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Facilitating interdisciplinarity: the contributions of boundary-crossing activities among disciplines

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Abstract

It is generally acknowledged that researchers who cross the boundary of disciplines are more likely to produce novel outputs. The knowledge exchanges contributed by boundary crossing provide a good explanation for the underlying mechanism. However, previous studies provide limited empirical evidence on whether and how these contributions are made. This paper analyzes how boundary crossing researchers originated from physics induce interdisciplinary knowledge flows. We find that applied sciences are the most common target domain for boundary crossing activities originating from physics. The normalized citation network shows that boundary crossing contributes to more knowledge exchanges between physics and the target fields than the average level. Beyond the original and target fields, boundary crossing activities also demonstrate spillover effects, causing additional knowledge flows among a wider range of fields beyond physics. Based on the induced knowledge exchanges, we define distinct roles that boundary crossing outputs play in this process, namely settlers, disseminators, transcenders, and maintainers, and reveal that they have distinct performances on interdisciplinarity. Given the contribution boundary crossing activities have made in fostering interdisciplinary research and knowledge flows, we encourage the funding bodies to break the limitation of disciplinary barriers and establish more grant schemes to support productive and meaningful interactions across different fields.

Keywords Interdisciplinarity · Boundary crossing · Physics · Knowledge Flows

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Introduction

The social structures of discipline, including the categorization and well-understood boundaries, are entrenched in researchers' whole careers (Abbott, 2010). Disciplines are perceived as exclusive communities, with boundaries keeping participants from other disciplines outside (Klein, 1996). On the contrary, the advancement of science does not take place within a single domain or field but thrives on the overlapping and integration of diversified knowledge. Therefore, activities that cross disciplinary boundaries, connecting disparate streams of information from various disciplines are fundamental to science (Leahey & Moody, 2014). For instance, creative outputs are typically produced through boundary crossing activities and new combinations of knowledge (Uzzi et al., 2013). Notably, despite the challenges posed by disciplinary barriers, boundary crossing activities are not rare in academia. There is a growing understanding that scientists, publications, and knowledge involved in boundary crossing activities merit more attention and support given their significance in fostering scientific advances and prevalence in the academic landscape.

The term "boundary crosser" or "boundary spanner" was initially introduced by Tushman (1977) in the field of management, where it was employed to analyze the distinctive roles played by individuals who cross the boundaries within Research and Development (R&D) departments. Subsequently, a series of studies further developed the concept of "boundary crossers" as the links between a unit and its environment (Cross & Prusak, 2002; Leifer & Delbecq, 1978), i.e., the individuals crossing the boundaries between different organizations. These boundary crossers facilitate information exchange, provide access to resources (Adams, 1976; Jemison, 1984), and represent the groups (Cross & Prusak, 2002; Friedman & Podolny, 1992), with information exchange being a primary focus (Haas, 2015). In 1999, Pierce (1999) brought this concept into the realm of science of science studies, redefining it as researchers publishing work in other disciplines, thereby exporting theories or methods to other disciplinary communities. Pierce (1999) also transplanted its function as the interdisciplinary information transfer in scientific literature. Whalen (2018) broadens this definition by regarding the researchers who draw on expertise from distinct and disparate fields as boundary crossers. Boundary crossing activities have also garnered attention in the field of sociology of science, with a primary concern about the consequences and impact of such boundary crossing on researchers' performance (Zhang et al., 2023). One classic example is researchers' risky innovation strategies presented by Kuhn (2012), which represents another facet of boundary crossing, proposing that researchers tend to change their initial research interests and devote themselves to a new field to achieve more novel outputs. Building upon the concept of boundary crossing, Chen (2012) extended the paradigm from the individual level to the publication level, identifying boundary spanning connections as the new links established between two clusters by the publications within the intellectual space. In this study, we adopt the classic definition of boundary crossing by Pierce (1999) and define boundary crossing activities as researchers crossing the boundaries between the target discipline and their original discipline and publishing articles beyond their field of origin. In this context, we refer to the researchers who cross the disciplinary boundaries as the boundary crossers or boundary crossing researchers in this paper.

Boundary-crossing is of great significance in scientific research, as a great number of scientific and technological innovation takes place at the interfaces between disciplines (Lemaine et al., 2012) or achieved by researchers who cross disciplinary boundaries (Small, 1999). In addition, novel ideas (Burt, 2004) and high-impact outputs (Chen, 2012;

Leahey et al., 2017; Shi et al., 2009; Tushman & Scanlan, 1981) have long been associated with boundary crossing activities. Several prior studies have provided empirical evidence demonstrating that researchers who cross the disciplinary boundary and venture into a new field are more likely to produce highly innovative outcomes (Azoulay et al., 2011; Foster et al., 2015; Leahey et al., 2017). Despite this clear understanding of the outputs of boundary crossing activities, the process itself is still underestimated in the existing literature. Consequently, more attention should be paid to the mechanisms through which boundary crossing activities foster innovation.

One of the most important mechanisms underlying this phenomenon is the knowledge transfer and flows facilitated by boundary crossing. Serving as *cognitive citizens* of multiple disciplines, boundary crossers often function as bridges for sharing knowledge and practices, encouraging collaboration across different disciplines (Hoffmann-Longtin et al., 2022). In this process, the movement of boundary crossing researchers from one discipline to another typically coincides with the flow of ideas and information in the same direction (Pollak, 1981). Simultaneously, researchers may channel dispersed knowledge in their original and relevant new disciplines, reinforcing weak links or initiating new connections (Palmer, 1999). Previous studies have implicitly demonstrated that knowledge flows and researcher flows between disciplines are complementary to each other by revealing the similarities of networks constructed based on physicists' movement and the citations between disciplines (Battiston et al., 2019; Hargens, 1986; Urata, 1990). However, as discussed above, the process through which boundary crossing activities contribute to knowledge flows and transfers has mainly been discussed at a theoretical level. Limited empirical and direct evidence drawn from large-scale datasets is available on this topic.

In this study, we empirically associate boundary crossing activities with multi-facets of interdisciplinarity they triggered using a dataset comprising 817,016 articles, shedding light on their interconnected dynamics and potential implications for scientific progress. Essentially, boundary crossing can be perceived as directed flows of human capital between disciplines. Through those flows of researchers, interdisciplinary knowledge flows and even interdisciplinary research emerge. If boundary crossers aim to address interdisciplinary problems or work in multidisciplinary teams, an explicit mode of interdisciplinary knowledge flows can be observed. Rather, when boundary crossers are driven by personal interest and curiosity to explore a new field, the initial field may exert implicit influence on the target field via flows of researchers and knowledge. The situation may vary, but we can induce that boundary crossing is intricately and closely related to the notion of interdisciplinarity. However, the associations between boundary crossing and interdisciplinarity, especially the interdisciplinary outputs generated from boundary crossing activities, remain underexplored in the literature. This study contributes to the literature by introducing another possible way for interdisciplinary research, boundary crossing. We chose physics as a case study because it often facilitates the development of other scientific disciplines like astronomy, chemistry, and medicine. A physics-like mindset, as well as the concepts, methods, and instrumentation of physics, are all required in these disciplines (Van Houten et al., 1983). Thus, the physics-based boundary crossing activities can be more meaningful and diversified. In particular, we focus on three research questions. By addressing the research questions outlined, we aim to contribute to a deeper understanding of the intricate relationships among disciplines and how boundary crossing facilitates the exchanges of knowledge.

RQ1: What fields do boundary crossers who originate from physics mainly target?

RQ2: How do boundary crossing activities contribute to the interdisciplinary knowledge flows, and how do these contributions evolve over time?

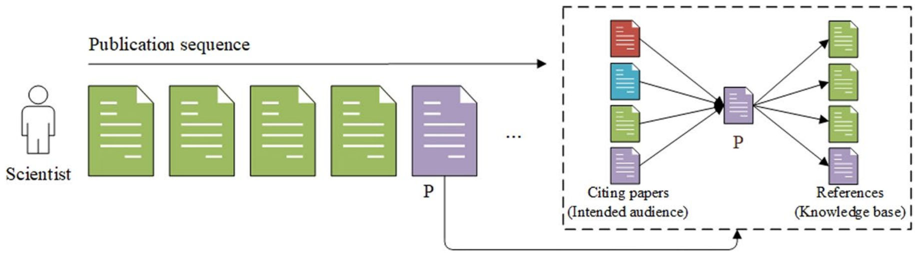

Fig. 1 Concept map of this study. The color of publications reflects the fields they belong to

RQ3: What roles do the outputs of boundary crossing play in the interdisciplinary knowledge flows, and how do these roles vary across target domains?

To answer the above questions, we focus on the researchers who originate from physics and then publish papers outside physics, as shown in Fig. 1. Those papers published outside researchers' original field are regarded as the outputs of boundary crossing activities. The dataset of this study is obtained from Scopus, containing the bibliographic information of more than 800 k boundary crossing journal articles published from 1991 to 2020. Citations of articles are obtained and employed to elucidate the flow of knowledge. To quantify the interdisciplinary knowledge flows, we constructed citation networks at the research field level. Furthermore, a two-dimensional coordinate system is also constructed to identify the roles of boundary crossing outputs play in knowledge flows.

Data and methodology

Data

The dataset of this study is collected from Scopus, a bibliographic database curated by Elsevier. The obtained data is processed in the following four steps.

1) Creating the raw dataset

We first collected journal articles published between 1991 and 2020 as the raw dataset (*A*). Considering journal articles are one of the primary forms of academic outputs in most disciplines, we restrict our dataset to this document type.

2) Identifying researchers originating from physics

To identify all the researchers who originate from physics (*P*) from dataset *A*, we introduce an operational framework to recognize researchers' original field, ascribing it as the field in which researchers primarily and largely published since the beginning of their academic career. In specific, we recognized researchers who originated from physics as candidates whose a) first first-authored journal article was published in physics, following the approach suggested by Robinson-Garcia et al. (2020) to identify researchers' start of academic careers and b) most papers over the first five-year of their academic careers are also published in physics. These criteria filtered the researchers who grasp knowledge from physics and are able to make use of this knowledge to publish peer-reviewed publications in physics. We confined our analysis to researchers whose scientific career started between 1991 and 2000 and whose total number of publications is no less than ten (N = 84,498). We did not follow the methodology in previous studies using all publication records of researchers to identify their expert domains (Battiston et al., 2019; Boekhout et al., 2021) as these methods are not consistent with the purpose of this study – the identification of researchers originated from physics. Moreover, these methods are likely to filter researchers who have constant research interests and could have a bias on the boundary crossers. To validate our method, we adopted the method from Battiston et al. (2019), whereby a researcher is considered to be significantly engaged in a subfield if the share of publications in the focal subfield is greater than that of the average scientist measured by Revealed Comparative Advantage (RCA) index (Balassa, 1965). We computed the RCA index of share of publications in physics in each researcher's first five years of their career and kept only the researchers with RCA > 1. We then made a comparison with the results of our method. Notably, our method returned a smaller set of researchers (84,498 researchers) when compared with the method employed by Battiston et al. (2019) (93,047 researchers), with 83,514 overlapping researchers (98.84% of our dataset) between these two datasets. It shows that our method holds a stricter standard, and thus is effective in identifying researchers' field of origin. Additionally, we collected 201 physicists nominated by American Physical Society (APS) as the APS fellow[1] in 1995. It yields an 81% overlap with our dataset.

3) Identifying boundary crossers

We then identify the boundary crossers (*B*) from dataset *P*. Following the definition of Pierce (1999), we define boundary crossers as researchers who publish papers outside one's original field. Hence, we filtered boundary crossers who, following the initial five years of their academic career, published papers beyond physics (N = 60,812).

4) Delineating boundary crossing activities

We collected the outputs of boundary crossing activities (*O*) along with their associated references and citing papers (*C*). Based on *B*, we were able to get all the articles (*O*) published by researchers outside their original fields, physics (N = 817,016). Citation is deemed one of the most common proxies of knowledge flow in bibliometrics (Lyu et al., 2022). To explore the citation-based knowledge flows contributed by boundary crossing activities, we collected all the references and citing papers of publications in *O*.

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 (Aman, 2018; Kawashima & Tomizawa, 2015; Moed et al., 2013). Considering the limitations of journal-based delineations (Zhang et al., 2022), 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

[1] https://www.aps.org/programs/honors/fellowships/archive-all.cfm

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).

Methodology

In this study, we constructed the citation network at the field level to observe the knowledge diffusion and flows among research fields. To quantify the interdisciplinary knowledge flows arising from boundary crossing activities accurately, we first accessed the full database of Scopus and extracted the citation relationships from all the journal articles published in the same period of our dataset (i.e., 1991–2020). Based on this full sample, we then constructed the baseline citation network. By comparing the citation network based on the outputs arising from boundary crossing with the baseline network, we are able to discern the changes in knowledge flows and structure brought by boundary crossing activities.

In the process of boundary crossing, the major concern is the nuanced interplay between boundary crossers' original field and target field. Theoretically, boundary crossers may initialize new links or enhance the existing links between their original field and target field, and thus import the knowledge from the former to the latter. However, the extent to which boundary crossers diffuse the knowledge from their original field can be heterogeneous. Furthermore, the degree to which boundary crossing outputs are recognized, for instance, cited, by the target field also varies. To quantify these two dimensions, we utilized the references and citations associated with boundary crossing outputs to characterize their knowledge base and audiences. Specifically, we present two indicators, the share of knowledge base in physics (i.e., the share of references from physics), measuring the knowledge proximity between focal paper with physics, and share of intended audiences (i.e., the share of citations from target field), measuring the audience proximity between focal paper with the targe field. These indicators were calculated and serve as critical metrics for discerning the roles played by boundary crossing outputs in interdisciplinary knowledge flows. To illustrate the central tendency of these two indicators, we also calculated the expected value (average) of these two indexes as the baseline with all the articles published in the same period and fields as axes. Consequently, we establish a two-dimensional coordinate system that enables the classification of boundary crossing outputs into four distinct roles within interdisciplinary knowledge flows, as shown in Fig. 2. We focus on the roles of boundary crossing outputs rather than the researchers because the role of a researcher may develop with time, while the role of a publication remains constant and enduring.

1) *Settler*: This category comprises boundary crossing outputs characterized by a lower share of knowledge base in physics, yet a higher share of intended audiences relative to the baseline. Those articles are no longer based on the knowledge mainly from the original field (physics) but are highly recognized by the target field, suggesting the notion of adaptation or assimilation into a new field.

2) *Disseminator*: Boundary-crossing outputs classified within this role exhibit a greater share of knowledge base in physics and intended audiences compared to the baseline. These publications, while predominantly rooted in physics-based knowledge, receive substantial

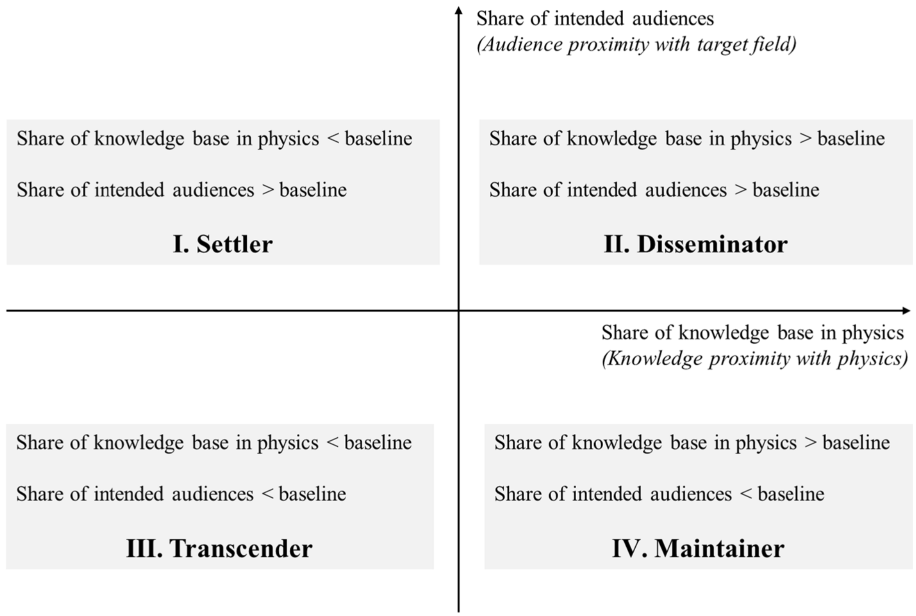

Fig. 2 Roles of boundary crossing outputs play

attention and recognition (measured by citations) from the target field. Although they are produced mainly based on knowledge of physics, they are of interest to the target community. Thus, those articles are considered critical media to disseminate knowledge from physics.

3) *Transcender*: Within this role, boundary crossing outputs exhibit a lower share of knowledge base in physics and intended audiences when compared to the baseline. Although those articles are published in the target field, they tend to possess a diversified knowledge base and audiences, resulting in lower values for both two indicators. These publications may be transcending traditional disciplinary boundaries, potentially representing emerging areas of research that don't fit neatly into established categories. The authors of those articles usually work in the intersecting area of multiple fields or the semi-periphery of a given domain.

4) *Maintainer*: Boundary crossing outputs categorized as *maintainers* of the original field manifest a higher share of knowledge base in physics, yet a lower share of intended audiences relative to the baseline. Although those articles cross the boundaries of disciplines and are published in a new field, they retain the fundamental attributes of articles within the original field. They continue to exhibit a higher frequency of references to physics-based literature and garner more citations from physicists.

To better understand different roles of boundary crossing outputs, we adopted the indicators from previous literature (Stirling, 2007) to capture their various dimensions of interdisciplinarity. These dimensions, namely *variety*, *balance*, and *disparity*, were quantified for both the references and citations associated with boundary crossing outputs to portray a comprehensive view of interdisciplinary knowledge flows.

In particular, *variety* denotes the number of fields in which referenced/citing papers are published. *Balance* reflects the distribution of the referenced/citing papers within different fields. *Disparity* refers to the degree to which the referenced/citing fields may be distinguished (Rafols & Meyer, 2010; Zhou et al., 2022). Specifically, let X be a paper that cites papers from j distinct fields, namely $f_1, f_2, \ldots, f_j$, and is cited by papers from k distinct fields, namely $f_1, f_2, \ldots, f_k$.

The *variety* of paper X's references and citations reveal the broadness of knowledge base and audiences, which are calculated as follows:

$$Variety_{ref} = j$$

$$Variety_{cit} = k$$

The *balance* of paper X's references and citations reflects the evenness of knowledge base and audiences, which are calculated as follows:

$$Balance_{ref} = -\sum_{i=1}^{j} p_i \log(p_i)$$

$$Balance_{cit} = -\sum_{i=1}^{k} p_i \log(p_i)$$

where p is the proportion of references/citations of X citing the papers/received from field f $\left(\sum_j p_j = 1; \sum_k p_k = 1\right)$. $Balance = 1$ indicates the maximum evenness and $Balance = 0$ shows extreme imbalance.

The *disparity* of paper X's references and citations examine the heterogeneity of the knowledge base and audiences, which are calculated as follows:

$$Disparity_{ref} = \frac{\sum_{i \neq j} d_{ij}}{Variety_{ref}\left(Variety_{ref} - 1\right)}$$

$$Disparity_{cit} = \frac{\sum_{i \neq j} d_{ij}}{Variety_{cit}\left(Variety_{cit} - 1\right)}$$

where d_{ij} is the dissimilarity between fields i and j (Zhang et al., 2016), which is calculated with all the publications in 2020 from the full database of Scopus and the article-level classification provided by Science-Metrix.

Results

In this section, we first present the chronological and disciplinary distribution of boundary crossing activities that originate from physics to uncover the overall trend. Then, we delve into the quantification of the boundary crossing activities' contribution to the interdisciplinary knowledge flows and identification of various roles they play in this process.

Prevalence of boundary-crossing activities

Based on the boundary crossing researchers who started their academic careers in physics from 1991 to 2000, Fig. 3 illustrates the publications of those boundary crossers published beyond physics. For all five domains, the number of boundary crossing outputs

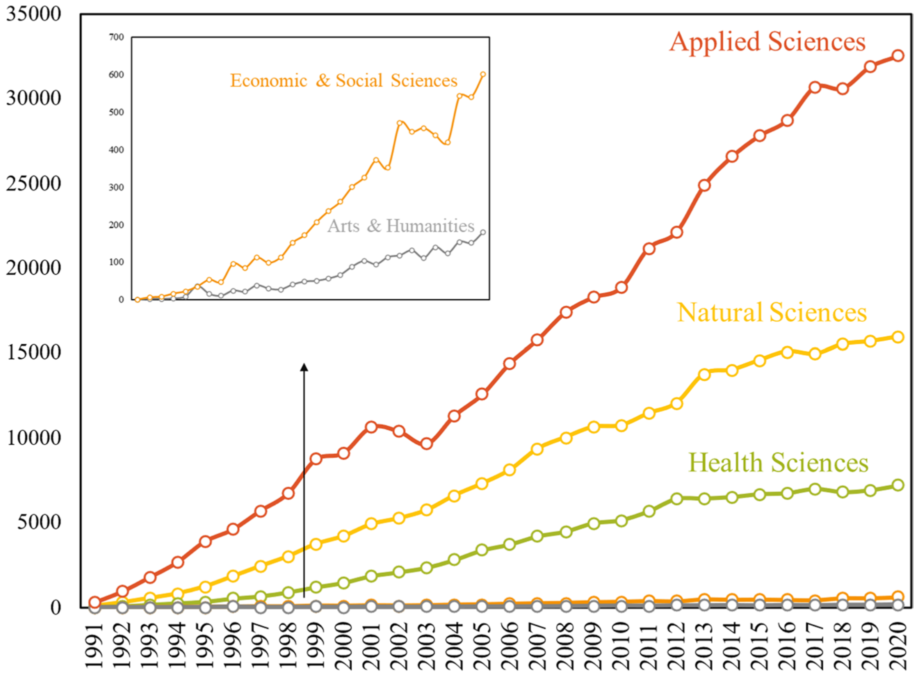

Fig. 3 Number of boundary-crossing outputs in five domains

keeps rising annually, which corresponds to the rise of interdisciplinarity in several fields in recent decades (Gates et al., 2019; Zhou et al., 2022). The interaction between physics and *applied sciences* has been increasing steadily, while the growth rate of boundary crossing outputs in *natural sciences* and *health sciences* slowed down in recent years. The small number of boundary crossing outputs published in SSH also increased in fluctuation. In the first decade, boundary crossers focused mainly on the research in their original field (physics), hence resulting in a small number of boundary crossing outputs, as depicted in Fig. 3.

In Fig. 4, the flows between bars represent the number of boundary crossing outputs. From left to right, the bars represent the original field, contribution type, target domain, and target field of boundary crossing successively. Figure 4 presents the boundary crossers who started from their original field (physics), did research in different ways (as the leading author or the supportive author), and published articles in various target fields and domains. The target fields of boundary crossers encompass a wide range of scientific domains, covering 19 out of 22 fields of science. Notably, *applied sciences* emerge as the dominant target domain, indicating that physics, as one of the most important fundamental research fields, can underpin and support plenty of applied research (i.e., *enabling & strategic technologies* and *engineering*). Many outputs of boundary crossing activities 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*. Additionally, *clinical medicine* is also another prevalent target field of boundary crossing. As expected, fewer boundary crossers chose domains like social sciences and humanities (SSH) as their target domain for boundary-crossing.

Regarding the contribution type, boundary crossers who cross disciplinary boundaries may act as the leading authors (e.g., 1st or corresponding authors) or supportive authors.

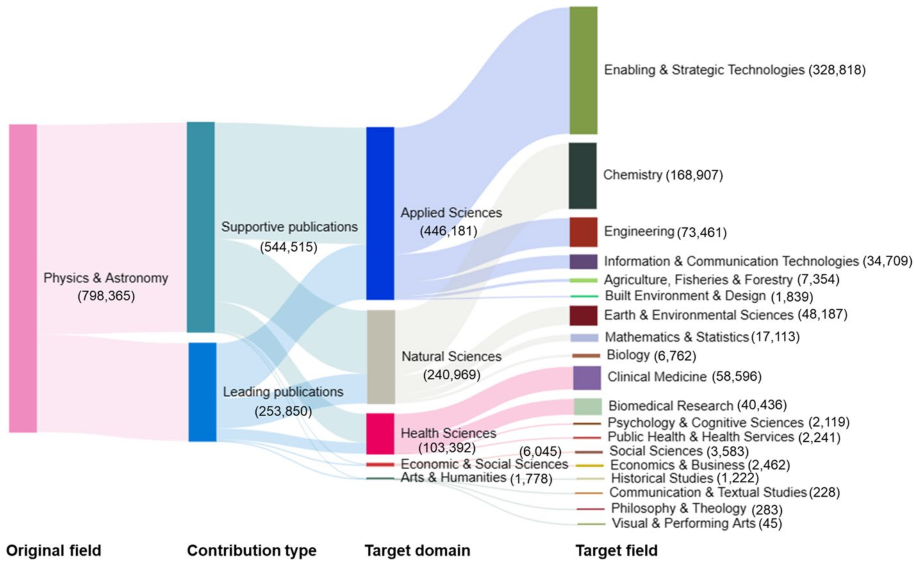

Fig. 4 Distribution of fields and domains of boundary-crossing publications

The boundary crossing outputs produced via these two contribution types are interpreted as the "leading publications" and "supportive publications" respectively in this study, which demonstrates the degree of researchers' involvement and leadership in boundary crossing activities. In general, when publishing outside their own fields, the number of leading boundary crossing outputs is notably smaller than that of supportive types. It indicates that interdisciplinary collaboration serves as a feasible mechanism for crossing the boundaries and bridging distinct disciplines. Differences also exist in various fields. The situation in *applied sciences*, *natural sciences*, and *health sciences* agrees with the general trend. In *clinical medicine*, leading publications only account for 24.9% of all the boundary crossing outputs, while supportive publications have notable dominance. The leadership of research in this field may be demanding for the boundary crossers who originate from physics. However, some fields and domains, i.e., *arts & humanities*, *mathematics & statistics,* and *philosophy & theology,* exhibit a higher share of leading boundary crossing outputs, with *philosophy & theology* standing out as the domain with the highest share of leading publications at 80.21%. On the one hand, these fields and domains are different from physics in epistemology and methodology significantly, making collaboration with researchers from irrelevant fields challenging. Thus, boundary crossers tend to lead the research with their own expertise even in fields beyond physics. On the other hand, single-authored papers are more prevalent in *arts & humanities* compared with hard sciences, thus may influencing the distribution of contribution types.

Interdisciplinary knowledge flows brought by boundary crossing activities

As a vital form of knowledge flow, citations can help spread the information and knowledge contained in scientific papers. In this section, we utilize citation data to illustrate the flows of knowledge among research fields. To quantify the contribution of boundary crossing outputs to the interdisciplinary knowledge flows, we use the references and citing papers of boundary crossing outputs to reflect their knowledge base and audiences and construct a citation network separately (Fig. 5). Figure 5 depicts the differences between the network based on boundary crossing outputs and the baseline network based on all the articles published in the same period. There are 20 nodes and 380 links in each network. According to the publication year of boundary crossing outputs, we divided them into three groups, namely 1991–2000, 2001–2010, and 2011–2020, to provide an evolutionary view.

Figure 5 shows the interdisciplinary knowledge flows exhibited in the references and citing papers of boundary crossing outputs. *Physics & astronomy* exhibit the highest in-degree and out-degree within the networks, reflecting that the papers from physics still serve as the main knowledge base and audiences of boundary crossing outputs even when researchers crossed the boundaries and published papers outside physics. Generally, most links are colored in blue, and only a few links are in red. Most red links are pointed to or from physics, indicating the predominant role of boundary crossing activities in fostering knowledge exchanges between physics and other fields, i.e., inflows and outflows of knowledge in physics. For instance, boundary crossing outputs published in fields such as *enabling & strategic technologies*, *chemistry*, and *engineering* have more references and citations in physics than the average level. In addition, boundary crossing also shows spillover effects contribute to knowledge flows among a wide range of fields other than physics. For instance, the red links among *chemistry*, *enabling & strategic technologies*, and *engineering* account for more knowledge exchanges within those fields in the networks of references and citing papers. Those knowledge exchanges might be caused by researchers who work in the overlapping area or their multiple boundary crossing activities among these fields.

Over the past thirty years, knowledge has been decreasingly brought from physics to the focal fields by boundary crossing researchers (Fig. 5a–c). Meanwhile, the dominant role of physics plays in the audiences of boundary crossing outputs are also weakening with time (Fig. 5d–f). However, the knowledge spillovers beyond physics show an increasing trend, e.g., citation links between *chemistry* and *enabling & strategic technologies.* Boundary crossers are becoming less dependent on their original field, physics, and are contributing to more diversified knowledge flows as time progresses. Overall, the amount of most interdisciplinary knowledge flows brought by boundary crossing activities, as portrayed in the networks of references and citing papers, is declining with time. The reason might be that the interdisciplinary knowledge flows in the baseline network are enhancing with time, supported by the increasing interdisciplinarity of science (Gates et al., 2019; Zhou et al., 2022). Consequently, citing references from other fields has become normal and regular in recent years. A noticeable decline in knowledge flows from 1991 to 2020 is observed between certain fields, for example, citations from *natural sciences* (e.g., *earth & environmental sciences, chemistry, and mathematics & statistics*) to *applied sciences* (e.g., *information & communication technologies, engineering, and enabling & strategic technologies*). In addition, boundary crossing activities also lead to some increasing knowledge flows between distinct fields. For instance, fields in *health sciences* (e.g., *biomedical research* and *clinical medicine*) have a growing amount of knowledge exchanges with some fields in *applied sciences* (e.g., *enabling & strategic technologies* and *engineering*) and *chemistry*. But the citation links between *health sciences* and physics are weakening at the same time. This phenomenon verifies the spillover effects of boundary crossing again, especially in triggering multiple knowledge flows and a wide range of applications in medical fields.

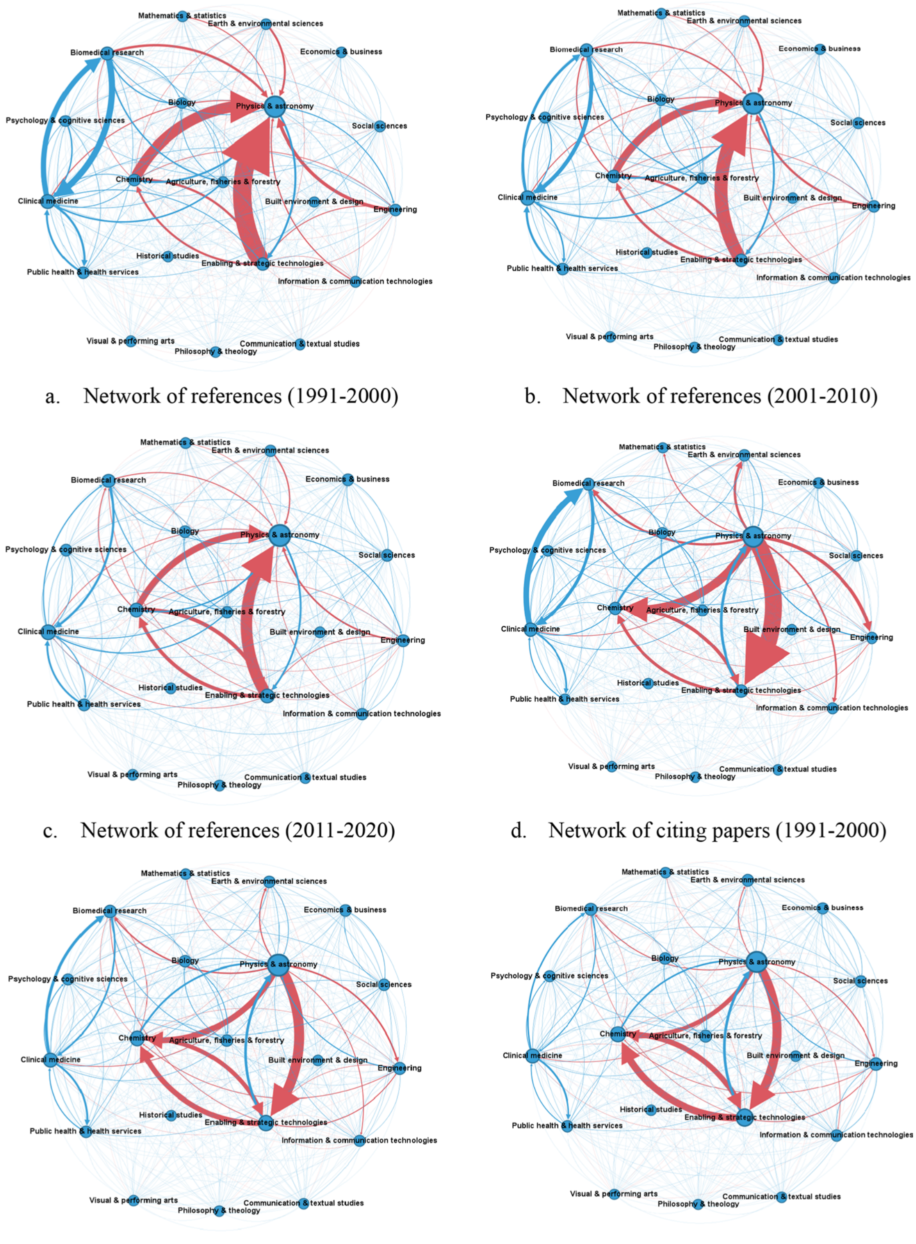

Fig. 5 Interdisciplinary knowledge flows brought by boundary crossing. Each dot represents a research field. The size of dots depends on their in-degree for Fig. 5**a–c** and out-degree for Fig. 5**d–f**, which is the number of edges pointing to or from the node. Links between dots represent the difference in normalized citations between the network based on boundary crossing outputs and the baseline network, with arrows pointing from citing fields to the referenced fields. Red links represent that the normalized citations between two fields extracted from the boundary crossing outputs are higher than that of the baseline. Correspondingly, blue links represent less normalized citations compared with the baseline

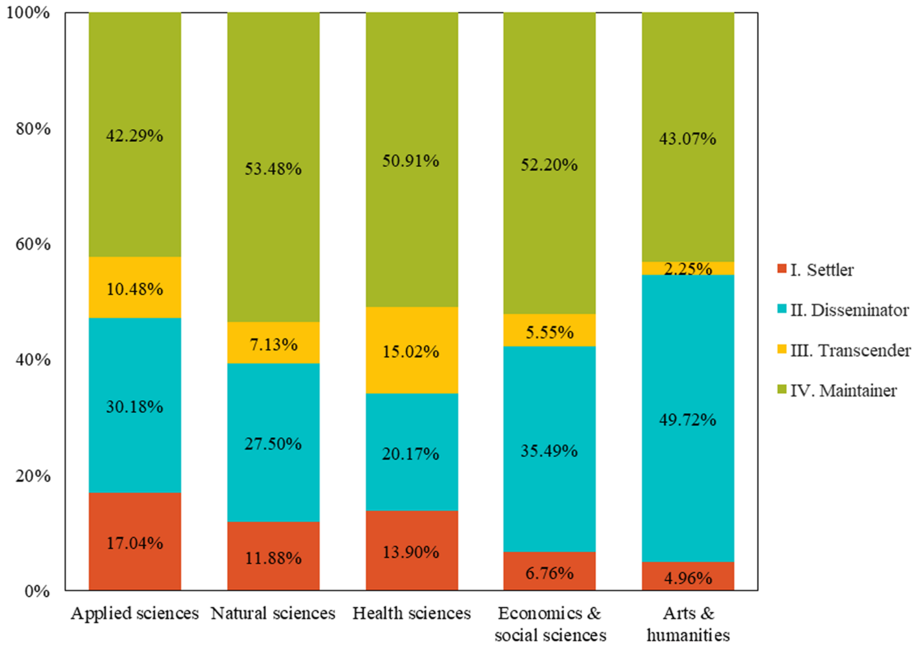

Fig. 6 Share of different roles of boundary crossing outputs

The roles of boundary crossing outputs in the interdisciplinary knowledge flows

In this section, we further examine the contributions made by boundary crossing activities in greater detail. Do boundary crossers typically develop research based on the knowledge from their original field? Does boundary crossing outputs have a more diversified knowledge base? To what extent are the boundary crossing outputs cited and recognized by the target fields? Do these boundary crossing outputs reach a wider range of audiences? To address these questions, we first classify boundary crossing outputs into four different roles in the interdisciplinary knowledge flows. Then, we calculate the interdisciplinarity among distinct roles to capture their variety, balance, and disparity within the knowledge base and intended audiences.

According to the conceptual design in Fig. 2, boundary crossing outputs are categorized into four types to delineate their roles in interdisciplinary knowledge flows. Figure 6 offers an overview of the distribution of these roles. In most domains, except for *arts & humanities*, boundary crossing outputs are predominantly classified as the role of *maintainer*. This role exhibits a wide range of values, and thus more papers are located within this category. Specifically, the share of *settlers* published in *applied sciences* exhibits the highest prevalence among all five domains and also surpasses the average level (i.e., share of *settlers* in all the boundary crossing outputs). These *settlers* can be regarded as cognitive immigrants who originate from physics and are more likely to assimilate into the community of *applied sciences*. *Disseminators*, who play a crucial role in importing substantial knowledge from physics and are well-recognized by the audiences in the target field, are more prevalent in *applied sciences*, *arts & humanities*, and *economics & social sciences*, particularly with a high share of 49.72% in *arts & humanities*. *Transcenders* account for the highest proportion of the boundary crossing outputs published in *health sciences* and a higher proportion

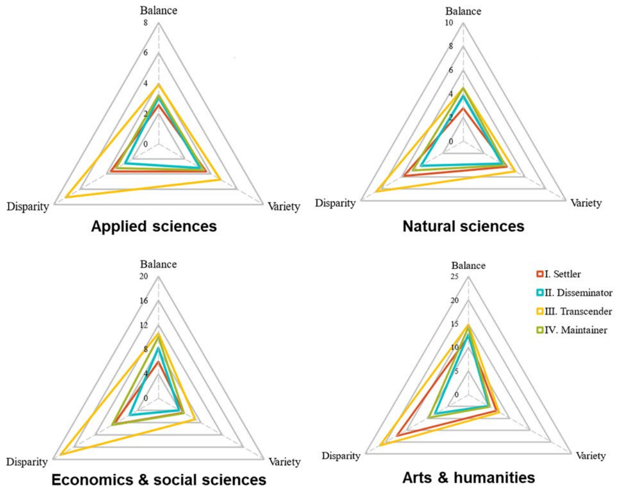

Fig. 7 Mean interdisciplinarity of boundary crossing outputs measured by references (The value of *Balance* is within [0, 1]. In Fig. 7 and 8, *Balance* is multiplied with the max value of axis for clear visulization.)

in *applied sciences* than the average level. Those papers may focus on the overlapping area of multiple fields beyond the original and target field of boundary crossing. There are more *maintainers* in boundary crossing outputs published in *economics & social sciences*, *health sciences*, and *natural sciences* than the average level, with *natural sciences* having the largest proportion of boundary crossing outputs. It indicates that assimilation into other fields of *natural sciences* can be particularly challenging for researchers who originate from physics, as their boundary crossing outputs continue to have more references and citations from physics.

To gain a more comprehensive understanding of the roles boundary crossing outputs play in knowledge flows, we examine the broadness, evenness, and heterogeneity of each role's interdisciplinarity with three indicators, namely variety, balance, and disparity. Figure 7 and 8 illustrate the interdisciplinarity of the knowledge base and audiences of boundary crossing outputs, reflected by their references and citing papers. From the perspective of knowledge base (Fig. 7), generally, *transcenders* emerge as the most interdisciplinary role of boundary crossing outputs across the various domains, demonstrating the highest values for variety and disparity and relatively higher values for balance. Notably, the disparity of *transcenders* is considerably higher compared to other roles. Those articles have a more diversified and evenly distributed knowledge base, spanning distinct fields that are cognitively distant. It is thus proved that those articles, with a lower share of references in physics but a greater share from other fields, are in the overlapping or peripheral area where the target field meets physics. *Settlers* exhibit the lowest value of balance across all five domains but a higher value of disparity in most domains, indicating an imbalanced and heterogeneous knowledge base. The value of disparity rises in domains where there is a larger cognitive distance between physics and the target domain. Thereby, it can be inferred that *settlers* have a higher share of references from target domains and are adapted to the established knowledge structures in the target domains. However, *settlers* in *arts & humanities* demonstrate greater interdisciplinary features, particularly in variety and disparity. *Disseminators* typically carry knowledge from physics and spread it to the target fields, resulting in a more physics-like rather than interdisciplinary knowledge base. Thus, the

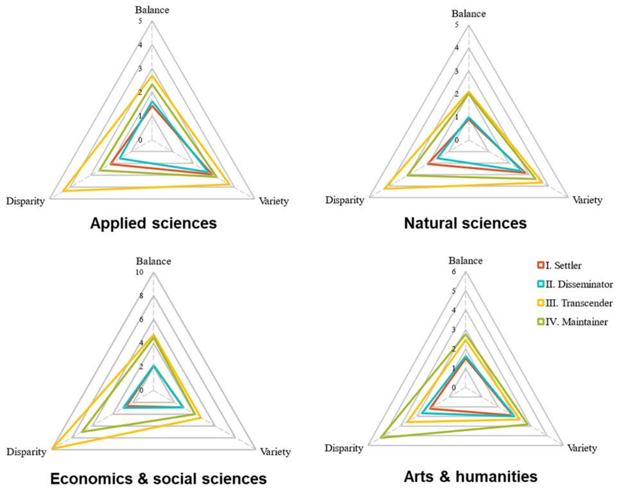

Fig. 8 Mean interdisciplinarity of boundary crossing outputs measured by citations

values of *disseminators*' variety and disparity are the lowest among four roles. *Maintainers* exhibit a moderate level of interdisciplinarity among four roles of boundary crossing outputs. But they are more interdisciplinary in *health sciences* in all three indicators, suggesting that researchers who originate from physics who engage in *health sciences* tend to draw on a more interdisciplinary knowledge base compared to *maintainers* in other domains.

Taking the variations across distinct domains into account, it is clear that boundary crossing outputs in *arts & humanities* and *economics & social sciences* exhibit higher interdisciplinarity than those in STEM domains, particular when it comes to the value of balance and disparity. While boundary crossing outputs in *applied sciences*, *natural sciences*, and *health sciences* are less interdisciplinarity, their performance in three indicators remains relatively balanced. Researchers inevitably citing references from physics and the target domain in their boundary crossing outputs. The heterogeneity between physics and the target domain results in the higher value of disparity in SSH. However, if researchers who originated from physics publish articles in neighboring fields or *applied fields*, the interdisciplinarity of their articles can be limited.

Figure 8 illustrates the interdisciplinarity of boundary crossing outputs' audiences. In general, the audiences for boundary-crossing outputs are typically less interdisciplinary than the knowledge bases. Additionally, we found that the audiences of *transcenders* exhibit the greatest value for all three indicators, indicating that they are the most interdisciplinary across all domains. This type of boundary crossing output is cited, concerned, and recognized by a wide range of audiences from diversified and heterogeneous fields. In addition, in *arts & humanities* and *health sciences*, the interdisciplinarity of *maintainers*' audiences is remarkable, where they are cited by a more diverse collection of fields. Despite those articles are developed primarily based on knowledge from physics, they are well-accepted by diversified audiences beyond their target domain. *Settlers* and *disseminators* tend to have less interdisciplinary audiences than other roles, as their primary audience consists of papers from the target domains. Specifically, disciplinary differences also exist. *Settlers* in *applied sciences* and *natural sciences* are more interdisciplinary, while *disseminators* are more interdisciplinary in *economics & social sciences* and *arts & humanities*.

Conclusions and discussion

This study elaborates on how boundary crossing activities induce knowledge exchanges and diffusion and thus facilitate interdisciplinarity. We also make contributions to the understanding of interdisciplinary research (IDR) from the perspective of publishing outside researchers' original field. The major conclusions of the study can be summarized as follows.

The boundary crossing activities originating from physics are more likely to take place in applied sciences (e.g., *enabling & strategic technologies* and *engineering*) and the neighboring fields (e.g., *chemistry* and *earth & environmental sciences*). This finding is consistent with previous studies (Griffith et al., 1974; Van Houten et al., 1983). Since boundary crossing activities are mostly accompanied by challenges and risks, it may induce less cognitive, communicational, operational costs and barriers for researchers to study in related STEM fields, instead of SSH; this also complies with the principle of least efforts raised by Zipf (Basu & Dobler, 2012). The boundary crossing outputs are mainly produced by interdisciplinary collaboration, where researchers originated from physics act as collaborators other than the first or corresponding authors. Previous literature also discussed physicists' active and important role in collaboration, who spent 13% of their time available "advising others on research", including "deepening the results, backing up results by giving theoretical interpretations, and developing formal theories" (Van Houten et al., 1983).

The original field of boundary crossers, physics, is still the main knowledge base and audience of boundary crossing outputs. This phenomenon may relate to the nature of physics, having higher levels of dependence, higher export/import ratios of knowledge flows, and transdisciplinary impact (Huang et al., 2022; Yan et al., 2013). Over time, boundary crossers have gradually become less dependent on their original field, physics, which corresponds to the trend of interdisciplinarity in recent years. Physics-based boundary crossing activities accelerate the knowledge exchanges between physics and target fields and also have knowledge spillovers to other fields and areas. Notably, the spillover effects of boundary crossing are increasingly evident, fostering knowledge exchanges among fields beyond physics and leading to more complex patterns of interdisciplinary knowledge flows, which supports the views from Pierce, 1999.

The roles of boundary crossing outputs play in interdisciplinary knowledge flows, whether as *settlers*, *disseminators*, *transcenders*, or *maintainers*, all make contributions to the interdisciplinarity research. The majority of boundary crossing are categorized as *maintainers*, which exhibit a moderate level of interdisciplinarity in knowledge base and a remarkable performance on the interdisciplinarity in intended audiences. Among all four roles of boundary crossing outputs, *transcenders* emerge as the most interdisciplinary role regardless of knowledge base or audiences. In contrast, *disseminators* focus on spreading knowledge from physics and thus have the lowest value on three indicators of interdisciplinarity.

This study has the following implications for the policy-making of Science & Technology. It is found that boundary crossing activities contribute to fostering interdisciplinary research and promoting the knowledge flows between distinct fields, which also can be very costly. The majority of boundary crossing outputs, categorized as *transcenders* and *maintainers*, received fewer citations from the target domains since their research focus might be different from the popular topics in the target domains. Meanwhile, they are more frequently cited by various fields beyond the target and original fields. Hence, boundary crossers might be biasedly treated under the discipline-oriented system of individual evaluations. Thereby, more grant schemes should be established for boundary crossers to reduce the risks and costs involved in this endeavor. Specifically, designated funds and projects should be established to break the limitation of disciplinary barriers to support researchers who work in the peripheral area or shift their research focus. Another efficient strategy to support boundary crossing activities is to encourage collaborations with the *original inhabitants* from target fields, which might be helpful in fitting in the different research paradigms and gaining acknowledgment from the target fields. This strategy is also partly proved in this study, showing that supportive outputs are more feasible for researchers to cross disciplinary boundaries.

There are some limitations in this study, indicating some directions for further studies. First, this is a case study only including researchers from physics. We should be careful in generalizing the conclusions to other fields. Second, we can only quantify the explicit knowledge flows with citation data. More knowledge exchanges during boundary crossing activities remain to be found with more data sources and methodology, such as surveys and interviews with boundary crossers. Third, we will further collect the information of researchers' educational backgrounds and work units to make the results more detailed and convincing.

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Declarations

Conflict of interest The corresponding author (Lin Zhang) is Editor-in-Chief of *Scientometrics*.

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