The advantages of interdisciplinarity in modern science

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As the increasing complexity of large-scale research requires the combined efforts of scientists with expertise in different fields, the advantages and costs of interdisciplinary scholarship have taken center stage in current debates on scientific production. Here we conduct a comparative assessment of the scientific success of specialized and interdisciplinary researchers in modern science. Drawing on comprehensive data sets on scientific production, we propose a two-pronged approach to interdisciplinarity. For each scientist, we distinguish between background interdisciplinarity, rooted in knowledge accumulated over time, and social interdisciplinarity, stemming from exposure to collaborators’ knowledge. We find that, while abandoning specialization in favor of moderate degrees of background interdisciplinarity deteriorates performance, very interdisciplinary scientists outperform specialized ones, at all career stages. Moreover, successful scientists tend to intensify the heterogeneity of collaborators and to match the diversity of their network with the diversity of their background. Collaboration sustains performance by facilitating knowledge diffusion, acquisition and creation. Successful scientists tend to absorb a larger fraction of their collaborators’ knowledge, and at a faster pace, than less successful ones. Collaboration also provides successful scientists with opportunities for the cross-fertilization of ideas and the synergistic creation of new knowledge. These results can inspire scientists to shape successful careers, research institutions to develop effective recruitment policies, and funding agencies to award grants of enhanced impact.

The debate on the comparative benefits of specialized and interdisciplinary scholarship boasts a longstanding tradition stretching back several centuries, and still remains largely controversial and unresolved [1–5]. The idea that knowledge can be organized into distinct and self-contained disciplinary fields can be traced as far back as ancient Greek philosophy, and arguments in favor of a hierarchical structure of knowledge proved remarkably resilient over time [2]. Equally, the quest for tighter connections among disciplines is not new. By the late Middle Ages, the growth of universities was marked by an emphasis on the universality of knowledge transcending disciplinary boundaries. A new fertile terrain for interdisciplinary scholarship was then found in the Renaissance movement. Indeed it is widely accepted that the finest minds of the Western intellectual tradition, from Leonardo da Vinci and Pico della Mirandola to Copernicus, were characterized by an extraordinary ability to master the breadth and depth of the disciplinary landscape. Calls for ‘the totality of sciences and arts’ [6, p.19] continued until modern times, and co-existed with a new focus that the Enlightenment enterprise placed on intellectual classification.

In more recent times, the debate on specialization and interdisciplinarity has been reshaped by the institutional changes spurred by the growth of modern universities and by the mounting pressure faced by the scientific community in connection with competitive funding, research assessment, and publication in top-ranked academic journals [2]. On the one hand, the rapid proliferation of new specialties has raised the costs that scientists bear for working outside their usual fields [7]. On the other, the increasing complexity of large-scale projects has prompted an increase in teamwork combining the efforts of multiple scientists with expertise in different fields [8,9]. Interestingly, the case for interdisciplinarity has recently been embraced by the same academic institutions that have contributed to the consolidation of specialized knowledge and intellectual hierarchies. The addition of “interdisciplinarity” as a special category of funding at prominent research institutes and as a submission category in highly regarded academic journals is a clear indication of recent cultural orientations toward a more integrated scientific scholarship [1].

In this article we contribute to this debate by studying how scientific performance varies as the scientist abandons specialization in favor of a more inclusive and integrative approach to research or vice versa. Our analysis casts light on the mechanisms, the career paths and the research strategies that nurture and sustain scientific success over time [10]. To this end, we propose a dual-faceted perspective on interdisciplinarity that blends individual learning with social exposure. To undertake research at the interface among disciplines, scientists can either acquire new expertise on their own, through “in-breadth” learning and training, or seek collaborators with the necessary knowledge and experience. In turn, exposure to collaborators’ knowledge may induce absorption or the synergistic creation of knowledge. Here we examine the implications of these research strategies for scientific success using two large-scale network data sets on scientific collaborations and citations, and we uncover the comparative benefits of interdisciplinary and specialized careers.

From the vantage point of individual scientists, we show that diversity trumps focus. In so doing, we do not argue that diverse groups outperform focused individuals...
FIG. 1. **Interdisciplinarity and success.** Scientific success depends on authors’ background and social entropy, both in physics (panels a,c) and in the natural sciences (panels b,d). The background entropy $B_i$ of an author $i$ quantifies the heterogeneity of the research topics with which $i$’s scientific production is concerned, whilst the social entropy $S_i$ reflects the variety of the knowledge to which author $i$ is exposed through the collaborators. The vignettes below panels a,b show that, even if two authors $i$ and $j$ have published the same number of articles, the of personal codes $PC_i$ and $PC_j$ (represented by the pie-charts) might differ: one author might focus just on a few scientific subjects (author $i$, with a small value of $B_i$), and the other might be interested in several different subjects (author $j$, with a larger value of $B_j$). Nevertheless, both authors, one specialized and the other interdisciplinary, can have a comparable level of scientific success, as indicated in panels a,b by the U-shaped line, which represents the average number of citations accumulated in his or her career by an author with a given value of background entropy. Similarly, as shown in the vignettes above panels c,d, the number of collaborators is not a predictor of the variety of knowledge to which authors are exposed through their networks (represented by the vertical color bars). Panels c,d indicate the average number of citations obtained by an author with a given value of social entropy. On average, authors whose collaborators are focused just on a few subjects (and with a small value of $S$) tend to be outperformed by authors with a more heterogeneous network (and with a high value of $S$). Error bars represent the standard error of the mean.

[11], nor that there are economies of scale associated with group production [9]. Rather, we suggest that individual scientists can reap the rewards of natural diversity by forsaking “in-depth” learning for a suitable admixture of “in-breadth” learning and social networking.

I. RESULTS

We study the association of interdisciplinarity with scientific success at two levels of analysis. To this end, we examine co-authorship networks, citations and research fields drawing on articles included in two databases: (i) the American Physical Society (APS) (micro level) [12]; and (ii) the Web of Science (WOS) (macro level) [13]. First, from the APS data set we extracted 380,913 articles published after 1980 and authored or co-authored by 136,871 scientists whose careers started after 1980. Each article is associated with up to four codes included in the Physics and Astronomy Classification Scheme (PACS). We obtained 1,154 distinct PACS codes identifying the research areas to which each article belongs, and used these codes to measure interdisciplinarity at a micro level (i.e., in physics) [14][15]. Second, from the WOS data set we extracted 1,125,729 articles published by 1,532,673 scientists between 1945 and 2014 in the top five journals with the highest impact factor in 50 different research categories concerned with the natural sciences, including biology, chemistry, computer science, mathematics, and physics. The breadth of scientific production embodied in the WOS data set enables us to conduct our study at a higher level, across disciplinary boundaries. Our analysis relies on a conservative method for disambiguating authors’ names, based on institutional affiliations, collaboration network, and citation network [16].

A. Quantifying interdisciplinarity

We use the PACS codes and research categories (respectively, for the APS and WOS data sets) associated with the articles of an author to identify the author’s research interests and expertise. To measure author $i$’s interdisciplinarity [7][10][17][19], we construct the list $PC_i$ of personal codes or categories, defined as the PACS codes or research categories extracted from all the articles published by $i$ during $i$’s scientific career. The list $PC_i$ thus reflects the disciplinary areas to which author $i$ has contributed, and can be used as a proxy for $i$’s (cumulative) background knowledge [5][19]. We measure author $i$’s background interdisciplinarity through the background entropy defined as the Shannon entropy of the list $PC_i$ of
the author’s personal PACS codes or research categories 

\[ B_i = - \sum_{\alpha} p_i^{[\alpha]} \log(p_i^{[\alpha]}), \]  

(1)

where \( p_i^{[\alpha]} = \frac{n_i^{[\alpha]}}{\sum_{\alpha} n_i^{[\alpha]}} \), and \( n_i^{[\alpha]} \) is the number of times the PACS code or research category \( \alpha \) is found in \( PC_i \) (i.e., the number of articles authored by \( i \) that belong to \( \alpha \)). Similar entropy-based measures have been used for quantifying the heterogeneity of the citations made by an article \([7, 17, 21]\). In general, authors with a more heterogeneous background are characterized by higher values of \( B \), whilst smaller values are typically associated with authors whose research is focused on a small number of scientific sub-fields or categories.

By forging collaborations, scientists are exposed to various sources of knowledge, which may not be entirely co-extensive with their own personal background, and on which they can rely to widen the scientific horizons of their research. To assess scientists’ exposure to their collaborators’ knowledge, we propose a measure that is meant to directly capture the social roots of interdisciplinarity. We define the list \( SC_i \) of social codes or categories of author \( i \) as the union of the lists of personal PACS codes or research categories of all the co-authors of \( i \), excluding the codes that are already in \( PC_i \). We then measure the social interdisciplinarity of author \( i \) through the social entropy \( S_i \) defined as the Shannon entropy of the list \( SC_i \):

\[ S_i = - \sum_{\alpha} q_i^{[\alpha]} \log(q_i^{[\alpha]}), \]  

(2)

where \( q_i^{[\alpha]} \) is the frequency of code or category \( \alpha \) in \( SC_i \).

### B. Interdisciplinarity and success

For different values of background entropy \( B \), Fig. [a,b] shows the average cumulative number of citations \( N^{\text{cit}} \) received by comparable authors with career lengths ranging between 5 and 15 years and with a number of publications ranging from 5 to 100. The vignettes in Fig. [a,b] illustrate the typical compositions of the two lists \( PC_i \) and \( PC_j \), respectively for a specialized author \( i \) and for an interdisciplinary author \( j \). On average, authors with intermediate values of background entropy (i.e., neither interdisciplinary nor specialized) are characterized by a relatively low value of scientific performance. Both in physics (Fig. [a]) and in the natural sciences (Fig. [b]), scientific performance exhibits a U-shaped trend, with a minimum around \( B_i \approx 0.2 \) and a maximum at \( B_i \approx 1.6 \) for APS and at \( B_i \approx 1.4 \) for WOS. Interestingly, a similar and relatively large number of citations can be obtained equally by highly specialized and highly interdisciplinary authors. However, the asymmetry in the U-shaped trend indicates that, on average, scientists with the widest range of research interests \( (B_i \gtrsim 1.4) \) tend to outperform not only less interdisciplinary scientists, but also the most specialized ones \( (B_i \approx 0) \). Overall, these results suggest that, at the micro level of physics as well as at the macro level of the natural sciences, both specialized and interdisciplinary scientists can be successful; yet extreme interdisciplinarity provides competitive advantage over extreme specialization. Moreover, success is thwarted as scientists abandon extreme specialization in favor of moderate degrees of interdisciplinarity.

Next, we examine whether scientists’ performance is associated not only with their background, but also with the variety of opportunities they can tap through their collaborators \([18]\). For the same subset of authors as in Fig. [a,b], Fig. [c,d] shows the relationship between average number of citations and social entropy. Results indicate that authors can amplify success as their social interdisciplinarity increases. An author with a more heterogeneous network (i.e., a higher value of social entropy \( S \)) will, on average, have a higher performance than an author with a more homogeneous network (and lower \( S \)). Thus, while specialization can be a successful strategy (Fig. [a,b]), seeking collaborators with few and overlapping specialties will be a hindrance. Scientists can instead enhance their performance by selecting interdisciplinary collaborators.

To test whether our findings differ from what would be expected if codes or research categories were randomly assigned to articles, we replicated the analysis in Fig. [a,b] using a null model that preserves the co-authorship network and the number of citations and codes per article, but in which codes and categories are randomly reshuffled across articles published within the same year. Fig. 2 shows the observed relationship between background and social interdisciplinarity for subsets of authors with a different number of citations accrued, compared with the relationship found in the corresponding null model. Interestingly, the more successful the authors, the larger and more correlated the values of their background and social interdisciplinarity. These results provide evidence of an interplay between scientists’ personal interests and expertise, on the one hand, and their collaborative patterns on the other, and suggest that such interplay is associated with scientific performance.

So far we have combined authors with different career lengths and productivity, and from different research fields. We shall now examine the relationship between interdisciplinarity and success by accounting for potential biases that may arise from confounding factors such as heterogeneity in the length of scientists’ careers and in the patterns of citations characterizing different periods and research fields.

### C. Comparing different career stages

For each year \( t \) of scientist \( i \)’s career, we consider the background entropy \( B_i(t) \) and the social entropy \( S_i(t) \)
FIG. 2. Interplay between background and social interdisciplinarity. The relationship between the two forms of interdisciplinarity plays a crucial role in sustaining success: the values of background and social entropy become more correlated as authors are associated with more citations, both in physics (panel a) and in the natural sciences (panel b). The Pearson linear correlation coefficient \( r \) between the two quantities consistently increases from \( r \approx 0.65 \) (APS) and \( r \approx 0.5 \) (WOS) to \( r \approx 0.8 \) (APS) and \( r \approx 0.6 \) (WOS) as the number of authors’ citations increases from values smaller than 100 to values around 1,000. The shaded circles along the dashed lines refer to values of the correlation coefficient obtained from a null model in which PACS codes and categories are randomly reshuffled across articles, while the number of citations, articles, codes and categories per author is preserved. Error bars represent 95% confidence intervals based on Fisher’s \( r \)-to-\( z \) transformation.

Calculated, respectively, on the set of \( i \)’s publications and collaborations up to \( t \). Moreover, drawing on the method proposed in [34], we measure the performance of scientist \( i \) at year \( t \) through the normalized number of citations \( \tilde{N}^\text{cit}(t) \). This enables us to account for variations in: (i) patterns and volume of citations across sub-fields and disciplines; (ii) attractiveness of research topics over time; and (iii) the starting year and duration of authors’ careers. To obtain \( \tilde{N}^\text{cit}(t) \), we compute the normalized number of citations of a given article \( a \) as the ratio between the total number of citations received by article \( a \) and the average number of citations received by all articles published in the same sub-field or discipline and year as \( a \) [32]. We then sum the normalized numbers of citations of all articles published by author \( i \) in each year up to \( t \), and obtain \( \tilde{N}^\text{cit}(t) \) (see vignette in Fig. 3). For instance, by evaluating \( B_i(5) \), \( S_i(5) \) and \( \tilde{N}^\text{cit}(5) \), we can compare values of background and social interdisciplinarity, and normalized number of citations, respectively, at the end of the first five years of each author \( i \)’s career. Following [33], we assess interdisciplinarity through the second level (i.e., the first four digits) of the PACS hierarchy, at which the universality of scaling holds.

Fig. 3 reports the normalized number of citations \( \langle \tilde{N}_i^\text{cit}(t) \rangle \) averaged over authors characterized by a certain value of background interdisciplinarity at four career stages, namely at \( t = 5, 10, 15, 20 \) years, in physics (panels a-d) and in the natural sciences (panels e-h). Interestingly, the U-shaped functional form of the relationship between success and background interdisciplinarity is found already at the fifth year of a scientist’s career, and persists across all career stages, both in physics and at the broader level of the natural sciences. In particular, scientists with a value of background entropy \( 0.2 \lesssim B_i \lesssim 0.6 \) have a poorer performance than scientists that are either highly specialized or highly interdisciplinary. Similarly, social interdisciplinarity is associated with scientific success across all stages of a scientist’s career.

Fig. 3 suggests that the relationship between interdisciplinarity and success is subject to a temporal drift. At the macro level of the natural sciences, while the maximum normalized number of citations accrued by the most interdisciplinary author \( i \) at the fifth year of career is, on average, \( \tilde{N}^\text{cit}(5) \approx 160 \), the largest value of \( \tilde{N}^\text{cit}(20) \) for an author \( j \) at the 20-th year of career is, on average, \( \tilde{N}^\text{cit}(20) \approx 250 \). Thus, an author \( i \) with, for instance, \( B_i \approx 1.0 \) at the fifth year of \( i \)’s career will have, on average, 30 normalized citations, namely 0.40 times as many citations as those accrued by the most specialized author \( j \) (i.e., with \( B_j \approx 0 \)), and only 0.20 times as many citations as those of the best-performing author (i.e., with \( B_j \approx 1.40 \)). At the 20-th year of his or her career, the same author \( i \) with \( B_i \approx 1.0 \) would still be able to accrue, on average, about 30 normalized citations. However, while \( i \)’s comparative disadvantage over the most specialized author would remain unaltered, the disadvantage over the most interdisciplinary one would further intensify. Author \( i \) would therefore need to keep increasing background interdisciplinarity over time, lest by the 20-th year of \( i \)’s career the total number of citations be, on average, only 0.12 times as large as the one of the best-performing author. The association of background interdisciplinarity with success thus becomes stronger as scientists’ careers progress. Moreover, in the long run, as careers approach their final stages, not only are highly interdisciplinary scientists more successful than specialized ones, but the difference in performance between the most interdisciplinary and the most specialized scientists reaches its peak.

D. Paths to interdisciplinarity

Given the advantages of interdisciplinarity, how do scientists widen their background over time, and which research strategies are associated with success? We identify three strategies: solo, absorptive and synergistic. First, we define the solo strategy as the acquisition of new knowledge through the publication of a single-authored article in the corresponding scientific area. With this strategy, scientists extend their background interdisciplinarity through “in-breadth” learning; yet they do not amplify their social exposure to new sources of knowledge. Second, the absorptive strategy is defined as the acquisition of new knowledge by an author through the
FIG. 3. Interdisciplinarity and success at different career stages. The normalized number of citations obtained by authors at different career stages as a function of their background entropy in physics (panels a-d) and the natural sciences (panels e-h). The vignette illustrates how performance and interdisciplinarity were measured. For each author $i$ and a given year $t$ of $i$’s career, both performance and interdisciplinarity were measured at $t$ on all articles published by $i$ since the beginning of $i$’s career up to $t$. The citations accrued by each article up to $t$ were normalized through the method proposed in [33]. The U-shaped dependency of $\langle N^\text{cit}(t) \rangle$ on background entropy and the presence of a minimum at intermediate values of $B(t)$ characterize both young authors and experienced ones, thus indicating that extreme interdisciplinarity as well extreme specialization are already beneficial at the very beginning of a scientist’s career. However, the competitive advantages of background interdisciplinarity become more pronounced as careers progress toward their final stages when the difference in performance between the most interdisciplinary and the most specialized authors reaches its peak. Error bars represent the standard error of the mean.

publication of a multi-authored article with at least one co-author who has already published in the corresponding area. Through this strategy, scientists absorb knowledge from their collaborators as soon as they are exposed to it, thus increasing their background interdisciplinarity (and possibly the heterogeneity of their collaboration networks). Finally, the synergistic strategy is defined as the acquisition of new knowledge by an author through the publication of an article with co-authors who have never published in the corresponding area. Through this strategy, collaboration promotes cross-fertilization of various disciplinary areas, and ultimately intensifies all co-authors’ (background) interdisciplinarity through the acquisition of new knowledge. An illustration of the three strategies is reported in Fig. 4(a).

We denote by $P_t^\text{solo}$, $P_t^\text{abs}$ and $P_t^\text{syn}$ the fraction of number of PACS codes acquired by author $i$ through, respectively, the solo, absorptive, and synergistic strategies, during $i$’s entire career. To understand how authors with different performance vary in their usage of the three strategies, in Fig. 4(b) we show the average frequencies of solo, absorptive, and synergistic strategies adopted by authors in the APS data set whose articles accrued a total number of citations exceeding various thresholds. Remarkably, the overall frequency of the solo strategy is just about 4% at all levels of success, whilst the vast majority of the new PACS codes (about 96%) originate from collaboration. In particular, not only are authors across all levels of performance more likely to embrace a new sub-field through a synergistic strategy than an absorptive one, but also the difference in usage frequencies between the two strategies widens as authors are more successful ($N^\text{cit} \sim 10,000$).

Exposure to collaborators’ knowledge may broaden a scientist’s background interdisciplinarity not only instantaneously through the absorptive strategy. When engaged in a joint endeavor, scientists can, in principle, gain access to the entire spectrum of knowledge offered by their collaborators. A fraction of this knowledge can indeed be absorbed as soon as collaboration occurs, through the absorptive strategy (Fig. 4b); the remaining can be acquired at a subsequent stage, through a process here referred to as postponed absorption. Diluting acquisition of new knowledge over time can have various
FIG. 4. Strategies for enhancing interdisciplinarity. (a) We identify three main strategies through which authors can expand their knowledge into a new field: (i) by publishing on their own in the new field (solo strategy); (ii) by collaborating with others that have already published in the field (absorptive strategy); and (iii) by collaborating with others that have never published in the field (synergistic strategy). (b) For authors in the APS data set whose articles obtained more than a given number of citations, we measured the average frequencies of solo, absorptive and synergistic strategies. Successful authors are more prone to synergistic strategies than less successful ones. Error bars represent the standard error of the mean. (c) The average fraction of social PACS codes eventually acquired by an author is positively correlated with the author’s success. (d) The average time needed to acquire new PACS codes from collaborators is negatively correlated with an author’s success. Successful authors are more likely not only to acquire knowledge from their collaboration network, but also to do so more quickly than less successful ones.

effects on performance, depending on how much knowledge is acquired and the time separating acquisition from exposure.

To study the degree to which knowledge acquisition is affected by past collaborations, for each author \( i \) we quantify the propensity, once exposed to a new social PACS code \( \alpha \), to acquire it at some subsequent stage. Exposure to sub-field \( \alpha \) occurs when author \( i \), with no experience in \( \alpha \), for the first time collaborates with someone who has already published in \( \alpha \). Postponed absorption of \( \alpha \) occurs when, for the first time after exposure, \( i \) appears as the solo author or co-author of an article \( a \) in \( \alpha \). Notice that the co-authors of \( a \) are assumed not to have experience in \( \alpha \) (or else knowledge acquisition would be classified as instantaneous absorption). Of the social PACS codes to which author \( i \) was exposed, we measure the fraction \( \chi_i \) that was eventually acquired by \( i \). Lastly, for each author \( i \) we measure the mean interval of time \( \xi_i \) separating postponed absorption from exposure.

Fig. 4(c) shows the average fraction \( \langle \chi_i \rangle \) over all authors, and suggests that successful authors in the APS data set are more likely to use up their collaboration networks to acquire new knowledge than less successful ones. Moreover, Fig. 4(d) shows the average interval of time \( \langle \xi_i \rangle \) over all authors, and suggests that the time separating exposure to new knowledge from acquisition tends to become shorter as authors’ performance increases. Not only do successful scientists choose their collaborators carefully so as to secure exposure to new areas, but they also prefer not to wait too long before they publish in those areas either on their own (solo strategy) or with other collaborators (synergistic strategy).

II. DISCUSSION

This study was concerned with intellectual diversity and diversification in science. First, we showed that there are larger returns to “in-breadth” than “in-depth” learning, especially as scientists’ careers progress. However, scientists bear opportunity costs as they begin to diversify their background, at least until they become highly interdisciplinary. Second, we found that scientists benefit from heterogeneous collaboration networks. Scientists with groups of collaborators spanning many different areas are more successful than those with collaborators focused on one or few overlapping areas. Third, results indicated that successful scientists tend to match the diversity of their background with the diversity of their collaborators.

Recent work on interdisciplinarity has focused mainly on the benefits and penalties associated with authors’ diversity of knowledge and background [7, 10, 18]. However, research on social capital and innovation has also suggested that performance is nurtured by the opportunities of knowledge recombination offered by the network in which individuals are embedded [11, 23–26]. In our study, we integrated the individual and social perspectives, and proposed a conception of interdisciplinarity that extends beyond the boundaries of the scientists’ background to also include their collaboration networks. We suggested that scientists can integrate and extend “in-breadth” learning by widening the breadth of their social network. This idea of trading off learning against collaboration is akin to models of embodied, environmentally embedded cognition put forward by recent developments in cognitive science and philosophy of mind [27]. Individuals can amplify their cognitive abilities and processes by exploiting external resources in their physical and social environment. Similarly, we have shown that scientists can enhance success by retrieving and recom-
bining external pools of knowledge.

Previous work has documented an increase in multi-authored articles over the last few decades [1], and has suggested that successful authors tend to develop interdisciplinary careers by specializing on various distinct topics at any particular time [10]. We integrated and extended these studies by investigating the collaborative strategies that sustain knowledge diffusion and acquisition. Intellectual diversification is most effective when it is pursued through absorption of new knowledge from others or through joint endeavors aimed at producing new knowledge. Lone scientists toiling away at extending their competence into new research areas tend to be less successful than those who instead leverage on social networking to extract new knowledge from collaborators [11]. Lacking visibility and credibility can also pose barriers to entry into hitherto uncharted territories of science [15, 28]. Relying on collaborators’ experience can help reduce such barriers and facilitate access to multiple scientific communities.

Our analysis is not without limitations, chiefly concerned with the use of citation-based metrics as indicators of scientific merit [29, 32] and with the generalizability of results beyond the natural sciences. Despite this, our study has far-reaching implications for research and policy. Opening up the black box of the scientist’s knowledge to also account for collaboration networks paves the way for more integrated approaches to scientific production that borrow insights from bibliometrics and citation analysis, complex networks, cognitive science and the sociology of science. Our findings can also inspire individuals to shape and sustain successful careers, research institutions to strengthen their scientific reputation and profile through effective recruitment policies and internal evaluation systems, and funding bodies to award research grants to projects with the highest potential impact.

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