Correction

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Correction for "Evolution and convergence of the patterns of international scientific collaboration," by Mario Coccia and Lili Wang, which appeared in issue 8, February 23, 2016, of *Proc Natl Acad Sci USA* (113:2057–2061; first published February 1, 2016; 10.1073/pnas.1510820113).

The authors note that Lili Wang should be credited with designing research, performing research, analyzing data, and interpreting data. The corrected author contributions footnote appears below.

Author contributions: M.C. conceived the study; M.C. and L.W. designed research; M.C. and L.W. performed research; M.C. contributed new analytic tools; M.C. acquired data; M.C. and L.W. analyzed data; M.C. and L.W. interpreted data; and M.C. wrote the paper.

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CORRECTION

Evolution and convergence of the patterns of international scientific collaboration

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International research collaboration plays an important role in the social construction and evolution of science. Studies of science increasingly analyze international collaboration across multiple organizations for its impetus in improving research quality, advancing efficiency of the scientific production, and fostering breakthroughs in a shorter time. However, long-run patterns of international research collaboration across scientific fields and their structural changes over time are hardly known. Here we show the convergence of international scientific collaboration across research fields over time. Our study uses a dataset by the National Science Foundation and computes the fraction of papers that have international institutional coauthorships for various fields of science. We compare our results with pioneering studies carried out in the 1970s and 1990s by applying a standardization method that transforms all fractions of internationally coauthored papers into a comparable framework. We find, over 1973–2012, that the evolution of collaboration patterns across scientific disciplines seems to generate a convergence between applied and basic sciences. We also show that the general architecture of international scientific collaboration, based on the ranking of fractions of international coauthorships for different scientific fields per year, has tended to be unchanged over time, at least until now. Overall, this study shows, to our knowledge for the first time, the evolution of the patterns of international scientific collaboration starting from initial results described by literature in the 1970s and 1990s. We find a convergence of these long-run collaboration patterns between the applied and basic sciences. This convergence might be one of contributing factors that supports the evolution of modern scientific fields.

international scientific collaboration | evolution of science | basic sciences | applied sciences | convergence

International collaboration has become a common characteristic in the production of scientific research (1, 2). In 1986, De Solla Price (3) claimed that one of the dominant characteristics in science is the communication patterns of scientists, also with "collaboration in an invisible college." The research collaboration, by sharing specific competencies and data, improves labor efficiency and research quality, and supports the process of scientific production, knowledge creation, and breakthroughs (4–6). Adams (7) argues that "the best science comes from international collaboration" and "scientific research is entering a new age, driven by international collaborations." As scientific collaboration networks are expanding and characterizing the social construction of science (8, 9), many studies have a growing interest in explaining the patterns of international scientific collaboration and coauthorship networks for different fields of science (10–12).

During the 1970s, seminal studies of science focused on the importance of the international research collaboration across scientific disciplines (13–15). The literature has showed a difference of scientific production across countries, citations of articles, and coauthored papers among countries/research institutions for various fields of science (6, 12, 14, 16–18). The pioneering study by Frame and Carpenter (14) showed, using the data from the 1973 Science Citation Index, that basic fields (e.g., physics) have higher levels of international collaboration than predominantly applied fields (e.g., engineering/technology). However, in studies of science, little is known about how the patterns of international scientific collaboration across scientific fields have evolved in the past four decades.

In this study, we analyze the recent fraction of internationally coauthored papers for different fields of science, which is compared with the results from earlier studies (14, 16) to detect the long-run patterns of international scientific collaboration.

First, our study uses a dataset from the National Science Foundation (19) based on articles in various scientific fields between 1997 and 2012. This dataset is the source to compute the fraction of papers that have international institutional coauthorships for different fields of science. We analyze data of 11 leading scientific countries and seven research fields to provide homogenous results with previous studies (14, 16).

Second, we compare our results with earlier studies (14, 16), performed in the 1970s and 1990s, by applying a standardization method that transforms all fractions of internationally coauthored papers into a comparable framework.

Finally, we plot these results on a geometric graph to detect and study the evolution of the long-run patterns of international research collaboration for various fields of science from 1973 to 2012.

Materials and Methods

Dataset. We use the dataset of the National Science Foundation (19), National Center for Science and Engineering Statistics, special tabulations (2013) from Thomson Reuters, Science Citation Index, and Social Sciences Citation Index; we consider articles from various scientific fields between 1997 and 2012. Articles are assigned to a country/economy on the basis of the institutional address(es) listed in the article. Articles in this database (19) are credited on a

Significance

The evolution of the patterns of international scientific collaboration plays an important role in the social construction of science to design efficient research policies and to support the production of knowledge. However, in studies of science, little is known about how patterns of international research collaboration for fields of science have evolved in the past four decades. This study shows, for the first time to our knowledge, starting from pioneering results described by literature in the 1970s and 1990s, that the long-run patterns of international scientific collaboration are generating a convergence between applied and basic fields. This convergence of collaboration patterns across research fields might be one of contributing factors that supports the evolution of scientific disciplines.

Author contributions: M.C. conceived the study; M.C. designed research; M.C. and L.W. performed research; M.C. contributed new analytic tools; M.C. acquired, analyzed, and interpreted data; and M.C. wrote the paper.

The authors declare no conflict of interest.

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SOCIAL SCIENCES

whole-count basis (i.e., each collaborating country/economy is credited with one count). Articles with domestic institutions only are counts of articles with one or more institutional addresses all within the country/economy. Articles with international institutions are counts of articles with one or more institutional addresses outside the country/economy (19). This dataset (19) is the source to compute the fraction of internationally coauthored papers for different fields of science.

Fraction of Papers with International Institutional Coauthorships for Scientific Fields. This study computes per each scientific field *i* the fraction of internationally coauthored papers (FCP_{it}) during the period 1997–2012. FCP_{it} is given by:

$$FCP_{it} = \frac{\text{coauthored articles with international institutions}_{it}}{\text{total coauthored articles with domestic and international institutions}_{it}}, \quad [1]$$

where *i* is scientific field and *t* is time (1997, . . ., 2012). In particular, the FCP_{it} for various fields of science is calculated at t = 1997, 2002, 2007, and 2012 (every 5 y).

Strategy for Comparing Results with Previous Studies. The study design computes the FCP_{it}, considering the same countries and same scientific fields of seminal studies by Frame and Carpenter (14) on 1973 data and Luukkonen et al. (16) on 1983 data to compare the results over time. There are 11 countries for comparing results: the United States, the United Kingdom, Germany, France, Italy, Canada, Australia, New Zealand, South Africa, Israel, and Sweden. Publications of these leading countries account for 65% of the worldwide production of scientific articles in 1990s (this share declined to 51% in 2010s). There are seven research fields for comparing results over time: astronomy (equivalent to space science in refs. 14 and 16), physics, mathematics, chemistry, biology, clinical medicine, and engineering/technology. The FCP values from these different studies (14, 16, and the present work) are systematized in a comparable framework by applying the following standardization formula for research field *i* in the year *t*:

$$Z_{it} = \frac{FCP_{it} - \mu_t}{\sigma_t}, \quad [2]$$

where Z_{it} is the standardized value of the FCP_{it} (*i* is scientific field; *t* is year; with $i = 1, \ldots, 7$; t = 1997, 2002, 2007 and 2012); FCP_{it} is the fraction of papers with international institutional coauthorships per research field *i* at the year *t*; μ_t is the arithmetic mean of the FCP in all fields of science at the year *t*; and σ_t is the SD (standard deviation) of the FCP in all fields of science at the year *t*. Z_{it} is negative when the raw score is below the mean, and positive when it is above. A zero value of Z_{it} indicates that the raw value is equal to the arithmetic mean.

Graphs and Estimated Relationships of Patterns of International Scientific Collaboration. In this paper, we have calculated the fractions of coauthored papers for different research fields and their standardized values Z_{it} to plot long-run patterns of international scientific collaboration on a graph, starting from results by Frame and Carpenter (14) based on 1973 data. The graphs (both in absolute and relative values) have time (in terms of years of similar studies performed on this topic) on the *x* axis to display the different pathways of internationally coauthored papers for fields of science over time. The pathway of the research field *i* is the geometric locus of all Z_{it} that indicates the changes of the standardized fraction of internationally coauthored papers in comparison with all research fields, at time *t*.

The pathways of international research collaboration for fields of science *i*, based on Z_{it}, fit to a linear regression model that is estimated with the ordinary least-squares method. The specification of the model is:

$$Z_{it} = \alpha - \beta t + \varepsilon_{it}, \quad [3]$$

where $i = 1, \ldots n$; $t = 1, \ldots, m$; Z_{it} is the standardized value of the fraction of papers with international institutional coauthorships; *i* is scientific field*;* *t* is time; α is constant; β is coefficient of regression; and ε is error term.

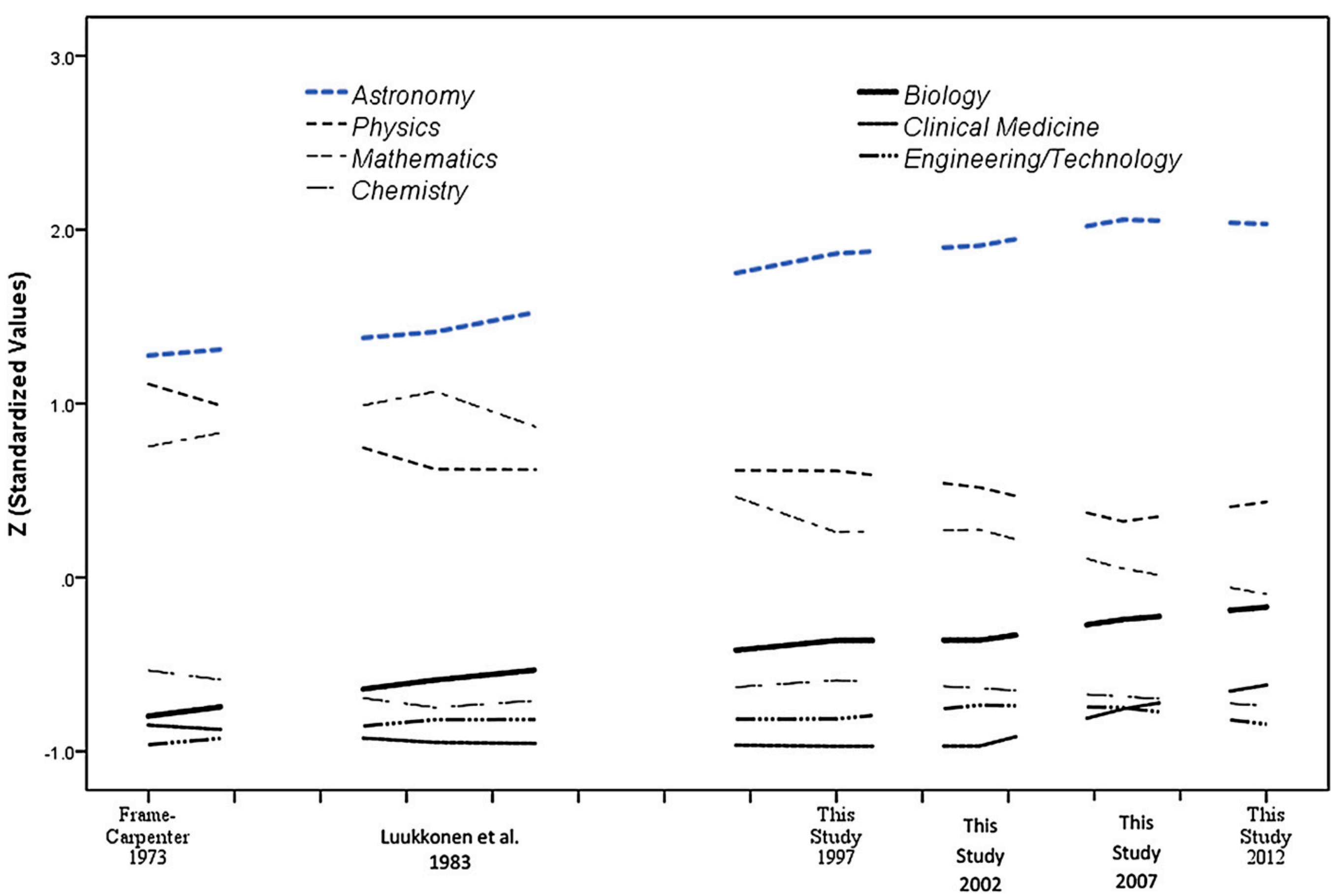

Fig. 1. Evolution of the long-run patterns of international research collaboration across scientific fields. *Z* is the standardized value of the fraction of internationally coauthored papers (*y* axis); the *x* axis has the years of similar studies performed on this topic.

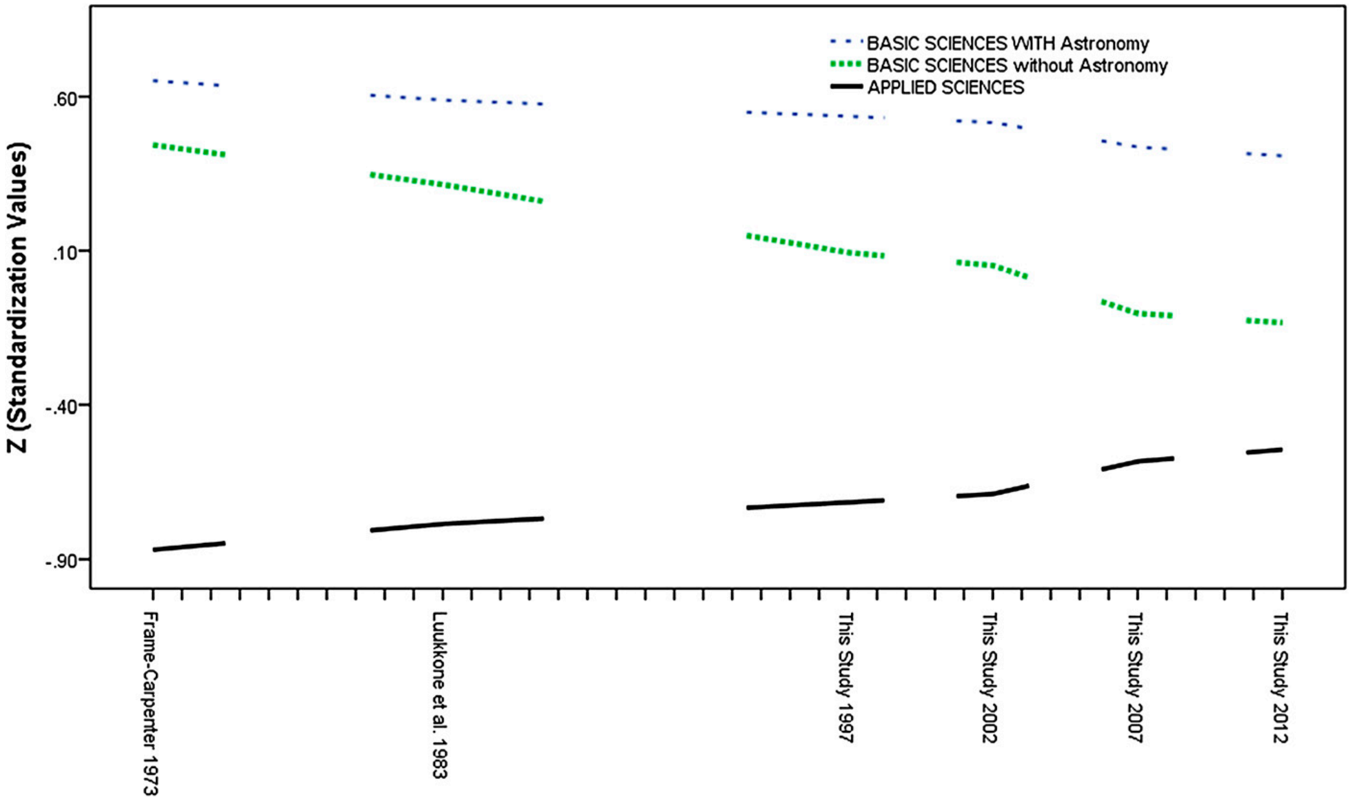

Fig. 2. Evolution and long-run convergence of patterns of international scientific collaboration between basic and applied sciences. Basic sciences include mathematics, astronomy, physics, and chemistry; applied sciences include biology, clinical medicine, and engineering/technology. *Z* is the standardized value of the fraction of internationally coauthored papers (*y* axis); the *x* axis has the years of similar studies performed on this topic.

The simple regression analysis [**3**] provides estimated coefficients of regression β for fields of science, which indicate approximately relative changes of the fraction of internationally coauthored papers over time. Statistical analyses are performed by means of the Statistics Software SPSS version 15.0.

Categorization of Basic and Applied Fields. Social studies of science show that the scientific research can be categorized into basic research—aiming at finding truth—and applied research—aiming at solving practical problems (5, 14). Nevertheless, this topic is the subject of ongoing discussion, because according to Kitcher (5), "The aim of science is not to discover any old truth but to discover significant truths."

In this study, we categorize the scientific fields as shown by Frame and Carpenter (14): i.e., basic fields include mathematics, astronomy (similar to space science), physics and chemistry; and applied research fields include biology, clinical medicine, and engineering/technology.

However, the literature shows that chemistry and biology are the two disciplines encountering more debate in being classified in either basic or applied fields (14, 17, 18). Global structure of all of science by Boyack et al. (17) showed chemistry in the same area of mathematics and physics. Simonton (20), analyzing the Comtean hierarchy of the science, also displayed chemistry at the top of the hierarchy, close to physics. In fact, Storer (21) and Smith et al. (22) considered chemistry and physics with about the same "rated hardness," which is characterized by a high degree of rigor. These studies (17, 20–22) support the placement, in our analysis, of chemistry in basic research fields.

Biology is also another discipline in the middle ground between basic and applied sciences (18, 20, 23). Frame and Carpenter (14) placed the research field of biology in applied or clinical fields. Moreover, studies of the map of science show that biological research fields are located in the map rather close to medicine and other applied disciplines (17). Considering these studies (14, 17), we place biology in applied research fields.

Overall, then, the categorization of basic and applied fields in the study here is coherent with the global structure of science detected predominantly in current literature (14, 17–25).

Findings

International scientific collaboration is increasing in volume in all research fields over time (16). De Solla Price (3) in 1986 asserted that since the turn of the century, "the proportion of multiauthor papers has accelerated steadily and powerfully." This study shows that the average FCP of the studied disciplines has increased from 1997 to 2012, tremendously. In fact, the absolute values of FCP for all fields of science show growing trends in Fig. S1. We have standardized the results of the studies performed in different time periods (14, 16, and this work), as explained in *Materials and Methods*, to create a comparable framework for detecting the evolution of different patterns of international scientific collaboration across scientific fields. Detailed results can be found in Tables S1 and S2. Specifically, the findings of this study are explained below.

Convergence of the Patterns of International Scientific Collaboration Between Basic and Applied Sciences Over Time

We plot the standardized values of FCP on a graph to display the pathways of international scientific collaboration across research fields over time. Fig. 1 shows that the distance of the FCP between different research fields (except astronomy) has been decreasing over time. In particular, the relative changes of international scientific collaboration in physics and mathematics have declined, whereas those in biology and clinical medicine have risen from 1973 to 2012 (Fig. 1). Astronomy has a path of international scientific collaboration that tends to be different from other research fields. The overview of these results in Fig. 1 seems to show a convergence of collaboration patterns across different research fields over time.

Moreover, if we classify all scientific disciplines studied in basic and applied research fields, as explained previously (i.e., basic

Table 1. Estimated relationships in basic and applied research fields

Parameters and statistical analyses	Basic fields (with astronomy)	Basic fields (without astronomy)	Applied fields
Constant α	12.440***	30.529***	−16.587***
(SE)	(1.402)	(1.769)	(1.869)
β	**−0.006*** **	**−0.015*** **	**0.008*** **
(SE)	(0.001)	(0.001)	(0.001)
F-test	72.289	295.667	72.292
Significance	0.001	0.000	0.001
Adjusted R^2	0.934	0.983	0.934

Note that estimated relationships are based on the regression model [**3**] specified in *Materials and Methods*. Dependent variable: Z_{it} is the standardized value of the fraction of papers with international coauthorships (1973–2012); explanatory variable: t is time; β is coefficient of regression (in bold), a proxy of the rate of growth of research fields over time; SE is the standard deviation; *F*-test indicates if the overall model is significant; ***significance of parameters, $p \leq 0.001$; goodness of fit of these equations is high: the coefficient of determination R^2 adjusted ≥ 93%. Basic fields include mathematics, astronomy, physics and chemistry; applied fields include biology, clinical medicine, and engineering/technology.

sciences include astronomy, physics, mathematics and chemistry; applied sciences include biology, clinical medicine and engineering/technology), Fig. 2 shows, clearly, a convergence between collaboration patterns of basic and applied sciences over time. This long-run convergence of scientific pathways is even more pronounced when astronomy is excluded.

Estimated linear relationships of the simple regression analysis [**3**] show a negative coefficient of regression in basic research fields, whereas it is positive in applied research fields (see β coefficients in Table 1).

General Stability of the Structure (Ranking) of Collaboration Patterns for Fields of Science Over Time

Another interesting finding of this study is that, although the patterns of internationally coauthored articles grew over time in all disciplines (Figs. S1 and S2 with absolute values), the general architecture, based on location of the relative change of each discipline in the ranking per year with all research fields, tends to have stability over time. Specifically, astronomy and physics, representatives of basic fields, had high levels of internationally coauthored papers in the study by Frame and Carpenter (14) on 1973 data and by Luukkonen et al. (16) on 1983 data, and these high values continued over 1997–2012 in our analysis (i.e., persistence of higher levels of international collaboration in basic fields). On the contrary, engineering/technology, a field of applied research to develop technology for solving practical problems, had lower levels of internationally coauthored papers in 1973 and 1983, and these results persisted over the period 1997–2012 (see Fig. 1). In short, although the volume of international scientific collaboration has grown over time in all disciplines and the convergence of collaboration patterns (Fig. S1 and Fig. 1), the current ranking (structure) of research fields, based on the fraction of papers with institutional coauthorships, tends to be similar to that studied by Frame and Carpenter (14) in the 1970s and Luukkonen et al. (16) in the 1980s (compare results of Tables S1 and S2).

Discussion and Concluding Observations

In this paper, we have analyzed the evolution of the long-run patterns of international scientific collaboration starting from seminal studies in 1970s. The results reveal that (*i*) although the absolute values of FCP have grown in all disciplines, the patterns of internationally coauthored papers seem to converge between basic and applied fields; (*ii*) the path of international scientific collaboration of astronomy tends to be different among research fields. In particular, astronomy has a higher level of international collaboration than other predominant scientific fields over time. Several studies reach similar results (14–16, 26). A possible explanation is that the high share of internationally coauthored papers in astronomy has been attributed to the "big science" phenomenon and necessity of sharing instruments and data (3, 27). In fact, astronomy is performed in large laboratories worldwide with an international community that share resources and data to analyze topics of universal interest (13, 14, 27, 28); and (*iii*) although the volume of international scientific collaboration for all fields of science has grown over time, the general architecture of collaboration patterns, based on the ranking of scientific fields considering the fraction of papers that have international coauthorships, has tended to be rather stable.

These findings may be due to several factors. The dataset of the National Science Foundation (19) applied in this study includes important emerging research fields from applied sciences, such as biochemistry and molecular biology. Boyack et al. (17) claim that "biochemistry is clearly one of the hubs of science. It is the largest discipline, both in terms of numbers of journals and number of citations." Newman (10) shows that "biological scientists tend to have significantly more coauthors than mathematicians or physicists, a result that reflects the labor intensive, predominantly experimental direction of current biology." Moreover, Small (18) argues that "crossover fields are frequently encountered, and the location of a field can occasionally defy its disciplinary origins." Sun et al. (29) claim that some theories consider the social interaction among groups of scientists "as the driving force behind the evolution of disciplines" (cf. 3, 26, 30, 31). These may be some of the factors contributing to the convergence between applied and basic sciences reported in this study.

Overall, then, the findings of this study reveal how patterns of international scientific collaboration tend to converge between basic and applied fields. This convergence of collaboration patterns for scientific fields might be an element of the "social dynamics of science" (29) to support the evolution of disciplines. However, much work remains if we are to understand in more depth the reasons for and the implications of greater internationalization in scientific collaboration across different research fields.

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