

## Analysis of Co-Authorship Pattern in Mathematics-Related Fields

Dmitry E. Chebukov<sup>1</sup>, Anthony M. Nwohiri<sup>2\*</sup>, Andrey A. Pechnikov<sup>3</sup>  
& Ekaterina A. Znamenskaya<sup>1</sup>

<sup>1</sup> Steklov Mathematical Institute, Russian Academy of Sciences, Moscow, Russia

<sup>2</sup> Department of Computer Sciences, University of Lagos, Lagos, Nigeria

<sup>3</sup> Institute of Applied Mathematical Research, Karelian Research Centre, Russian Academy of Sciences, Petrozavodsk, Russia

### Abstract

**Introduction:** Scientific collaboration is often a defining feature and critical component of modern academic research. The analysis of networks of collaboration between scientists reveals features of academic communities that help in understanding the specifics of collaborative scientific work and identifying the notable researchers.

**Objectives:** This paper aims to investigate the patterns in scientific collaboration in the field of mathematics and related areas via graph theory, social network analysis, and bibliometric analysis.

**Methods:** Our research materials consist of journals indexed by Math-Net.Ru, a Russian mathematical portal that provides different scientific resources in mathematics, computer science, physics, information technology and related fields of science. The study covers a 20-year period – from 2000 to 2020.

**Results:** Most of the papers (> 54%) are found to be single-author publications, while 39% are co-authored by 2 to 4 people. The remaining 2% are papers written by 5 to 44 authors. This co-authorship structure shows that our object of study, Math-Net.Ru, does not follow the widely reported trend of a surge in ghost and honorary/guest/gift authorship. The main features of the constructed co-authorship graph—graph diameter, average path length, and percentage of vertices belonging to the maximally connected component—stabilize when the authorship count reaches 4.

**Conclusions:** Contrary to existing recommendations to acknowledge and separately describe the presence, in any sample, of articles with more than 10 co-authors, our results suggest that such recommendations are more appropriate and precise for papers co-authored by over 5 persons.

**Keywords:** bibliometrics, co-authorship, honorary authorship, Math-Net.Ru, research collaboration, scientometrics.

### 1. Introduction

Research work is a mentally demanding and complex type of human activity. It cannot be evaluated using a single universal scheme. Interaction among scientists has for long been the essence of scientific practice. Collaboration is one of the most efficient methods for conducting multidisciplinary research in science and for utilizing new ideas, talents, and resources [1]. Scientific collaboration networks, according to Wang et al. [2] and Zare-Farashbandi et al. [3], are a hallmark of contemporary academic research. Co-authorship is one of the most tangible forms of research collaboration. It is a collaboration between two or more authors if they publish a scientific work together. Co-authorship networks and social network analysis are becoming more and

more popular as effective methods for assessing collaboration trends, identifying top scientists and research institutions.

As scientific collaboration evolved in the 20th century, people started collaborating in many research fields. Rather than remaining solitary authors, researchers and scientists now cooperate to advance fundamental understandings of their research domains. They no longer play independently; instead, they are a part of teams that combine diverse perspectives and complementary skills to achieve shared objectives [4].

Recent decades have witnessed a rise in the number of papers with multiple authors with increasing instances of authorship abuse. However,

multi-authorship is not necessarily due to undeserving authorship [5]. It may be warranted by multidisciplinary research, evolution of a discipline, knowledge complexity, or intent to improve research quality [6, 7]. This issue is comparatively under-researched, especially in the social sciences [8]. Collaborative writing comes with additional challenges, including varying levels of involvement of coauthors, assignment of fair credit, compatibility of various work styles, and the need for efficient communication [9].

De Solla Price [10] was one of the first that studied co-authorship networks. The work is associated with the emergence of electronic repositories of scholarly publications. The main objects investigated since then and up to the present time are citation and co-authorship networks built using data obtained from various electronic sources and investigated using mathematical models; the results are further subjected to in-depth interpretation.

Co-authorship networks are one of the most commonly studied scientific collaboration networks [3, 11]. Perhaps this is because of the inherently obvious definition of the term scientific acquaintance as documented by the very papers that scientists write. Newman [12] defines co-authorship relationship in its entirety as: "...two scientists are considered connected if they have coauthored a paper. This seems a reasonable definition of scientific acquaintance: most people who have written a paper together will know one another quite well. It is a moderately stringent definition, since there are many scientists who know one another to some degree but have never collaborated on the writing of a paper". Further in this paper, we will stick to this definition of scholarly collaboration through co-authorship.

In this study, we have analyzed the co-authorship network of scientists whose core work is in the area of mathematics. Adams et al. [13] examined 15.7 million documents identified specifically as articles (not reviews or other document types) in Web of Science journals from 2009 to 2018. Some of the results (for mathematics, computer science and physics only) are presented in table 1.

In the Mathematics category (184,499 articles), 99.2% of articles were written by groups of 1 to 5 authors and a mere 0.8% by 6 to 10 authors. In the

Computer Science category, there was a relatively higher authorship count: 90.8% (1 to 5 authors), 8.7% (6-10), 0.4% (11-15), and 0.1% (16-20). In addition, there are groups of 31-51 authors accounting for 0.1% and groups of 101-500 authors making up 0.001% (not shown in the table). By comparison, the Physics category has a much higher authorship count. Besides, a group of 501 to 1000 authors accounted for 0.084% of the articles. Curiously, there was no separate category for Applied Mathematics. One possible reason is that applied mathematics articles fall either under the Mathematics or Computer Science category.

Over the past two decades, starting around the time Cronin [14] published his study on hyperauthorship and on how to address some issues associated with it, the rising trend in papers with multiple authors has continued to raise so many major ethical issues and concerns bordering on attribution and authorship misconduct [15-18]. Although co-authorship in a scholarly publication brings numerous benefits to the participating authors, it has also given rise to questions about publication integrity, such as ghost and honorary/guest/gift authorships. For example, there is substantial evidence that articles from international collaborations are more cited than articles from domestic collaboration [19-23]. Some authors could exploit this in an attempt to influence scientific performance indicators. Therefore, there have been proposals that authors be replaced by lists of contributors, whose specific inputs to a given study would be recorded unambiguously [14, 24]. Others have come up with recommendations that represent ethical practices for ensuring credit where (and only where) credit is due [25-27]. The need to survey and follow up the collaboration issue calls for statistical indicators sensitive enough to reveal the structure and change of collaborative networks.

**Table 1. Frequency of author counts (in percentages within category) for papers indexed in Web of Science (2009-2018)**

Article count 2009-2018	Category	Author count					
		1-5	6-10	11-15	16-20	21-30	31-50
184,499	Mathematics	99.2	0.8	0.0	0.0	0.0	0.0
387,710	Computer Science	90.8	8.7	0.4	0.1	0.0	0.1
1,049,588	Physics	74	21.5	2.8	0.6	0.3	0.18

Adams et al. [13] noted that authorship count poses a number of questions for research analysts and policy makers related to the evaluation of scientific performance. In our paper, we explore two of the questions using data retrieved from Math-Net.Ru. The first is to document and understand authorship changes, and to compare the results in the areas of mathematics and computer science with the more global Web of Science data. The second is to find out whether there is any association between increasingly large author count and the main features of communication as a result of co-authorship.

## 2. Original observations

In major studies on scientific collaboration networks, raw data is mostly obtained from large Internet platforms such as Web of Science and Scopus, with tools such as Journal Citation Reports (<https://jcr.clarivate.com>), and specialized resources, such as PubMed (<https://www.pubmed.ncbi.nlm.nih.gov/>). There are very few Russian-language journals and publications represented in these resources. For example, in Web of Science, the number of Russian-language scholarly publications is less than 0.5% of the total number of publications there. Therefore, using Web of Science studies alone to assess the patterns of scientific collaboration and co-authorship among Russian mathematicians is rather inappropriate.

Unlike the above resources, we have access to *Math-Net.Ru* (<http://www.mathnet.ru>), an all-Russian mathematical portal, which is an informational system that provides different scientific resources in mathematics, computer science, physics, information technology and related fields of science [28]. With this access privilege, we are able to, to a certain extent, investigate the above-mentioned problems in the field of mathematics and computer science in

Russia. *Math-Net.Ru* is a well-known web resource that contains a rich collection of full-text archives of Russia's leading mathematical journals. Authors' information is also featured. As of mid-April 2022, there were about 146,000 authors and 314,000 scientific articles from 144 journals (periodicals) registered on the portal.

*Math-Net.Ru* indexes scholarly publications and stores them in a database in a structured form [29, 30]. The metadata of all publications are contained in a single database table that stores article titles, abstracts, keywords, as well as year of publication, volume, issue, and number of pages in separate columns. Text data (titles, abstracts, keywords) are stored in Russian and English languages. References to pages of publications in international bibliographic databases, such as Web of Science, Scopus, MathSciNet, ZbMATH Open, NASA ADS, and RSCI are also stored. Authors and their affiliations are recorded in corresponding separate tables. Columns of the personalities table contain surnames, first names and middle names of authors in Russian and English, references to personal pages in abstract databases, keywords, scientific biographies, and some other personal data. The authors are linked to publications by means of an auxiliary table containing only the publication and author codes. Association of the publications table and auxiliary table makes it possible to single out a group of journal articles published in the selected range of years. It also allows to search for groups of co-authors, single out publications with one, two, three, etc. authors.

*Math-Net.Ru* has accumulated data for the past 15 years. It covers a large time interval. The earliest citing articles (have bibliographic references to publications in *Math-Net.Ru*) date back to 1936. The earliest cited articles date back to 1866. The content of *Math-Net.Ru* by year was rather heterogeneous for various reasons. Article dating time interval for the study was chosen to be 2000

to 2020. The year 2021 was not included because the database is still being populated.

To solve the set tasks, 56 leading Russian journals and journals from neighboring countries that are indexed in *Math-Net.Ru* due to their full or significant volume of issues, were selected from the total number of over 140 journals available. In addition, such journals as *Physics-Uspekhi*

(Advances in Physical Sciences), *Uspekhi Khimii* (Russian Chemical Reviews), and a number of others that obviously do not belong to the Mathematics and Computer Science categories were excluded from consideration. The mathematics, applied mathematics, and computer science journals studied are listed in Table 2.

**Table 2. List of journals included in the study**

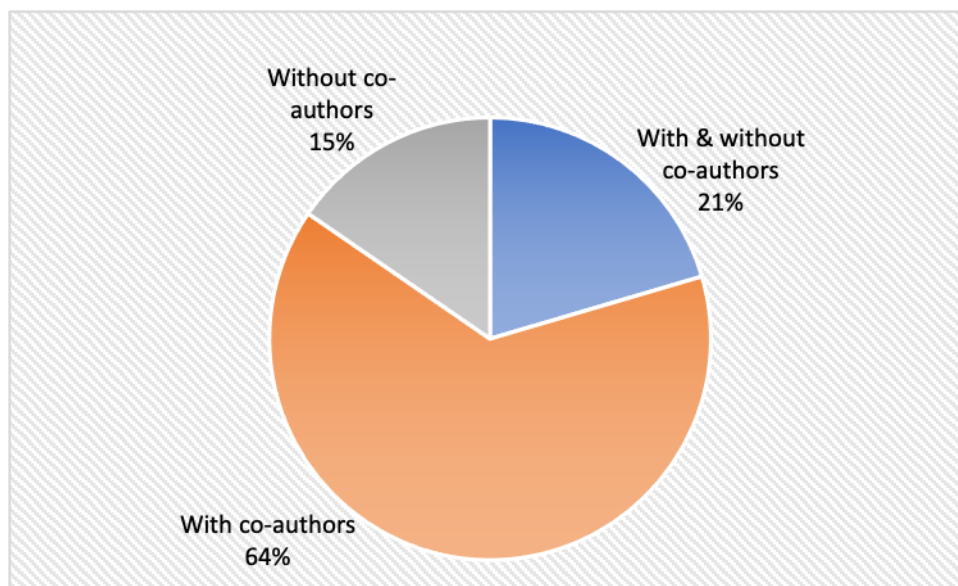
S/N	Journal name	Article count	Author count
1	Algebra and Analysis	1,040	933
2	Algebra and Logic	857	436
3	Moscow University Bulletin. Series 1: Mathematics. Mechanics	1,816	1,383
4	Bulletin of Samara State Technical University. Physical and Mathematical Sciences Series.	1,384	1,238
5	Bulletin of St. Petersburg State University. Series 10. Applied Mathematics. Computer Science. Control Processes.	467	612
6	Bulletin of Udmurt University. Mathematics. Mechanics. Computer Science	748	631
7	Vladikavkaz Mathematical Journal	708	579
8	Far Eastern Mathematical Journal	434	339
9	Discrete Mathematics	939	592
10	Discrete Analysis and Operations Research	757	425
11	Journal of Computational Mathematics and Mathematical Physics	3,686	2,790
12	Journal of Mathematical Physics, Analysis, Geometry	570	533
13	Journal of the Siberian Federal University. Mathematics and Physics Series	819	1,019
14	Proceedings of Scientific Seminars of St. Petersburg Department of Steklov Mathematical Institute	3,004	1,550
15	Proceedings of Higher Educational Institutions. Mathematics	2,421	1,840
16	Proceedings of the Institute of Mathematics and Informatics, Udmurt State University	407	320
17	Proceedings of the Russian Academy of Sciences. Mathematical Series	999	754
18	Results of Science And Technique. Contemporary Mathematics and its Applications. Thematic Reviews.	672	799
19	Lecture courses of the Scientific and Educational Center	30	23
20	Mathematical Game Theory and Its Applications	263	216
21	Mathematical Issues in Cryptography	327	192
22	Mathematical Notes	4,185	3,104
23	Mathematical Proceedings	351	256
24	Mathematical Collection	1,632	1,249
25	Mathematical Modeling	2,668	3,266
26	Mathematical Education	529	272
27	Preprints of the Keldysh Institute of Applied Mathematics	2,374	1,440
28	Applied Discrete Mathematics	721	487
29	Applied Discrete Mathematics. Application	520	345
30	Control Problems	1,171	1,194
31	Siberian Electronic Mathematical News	1,333	1,130
32	Siberian Journal of Computational Mathematics	677	708
33	Siberian Journal of Industrial Mathematics	1,030	950

34	Siberian Journal of Pure and Applied Mathematics	486	532
35	Siberian Mathematical Journal	2,319	1,593
36	Contemporary Mathematics and its Applications	77	102
37	Contemporary Mathematics. Fundamental Directions	408	464
38	Modern Problems of Mathematics	67	83
39	Theoretical and Mathematical Physics	2,843	2,355
40	Probability Theory and its Applications	1,185	955
41	Proceedings of the Institute of Mathematics and Mechanics, Ural Branch of the Russian Academy of Sciences	1,617	970
42	Proceedings of Steklov Mathematical Institute	1,566	1,432
43	Proceedings of the Moscow Mathematical Society	121	164
44	Proceedings of the Petrovsky Seminar	113	140
45	Large systems Control	726	829
46	Advances in Mathematical Sciences	1,571	1,691
47	Ufa Mathematical Journal	526	500
48	Academic Notes of Kazan University. Physics and Mathematics Series	985	1,317
49	Fundamental and Applied Mathematics	1,479	1,340
50	Functional Analysis and its Applications	866	712
51	Chebyshev Collection	943	839
52	Algebra and Discrete Mathematics	769	890
53	Regular and Chaotic Dynamics	934	877
54	Russian Journal of Nonlinear Dynamics	658	629
55	Symmetry, Integrability and Geometry: Methods and Applications	1,681	2,236
56	Theory of Stochastic Processes	292	277

Nearly 62,000 articles authored by about 33,000 scientists were published in these 56 journals from 2000 to 2020.

### 3. Co-authorship arithmetic

Analysis shows that the set of nearly 33,000 authors can be divided into three non-intersecting subsets as demonstrated in Figure 1.



**Fig. 1** Author subsets

The percentage of authors that publish alone is quite high, but a large proportion of authors have

co-authored papers. Table 3 summarizes the number of articles published by groups of authors.

A group is understood here to be a group of scientists who have coauthored at least one or more papers (formally, a group may consist of one author). As can be seen from table 3, over 54% of articles are written by one author, and about 30% are co-authored by two people. One- and two-author groups are almost equal in number. However, the average number of articles written by one author is twice that of two authors. Groups of 4 to 10 co-authors have, on average, slightly more than one co-authored article.

With the above results, we are able to compare the co-authorship situation of Math-Net.Ru with that of Web of Science. Let us take into account that in the case of Math-Net.Ru, there is no difference between journals in the mathematics and in the computer science categories. Therefore, we compare our results with the two Web of Science categories. In addition, data for Web of Science are given for aggregated cases – 1-5, 6-10 authors, etc.

**Table 3. Articles published by author groups.**

<b>Author count</b>	<b>Group count</b>	<b>Article count</b>	<b>Articles per group</b>	<b>% of total article count</b>
1	11,793	33,502	2.841	54.24
2	12,460	18,592	1.492	30.10
3	5,251	6,495	1.237	10.51
4	1,593	1,746	1.096	2.83
5	622	654	1.051	1.06
6	255	267	1.047	0.43
7	121	126	1.041	0.20
8	76	76	1.000	0.12
9	69	71	1.029	0.11
10	46	46	1.000	0.07
11-12	104	107	1.029	0.17
16-44	87	89	1.023	0.14
<b>Total papers</b>		<b>61,771</b>		

In addition, in Adams et al. [13] (p. 7, Table 1) in the 'Computer Science' row, an error was made: the sum of the values in this row is more than 100, so we limited ourselves to the first three values. Our comparison is summarized in Figure 2. The table

shows that the co-authorship structure in Math-Net.Ru for the 1-5 and 6-10 groups is very similar to that of Web of Science for the mathematics category.

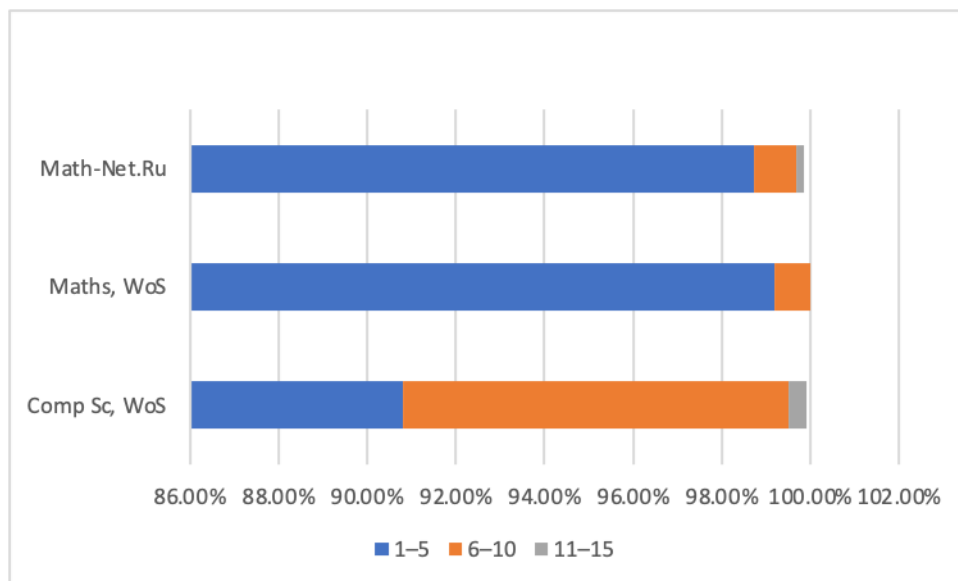


Fig. 2 Comparison of co-authorship structure: Math-Net.Ru vs. Web of Science

#### 4. Co-authorship graphs

The term "co-authorship graph" that we use here is more strictly defined as a graph of scientific collaboration as defined by Newman [12]: *two scientists are considered connected if they have coauthored a paper*. Our aim here is not to study collaboration strength depending on the number of co-authored papers. Therefore, the edges in our co-authorship graph are of a multiplicity of 1 and have no weights.

The co-authorship graph is conventionally denoted as  $G=G(V,E)$ , where  $V$  is the set of vertices representing authors, and  $E$  is the set of edges representing co-authorship. To denote the cardinality of a set, we use the notation "card", i.e.  $card(A)$  is the number of vertices in set  $A$ .

We investigated the co-authorship graphs in two stages. First, we constructed and studied co-authorship graphs for a given number of co-authors – from 2 to 10. We denote such graphs by  $G_i(V_i,E_i)$ ;  $i$  represents the number of co-authors and it is called authorship count.

Here is an example of how graph  $G_3(V_3, E_3)$  is constructed:

Step 1: In the database, pick all articles with three authors.

Step 2: For these selected articles, form a list. Each record in the list is of the form  $\langle id1, id2, id3, n \rangle$ , where  $id1, id2$ , and  $id3$  are the identifiers of three co-authors in ascending order of value, and  $n$  is the number of articles written by each unique trio of authors.

Step 3: With this list, build  $V_3$ , which is a set of vertices representing all the authors identified in step 2 above.

Step 4: Using the list created in step 3, each trio  $\langle id1, id2, id3 \rangle$  is transformed into a set of pairs  $(id1, id2), (id1, id3), (id2, id3)$  representing a set of edges  $E_3$ ; multiple edges are not considered.

At the end, we get graph  $G_3(V_3,E_3)$ , where  $V_3$  vertices represent authors who have co-authored three-author papers. Accordingly, edges  $E_3$  reflect the relations between those authors who have co-authored some papers.

Graphs  $G_2, G_4-G_{10}$  are constructed in a similar manner. The graphs were processed using Gephi (<https://gephi.org>), a free software solution for network visualization and investigation. The results are summarized in Table 4.

Table 4. Main characteristics of graphs  $G_2-G_{10}$ .

Co-authorship graph	card(V)	card(E)	card( $V_{maxCC}$ )	fract	diam
$G_2$	16,618	12,460	3,079	0.185	57

G <sub>3</sub>	10,936	14,358	1,747	0.160	36
G <sub>4</sub>	4,835	8,692	402	0.083	15
G <sub>5</sub>	2,442	5,673	296	0.121	13
G <sub>6</sub>	1,268	3,580	139	0.110	11
G <sub>7</sub>	706	1,949	154	0.218	13
G <sub>8</sub>	521	2,005	149	0.286	9
G <sub>9</sub>	502	2,323	248	0.494	7
G <sub>10</sub>	350	1,949	255	0.729	6

Here  $V_{maxCC}$  denotes the set of vertices in the maximally connected component (*maxCC*) of the respective co-authorship graph, *fract* is the fraction of vertices  $V$  that are in *maxCC*, and *diam* is the diameter of the graph.

Graph  $G_{10}$  is built using a set of scientists that have co-authored 10-author papers (Figure 3). The maximally connected component of graph  $G_{10}$  includes almost 73% of all vertices, and the maximum distance between any pair is 6. The second largest component contains 15 vertices, and 8 other components contain 10 vertices each, which is equal to the number of co-authors given for construction of  $G_{10}$ .

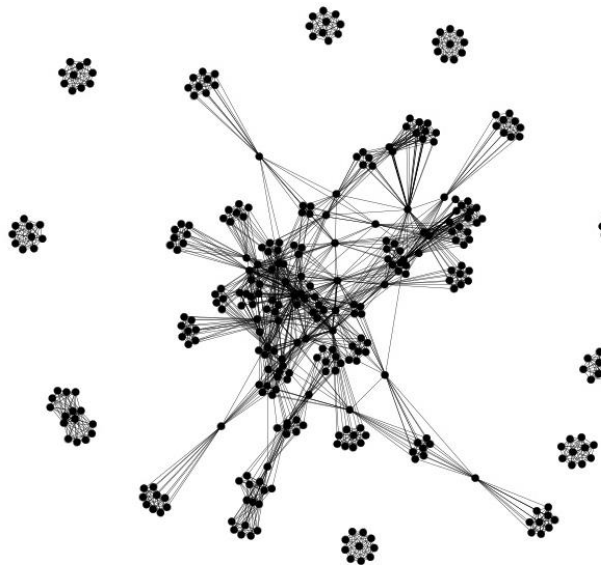


Fig. 3 Graph  $G_{10}$

It can be concluded, therefore, that co-authors of 10-author papers are mostly known to each other. This is consistent with the well-known small world problem [31]. The same can be said about the  $G_9$  graph, but not about the other graphs  $G_2$ - $G_8$ . It should be noted also that *fract* decreases for authorship count 2-4 and increases for count 6-10. This again is evidence to the communication features (e.g., ghost and honorary/guest/gift authorship) for multi-authorship.

In the second stage, we perform disjoint union of graphs. We take graph  $G_2$  as the initial graph and perform a disjoint union of graphs  $G_2$  and  $G_3$ . The resulting graph is denoted as  $G_{2-3}(V_{2-3}, E_{2-3})$ , where  $V_{2-3} = (V_2 \cup V_3) \setminus (V_2 \cap V_3)$  is the set of vertices of the resulting graph, and  $E_{2-3}$  is a set of edges, which consists of all  $E_2$  edges plus all  $E_3$  edges that are not in  $E_2$ :  $E_{2-3} = (E_2 \cup E_3) \setminus (E_2 \cap E_3)$ .

At the next step we perform a disjoint union of graphs  $G_{2-3}$  and  $G_4$  to get  $G_{2-4}$ , then  $G_{2-4}$  and  $G_5$  to get  $G_{2-5}$ , and so on until we get  $G_{2-10}$ .

Unlike the traditional approach (building a common co-authorship graph for all authors) we trace the changes in graph characteristics as the authorship count changes and find some important features and patterns.

The main characteristics of the co-authorship graphs are given in Table 5.

Table 5. Main characteristics of the co-authorship graphs.

Co-authorship graph	card(V)	card(E)	card(maxCC)	fract	diam	mid_path
$G_2$	16,618	12,460	3,079	0.185	57	19.76
<b><math>G_3</math></b>	<b>10,936</b>	<b>14,358</b>	<b>1,747</b>			
$G_{2-3}$	23,119	24,806	8,574	0.371	32	12.44
<b><math>G_4</math></b>	<b>4,835</b>	<b>8,692</b>	<b>402</b>			

$G_{2-4}$	25,579	31,876	10,799	0.422	31	10.83
<b><math>G_5</math></b>	<b>2,442</b>	<b>5,673</b>	<b>296</b>			
$G_{2-5}$	26,678	36,257	11,860	0.445	29	10.12
<b><math>G_6</math></b>	<b>1,268</b>	<b>3,580</b>	<b>139</b>			
$G_{2-6}$	27,149	38,902	12,491	0.460	29	9.60
<b><math>G_7</math></b>	<b>706</b>	<b>1,949</b>	<b>154</b>			
$G_{2-7}$	27,404	40,366	12,809	0.467	29	9.262
<b><math>G_8</math></b>	<b>521</b>	<b>2,005</b>	<b>149</b>			
$G_{2-8}$	27,543	41,994	13,079	0.475	28	8.817
<b><math>G_9</math></b>	<b>502</b>	<b>2,323</b>	<b>248</b>			
$G_{2-9}$	27,675	43,951	13,427	0.485	28	8.249
<b><math>G_{10}</math></b>	<b>350</b>	<b>1,949</b>	<b>255</b>			
$G_{2-10}$	27,723	45,466	13,595	0.490	27	7.837

The *mid\_path* column shows the average path length between any two vertices in the graph. In each shaded row, some characteristics (*card(V)*, *card(E)*, *card(maxCC)*) of graphs resulting from disjoint union with the graphs in the row above are given in a smaller italicized font for information. For instance, the  $G_{2-3}$  graph is a result of a disjoint union of  $G_3$  and  $G_2$ . Transition from  $G_2$  to  $G_{2-3}$  is characterized by a sharp change in all three

characteristics, *fract*, *diam* and *mid\_path*. With a transition to graph  $G_{2-4}$ , *fract* increases, *diam* remains almost the same, but *mid\_path* decreases significantly. After this transition, the values of three main characteristics stabilize relatively. Changes in diameter and average path length, depending on the authorship count, is shown in Figure 4 for clarity and illustration purposes.

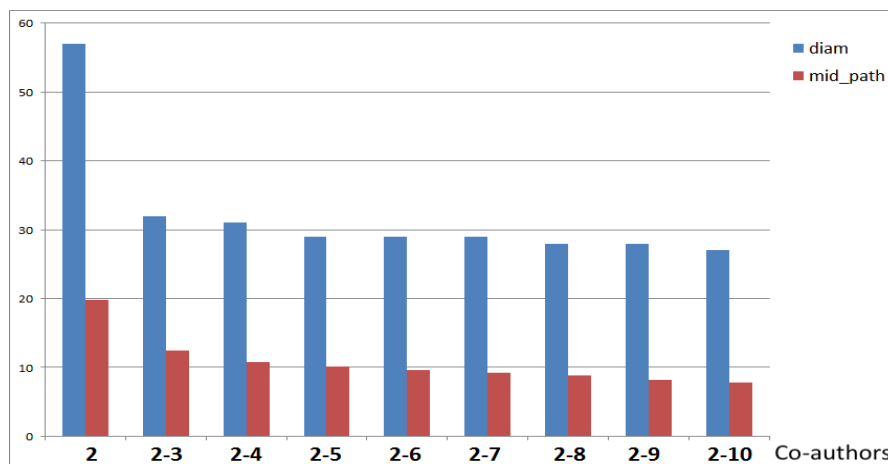


Fig. 4 Changes in diameter and average path length as authorship count changes

## 5. Discussion & Conclusion

We have investigated research collaboration among mathematicians using data from the *Math-Net.Ru* portal. The study period was 2000 to 2020. Our findings have led us to some conclusions with respect to co-authorship pattern and the relationship between authorship count and pattern of scientific communication and collaboration.

The study featured almost 62,000 articles written by nearly 33,000 authors. An overwhelming

number of authors (85%), apart from having single-authored papers, have co-authored publications. Over 63% of authors have no single-authored articles to their credit, all their publications are co-authored. The percentage of authors who have published alone without having any co-authored work is also quite high, 15%. More than 53% of articles are single-authored papers publications, while 43% are two- to four-author papers. The remaining 4% of the articles have 5 to 44 co-

authors. This co-authorship structure shows that our research object, Math-Net.Ru, *does not follow the trend of a rise in ghost and honorary authorship* as has been widely reported, for example, by Adams et al. [13] and Cronin [14].

Having analyzed our constructed co-authorship graphs, the graph diameter, average path length, and percentage of vertices in the maximally connected component were found to stabilize as the authorship count reaches 4. Consequently, we recommend that *the presence, in any sample, of papers with over 5 authors should be acknowledged and separately described* because such articles will affect how results are interpreted.

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