

Coauthorship and citation patterns in the Physical ReviewTravis Martin,^{1,*} Brian Ball,² Brian Karrer,² and M. E. J. Newman^{2,3}¹*Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109, USA*²*Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA*³*Center for the Study of Complex Systems, University of Michigan, Ann Arbor, Michigan 48109, USA*

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A large number of published studies have examined the properties of either networks of citation among scientific papers or networks of coauthorship among scientists. Here we study an extensive data set covering more than a century of physics papers published in the Physical Review, which allows us to construct both citation and coauthorship networks for the same set of papers. We analyze these networks to gain insight into temporal changes in citation and collaboration over the long time period of the data, as well as correlations and interactions between the two. Among other things, we investigate the change over time in the number of publishing authors, the number of papers they publish, and the number of others with whom they collaborate, changes in the typical number of citations made and received, the extent to which individuals tend to cite themselves or their collaborators more than others, the extent to which they cite themselves or their collaborators more quickly after publication, and the extent to which they tend to return the favor of a citation from another scientist.

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I. INTRODUCTION

Citation networks [1,2] and coauthorship networks [3–5] are distinct network representations of bodies of academic literature that have both been the subject of quantitative analysis in recent years. In a citation network the network nodes are papers and a directed edge runs from paper A to paper B if A cites B in its bibliography. In a coauthorship network the nodes are authors and an undirected edge connects two authors if they have written a paper together. Both kinds of network can shed light on habits and patterns of academic research. Citation networks, for instance, can give a picture of the topical connections between papers, while coauthorship networks can shed light on patterns of collaboration such as the size of collaborative groups or the frequency of repeated collaboration.

In this paper we analyze networks of citation and coauthorship derived from a large data set made available by the American Physical Society, which consists of bibliographic and citation data for the Physical Review family of physics journals and spans the entire history of those journals, more than 100 years, from their inception in 1893 to 2009 [6]. The data set is unusual both because of the length of time it spans and also because it contains information on both citation and coauthorship for the same body of literature. A number of previous analyses of the data have been published [7–10], but our work adopts a somewhat different viewpoint from other studies in focusing on the interactions between authorship and citation, as well as on long time-scale patterns in the data. In particular, the simultaneous availability of citation and coauthorship data allows us to associate citations not only with papers but with individual authors so that we can tell whether or not a particular author cites another. Combining this insight with the temporal aspects of the data we find, for example, that researchers cite their own or coauthors' papers more quickly after publication than they do the work of others; that authors show a strong tendency to return the favor of a citation from another author,

especially a previous coauthor; that, contrary to some recent conjectures, having a common coauthor does not make two authors likely to collaborate in future [11–13]; and that there has not (at least within the journals we study) been any increase over time in self-citations, the number holding roughly constant at about 20% of all citations for over a century.

II. DATA SET

In its raw form the data set we study contains records for 462 090 papers published in the various Physical Review journals, each identified with a unique numerical label. Data for each paper include paper title, date of publication, the published names and affiliations of each of the authors, and a list of the numerical labels of previous Physical Review papers cited. The data set is unusual in two respects: the long period of time it covers, which spans 116 years from 1893 to 2009, and the fact that it includes citation data and hence allows us to compare coauthorship patterns with citations, at least for that portion of the citation network that appears in the Physical Review; citations to and from non-Physical-Review journals, of which there are many, are not included.

Before performing any analysis, however, there are some hurdles to overcome. Foremost among them is the fact that the name of an author alone does not necessarily identify him or her uniquely. Two authors may have the same name or the same author may be identified differently in different publications (with or without a middle initial, for example). Unlike some journals, such as those of the American Mathematical Society [14], the Physical Review does not maintain unique author identifiers that can be used to attribute authorship unambiguously. As a first step in analyzing the data, therefore, we have processed it using a number of disambiguation techniques in order to infer actual author identity from author names as accurately as possible. Details of the disambiguation process are given in the Appendix.

In addition, we have performed a modest culling of the data to remove outliers, the most substantial action being the removal of all papers with 50 or more authors, which are

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TABLE I. Mean values of some statistics for our data set, with and without papers having over 50 authors.

Measurement	All papers	Papers with 50 authors or fewer
total papers	460 889	457 516
total authors	235 533	226 641
mean authors per paper	5.35	3.34
citations made per paper	10.16	10.16
mean collaborators per author	59.44	17.24
mean papers per author	10.47	6.74

primarily recent papers in experimental high-energy physics. (Almost all of them, about 91%, were published in either Physical Review D, which covers high-energy physics, or Physical Review Letters; the remainder were in Physical Review C, which covers nuclear physics.) As we show shortly, though papers with more than 50 authors are only a small fraction of the whole (about 0.7%), their inclusion skews results for the last 30 years substantially by comparison with the rest of the time period. For results whose outcome depends strongly on the presence or not of these papers, we quote results both with and without, for comparison. Table I gives some basic parameters of the resulting data set.

III. ANALYSIS

In the next few sections we present a variety of analyses of the Physical Review data set. We begin by looking at some basic parameters of authorship and coauthorship.

A. Authorship patterns

Figure 1 shows a cumulative distribution function for the number of papers an author publishes, aggregated over the entire data set. That is, the figure shows the fraction of authors who published n papers or more as a function of n , which is a crude measure of scientific productivity. The axes in the figure are logarithmic and the approximate straight-line form

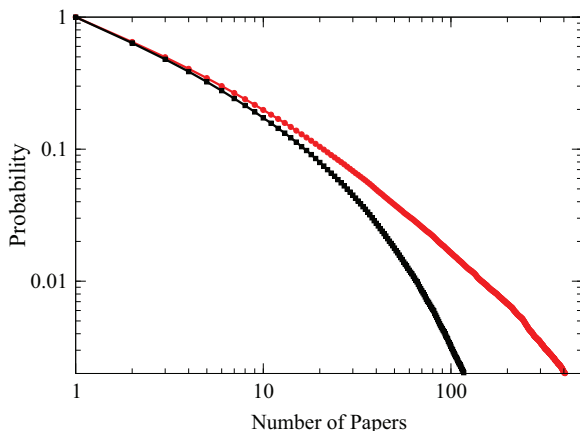


FIG. 1. (Color online) Probability that an author wrote more than a given number of papers. Red circles indicate values calculated from the full data set; black squares are values from the data set after papers with 50 or more authors have been removed. The plot is cut off around 500 papers because there is very little data beyond this point.

of the distribution function implies that scientific productivity follows, roughly speaking, a power law, a result known as Lotka's law, first observed by Lotka in 1926 [15] and confirmed by numerous others since. (It has also been suggested that the distribution is log-normal rather than a power law [16]. It is known to be hard to distinguish empirically between log-normal and power-law distributions [17].) In Fig. 1 we give separate curves with and without the papers that have 50 or more coauthors. As the figure shows, the difference between the two is primarily in the tail of the distribution, among the authors who have published the largest number of papers, indicating that a significant fraction of the most productive authors are those in large collaborations. In fact, if one compiles a list of the 50 authors publishing the largest numbers of papers, only one of them remains on that list after papers with 50 or more authors are excluded. This probably results from a combination of two effects: First, larger groups can publish more papers simply because they have more people available to write them and second, a large and productive group of collaborators contributes many apparently prolific authors to the statistics—each of the many coauthors separately gets credit for being highly productive. It is precisely because of biases of this kind that we exclude papers with many authors from some of our calculations.

We can remedy this problem to some extent by measuring productivity in a more sophisticated fashion. Rather than just counting up all the papers an author was listed on, we can instead divide up the authorship credit for a paper among the contributing authors so that, for example, each author on a two-author paper is credited with half an authorship for that paper. This reduces significantly the impact of large collaborations on the statistics, though the distribution of the number of papers authored is still highly skewed, with certain authors producing much more science than others. A common way to visualize such skewed distributions is to use a Lorenz curve, a plot of the fraction of papers produced by the most prolific authors against the fraction of authors that produced them. Such a curve is shown for our data set in Fig. 2; the sharp rise in the curve at the left-hand side indicates the concentration of scientific productivity among the most productive scientists. Note, for instance, that productivity appears roughly to follow the so-called 80-20 rule, such that about 80% of the output is produced by the 20% most productive authors. Notice also that there is almost no difference in the Lorenz curves with and without the 50-plus-author papers, precisely because we have divided up the authorship credit so that the effect of many-author papers is diminished.

The distribution can be further quantified by measuring a Gini coefficient, which is defined as the excess area under the Lorenz curve compared to the case where everyone has the exact same productivity. In our data set, the Gini coefficient is 0.70, a relatively large figure as such coefficients go, indicating high skew. (Gini coefficients for wealth inequality, for example, which is the context in which such coefficients are perhaps best known, rarely rise above 0.6, even in the most inequitable countries.)

The data set also allows us to measure the productivity of the entire field of physics over time, something that cannot be done with many other data sets. Figure 3 shows the total number of papers published in the Physical Review in five-year time

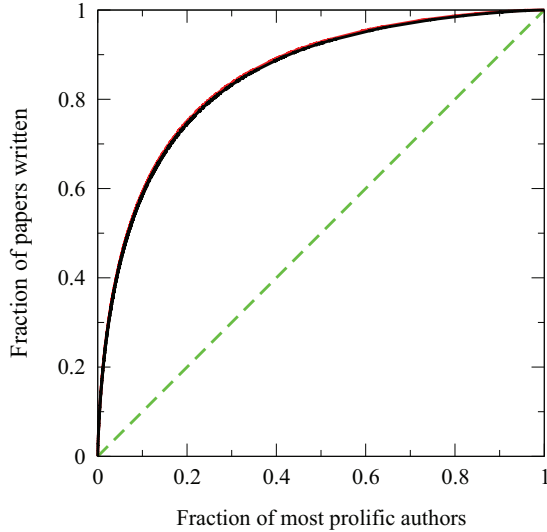


FIG. 2. (Color online) Fraction of papers written by the most prolific authors (with credit for multi-author papers divided among coauthors, as described in the text). The red (grey) curve represents values calculated from the full data set; the black curve represents values after papers with fifty or more authors have been removed. Note that the two curves are almost indistinguishable. The dashed line indicates the form the curve would take if all authors published the same number of papers.

blocks since 1893. With the important caveat that these results are for a single collection of journals only and one moreover whose role within the field has evolved during its history from provincial upstart to one of the leading physics publications on the planet, we see that there is a steady increase in the volume of published work, which appears roughly to follow an exponential law (a straight line on the semilogarithmic scales of the figure). An interesting feature is the dip in the curve in the 1940s, which coincides with the second World War, followed by a recovery in the 1950s, perhaps attributable in part to increased science funding in the postwar period. The combined result of these deviations, however, is only to put

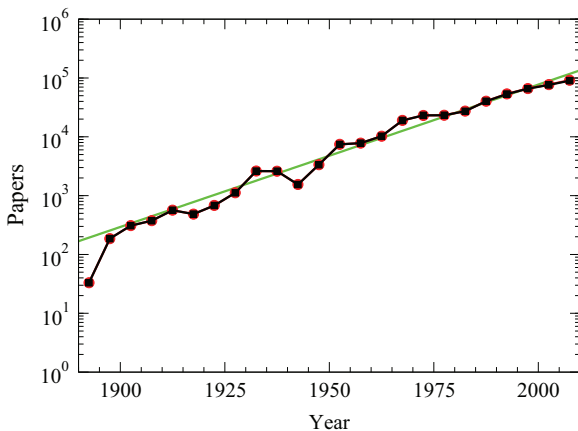


FIG. 3. (Color online) Number of papers published in each five-year block. Red circles indicate numbers calculated from the full data set; black squares are calculated from the data set after papers with 50 or more authors have been removed. Note that the two values are almost indistinguishable. The straight line is the best-fit exponential.

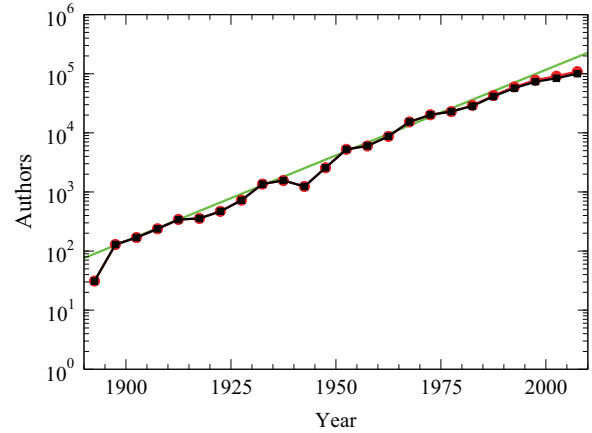


FIG. 4. (Color online) Number of unique authors who published a paper in each five-year block. Red circles indicate numbers calculated from the full data set; black squares are calculated from the data set after papers with 50 or more authors have been removed. Note that the two values are almost indistinguishable. The straight line is the best-fit exponential.

the curve back on the same path of exponential growth after the war that it was already on before it. In his early studies of secular trends in scientific output, Price [18,19] noted a similar exponential growth interrupted by the war and measured the doubling time of the growth process to be in the range from 10 to 15 years. The best exponential fit to our data gives a compatible figure of 11.8 years.

Figure 4 shows the corresponding plot of the number of unique authors in the data set in each five-year block as a function of time. Like the number of papers published, the number of authors appears to be increasing exponentially and with a roughly similar (but slightly smaller) doubling time of 10.4 years. Thus, despite the marked increase in productivity of the field as a whole, it appears that each individual scientist has produced a roughly constant, or even slightly decreasing, number of papers per year over time.

The natural complement to measurement of the number of papers per author is measurement of the number of authors per paper, i.e., the size of collaborative groups. Figure 5 shows the mean number of authors per paper in our data set as a function of time and there is a clear increasing trend throughout most of the time period covered, with the average size of a collaborative group rising from a little over one a century ago to about four today. A similar effect has been noted previously by, for example, Grossman and Ion [3], for the case of mathematics collaborations. In our calculations we have again calculated separate curves with and without papers having 50 or more authors and a comparison between the two reveals a startling effect: While there is almost no difference at all between the curves prior to about 1975, there is a large and rapidly growing gap between them in the years since. Without these papers the growth in group sizes has been slow and steady for decades; with them it departs dramatically from historical trends after the 1970s, indicating a large and growing role in physics (or at least in physics publication) for big collaborations.

An alternative view of the same trend is given in Fig. 6, which shows the number of unique coauthors an author has, on average, during each five-year time block. Every coauthor

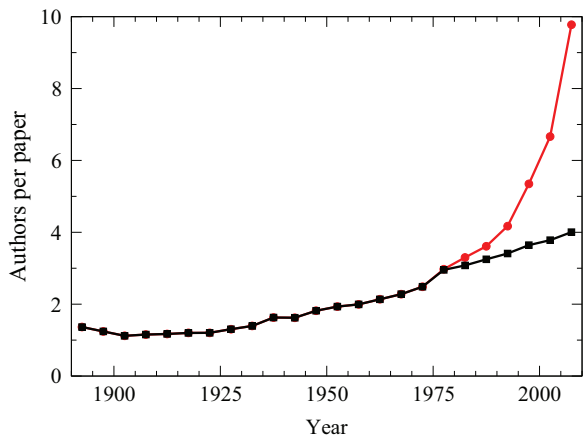


FIG. 5. (Color online) Number of authors per paper averaged over five-year blocks. Red circles indicate the full data set; black squares are the data set after papers with 50 or more authors have been removed.

in a time block is counted, even if he or she was also counted in a previous time block (but previous coauthors are not counted unless they are also coauthors in the new time block). As the figure shows, this number has also risen significantly over the past century, from a little over one to more than ten today (and more than 60 if one includes collaborations with 50 or more members). Since we only have data from the Physical Review, it is likely that we miss some collaborators, so these numbers are in practice only lower bounds on the actual numbers.

B. Citation patterns

Let us now add the citation portion of the data set to our analyses and examine citation patterns over time in the Physical Review, as well as interactions between citation and coauthorship.

Figure 7 shows the average number of citations by a paper and to a paper, over the time period covered by the Physical Review data set, however, since the most recent papers are too recent to have accrued a significant number of citations and hence we expect a drop at the rightmost end of the curve, as seen in the figure.

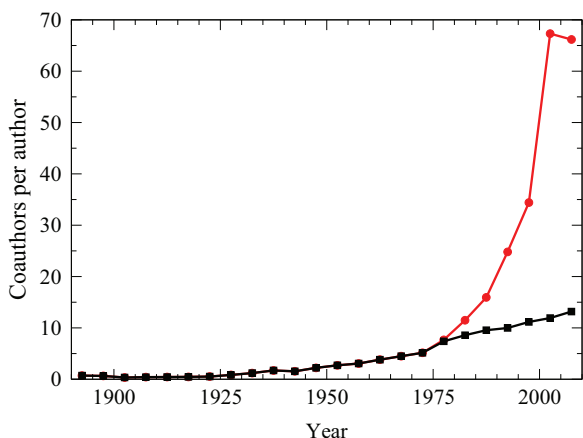


FIG. 6. (Color online) Average number of unique coauthors of an author, averaged in five-year blocks. Red circles indicate the full data set; black squares are the data set after papers with 50 or more authors have been removed.

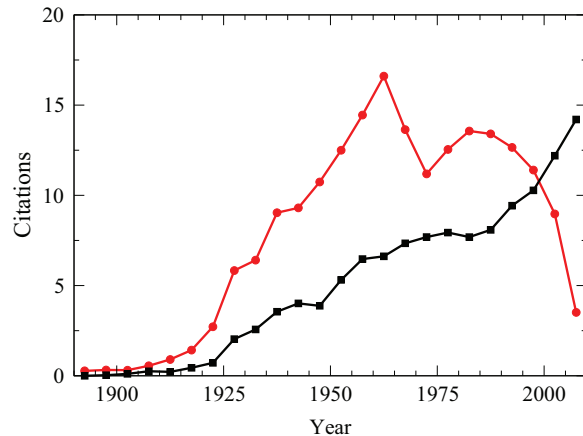


FIG. 7. (Color online) Average numbers of citations made (black squares) and received (red circles) per paper, in five-year blocks.

used to cite fewer papers and have been citing steadily more in recent decades. One possible explanation for this phenomenon is the increase in the volume of literature available to be cited, although it has also been conjectured that authors have been under greater pressure in recent decades, for example, from journal editors or referees, to add more copious citations to papers [20].

The red curve in Fig. 7 is the average number of citations received by a paper, which shows more irregular behavior, rising to a peak twice before dropping off in recent times. A number of effects are at work here. First, if (as we will shortly see) most citations are to papers in the recent past, then a steady increase in citations *by* papers should lead to an increase in citations *to* papers published slightly earlier. Behavior of this kind has been observed in previous studies, such as the comprehensive study by Wallace *et al.* using data from the Web of Science [21]. The growth in number of citations received cannot continue to the very end of the data set, however, since the most recent papers are too recent to have accrued a significant number of citations and hence we expect a drop at the rightmost end of the curve, as seen in the figure.

There is, however, also a notable dip in the red curve around 1970, whose origin is less clear. (It is not seen, for instance, in the work of Wallace *et al.*) In examining the data for this period in detail, we find that the dip in citations per paper is due primarily to an increase in the number of papers published in the Physical Review (which expanded considerably during this period), while the number of citations received by those papers, in aggregate, remains roughly constant. The increase in papers published may have been in part a response to the general expansion of US physics research during the 1960s, following the establishment of the National Science Foundation, but the data indicate that the greater volume of research did not, at least initially, result in a greater number of citations received and hence the ratio of the two displays the dip visible in Fig. 7. However, the upward trend in the curve reestablishes itself from about 1970 onward, suggesting that in the long run there was an increase not only in the number of papers published, but also in the number that are influential enough to be later cited.

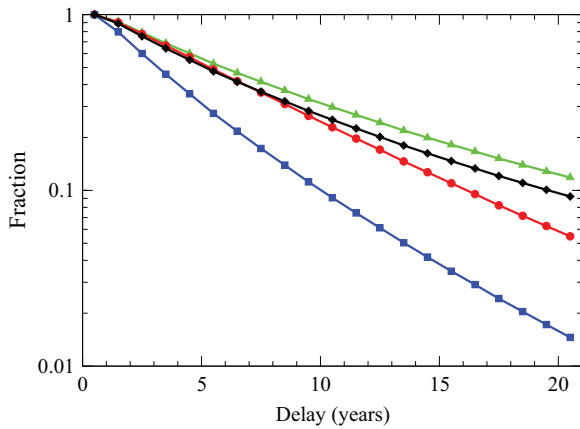


FIG. 8. (Color online) Fraction of citations made more than a given number of years after publication. Black diamonds include all citations, blue squares are self-citations, red circles are coauthor citations, and green triangles are distant citations.

It is interesting to compare the data for citations received with the predictions of theoretical models for the citation process. Perhaps the best known class of models are the preferential attachment models [22], particularly the 1976 model of Price [23], a simple model in which the rate at which a paper receives citations is assumed to vary linearly with the number it already has. In its most naive application, this model makes predictions that differ strongly from the observations plotted in Fig. 7. The model predicts that the largest number of citations should go to the oldest papers and the smallest to the youngest, so that the red curve in the figure should be monotonically decreasing. There are a number of possible explanations for the disagreement. A popular theory is that papers “age” over time, becoming less well cited as they become older [24,25], perhaps because their field has moved on to other things, because they have been superseded by more advanced or accurate work, or because their results are so well known that authors no longer feel the need to cite them. Were this the case, most citations would be to recent papers and the curve of citations received would mostly mirror the curve of citations given, albeit with a time lag whose length would be set by the rate at which papers age. An alternative theory, for which there is some empirical evidence, is that preferential attachment models do represent citation patterns quite well within individual subfields [26], but not when applied to the literature as a whole. A central parameter in the preferential attachment models is the date of the start of a subfield, and since different subfields have different start dates, the model might be expected to work within subfields but not for the overall data set.

Figure 8 tests the aging of papers within the Physical Review data set by plotting the fraction of citations that are to papers a certain time in the past. Let us focus for the moment on the black curve, which includes all citations in the entire data set. The figure shows that there does indeed appear to be a strong aging effect, with the citation rate dropping off approximately exponentially over time (which would be a straight line on the semilogarithmic scales of the plot). This finding is in agreement with previous studies of aging [24], which also found exponential decay. An alternative

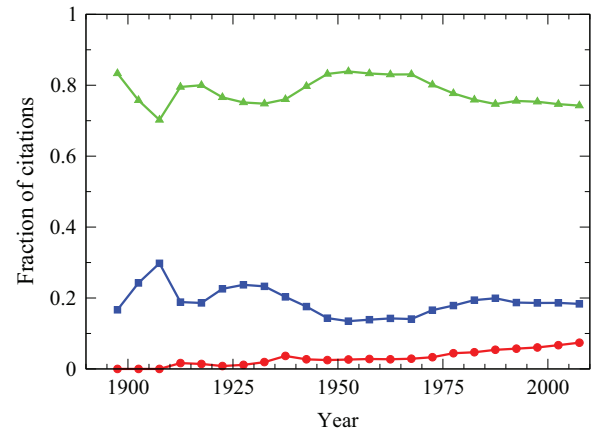


FIG. 9. (Color online) Fraction of citations made, by type, in five-year blocks. There were no citations made in the 1890–1894 block. Blue squares represent self-citations, red circles are coauthor citations, and green triangles are distant citations.

interpretation of the data, however, is that there is no aging occurring at all and that the drop in citations is a purely mechanical effect that results from dilution of the literature: In a small, young field there are only a few papers to cite and hence each receives many citations; in an older field there are more papers and so individual citation rates fall off. To the extent that it has been tested, the latter theory appears to agree well with available citation data and also with the prediction of the preferential attachment models [27], so at present the evidence for (or against) aging in our data set is inconclusive.

C. Interactions between citation and coauthorship

Perhaps the most interesting aspect of the Physical Review data, however, is the window it gives us on the interplay between citation and coauthorship. One way to probe this interplay is to divide citations according to the collaborative roles assumed by the authors of the citing and cited papers and then compare the resulting citation patterns. In the present work, we divide citations into three classes, following Wallace *et al.* [28]: self-citations, where the citing and cited papers shared at least one coauthor; coauthor citations, where at least one author of the citing paper has previously collaborated with at least one author of the cited paper (but there are no common authors between papers, so that self-citations and coauthor citations are disjoint); and distant citations, which includes all citations other than self-citations and coauthor citations. (Other authors who have examined citation and collaboration have gone further and considered also citations between coauthors of coauthors [28], but this proves computationally unfeasible in the present case because of the size of the Physical Review data set.) We emphasize that we only consider individuals to be coauthors if they have *previously* coauthored when the citation occurs. Coauthorship that comes after the citation is not counted. Also our data are limited to the Physical Review, so the number of coauthor citations will in reality be higher than presented here, both because some citations are missing from our data and because some coauthorships are.

Figure 9 shows the fraction of citations that fall into each of the three classes as a function of the year of publication

TABLE II. Mean time delay between a paper's publication date and the dates of the papers it cites.

Citation type	Mean delay (years)
self-citations	4.12
coauthor citations	6.92
distant citations	9.02
all citations	7.89

of the citing paper. Roughly speaking, the three curves appear flat over time. There is a modest increase in the fraction of coauthor citations (the lowest, red curve in the figure), but this can be explained by the increase in the number of coauthors available for citation, shown in Fig. 6, which is of a similar magnitude. In other respects, the rule of thumb seems to be that a constant 20% or so are self-citations, 75% or 80% are distant citations, and the small remaining fraction are to coauthors.

The distribution of time between the publication dates of a new paper and the papers it cites is shown for the three classes of citation in Fig. 8, as the blue, red, and green curves. Here we do notice a significant difference between the classes. In particular, the self-citations (in blue) fall off faster than coauthor and distant citations. This implies that a larger fraction of self-citations occur rapidly after publication, compared with citations in the other classes. This is not unexpected, given that a researcher presumably knows about their own research sooner, and in more detail, than they know about others'. We note also that coauthor citations are slightly earlier than distant citations, which again seems reasonable. One must be careful in the interpretation of these results, however. An alternative explanation for the same observations is that a paper can be cited by others long after the author retires or leaves the field, which could make the average delay for citations by others longer than that for self-citation. There is no way to tell, purely from the delay statistics themselves, which explanation is the better one.

Table II summarizes the mean delay to citation for the three citations classes. We explore the differences between citation classes further in the next section.

D. Self-citation and coauthor citation

Consider Table III, which gives the percentages of papers that make or receive at least one self-citation or coauthor citation, provided such a citation is possible. Nearly 70% of papers cite at least one paper by the same author (or one of the same authors, if there are several) and 60% of them receive such a citation. These numbers may at first appear

TABLE III. Percentage of papers that make or receive at least one citation of a given type.

Citation type	Made (%)	Received (%)
self-citation	68.9	60.3
coauthor citation	42.0	31.3
both	35.6	26.3
either	75.0	64.2
either given both possible	76.4	66.4

large and raise concerns, given the use of citation counts as a measure of impact, that authors might be inflating their counts by self-citing [29,30]. However, taken with the fact that the number of citations per paper and the fraction that are self-citations are both sizable, these large numbers are not unexpected. Figure 9 shows that overall self-citation has remained constant and moderate, around 20%, and that there has been no sizable recent excess in self-citation.

A more interesting question is whether researchers have a tendency to reciprocate citations by others. If author A cites a paper of author B, does B return the favor by later citing A? To address this question we measure the fraction of citations of one author by another (excluding citations of one's own papers) that are reciprocated in one or more later publications. We calculate separate figures for pairs of authors who have previously coauthored a paper and those who have not and find that 13.5% of citations between noncoauthors are reciprocated when possible, while an impressive 43.8% of citations between coauthors are reciprocated. (Keep in mind that no authors can overlap between a citing and a cited paper for the citation to be considered a coauthor citation and not a self-citation.) Both these numbers are very high compared to the expected reciprocity if citations were made uniformly at random, but this does not necessarily imply a tit-for-tat return of citations. A citation is presumptively an indication that two papers fall in similar subject areas and thus the presence of a citation greatly increases the chances that the authors are working in the same area, which in turn increases the likelihood of citation in general and therefore the chances of reciprocated citation. In the case of previous coauthors, the chances of working in the same field are likely even higher. Unfortunately, we currently do not have any model of the citation process detailed enough to make a quantitative prediction of the size of this effect against which we could compare our measurements to test for significance.

E. Transitivity

Transitivity, in the context of networks, refers to the observation that "the friend of my friend is also my friend" [31]. In the context of coauthorship, for example, it is observed that if A has coauthored a paper with B and B with C, then A and C are more likely also to have coauthored a paper. One can define a so-called clustering coefficient that quantifies this effect, measuring the average probability that the friend of your friend is also your friend [32], and such coefficients have been measured in many networks [12,33–35]. Typically one finds that the values are significantly higher than one would expect if network connections were made purely at random and our coauthorship network is no exception. For the data set studied here we find a clustering coefficient of 0.212, which is comparable to other figures reported for coauthorship networks [5].

In this case, however, the nature of the data set allows us to go further. The conventional explanation for high transitivity in networks relies on a triadic closure mechanism, under which two authors who share a common coauthor are more likely to collaborate in future, perhaps because they revolve in the same circles, attend the same conferences, work at the same institution, or are introduced to one another by

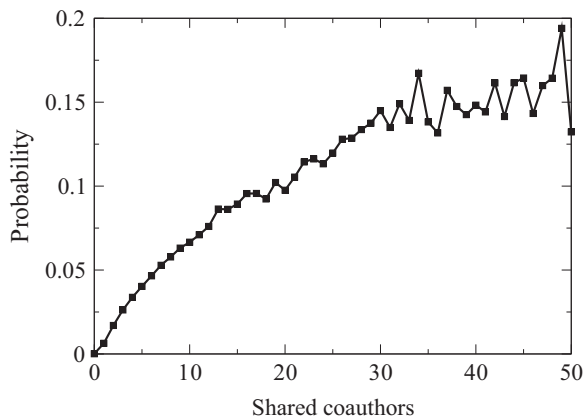


FIG. 10. Probability of future coauthorship with another author as a function of the number of shared coauthors. The number of shared coauthors is counted at the time of first coauthorship or the date of either coauthor's last published paper, whichever comes first.

their common acquaintance [11–13]. The present data set's time-resolved nature allows us to test this hypothesis directly. We can calculate what fraction of the time individuals who share a common coauthor but have not previously collaborated themselves later write a paper together. When we make this measurement for the Physical Review data we find the fraction of such author pairs to be only 0.0345—a much smaller fraction than the clustering coefficient of the whole network reported above. One reason for this small figure is that a large fraction of the transitivity seen in coauthorship networks comes from papers with three or more authors, which automatically contribute closed triads of nodes to the coauthorship network. Such triads, however, are excluded from our calculation of the probability of later collaboration. The large difference between the two probabilities we calculate implies that only a small fraction of the network transitivity comes from true triadic closure processes.

Nonetheless, the triadic closure process does appear to be present in our data set. Figure 10 shows the probability of future coauthorship between two individuals as a function of their number of common coauthors and we see that the probability increases sharply, a finding that is consistent with previous results [11,36].

IV. DISCUSSION AND CONCLUSIONS

In this paper we have analyzed a large data set from the Physical Review family of journals, taking a network perspective. Rather than focus solely on either citation or coauthorship networks, as most previous studies have done, we have instead combined the two, which allows us to study questions about the ways in which people—and not just papers—cite one another and the extent to which scientists collaborate with those they cite or cite those with whom they collaborate. The time span of the data set is unusually large, covering more than a century of publication, which allows us to study long-term changes in collaboration and citation patterns that are not accessible with smaller data sets.

Our main findings are that the Physical Review appears to be growing exponentially, with a doubling rate slightly less than 12 years, and the number of citations per paper within the journals also appears to be growing. The fraction of self-citations and citations among coauthors is more or less constant over time and authors tend to cite their own papers sooner after publication than do their coauthors, who in turn cite sooner than noncoauthors. We observe a strong tendency towards reciprocal citations, researchers who cite another author often receiving a citation in return later on, with especially high rates for citations between coauthors. Contrary to some previous claims [11–13], however, there is only a small triadic closure effect in the coauthorship patterns: Two researchers who share a common coauthor but have never collaborated themselves have only a rather small probability of collaborating in future, about 3.5%. This number is nonetheless much higher than the probability for two randomly chosen researchers and moreover increases sharply as the number of common coauthors increases.

A limitation of our analysis is that the data we use come from a single family of journals in a single field. There are, however, some results for other journals and fields that suggest that the patterns we observe extend beyond physics and the Physical Review. In one recent study, for example, Huang *et al.* [37] examined a collection of papers in computer science drawn from the CiteSeer database of online preprints. They found, as we also do, that the number of papers and number of authors both increase roughly exponentially over time, while the number of authors per paper and number of coauthors per author increase roughly linearly. Wuchty *et al.* [38] examined a large set of papers drawn broadly from the sciences and engineering, using data from the commercial Web of Science database (formerly the Science Citation Index). They observe in particular that the average number of authors on a paper has increased steadily over time, at least for papers with more than one author, which again agrees qualitatively with our observations. Wagner-Döbler [39] studied a data set representing the fields of mathematics, logic, and physics from 1800 to 1998 and found again that collaboration has increased over time, albeit intermittently, and at a rate that depends on the field.

There are many other questions that could be addressed with the data we have analyzed, the unusually long time span and combination of publication and citation data opening up a variety of possibilities. For instance, we know which papers are published in which of the various Physical Review journals and hence we have a crude measure of paper topic, which would allow us to answer questions about how the patterns of coauthorship and citation vary between fields within physics. We could also study geographical variations by making use of the data on authors' institutional affiliations [40]. Our analysis of long-term historical trends could also be extended; for the researcher interested in the history of US physics, there are no doubt many interesting signatures of historical events hidden within the data. The data set also offers the possibility of tracking the careers of individual scientists, possibly over long periods of time, or of tracking research on a particular topic. Finally, any of our analyses could be extended to data sets that cover other journals or fields other than physics, if and when such data become available. All of these would make excellent subjects for future investigation.

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APPENDIX: DATA PROCESSING

As mentioned in the main text, we performed some preprocessing on the raw Physical Review data to disambiguate author names and remove extreme outliers. This Appendix describes the steps taken.

1. Author name disambiguation

The data were supplied in two blocks: (i) a list of papers with associated information, such as authors, author affiliation, journal, and year of publication, and (ii) a list of citations, using unique paper identifiers that correspond to entries in the first block. There are, however, no unique identifiers for authors that are consistent between papers, making unambiguous author identification difficult. Not all authors use the same form for their name on every publication and there are many examples of distinct researchers with the same name. Before using the data set, therefore, we made an effort to associate names of authors with unique people. As in previous work on author disambiguation, our process starts by assuming every name on every paper to represent a different individual [10], then computes a number of measures of author similarity, and assumes authors who are sufficiently similar by these measures to be the same person. After completing this disambiguation process we checked a subset of the results by hand to estimate error rates for the process and found that it performs well. Details are as follows.

Our approach relies not only on the author names themselves to establish similarity, but also on collaboration patterns and institutional affiliation, since authors with similar names who have many of the same collaborators or who are at the same institution are more likely to be the same person. Affiliation information, however, like the author names themselves, tends to be ambiguous and inconsistent, so our first step is to combine affiliations that are deemed similar enough. We measure similarity using a variant of edit distance applied to the affiliation text strings, implemented using the Python `diffib` library.

Once the affiliations are processed in this way, we process the author names as follows.

(a) We combine all authors with identical names who share an institutional affiliation. It appears to be uncommon for two physicists at the same university to publish under identical names, so this seems to be a safe step.

(b) We find author pairs with similar but not identical names. Our criterion for similarity at this stage is that authors should have identical last names and compatible first and middle names (i.e., identical if fully written out or compatible initials where initials are used). Also authors should not have published together on the same paper (which rules out, for example, family members with similar names who publish together). For all pairs with similar names we then calculate a further similarity measure based on how many affiliations they share, how many coauthors they share, whether their full names

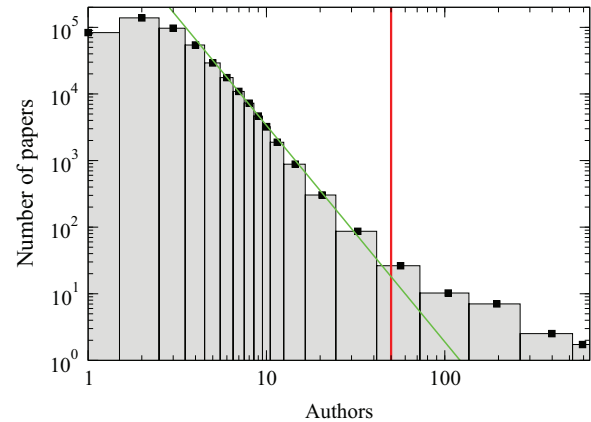


FIG. 11. (Color online) Histogram of the number of papers with a given number of authors. The vertical line falls at 50 authors and corresponds roughly to the point at which the distribution deviates from the power-law form indicated by the fit. The data for ten authors and more have been binned logarithmically to minimize statistical fluctuations.

are identical, and whether they have published in the same journal. Authors with a high enough similarity are combined, most similar pairs first.

We have tested the accuracy of this process by drawing two lists at random from its output, the first containing 79 instances in which authors with similar names have been combined into a single author and the second containing 111 instances in which they have not. We then performed, by hand, a blind search—without knowing the choice the algorithm has made—for publicly available on-line information about the names in question, to determine whether they do indeed represent the same or distinct researchers. We find the false positive rate to be 3% (i.e., 3% of pairs are incorrectly judged to be the same person when in reality they are distinct) and the false negative rate to be 12%.

We also tested the effect on our results of the disambiguation process by calculating a number of the statistics reported in this paper both for the disambiguated data and for the raw data set before disambiguation, in which we naively assume that every unique author string represents a unique author and every pair of authors with the same string are the same person. We found substantial differences between the two in some of the most basic statistics, such as total number of distinct authors: The number was 328 938 in the raw data set, but fell to 235 533 after disambiguation. In contrast, some other statistics changed very little, indicating that these are not particularly sensitive to details of author identification. For example, the clustering coefficient changes from 0.222 in the raw data set to 0.212 in the disambiguated data set.

2. Data culling

In addition to author disambiguation we cull the data according to a few simple rules. There are a number of papers in the data set that have no authors listed, primarily editorials and other logistical articles without scientific content. These we remove entirely. As mentioned in the text, we also identify all papers with 50 or more coauthors and many of our calculations are performed in two versions, with and without these papers.

The choice of 50 authors as the cutoff point was made by inspection of the distribution of author numbers shown in Fig. 11. As the figure shows, the number of papers with a specific number of coauthors appears, roughly speaking, to follow a power law (in agreement with some previous studies [41], but not others [42]), but there is a marked deviation from the power-law form for the highest numbers of coauthors, above about 50, indicating potentially different statistical laws in this regime and possibly different underlying collaborative processes.

We also removed from the data a small number of citations. In a few cases a paper is listed as citing itself, which we assume to be an error. In a number of other cases papers cite others that were published at a later time, which violates causality. These too are assumed to be erroneous and are removed. Finally, the data indicate that some papers cited the same other paper several times within the one bibliography; such multiple citations we count as a single citation.

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