How do boundary-crossing researchers contribute to the interdisciplinary knowledge flows? Evidence from physics

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Abstract
It is generally acknowledged that scientists who cross the boundary of disciplines are likely to produce novel outputs. The mobility of scientists to new fields is often accompanied by knowledge flows in the same direction. However, previous studies that provide empirical evidence on the knowledge exchanges caused by boundary-crossing activities are limited. Also, it has seldom been investigated how boundary-crossing scientists induce knowledge exchange. This paper analyzes how boundary-crossing physicists contribute to interdisciplinary knowledge flows, taking physicists as a case study for a 20-year comprehensive view. We find that 64.53% of boundary-crossing physicists publish papers in applied sciences. Such boundary-crossing activities lead to interdisciplinary knowledge flows even beyond physics and target fields (fields physicists migrated to). Through boundary crossing, physicists produced highly interdisciplinary papers, which are also cited by diversified domains. We also found that boundary-crossing publications led by physicists can bring more knowledge from physics to their target fields. Yet other boundary-crossing publications that physicists act as co-authors possess more interdisciplinary knowledge bases and also attract multidisciplinary audiences. Considering the contribution boundary-crossing physicists made in fostering interdisciplinary research and knowledge flows, the funding bodies are encouraged to break the limitation of disciplinary barriers and establish more grant schemes to support them.

Introduction
Disciplines are characterized as exclusive communities with boundaries keeping participants from other disciplines outside (Klein, 1996), which makes it challenging for boundary-crossing production (Bauer, 1990). Nevertheless, creative outputs are typically achieved by boundary-crossing activities and new combinations of knowledge. There is a growing understanding that scientists, publications, and knowledge involved in boundary-crossing activities merit more attention and support due to their significance in fostering scientific advances.

Scientists play a particularly important role in such boundary-crossing activities (van Houten, 1983). The movement of boundary-crossing scientists typically coincides with the flow of ideas and information in the same direction (Gaston, 1981). Despite the challenges posed by disciplinary barriers, it is not rare that scientists read, cite, and even publish outside their own fields. In addition, when scientists choose risky innovation strategies in scientific careers, they tend to change their initial research interests and devote themselves to a new topic (Kuhn, 1962). Boundary-crossing activities happen correspondingly when they publish in a new field, and it is deemed an important route for knowledge to transfer between fields (Pierce, 1999).

Boundary-crossing scientists have attracted particular attention because they often deliver novel insights and promote the evolution of science. Several prior studies performed individual analyses on this topic and demonstrated that scientists who cross the boundary and enter a new field are more likely to produce highly innovative outcomes (Azoulay et al., 2011; Foster et al., 2015; Leahey et al., 2017). A main concern of these studies is how boundary-crossing activities affect scientists' performance. However, little attention has been paid to the mechanism through which these boundary-crossing activities support innovation. Fisch (1977) held that the movement of scientists is perhaps the most efficient way of knowledge transfer. Previous studies found that the network of physicists' boundary-crossing activities is similar to the citation network between fields (Hargens, 1985; Urata, 1989; Battiston et al., 2019) and argued that *citation flows* and *scientist flows* between fields are complementary to each other. However, little empirical evidence is available on how these two types of flows are related.

In this study, we associate *boundary-crossing researchers* with the *citation flows* they triggered empirically. As shown in Figure 1, we focus on scientists with boundary-crossing activities, i.e., publishing papers outside their field of origin. We define the papers published outside boundary-crossing scientists' original fields as the boundary-crossing publications. Compared with knowledge flow measures using citations, the boundary-crossing activities of scientists constitute an implicit mode of knowledge flow. Citation flows generated in these activities can therefore be used to illustrate how boundary-crossing activities promote interdisciplinary knowledge flows explicitly. We chose physicists as a case study since physics often facilitates the development of other scientific disciplines like astronomy, chemistry, medicine. A physics-like mindset, as well as the concepts, methods, and instrumentation of physics, are all required in these disciplines (van Houten, 1983). Thus, we analyzed the bibliographic information of more than 1.6 million publications from Scopus to investigate how boundary-crossing activities of physicists contribute to interdisciplinary knowledge flow. In particular, we focus on two research questions:

RQ1: What are the characteristics of boundary-crossing publications' knowledge base? Do boundary-crossing physicists borrow much knowledge from physics?
RQ2: What are the characteristics of boundary-crossing publications' citations? To what extent are these publications cited and recognized by the target disciplines physicists migrate to?

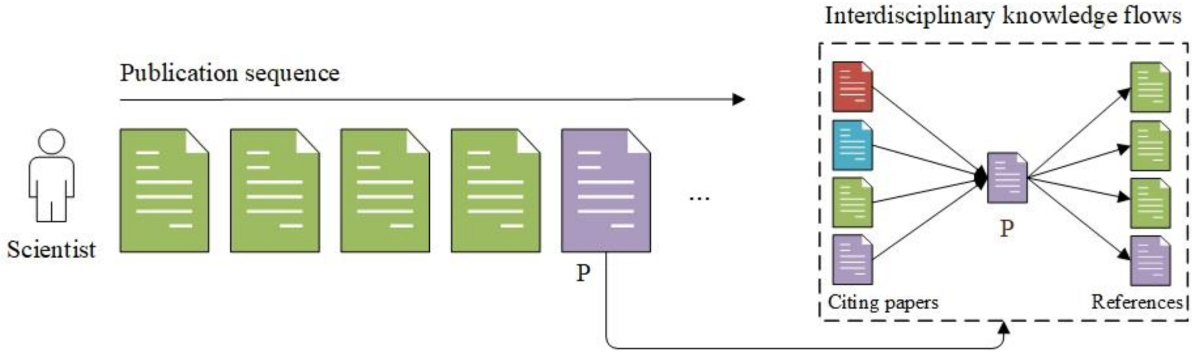


Figure 1. Concept map of this study.

Note: the color of publications reflects the fields they belong to.

Methodology and data

Method

Identifying physicists (*S*)

To identify scientists who cross disciplinary boundaries, we need to first determine a scientist's field of origin. In this study, we recognize physicists as researchers who primarily publish papers in physics since the beginning of their academic career, that is to say, those whose original field is physics. We start by collecting a candidate sample with researchers who publish papers in "physics & astronomy" (hereinafter physics) according to the article-level classification of Science Metrix. For each candidate researcher, we then identify the start year of their academic careers as the year of their first first-authored publication, following the approach suggested by Robinson-Garcia et al. (2020). Finally, we recognize physicists (*P*) as candidates whose most publications are in physics over the first five years of their academic careers. Physicists in this study refer to the scientists whose scientific careers started in physics. It means that these scientists grasp knowledge from physics and make use of this knowledge to publish peer-reviewed publications. We did not follow the previous studies using all the publication records of scientists to identify one's expert domains (Battiston et al., 2019; Boekhout, Weijden, & Waltman, 2021) because these methods can be biased on the boundary-crossing scientists. To verify our methods, we applied different parameters: a) scientists whose first first-authored article is published in physics and published most articles in physics in ten years since then; b) scientists whose first article is published in physics and published most articles in physics in five years since then; c) scientists whose first article is published in physics and published most articles in physics in ten years since then; d) random 100 physicists nominated by American Physical Society (APS) as the APS fellow in 2010. It turns out that the dataset of this study has a 98.31% overlap with dataset a, a 98.05% overlap with dataset b, a 97.65% overlap with dataset c, and a 81% overlap with dataset d.

Identifying boundary-crossing physicists (*Sc*)

In this study, we defined boundary-crossing behaviour as publishing papers outside one's original field (Pierce, 1999). In some previous studies, the term "boundary-crossers" also refers to scientists who break disciplinary boundaries and collaborate with someone from a different discipline (Fields, 2015). The disciplinary boundaries discussed in this study refer to the barrier to publishing. Scientists who intend to publish outside their original disciplines may need interdisciplinary collaborations as well. Based on physicists set *S*, we filtered physicists who published papers beyond physics as *Sc, i.e., crossing disciplinary boundaries of physics*.

Collecting boundary-crossing papers of boundary-crossing physicists (*Pc*)

Based on *Sc*, we were able to get all of the articles (*Pc*) published by physicists outside their original fields. Considering journal articles are one of the main forms of academic outputs in most disciplines, we restrict our dataset to this document type. A comprehensive view of knowledge exchanges contributed by boundary-crossing physicists from 2001 to 2020 is presented in this study.

Collecting references (*Rc*) and citations (*Cc*) of boundary-crossing papers

Citation is deemed one of the most common proxies of knowledge flow in bibliometrics (Lyu et al., 2022). To explore the citation-based knowledge flow contributed by boundary-crossing activities, we collected all the references and citing papers of publications from *Sc*.

To analyze the knowledge base and diffusion of boundary-crossing publications, we first construct the citation network between different fields to illustrate the knowledge flow from the macroscopic prospect. Then, we focus on the specific distribution and diversity of knowledge flow to further analyse the traits of boundary-crossing publications. In this study, we adopted the Shannon diversity index to measure the diversity of references and citations (Chakraborty, Ganguly, and Mukherjee, 2014).

Let *X* be a paper from domain d_i. It cites papers of *j* distinct domains, namely $d_1, d_2, \ldots, d_j$. The reference diversity index of paper *X* denoted by *RDI (X)* is defined as follows:

$$\mathrm{RDI}\ (\mathrm{X}) = -\sum_{j} p_j \log(p_j)$$

X is cited by the papers from *k* distinct domains, namely $d_1, d_2, \ldots, d_k$. The citation diversity index of paper *X* denoted by *CDI (X)* is defined as follows:

$$\mathrm{CDI}\ (X) = -\sum_{k} p_k \log(p_k)$$

where *p* is the proportion of references/citations of *X* citing the papers/received from domain *d*. $\left(\sum_j p_j = 1\,;\ \sum_k p_k = 1\right)$

Data

The dataset of this study is collected from Scopus (Elsevier). We utilized papers of boundary-crossing physicists that were published between 2001 and 2020 to perform the empirical analysis. Each author ID in Scopus is identified as a scientist in our study. The author disambiguation of author ID is based on the author name, affiliations, co-authors, subject areas, and publications. This method is verified reliable for large-scale analysis at the individual level by numerous studies (Moed et al., 2013; Kawashima & Tomizawa, 2015; Aman, 2017). Article-level classification from Science-Metrix is adopted to assign research fields and domains to papers. The Science-Metrix classification is hierarchical and categorizes articles by six domains, 22 fields, and 176 subfields, with the subfields being mutually exclusive. In this classification, a scientific publication is attributed to a domain, field, and subfield based on its title, abstract, keywords, author affiliation, and citations, using a deep neural network. Such wealth of information makes up for the shortcomings of simple label propagation approaches, such as bibliographic coupling- and direct citation-based classifications, and allows the algorithm to function even in the absence of reference or citation information. It has also been proven to be as precise as the simple label propagation approach above (Rivest et al., 2021)

Results

Prevalence of boundary-crossing physicists and publications

In this section, we analyze how boundary-crossing physicists and publications are distributed over the years (Figure 2) and disciplines (Figure 3) to uncover the trend of boundary-crossings in physics.

Concerning the temporal distribution, Figure 2 demonstrates that in the majority of domains, the number of boundary-crossing physicists has been rising annually, which corresponds to the rise of interdisciplinarity in several fields in recent decades (Gates et al., 2019; Zhou, Guns, and Engels, 2022). After 2018, boundary-crossing physicists experienced rapid growth, especially observed in applied sciences and economics & social sciences. The interaction of knowledge between physics and other fields has been increasing during the most recent years, and the tendency could be observed in almost all fields. Only the number of physicists who publish in arts & humanities fluctuated irregularly over the years.

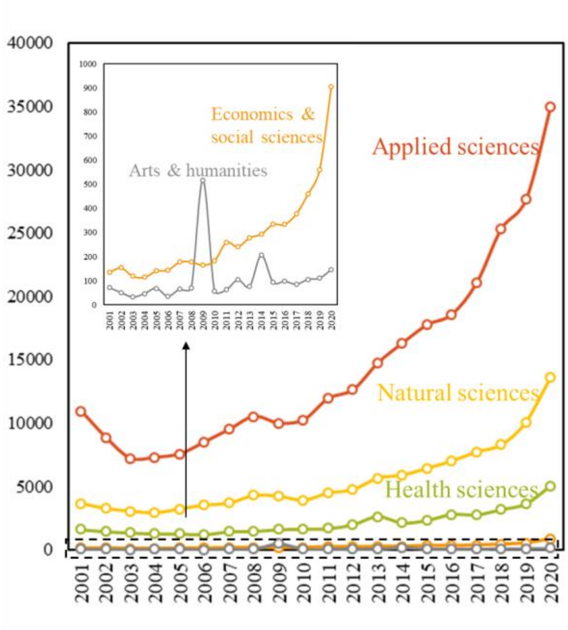


Figure 2. Number of boundary-crossing physicists who publish in five domains.

Figure 3 presents the fields and domains in which boundary-crossing papers are published, which are defined as the target fields/domains in this study. Figure 4 fills in the details of the contribution type of Figure 3, presenting the proportion of single-authored boundary-crossing publications. We found that physicists cross disciplinary boundaries and publish articles in five domains and 19 fields in total, covering most fields of science (19/22). The flows between bars represent the number of boundary-crossing publications. Applied sciences are the most prevalent target domain among all. It indicates that physics, as one of the most important fundamental research fields, can support plenty of applied research. Many publications from boundary-crossing physicists have also been published in some branches of the natural sciences that are in close proximity to physics, such as *chemistry* and *earth & environmental sciences*. As expected, fewer physicists chose domains like social sciences and humanities (SSH) as their target domain for boundary-crossing.

Regarding the contribution type, physicists who cross disciplinary boundaries may act as the leading authors (e.g., 1st or corresponding authors) or supportive authors. The publications produced via these two contribution types are interpreted as the “leading publications” and “supportive publications” in this study, which demonstrates the degree of physicists’ involvement and leadership in boundary-crossing activities. In general, when publishing outside their own fields, the number of boundary-crossing publications led by physicists is similar to that of publications physicists contribute as supportive authors. But disciplinary differences also exist. Against our expectation, there are more leading publications than supportive ones in the fields of SSH. Leading publications take up 63.95% of *communication & textual studies*, 74.24% of *philosophy & theology*, and 64.95% of *visual & performing arts*. On the one hand, SSH are different from physics in epistemology and methodology significantly. Thus, it is demanding to cooperate with scholars from irrelevant fields. Physicists may lead the research with their expertise. On the other hand, physicists publish a large proportion of single-authored papers when they cross the boundary to SSH (Figure 4), resulting in a low share of supportive publications in this domain. The single-authored papers are more prevalent in SSH compared with natural and health sciences. Hence, the boundary-crossing scientists can be influenced by the collaboration preference of target fields.

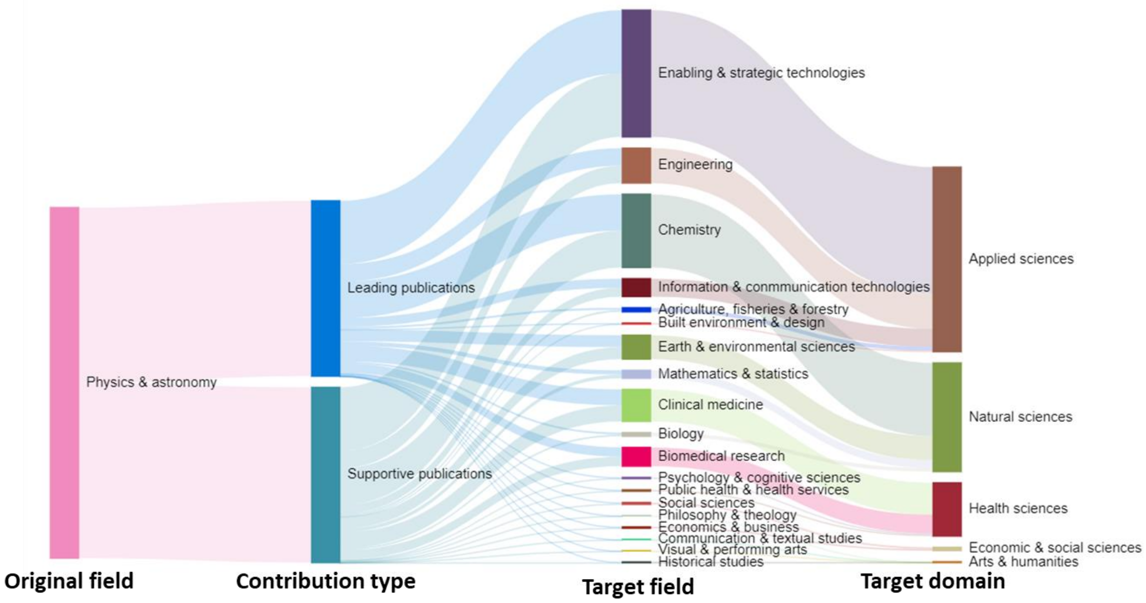


Figure 3. Distribution of fields and domains of boundary-crossing publications

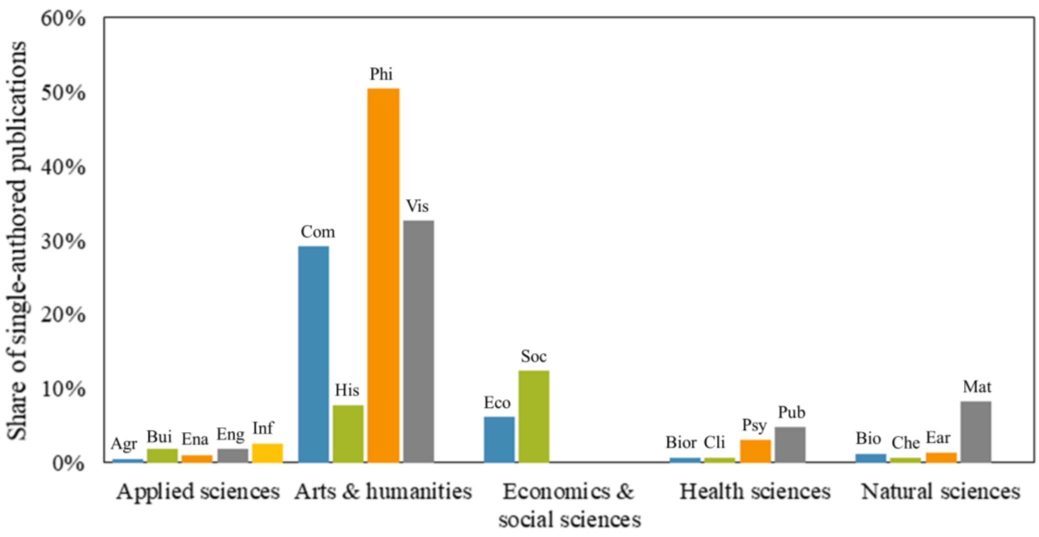
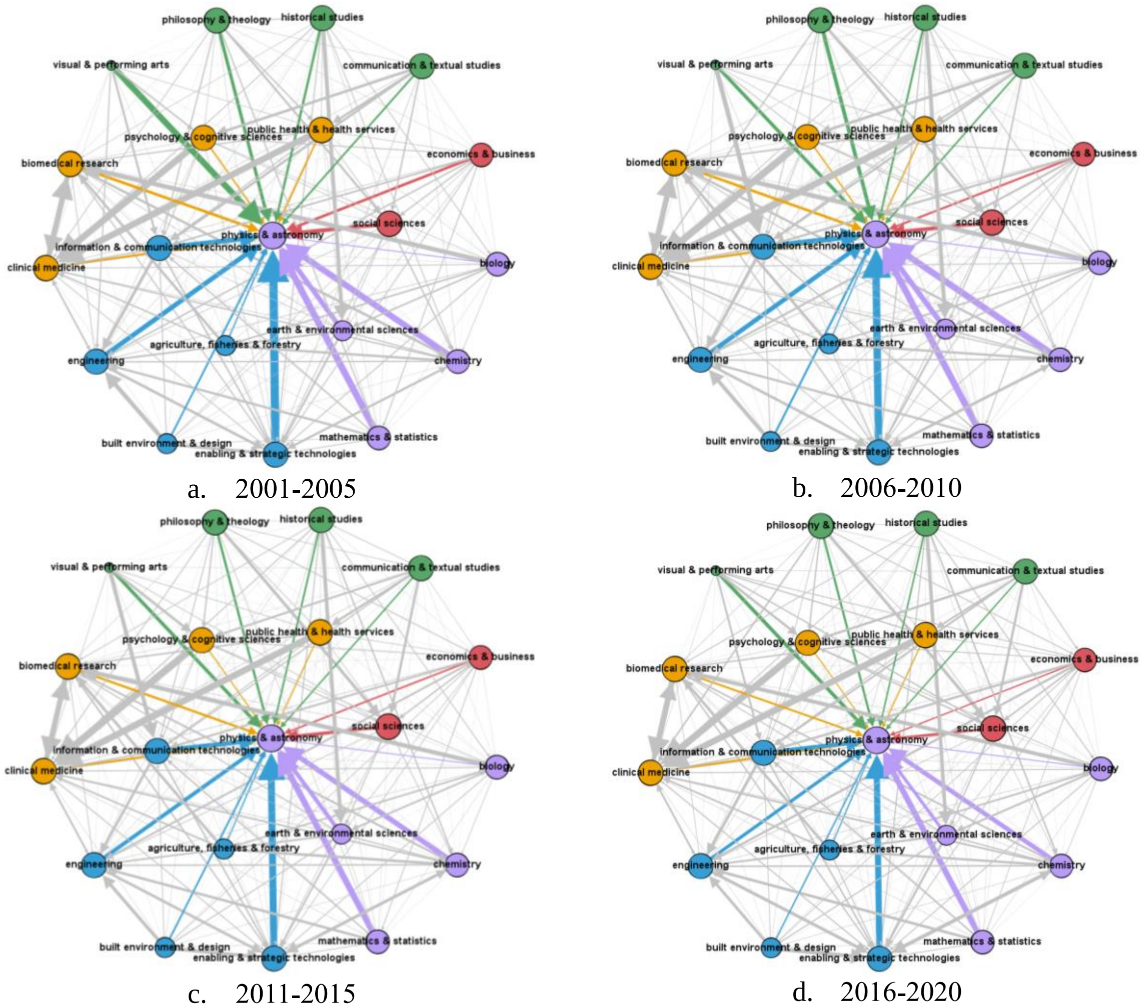


Figure 4. The proportion of single-authored publications that boundary-crossing physicists publish in other domains/fields.

Bringing knowledge from physics into other fields

The knowledge sources of scientific papers can be uncovered in references. The structure and distribution of a paper's knowledge sources can also be used to infer its interdisciplinarity. Do boundary-crossing physicists often develop their outputs based on the knowledge from physics? Are the knowledge sources of boundary-crossing publications more diversified? In this section, we use the reference data of boundary-crossing publications to answer these questions.

Figure 5 shows the knowledge sources of boundary-crossing publications exhibited in the references. In the directed citation network, the arrows point from the citing fields to the referenced fields. The size of links indicates the normalized number of citations between fields. Hence, the density of citation network can inform the frequency of interdisciplinary reference counts. References in physics are highlighted. We found that *physics & astronomy* is cited most frequently by publications of boundary-crossing physicists. But the knowledge is decreasingly brought from physics to the focal fields by physicists illustrated from the citation networks of four periods over the past twenty years. Most boundary-crossing publications show less dependence of knowledge from physics. But the share of references in physics of some publications in *chemistry*, *earth & environmental sciences*, and *information & communication technologies* experienced a “rise and fall” trend over the twenty years. Physicists who published in *enabling & strategic technologies*, *mathematics & statistics*, and *chemistry* cited the most share of references from physics through boundary crossing.



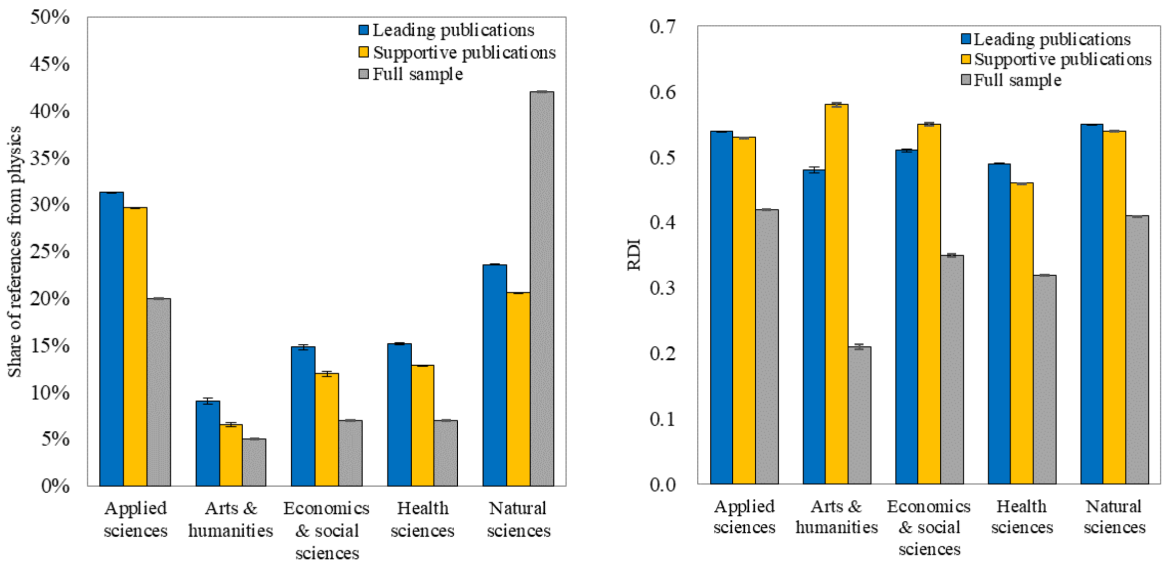
a. 2001-2005   b. 2006-2010

c. 2011-2015   d. 2016-2020

Figure 5. Knowledge source of boundary-crossing publications inferred from references

Note: Each dot represents a field. The size of dots depends on their in-degree, which is the number of edges pointing to the node. purple: natural sciences; green: arts & humanities; red: economics & social sciences; blue: applied sciences; yellow: health sciences. Links between dots represent the normalized volume of citations, with arrows pointing from citing fields to the referenced fields.

We further analyze whether the amount of knowledge flows contributed by boundary-crossing physicists varies when they act as different roles (leading vs. supportive) in collaboration. Meanwhile, we also look into if the knowledge sources of boundary-crossing publications, measured by proportion of references from physics and Reference diversity index (RDI), differ from those of the target domains. For this purpose, we calculated the mean value of these two indicators of all the papers published in the target domains during 2001-2020 as the baseline. For all domains, the boundary-crossing publications authored by leading physicists cite relatively more references from physics compared to those with a supportive physicist co-author (Figure 6a). Compared with the baseline (all publications in target domains), boundary-crossing publications in most domains cited more references from physics, except for natural sciences. One possible interpretation is that physicists who migrate to other fields of natural sciences are more inclined to absorb knowledge than to export knowledge. According to Hargens' (1986) theory, scholarly fields are hierarchical as one export knowledge and the other import knowledge in turn. Some fields of natural sciences (e.g., mathematics) are at a higher level of the hierarchy of disciplines than physics, and thus they export more knowledge in contrast to taking in more knowledge from physics. A survey by van Houten et al. (1983) also found that physicists who entered the field of mathematics and philosophy felt they had left their original field entirely, which can also explain the reason why physicists cite fewer references from physics when they cross the boundary and enter other fields in natural sciences. Regarding the diversity of knowledge sources, we found that boundary-crossing activities produce more interdisciplinary papers (Figure 6b). It's also interesting to see that publications with supportive physicist co-authors have higher interdisciplinarity in social sciences and humanities, while physicists as leading authors generate more interdisciplinary work in applied sciences, natural sciences, and health sciences.



a. Proportion of references from physics

b. Reference diversity index (RDI)

Figure 6. Knowledge base of boundary-crossing publications

Spreading knowledge of boundary-crossing work to other fields

As a vital form of knowledge flow, forward citations can help spread the information and knowledge included in scientific papers. Through citations, we can also uncover the scope of papers' audience. To what extent are the boundary-crossing publications cited and recognized by the target domains? Do these boundary-crossing publications reach a wide range of audiences? In this section, we use the citation data of boundary-crossing publications to answer these questions.

Figure 7 shows how publications created by boundary-crossing activities are cited by other fields. The density of the citation network denotes the normalized frequency of interdisciplinary citation relationships. Citations in physics are highlighted. The boundary-crossing works are still cited by papers from physics most frequently. This phenomenon is increasingly notable over time. Publications in *enabling & strategic technologies*, *mathematics & statistics*, and *chemistry* have the highest share of citations from physics. Besides, the share of citations from physics for most publications is decreasing with time. Only publications in *mathematics & statistics*, *chemistry*, and *engineering* etc. are getting more citations and impacts in physics over the twenty years.

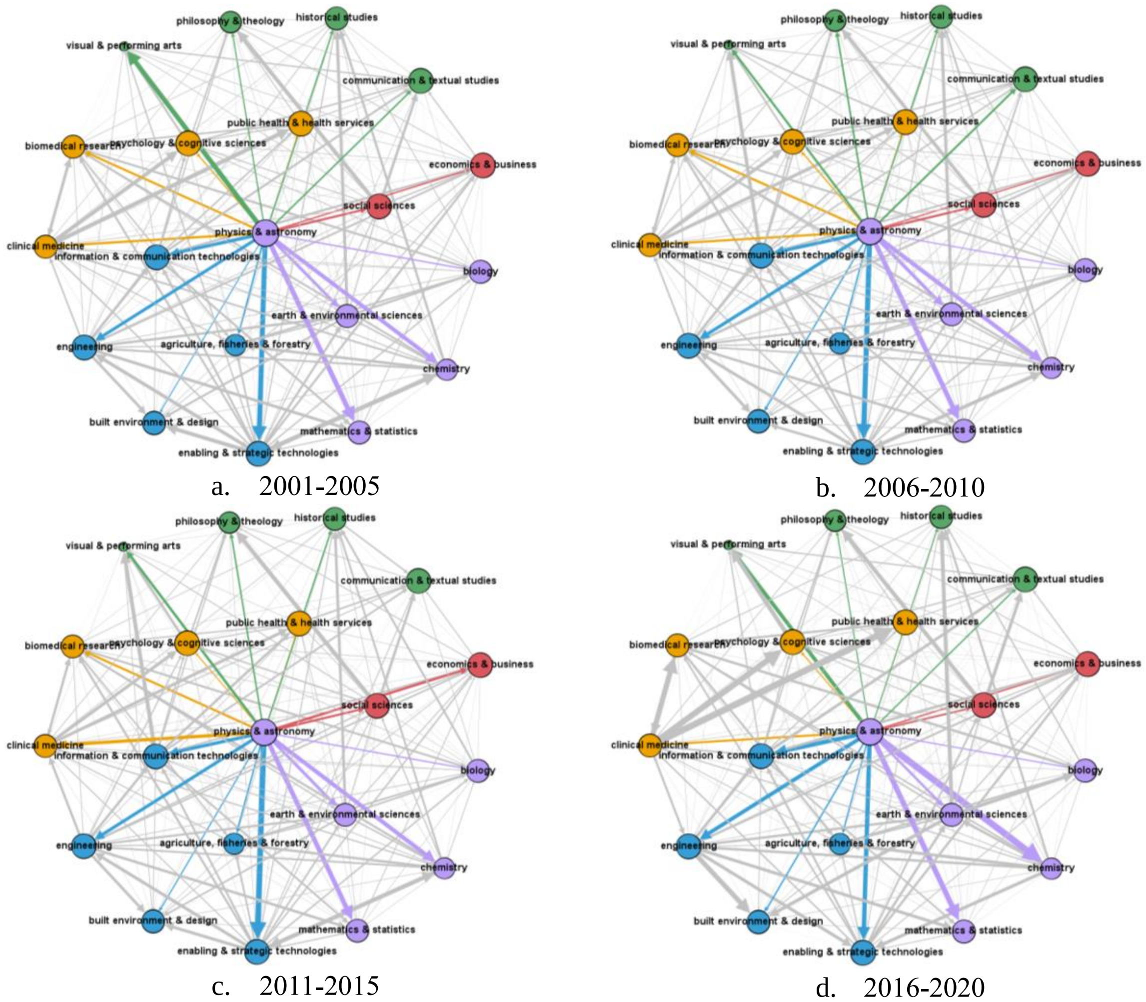
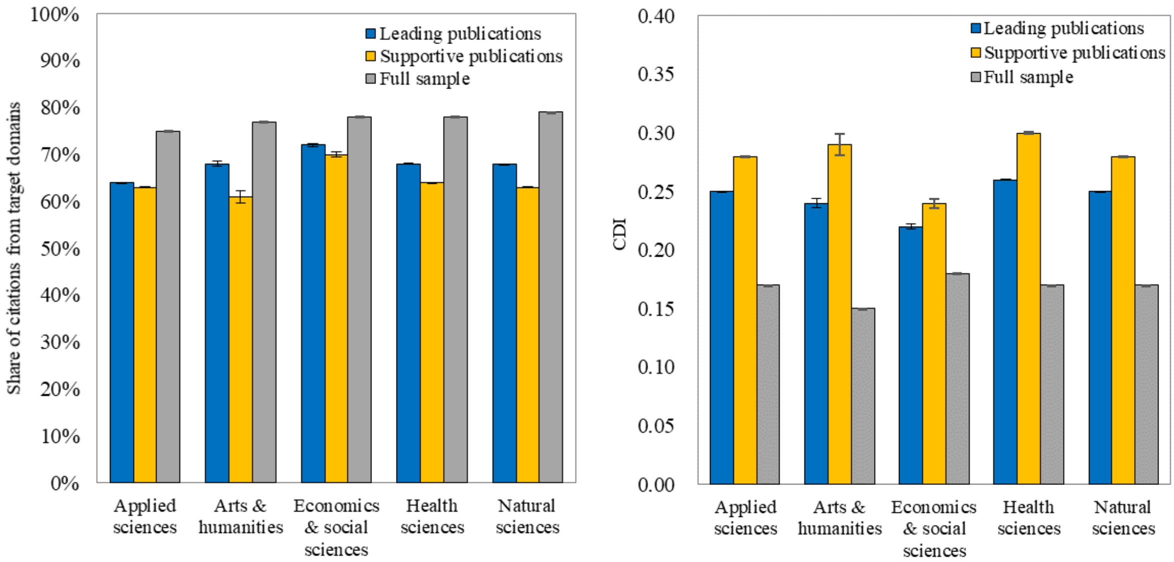


Figure 7. Diffusion of boundary-crossing publications measured by citation

Note: Each dot represents a field. The size of dots depends on their out-degree, which is the normalized number of edges pointing out of the node. (purple: natural sciences; green: arts & humanities; red: economics & social sciences; blue: applied sciences; yellow: health sciences). Links between dots represent the normalized volume of citations, with arrows pointing to the referenced fields.

We further examine whether the citation patterns of boundary-crossing publications vary when boundary-crossing physicists act as different roles in collaboration (leading vs. supportive). Overall, the boundary-crossing publications received a lower proportion of citations from their target domains compared with the full sample (Figure 8a). But they are cited by a more diverse collection of fields (Figure 8b). In particular, boundary-crossing publications led by physicists are more likely to be cited by the target domains than those are supported by physicists. The citation diversity index (CDI) of boundary-crossing publications supported by physicists is higher than those are led by physicists and the baseline. It indicates that publications supported by physicists attract a wide range of audiences.



a. Share of citations from target domain

b. Citation diversity index (CDI)

Figure 8. Citation patterns of boundary-crossing publications

Conclusions and discussion

This study utilized citation data to examine whether and how boundary-crossing physicists contribute to interdisciplinary knowledge flows. We attempt to elaborate on how boundary-crossing activities induce knowledge exchange and diffusion. We also make contributions to the understanding of interdisciplinary research (IDR) by combining the intellectual mobility of scientists with citation flows. The major conclusions of the study can be summarized as follows. As for the target fields and domains, we found that the boundary-crossing activities of physicists are likely to take place in applied sciences (e.g., *enabling & strategic technologies*, *engineering*) and the neighboring fields (e.g., *chemistry*, *earth & environmental sciences*), which is consistent with previous studies (van Houten, 1983; Griffith et al., 1974). Physics has higher levels of dependence, higher export/import ratios of knowledge flows, and transdisciplinary impact (Yan et al., 2013; Huang et al., 2020). In addition, since boundary-crossing activities are mostly accompanied by challenges and risks, physicists' higher engagements in STEM fields, with lower costs of boundary-crossing, instead of SSH also complies with the principle of least efforts raised by Zipf (Basu & Dobler, 2012).

The boundary-crossing scientists can be seen as the *immigrants* with intellectual mobility from their original fields to the target fields. Accordingly, other scientists of the target fields are the *original inhabitants.* We subsequently compared the characteristics of publications' references and citations between these two groups of scientists. We found that boundary-crossing activities contributed more interdisciplinary outputs, whose knowledge sources and audiences are more diversified than the average level of *original inhabitants*. In contrast, it is hard for boundary-crossing publications to receive as many citations as the *original inhabitants*. Furthermore, the share of references from physics mentioned in the boundary-crossing publications is higher than the average level of the full sample, which accelerates the knowledge exchanges between physics and other fields. A previous survey found that one-third of the boundary-crossing physicists still consider themselves to be mainly physicists (van Houten et al., 1983), which may help to understand why they cited a large proportion of references from physics. Furthermore, boundary-crossing publications are also cited by fields beyond their original and target fields, suggesting that boundary-crossing activities may lead to more complex patterns of interdisciplinary knowledge flows (Pierce, 1999).

Concerning contribution types, we found that boundary-crossing publications led by physicists cite more references from physics than the publications of *original inhabitants*. Yet other boundary-crossing publications that physicists act as co-authors are more interdisciplinary in terms of references or citation diffusions. In fact, physicists are found very helpful in collaboration with other domains. It was found that physicists who migrated to other fields spent 13% of their time available on “advising others on research”, including “deepening the results, backing up results by giving theoretical interpretations, and developing formal theories” (Houten et al., 1983).

There are some limitations in this study. First, this is a case study only including scientists from physics. We should be careful in generalizing the conclusions to other fields. Second, the results might be affected by the article-level subject classification we adopted. In the future, different article-level classifications of scientific papers should be included as the robustness test. Third, since not all subfields of physics are basic science, we will verify our results by dividing physics into subfields and making comparisons among them.

This study has the following implications for the policy-making of Science & Technology. It is found that boundary-crossing activities contribute a lot in fostering interdisciplinary research and promoting the knowledge flows between different fields. More grant schemes should be established for boundary-crossers to reduce the risks and costs involved in this endeavor, e.g., the difficulty of meeting the expectations of editors and reviewers outside one’s own field (Perper, 1989). In this study, the share of citations from the target domains received by boundary-crossing publications is lower than the average level. Encouraging collaborations with the *original inhabitants* from target fields can be an efficient strategy for fitting in the different research paradigms and gaining acknowledgment from the target fields. In addition, it is hard for boundary-crossing publications to be recognized by the target fields and be fairly evaluated. But they are more frequently cited by various fields beyond the target ones. Hence, boundary-crossing physicists might be biasedly treated under the discipline-oriented system of talent evaluations. Designated funds and projects should be established to break the limitation of disciplinary barriers to support scientists who work in the peripheral area or shift their research focus.

Acknowledgments

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