The evolution of interdisciplinarity and internationalization in scientific journals

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Abstract

There is a widely-held perception that science is becoming increasingly international — both in terms of collaborations involving authors from multiple countries and in terms of publications from authors from a broader group of countries — and more interdisciplinary, i.e., drawing on knowledge and methods from multiple scholarship domains. However, these hypothesized trends have not yet been characterized quantitatively at the level of individual discipline. The widespread availability of scholarly metadata on scientific publications makes it possible to examine how science has evolved over time. Here, we use OpenAlex metadata to examine potential trends in two groups of peer-reviewed research journals: disciplinary journals in biology, chemistry, economics, medicine, physics, and political science, and multidisciplinary journals that publish articles from multiple fields. Supporting existing perceptions, we find an almost universal trend towards increasing internationalization of both sets of journals. Nevertheless, we find disparities: journals in medicine are less international than journals in other disciplines and are not increasing their levels of internationalization, whereas journals in physics appear to be segregating between those that are international and those that are not. We also find that multidisciplinary journals have undergone significant shifts in their disciplinary focuses over the past century, whereas disciplinary journals appear to have largely maintained their degree of interdisciplinarity.

Keywords: Scientific enterprise, Interdisciplinarity, Internationalization, Bibliometrics

Introduction

Peer-reviewed scientific journals are the backbone of scholarly communication for the worldwide community of scholars [1]. Remarkably, the volume of publications in scholarly journals has been growing exponentially for over a century (See Fig. 1b) [2]. The dominance of journal articles was not always the state of affairs in scientific communication. The longest-running scholarly journal was launched in 1665[1] — the Royal Society of London launched the *Philosophical Transactions of*

[1]The French *Le Journal des Sçavans* (or *Journal des sąvans*) was published for the first time a few months earlier but its publication was interrupted twice [3].

the Royal Society to collect and distribute important scientific findings and news [4]. Unlike nowadays, in the 18th and 19th centuries monographs, literary essays, public and private presentations, personal letters, pamphlets and full-length books were all significant channels for communicating research findings and established priority [5]. By the turn of the 20th century, printed scientific journals emerged as the primary means of disseminating new scientific discoveries [5, 6]. In this new millennium, digital publications, still within the framework of scholarly journals, have overtaken printed publications [7].

The scope of scientific enterprise has also evolved over time. In the 380s B.C.E, Aristotle classified all human knowledge into two philosophical categories: speculative and practical [8]. Practical philosophy encompassed topics such as economics, ethics, and politics. Speculative philosophy encompassed aesthetics, mathematics, metaphysics, and physics (also called natural philosophy) [9]. Not until the 19th century did the current partitioning of scholarly endeavors start to take shape [10].

This re-arrangement of human knowledge was accompanied by its exponential growth, prompting increasing specialization of scholars and the emergence of ever more specialized venues for sharing discoveries. Perhaps as a result of this specialization trend, the number of scholarly journals has been doubling approximately every 14 years (Fig. 1c). Much of this growth has occurred within the dominant natural sciences — biology, chemistry, and physics — each now encompassing a multitude of subfields [11–13]. Counter-intuitively, increasing specialization has produced a drive for interdisciplinarity, with researchers increasingly collaborating to exchange knowledge and methods across domains and bridge disciplinary boundaries [14–17]. Due to this drive, there had been a second trend in opposition to ever more specialized journals: the increasing prominence of multidisciplinary journals (e.g. *Nature*, *Science*, and *PNAS*), which feature research contributions from multiple disciplines [11, 16].

Another factor that has transformed the worldwide scientific enterprise is its increasing internationalization, with scientific collaborations now extending across national boundaries. Whereas France, Germany, the United Kingdom (U.K.), and the United States (U.S.), dominated knowledge production in the 19th and 20th centuries, in recent decades we have witnessed the increasing importance to knowledge creation of Asian nations, such as China, India, and Japan (Fig. S1 in **Extended Data: Statistics on journal publications at the country level**).

In fact, there has been a significant expansion in the number of countries where scientists are publishing in selective journals. As seen in Fig. 1d, this expansion is well described by a logistic model with a growth rate that peaked in 1970, but extends over the period 1949 to 1991. Plausibly, the widespread focus on increased scientific research was due to the importance of science and technology to the outcomes of the World Wars.

Recent literature has highlighted the importance of team science in the production of knowledge, especially impactful knowledge, in recent decades. A less well-understood aspect in the growth of team science is the impact of interdisciplinarity and internationalization. A driving thrust of this study is the assumption that perceived trends towards greater interdisciplinarity and internationalization will be visible and quantifiable using data-driven approaches. We further hypothesize that quantifying these processes will yield a deeper understanding of the observed changes. These insights will guide researchers and policymakers in promoting collaborations among different disciplines and countries, thus encouraging the type of innovative research necessary to address the complex challenges currently faced by humanity.

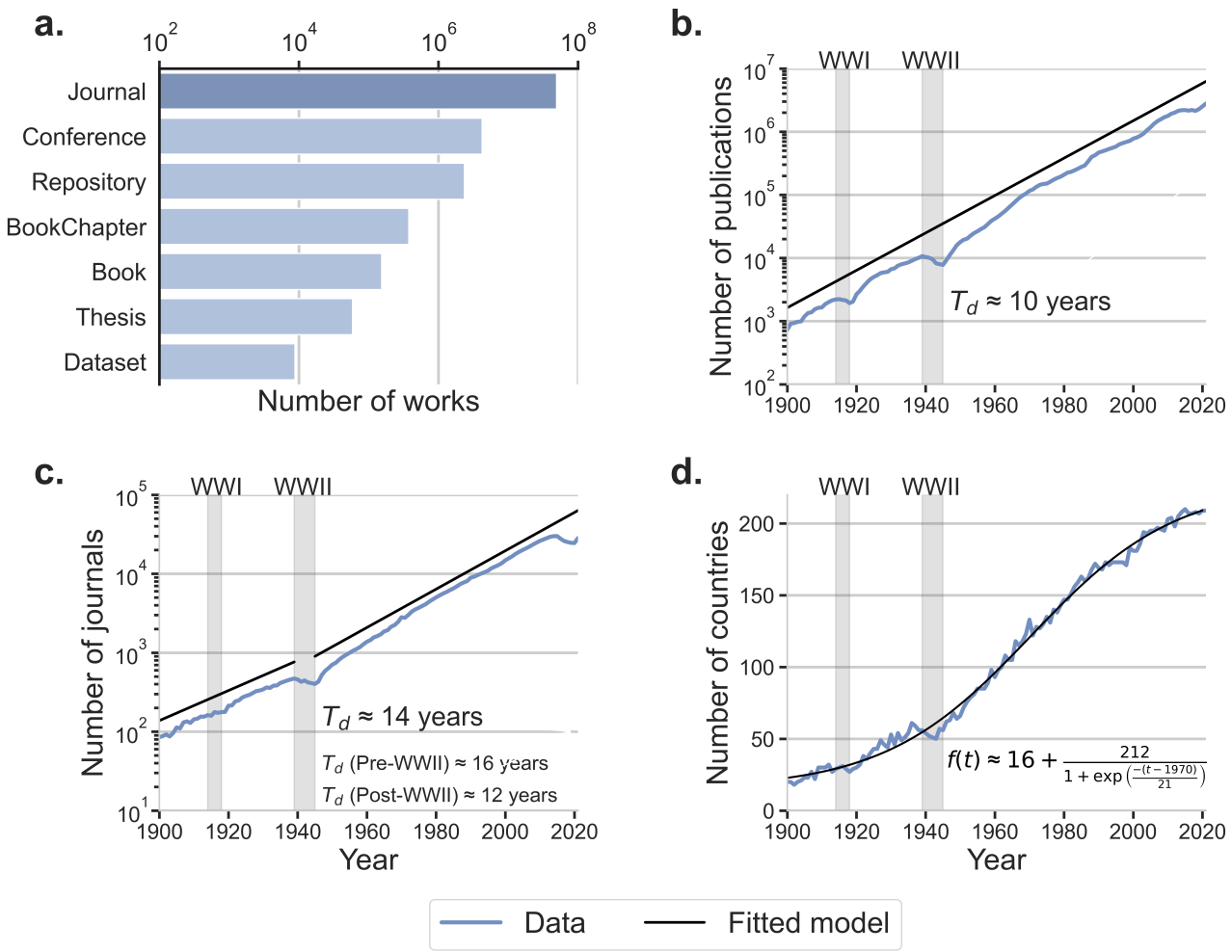

Figure 1: Scholarly journal articles are the largest category of scholarly publications. The number of journal publications increased steadily except during the two World Wars. Solid lines show the fits to the data which have, in some cases, been shifted vertically for clarity. **a.** Scholarly works (with relevant metadata) indexed in the OpenAlex database are categorized into seven groups. Most publications are journal articles. **b.** Number of journal articles has been doubling approximately every 10 years for over a century. While there were significant drops during World War I (1914 to 1918) and World War II (1939 to 1945), the growth of journal article publications quickly recovered. The solid line shows a linear fit to the logarithm of the dependent variable. **c.** Number of actively publishing journals has been doubling approximately every 14 years for over a century, but the growth rate has not been constant. The two solid lines show the linear fits to the logarithm of the dependent variable to different time periods. **d.** Number of countries represented in the affiliations of the authors of annually published journal articles. The data is well-described by a logistic curve centered at 1970. Most of the growth in the number of countries occurred between 1949 and 1991.

Data and Methods

We focused our analysis on the March 2022 snapshot of OpenAlex, a large-scale and open scholarly metadata source. When Microsoft ceased updates of the Microsoft Academic Graph (MAG), at the end of 2021 [18], the non-profit organization OurResearch [19] incorporated the entire MAG corpus — excluding patent data — into OpenAlex [20]. Hence, the snapshot of OpenAlex we studied

maintains all features and data schemas used by the MAG.

The March 2022 snapshot of OpenAlex contains information on 208,755,206 scholarly works. OpenAlex categorizes scholarly works into seven types: journal articles, conference proceedings, repositories, book chapters, books, theses, and datasets (Fig. 1a). We refined the downloaded data by filtering out entries lacking essential information for our analysis, such as publication year, document type, authorship, affiliation, and field of study information. We then restricted our attention further to scholarly works published after 1900 (due to poor coverage of earlier works), and before 2021 (due to incomplete inclusion of more recent works). This filtering procedure left us with a corpus comprising 56,697,402 publication records, 87% of which are journal articles.

These ~ 50 million articles were published across 51,062 scholarly journals. Remarkably, Fig. 1b shows that the number of journal articles published annually has been growing exponentially with an astonishing doubling period of a decade. Even the significant impacts on publication rates of the two World Wars were quickly overcome, and exponential growth resumed.

As journals comprise the largest share of scholarly publications, we choose to study how two characteristics of journal articles — such as diversity of topics and countries — evolved over the last century. A significant challenge with these records, however, is the frequent unavailability of authorship or affiliation metadata —- a limitation that also affected the MAG (see Fig. S2 for a comparison to other databases). The reasons behind this missing metadata in OpenAlex remain unclear. Due to the difficulty of accurately imputing these missing affiliations, our analysis focuses exclusively on journal article publications that include both authorship and affiliation metadata. Approximately 54% of journal articles in the database have complete authorship and affiliation metadata.

Metadata. Every journal article recorded by OpenAlex is assigned to a unique identifier: 'PaperId', and the journal where it was published is also assigned to a unique identifier:'JournalId' [20]. These internal identifiers also connect to external identifiers, such as the International Standard Serial Number (ISSN) [21], the electronic ISSN (eISSN) [21], and the Research Organization Registry Identifier (ROR ID) [22], enabling us to connect information across multiple external data sources. In particular, we can connect authors' affiliations to institutions listed in the ROR database [22] and thus identify the country where the institution is located.

We then referred to the Clarivate Analytics' Journal Citation Reports [23] to obtain the disciplinary classification of the journals in our corpus [24, 25]. We selected for detailed investigation 7 multidisciplinary journals and 16 journals for each of six disciplines across the natural sciences (Chemistry and Physics); life sciences (Biology and Medicine); and social sciences (Economics and Political Science). We selected journals with long publishing history, large number of articles published annually, high impact factors (based on the journal impact factor in 2022), and restricted our attention to journals primarily publishing original research, thus excluding journals focusing on reviews. We then obtained the full publication records of each journal from OpenAlex corpus [20] (see **Extended Data: Fields of study** and Fig. S3).

Quantification. The interdisciplinarity of a journal is measured by the extent to which its articles draw upon knowledge and methods from diverse disciplines. To quantify this, we make use of the fact that we can calculate the probability distribution $p_{jt}(d)$ of the primary — i.e., level L0 (see **Extended Data: Field of Study** for details) — disciplines d of the articles published in a given journal j in a given year t. Since a single article may cover more than one discipline, indicating the integration of knowledge and methods from different fields of study, we compute a fractional discipline count for every article, sum across all articles published in the journal in the specified year, and divide by

the total number of articles so as to get the probability. We use $p_{jt}(d)$ to define an interdisciplinarity index $I_d(j,t)$ by making use of Shannon's entropy [26], which captures the diversity of disciplinary representation in the journal's content:

$$I_d(j,t) = -\sum_d p_{jt}(d) \log_2 \left(p_{jt}(d)\right) . \tag{1}$$

A higher index value indicates greater diversity in the disciplinary focus of a journal, while a lower index value suggests a more concentrated disciplinary focus. Figure S4 demonstrates that higher values of I_d are due to more papers drawing from multiple disciplines than to single discipline papers from multiple disciplines being published in the journal.

Similarly, to quantify the internationalization of a journal, we make use of the fact that we can calculate the probability distribution $p_{jt}(n)$ of the countries n of affiliation of the authors of the articles published in a given journal j in a given year t. Since a single article may include affiliations from more than one country, we calculate a fractional country count for every article, sum across all articles published in the journal in the specified year, and divide by the total number of articles so as to get the probability. We use $p_{jt}(c)$ to define an internationalization index $I_n(j,t)$ by making use of Shannon's entropy [26]:

$$I_n(j,t) = -\sum_n p_{jt}(n) \log_2 \left(p_{jt}(n)\right) . \tag{2}$$

A higher index value indicates greater diversity in the country affiliations of the authors of the articles published in a journal, while a lower index value suggests a more restricted set of countries. Figure S4 suggests that higher values of I_n are not necessarily due to more papers authored by researchers from multiple countries but can be due (see case of Chemistry) to papers from authors from a single country but with greater variety of the specific country.

Shannon's entropy is one of many measures widely used to quantify deviation from random expectation [27, 28]. Indeed, many researchers in scientometrics and science of science have focused on so-called Rao-Stirling indices [29], which can accounts for heterogeneous distances between disciplines and sub-disciplines. Because we are focusing on the highest level in the hierarchy for Field-of-Study, this is not as much a concern for us. Additionally, the raising 2 to the index values provides the an "effective" number of different categories in the data, something that helps with gaining insight from the results.

Results

Top multidisciplinary journals. To build confidence on our metrics, we start by investigating the interdiciplinarity and internationalization of three of the most highly regarded multidisciplinary journals — *Nature*, *Science*, and *The Proceedings of the National Academy Sciences of the United States of America* (*PNAS*). All three journals have a long history and publish a large number of articles annually, mostly original research.

Figure 2a shows the temporal evolution of the interdisciplinarity index for these three journals. It is visually apparent that *Nature* and *PNAS*, in particular, have experienced significant shifts in the degree of interdisciplinarity of the articles they publish. To better understand the specifics of these changes, we next explore how different disciplines received evolving degrees of attention in each of these journals over time (Figs. 2b-d). Because of their preponderance in the data, we split Biology, Chemistry, and Physics articles into separate groups and pool all articles on other major fields of study into an "Other Fields" group.

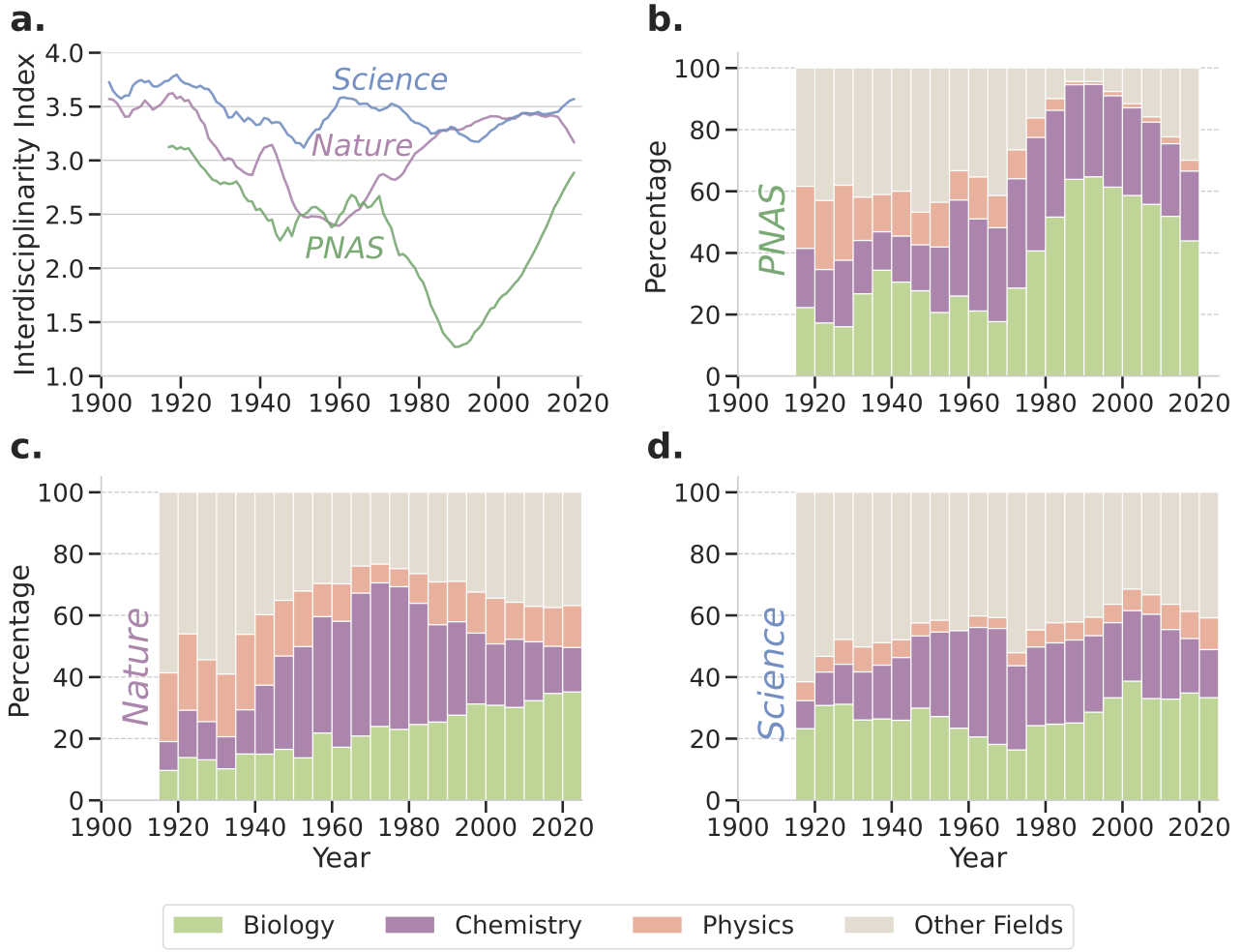

Figure 2: Long-standing, high reputation multidisciplinary journals have shifted their disciplinary focus quite dramatically over the last 100 years. a. Time evolution of the interdisciplinarity indices, I_d, of *Nature*, *Science*, and *PNAS*, measured by the entropy of the annual distribution of disciplines in published articles. **b-d.** Time evolution of the disciplinary partitioning of articles published in *PNAS* (b), *Nature* (c), and *Science* (d). For all three journals, there has been a shift from 'Other Fields' to Physics, Chemistry and Biology. In the 1920s, nearly 60% of articles in *Nature* or *Science* were in fields other than Physics, Chemistry and Biology. Interestingly, after following different paths, all three journals are now publishing nearly 40% of their articles in fields other than Physics, Chemistry and Biology. In *PNAS*, there was a noticeable shift towards Biology from 1960 to 1990 and away from Physics and "Other Fields". After 1990, "Other Fields" grew at the expense of Biology. In *Nature*, there has been a steady growth of Biology focused articles. For both *Nature* or *Science*, the number of Chemistry publications began its ascent in 1940, reaching a pinnacle around 1970, and a slower decline after that.

Upon this breakdown, a clear trend emerges across all three journals. An initial period where a broad range of disciplines are published in those journals, followed by a transition to a greater emphasis on Biology, Chemistry, and Physics. Specifically, in the 1920s, nearly 60% of articles in *Nature* and *Science* concerned disciplines other than Biology, Chemistry, or Physics (Figs. 2c,d). By 1990, approximately 90% of articles in *PNAS* reported on either Biology or Chemistry studies (Fig. 2b). For *Nature*, the peak concentration was reached in the 1970s, when 60% of articles reported

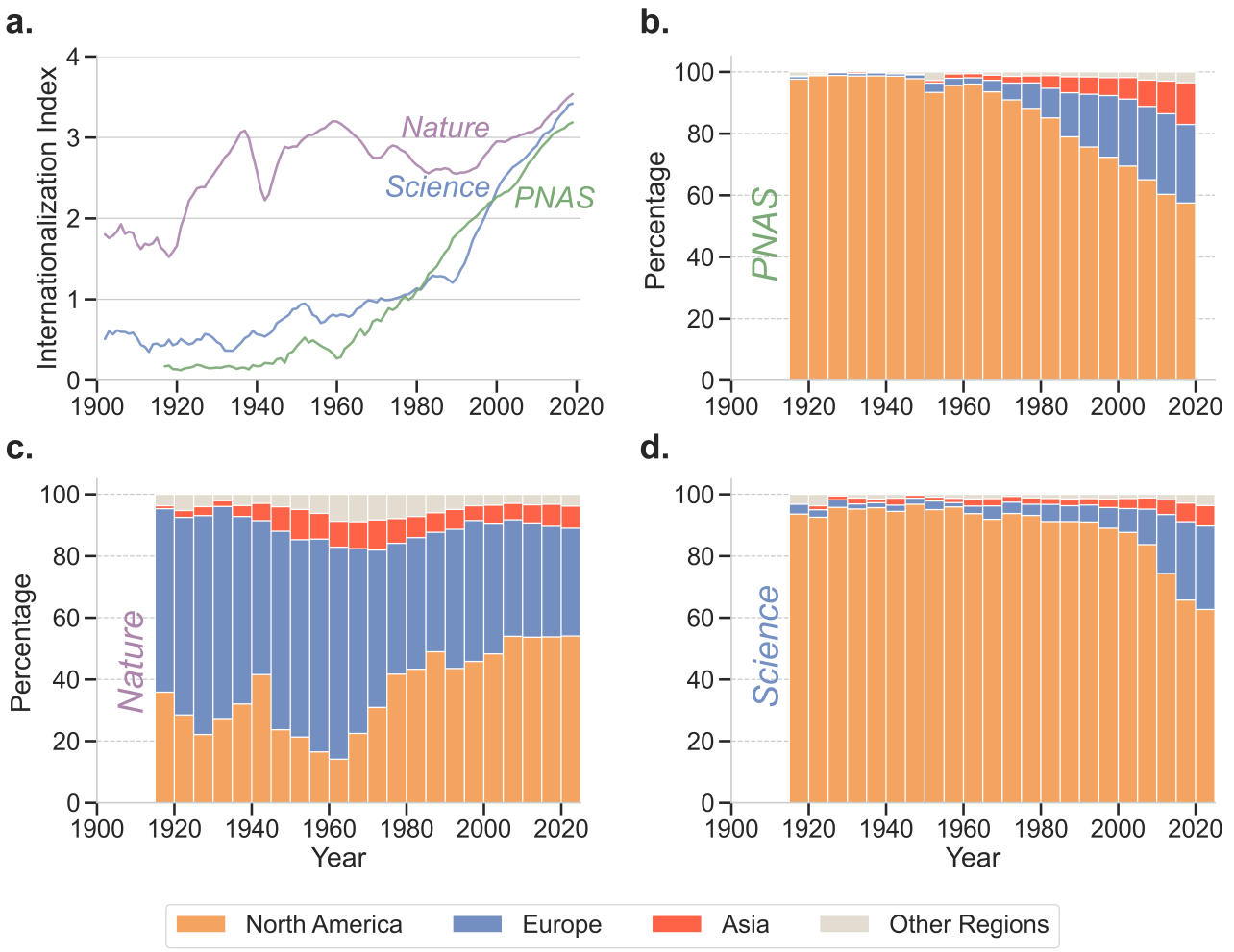

Figure 3: Long-standing, high reputation multidisciplinary journals have become more international. a. Time evolution of the internationalization indices, I_n, of *Nature*, *Science*, and *PNAS*, measured by the entropy of location of the affiliations of the authors of published articles. The index has increased drastically over the last 100 years for all three journals. **b-d.** Time evolution of the percentage of articles whose authors are affiliated with institutions from Asia, Europe, or North America in *PNAS* (b), *Nature* (c), and *Science* (d). For all three journals, the greatest growth has occurred for authors with affiliations in institutions located in Asia. Surprisingly, *PNAS* has now the largest fraction of authors from Asian institutions, even though *Nature* had a higher level in the 1940s. For both *Science* and *PNAS*, the fraction of authors from European institutions has increased dramatically since the 1960s. Around the same time, the fraction of authors from European institutions publishing in *Nature* decreased dramatically as the fraction of authors from North American institutions grew rapidly.

on either Biology or Chemistry studies. Despite distinct historical trajectories, all three journals have evolved in recent years toward a situation where nearly 40% of the articles they publish fall outside of the dominant disciplines, but where Biology studies account for 20–30% of all publications.

Figure 3a shows the time evolution of the internationalization index for *Nature*, *PNAS*, and *Science*. It is visually apparent that *PNAS* and *Science*, in particular, have experienced an extraordinary growth in the diversity of countries from which authors of published articles originate. To better understand the specifics of these aggregate trends, we next explore how authors affiliated with in-

stitutions located in countries from different regions were increasingly able to publish in these leading multidisciplinary journals (Figs. 3b-d). Because of their preponderance in the data, we group countries into three main regions: Asia, Europe, and North America. We group all affiliations to institutions outside of those regions into "Other Regions."

Upon this breakdown, a clear trend emerges for the two U.S. based journals. Both *PNAS* and *Science* started as a publication outlet for only authors with affiliations in North American institutions (Figs. 3b,d). Starting in the 1980s, both experience an increase in the fraction of papers authored by researchers affiliated with European institutions and, to a lesser extent, Asian institutions. Currently, about 60% of papers published in *PNAS* and *Science* are authored by researchers affiliated with North American Institutions, but that percentage appears likely to continue to decline.

The story is more complex for *Nature* (Fig. 3c). Already over a century ago, authors from institutions in Europe and North American were publishing in this U.K.-based journal. Moreover, already by the 1940s, authors affiliated with institutions in Asia started publishing in *Nature*. Despite this early internationalization effort, *Nature* now publishes about the same fractions of Asian, European and North American authors as *Science*, but a smaller fraction of authors affiliated with institutions from Asia than *PNAS*.

This internationalization shift may be partially attributed to external factors such as the rise of electronic publishing which now offers researchers a multitude of platforms for communicating their research and an easier path to submitting manuscripts to — or reviewing manuscripts for — journals based in other continents. Electronic publishing also enabled a new model — open access [7,30]. Initial studies suggested that open access publication produced greater research visibility and greater number of citations [31]. Another important factor impacting journal internationalization is the growth of team sizes [32,33] and of international collaborations as more diverse collaborating teams may prioritize different factors in the choice of publication venue.

Disciplinary and Multidisciplinary journals: Interdisciplinarity. Next, we compare the changes in interdisciplinarity and internationalization for disciplinary journals (see **Data and Methods** for details). Reassuringly, our analysis shows that over the observed time periods, the interdisciplinarity index (I_d) of multidisciplinary journals consistently remains significantly higher than that of disciplinary journals (Fig. 4, **Extended Data: Interdisciplinarity dynamics**, and Fig. S5). Considering just the most recent indices (as shown in Table S1), we found that the average interdisciplinarity index for multidisciplinary journals is approximately 3 (*Science* has the highest interdisciplinarity index, $I_d \approx 3.5$). Moreover, the interdisciplinarity of multidisciplinary journals appears to reach as steady-state after 1990.

The evolution of interdisciplinarity is more diverse for disciplinary journals. Physics and Chemistry journals display intriguing changes in interdisciplinarity. A majority of those journals has increase dramatically in interdisciplinarity over time, with Physics journals, in particular, reaching very high degrees of interdisciplinarity. In contrast, a smaller subset of journals have become very mono-disciplinarity. Consistent with this finding, we categorize disciplinary journals into two groups according to their interdisciplinarity index: mono-disciplinary ($I_d \approx 0$) and moderately interdisciplinary ($I_d \approx 1.5$).

A segregation between moderately interdisciplinary and mono-disciplinary journals is not as apparent for Biology and Medicine journals. The small values of the 5-year trends show that the interdisciplinarity of Biology and Medicine journals is also more stable than that of Physics and Chemistry journals.

Economics journals show a trend similar to that of the journals in the natural and life sciences. That is, their interdisciplinarity has increase over time and there is a spread in the levels of interdisci-

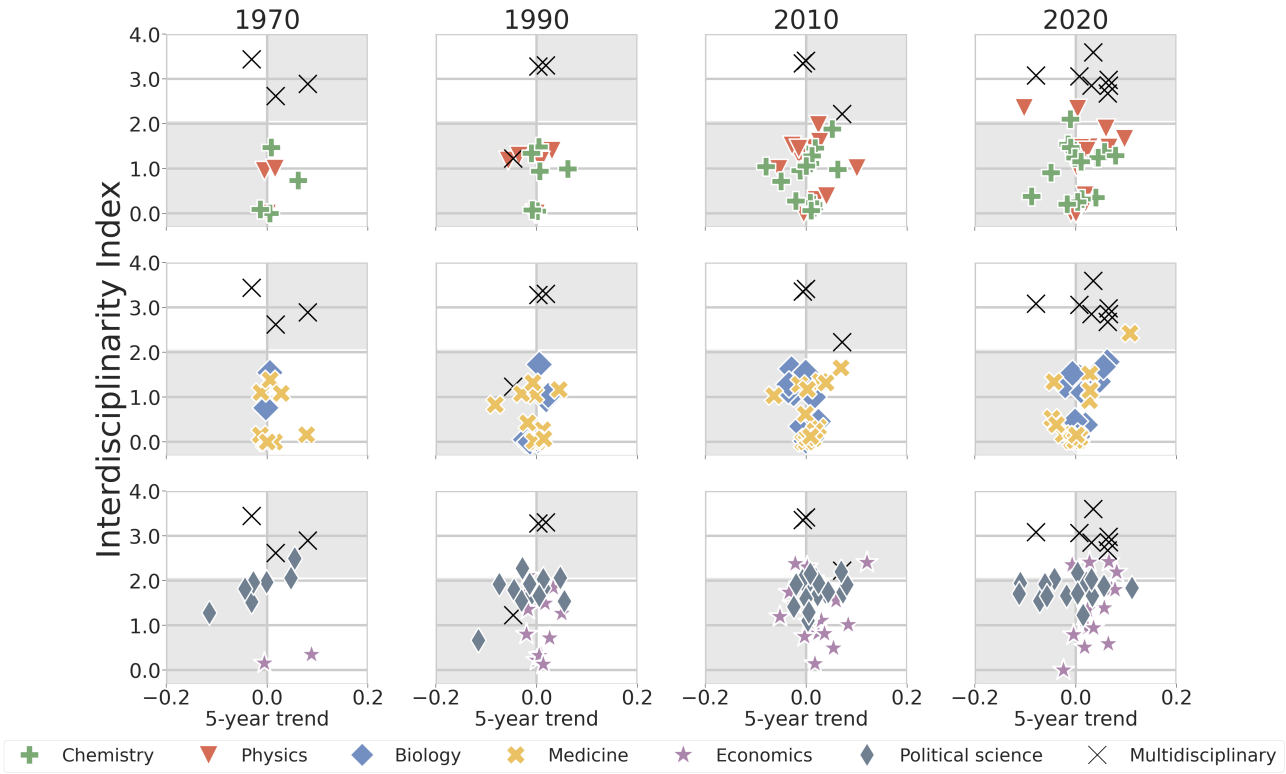

Figure 4: Trends in interdisciplinarity across journals in natural sciences, life sciences, social sciences, and multidisciplinary sciences in 1970, 1990, 2010, and 2020. Most recent interdisciplinarity index at a specific year, I_d, versus the linear trend of the journal's interdisciplinarity index over the preceding 5 years. Multidisciplinary journals consistently exhibit a substantially higher interdisciplinarity index ($I_d \approx 3$) compared to all disciplinary journals throughout the observed period (Table S1). Disciplinary journals in natural science (Chemistry and Physics) and life science (Biology and Medicine) appear to fall into two groups based on their interdisciplinarity indices: The first group of journals maintains a narrow focus, publishing research that draws on a single discipline ($I_d \approx 0$). The second group of journals publishes moderately interdisciplinary research ($I_d \approx 1.5$). This separation between mono-disciplinary and moderately interdisciplinary journals is visually apparent for journals in natural and life sciences. In contrast, the disciplinary journals in Economics and Political Science we studied seem to be moderately interdisciplinary ($I_d \approx 1.5$).

plinarity around moderate interdisciplinarity. In contrast, Political Science journals have maintained high levels of interdisciplinarity for the entire period studied — a level that was achieved only recently by the most interdisciplinary Physics journals. Perhaps this is not surprisingly as political science is a multifaceted discipline that incorporates insights from fields as diverse as business, economics, law, psychology, and sociology [34].

Thus, despite there being an overall perception of a growing emphasis on interdisciplinary research, the reality is that some disciplinary journals have strengthened their mono-disciplinary focus. The reasons for this are likely complex and multifaceted but may be, at least in part, due to traditional academic structures and publishing norms that favored depth over breadth. Indeed, some of the mono-disciplinary journals in Biology, Chemistry and Physics are highly regarded journals — *Molecular Cell* ($I_d \approx 0.03$), *Journal of the American Chemical Society* ($I_d \approx 0.3$), and *Nature Physics* ($I_d \approx 0.3$). However, we also observe a statistically significant positive correlation between the latest value of I_d and its most recent 5-year trend for Biology journals (Table S1) suggesting that Biology

journals which are already interdisciplinary are continuing to increase their degree of interdisciplinarity. The emergence of novel areas such as Systems and Synthetic Biology may be responsible for this trend [35].

Disciplinary and Multidisciplinary journals: Internationalization. We next compare the internationalization index of disciplinary and multidisciplinary journals over time (Fig. 5, **Extended Data: Internationalization dynamics** and Fig. S7). With regards to internationalization, multidisciplinary journals are not the trend setters (Table S2). Instead, disciplinary journals in Physics have the highest I_n, while disciplinary journals in Biology and Chemistry have internationalization indices comparable to that of multidisciplinary journals. An exception to this pattern is the pair of mega open-access journals — *PLOS One* and *Scientific Reports* — which have internationalization indices as high as those of the most internationalized Physics journals. The remaining five multidisciplinary journals exhibit internationalization indices comparable to those of Biology and Chemistry journals. This finding is perhaps unsurprising, given the substantial representation of biological and chemical research within these multidisciplinary journals.

The very high degree of internationalization of Physics journals is also not surprising. Large international initiatives such as the Conseil Européen pour la Recherche Nucléaire (CERN) colliders [36], the Super-Kamiokaze neutrino detection facility [37], the Laser Interferometer Gravitational-Wave Observatory (LIGO) [38] and the Paranal Observatory [39] have been a constant of the Physics research landscape since the 1950s.

Our data also reveals a statistically significant correlation between the latest value of I_n and its most recent 5-year trend for disciplinary journals in Physics. This correlation is consistent with idea that Physics journals that are already highly internationalized are becoming even more internationalized, while the least internationalized are becoming less internationalized. This trend highlights a growing divide between journals actively pursuing internationalization and those either unwilling or unable to do so.

Similarly to Physics, biological research has been revolutionized by global initiatives such as the Human Genome Project (HGP) [40], the International HapMap Project [41], or the 1000 Genomes Project (1KGP) [42]. Remarkably, disciplinary journals in Chemistry have achieved a similarly high degree of internationalization without the benefit of large international collaborations. The explanation here may be the global need for the spread of the fossil fuels that are so critical to the chemical industry and have promoted development of the discipline across the globe [43].

Among disciplinary journals, journals in Medicine exhibit the lowest level of internationalization (mean $I_n \approx 1.9$). This finding aligns with prior reports that highlight the relatively lower levels of international collaboration in applied and clinical medicine [44]. There are, however, two notable exceptions: *The Lancet* ($I_n \approx 4.0$) and the *European Journal of Clinical Investigation* ($I_n \approx 4.4$). Since most Medical journals maintain a modestly low internationalization index, we surmise that medical research adopts a predominantly regional focus and field-specific norms, such as localized health issues, regional regulatory standards, etc. Nonetheless, it is likely that global epidemics — Acquired immunodeficiency syndrome (AIDS), Severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), or Coronavirus disease 2019 (COVID-19) — will increase the pressure to internationalize medical research.

The need for an increase in the internationalization of social sciences research may be less obvious. Indeed, even some Political Science have low internationalization (mean $I_n \approx 2.7$). This may be due to differences in what type of questions researchers from different countries may want to investigate. However, there has been a recent interest by research in the Western world in investigating phenomena that extend beyond what is expected from Western, educated, industrialized, rich and

democratic (WEIRD) societies.

Disciplinary journals: Impact of team size. Since very large collaborations are not unusual in Biology, Medicine or Physics (Table S3), we investigated whether our findings for those two disciplines could have been due to the characteristics of the largest teams. As a control, we repeated the previous analyses for these three disciplines but excluding all publications with 10 or more authors.

Consistent with other studies, we found that there has been a consistent and significant rise in the number of publications authored by teams of 10+ individuals. This increase was already visible in Physics and Medicine by the 1960s. For Biology, the increase becomes noticeable after 1980 (Fig. S8).

Our control analyses confirm the results obtained when considering all teams, thus demonstrating that the trends in interdisciplinarity and internationalization are not explainable by the presence of very large teams in those disciplines (Fig. S9). That is, the observed internationalization of the research published in these top disciplinary journals occurs because the disciplines have created a truly

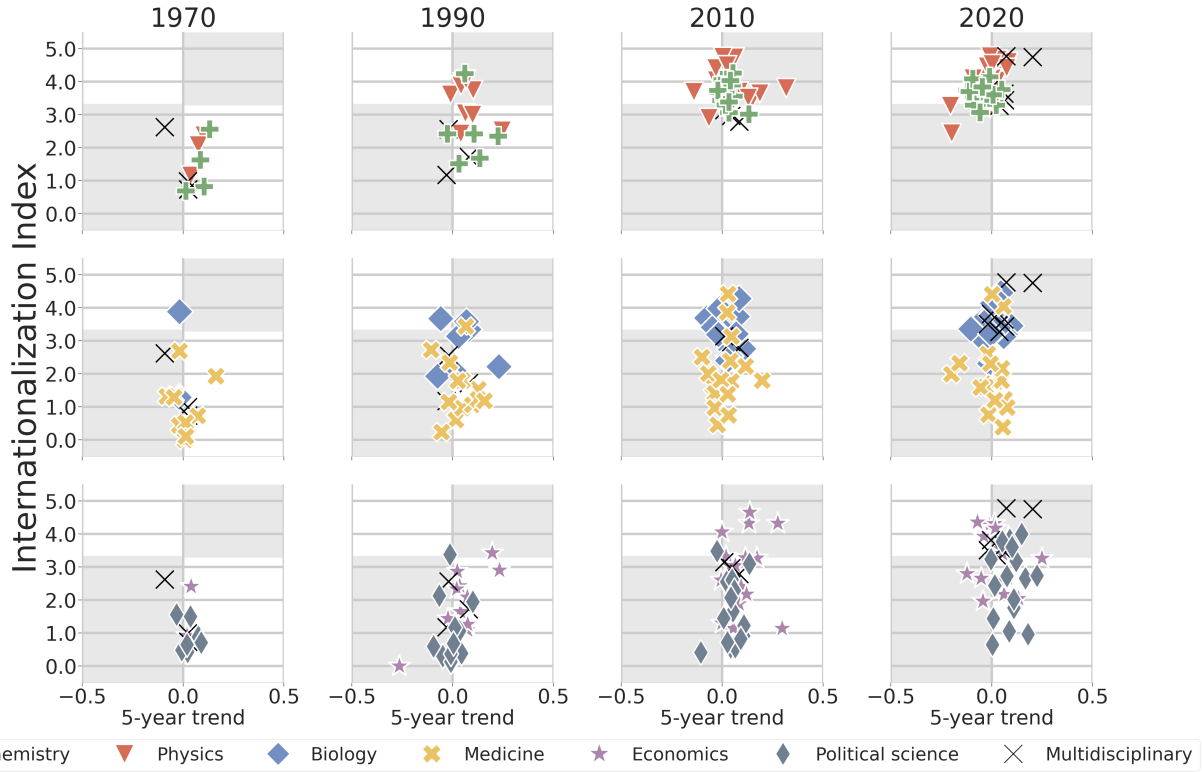

Figure 5: Trends in internationalization across journals in natural sciences, life sciences, social sciences, and multidisciplinary sciences in 1970, 1990, 2010, and 2020. Most recent internationalization index at a specific year, I_n, versus the linear trend of the journal's internationalization index over the preceding 5 years. The internationalization of disciplinary journals exhibits a variety of behaviors (see also Table S2). Physics journals have steadily increased their internationalization, which is now higher than for most multidisciplinary journals. comparable to those of multidisciplinary journals during this period. In 2020, the mean I_n of Physics journals is approximately 4.1. Journals in Biology and Chemistry display similar trends, but with lower mean I_n, approximately 3.6 for both Chemistry and and Biology journals. In contrast, while a few Medicine and Economics journals have $I_n \approx 4$, most journals in these disciplines and in Political Science have $I_n < 3$.

international enterprise.

Discussion

Our findings highlight a transformational shift within the landscape of scientific publishing — the increasingly interconnected nature of scientific research both at the international and interdisciplinary levels. The reasons for this increased interconnectedness are multifaceted. Increased journal competition for the most exciting research, the need for access to scarce or unique resources, the desire to attract a talented workforce. Whatever the reasons, it is critical to recognize the need for such interconnectedness if one aims to tackle the enormous societal challenges that face us, from climate change to increased conflict.

While this shift may bring hope to some, it may be seen as threatening by others. Either because of a misguided focus on competition between nations and the need to retain claims of primacy, or because of wishes to preserve disciplinary purity. Indeed, some current efforts in some countries to "safeguard their national research enterprises" may prove costly to the creation of new knowledge within their own nations. Whatever the motivation, it would be wise for policy makers, research funding organizations, and research institutions to understand and adapt to this shifting landscape in order to effectively promote innovation.

Our study is not without limitations. Perhaps the greatest limitation is that we focus on disciplines where journal articles are the primary scholarly communication channel. This limitation prevents us from being able to generalize our findings to disciplines in the Humanities, which rely on books or book chapters, or in Computer Science and Engineering, which rely on conference proceedings [45]. A second limitation of our study is the fact that we only consider 7 multidisciplinary journals and 16 journals for each discipline. The reason for the small number of multidisciplinary journals considered is that there are not that many highly respected journals thus classified.

Another limitation we must discuss relates to the completeness and representativeness of the data across disciplines. This concern was foremost in our minds when deciding on the time period for analysis. Indeed, the reason why we consider the period 1900–2021 for only the the three major interdisciplinary journals — *Nature, PNAS, Science* — has to do precisely with the fact that those journals are the most likely to be accurately covered. When considerring disciplinary journals we restrict our attention to the period 1960–2021. Even then, for some journals and disciplines covered can be spotty prior to 2000. For this reason, we perform analyses that focus on manually selected journals and for specific time points (1970, 1990, 2010, 2020).

Moreover, the selected journals are among the most reputable in their fields and publish large volumes of articles (see **Data and Methods** for details). While the requirements we impose limit the number of disciplinary journals that we can consider, we believe that the selected journals provide an accurate reflection of the changes occurring within the disciplines we consider.

Data Availability

The latest version of OpenAlex data snapshot is freely available for download at here. The Clarivate Analytics' Journal Citation Reports are available and downloaded here.

Code Availability

The code needed to reproduce these results is available for download at GitHub repository: here.

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Contributions

H.Z. and L.A.N.A. conceived and designed the study. H.Z. contributed to the data preparation, wrote the codes for data analysis, numerical calculation and figure plotting. H.Z. and L.A.N.A. contributed to the interpretation of the results and drafted the manuscript. H.Z. and L.A.N.A. wrote, read, and approved the final version of the paper.

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Ethics declarations

Competing interests

The authors declare no conflict of interest.

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Extended Data

Tables

Discipline	Mean I_d	Mean 5-yr trend	ρ	p-value
Biology	0.86	0.01	**0.56**	0.02
Chemistry	1.04	0.02	0.28	0.30
Physics	1.14	0.01	0.32	0.24
Economics	1.53	0.04	0.36	0.16
Medicine	0.68	-0.01	0.15	0.58
Political Science	1.78	-0.01	0.06	0.83
Multidisciplinary	3.02	0.02	**-0.75**	0.05

Table S1: Average interdisciplinarity characteristics of journals from different disciplines. We report the average Interdisciplinarity Index I_d, its most recent 5-year trend, the Spearman's correlation coefficient of I_d and the most recent 5-year trend, and the p-value of the correlation. We highlight statistically significant cases in bold face.

Discipline	Mean I_n	Mean 5-yr trend	ρ	p-value
Biology	3.58	0.02	0.18	0.51
Chemistry	3.61	-0.03	-0.06	0.82
Physics	4.08	-0.02	**0.54**	0.03
Economics	3.24	0.01	0.16	0.54
Medicine	1.94	-0.01	-0.19	0.47
Political Science	2.68	0.11	0.17	0.53
Multidisciplinary	3.90	0.05	0.36	0.43

Table S2: Average internationalization characteristics of journals from different disciplines. We report the average Internationalization Index I_n, its most recent 5-year trend, the Spearman's correlation coefficient of I_n and the most recent 5-year trend, and the p-value of the correlation. We highlight statistically significant cases in bold face.

Discipline	**Mean** Team Size	σ
Biology	4.84	4.96
Chemistry	5.02	3.12
Physics	**8.52**	**75.48**
Economics	1.95	1.21
Medicine	3.31	6.77
Political Science	1.36	0.85
Multidisciplinary	5.40	6.89

Table S3: Average team size of journal publications in different disciplines. We report the average team size and its standard deviation for publications across various disciplines. We highlight Physics in bold face since it stands out for having the largest average team size.

Statistics on journal publications at country level

Journal articles indexed in OpenAlex include information on authors and their corresponding affiliations. We extracted the countries of those affiliations and aggregate total volume of journal articles published by each country from 1900 to 2021. The five countries with the most publications are the United States (the U.S.), China, the United Kingdom (the U.K.), Japan, and Germany (Fig. S1a). Figure S1 shows their annual number of publication over. The number of journal articles published by Japan surpassed those by Germany in 1970 and those by the U.K. in 1980. Since 2005, China has published more journal articles annually than Germany, Japan, or the U.K., suggesting its rising role in knowledge creation.

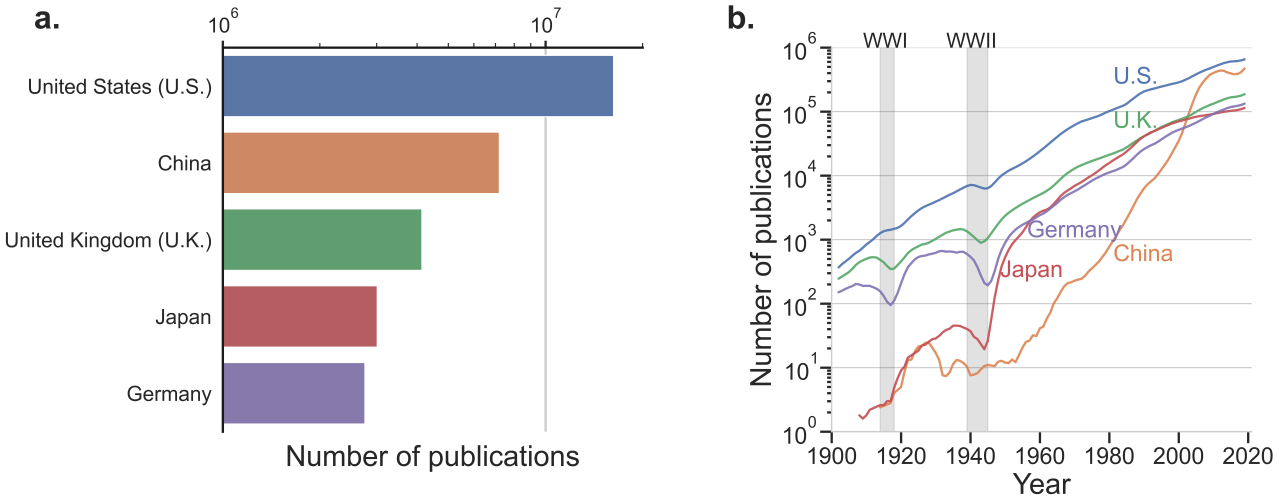


Figure S1: Journal article publication trends of the five most prolific countries. a. Total number of journal publications (1900-2021) of the most five prolific countries. **b.** Annual number of journal articles published by those five countries. For clarity, we show 5-year moving averages.

Reliance on single data source

OpenAlex is far from comprehensive (especially for works published prior to 1960) and is not perfectly accurate. Thus one may question how much can results obtained using its data be trusted. In order to answer this question, it is important to also acknowledge that these weaknesses are not unique to OpenAlex — they are shared by other bibliometric databases. For example, we observed that both the original Microsoft Academic Graph database [46], and the subscription-based Dimensions database [47] display similar patterns regarding fraction of records with some missing information (Fig. S2). Scopus [48], another popular database for bibliometric studies, does not have appropriate coverage for works published prior to 1996 [49].

Because all datasets have similar weaknesses but not all are equally available to all researchers, we chose to conduct our study using OpenAlex because its openness increases the reproducibility of our study. In addition, we focused our attention on what we believed would be the highest quality records. Specifically, we decided to focus on (i) complete records (i.e., those with authorship, affiliations, and field of study tags), and (ii) the most well-known, highest reputation journals.

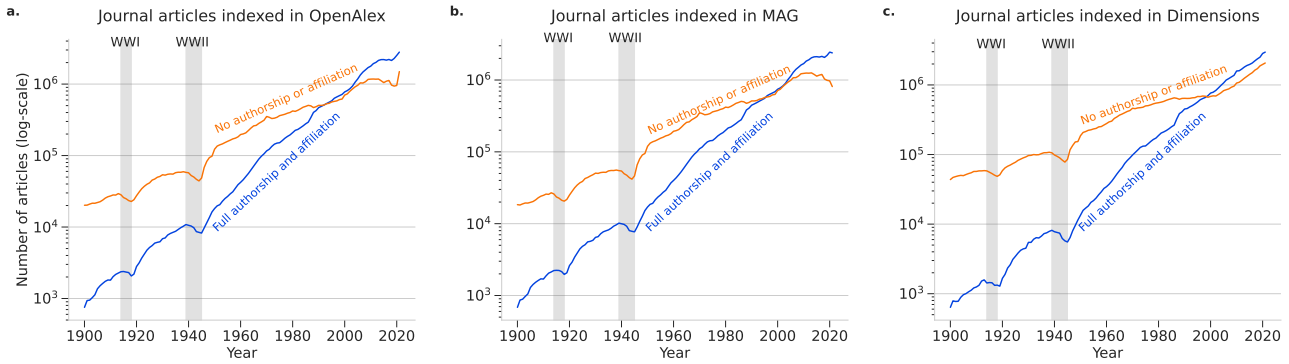


Figure S2: Number of journal articles over time across three bibliometric databases. a. Number of journal articles indexed in OpenAlex over the past decade, categorized by the presence or absence of authorship and affiliation metadata. **b.** Number of journal articles indexed in Microsoft Academic Graph (MAG) over the past decade, categorized by the presence or absence of authorship and affiliation metadata. **c.** Number of journal articles indexed in Dimensions over the past decade, categorized by the presence or absence of authorship and affiliation metadata.

Fields of study

Journal articles indexed in OpenAlex are assigned one or more topics called 'Field-of-Study' (FoS). The FoS classification system is structured hierarchically across six levels (L0 up to L5). The snapshot adheres to the Microsoft Academic Graph (MAG) schema, wherein the classification process involves several stages: concept discovery (identifying relevant topics within the text), concept tagging (associating the identified topics with the corresponding papers), and hierarchy construction (organizing topics into a coherent structure). This process is largely automated, relying on web crawling, scraping, natural language processing, and machine learning algorithms to assign topics efficiently. Following automation, the outcomes were rigorously evaluated by a panel of human experts to ensure accuracy and relevance [50]. The FoS classification has been widely applied in other research contexts to determine the disciplinary focus of journal articles [51] and to build cumulative knowledge portfolio for scholars [52].

We focus here on the top level (L0). The classifications at L0-levels contain 19 distinct fields representing traditional academic disciplines (e.g. Medicine, Biology and Chemistry). Figure S3 a shows the total number of journal articles published for each L0 field; Figure S3 b-f display the number of journal articles published annually in each respective L0 field (from the largest to the smallest number of publications).

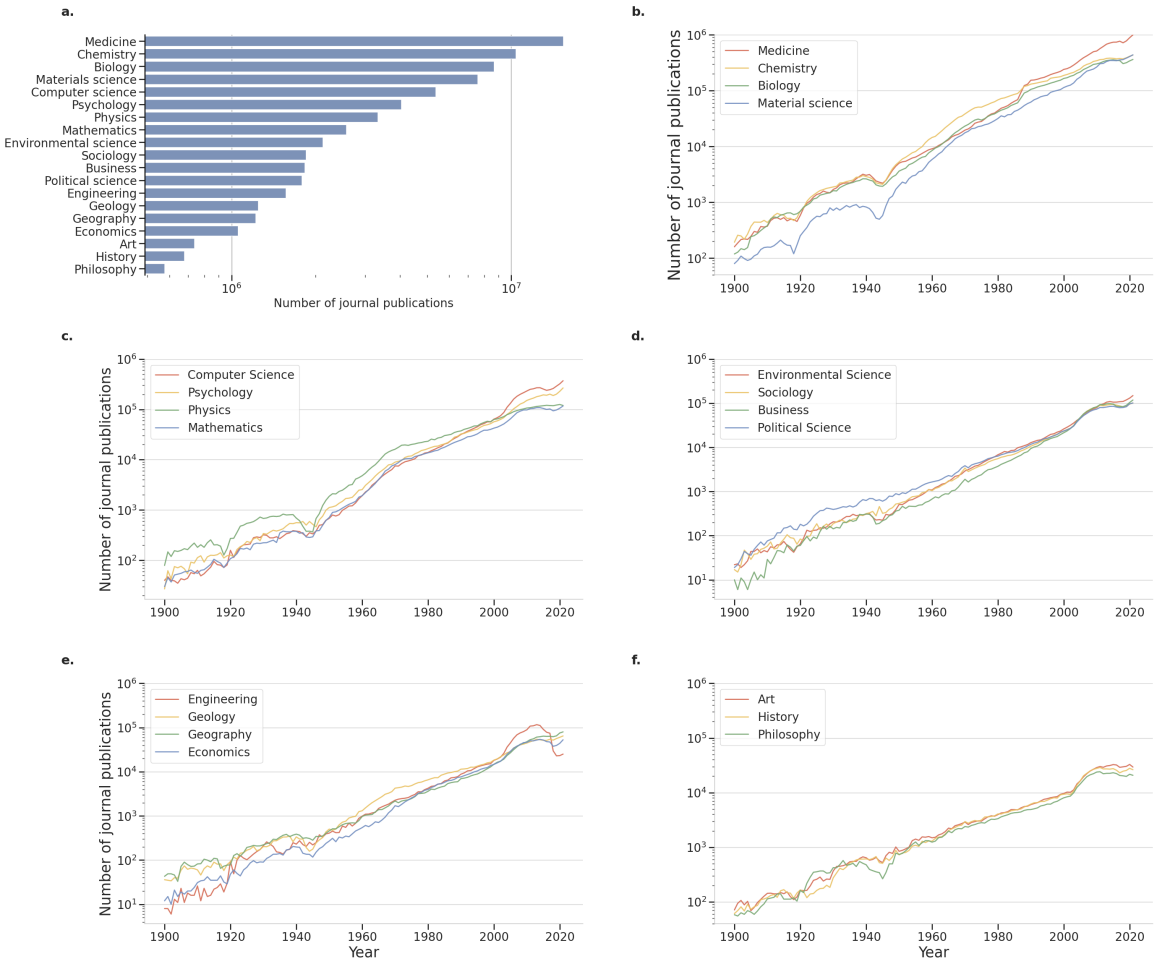


Figure S3: Number of journal publications in each Field of Study (FoS). a. Total number of journal publications (1900-2021) in each L0 FoS. **b-f.** Annual publication count of each L0 FoS.

Journal selection

We focus on journals classified by the Clarivate Analytics' Science Citation Index Expanded (SCIE) into the following 5 categories: Multidisciplinary Sciences (73 journals in total), Biochemistry and Molecular Biology (285 journals in total), Multidisciplinary Chemistry[2] (175 journals in total), Multidisciplinary Physics[3] (84 journals in total), and General and Internal Medicine (167 journals in total).

We also focus on journals classified by the Clarivate Analytics' Social Science Citation Index (SSCI) into the following 2 categories: Economics (381 journals in total) and Political Science (187 journals in total).

We selected journals in each category based on length of publication history, impact of pulblications, and volume of publications. We list the journals selected below along with their Journal Citation Report (JCR) abbreviations in parenthesis, unless the JCR abbreviation matches the title of the journal (journals in each category are listed in alphabetic order).

Multidisciplinary Sciences — We selected the following 7 journals:

- *Nature*
- *Nature Communications* (*Nat Commun*)
- *PLOS One*
- *Proceedings of National Academy of Sciences* (*PNAS*)
- *Science*
- *Science Advances* (*Sci Adv*)
- *Scientific Reports* (*Sci Rep-UK*)

The average Journal Impact Factor of these seven journals is 24.5, the average publication volume is 114,043 articles, and the average age is approximately 56 years.

Multidisciplinary Chemistry — We selected the following 16 journals:

- *ACS Nano*
- *Advanced Functional Materials* (*Adv Funct Mater*)
- *Advanced Materials* (*Adv Mater*)
- *Angewandte Chemie International Edition* (*Angew Chem Int Edit*)
- *Archiv der Pharmazie* (*Arch Pharm*)
- *Bioconjugate Chemistry* (*Bioconjugate Chem*)
- *ChemSusChem*
- *Green Chemistry* (*Green Chem*)
- *Journal of the American Chemical Society* (*J Am Chem Soc*)
- *Journal of Controlled Release* (*J Control Releas*)
- *Journal of Physics and Chemistry of Solids* (*J Phys Chem Solids*)
- *Lab on a Chip* (*Lab Chip*)
- *Langmuir*
- *Nano Letters* (*Nano Lett*)
- *Small*
- *Ultrasonics Sonochemistry* (*Ultrason Sonochem*)

The average Journal Impact Factor in 2022 of these 16 journals is 11.4, the average publication volume is 22,309 articles, and the average age is approximately 45 years.

[2] Although the term used in the SCIE is Multidisciplinary Chemistry, these journals are considered as Chemistry journals.

[3] Although the term used in the SCIE is Multidisciplinary Physics, these journals are considered as Physics journals.

Multidisciplinary Physics — We selected the following 16 journals:

- *Annalen der Physik* (*Ann Phys-Berlin*)
- *Annals of Physics* (*Ann Phys-New York*)
- *Chaos Solitons and Fractals* (*Chaos Soliton Fract*)
- *Classical and Quantum Gravity* (*Classical Quant Grav*)
- *Europhysics Letters* (*EPL-Europhys Lett*)
- *European Physical Journal-Special Topics* (*Eur Phys J-Spec Top*)
- *Foundations of Physics* (*Found Phys*)
- *General Relativity and Gravitation* (*Gen Relat Gravit*)
- *International Journal of Theoretical Physics* (*Int J Theor Phys*)
- *Journal of Physics A-Mathematical and Theoretical* (*J Phys A-Math Theor*)
- *Nature Physics* (*Nat Phys*)
- *New Journal of Physics* (*New J Phys*)
- *Physical Review Letters* (*Phys Rev Lett*)
- *Physica Scripta* (*Phys Scripta*)
- *Quantum Information Processing* (*Quantum Inf Process*)
- *Soft Matter*

The average Journal Impact Factor in 2022 of these 16 journals is 4.3, the average publication volume is 13,981 articles, and the average age is approximately 44 years.

Biochemistry and Molecular Biology — We selected the following 16 journals:

- *American Journal of Respiratory Cell and Molecular Biology* (*Am J Resp Cell Mol*)
- *Biomacromolecules*
- *Cell*
- *Cellular and Molecular Life Sciences* (*Cell Mol Life Sci*)
- *Current Biology* (*Curr Biol*)
- *EMBO Journal* (*EMBO J*)
- *Free Radical Biology and Medicine* (*Free Radical Bio Med*)
- *Genome Research*
- *International Journal of Biological Macromolecules ()*
- *Journal of Lipid Research* (*J Lipid Res*)
- *Molecular Biology and Evolution* (*Mol Biol Evol*)
- *Molecular Cell* (*Mol Cell*)
- *Nature Structural and Molecular Biology* (*Nat Struct Mol Biol*)
- *Nucleic Acids Research* (*Nucleic Acids Res*)
- *Plant Cell*

The average Journal Impact Factor in 2022 of these 16 journals is 17.4, the average publication volume is 15,879 articles, and the average age is approximately 42 years.

General and Internal Medicine — We selected the following 16 journals:

- *American Journal of Medicine* (*Am J Med*)
- *American Journal of Preventive Medicine* (*Am J Prev Med*)
- *Annals of Internal Medicine* (*Ann Intern Med*)
- *British Journal of General Practice* (*Brit J Gen Pract*)
- *Chinese Medical Journal* (*Chinese Med J-Peking*)
- *European Journal of Clinical Investigation* (*Eur J Clin Invest*)

- *JAMA - J Am Med Assoc*
- *JAMA Internal Medicine*
- *Journal of General Internal Medicine* (*J Gen Intern Med*)
- *Journal of the Royal Society of Medicine* (*J Roy Soc Med*)
- *Lancet*
- *Medical Clinics of North America* (*Med Clin N Am*)
- *Medical Journal of Australia* (*Med J Australia*)
- *Nature Medicine* (*Nat Med*)
- *New England Journal of Medicine* (*New Engl J Med*)
- *Preventive Medicine*

The average Journal Impact Factor in 2022 of these 16 journals is 39.1, the average publication volume is 16,159 articles, and the average age is approximately 88 years.

Economics — We selected the following 16 journals:

- *American Economic Review* (*Am Econ Rev*)
- *Ecological Economics* (*Ecol Econ*)
- *Economic Geography* (*Econ Geogr*)
- *Economic Modelling* (*Econ Model*)
- *Energy Economics* (*Energ Econ*)
- *International Journal of Forecasting* (*Int J Forecasting*)
- *Journal of Development Economics* (*J Dev Econ*)
- *Journal of Econometrics* (*J Econometrics*)
- *Journal of Monetary Economics* (*J Monetary Econ*)
- *Journal of Public Economics* (*J Public Econ*)
- *Journal of Urban Economics* (*J Urban Econ*)
- *Quarterly Journal of Economics* (*Q J Econ*)
- *Review of Economic Studies* (*Rev Econ Stud*)
- *Review of Financial Studies* (*Rev Financ Stud*)
- *Small Business Economics* (*Small Bus Econ*)
- *World Development* (*World Dev*)

The average Journal Impact Factor in 2022 of these 16 journals is 7.9, the average publication volume is 3,662 articles, and the average age is approximately 55 years.

Political Science — We selected the following 16 journals:

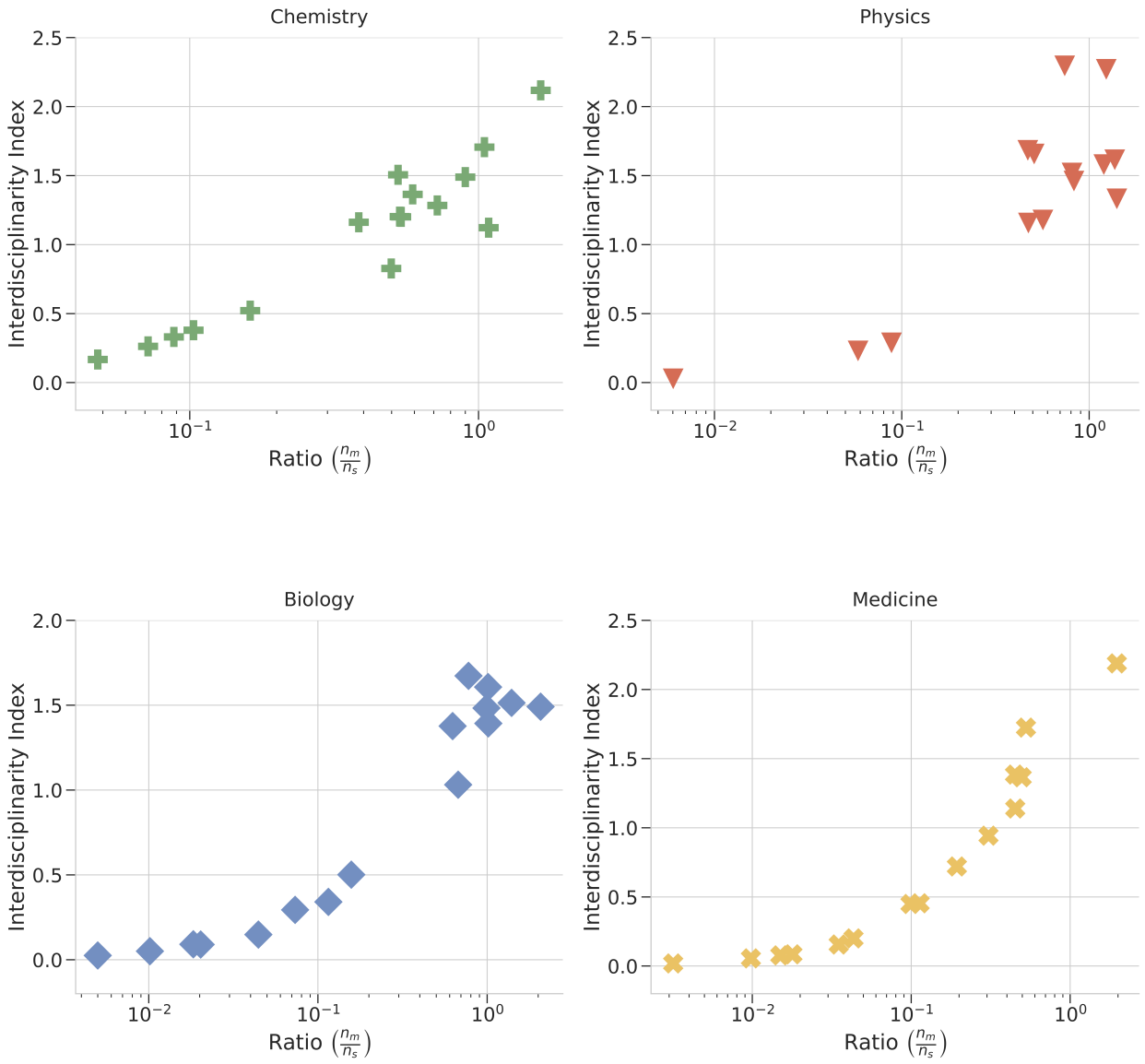
- *American Journal of Political Science* (*Am J Polit Sci*)
- *American Political Science Review* (*Am Polit Sci Rev*)
- *Canadian Journal of Political Science* (*Can J Polit Sci*)
- *Comparative Political Studies* (*Comp Polit Stud*)
- *European Journal of Political Research* (*Eur J Polit Res*)
- *International Studies Review* (*Int Stud Rev*)
- *Journal of Conflict Resolution* (*J Conflict Resolut*)
- *Journal of Peace Research* (*J Peace Res*)
- *Journal of Politics* (*J Polit*)
- *Policy Studies Journal* (*Policy Stud J*)
- *Political Geography* (*Polit Geogr*)
- *Political Psychology* (*Polit Psychol*)

- *Political Studies* (*Polit Stud-London*)
- *PS: Political Science and Politics* (*PS-Polit Sci Polit*)
- *Public Administration* (*Public Admin*)
- *Public Opinion Quarterly* (*Public Opin Quart*)

The average Journal Impact Factor in 2022 of these 16 journals is 4.0, the average publication volume is 3,338 articles, and the average age is approximately 60 years.

Relation between Interdisciplinarity index and fraction of papers assigned multiple disciplines

We calculate the ratio between the number n_m of papers with multiple disciplines (or FoS tags) and the number n_s of papers with a single discipline (or FoS tag) for disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, and Political Science. We then plot the ratio versus the 2021 Interdisciplinarity Index of the journal. A positive slope in these plots indicated that greater values of I_d correspond to higher proportions of papers drawing from multiple disciplines.



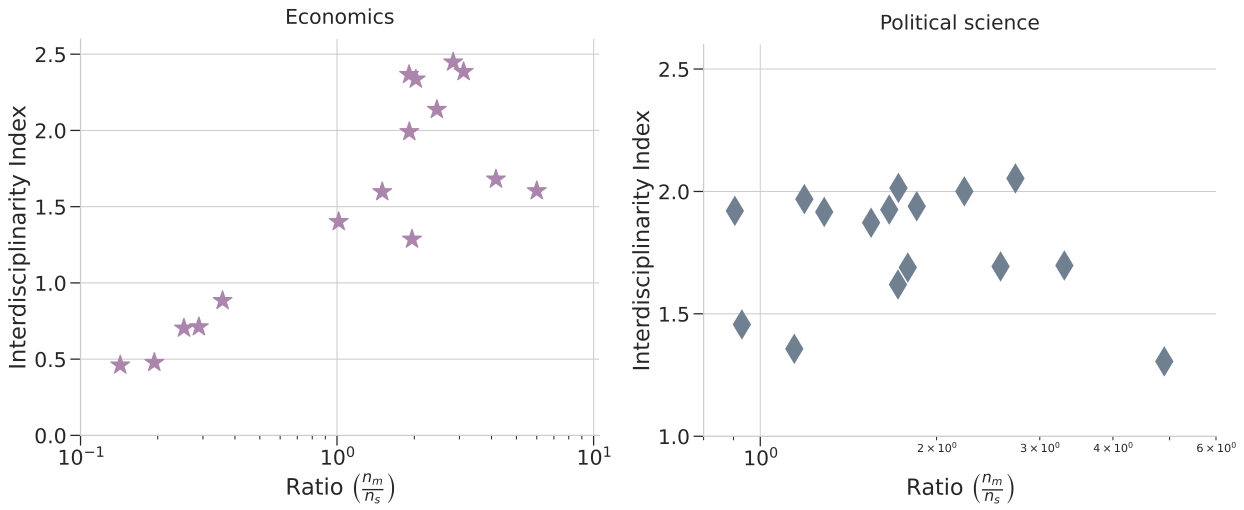
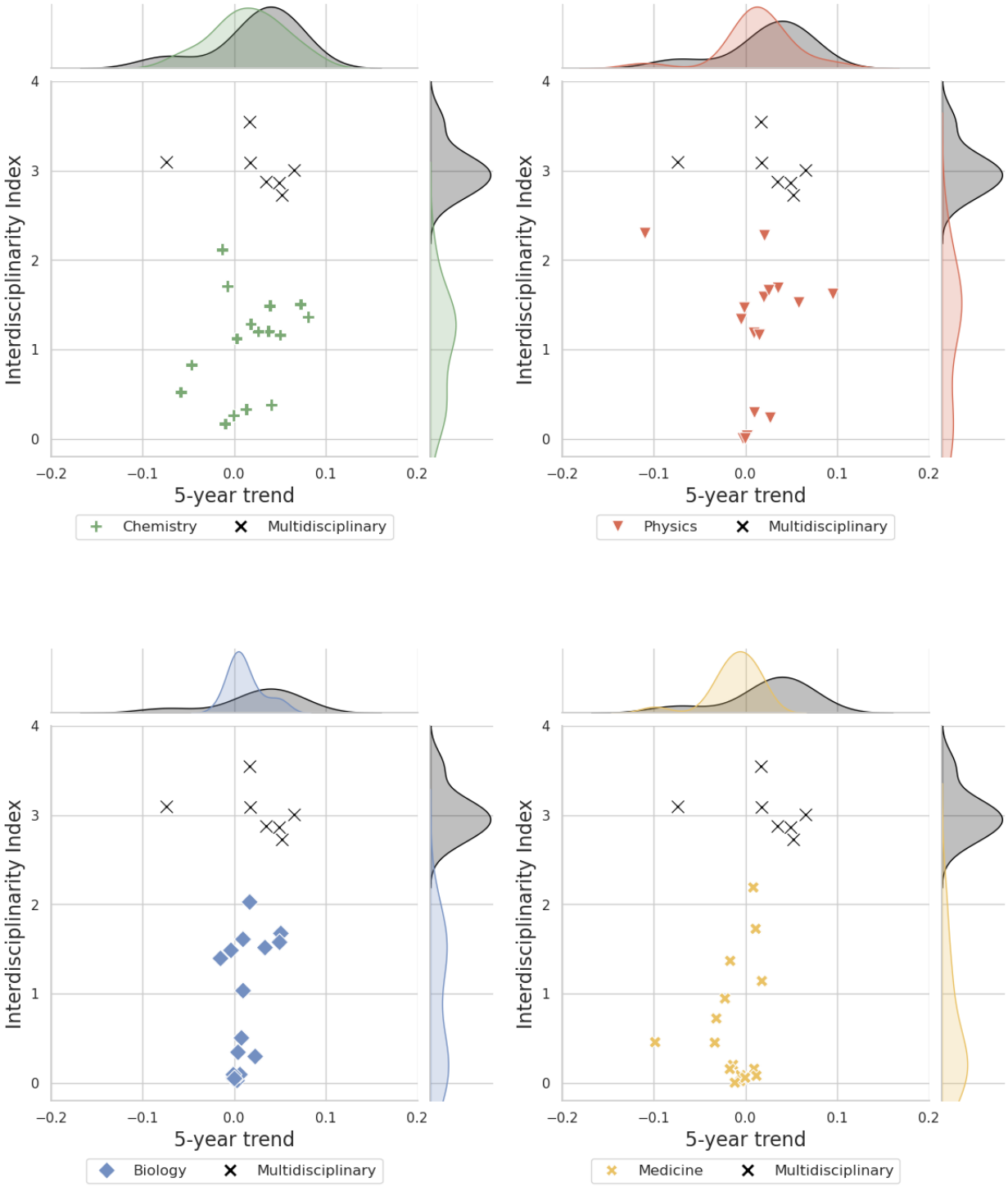


Figure S4: Relationship between the 2021 Interdisciplinarity Index and the ratio ($\frac{n_m}{n_s}$) for disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, and Political Science. Two Physics journals — *Annals of Physics* and *General Relativity and Gravitation* — and one journal in Medicine, *Medical Clinics of North America* have ratio values equal to zero, meaning that they do not display in the semi-logarithmic plot. Notice also that, for Political Science, the range for the values of both variables is quite narrow.

Interdisciplinarity dynamics

The marginal distributions of Interdisciplinarity Index and 5-year trend of 16 disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, Political Science and 7 multidisciplinary journals.



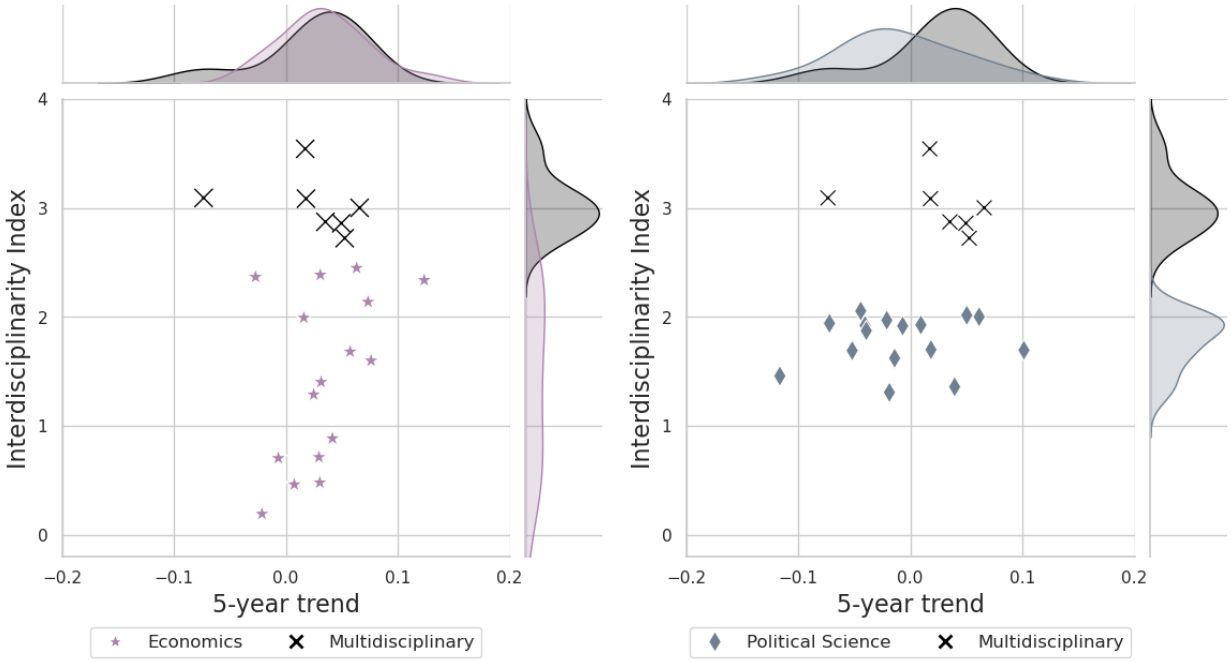
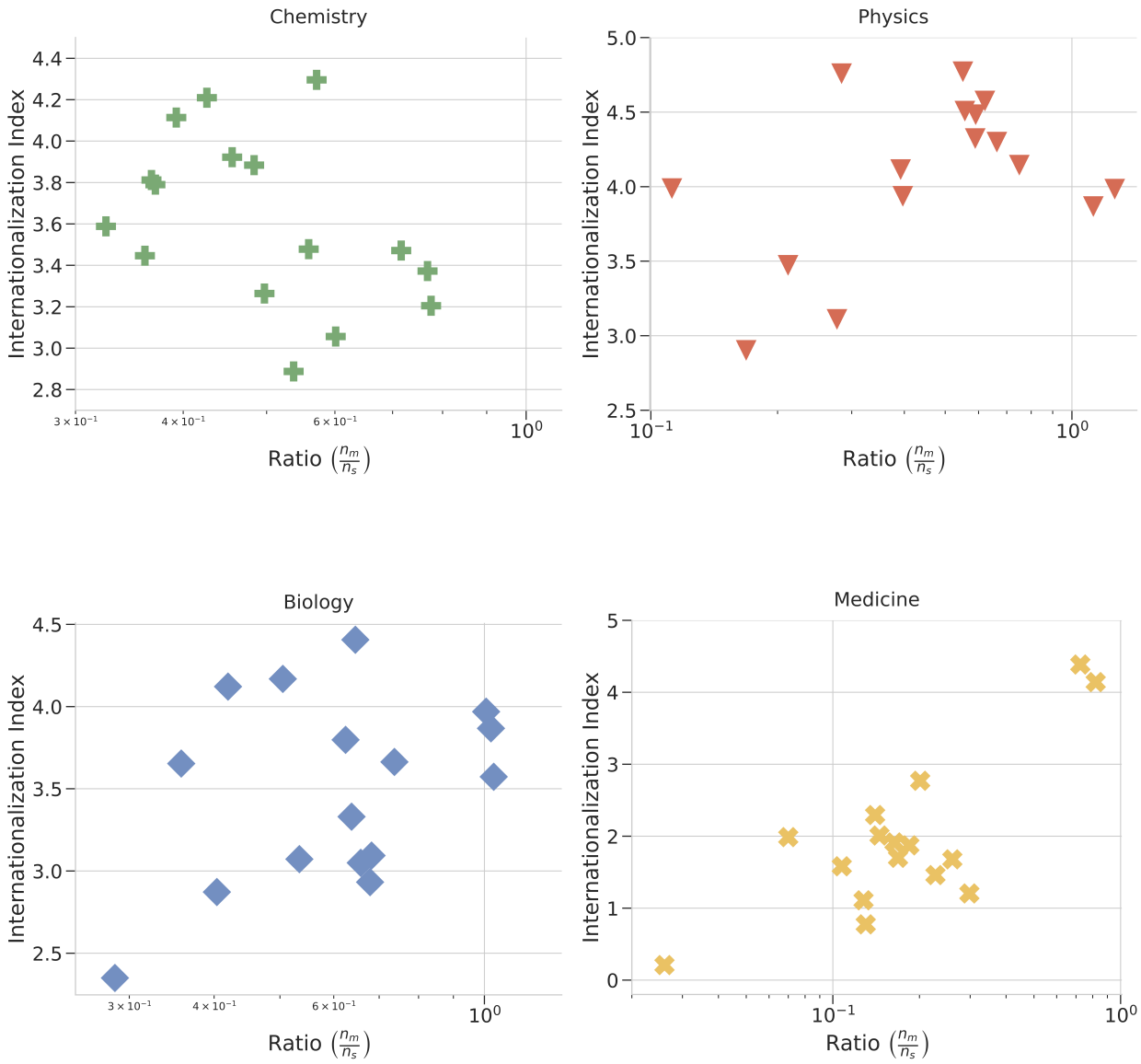


Figure S5: The marginal distribution of the Interdisciplinarity Index and the 5-year trend of 16 disciplinary journals compared to seven multidisciplinary journals for 2020.

Relation between Internationalization Index and the fraction of papers with authors with affiliations in multiple countries

We calculate the ratio between the number n_m of papers with authors affiliated to institutions from multiple countries and the number n_s of papers with authors affiliated to institutions in a single country for disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, and Political Science. We then plot the ratio versus the 2021 Internationalization Index of the journal. A positive slope in these plots indicated that greater values of I_n correspond to higher proportions of papers drawing from authors from multiple countries.



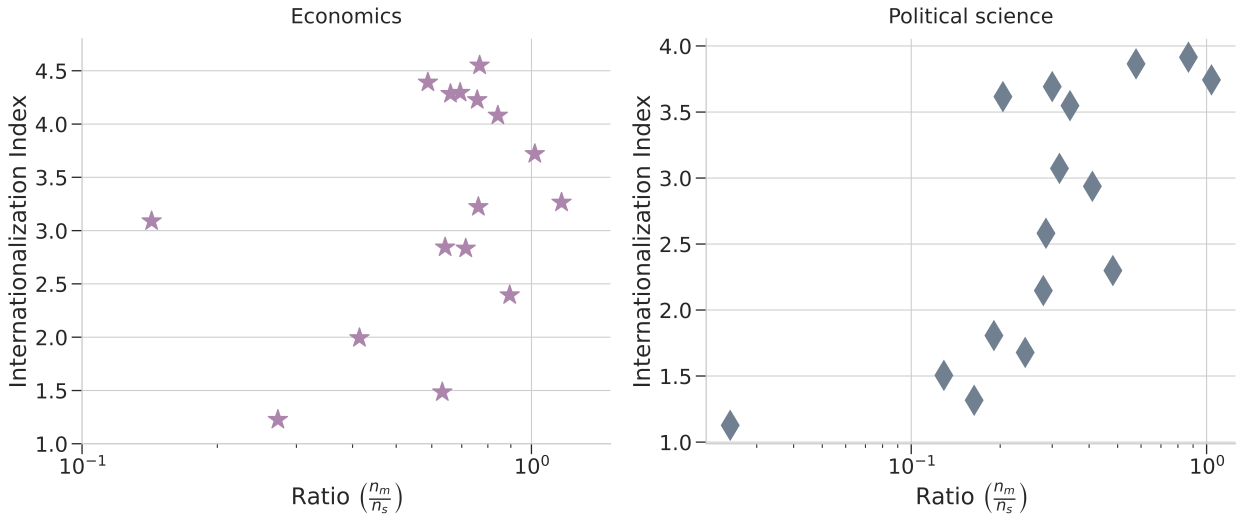
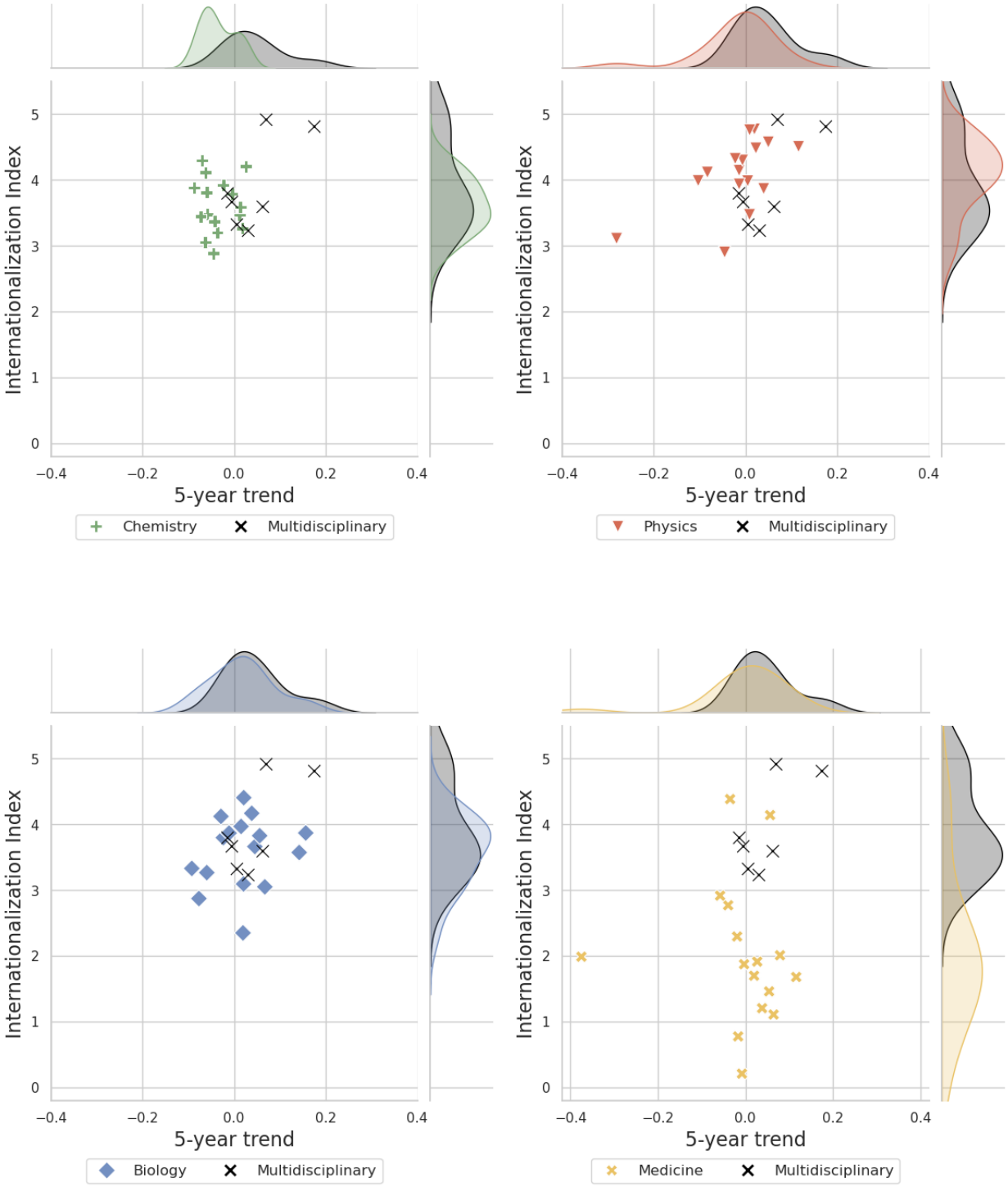


Figure S6: Relationship between the 2021 Internationalization Index and the ratio ($\frac{n_m}{n_s}$) for disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, and Political Science. Notice that the range of values of the ratio is in many cases quite limited and close to 1, unlike the findings for the interdisciplinarity. Moreover, correlation is not always positive.

Internationalization dynamics

The marginal distributions of Internationalization Index and 5-year trend of 16 disciplinary journals in Chemistry, Physics, Biology, Medicine, Economics, Political Science and 7 multidisciplinary journals.



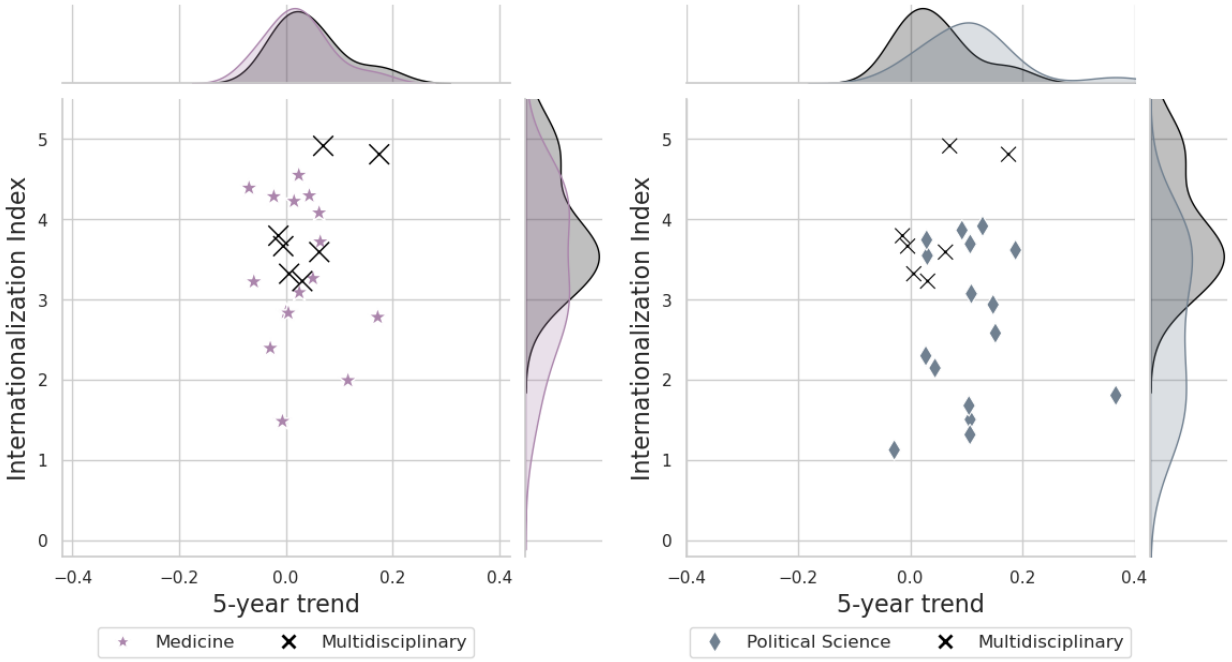


Figure S7: The marginal distribution of the Internationalization Index and the 5-year trend of 16 disciplinary journals to seven multidisciplinary journals for 2020.

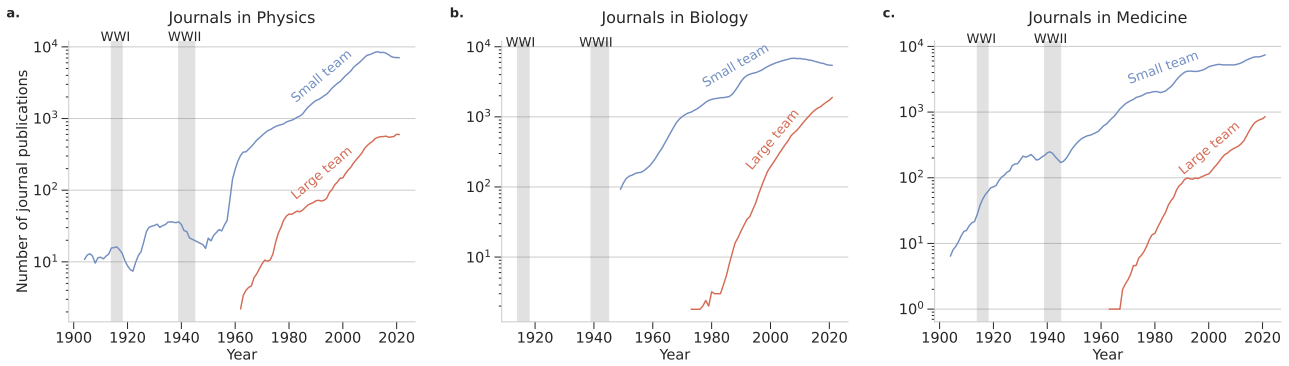
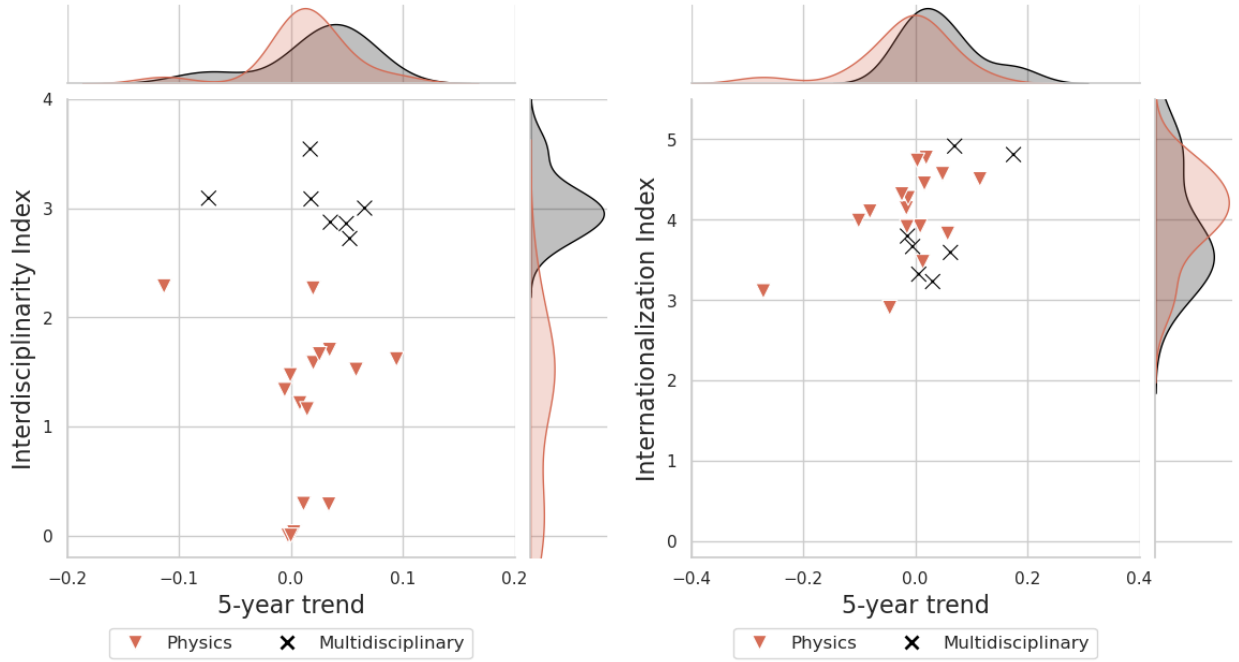


Figure S8: Team sizes in journal articles are notably large in the fields of Physics, Biology, and Medicine. The maximum number of authors in a Physics journal article is 4,473, while Biology and Medicine journals have maximum author counts of 676 and 798, respectively. We define large teams as those with 10 or more authors and small teams as those with fewer than 10 authors across all three disciplines. The 5-year moving average of articles with large teams began to increase across all three fields after 1960.

Team size

We investigated whether our findings for those three disciplines (Biology, Physics, and Medicine) could have been due to the characteristics of the largest teams. As a control, we repeated the previous analyses for these three disciplines but excluding all publications with 10 or more authors.



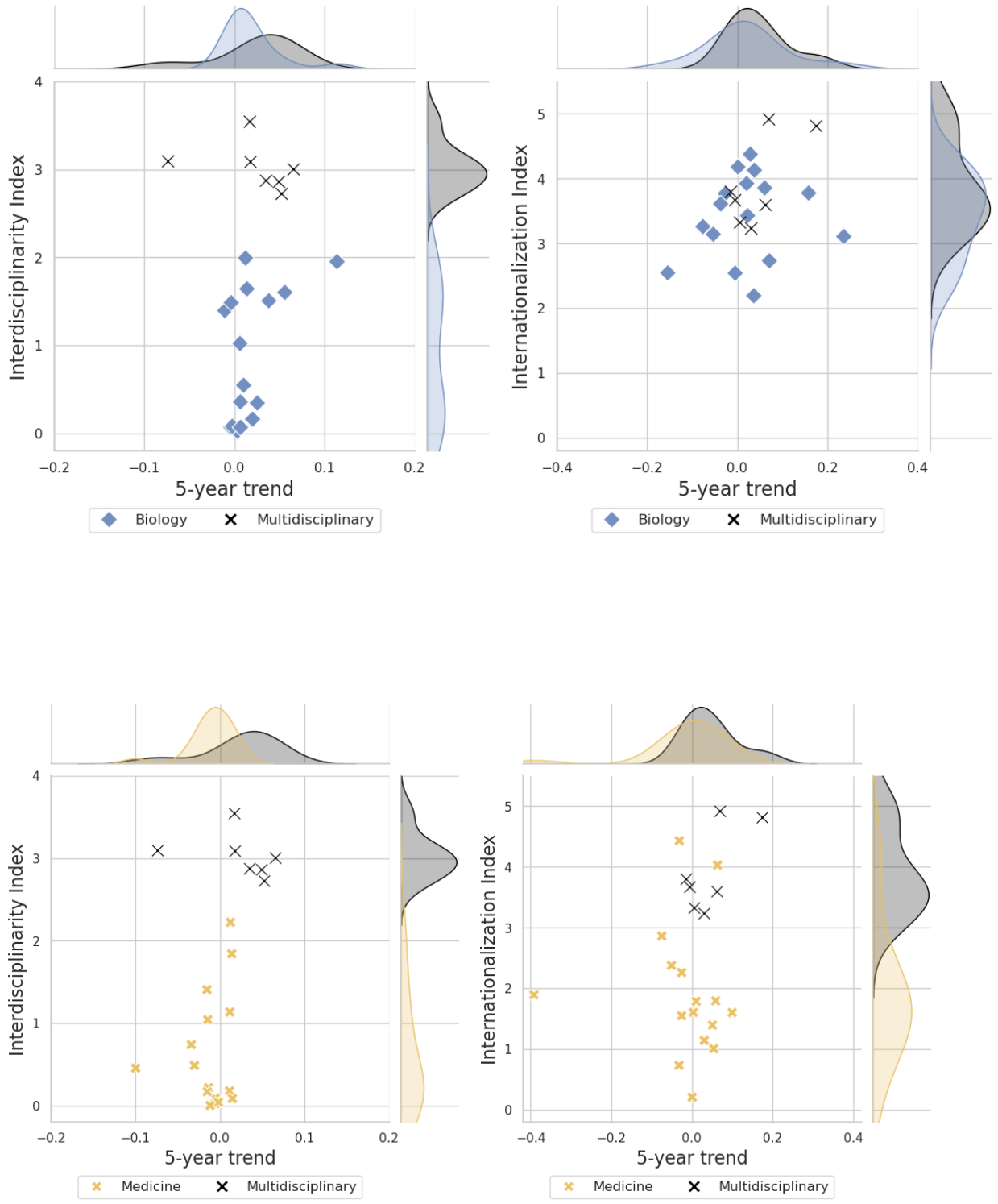


Figure S9: The marginal distribution of the Interdisciplinarity Index (Left) and Internationalization Index (Right) and the 5-year trend of 16 journals in Physics, Biology or Medicine excluding the articles with 10 and more authors compared to seven multidisciplinary journals.

Supplementary Information

Calculation of the doubling time

The doubling time serves as an indicator of the growth rate of scientific publications [2], representing the time required for the total output to double in volume. The doubling time T_d is given by:

$$T_d = \frac{\ln(2)}{\frac{\ln(V_t/V_0)}{t}} \tag{3}$$

where:

V_0: Initial value at t_0
V_t: Final value after time period t
t: Time period
T_d: Doubling time

The denominator is called the growth rate r :

$$r = \frac{\ln\left(\frac{V_t}{V_0}\right)}{t} \tag{4}$$

Sometimes, the doubling time can also be written as

$$T_d = \frac{\ln(2)}{r} \tag{5}$$

Index temporal trend

We use two-dimensional plots showing the value of the Index for a given journal in a given year against the 5-year trend in the Index as a way to visualize the paths toward interdisciplinarity or internationalization followed by different disciplines.

In order to clarify exactly how the 5-year trend is calculated, consider the data in Fig. S10. The figure shows the Interdisciplinary Index for two physics journals between 2005 and 2010, inclusive. The 5-year trend is defined as the linear coefficient of an ordinary least squares linear fit to the 6 data points for the Index in years 2005–2010.

The data suggest the reasons why we consider 5-year trends instead of other values such as 3-, 10- or 20-year trends. Smaller time windows would yield more uncertain trend estimates, making comparisons across years or journals less reliable. Larger time windows would potentially aggregate over changes in the trend.

The fact that reasonable values for the size of the time window are constrained between 4 and 7 years precludes the need for a sensitivity analysis of the window size.

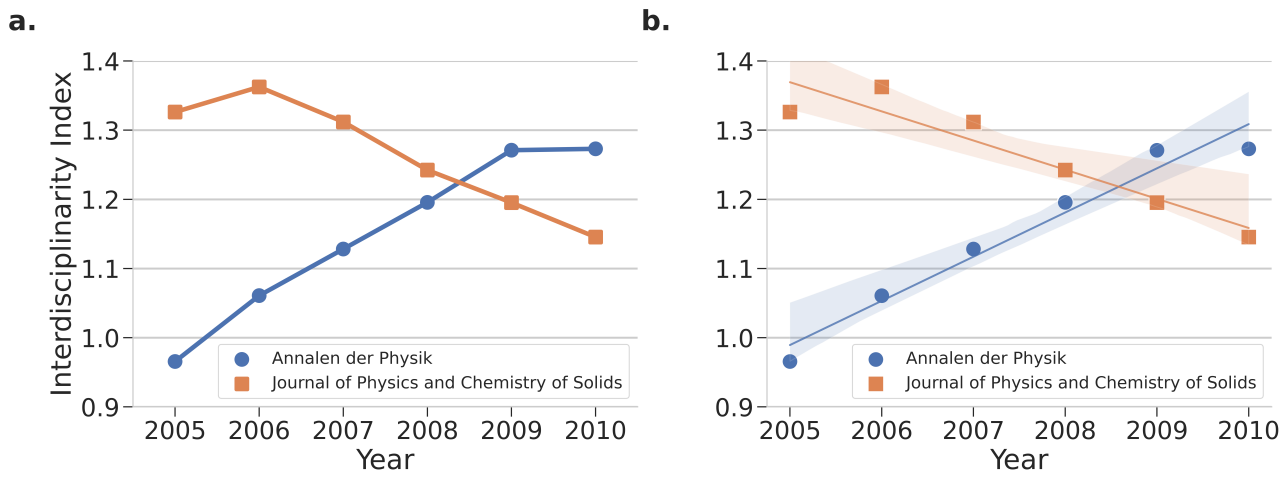


Figure S10: The Interdisciplinarity Index (I_d) of *Annalen der Physik* and *Journal of Physics and Chemistry of Solids* from 2005 to 2010 a. Time evolution of I_d for the two journals from 2005 to 2010. **b.** The best-fit regression lines for I_d over the same period with 95% confidence intervals (shaded regions).