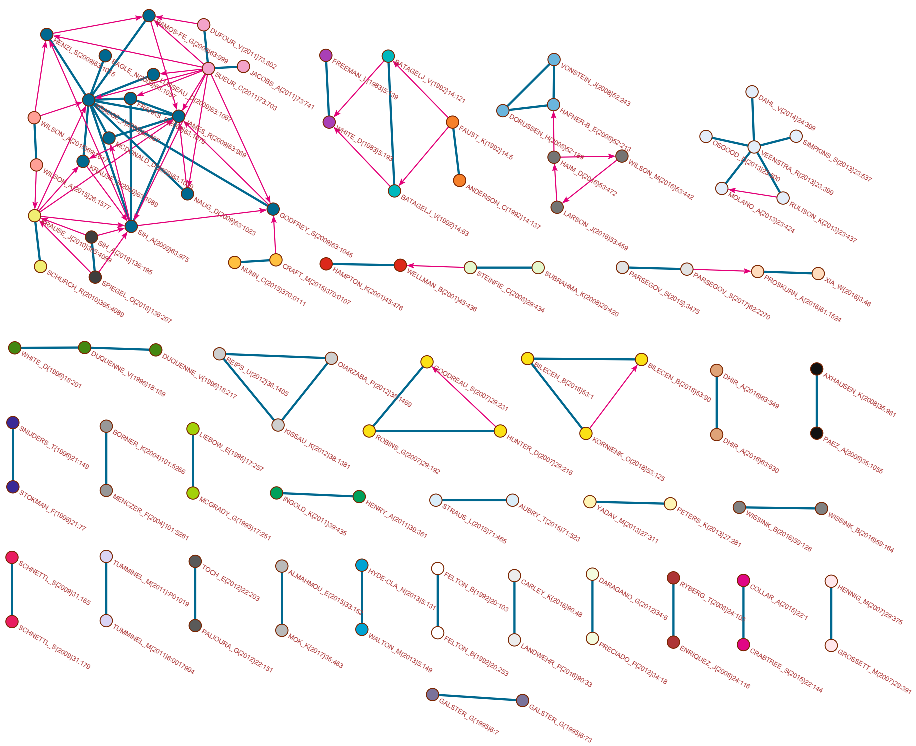

Fig. 11 CiteB net: Strong components

links) are colored in pink. In the majority of cases, mutual referencing between the works is a characteristic of papers published in the same issue of a journal. For example, the first large strong component is combined of 12 works published in a special issue *Social Networks: New Perspectives* in *Behavioral Ecology and Sociobiology* (Volume 63, Issue 7, May 2009). Another example are the works `BATAGELJ_V(1992)14:63` and `BATAGELJ_V(1992)14:121`, and `FAUST_K(1992)14:5` and `ANDERSON_C(1992)14:137` in the special issue on blockmodels in *Social Networks* (Volume 14, Issues 1-2, March-June 1992).

Other cases are connections due to the same author (`TUMMINEL_M(2011):P01019` and `TUMMINEL_M(2011)6:0017994`, `WILSON_A(2015)69:1617` and `WILSON_A(2015)26:1577`, `PARSEGOV_S(2015):3475` and `PARSEGOV_S(2017)62:2270`) or journal (`VEENSTRA_R(2013)23:399` and `DAHL_V(2014)24:399`). However, there are cases when the authors and journals of publications are different (`ALMAHMOU_E(2015)33:152` and `MOK_K(2017)35:463`, `XIA_W(2016) 3:46` and `PROSKURN_A(2016)61:1524`).

C Appendix: Main publications

See Table 3.

Table 3 Citation CiteT net: Overlapping of important subnetworks

Year	Code	Author	Title	Jour or book
1934	6	Moreno JL	Who shall survive: A new approach to the problem of human interrelations	Book
1941	6	Davis A	Deep south: A social anthropological study of caste and class	Book
1944	12	Heider F	Social perception and phenomenal causality	Psychol Rev
1946	12	Heider F	Attitudes and cognitive organization	J Psychol
1948	6	Bavelas A	A mathematical model for group structure	Hum Organ
1950	6	Homans GC	The human group	Book
1951	6	Leavitt HJ	Some effects of certain communication patterns on group performance	J Abnorm Soc Psych
1953	6	Katz L	A new status index derived from sociometric analysis	Psychometrika
1954	6	Barnes JA	Class and committees in a norwegian island parish	Hum Relat
1955	6	Katz E	Personal influence	Book
1956	12456	Cartwright D	Structural balance - a generalization of Heider theory	Psychol Rev
1957	6	Bott E	Family and social network: roles	Book
1958	6	Heider F	The psychology of interpersonal relations	Book
1959	6	Goffman E	The presentation of self in everyday life	Book
1959	6	Erdos P	On random graphs I	Book
1960	6	Erdos P	On the evolution of random graphs	Publ Mat Inst Has
1962	6	Rogers EM	Diffusion of innovations	Book
1965	6	Price DJD	Networks of scientific papers	Science
1965	6	Harary F	Structural models: an introduction to the theory of directed graphs	Book
1965	6	Hubbell CH	An input-output approach to clique identification	Sociometry
1966	6	Sabidussi G	The centrality of a graph	Book
1966	6	Coleman JS	Equality of educational opportunity	Book
1967	6	Glaser BG	The discovery of grounded theory: strategies for qualitative theory	Book
1967	6	Milgram S	The small world problem	Psychol Today
1967	6	Milgram S	The small world problem	Book

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1969	6	Travers J	An experimental study of the small world problem	Book
1969	6	Kauffman S	Metabolic stability and epigenesis in randomly constructed genetic nets	Theoret Biol
1969	6	Mitchell JC	Social networks in urban situations: analyses of personal relationships in central african towns	Book
1970	1245	Holland PW	Method for detecting structure in sociometric data	Amer J Sociol
1970	5	White HC	Search parameters for small world problem	Soc Forces
1970	6	Kernighan BW	An efficient heuristic procedure for partitioning graphs	Book
1971	145	Holland PW	Transitivity in structural models of small groups	Comp Group Stud
1971	6	Lorrain F	Structural equivalence of individuals in social networks	Book
1972	6	Bonacich P	Factoring and weighting approaches to status scores and clique identification	J Math Sociol
1973	12456	Granovetter MS	Strength of weak ties	Amer J Sociol
1973	4	White HC	Everyday life in stochastic networks	Sociol Inq
1973	5	Holland PW	Structural implications of measurement error in sociometry	J Math Sociol
1973	6	Laumann EO	Bonds of pluralism: the form and substance of urban social networks	Book
1974	45	Breiger RL	Duality of persons and groups	Soc Forces
1974	6	Granovetter MS	Getting a job: a study of contacts and careers	Book
1975	1245	Breiger RL	Algorithm for clustering relational data with applications to SNA and comparison with multidimensional-scaling	J Math Psychol
1975	6	Fishbein M	Intention and behavior: an introduction to theory and research	Book
1976	12456	White HC	Social-structure from multiple networks 1 Blockmodels of roles and positions	Amer J Sociol
1976	1245	Alba RD	Intersection of social circles - new measure of social proximity in networks	Sociol Method Res
1976	145	Burt RS	Positions in networks	Soc Forces
1976	145	Boorman SA	Social-structure from multiple networks 2 Role structures	Amer J Sociol
1977	1245	Burt RS	Positions in multiple network systems 1 General conception of stratification and prestige in a system of actors cast as a social topology	Soc Forces
1977	1245	Burt RS	Positions in multiple network systems 2 Stratification and prestige among elite decision-makers in community of altneustadt	Soc Forces

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1977	145	Holland PW	Social-structure as a network process	Z Soz
1977	45	Laumann EO	Community-elite influence structures - extension of a network approach	Amer J Sociol
1977	45	White HC	Probabilities of homomorphic mappings from multiple graphs	J Math Psychol
1977	6	Freeman LC	Set of measures of centrality based on betweenness	Sociometry
1977	6	Zachary WW	An information flow model for conflict and fission in small groups	Book
1978	1245	Burt RS	Cohesion versus structural equivalence as a basis for network subgroups	Sociol Method Res
1978	145	Holland PW	Omnibus test for social-structure using triads	Sociol Method Res
1978	145	Laumann EO	Community structure as interorganizational linkages	Annu Rev Sociol
1978	145	Breiger RL	Joint role structure of 2 communities elites	Sociol Method Res
1978	456	Pool ID	Contacts and influence	Soc Networks
1978	45	Killworth PD	Reversal small-world experiment	Soc Networks
1978	45	Burt RS	Stratification and prestige among elite experts in methodological and mathematical sociology circa 1975	Soc Networks
1978	6	Granovetter M	Threshold models of collective behavior	Am J Sociol
1979	1245	Burt RS	Relational equilibrium in a social topology	J Math Sociol
1979	145	Wellman B	Community question - intimate networks of east yorkers	Amer J Sociol
1979	45	Breiger RL	Toward an operational theory of community elite structures	Qual Quant
1979	45	Burt RS	Structural theory of interlocking corporate directorates	Soc Networks
1979	6	Freeman LC	Centrality in social networks conceptual clarification	Soc Networks
1979	6	Berkman LF	Social networks, host-resistance, and mortality—9-year follow-up-study of alameda county residents	Amer J Epidemiol
1979	6	Garey MR	Computers and intractability: a guide to the theory of NP-completeness	Book
1980	1245	Burt RS	Models of network structure	Annu Rev Sociol
1980	1245	Burt RS	Testing a structural theory of corporate cooptation—interorganizational directorate ties as a strategy for avoiding market constraints on profits	Amer Sociol Rev
1980	45	Burt RS	Cooptive corporate actor networks—a reconsideration of interlocking directorates involving American manufacturing	Admin Sci Quart
1980	45	Burt RS	Autonomy in a social topology	Amer J Sociol

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1981	145	Mizruchi MS	Influence in corporate networks—an examination of 4 measures	Admin Sci Quart
1981	145	Burt RS	A note on inferences regarding network subgroups	Soc Networks
1981	6	Holland PW	An exponential family of probability-distributions for directed-graphs	J Amer Statist Assn
1981	6	Feld SL	The focused organization of social ties	Am J Sociol
1982	1245	Mcpherson JM	Hypernetwork sampling—duality and differentiation among voluntary organizations	Soc Networks
1982	1245	Mariolis P	Centrality in corporate interlock networks - reliability and stability	Admin Sci Quart
1982	145	Bernard HR	Informant accuracy in social-network data 5 An experimental attempt to predict actual communication from recall data	Soc Sci Res
1982	145	Romney AK	Predicting the structure of a communications network from recalled data	Soc Networks
1982	145	Dow MM	Network auto-correlation—a simulation study of a foundational problem in regression and survey-research	Soc Networks
1982	6	Fischer CS	To dwell among friends: personal networks in town and city	Book
1982	6	Burt RS	Toward a structural theory of action: network models of social structure, perception and action	Book
1983	145	Cook KS	The distribution of power in exchange networks - theory and experimental results	Am J Sociol
1983	6	Granovetter M	The strength of weak ties: a network theory revisited	Sociol Theory
1983	6	Salton G	introduction to modern information retrieval	Book
1984	1245	Mizruchi MS	Interlock groups, cliques, or interest-groups - comment	Soc Networks
1984	45	Burt RS	Network items and the general social survey	Soc Networks
1984	45	Marsden PV	Mathematical ideas in social structural-analysis	J Math Sociol
1984	6	Lazarus R	Stress, appraisal, and coping	Book
1984	6	Axelrod R	The evolution of cooperation	Book
1984	6	Kuramoto Y	Chemical oscillations, waves, and turbulence	Book
1985	145	Faust K	Does structure find structure—a critique of burt use of distance as a measure of structural equivalence	Soc Networks
1985	145	Tutzauer F	Toward a theory of disintegration in communication-networks	Soc Networks
1985	6	Cohen S	Stress, social support, and the buffering hypothesis	Psychol Bull
1985	6	Granovetter M	Economic-action and social-structure—the problem of embeddedness	Amer J Sociol

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1985	6	Bollobas B	Random graphs	Book
1986	145	Breiger RL	Cumulated social roles—the duality of persons and their algebras	Soc Networks
1986	45	Burt RS	A cautionary note	Soc Networks
1986	6	Bourdieu P	The forms of capital	Book
1986	6	Baron RM	The moderator mediator variable distinction in social psychological-research—conceptual, strategic, and statistical considerations	J Personal Soc Psychol
1986	6	Bandura A	Social foundations of thought and action: a social cognitive theory	Book
1987	1456	Bonacich P	Power and centrality—a family of measures	Amer J Sociol
1987	145	Burt RS	Social contagion and innovation—cohesion versus structural equivalence	Amer J Sociol
1988	145	Faust K	Comparison of methods for positional analysis—structural and general equivalences	Soc Networks
1988	6	House JS	Social relationships and health	Science
1988	6	Coleman JS	Social capital in the creation of human capital	Am Jour Soc
1988	6	Wellman B	Social structures: a network approach	Book
1989	1245	Stephenson K	Rethinking centrality—methods and examples	Soc Networks
1989	6	Kamada T	An algorithm for drawing general undirected graphs	Inform Process Lett
1989	6	Davis FD	Perceived usefulness, perceived ease of use, and user acceptance of information technology	Mis Quart
1989	6	Kochen M	The small world	Book
1990	1456	Marsden PV	Network data and measurement	Annu Rev Sociol
1990	4	Burkhardt ME	Changing patterns or patterns of change—the effects of a change in technology on soc. netw. structure and power	Admin Sci Quart
1990	4	Rice RE	Individual and network influences on the adoption and perceived outcomes of electronic messaging	Soc Networks
1990	6	ColemanJ.	Foundations of social theory	Book
1990	6	Guare J	Six degrees of separation: a play	Book
1990	6	Deerwester S	Indexing by latent semantic analysis	J Am Soc Inf Sci Tec
1991	1245	Freeman LC	Centrality in valued graphs—a measure of betweenness based on network flow	Soc Networks
1991	6	Ajzen I	The theory of planned behavior	Organ Behav Hum Dec

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1991	6	Scott J	Social network analysis: a handbook	Book
1991	6	Lave J	Situated learning: legitimate peripheral participation	Book
1991	6	Fruchterman TMJ	Graph drawing by force-directed placement	Software Pract Exper
1992	145	Milardo RM	Comparative methods for delineating social networks	J Soc Person Relat
1992	45	Faust K	Blockmodels - interpretation and evaluation	Soc Networks
1992	5	Batagelj V	Direct and indirect methods for structural equivalence	Soc Networks
1992	5	Batagelj V	An optimizational approach to regular equivalence	Soc Networks
1992	6	Burt RS	Structural holes: the social structure of competition	Book
1992	6	Nowak MA	Evolutionary games and spatial chaos	Nature
1993	145	Michaelson AG	The development of a scientific specialty as diffusion through social-relations—the case of role analysis	Soc Networks
1993	6	Putnam RD	Making democracy work: civic institutions in modern italy	Book
1993	6	Padgett JF	Robust action and the rise of the medici, 1400-1434	Amer J Sociol
1993	6	Manski CF	Identification of endogenous social effects—the reflection problem	Rev Econ Stud
1993	6	Ahuja RK	Network flows: theory, algorithms, and applications	Book
1994	145	Neaigus A	The relevance of drug injectors social and risk networks for understanding and preventing hiv-infection	Soc Sci Med
1994	45	Doreian P	Partitioning networks based on generalized concepts of equivalence	J Math Sociol
1994	6	Wasserman S	Social network analysis: methods and applications	Book
1995	145	Rothenberg RB	Choosing a centrality measure—epidemiologic correlates in the colorado-springs study of social networks	Soc Networks
1995	6	Molloy M	A critical-point for random graphs with a given degree sequence	Random Struct Algor
1995	6	Rogers EM	Diffusion of Innovation. 4th	Book
1995	6	Granovetter MS	Getting a Job: A Study of Contacts and Careers	Book
1995	6	Nonaka I	The knowledge creation company: how Japanese companies create the dynamics of innovation	Book
1995	6	Putnam RD	Bowling Alone: America's Declining Social Capital. An Interview with Robert Putnam	J Democr
1996	1245	Valente TW	Social network thresholds in the diffusion of innovations	Soc Networks
1996	145	Rothenberg R	The relevance of social network concepts to sexually transmitted disease control	Sex Transm Dis

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1996	45	Doreian P	A partitioning approach to structural balance	Soc Networks
1996	4	Frank KA	Mapping interactions within and between cohesive subgroups	Soc Networks
1996	6	Wasserman S	Logit models and logistic regressions for social networks 1. An introduction to Markov graphs and p	Psychometrika
1996	6	Kretzschmar M	Measures of concurrency in networks and the spread of infectious disease	Math Biosci
1997	45	Friedman SR	Sociometric risk networks and risk for HIV infection	Amer J Public Health
1997	45	Batagelj V	Notes on blockmodeling	Soc Networks
1997	6	Uzzi B	Social structure and competition in interfirm networks: The paradox of embeddedness	Admin Sci Quart
1998	145	Rothenberg RB	Social network dynamics and HIV transmission	Aids
1998	14	Rothenberg RB	Using social network and ethnographic tools to evaluate syphilis transmission	Sex Transm Dis
1998	45	Frank KA	Linking action to social structure within a system: Social capital within and between subgroups	Amer J Sociol
1998	6	Watts DJ	Collective dynamics of ’small-world’ networks	Nature
1998	6	Portes A	Social Capital: Its origins and applications in modern sociology	Annu Rev Sociol
1998	6	Nahapiet J	Social capital, intellectual capital, and the organizational advantage	Acad Manage Rev
1998	6	Redner S	How popular is your paper? An empirical study of the citation distribution	Book
1998	6	Wenger E	Communities ofpractice: Learning, meaning, and identity	Book
1998	6	Page L	The pagerank citation ranking: Bringing order to the web.	Book
1998	6	Brin S	The anatomy of a large-scale hypertextual Web search engine	Comput Networks ISDN
1998	6	Huberman B	Strong regularities in world wide web surfing	Science
1999	1245	Newman MEJ	Scaling and percolation in the small-world network model	Phys Rev E
1999	145	Potterat JJ	Chlamydia transmission: Concurrency, reproduction number, and the epidemic trajectory	Amer J Epidemiol
1999	145	Potterat JJ	Network structural dynamics acid infectious disease propagation	Int J Std Aids
1999	45	Batagelj V	Partitioning approach to visualization of large graphs	Lect Note Comput Sci
1999	6	Barabási AL	Emergence of scaling in random networks	Science
1999	6	Hansen MT	The search-transfer problem: The role of weak ties in sharing knowledge across organization subunits	Admin Sci Quart
1999	6	Faloutsos M	On power-law relationships of the internet topology	Book

Table 3 (continued)

Year	Code	Author	Title	Jour or book
1999	6	Watts DJ	Small Worlds: The Dynamics of Networks Between Order and Randomness	Book
1999	6	Barabási AL	Mean-field theory for scale-free random networks	Physica A
1999	6	Albert R	Internet—Diameter of the World-Wide Web	Nature
1999	6	Banavar JR	Size and form in efficient transportation networks. Nature,	Nature
1999	6	Kleinberg JM	Authoritative sources in a hyperlinked environment	J ACM
1999	6	Haberman B	Internet: growth dynamics of the world-wide web	Nature
1999	6	Lawrence S	Accessibility of information on the Web.	Nature
1999	6	Barthélémy M	Small-world networks: Evidence for a crossover picture	Phys Rev Lett
2000	1245	Newman MEJ	Models of the small world	J Statist Phys
2000	1245	Moore C	Exact solution of site and bond percolation on small-world networks	Phys Rev E
2000	145	Callaway DS	Network robustness and fragility: Percolation on random graphs	Phys Rev Lett
2000	145	Newman MEJ	Mean-field solution of the small-world network model	Phys Rev Lett
2000	145	Ferguson NM	More realistic models of sexually transmitted disease transmission dynamics—Sexual partnership networks, pair models, and moment closure	Sex Transm Dis
2000	45	Batagelj V	Some analyses of Erdos collaboration graph	Soc Networks
2000	6	Putnam RD	Bowling alone: America's declining social capital	Book
2000	6	Jeong H	The large-scale organization of metabolic networks	Nature
2000	6	Berkman LF	From social integration to health: Durkheim in the new millennium	Soc Sci Med
2000	6	Albert R	Error and attack tolerance of complex networks	Nature
2000	6	Amaral LAN	Classes of small-world networks	Proc Nat Acad Sci USA
2000	6	Broder A	Graph structure in the Web	Comput Netw
2000	6	Scott J	Social Network Analysis: A Handbook	Book
2000	6	Shi JB	Normalized cuts and image segmentation	IEEE T Pattern Anal
2001	12456	Newman MEJ	Clustering and preferential attachment in growing networks	Phys Rev E
2001	12456	Strogatz SH	Exploring complex networks	Nature
2001	145	Liljeros F	The web of human sexual contacts	Nature

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2001	456	Newman MEJ	Scientific collaboration networks. II. Shortest paths, weighted networks, and centrality	Phys Rev E
2001	45	Moody J	Race, school integration, and friendship segregation in America	Amer J Sociol
2001	45	Rothenberg R	The risk environment for HIV transmission: Results from the Atlanta and Flagstaff network studies	J Urban Health
2001	4	Yook SH	Weighted evolving networks	Phys Rev Lett
2001	4	Bianconi G	Competition and multiscaling in evolving networks	Europhys Lett
2001	6	Mcpherson M	Birds of a feather: Homophily in social networks	Annu Rev Sociol
2001	6	Newman MEJ	The structure of scientific collaboration networks	Proc Nat Acad Sci USA
2001	6	Lin N	Social capital. A theory of social structure and action.	Book
2001	6	Brandes U	A faster algorithm for betweenness centrality	J Math Sociol
2001	6	Domingos P	Mining the network value of customers	Book
2001	6	Goldenberg J	Talk of the network: A complex systems look at the underlying process of word-of-mouth	Mark Lett
2001	6	Pastor-Satorras R	Epidemic spreading in scale-free networks	Phys Rev Lett
2002	12456	Albert R	Statistical mechanics of complex networks	Rev Mod Phys
2002	12456	Newman MEJ	Spread of epidemic disease on networks	Phys Rev E
2002	456	Girvan M	Community structure in social and biological networks	Proc Nat Acad Aci USA
2002	456	Newman MEJ	Assortative mixing in networks	Phys Rev Lett
2002	45	Dorogovtsev SN	Evolution of networks	Adv Phys
2002	45	Newman MEJ	Random graph models of social networks	Proc Nat Acad Sci USA
2002	4	Ravasz E	Hierarchical organization of modularity in metabolic networks	Science
2002	4	Newman MEJ	The structure and function of networks	Comput Phys Commun
2002	6	Watts DJ	Identity and search in social networks	Science
2002	6	Barabási AL	Linked: The New Science Of Networks	Book
2002	6	Barabási AL	Evolution of the social network of scientific collaborations	Physica A
2002	6	Adler PS	Social capital: Prospects for a new concept	Acad Manage Rev
2002	6	Otte E	Social network analysis: a powerful strategy, also for the information sciences	J Inform Sci

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2002	6	Richardson M	Mining knowledge-sharing sites for viral marketing	Book
2003	12456	Newman MEJ	The structure and function of complex networks	SIAM Rev
2003	12456	Newman MEJ	Mixing patterns in networks	Phys Rev E
2003	145	Newman MEJ	Why social networks are different from other types of networks	Phys Rev E
2003	145	Gleiser PM	Community structure in jazz	Adv Complex Syst
2003	45	Meyers LA	Applying network theory to epidemics: Control measures for Mycoplasma pneumoniae outbreaks	Emerg Infect Dis
2003	4	Jeong H	Measuring preferential attachment in evolving networks	Europhys Lett
2003	56	Guimera R	Self-similar community structure in a network of human interactions	Phys Rev E
2003	6	Rogers EM	Diffusion of innovations	Book
2003	6	Borgatti SP	The network paradigm in organizational research: A review and typology	J Manage
2003	6	Dorogovtsev SN	Evolution of Networks: From Biological Nets to the Internet and WWW	Book
2003	6	Watts DJ	Six Degrees: The Science of a Connected Age	Book
2003	6	Blei DM	Latent Dirichlet allocation	J Mach Learn Res
2003	6	Adamic LA	Friends and neighbors on the Web	Soc Networks
2003	6	Lusseau D	The bottlenose dolphin community of Doubtful Sound features a large proportion of long-lasting associations—Can geographic isolation explain this unique trait?	Behav Ecol Sociobiol
2003	6	Venkatesh V	User acceptance of information technology: Toward a unified view	Mis Quart
2003	6	Kempe D	Maximizing the spread of influence through a social network	ACM Sigkdd Conf
2003	6	Kempe D	Maximizing the spread of influence through a social network	ACM Sigkdd Conf
2004	12456	Newman MEJ	Finding and evaluating community structure in networks	Phys Rev E
2004	12456	Newman MEJ	Detecting community structure in networks	Eur Phys J B
2004	12456	Clauset A	Finding community structure in very large networks	Phys Rev E
2004	1456	Radicchi F	Defining and identifying communities in networks	P Natl Acad Aci USA
2004	1456	Newman MEJ	Fast algorithm for detecting community structure in networks	Phys Rev E
2004	145	Arenas A	Community analysis in social networks	Eur Phys J B
2004	145	Newman MEJ	Analysis of weighted networks	Phys Rev E

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2004	6	Cross RL	The hidden power of social networks: Understanding how work really gets done in organizations	Book
2004	6	Freeman LC	The development of social network analysis. A Study in the Sociology of Science	Book
2004	6	Eubank S	Modelling disease outbreaks in realistic urban social networks	Nature
2004	6	Burt RS	Structural holes and good ideas	Amer J Sociol
2005	145	Danon L	Comparing community structure identification	J Stat Mech-Theory E
2005	456	Guimera R	Functional cartography of complex metabolic networks	Nature
2005	456	Palla G	Uncovering the overlapping community structure of complex networks in nature and society	Nature
2005	4	Croft DP	Assortative interactions and social networks in fish	Oecologia
2005	6	Burt RS	Brokerage and closure: An introduction to social capital	Book
2005	6	Adomavicius G	Toward the next generation of recommender systems: A survey of the state-of-the-art and possible extensions	Book
2005	6	Carrington P	Models and Methods in Social Network Analysis	Book
2005	6	Borgatti SP	Centrality and network flow	Soc Networks
2005	6	Gross R	Information revelation and privacy in online social networks	Book
2006	12456	Boccaletti S	Complex networks: Structure and dynamics	Phys Rep-Rev Sect Phys Lett
2006	12456	Newman MEJ	Finding community structure in networks using the eigenvectors of matrices	Phys Rev E
2006	1456	Newman MEJ	Modularity and community structure in networks	Proc Nat Acad Sci USA
2006	6	Kossinets G	Empirical analysis of an evolving social network	Science
2006	6	Newman M	The Structure and Dynamics of Networks	Book
2006	6	Eagle N	Reality mining: sensing complex social systems	Pers Ubiquit Comput
2007	145	Newman MEJ	Mixture models and exploratory analysis in networks	Proc Nat Acad Sci USA
2007	5	Krause J	Social network theory in the behavioural sciences: potential applications	Behav Ecol Sociobiol
2007	6	Onnela JP	Structure and tie strengths in mobile communication networks	Proc Nat Acad Sci USA
2007	6	Palla G	Quantifying social group evolution	Nature
2007	6	Christakis NA	The spread of obesity in a large social network over 32 years	N Engl J Med

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2007	6	Mazer JP	I'll see you on Facebook: The effects of computer-mediated teacher self-disclosure on student motivation, affective learning, and classroom climate	Book
2007	6	Liben-Nowell D	The link-prediction problem for social networks	J Am Soc Inf Sci Technol
2007	6	Robins G	An introduction to exponential random graph (p*) models for social networks	Soc Networks
2007	6	Fortunato S	Resolution limit in community detection	Proc Nat Acad Sci USA
2007	6	Boyd DM	Social network sites: Definition, history, and scholarship	J Comput-Mediat Comm
2007	6	Raghavan UN	Near linear time algorithm to detect community structures in large-scale networks	Phys Rev E
2007	6	Mislove A	Measurement and Analysis of Online Social Networks	Book
2007	6	Leskovec J	Cost-effective Outbreak Detection in Networks	Book
2007	6	Josang A	A survey of trust and reputation systems for online service provision	Decis Support Syst
2007	6	Steinfield C	The benefits of Facebook friends: Social capital and college students' use of online social network sites.	J Comput-Mediat Comm
2007	6	Dwyer C	Trust and privacy concern within social networking sites: A comparison of Facebook and MySpace.	Amcis 2007 Proc
2007	6	Lenhart A	Teens, Privacy and online social networks: how teens manage their online identities and personal information in the age of Myspace	Book
2007	6	Ellison NB	The benefits of Facebook friends: Social capital and college students' use of online social network sites	J Comput-Mediat Comm
2008	1245	Lusseau D	Incorporating uncertainty into the study of animal social networks	Anim Behav
2008	145	Wey T	Social network analysis of animal behaviour: a promising tool for the study of sociality	Anim Behav
2008	145	Monni S	Vertex clustering in random graphs via reversihle jump Markov chain Monte Carlo	J Comput Graph Stat
2008	6	Blondel VD	Fast unfolding of communities in large networks	J Stat Mech-Theory E
2008	6	Smith KP	Social networks and health	Annu Rev Sociol
2008	6	Gonzalez MC	Understanding individual human mobility patterns	Nature
2008	6	Christakis NA	The collective dynamics of smoking in a large soc.l netw.	New Engl J Med
2008	6	Fowler JH	Dynamic spread of happiness in a large soc. netw.: longit. analysis over 20 years in the Framingham Heart Study	Brit Med J
2009	1245	Kasper C	A social network analysis of primate groups	Primates
2009	1245	Ramos-FernandezG	Association networks in spider monkeys (Ateles geoffroyi)	Behav Ecol Sociobiol

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2009	1245	Lusseau D	The emergence of unshared consensus decisions in bottlenose dolphins	Behav Ecol Sociobiol
2009	145	Croft DP	Behavioural trait assortment in a social network: patterns and implications	Behav Ecol Sociobiol
2009	145	James R	Potential banana skins in animal social network analysis	Behav Ecol Sociobiol
2009	145	Krause J	Animal social networks: an introduction	Behav Ecol Sociobiol
2009	145	James R	Potential banana skins in animal social network analysis	Behav Ecol Sociobiol
2009	145	Krause J	Animal social networks: an introduction	Behav Ecol Sociobiol
2009	14	Lehmann J	Network cohesion, group size and neocortex size in female-bonded Old World primates	P Roy Soc B-Biol Sci
2009	45	Godfrey SS	Network structure and parasite transmission in a group living lizard, the gidgee skink, Egernia stokesii	Behav Ecol Sociobiol
2009	45	Sih A	Social network theory: new insights and issues for behavioral ecologists	Behav Ecol Sociobiol
2009	45	Naug D	Structure and resilience of the social network in an insect colony as a function of colony size	Behav Ecol Sociobiol
2009	45	Madden JR	The social network structure of a wild meerkat population: 2. Intragroup interactions	Behav Ecol Sociobiol
2009	45	Henzi SP	Cyclicity in the structure of female baboon social networks	Behav Ecol Sociobiol
2009	45	Sih A	Social network theory: new insights and issues for behavioral ecologists	Behav Ecol Sociobiol
2009	5	Mcdonald DB	Young-boy networks without kin clusters in a lek-mating manakin	Behav Ecol Sociobiol
2009	6	Pempek TA	College students' social networking experiences on Facebook	J Appl Dev Psychol
2009	6	Borgatti SP	Network Analysis in the Social Sciences	Science
2009	6	Chen W	Efficient Influence Maximization in Social Networks	Book
2009	6	Clauset A	Power-Law Distributions in Empirical Data	SIAM Rev
2009	6	Eagle N	Inferring friendship network structure by using mobile phone data	P Natl Acad Sci USA
2010	1245	Voelkl B	Simulation of information propagation in real-life primate networks: longevity, fecundity, fidelity	Behav Ecol Sociobiol
2010	145	Franks DW	Sampling animal association networks with the gambit of the group	Behav Ecol Sociobiol
2010	45	Drewe JA	Who infects whom? Social networks and tuberculosis transmission in wild meerkats	P Roy Soc B-Biol Sci
2010	35	Lea AJ	Heritable victimization and the benefits of agonistic relationships	P Natl Acad Sci USA
2010	35	Wey TW	Social cohesion in yellow-bellied marmots is established through age and kin structuring	Anim Behav
2010	35	Schurch R	The building-up of social relationships: behavioural types, social networks and cooperative breeding in a cichlid	Philos T R Soc B

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2010	35	Perreault C	A note on reconstructing animal social networks from independent small-group observations	Anim Behav
2010	35	Krause J	Personality in the context of social networks	Philos T R Soc B
2010	6	Fortunato S	Community detection in graphs	Phys Rep
2010	6	Kaplan AM	Users of the world, unite! The challenges and opportunities of Social Media	Bus Horizons
2010	6	Centola D	The Spread of Behavior in an Online Social Network Experiment	Science
2010	6	Roblyer MD	Findings on Facebook in higher education: A comparison of college faculty and student uses and perceptions of social networking sites	Internet High Educ
2011	1235	Croft DP	Hypothesis testing in animal social networks	Trends Ecol Evol
2011	1235	Brent LJN	Social Network Analysis in the Study of Nonhuman Primates: A Historical Perspective	Am J Primatol
2011	1235	Sueur C	How Can Social Network Analysis Improve the Study of Primate Behavior?	Am J Primatol
2011	1235	Lehmann J	Baboon (Papio anubis) Social Complexity-A Network Approach	Am J Primatol
2011	1235	Sueur C	How Can Social Network Analysis Improve the Study of Primate Behavior?	Am J Primatol
2011	135	Voelkl B	Network Measures for Dyadic Interactions: Stability and Reliability	Am J Primatol
2011	1	Clark FE	Space to Choose: Network Analysis of Social Preferences in a Captive Chimpanzee Community, and Implications for Management	Am J Primatol
2011	35	Bode NWF	Soc.l netw. and models for collective motion in animals	Behav Ecol Sociobiol
2011	35	Kanngiesser P	Grooming Network Cohesion and the Role of Individuals in a Captive Chimpanzee Group	Am J Primatol
2011	35	Bode NWF	The impact of social networks on animal collective motion	Anim Behav
2011	6	Kietzmann JH	Social media? Get serious! Understanding the functional building blocks of social media	Bus Horizons
2011	3	Kelley JL	Predation Risk Shapes Social Networks in Fission-Fusion Populations	Plos One
2012	1235	Farine DR	Social network analysis of mixed-species flocks: exploring the structure and evolution of interspecific social behaviour	Anim Behav
2012	135	Mourier J	Evidence of social communities in a spatially structured network of a free-ranging shark species	Anim Behav
2012	135	Cantor M	Disentangling social networks from spatiotemporal dynamics: the temporal structure of a dolphin society	Anim Behav
2012	135	Foster EA	Social network correlates of food availability in an endangered population of killer whales, Orcinus orca	Anim Behav
2012	35	Blonder B	Temporal dynamics and network analysis	Methods Ecol Evol

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2013	1235	Aplin LM	Individual personalities predict social behaviour in wild networks of great tits (Parus major)	Ecol Lett
2013	135	Wilson ADM	Network position: a key component in the characterization of social personality types	Behav Ecol Sociobiol
2013	135	Hobson EA	An analytical framework for quantifying and testing patterns of temporal dynamics in social networks	Anim Behav
2013	35	Farine DR	Animal social network inference and permutations for ecologists in R using asnipe	Methods Ecol Evol
2013	35	Krause J	Reality mining of animal social systems	Trends Ecol Evol
2013	35	Kurvers RHJM	Contrasting context dependence of familiarity and kinship in animal social networks	Anim Behav
2013	35	Farine DR	Social organisation of thornbill-dominated mixed-species flocks using social network analysis	Behav Ecol Sociobiol
2014	1235	Farine DR	Measuring phenotypic assortment in animal social networks: weighted associations are more robust than binary edges	Anim Behav
2014	1235	Silk MJ	The importance of fission-fusion social group dynamics in birds	Ibis
2014	135	Pinter-Wollman N	The dynamics of animal social networks: analytical, conceptual, and theoretical advances	Behav Ecol
2014	135	Castles M	Social networks created with different techniques are not comparable	Anim Behav
2014	135	Boogert NJ	Perching but not foraging networks predict the spread of novel foraging skills in starlings	Behav Process
2014	35	Boogert NJ	Developmental stress predicts social network position	Biol Letters
2014	35	Godfrey SS	A contact-based social network of lizards is defined by low genetic relatedness among strongly connected individuals	Anim Behav
2014	3	Shizuka D	Across-year social stability shapes network structure in wintering migrant sparrows	Ecol Lett
2015	1235	Farine DR	Constructing, conducting and interpreting animal social network analysis	J Anim Ecol
2015	1235	Farine DR	Selection for territory acquisition is modulated by social network structure in a wild songbird	J Evolution Biol
2015	1235	Farine DR	The role of social and ecological processes in structuring animal populations: a case study from automated tracking of wild birds	Roy Soc Open Sci
2015	1235	Farine DR	Proximity as a proxy for interactions: issues of scale in social network analysis	Anim Behav
2015	135	Adelman JS	Feeder use predicts both acquisition and transmission of a contagious pathogen in a North American songbird	P Roy Soc B-Biol Sci
2015	35	Silk MJ	The consequences of unidentifiable individuals for the analysis of an animal social network	Anim Behav
2015	35	Aplin LM	Consistent individual differences in the social phenotypes of wild great tits, Parus major	Anim Behav

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2015	35	Farine DR	Estimating uncertainty and reliability of social network data using Bayesian inference	Roy Soc Open Sci
2015	35	Firth JA	Experimental manipulation of avian social structure reveals segregation is carried over across contexts	P Roy Soc B-Biol Sci
2015	35	Farine DR	Interspecific social networks promote information transmission in wild songbirds	P Roy Soc B-Biol Sci
2016	1235	Spiegel O	Socially interacting or indifferent neighbours? Randomization of movement paths to tease apart social preference and spatial constraints	Methods Ecol Evol
2016	1235	Croft DP	Current directions in animal social networks	Curr Opin Behav Sci
2016	1235	Leu ST	Environment modulates population social structure: experimental evidence from replicated social networks of wild lizards	Anim Behav
2016	35	Firth JA	Social carry-over effects underpin trans-seasonally linked structure in a wild bird population	Ecol Lett
2016	5	Jacoby DMP	Emerging Network-Based Tools in Movement Ecology	Trends Ecol Evol
2017	1235	Fisher DN	Analysing animal social network dynamics: the potential of stochastic actor-oriented models	J Anim Ecol
2017	1235	Silk MJ	Understanding animal social structure: exponential random graph models in animal behaviour research	Anim Behav
2017	1235	Fisher DN	Social traits, social networks and evolutionary biology	J Evolution Biol
2017	135	Silk MJ	The application of statistical network models in disease research	Methods Ecol Evol
2017	35	Farine DR	A guide to null models for animal social network analysis	Methods Ecol Evol
2017	5	Formica V	Consistency of animal social networks after disturbance	Behav Ecol
2017	5	Mourier J	Does detection range matter for inferring social networks in a benthic shark using acoustic telemetry?	Roy Soc Open Sci
2017	3	Spiegel O	What's your move? Movement as a link between personality and spatial dynamics in animal populations	Ecol Lett
2018	1235	Montiglio PO	Social structure modulates the evolutionary consequences of social plasticity: A social network perspective on interacting phenotypes	Ecol Evol
2018	135	Dougherty ER	Going through the motions: incorporating movement analyses into disease research	Ecol Lett
2018	135	Silk MJ	Contact networks structured by sex underpin sex-specific epidemiology of infection	Ecol Lett
2018	135	Farine DR	When to choose dynamic vs. static social network analysis	J Anim Ecol
2018	135	Sah P	Disease implications of animal social network structure: A synthesis across social systems	J Anim Ecol
2018	35	Spiegel O	Where should we meet? Mapping social network interactions of sleepy lizards shows sex-dependent social network structure	Anim Behav

Table 3 (continued)

Year	Code	Author	Title	Jour or book
2018	35	Sih A	Integrating social networks, animal personalities, movement ecology and parasites: a framework with examples from a lizard	Anim Behav
2018	35	Spiegel O	Where should we meet? Mapping social network interactions of sleepy lizards shows sex-dependent social network structure	Anim Behav
2018	35	Sih A	Integrating social networks, animal personalities, movement ecology and parasites: a framework with examples from a lizard	Anim Behav
2018	5	Blaszczyk MB	Consistency in social network position over changing environments in a seasonally breeding primate	Behav Ecol Sociobiol
2018	3	Bani-Yaghoub M	A methodology to quantify the long-term changes in social networks of competing species	Ecol Model

1-Key Routes, 2-CPM Main Path, 3-Island 5, 4-Island 4, 5-Node Island, 6-Probabilistic Flow

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