The role of mainstreamness and interdisciplinarity for the relevance of scientific papers

Stefan Thurner\textsuperscript{1,2,3,4}, Wenyuan Liu\textsuperscript{5}, Peter Klimek\textsuperscript{1,2}, Siew Ann Cheong\textsuperscript{5}

\textsuperscript{1} Section for the Science of Complex Systems, CeMSIIS, Medical University of Vienna, Spitalgasse 23, A-1090, Vienna, Austria
\textsuperscript{2} Complexity Science Hub, Vienna Josefstädterstrasse 39, A-1090 Vienna, Austria
\textsuperscript{3} Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA
\textsuperscript{4} IIASA, Schlossplatz 1, 2361 Laxenburg, Austria
\textsuperscript{5} Division of Physics & Applied Physics, School of Physical and Mathematical Sciences, Nanyang Technological University, 21 Nanyang Link, 637371, Singapore

There is demand from science funders, industry, and the public that science should become more risk-taking, more out-of-the-box, and more interdisciplinary. Is it possible to tell how interdisciplinary and out-of-the-box scientific papers are, or which papers are mainstream? Here we use the bibliographic coupling network, derived from all physics papers that were published in the Physical Review journals in the past century, to try to identify them as mainstream, out-of-the-box, or interdisciplinary. We show that the network clusters into scientific fields. The position of individual papers with respect to these clusters allows us to estimate their degree of mainstreamness or interdisciplinarity. We show that over the past decades the fraction of mainstream papers increases, the fraction of out-of-the-box decreases, and the fraction of interdisciplinary papers remains constant. Studying the rewards of papers, we find that in terms of absolute citations, both, mainstream and interdisciplinary papers are rewarded. In the long run, mainstream papers perform less than interdisciplinary ones in terms of citation rates. We conclude that to avoid a trend towards mainstreamness a new incentive scheme is necessary.

I. INTRODUCTION

Science has become a tremendously expensive industry over the past century. The world’s current total nominal Research and Development spending is approximately two trillion US dollars \cite{1}. The amount of publications has increased exponentially for more than a century. Scientific output measured in numbers of papers has increased from about 2000 in 1900 to one million papers in 2010 (Web of Science). In physics alone, in the same timespan papers rose from about 200 to 200,000 \cite{2}. There are signs, however, that science might become less efficient and that its output in terms of groundbreaking discoveries and inventions—not the number of papers published or PhDs granted—is declining. In 1996, Leo Kadanoff stated “The truth is, there is nothing—there is nothing—of the same order of magnitude as the accomplishments of the invention of quantum mechanics or of the double helix or of relativity. Just nothing like that has happened in the last few decades.” \cite{3}. In a more recent study, a similar conclusion is drawn in a survey of leading scientists in various fields based on their opinion on relevant contributions to science over the past century \cite{4}. There are various possibilities to explain a possible decline of rates for fundamental scientific discoveries. Either most of the discoverable things have been discovered already\cite{1} or the quality of scientists is going down, or the appetite and incentives for solving new and big problems with new and risky frameworks is declining.

When choosing a scientific problem, a scientist can choose a big problem that no one was able to solve before—most likely because a methodological framework or the technological means are not yet there—or a small one that only incrementally improves upon generally accepted knowledge, and for which an accepted framework, technology, and an informed community already exists. Doing innovative science often means not only to step out-of-the-box and think anew, invent novel and adequate frameworks, views and eventually solutions, but also—in case of success—one has to fight the community and the keepers of current dogmas to accept new ways of thinking \cite{6}. This is risky and—even though beneficial to science—can be detrimental to scientific careers. Indeed, most scientists seem to opt for the low-risk option. In \cite{7} it was found that the vast majority of papers in biomedicine and chemistry published between 1934 and 2008 were building on existing knowledge rather than generating novel and innovative findings. They attribute their findings to an inadequate incentive structure with a
The prevalent incentive scheme in science production is based on productivity factors, such as numbers of papers, quality factors, such as citations, and cumulative indicators, like the h-factor and its variations. These indicators create the questionable belief that people without knowledge in science can make decisions such as which scientists should be hired or funded. This is maybe true for incremental science but certainly not for judging, who is creative enough and has the potential, strength, and courage to carry through true breakthroughs that move knowledge forward. These indicators pose incentives to produce papers that stay close to the mainstream. The mainstream—by definition—contains the largest pool of scientists that can cite you. Papers receive more citations than others published on the same topic at the same time, if their abstract simply uses keywords occurring in a larger number of other abstracts [8]. Most scientists know the mainstream literature well. Incremental mainstream—by definition—contains the largest pool of scientists that can cite you. Papers receive more citations than others published on the same topic at the same time, if their abstract simply uses keywords occurring in a larger number of other abstracts [8]. Most scientists know the mainstream literature well. Incremental mainstream papers do not make much headway towards new big discoveries.

Science progresses discovery by discovery. Usually discoveries are presented in papers. Not every paper is a discovery; mainstream science papers often are not. Typically, new innovations build on existing knowledge, often novelty arises from new re-combinations of existing knowledge and ideas. The case in science is similar to progress of technology [12]. Figure 1 (a) shows a cartoon image of the “progress of science”. Every node represents a paper that made a significant contribution to science (innovation or breakthrough). Red nodes are discoveries made in the past that have been published. Grey nodes are hitherto undiscovered—but discoverable—scientific facts. Black arrows indicate which work influenced which. The set of dashed green lines is the so-called “adjacent possible”, the set of scientific facts that can be discovered within the next time period, given the state of current knowledge, i.e. the set of red nodes. Dashed grey lines show the possibilities that open up once new progress has been made. Once a discovery is made, the corresponding grey node turns into a red one. Incremental or timid mainstream research is depicted in Fig. 1 (b). It shows a blow up of (a).

In this paper, we want to find out if this picture is correct and can be supported by data. In particular, we ask how innovative and bridging science is rewarded in terms of citations in the long run compared to mainstream. We use several measures to estimate the degree of “interdisciplinarity” of individual papers. For this, we use the bibliographic coupling (BC) network [13] of all papers that appeared in one of the Physical Review journals in the last century. It is a way to quantify the similarity of papers. In the BC network, \( M \), papers are represented as nodes, a link is defined between two papers \( i \) and \( j \) if they both cite a common paper. The weight of the link, \( M_{ij} \), is the overlap of the reference lists of the two citing papers. The BC network can be seen as a rough proxy for the picture shown in Fig. 1 in particular for the existing red nodes. BC networks clearly exhibit clusters of similar scientific areas or fields, as papers within

![Image](image1.png)
closely related areas are linked with each other through the same references, see Fig. 2. This reflects the fact that authors that constitute a discipline tend to read the same literature.

Interdisciplinary papers often “link” works from different areas. In this sense, Einstein’s 1905 relativity paper would bridge the areas of mechanics and electrodynamics. To quantify interdisciplinarity, we take two approaches. First, we use the minimal distance of a paper to the center of the nearest cluster. Clusters we compute by k-means clustering, see Methods. Mainstream papers would appear near the cluster centers. As a quantity for reward and a proxy for relevance of a paper in the long run, we look at the number of citations it acquired two ($C_i^2$) and twenty years ($C_i^{20}$) after its publication. We hypothesize that two things should be observable: (i) the existence of many immediately well-performing papers in the cluster centers, and (ii) an over-representation of well-performing papers located at the periphery and between clusters at a later stage. These need some time to be discovered and understood, and should not appear immediately, but only after some time. For a second measure of interdisciplinarity, we follow an idea reported in [14], based on the Physics and Astronomy Classification Scheme (PACS) numbers that are used by authors to assign research areas to their papers. Typically, more than one PACS number is used. The interdisciplinarity of a paper is associated with the diversity of the PACS numbers of its references. The diversity of every paper $i$ is measured by its “PACS entropy”, $I_i$, see Methods.

It is not the purpose of this paper to predict scientific success of papers and scientists. This has been done in recent works [2, 15–17]. Here we use the BC network to identify papers as mainstream, out-of-the-box, or interdisciplinary. We want to elucidate the positions of important papers within that network and show that these often are indeed out-of-the-box and interdisciplinary, especially at longer timescales.

RESULTS

In Fig. 2 (a) we show the BC network of the 8673 papers published in 1991 in all of the Physical Review journals (PR A, PR B, PR C, PR D, PR Letters, and Reviews of Modern Physics). Small and large clusters of research areas are clearly distinguishable, ranging from a few to hundreds of papers. Node colors mark different journals. Node size is the number of citations in 2011, $C_i^{20}$. In this network, interdisciplinary or bridging papers would be positioned between clusters; “out-of-the-box” papers would be found in the periphery of clusters. Mainstream papers are typically in the center of clusters. Papers of all this type are visible in Figs. 2 (b) and (c). Here node size is the annual citation rate measured two years after publication in (b), $C_i^2/2$, and after twenty years, $C_i^{20}/20$, in (c). We show rates to be able to sensibly compare rewards at the two time scales in (b) and (c). Obviously, annual citation rates observed over 20 years are smaller than when measured in the first two years after publication. It is visible by plain inspection that many well-cited papers on the long timescale, (c), appear in the periphery of clusters (out-of-the-box) and between the clusters (bridging). Papers in the cluster centers seem to become relatively more marginal in the long term. Note the positions of PRL papers (red) and the review articles (brown). PRL papers seem to attract much short-term attention but cease to be dominant in the long run. One of the two review articles (brown) ap-
FIG. 3. (a) Distribution of the distances of individual papers to the centers of their nearest clusters in the years 1981 (blue), 1991 (red), and 2011 (green). Over time, the distribution shifts toward smaller distances, i.e. more papers tend to appear in cluster centers. (b) The distribution of degrees over the same years shift towards much larger values (tail increase), i.e. there is a tendency to increasingly link to more similar papers. (c) Scatterplot of citations of papers published in 1991, twenty years after their publication, $C_{20}$, versus their distance to cluster centers. The 90%, 70%, and 50% quantiles are shown in green, red, and blue, respectively. Citations increase with higher distances from clusters; bridging papers are awarded in the long run. (d) Citations, $C_{20}$, versus their degree. A clear increase is apparent. (e) Distribution of citations for small and large values of distance. The plot is a normalized histogram of the 400 papers with the shortest distances. The blue distribution is for the 400 papers with the largest distance. (f) Distribution of citations for small and large degree.

Temporal trends. We next look at historical trends of where papers are localized in the BC network. In Fig. 3 (a) we see the distribution of the distances to the nearest k-means cluster, $D_i$, for the years 1981, 1991, and 2001. Over the three years the distribution shifts to the left; the medians change from $2.25 \times 10^{-3}$ in 1981, to $1.96 \times 10^{-3}$ and $1.84 \times 10^{-3}$, in 1991 and 2001, respectively. A Wilcoxon rank sum test for equal medians yields p-values $< 10^{-9}$ for all possible pairs of years. The tail of the distribution is similar for the three years. This means that there is a tendency of papers shifting towards the cluster centers, at the expense of the fraction of papers that sit at the periphery; there is practically no change in the fraction of papers between clusters. The tendency that clusters get more populated in the center is also seen in the degree distributions of papers in the BC network. The distribution functions for the same three years are shown in Fig. 3 (b). The distribution changes toward higher degrees; medians shift from 16 in 1981 to 26 and 41 in 1991, and 2001, respectively. The Wilcoxon rank sum test yields highly significant p-values $< 10^{-81}$ for all pairs of years. Papers get more similar to many others. Both plots indicate that over time, clusters become more populated in the centers and that the relative contribution of bridging papers does not change over time.

Conditional distributions of citations. Figure 3 shows the 50%, 70%, and 90% quantiles of the distribution of the 20 year citations, $C_{20}$, in 1991, conditioned on the minimal distance to the nearest cluster, $D_i$, see (c), and conditioned on the degree of the papers, see (d). The 50% quantile is the median. We partitioned the data along distance and degree into bins that contain 400 data points each. In this way, a reasonable definition of the quantiles along distance and degree is possible. In both cases, (c) and (d), it is visible that the median (blue), the 70% (red), and the 90% (green) quantiles rise significantly with distance and degree. This means that two effects take place simultaneously: first, out-of-the-box and interdisciplinary papers seem to be rewarded (large distances) and, second, as one would expect, mainstream publications are rewarded in terms of citations. Not surprisingly, the more papers a given paper is linked to (degree) it is cited. We verified that if citations are assigned to randomly chosen papers, constant quantiles at the appropriate levels are obtained.

In Fig. 3 (e) we present the distribution function of twenty-year citations for short distances to the nearest cluster (red), and for large ones (blue). The distribution for short distances (in the leftmost bin in (c)) contains all papers with a distance in the range of $D_i \in [0, 2.3 \times 10^{-4}]$. Large distances (rightmost bin in (c)) cover the data in the range of $D_i \in [9.2 \times 10^{-3}, 1.27 \times 10^{-2}]$. The citation distribution changes visibly towards larger medians, from 3 to 13 (Wilcoxon test $p < 1.68 \times 10^{-56}$). The same type of citation distribution is shown in Fig. 3 (f) for small (red) and large (blue) values of the degree. The same pattern is found: for high degree papers, the citation distribution has a higher median (Wilcoxon test $p < 2.01 \times 10^{-35}$). We find similar results also for the betweenness, see SI Fig. VII (a) and (b), however, somewhat less pronounced.
...inferred. To naively control for the length of the reference from which a linear relation of the median (blue) can be...median of the respective distributions increase from 3.0 to 12.3 (Wilcoxon p < 10^{-300}). For the betweenness, seen in (e)-(f), medians for small and large values shift from 4.5 to 9.8 (Wilcoxon p < 4.35 \times 10^{-5}). The results for the short-term citations of authors can be seen in SI VII, where the cumulative combined citations in 1993 of all papers produced between 1981-1991 are shown; same panels as in Fig. 5.

Regression analysis and robustness tests. To better understand the extent to which our results could be confounded by the length of the reference list, L_i, we perform a regression analysis, see SI. For each considered dependent variable, we find a strongly significant positive linear relationship with citations after 20 years, C_{i}^{20}, see Tab. 1 in SI. The strongest relations are observed for the degree, which increases with citations by a factor of 0.33(1), and for distances that increase with a factor of 0.26(1). Numbers in brackets denote standard deviations at the last significant digit. In both cases we have p < 10^{-130} against the null hypothesis that the true coefficient value is zero. After adjusting for the length of the reference list, L_i, these relations remain strongly significant (coefficients of 0.31(1), p < 10^{-100}, for the degree; 0.18(1), p < 10^{-46}, for the distance). The correlation with the PACS entropy vanishes almost entirely (from 0.22(2), p < 10^{-28}, to 0.08(3), p = 0.008, after the adjustment), see Tab. 1 in SI. Similar observations hold for author-level results; see Tab. 1 in SI, where we show that the correlations of author citations with degrees, distances, closeness, and betweenness remain strongly significant after adjusting for reference list length or the number of publications.

From papers to authors. Do these findings also hold for authors? By associating papers to authors we observe similar results. In Fig. 5 we show the citations of authors versus the same network measures as in Fig. 3 (c)-(d). To this end, we identify all papers of authors that were published in the period 1981-1991. We count all citations of all of these papers up to 2011. For every year between 1981-1991, we construct the BC network and compute the average distance to nearest clusters, the average degree, and the average betweenness for all the papers of that author in that year. We finally average over all years 1981-1991 for all authors. Figure 5 (a) shows scatterplot and quantiles for author citations versus the average nearest distances. In Fig. 5 (b) the corresponding distributions for small (red) and large (blue) distances are shown. Medians shift from 3.5 to 9.0 (Wilcoxon p < 10^{-202}). Figures 5 (c)-(d) display the situation for the degree. For small and large values the medians of the respective distributions increase from 3.0 to 12.3 (Wilcoxon p < 10^{-300}). The correlation of the degree, see Fig. 5 (c)-(d), medians for small and large values shift from 4.5 to 9.8 (Wilcoxon p < 4.35 \times 10^{-5}). The results for the short-term citations of authors can be seen in SI VII, where the cumulative combined citations in 1993 of all papers produced between 1981-1991 are shown; same panels as in Fig. 5.

Regression analysis and robustness tests. To better understand the extent to which our results could be confounded by the length of the reference list, L_i, we perform a regression analysis, see SI. For each considered dependent variable, we find a strongly significant positive linear relationship with citations after 20 years, C_{i}^{20}, see Tab. 1 in SI. The strongest relations are observed for the degree, which increases with citations by a factor of 0.33(1), and for distances that increase with a factor of 0.26(1). Numbers in brackets denote standard deviations at the last significant digit. In both cases we have p < 10^{-130} against the null hypothesis that the true coefficient value is zero. After adjusting for the length of the reference list, L_i, these relations remain strongly significant (coefficients of 0.31(1), p < 10^{-100}, for the degree; 0.18(1), p < 10^{-46}, for the distance). The correlation with the PACS entropy vanishes almost entirely (from 0.22(2), p < 10^{-28}, to 0.08(3), p = 0.008, after the adjustment), see Tab. 1 in SI. Similar observations hold for author-level results; see Tab. 1 in SI, where we show that the correlations of author citations with degrees, distances, closeness, and betweenness remain strongly significant after adjusting for reference list length or the number of publications.
FIG. 5. Dependence of citations of authors on network measures; dots now represent authors. (a) Scatterplot of all citations up to 2011 of all those papers an author has published between 1981 and 1991, versus the average distance of these papers to their respective closest cluster in the BC network in the year of publication. 90%, 70%, and 50% (median) quantiles are shown in green, red, and blue, respectively. Citations increase with higher average distances. (b) Distribution of authors’ citations for short (red) and large (red) distances. The plot is a normalized histogram of the 4000 authors with the smallest distance. The blue distribution is for the 4000 authors with the largest distance. (c) and (d) show the case for the degree. Again, citations increase strongly with degree. The betweenness results are seen in (e) and (f). As for papers, the effect for betweenness is weak.

DISCUSSION AND CONCLUSION

Current incentive structures almost exclusively reward the production of mainstream science. It is not only the increasing importance of the number of citations or the h-index, it is also that papers and proposals will only be accepted if they are sufficiently understood by peers—which is often not the case for out-of-the-box and novel ideas that need backgrounds from more than one field to be understood. To suggest high-risk papers, projects, or individuals poses reputational risk for referees and committee members. Even though high-risk/high-reward science is highly needed by society it is only happening to an astonishingly low degree in academia.

Here we explored the extent to which scientific work can be quantified as mainstream, out-of-the-box, or interdisciplinary. We study the bibliographic coupling network and find that it is nicely structured into clusters of various sizes. Clusters are groups of papers that cite the same literature, i.e. constitute scientific areas. The existence of these clusters allows us to actually visualize how mainstream, out-of-the-box, or interdisciplinary a paper is by locating it in this network, relative to nearby clusters. Mainstream papers are located close to cluster centers. Bridge- and interdisciplinary papers are found between clusters.

To estimate the reward of papers we simply count their citations two and twenty years after their publication. We find that mainstream is indeed rewarded in terms of absolute numbers of short-term citations. However, this is not the case for citation rates, where many out-of-the-box and interdisciplinary papers do better in the long run. In the long run, citation rates near the cluster centers decline when compared to many papers on the periphery or between clusters. When looking at temporal trends, we see that the fraction of mainstream papers increases considerably from 1981 to 2001, while the fraction of interdisciplinary papers stays practically constant. The number of out-of-the-box papers decreases in favor of the mainstream papers.

Several recent studies in the new field of “Science of Science” focus on various aspects of science production, in particular on the citation mechanism [15], impact prediction [10], or on scientific careers [21]. In [15] a mechanistic model that incorporates preferential attachment, attention decay, and “fitness” was proposed to predict the long-term citation impact based on a paper’s early citation history. A study of 2887 physicists in [16] found that factors leading to highly cited papers are not random. By combining productivity and a scientist-specific “Q factor”, they propose a stochastic model to explain scientific success. Analyzing data of 200 leading scientists and 100 assistant professors, [21] found that persistent career trajectories lead to increasing returns in the scientific production. The model there also shows that short-term contracts may lead to early career termination [21]. The role of early career co-authorships is studied in [17]. The importance of a mesoscopic picture on knowledge evolution was realized in [20]. There topical clusters of APS papers were analyzed and visualized across a century with alluvial diagrams. The roles of mainstreamness and interdisciplinarity have so far not received much attention, even though the topic has been identified, discussed, and even used by funding agencies [22]. An important contribution in this direction is [14] that uses the PACS diversity of authors (defined differently than here) to demonstrate that authors with very low (experts) and very high PACS diversity (very interdisciplinary) are on average cited much better than authors with intermediate PACS diversity. We see our paper as a contribution to

4 See changes in node sizes from Fig. 2 (b) to (c).
5 This is visible in Fig. 3 (a), where there is a strong increase in the first bin, whereas bins 3-5 decrease from 1981 to 2001. The tail is practically unaffected, meaning that the fraction of bridging papers remains constant.
an appropriate and robust quantitative framework that can be used to build new incentive schemes for science production.

The presented approach has obvious shortcomings. The most striking is that papers are not classified by experts, neither as being mainstream or interdisciplinary, nor their quality in terms of being breakthrough or mediocre. The rewards studied to demonstrate that the BC network is indeed a useful concept for thinking of mainstream and interdisciplinary, is itself still based on numbers of citations and rates thereof. A technical problem is the use of k-means clustering that we need for defining cluster centers. It is well possible that k-means clustering of the adjacency matrix of the BC network is too naive an approach. However, the fact that a similar effect is visible in the betweenness, even though smaller, indicates validity of the approach.

In conclusion, we think that in order to make science more than a self-sustained academic exercise and to avoid the dangers of being seen by the public and decision makers as a mere pastime of academics, it is paramount to change the current incentive scheme for science and research. To avoid the reported convergence towards mainstream it is necessary to think of how to reward authors in ways that incentivize out-of-the-box thinking, interdisciplinarity, and of course, actual problem-solving. A metric for such a reward scheme could indeed include the distance to clusters, measures of betweenness, and the degree of the BC network. It is conceivable that authors will try to optimize such schemes by using particular citing strategies and without producing more content. However, it would incentivize them to keep an open eye for developments in other areas of science other than their own.

**DATA AND METHODS**

**Data.** The American Physical Society (APS) data set used here includes 6,040,030 citations in all APS journal papers (Physical Review) published between 1893 and 2013 [23]. Besides citations, metadata records for 541,448 papers over the same time period are available. Each record includes the digital objective identifier (doi), title, author(s), affiliation(s), publication date, and PACS numbers (if available).

**Bibliographic coupling network.** In 1991 there were 9688 papers published in all the Physical Review journals A, B, C, D, Letters, and Reviews of Modern Physics [23]. Papers are uniquely identified by their digital objective identifier (doi). After removing editorials and errata (as provided in the meta information file of the APS data) 8831 papers remain. From these we construct the bibliographic coupling (BC) network, $M$, where paper $i$ is linked with paper $j$ if they both cite at least one common paper that was published before 1991. The weight on the (undirected) link, $M_{ij}$, is the overlap of the reference lists of paper $i$ and $j$. If both papers do not cite any third paper in common, $M_{ij} = 0$. Nodes that are not linked to the largest connected component are excluded. The resulting BC network is finally composed of 8673 nodes and undirected 235,971 weighted links. The BC network does not change with the arrival of new papers and their citations. Note that BC networks are very different from co-citation networks [24]. We identify 62 authors in the author lists of the considered 8831 papers. We do not distinguish between authors and large collaborations that are identified as such.

**Characteristics of papers.** We record the number of citations of every paper $i$ after two, $C_i^2$, ten, $C_i^{10}$, and twenty, $C_i^{20}$, years after its publication in 1991. The number of references cited in every paper is denoted by $L_i$. For every paper that appears in the BC network we compute the following properties. Weighted betweenness, $B_i = \sum_{s,t \in V} \frac{\sigma(s,t|v)}{\sigma(s,t)}$, where $V$ is the set of nodes, $\sigma(s,t)$ is the number of weighted shortest paths between nodes $s$ and $t$, and $\sigma(s,t|v)$ is the number of those paths going through node $v$. Weighted closeness, $K_i = \frac{1}{\sum_j d_{ij}}$, where $d_{ij}$ is the weighted network distance from node $i$ to $j$. The diversity of a paper we quantify by its PACS entropy: for every paper $i$ we construct the list, $PC_i$, of all PACS codes that appear in all the papers listed in the references of paper $i$. We then calculate the Shannon entropy of $PC_i$ as $I_i = -\sum_j p_i^c \log_2 p_i^c$, where $p_i^c$ is the (normalized) frequency of the PACS code, $\alpha$, in the list, $PC_i$. Not all papers have PACS information. To compute $I_i$ we only take papers for which there is PACS information for more than 80% of its cited references. Different thresholds were tested; results are very similar. Only 2491 papers meet the 80% criterion. To measure the distance, $D_i$, of paper $i$ to its nearest cluster center we use k-means clustering with a Hamming distance. $D_i = \min_{\ell} \| \text{cluster}_\ell - \text{position}_i \|_h$, where cluster$\ell$ is the position of the center of cluster $\ell$, and position$_i$ is the position of node $i$. We chose $k = 20$ clusters. All reported results are qualitatively very similar when 100 clusters are used. Because of their non-normality, we tested whether the medians of the distribution of $D_i$ changed over time with a two-sided Wilcoxon rank sum test.

**ACKNOWLEDGMENTS**

We acknowledge support from the Singapore Ministry of Education Academic Research Fund under grant number MOE2017-T2-2-075 and from the Austrian FFG Project 857136.

[1] Global Research and Development Expenditures: Fact Sheet, Report R44283, update from Sept 19, 2019.

[2] Sinatra, R., Deville, P., Szell, M., Wang, D., Barabasi,
A.-L. (2015). A century of physics. *Nature Physics* **11**, 791-796.

[3] Horgan, J. The end of science: facing the limits of knowledge in the twilight of the scientific age. (Addison-Wesley Pub., 1996).

[4] Collison, P., Nielsen, M. Science is getting less bang for its buck. *The Atlantic* Nov 16, 2018.

[5] Lord Kelvin. (1900) maybe in an address before the British Association for the Advancement of Science, 1900.

[6] Kuhn, T. The structure of scientific revolutions. (University of Chicago Press,1962).

[7] Foster, J. G., Rzhetsky, A., Evans, J. A. Tradition and innovation in scientists’ research strategies. *American Sociological Review* **80** (5), 875-908.

[8] https://en.wikipedia.org/wiki/Replication_crisis

[9] Klimek, P., Jovanovic A.S., Egloff, R., Schneider, R. (2016) Successful fish go with the flow: citation impact prediction based on centrality measures for term-document networks. *Scientometrics* **107**:1265–1282.

[10] Sandström, U., Van den Besselaar, P. (2018) Funding, evaluation, and the performance of national research systems. *Journal of Informetrics* **12** (1), 365-384.

[11] Thurner, S., Hanel, R. (2011) Peer-review in a world with rational scientists: toward selection of the average. *European Physical Journal B* **84**, 707-711.

[12] Arthur, W. B. The nature of technology: what it is and how it evolves. (Free Press, 2009).

[13] Kessler, M.M. (1963) Bibliographic coupling between scientific papers. *American Documentation* **14** (1), 10-25.

[14] Bonaventura, M., Latora, V., Nicosia, V., Panzarasa, P. (2017) The advantages of interdisciplinarity in modern science. arXiv:1712.07910v1.

[15] Wang, D., Song, C., Barabasi, A.-L. (2013) Quantifying long-term scientific impact. *Science* **342** (6154), 127-132.

[16] Sinatra, R., Wang, D., Deville, P., Song, C., Barabasi, A.-L. (2016). Quantifying the evolution of individual scientific impact. *Science* **354**, 6312.

[17] Li, W., Aste, T., Caccioli, F., Livan, G. (2019) Achieving competitive advantage in academia through early career co-authorship with top scientists. arXiv:1906.04619v1.

[18] Manousakis, E. (1991) The spin-$\frac{1}{2}$ Heisenberg antiferromagnet on a square lattice and its application to the cuprous oxides *Rev. Mod. Phys.* **63**, 1.

[19] Sigrist, M., Ueda, K. (1991) Phenomenological theory of unconventional superconductivity. *Rev. Mod. Phys.* **63**, 239.

[20] Liu, W., Nanetti, A., Cheong, S. A. (2017) Knowledge evolution in physics research: an analysis of bibliographic coupling networks. *PLoS one* **12** (9), e0184821.

[21] Petersen, A. M., Riccaboni, M., Stanley, H. E., Pamolli, F. (2012). Persistence and uncertainty in the academic career. *Proceedings of the National Academy of Sciences*, **109** (14), 5213-5218.

[22] Qualitative evaluation of completed projects funded by the European Research Council (2017). https://erc.europa.eu/sites/default/files/document/file/2018-qualitative-evaluation-projects.pdf

[23] APS Data Sets for Research. https://journals.aps.org/datasets. Downloaded in March 2016.

[24] Zhao, D., Strotmann, A. (2008) Evolution of research activities and intellectual influences in information science 1996-2005: introducing author bibliographic-coupling analysis. *J of the American Society for Information Sci-
In Fig. VI (a) we mark two review papers with brown arrows. The one that appears in the periphery of the upper right cluster is Rev. Mod. Phys. 63.118. It explicitly states in its abstract that it uses a variety of methods from different fields, "[...] and rather conventional picture emerges from a number of techniques—analytical (spin-wave theory, Schwinger boson mean-field theory, renormalization-group calculations), semianalytical (variational theory, series expansions), and numerical (quantum Monte Carlo, exact diagonalization, etc.)." This is exactly what is expected. The paper uses methods from various fields and finds a "conventional picture", that is maybe not so far from the mainstream. It is a clear periphery paper.

The other review paper (brown arrow) that appears in the lower right corner of Fig. II (c) is Rev. Mod. Phys. 63.23919. Its title, "Phenomenological theory of unconventional superconductivity" already hints at its non-mainstreamness. The paper only got significant recognition in the long run. The paper appears as one in a group of several papers that form a small cluster of papers working on similar problems. All of the papers have a large betweenness and distance to their nearest k-means cluster. Most of them did not gain recognition later on, except for Rev. Mod. Phys. 63.239.

Figure VI shows the same section of the BC network as in Fig. II (b). Node size represents the annual citation rates after two years. In Fig. VI (b) we make all nearest neighbours of a paper (marked by arrow) located in the upper right cluster visible. It is obvious that the marked paper is linked to papers that are located predominantly in the same cluster. Figure VI (c) shows that the same is true for papers in other clusters; the neighbours of a randomly chosen paper in the lower left cluster are made visible, almost all belong to the same cluster. Finally, in Fig. VI (d) we mark a paper that is situated between the clusters (arrow). Its neighbors in the BC network are clearly papers from both clusters. The marked paper is clearly a bridging paper. Note that not all papers that appear between clusters are bridging papers.

Details of Figure 2

In Fig. II we visually inspect the situation of how the position of papers is related to their performance shortly (2 years) after publication (b), and within a twenty year timespan (c). Here we provide more detailed information on a few example papers.

The largest node in the lower left cluster (green arrow in Fig. II (c)) is the Phys. Rev. B article 43.130, entitled "Thermal fluctuations, quenched disorder, phase transitions, and transport in type-II superconductors". Within our scheme, it would classify as a periphery or out-of-the-box paper. It was recognized as important immediately and is still relevant on the long timescale. Many papers in its surrounding, that are more towards the cluster center (many PRLs) got immediate citations but they are not well-cited in the long run. This is seen for example in the Phys. Rev. Lett. 66.953, which appears directly to the southeast of Phys. Rev. B 43.130. Its title is "SQUID picovoltometry of YBa2Cu3O7 single crystals: evidence for a finite-temperature phase transition in the high-field vortex state". It was well-cited immediately after publication but lost impact over time; note how the citation rate (node size) reduces from Fig. II (b) to (c).

Dependence on other network measures

An obvious candidate measure for interdisciplinarity is the weighted betweenness. In Fig. VII (a) and (b) we show the scatterplot for the twenty year citations, \( C_{20} \), versus betweenness, \( B_i \), in the same style as in Fig. III (c) and (e). For completeness, we also show the corresponding plots for the closeness, \( K_i \), and the length of reference list, \( L_i \), in Fig. VII (c) and (d), and (e) and (f), respectively.

Regression analysis

In the regression analysis we use the degree, PACS entropy, \( I_i \), the reference list length, \( L_i \), the closeness
centrality, $K_i$, betweenness, $B_i$, and distance, $D_i$, as dependent and the twenty year citation rate, $C_{20}^i$, as the response variable. Each observation is one paper. First, with a Kolmogorov–Smirnov test we inquire whether to take these variables on a linear or a logarithmic scale (to be closer to a normal distribution). A bivariate linear regression model is then fitted between the response and each dependent variable. Finally, each model receives an additional adjustment term with the reference list length, $L_i$, to assess the extent to which this variable might confound the observed correlations (length-adjusted model).

Table I shows the results of the regression analysis performed on the 8673 papers in 1991. For results that involve the PACS entropy, $I_i$, we considered only those 2491 papers for which enough PACS information was available. For each of the dependent variables (degree, entropy, $I_i$, reference list length, $L_i$, closeness, $K_i$, betweenness, $B_i$, distance, $D_i$) we report estimates of the coefficients in a linear bivariate regression on the response variable $C_{20}^i$ in the column labeled “bivariate”. We then show how these coefficients change after adjusting for the length of the reference list, column “length-adjusted”. For completeness, we also show results for regressing the two year, $C_2^i$, and ten year, $C_{10}^i$, citation rates on $C_{20}^i$.

Table II shows the regression results for the author-level analysis. There we consider two adjustment steps, namely (i) the average length of the reference lists of an author’s papers, and (ii) the total number of publications.

**Author citations**

In Fig. VIII we show the dependence of short-term citations of authors. The figure shows the same panels as Fig. V with the difference that citations of the authors were assessed only 2 years after the time period in which the papers were written (1981-1991). Figure IX shows results for author citations in 2011 for closeness (a), length of reference list (c), and the number of papers (e) that individual authors have written in 1981-1991. Panels (b), (d), and (f) show the corresponding distributions for small and large values. Citations
show a strong, super-linear increase with closeness (a), while for the length of the reference list and the number of publications the quantiles increase almost linearly.

FIG. IX. Author citations in 2011 versus (a) closeness, (c) length of the reference list, and (e) the number of papers that authors have written in 1981-1991. Every dot represents an author. Panels (b), (d), and (f) show the corresponding distributions for small and large values.
TABLE II. Results of the author-level linear regression analysis for the bivariate, length-adjusted, and number-of-paper adjusted model. We report estimates together with their standard deviations (SD, numbers in brackets) and p-values against the null hypothesis that the true coefficient value is zero. Variables marked with * were taken on a logarithmic scale.

| citations after 20y* ~ | bivariate estimate (SD) | bivariate p-value < | length-adjusted estimate (SD) | length-adjusted p-value < | no.-of-paper-adjusted estimate (SD) | no.-of-paper-adjusted p-value < |
|-----------------------|-------------------------|---------------------|------------------------------|---------------------------|------------------------------------|-----------------------------|
| Degree*               | 0.313(4) 10^{-256}      | 0.285(4) 10^{-256}  | 0.287(4) 10^{-256}           |                            |                                    |                             |
| Distance              | 0.176(4) 10^{-256}      | 0.0561(9) 10^{-10}  | 0.164(4) 10^{-256}           |                            |                                    |                             |
| Closeness             | 0.221(4) 10^{-256}      | 0.177(4) 10^{-256}  | 0.214(4) 10^{-256}           |                            |                                    |                             |
| Betweenness           | 0.093(4) 10^{-110}      | 0.025(4) 10^{-7}    | 0.090(4) 10^{-106}           |                            |                                    |                             |
| Length                | 0.183(4) 10^{-256}      | 0.173(4) 10^{-256}  | 0.172(4) 10^{-256}           |                            |                                    |                             |
| No. papers            | 0.183(4) 10^{-256}      | 0.173(4) 10^{-256}  | 0.172(4) 10^{-256}           |                            |                                    |                             |