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Philosophy in Science: Can Philosophers of Science Permeate through Science and Produce Scientific Knowledge?

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Most philosophers of science do philosophy 'on' science. By contrast, others do philosophy 'in' science (PinS), that is, they use philosophical tools to address scientific problems and to provide scientifically useful proposals. Here, we consider the evidence in favour of a trend of this nature. We proceed in two stages. First, we identify relevant authors and articles empirically with bibliometric tools, given that PinS would be likely to infiltrate science and thus to be published in scientific journals ('intervention'), cited in scientific journals ('visibility'), and sometimes recognized as a scientific result by scientists ('contribution'). We show that many central figures in philosophy of science have been involved in PinS, and that some philosophers have even 'specialized' in this practice. Second, we propose a conceptual definition of PinS as a process involving three conditions (raising a scientific problem, using philosophical tools to address it, and making a scientific proposal), and we ask whether the articles identified at the first stage fulfil all these conditions. We show that PinS is a distinctive, quantitatively substantial trend within philosophy of science, demonstrating the existence of a methodological continuity from science to philosophy of science.

1. Introduction

Most philosophers of science do philosophy 'on' science, that is, they contribute to our knowledge of the methods, concepts, objects, and problems of science, and/or address philosophical problems using lessons taken from science (Malaterre et al. [2019], [2020]). By contrast, some philosophers of science do philosophy 'in' science, that

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is, they use philosophical tools to produce scientific knowledge rather than knowledge about science (Chang [1999]). Instead of studying, discussing, or talking about science, they permeate through science and try to participate in resolving problems that scientists raise or encounter in their work—problems that most other philosophers of science consider local and technical. We propose calling this trend in philosophy of science, in which philosophers use philosophical tools to address scientific problems and provide scientifically useful proposals, 'philosophy in science' (PinS).

The idea that philosophers of science can directly contribute to scientific knowledge will be met with surprise or scepticism by some, scientists (Weinberg [1992]; Hawking [2010]) and philosophers (Curd and Cover [1998], p. xvii) alike, even philosophers who have permeated through science (Okasha [2019], pp. 5–6). This reaction is based on the intuition that only a few philosophers of science intend to produce science, and that even fewer succeed in doing so, or on the assumption that philosophy of science simply cannot produce science. But what if philosophy in science—in this strong sense of addressing scientific problems, not just having an impact on science—had a significant number of instances and a rich history? The finding that there is, indeed, a community of philosophers 'in' science would have a major impact on several issues that have been central to philosophy of science throughout its history (for example, Suppes [1990]; Callebaut [1993]; Chang [1999]; Hull [2001]; Pernu [2008]; Laplane et al. [2019]; De Haro [2020]): Are philosophy of science and science continuous? Is philosophy of science useful to science? Does a philosophy that permeates science *ipso facto* cease to be philosophy?

Several names and approaches immediately come to mind when we think about philosophers of science meddling with science, but they usually either have two distinct activities (one in science, another in philosophy), or claim closeness to science to treat philosophical, not scientific problems. Suppes is a perfect example of a philosopher of science who has also made scientific contributions (for example, Suppes et al. [1997]). One may wonder whether all of his scientific papers have a strong philosophical content. At least in some cases, philosophers of science permeating through science may not do so *qua* philosophers, but as a parallel activity, especially if they have a double background in science and philosophy. Various approaches, such as philosophy of science in practice and experimental philosophy, have promoted a convergence of science and philosophy. Philosophy of science in practice 'is dedicated to fostering the pursuit of a philosophy of science that considers theory, practice and the world simultaneously, and never in isolation from each other' (Ankeny et al. [2011], p. 304). Most philosophy of science in practice is philosophy 'on' science.[1] Experimental philosophy is characterized by the use of 'experimental methods traditionally associated with psychology and cognitive science' (Knobe and Nichols [2017]). Most experimental philosophy treats philosophical problems with experimental methods, rather than

[1] For example, 'philosophers do not necessarily collaborate with scientists, but use empirical methods drawn from the historical or social sciences (such as archival research, ethnographies or interviews) to acquire insights into and evidence of scientists' research behavior' (Boumans and Leonelli [2013], p. 260).

scientific problems with philosophical tools. The meaning of PinS is not, therefore, immediately captured by these sister trends in philosophy of science.

It does not seem appropriate to rely on intuitions or preconceived ideas alone to determine which people or articles belong to PinS, because there is a high risk of disputes focusing purely on the meaning of 'producing scientific knowledge with philosophical tools', given certain conceptions of philosophy and science. Instead, we need an empirical and philosophically unbiased method to detect a corpus of likely PinS authors and papers, which we can use to characterize more precisely the nature of PinS. We reasoned that philosophers aiming to address scientific problems and to provide scientifically useful proposals would attempt to establish a dialogue with scientists, and that even minimal success in this endeavour would probably have led to their work being published, cited, or explicitly mentioned as contributive by scientists in scientific journals (intervention, visibility, and contribution, respectively, collectively constituting 'permeation'). We propose the use of bibliometric tools and qualitative analysis of citation to identify our corpus of interest on the basis of these three measurable criteria. We do not use bibliometrics for evaluative or sociological purposes, to learn something about an already well-identified object: philosophy of science (Wray [2010]; Weingart [2015]; Wray and Bornmann [2015]; McLevey et al. [2018]; Pence and Ramsey [2018]; Malaterre et al. [2019]; Khelfaoui et al. [2021]; Plaisance et al. [2021]). Instead, we use bibliometrics for investigating philosophically the unique achievements in a subset of philosophy of science. This bibliometric method is as imperfect as any other detection strategy for the definition of this field, so we consider it essential to combine it with a second, philosophical stage. As discussed below, it is possible, but extremely unlikely, that our detection method generates false negatives: papers raising a scientific problem and offering a scientific proposal that have never attracted the interest of scientists and have never been cited, even once, by scientists. By contrast, our method seems to generate a large number of false positives, that is, papers published in scientific journals, and/or cited in scientific journals, and/or considered to constitute significant scientific contributions that do not meet the definition of PinS as the use of philosophical tools to produce scientific knowledge. For this reason, the second stage of our analysis consists of a sort of 'reflective equilibrium': we use the *a priori* definition above to filter out the papers of the corpus identified by bibliometrics that do not really correspond to PinS. Conversely, we obtain a much more precise characterization of PinS by analysing the content of many papers that have succeeded in raising scientific problems and using philosophical tools to propose a solution to these problems.

In other words, we adopt a two-stage method. The first stage is detection (we use bibliometrics to identify a corpus *a posteriori*), and the second stage is definition (we apply qualitative, *a priori*, criteria to select some genuinely PinS papers among those identified in the first stage, and we arrive at a much more precise description of PinS). We define 'permeating through science' as the traceable presence, via bibliometrics, of philosophers in scientific journals, and 'participating in science' as the production of scientific knowledge. Permeation is not a necessary condition for participation; rather, it is the best external criterion for detecting the presence of PinS in an immense set of texts.

This article demonstrates that PinS is a distinctive, significant trend within philosophy of science. Our argumentation is structured as follows: In section 2, we present intervention, visibility, and contribution as three ways for philosophers to permeate through science. Sections 3–5, corresponding to the detection stage, examine these elements in detail. Sections 6–8 go beyond the limitations of our detection method and provide a philosophical analysis of features specific to PinS. In the conclusion, we discuss the status of PinS as a well-identified community of philosophers, texts, and methods, and draw the consequences of the existence of PinS on interactions between philosophy and science.

This article should be of interest to all philosophers of science reflecting on dialogue with the sciences. Even if some readers object to the bibliometric analysis, we hope to show that it is instrumental for our demonstration. All the technical bibliometric discussions appear in the appendix; experts in bibliometrics will find a note with the full description of our methodology in the online supplementary material for this article.

2. Key Concepts for the Detection of a Philosophy in Science Corpus: Intervention, Visibility, and Contribution

'Permeating through science' may mean different things to different philosophers of science: participating at science conferences, discussing a scientific point with scientists, joining a scientific society, or publishing papers in scientific journals. The last of these activities would undoubtedly be seen by scientists as the most significant. As sociologists of science have shown, publishing papers in peer-reviewed journals is at the heart of scientific activity and constitutes the principal route to becoming a member of the scientific community and gaining scientific recognition (Hagstrom [1965]). Moreover, philosophers of science intending to use philosophical tools to produce scientific knowledge are likely to try to establish a dialogue with scientists by publishing in scientific journals. We define 'intervention' as the act of publishing a paper in a scientific journal.

We define 'visibility' as the citation, in a scientific paper, of a paper written by a philosopher of science. It is, of course, possible for philosophers to be visible in science without actually publishing in scientific journals or being cited by scientists. Plato, Kant, and Schopenhauer were once visible in physics, and Popper and Kuhn are visible in fields in which they have not published. However, this visibility is often non-specific, and difficult to measure at the level of a whole scientific community. We overcome this problem here by using quantitative citation analysis. We define visibility operationally as the level of citation of the works of philosophers of science in scientific journals, for the papers they have published in both science and philosophy of science journals. It seems likely that philosophers using philosophical tools to produce scientific knowledge will be cited at least once in a scientific journal if they are at least minimally successful.

An analysis of citation contexts showed that across all domains, many of the citations are perfunctory rather than substantial: they do not explicitly draw on the content of the cited paper, and are therefore rather hollow (Moravcsik and Murugesan [1975]). It may be that the citations of philosophy of science papers by scientists are generally of this type, and perhaps a sceptic will think that they are all of this type. We therefore used a third notion, contribution, to measure the magnitude of the impact of a given philosophy of science paper within science. We define 'contribution' as the explicit and substantial recognition, by scientists, that a philosophical work advances science. Unlike the first two notions, which are quantitative, contribution is a qualitative notion based on an analysis of citation context. Contribution is a subset of visibility, because a paper that is never cited in scientific journals cannot be considered a scientific contribution. The contribution criterion is the most demanding, as few papers written by philosophers are likely to be explicitly acknowledged by scientists as significant scientific contributions. So, this criterion is likely to exclude many genuine PinS papers (that is, to generate false negatives). However, its consideration is crucial, because it constitutes the highest level of achievement for philosophers of science intending to permeate through science, and would constitute a major objection to the existence of PinS if no scientific citations to papers written by philosophers of science were substantial rather than perfunctory.

Both philosophers and their papers can qualify as interventionist, visible, or contributive. Intervention is binary, while visibility and contribution come in degrees.

As shown in figure 1, a visible philosophical paper is not necessarily an intervention. Papers published in philosophy of science journals rather than in scientific journals (that is, 'non-interventionist' papers) can be cited in scientific journals. A philosophical contribution to science is not necessarily interventionist either, as non-interventionist papers can contribute to science. Below, we provide a more detailed description of intervention, visibility, and contribution, and an examination of the features unique to PinS.

3. Intervention

Is there a distinctive group of philosophers of science who permeate through science? A first, albeit imperfect, sign would be that such a group would be likely to publish in science journals.

We identified philosophers of science as individuals who had published at least two papers in 17 journals specializing in philosophy of science, between 1977 and 2017. Crucially, to prevent biases, we excluded all non-peer-reviewed items and philosophy of science articles written by professional scientists. A detailed description of our methodology, including an explanation of why we adopted an extensive

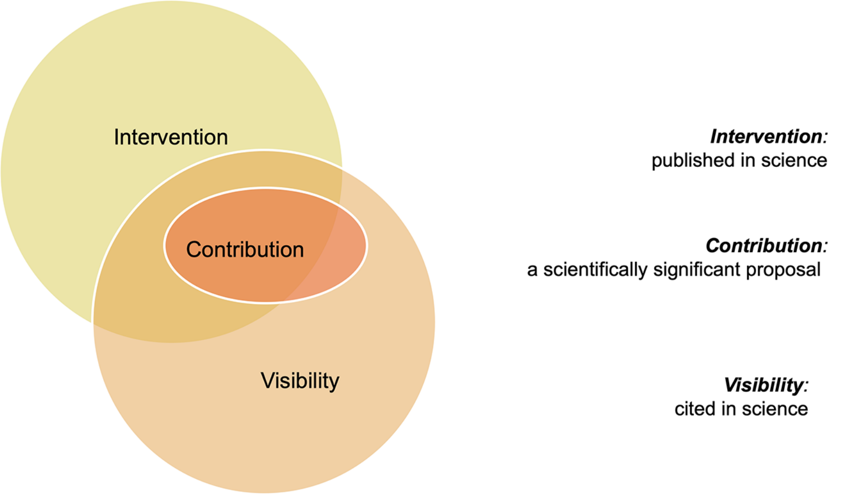

Figure 1. Definition and intersection of three different ways in which philosophers of science can permeate through science.

definition of 'professional scientists' to avoid overestimating PinS, is provided in appendix A.1.

We first considered the 100 most cited philosophers of science in philosophy of science journals between 1977 and 2018.[2] We investigated how many of these philosophers had published peer-reviewed articles in scientific journals: 78 had done so at least once, 58 at least twice, 29 at least five times, and 22 had never done so. On average, these 100 philosophers had published 4.25 papers in scientific journals, and 14.5 papers in philosophy of science. The highly interventionist philosophers identified in this list included Butterfield and Redei (17 papers each published in scientific journals), Redhead and Glymour (14 each), Schurz (12), Sober, Godfrey-Smith, and Moreno (11 each). However, what matters here (as in our other bibliometric analysis) is not individuals concerned, but the general trend. A significant minority of these 100 philosophers have frequently published in scientific journals. Nevertheless, the ratio of papers published by these philosophers in scientific journals relative to philosophy of science journals (0.29 on average) clearly indicates that the intellectual activities of these central figures of philosophy of science remain firmly focused on their own field.

We then identified highly interventionist philosophers of science, defined as those who had published at least five papers in scientific journals between 1977 and 2017. We identified 101 such philosophers of science. The majority (71) of these highly

2 These philosophers are the most cited in our list of 17 journals for their papers published in the same list of 17 journals. Our timeframe for cited references is 1977–2017, while our timeframe for citing references is 1977–2018. This one-year difference allows us to count citations to the papers published in 2017.

interventionist philosophers were not among the 100 most highly cited philosophers of science described above. On average, these philosophers had published 11.5 papers in scientific journals and 10.2 in philosophy of science journals. Strikingly, 56 had published at least as many papers in science journals as in philosophy of science journals. Extreme examples include Barry Smith (26 times as many papers in scientific journals as in philosophy journals) and Jerome Wakefield (12.5 times as many papers in scientific journals). The mean ratio in this group of 101 philosophers was 1.75, contrasting with the value reported above (0.29), and suggesting that there is, indeed, a subset of philosophers of science for whom publishing in scientific journals is a major aim, to which a large fraction of their research time is devoted. Thus, being part of a scientific community by intervening in science is an important output for a large and distinctive set of philosophers of science, most of whom are not highly cited in philosophy of science journals.

4. Visibility

One sign that a distinct group of philosophers of science participate in solving scientific problems is the citation of their articles by scientists. Citation alone is not enough, but philosophers who are not cited by scientists are unlikely to participate in a meaningful way in science.

We performed a citation analysis to determine the extent to which different groups of philosophers are cited in science, first, for their articles in philosophy of science journals, and then for their articles in scientific journals. The absolute number of citations is not an appropriate measurement, because citation practices vary considerably between domains, rendering inter-domain comparisons meaningless. Instead, we focused on two proportions. We first considered the proportion of citations in scientific and philosophy of science journals obtained by philosophers of science for their articles published in philosophy of science. We then compared the mean number of citations obtained by philosophers for their articles published in journals of a given scientific discipline, relative to the mean number of citations in that discipline in general. This made it possible to determine whether philosophers of science intervening in a given scientific domain were cited more or less frequently than typical scientists from the domain concerned.

How frequently are papers published in philosophy of science journals cited in scientific journals? We distinguished four categories of philosophers of science (table 1):

- highly interventionist in science and highly cited in philosophy of science;
- highly interventionist in science but not highly cited in philosophy of science;
- not very interventionist but highly cited in philosophy of science;
- neither very interventionist in science nor highly cited in philosophy of science.

Table 1. Mean percentage of citations of philosophy of science papers in scientific and philosophy of scientific journals, by author category. The sum is less than 100%, because these papers are also cited in the social sciences and humanities (including general philosophy).

Author category	Number of philosophers	Mean percentage of citations in philosophy of science journals	Mean percentage of citations in scientific journals
Highly interventionist in science and highly cited in philosophy of science	29	47.2	21.7
Highly interventionist in science and not highly cited in philosophy of science	73	36.5	27.6
Not very interventionist but highly cited in philosophy of science	49	50.2	14.3
Neither very interventionist in science nor highly cited in philosophy of science	Sample of 200 from several thousand	41.1	14.9

By construction, this fourth category groups together the vast majority of philosophers of science (several thousand). Therefore, the descriptions 'not very interventionist in science' and 'not highly cited in philosophy of science' should not be interpreted too literally: many philosophers of science in this category have published in scientific journals and/or are cited in philosophy of science journals, but not enough to be considered among the most interventionist or the most visible. Tracking the citations of all philosophers in this category would require manual curation of thousands of articles potentially written by homonyms. We therefore randomly selected 200 philosophers from the 1,000 most cited philosophers of this category.

Table 1 shows that, on average, articles in philosophy of science journals:

- get a higher proportion of citations in scientific journals when their authors are highly interventionist (24.6%) (combining rows 1 and 2) rather than not highly interventionist (14.6%);
- are not proportionally more cited in science when their authors are highly cited in philosophy of science (18%) (combining rows 1 and 3) rather than not highly cited in philosophy of science (21.25%);
- are more cited in scientific journals when their authors are highly interventionist but not highly cited in philosophy of science (27.6%) rather than highly interventionist and highly cited in philosophy of science (21.7%).

This suggests the existence of a group, among philosophers of science publishing in canonical journals, for which publishing in scientific journals is an active choice,

Table 2. Mean average ratio of citations (ARC) for papers published in scientific journals by philosophers of science from four categories.

Author category	Number of authors	Mean ARC in science journals
Highly interventionist in science and highly cited in philosophy of science	29	0.63
Highly interventionist in science and not highly cited in philosophy of science	73	0.64
Not very interventionist and highly cited in philosophy of science	49	0.39
Neither very interventionist in science nor highly cited in philosophy of science	200	0.31

rewarding in terms of number of citations in science, independent of their number of citations in philosophy of science.

We then assessed the visibility philosophers obtain for their articles published in scientific journals, relative to that of scientists. We used the field/year-normalized average ratio of citations (ARC).[3] An ARC in science of 1.00 means that a philosopher's papers published in a given scientific domain and a given year receive the same number of citations as the average for scientists active in the domain concerned, for papers published in the same year; values of 1.25 or 0.75 means that they receive 25% more or fewer citations, respectively, than the average scientist in the same domain.

Table 2 shows that, unsurprisingly, articles published in scientific journals by philosophers generally result in less visibility for the philosophers than for scientists in the scientific field concerned. Visibility was higher for philosophers who intervened frequently. The visibility of philosophers who intervened frequently but were not highly cited in philosophy of science was similar to that of philosophers who were highly cited and intervened frequently.

Together, the results shown in tables 1–2 support the hypothesis that highly interventionist philosophers of science have a hybrid philosopher-scientist profile. Their ARC in science is two-thirds what it would be if they were scientists, whether or not they are frequently cited in philosophy of science journals.

We will now turn our attention away from the philosophers, to their articles. We focused on 229 of the most visible papers (defined by an ARC in scientific journals greater than or equal to 0.1 and an absolute number of citations in scientific journals greater than or equal to 20) published by philosophers of science in

[3] The ARC makes it possible to make inter-domain comparisons; so, it is not useful to give an ARC for citations within philosophy of science exclusively.

scientific journals. The mean ARC in scientific journals for these 229 papers was 2.19, indicating that, on average, these papers obtained more than twice the number of citations obtained by scientific papers in the same scientific domain published the same year. Appendix A.2 gives the 38 papers (of the 229) with an ARC in scientific journals of three or more. A handful of these papers even had an ARC greater than or equal to ten (Fine [1982]; Oreskes et al. [1994]; Laland et al. [2015]). (These papers should be considered extreme examples, not typical of the visibility of philosophers in science.)

Half of the highly visible articles in scientific journals are authored by highly interventionist philosophers not highly cited in philosophy of science, confirming the hypothesis that they constitute a distinctive group of philosophers.[4] Highly interventionist philosophers of science not only form a specific subgroup within philosophy of science, but their level of visibility in the scientific discipline in which they intervene suggests that they are also part of the corresponding scientific community. Philosophers of science who both intervene in science and are visible in scientific journals seem to bridge the gap between philosophy of science and science, with training in philosophy but a more significant publication activity in science than in philosophy. As this activity is mostly invisible in philosophy of science journals, it is vastly underestimated, although it may prove to be a highly significant part of philosophy of science. A crucial question is now to determine whether scientists who cite these philosophical papers published in science journals consider at least some of them to be contributive to science itself.

5. Contribution

A paper written by a philosopher may be visible without bringing something really new to a scientific domain. A third criterion for detecting science permeation is the paper being a scientific contribution, that is, being acknowledged by scientists as a significant advancement of their field. As opposed to the previous quantitative bibliometric criteria, what we call 'contribution' here is classically assessed through qualitative citation analysis, exploring papers on a one-by-one basis with a particular

[4] Physics is the discipline in which philosophers have intervened the most, with the lowest impact (338 papers; ARC in science 0.41). Biology is the discipline in which they have intervened most efficiently (253 papers; ARC in science 0.84). The other disciplines in which they have mostly intervened are computer sciences (ARC = 0.49), mathematics (ARC = 0.70), and medicine (ARC = 0.81). Philosophy of mind, psychology, cognitive science, and philosophy of the social sciences have been mostly omitted from our results; they deserve special treatment and require a different bibliometric approach. Many authors in these domains are interventionist and visible, typically, Dennett (Dennett [1978]; McKay and Dennett [2009]) and Fodor (Fodor [1983]; Fodor and Pylyshyn [1988]); on this, see (Thagard [2009]). Some papers in philosophy of the social sciences have been published in social science journals and have been visible; an example is the work of Dietrich and List (for example, [2007]), providing detailed proof that, contrary to the received view, Arrowian preference aggregation is a special case of judgement aggregation, rather than the converse. We have used a dozen examples from these fields to check that the rest of our argumentation is consistent with most of these works, at least for those published in scientific journals.

attention to the scientific context of the paper (Moravcsik and Murugesan [1975]; criteria in appendix A.3).

In science, most citations are known to be perfunctory. There is no reason to think that PinS is different. Conversely, some citations in science are substantive and reveal a genuine contribution to a scientific field. The questions are (1) whether this can happen with PinS papers, (2) whether the level of contribution can be significant, and (3) what the nature of the contribution is. Of course, a paper may constitute a genuine scientific achievement without being recognized as such by the scientific community. Conversely, it is likely to exclude genuine scientific achievements simply because they have not been recognized as such. Nevertheless, it provides the best evidence that certain papers by philosophers have really contributed to science. As a result of an inquiry, we have established a preliminary list of papers by philosophers that were likely to be contributive, then checked that they were according to specific criteria (length, accuracy, non-redundancy, and so on), and finally retained only the most significant (level of contribution) (see appendix A.3).

Contribution is a very exacting criterion. Sceptics might think that papers written by philosophers are never contributions in this sense. Yet some papers written by philosophers provide an indisputable scientific contribution, as demonstrated by the following major examples. These examples illustrate three main ways that philosophers of science have made scientific contributions: by producing novel scientific results (including theorems and observations), producing novel scientific tools, or by participating in a scientific debate.

Some philosophers produce novel scientific results. This is rare but compelling. For example, Malament ([1977]), by generalizing a result due to (Hawking et al. [1976]), formulated a theorem, widely used in quantum gravity, especially in the causal set theory approach (Surya [2019]). This theorem, often referred to as the 'Hawking–King–McCarthy–Malament theorem' (Bombelli and Meyer [1989]; García-Parrado and Senovilla [2005]; Surya [2019]), states that the causal structure determines the topology, differential structure, and conformal geometry of a future and past distinguishing causal space-time. This explains why Malament, whose work was driven by philosophical considerations about the connections between time and causality, is regularly cited together with Hawking, and is specifically recognized as having made an important contribution to physics. Some physicists, especially the more experimentally oriented, do not see theorems as typical products of physics. Yet, there is no doubt that theorems are a typical scientific product in theoretical physics, accounting for the appearance of Malament's work in widely used theoretical physics textbooks (for example, Isham [1989]) and in recent reviews of quantum gravity by leading physicists (Oriti [2009]). Another important example is provided by the work of Shimony in quantum mechanics. Replying to Einstein, Podolsky, and Rosen, Bell showed, in 1965, the disagreement between quantum mechanics and local realistic theories. Building on the crucial work of Clauser and colleagues ([1969]), Clauser and Shimony ([1978]) showed that Bell's results could be extended to actual systems and discussed the experiments that they and others proposed for testing this hypothesis. They concluded that either the realism held by most working scientists should be abandoned, or that a drastic revision of our space-time concept was required.

Other philosophers have made observations or performed experiments, another prototypic scientific product. Such philosophers have contributed to the establishment of facts, something generally unexpected from philosophers. Wakefield (Wakefield et al. [2007]) provides an interesting example. Wakefield showed in a retrospective epidemiological study that uncomplicated grief and complicated grief present with the same symptoms, but that the former reaction gives a lower score than the latter on all measurement scales. They concluded that the 'bereavement exclusion', according to which all bereaved individuals should be excluded from a diagnosis of major depression, should not be abandoned, but rather extended to any form of significant loss. The results were accepted by the community, but the conclusion drawn has been a matter of debate among prominent psychiatrists, some siding with Wakefield (Belmaker and Agam [2008]), and others opposing him (Kendler et al. [2008]). Wakefield's view did not prevail, but his contribution is visible in the current definition of major depressive disorder (American Psychiatric Association [2013], p. 5).

A second category is the production of fruitful scientific tools. Not all the tools proposed by philosophers can be considered scientific contributions, only those that are successful, that is, adopted by scientists and used to generate novel scientific results. Two sets of tools are examined here: methodologies and conceptual tools. Philosophers can propose new scientific methodologies, or improve existing methodologies. An important example here is Smith's role in the development of biomedical ontologies. For example, one of his major goals was to explicate the broad ontological category of 'relation' (Smith et al. [2005]). Various ontologies use relational terms ('is_a', 'part_of', and so on), without explicit, compatible, or even consistent definitions. The paper proposed distinguishing relations between classes, between instances, and between a class and an instance, on the one hand, and distinguishing between 'continuants' and 'processes', on the other. A list of relations followed, designed to be both sufficiently intuitive and maximally compatible with existing ontologies. The clearest confirmation of the scientific importance of this proposition is its integration into the Open Biological and Biomedical Ontologies Foundry project, and its use in practice (Mungall and Emmert [2007]; Courtot et al. [2011]; Carbon et al. [2019]). The Chemical Entities of Biological Interest ontology has amended its 'ambiguous and incorrect usage of the relationships "is a" and "is part of"' (de Matos et al. [2010], p. D251) in light of Smith's work (Smith et al. [2005]).

In addition to methodologies, philosophers can provide conceptual tools. It would be absurd to consider all of the almost infinite instances of conceptual analysis proposed by philosophers of science as scientific contributions. However, whenever a new conceptual framework proposed by philosophers is used by scientists to generate novel scientific results, it should be considered a scientific contribution. Many examples exist across the subdomains of philosophy of science. One particularly productive area is philosophy of evolutionary biology, as highlighted by many biologists (for example, Orzack [2012]). Two examples are provided by the contributions of Hull and Sober. Integrated into the biological community to the point of being elected president of the Society for Systematic Biology, Hull saw his work as continuous with science (Callebaut [1993], pp. 201, 215; Hull [2001]). For instance, he proposed clarifying the debate over 'units of selection' by adopting a novel and empirically neutral vocabulary: 'replicators' and 'interactors' (Hull [1980]). This distinction (differing from Dawkins's distinction between 'replicators' and 'vehicles'; Hull [1994]) was instrumental in revealing that the scientific debate over units of selection had, in part, been a pseudo-debate, in which scientists frequently used words to mean different things. The utility of this distinction is attested by many supportive comments from biologists. For example, Gould and Lloyd ([1999], p. 11905) stressed that 'Hull's important distinction between replicators and interactors helped to clarify conceptual and empirical issues at the center of debates about units of selection'. Szathmáry and Maynard Smith ([1997]) explicitly used Hull's definitions to develop their own classification of different types of replicators.

Another important example of conceptual clarification is Sober's work with evolutionist Wilson (Wilson and Sober [1989]). Together, they proposed a reexamination of the long-standing debate in evolutionary biology about the possibility of natural selection acting at the level of groups and 'superorganisms'. They proposed that 'superorganisms', defined as collections of single creatures in which between-unit selection overwhelms within-unit selection, are not only logically possible, but really exist in nature. This proposal has been widely used and discussed in the scientific literature, particularly by biologists interested in testing whether this definition of a superorganism works for particular species (for example, Ratnieks and Reeve [1992]). In another study, Szathmáry and Maynard Smith ([1995]) used their framework directly to make a novel scientific contribution, extensively citing Wilson and Sober's criteria for superorganismality and applying them to a different issue, namely, explaining the origins of a novel cohesive group in evolution.

The third category is participation in a scientific debate, which does not generate immediate scientific results, either directly or indirectly, but is nonetheless recognized as useful by scientists. Churchland's 'neurophilosophy' defends a neurobiological approach to questions relating to cognition. Neurophilosophy did not launch this now dominant approach in contemporary neuroscience, but it participated in it by eliminating philosophical obstacles, such as the belief that the brain does not think. Her methodological articles were published in prestigious journals (Churchland and Sejnowski [1988]), and major neuroscientists have thanked Churchland for preliminary discussions on some of their papers (Craig [2009]).

A radical take on the contribution of philosophers to science involves the use of a counterfactual approach, asking: would this scientific field have been different without this contribution? Obviously, only a few contributions have radically changed the scientific field, but this is also true for most papers published by scientists. 'Game-changers' are rare in science, but some of the examples of papers written by philosophers examined above would probably qualify (for example, Malament [1977]).

Defining and assessing 'scientific contribution' is difficult and partly subjective (see appendix A.3), and not all philosophical work cited by scientists can be considered as scientific contributions. The aim of this section was to demonstrate that, despite such obstacles, there are examples of philosophical work that unequivocally qualify as scientific contributions. Importantly, it also sketches what kind of results of a philosophical analysis scientists may accept as a contribution.

6. Detection versus Definition of Philosophy in Science Papers

As stated in the introduction, our aim is to identify and characterize PinS, understood as the activity by which philosophers of science address a scientific problem and use philosophical tools to make a scientifically useful proposal. The investigation above (sections 2–5) is a preliminary detection, constituting only the first stage towards this identification. It offers an empirical approximation of the extension of the set of possible PinS authors and papers, focusing on the work of philosophers of science who publish in scientific journals, are cited in scientific journals, or make scientific contributions (referred to as 'permeating through science'). However, this method can miss papers that raise a scientific problem and use philosophical tools to make a scientifically useful proposal, but are not published in scientific journals, cited in such journals, or considered contributive (false negatives), and it can include papers that are published and/or cited in scientific journals and/or are considered contributive but that do not actually address a scientific problem nor use philosophical tools to make a scientifically useful proposal (false positives).

Our method is highly unlikely to generate many false negatives, because if a paper attempts to establish a dialogue with science, its failure to meet at least one of our conditions for permeation (published in scientific journals, cited in scientific journals, considered a contribution) would be a clear sign that it missed its target. Such 'PinS sleeping beauties' may exist but, again, it seems unlikely.

By contrast, false positives are a major challenge. There is no reason to assume that all the papers permeating through science address a scientific problem and use philosophical tools to make a scientifically useful proposal. In particular, there is no reason to assume that they have a strong philosophical content: perhaps the papers published by philosophers of science in scientific journals, cited in scientific journals, and/or considered contributive are so close to science that their philosophical dimension is weak, or even non-existent.

A second stage of analysis, centred on a philosophical rather than bibliometric approach, is therefore necessary to establish which papers and authors constitute PinS.

The following three elements are essential for inclusion in PinS: addressing a scientific problem, using philosophical tools, and making a scientific proposal. We now use these elements as criteria and apply them to some of the papers identified in sections 2–5, to identify genuine instances of PinS.

Section 7 establishes a PinS corpus composed of a significant number of papers that both permeate through science (that is, meet at least one of the criteria of intervention, visibility, and contribution) and include the three elements of PinS. Section 8 shows that it is these three elements that render PinS unique within the domain of philosophy of science. We conclude that PinS does indeed exist as a distinctive and important, albeit largely invisible to date, trend in philosophy of science.

7. The Three Elements Essential to Philosophy in Science

The present section describes the three elements essential to a PinS paper based on a sample of significant examples, then provides quantitative evidence that there are many more than these few examples.

7.1. First element: Addressing a scientific problem

PinS papers address a scientific problem, that is, a problem that scientists of a given field themselves can address with their usual methods. Not many philosophers address scientific problems. Intuitively, it might be thought that philosophers cannot address such problems, but this is exactly what the practice of PinS contradicts. Column 2 of table 3 shows a list of problems addressed by PinS papers, across different domains.

Certain permeating papers, despite their publication and/or citation in scientific journals, do not address a scientific problem. Some use science to shed light on a traditional philosophical problem, for example, self (Churchland [2002]) or morality (Churchland [2008]). Others raise paradigmatic problems of general philosophy of science, similar to those traditionally found in philosophy of science journals (for example, about models, theories, or explanations), albeit in a manner attractive to scientists. For instance, some papers published in scientific journals, even by notoriously interventionist philosophers of science, raise general questions about science (Hull [1996]). By contrast, Churchland and Winkielman ([2012]), for example, investigated whether oxytocin modulates social cognition, and Hull ([1980]) investigated the scientific question of units of selection.

7.2. Second element: Using philosophical tools

The second key element of PinS is the use of philosophical tools to address the scientific problem in an original manner. Without philosophy, there can be no PinS. Obviously, not all papers published and/or cited in scientific journals have a strong

Table 3. An analytical list of paradigmatic examples of philosophy in science (PinS) papers. These papers include the three key elements of the process. For each paper, column 2 describes the specific question addressed, column 3 describes the main tool type, and column 4 describes the specific scientific proposal and its type (in bold typeface).

Article	Scientific Problem (2)	Main Philosophical Tool (3)	Scientific Proposal (4)
(Clarke et al. [2014])	Is evidence of a mechanism between treatment and better outcome a low form of evidence?	**Questioning a claim.** Questions the received method advocated by evidence-based medicine on the ground of views on evidence of causality	**Method.** Specific methodological guidelines are proposed to assess evidence of the effectiveness of a treatment in light of evidence of mechanisms
(Clauser and Shimony [1978])	Following Bell's theorem, should we say that either the thesis of realism or that of locality must be abandoned?	**Questioning consistency.** Checks the consistency between realism and different theoretical and experimental approaches inspired by Bell's theorem	**Experiment.** Extends previous work about Bell's theorem, and proposes new experiments to test it
(Craver et al. [2014])	Is risk aversion in decision-making a consequence of anticipated regret?	**Combination of scientific domains.** Combines a debate in decision theory and economics with neurosciences to make the claim testable	**Experiment.** A test on a person with hippocampal lesions incapable of anticipating regret shows that this person takes risk-aversive decisions, thereby challenging the view that risk aversion is a consequence of anticipated regret
(Feferman [1984])	Are usual solutions to some semantic and mathematical paradoxes (like the liar's paradox), including hierarchies of levels and theories of types, overly constraining?	**Proposing a distinction.** Distinguishes between useful type-free theories and merely logical solution by a thorough, comparative analysis of semantic and mathematical paradoxes	**Demonstration.** A demonstration that type-free, but useful, theories are possible
(Heywood and Redhead [1983])	Can locality be reconciled with realism in quantum mechanics?	**Proposing a definition.** Defines and distinguishes two commonly confused types of contextuality, ontological and environmental	**Demonstration.** Proposes a novel demonstration: any local realism leads to a Kochen–Specker type of contradiction, which connects the results of Kochen–Specker to those of Bell

(Laland et al. [2011])	Should two types of causes (proximal and ultimate) be distinguished in biology?	**Questioning a claim.** Questions Mayr's distinction between proximal and ultimate causes, based on recent work on evo-devo, niche construction, and other domains	**Method.** Biologists must consider the influence of developmental aspects on evolutionary processes, and more generally be open to processes of reciprocal causation
(Mayo and Spanos [2006])	Where should probability enter in inductive inference in science?	**Rooting a scientific problem in a context.** An analysis of the historical and philosophical context of traditional statistical tools reveals three approaches to the significance test: behavioristic, inferential, and degrees of belief	**Concept.** A fourth approach to the significance test is proposed, according to which it is interpreted by the concept of the degree of severity of the test
(Oreskes et al. [1994])	Are claims of validity and verity of numerical models in the earth sciences legitimate?	**Proposing definitions.** A conceptual analysis of 'validation' and 'verification'	**Method.** The justification of models should not be understood in terms of validation or verification, but only in terms of degrees of confirmation and relative to specific observational data and specific hypotheses
(Schaffner [1993])	How should the causal efficacy of medical treatments be assessed?	**Proposing a distinction.** Reveals a discrepancy between the notion of a 'cause' used by most biomedical scientists and the notion of a 'cause' used by epidemiologists	**Concept.** Proposes a unified concept of 'clinical causation' that helps interpret correctly the actual information provided by a randomized trial as an approximation to causal effects at the individual level
(Skyrms and Pemantle [2000])	How to model dynamic social interactions (that is, social interactions that change over time via reinforcement, punishment, and so on)?	**Proposing a combination.** Combines different scientific domains, namely, the social sciences, philosophy, evolutionary biology, and mathematics	**Model.** Proposes a new model of structure dynamics
(Wilson and Sober [1989])	Can group selection exist, and can natural selection act at the level of superorganisms?	**Questioning consistency.** Shows an inconsistency in the dominant idea that the organism can be a unit of selection, whereas the group cannot	**Hypothesis.** Provides a precise and testable hypothesis about selection occurring at the level of superorganisms, illustrated by examples and the suggestion of a novel experiment (to test community-level selection in the laboratory)

philosophical content. We have already mentioned Suppes's parallel activities. Philosopher-scientist Calcott's participation in the work of Lanfear et al. ([2012]) is purely scientific (personal communication, 20 May 2019), whereas many of his other contributions, concerning the relationship between biology and engineering (Calcott et al. [2015]), for example, are as philosophical as they are scientific. We propose that papers should be considered to include this second element if, and only if, they use some of the traditional tools of philosophy (conceptual analysis, attention to the 'big picture', metaphysical distinctions, and so on), using them to address a scientific problem.

Our investigation reveals that a significant number of permeating papers achieve just that. In other words, PinS papers do not cease to be philosophical because they are also scientific. This investigation also inductively reveals the types of philosophical tools crucial for PinS. They include:

- investigating and/or proposing a scientific definition or distinction;
- rooting a scientific problem in its broadest philosophical or historical context;
- questioning the consistency of a set of claims made in a scientific field;
- questioning methods on the grounds of broader views on methodological concepts;
- questioning a scientific claim;
- proposing a combination of scientific domains.

This should be considered as a working hypothesis based on the confrontation of the list provided by Laplane et al. ([2019]) to many more examples. These tools are not intended to define philosophy of science, but only to detect its presence. The list is non-exhaustive, as other tools may be added to the list; moreover, it is not entirely specific to philosophy of science, as scientists may also resort to them, albeit less frequently and less thoroughly. Column 3 of table 3 lists selected examples of successful uses of these philosophical tools in PinS articles. The philosophical dimension is not highly visible in all PinS papers, but the key point is that it is never entirely absent.

7.3. Third element: Making a scientific proposal

The third key element of PinS is making a scientific proposal to solve at least a part of the scientific problem identified in element 1, and necessarily via the philosophical tools used in element 2. If, in addition, a scientific proposal from philosophers of science happens to be accepted as useful by scientists, then it becomes a contribution (as defined above), but this is not a necessary condition for achieving element 3. This element concerns the making of a scientific proposal, not the recognition of this proposal, by scientists, as a significant contribution.

Many permeating papers do not include this third element, even if they include the first two elements. There are numerous examples in philosophy of statistics of illuminating concepts that are simply not developed to the point of being immediately operational, although they could be rendered operational in principle (for example, Cartwright's notion of 'stable capacity'; Cartwright and Munro [2010]).

However, a significant number of permeating papers do include this element (column 4 of table 3). They propose new ideas to scientists under the guise of new theories, concepts, observations, and so on, which scientists can discuss, test, endorse, or reject. For example, Clifton et al. ([2003]) played a key role in the development of an information-based approach to quantum theory, whereas other philosophers, as we have seen, suggested new demonstrations (Fine [1982]) or new theorems (Malament [1977]). It is very rare for philosophers to propose new experiments, but even that is not entirely unheard of. For example, Shimony participated in the formulation of novel experimental programmes for testing Bell's theorem (Clauser et al. [1969]; Clauser and Shimony [1978]). A handful of philosophers have been involved directly in novel experimental work (Lenski et al. [2003]; Gazave et al. [2013]; Craver et al. [2014]). Appendix A.4 provides other examples of papers making scientific proposals.

Establishing that a significant number of papers include these three elements is necessary to justify the existence of a PinS trend within philosophy of science. The inquiry described in appendix A.4 resulted in 177 PinS articles. To be sure, there are many more, including among non-interventionist and less visible papers, but these numbers are sufficient to establish the existence of a significant trend.

8. How Does Philosophy in Science Differ from the Rest of Philosophy of Science?

It is not straightforward to determine what makes PinS distinctive within philosophy of science. Treating a question that matters to scientists with philosophical tools and hoping for the result to have an impact is, after all, quite common.

First, most papers in philosophy of science do not raise a scientific problem, that is, a problem that scientists can address with the methods usually used in their field. For example, most papers about explanation, causality, or modelling raise problems that are too general to be considered by scientists as problems that must be addressed scientifically, such as whether theories can be reduced to 'families of models', in line with the semantic view of scientific theories (Morrison [2007])? By contrast, PinS begins with a deliberate restriction to questions that can be addressed scientifically. Much of contemporary philosophy of science is scientifically informed and, in the case of philosophy of the special sciences, can be highly specialized; but being scientifically informed is not the same as addressing a scientific problem.

General philosophy of science uses traditional philosophical tools as much as PinS does. However, whereas in philosophy of science the philosophical treatment of a question is naturally developed in its own right (that is, articulated with alternative philosophical proposals, fully explicit, and sometimes even an object of discussion itself), PinS papers are often less connected to philosophical tradition and more focused on the applicability of the proposed solution.

Finally, philosophy of science papers do not generally develop a scientific proposal, and if there is one, it generally remains implicit and potential.[5] Consider the example of theories. Most papers on theories do not propose a new model or theory. Instead, they discuss theories suggested by others, which is undeniably useful but does not constitute a scientific proposal, strictly speaking. Historically inclined papers about past theories are archetypal here (Norton [1993]), but discussions of present-day competing theory interpretations (Popper [1967]) or theoretical frameworks (for example, Rubin [2018]) are similar. Many of these papers raise a scientific problem and use philosophical tools, but they do not include the third element, because they do not push their discussion far enough for it to become a scientific proposal. By contrast, it is essential to PinS that the solution to a problem is sufficiently developed and explicit.

We have shown above that PinS is clearly different from the rest of philosophy of science. A majority of philosophy of science papers illustrate what we called 'philosophy on science', that is, their aim is to contribute to our knowledge of the methods, concepts, objects, and problems of science, and/or to address philosophical problems using lessons taken from science. This aim is essential and legitimate, but it clearly differs from the aim of PinS (fig. 2). An interesting case here is philosophy of science in practice, a major emerging trend in recent philosophy of science, which it is instructive to compare with PinS. Dupré distinguished between 'philosophy of science-in-practice' and 'philosophy-of-science in practice'. Most of philosophy of science in practice is philosophy on science. An example is provided by the work of Leonelli and Ankeny ([2012], [2015]) on the emergence of scientific communities around model organisms and databases. How these communities emerge and what constitutes them is typically not a question that these communities try to address in their scientific work, although it is a major philosophical question that cannot be raised fruitfully without scientific competence. On the contrary, philosophy-of-science in practice is characterized by 'philosophy directly engaged with scientific research through interaction with scientists about philosophical problems' (Boumans and Leonelli [2013], p. 259). A good example of philosophy-of-science in practice is provided in (O'Malley and Dupré [2005]), because this paper constituted an intervention in the then emerging field of systems biology and proposed useful avenues for further research. One way to define PinS would be to say that it is a subset of philosophy-of-science in practice with a specific goal: participating in the solution of a scientific problem.

Once PinS has been defined and established as a trend in philosophy in science, further features of interest will emerge. On the basis of our detailed analysis of this corpus, we provide three. First, in PinS papers, philosophers see scientists, rather than philosophers of science, as their most direct 'peers' (that is, the people to whom they talk and who will judge the value of their work). This is demonstrated by the fact that in almost

[5] There are, of course, exceptions. For example, the work of Price ([1997], [2012]) on time irreversibility and retrocausality, although published in philosophy of science journals and books, provides a novel understanding of the concept of time, and this proposal has been discussed by leading physicists, for example, Rovelli ([2018]).

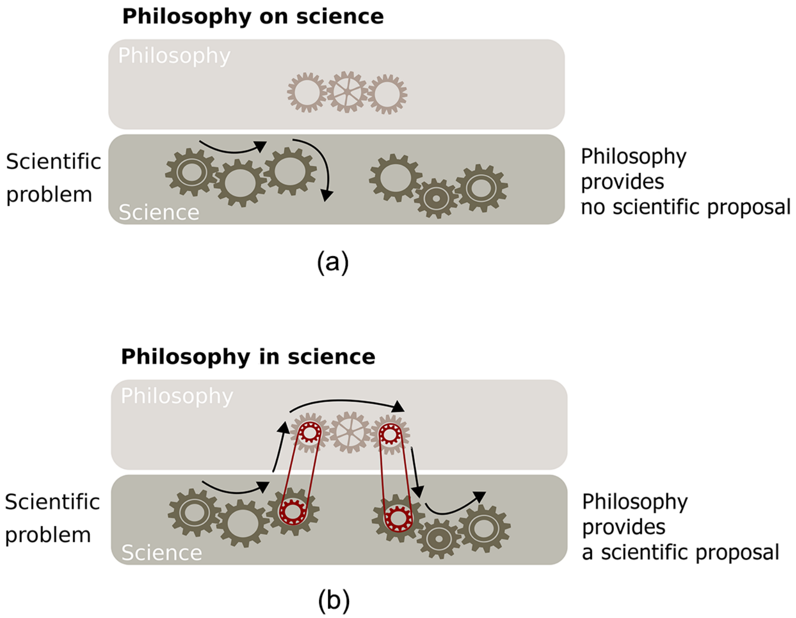

Figure 2. While philosophy on science does not contribute to solve a scientific problem, philosophy in science does.

all the examples analysed, more than 75% of the cited references related to scientific articles rather than to philosophy articles. Similarly, many PinS papers discuss and/or criticize in depth one precise scientific claim (a theory, an empirical hypothesis, an approach, and so on). In addition, 66% of PinS papers are co-authored by philosophers and scientists. Some PinS papers connect the scientific problem to a central question of the philosophical tradition, for example, realism/anti-realism or the definition of individuality, and many PinS papers use general philosophy of science but very few remain at that level, suggesting overall that to generate scientific results, it is indispensable to dive into a specific scientific field. Second, the main philosophical tool in PinS papers seems to be conceptual analysis in the empirical sciences, but not in more formalized sciences, such as logic, statistics, or some domains of philosophy of physics or philosophy of social science. Third, most proposals by philosophers are conceptual tools or participations in scientific debates. Some are methodological proposals. Very few are scientific results. Most articles with an extensive scientific content (experiments, typically) have a short philosophical development, and vice versa.

9. Conclusion

A crucial and long-standing question for philosophers of science (Callebaut [1993]; Chang [1999]; Hull [2001]; Laplane et al. [2019]; De Haro [2020]; Khelfaoui et al. [2021]) and some scientists (Weinberg [1992]; Pigliucci [2008]; Hawking [2010];

Orzack [2012]; Rovelli [2018]) is how philosophy of science relates to science, including, in particular, its possible impact on science. Various important ways in which philosophy of science can have an impact on science have been documented in the past, from the influence of Mach, Poincaré, and Schopenhauer on the development of the theory of relativity (Rovelli [2018]) to Popper's long-recognized influence on scientists, such as Eccles and Medawar,[6] and some recent reflections on how best to organize science institutionally (for example, Leonelli [2017]). Here, we identify and describe an approach that we propose to call PinS, which adds another, in our view essential, layer to this picture.

By combining quantitative and qualitative tools, we demonstrate the existence of a corpus of articles by philosophers of science, either published in philosophy of science journals or in scientific journals, raising scientific problems and aiming to contribute to their resolution via the use of philosophical tools. PinS constitutes a subdomain of philosophy of science, which has a long history, with canonical texts and authors, but, to our knowledge, this is the first time this domain is delineated and analysed.

Now that the main features of PinS have been analysed, a promising avenue for future research will be to use further bibliometric or text mining tools (for example, Pence and Ramsey [2018]; Malaterre et al. [2019]) to reach a finer characterization of PinS. Importantly, successful text mining requires a rigorous ontology, which, for PinS, could be based on the kind of qualitative analysis provided here.

The description we propose is closer to the view that philosophy and science belong to a continuum than to the view that they are different activities. Like most of the defenders of the view of a philosophy–science continuum (Frank [1957]; Suppes [1979], [1990]; Callebaut [1993]; Chang [1999]; Hull [2001]) and most of those who have recognized that philosophers of science sometimes participate in science (Suppes [1954], [1990]; Chang [1999], [2011]), we consider that there are clusters of activities that are typical of what philosophers do and others typical of what scientists do (Laplane et al. [2019]). For various reasons—from training background to peers' expectations and time investment—experimental design and model building, for example, seem to be typical practices of scientists only sometimes used by philosophers; whereas conceptual analysis and cross-domain comparisons, for example, are typical practices of philosophers only sometimes used by scientists.[7]

Do philosophers in science constitute a 'community' within philosophy of science? Assuming that this would require a sense of belonging grounded in shared problems, methods, classic texts, and institutional markers, such as journals, societies, and conferences (Hagstrom [1965]), our analysis suggests that there is not yet a PinS community. PinS is thematically scattered, to almost the same extent as the scientific domains in which it intervenes. This probably explains why PinS has remained largely invisible

[6] For a critical examination of Popper's influence on scientists, see (Mulkay and Gilbert [1981]).

[7] Many scientists, including very influential ones, use some tools of the philosophical toolbox described above (for example, Mayr and Lewontin in biology, Rovelli in physics). What matters for our argument is that the majority of scientists do not use such tools in most of their daily research activities.

at the level of the philosophy of science community as a whole. By making PinS more visible and describing its common features, this article may contribute to the emergence of a self-conscious community of philosophers in science.

This group clearly contains scientists, especially those who are philosophically inclined and have collaborated with philosophers, as illustrated by many of the examples discussed in this article, and as explained in appendix A.1. The reason for which scientists were excluded from our analysis of the 'permeation' of science (sections 2–5) is a pragmatic one, as their inclusion would have led to an overestimation of the number of papers published and cited in scientific journals.

Finally, the existence of PinS demonstrates that philosophy of science plays a role in the construction of our knowledge of the world. Philosophers of science can use philosophical tools to contribute to the specific knowledge of a given part of the world, that is, to the construction of a local scientific image (Van Fraassen [1980]; Guay and Pradeu [2020]). When engaged in PinS, philosophers of science contribute to the special ontology of a given science (asking, for example, 'should we admit superorganisms to our ontology of the living world?'). Distinctively, philosophers in science do not content themselves with putting together the local images of the world built by scientists, but instead participate in the building of those images. This activity and others confirm the main conclusion of this article, that some philosophers of science not only talk about science, but produce scientific knowledge.

Appendix

A.1. Basic bibliometric definitions used in this article

To measure the number of publications by and citations to philosophers of science, we used the Web of Science (WoS) reference database (more specifically, the WoS Core collection), for the period 1977–2017. Queries were made through a SQL relational database hosted by the Observatoire des Sciences et des Technologies, generally updated once a year by data from Clarivate Analytics. Excel tables were generated according to specific queries. We cannot make the micro data public because the Observatoire des Sciences et des Technologies is bound by a legal contract with Clarivate Analytics forbidding such distribution from the WoS. Of note, the WoS is not a perfect reflection of scientific production, but for our purposes, it is safe to assume that it is representative.

A.1.1. Paper types

We excluded all non-peer-reviewed items, such as editorials, comments, replies, letters to the editor, book reviews, obituaries, vulgarization, and educational documents, so as not to overestimate the intervention, visibility, and contribution of philosophers.

A.1.2. Definition of philosopher of science publishing in science journals

The WoS does not categorize authors according to their specialty. It is not, therefore, straightforward to generate a list of philosophers who have published in scientific journals. We first generated a list of 32,468 articles by 1,569 unique authors with at least two publications in philosophy of science journals and two in scientific journals. We then manually excluded (1) scientists who have published in philosophy of science journals, and (2) homonyms (that is, scientists with the same names as philosophers).

We stipulated that two conditions had to be jointly met for an author to be a philosopher of science in the bibliometric sense:

- an author of at least two papers on our list of papers published in 17 journals specializing in philosophy of science;
- a person holding a PhD in the domain of philosophy and/or working in a philosophy department.

The second condition was used to avoid overestimating PinS's weight. For example, Rob Knight, an eminent biologist, has published four papers in philosophy of science journals, and 18 of his scientific papers have been cited more than 1,000 times. Including him and other scientists with a similar profile (Mayr, Lewontin, Kendler, Rovelli, and so on) would have led to an overestimation of the impact of philosophy of science on science. We therefore excluded all the papers such scientists published in science journals or philosophy of science journals, except when they were co-authored with philosophers of science in the above sense.

The downside is that many such scientists have published significant philosophical contributions in philosophy of science or in science journals (for example, Mayr [1969]; Good [1983]), and that many philosophers in science are both philosophers and scientists. These individuals include people with two successive careers in science and philosophy (for example, Alfred Tauber, Massimo Pigliucci), and people who have two simultaneous careers in these two domains (for example, Brett Calcott, Dennis Dieks, Peter Gärdenfors, Eva Jablonka, Sahotra Sarkar). Here again we applied a stringent rule: for those who, in addition to a scientific career, hold a PhD in philosophy and/or work in a philosophy department, we kept their papers published in science journals only if that had an explicit philosophical content (for example, Clauser and Shimony [1978]).

A.1.3. List of journals in philosophy of science

The WoS has a 'history and philosophy of science' (HPS) category for classifying journals, but it was not suitable for direct use here, as WoS categories are non-exclusive: a given paper can appear, for instance, as both a HPS paper and a philosophy paper. We overcame this problem by constructing a list of 17 philosophy of science journals (table 4).

Table 4. List of 17 philosophy of science journals.

Philosophy of science journal name	Time period covered
Biology and Philosophy	1988–2017
British Journal for the Philosophy of Science	1956–2017
Erkenntnis	2000–2017
European Journal for Philosophy of Science	2011–2017
Foundations of Science	2008–2017
History and Philosophy of the Life Sciences	1988–2017
Hyle	2005–2017
International Studies in the Philosophy of Science	2010–2017
Journal for General Philosophy of Science	2008–2017
Journal of Medicine and Philosophy	1976–2017
Medicine Health Care and Philosophy	2008–2017
Philosophy of Science	1956–2017
Studies in History and Philosophy of Science	1974–2017
Studies in History and Philosophy of Modern Physics	1998–2017
Studies in History and Philosophy of Biological and Biomedical Sciences	1998–2017
Synthese	1966–2017
Theoretical Medicine and Bioethics	1998–2017

Arguably, philosophy of science articles are also published in more generalist philosophy journals, such as the *Journal of Philosophy*, and, most importantly, in philosophy books and edited volumes. Citations from books are not included in the WoS database and are, thus, not considered in our analysis. However, the list of 17 journals includes the most central journals in philosophy of science, making it possible to define a community representative of the field (Khelfaoui et al. [2021]). It is very unlikely that a philosopher of science who has published a visible monograph or paper in a general philosophy journal between 1977 and 2017 would not also have published in a philosophy of science journal. Finally, it has been shown that the ranking of the most cited philosophers obtained in a database of book citations, the Book Citation Index, is strongly correlated with the ranking obtained using the WoS (Gingras and Khelfaoui [2019]).

Another potential objection to our list is that it includes contributions in domains other than philosophy of science, such as ethics and the history of science. As a means of addressing this problem and avoiding overestimation, we manually removed all articles in ethics or history of science that did not have a strong philosophy of science dimension.

An important practical limitation to our work was that *Studies C*, a central journal in philosophy of biology and philosophy of medicine, is not included in the WoS database of publications. However, crucially, this journal is in the database of cited journals, so our results include all citations to papers published in this journal. We felt that the inclusion of *Studies C* was essential. We therefore used a supplementary table to incorporate the articles published in this journal.

A.1.4. What counts as a scientific journal?

'Scientific journals' are defined here in the sense of the National Science Foundation, covering biology, biomedical sciences, chemistry, engineering, earth science, mathematics, medicine, and physics. This classification was used in the regular publication of the Science and Engineering Indicators.[8]

A.2. Papers published by philosophers of science in scientific journals with the highest average ratio of citations in science

Table 5. Papers published by philosophers of science in scientific journals with the highest average ratio of citations (ARC) in science (≥3).

Name	Name of philosopher(s) involved	Specialty	Discipline	No. of citations in science journals	ARC in science journals
(Fine [1982])	Fine	General Physics	Physics	427	15.81
(Oreskes et al. [1994])	Shrader-Frechette	Earth and Planetary Science	Earth and Atmospheric Science	1,167	10.91
(Laland et al. [2015])	Sterelny	General Biology	Biology	97	10.78
(Pacheco et al. [2009])	Skyrms	Probability and Statistics	Mathematics	108	7.71
(Vogeley et al. [2001])	Newen	Neurology and Neurosurgery	Neuroscience	394	7.58
(Kaptchuk et al. [2010])	Miller	General and Internal Medicine	Medicine	206	7.10
(Churchland and Winkielman [2012])	Churchland	Neurology and Neurosurgery	Neuroscience	123	6.15
(Lenski et al. [2003])	Pennock	General Biology	Biology	232	6.11
(Regan et al. [2002])	Colyvan	Ecology	Biology	313	5.91
(Peterson et al. [2009])	Dietrich	General Biology	Biology	129	4.96
(Skyrms and Pemantle [2000])	Skyrms	Probability and Statistics	Mathematics	125	4.63
(Fine [1982])	Fine	General Physics	Physics	123	4.56

[8] Available at <ncses.nsf.gov/indicators>.

Table 5. (*Continued*)

Name	Name of philosopher(s) involved	Specialty	Discipline	No. of citations in science journals	ARC in science journals
(Hull [1980])	Hull	Ecology	Biology	195	4.53
(Nahum et al. [2015])	Godfrey-Smith	General Zoology	Biology	26	4.33
(Colloca and Miller [2011])	Miller	Psychiatry	Psychiatry	103	4.29
(Laland et al. [2011])	Sterelny	General Biology	Biology	94	4.27
(Smith et al. [2005])	Smith	Genetics and Heredity	Biology	229	4.24
(Pollock [1992])	Pollock	Computers	Computers	71	4.18
(He et al. [2014])	Smith	Applied Mathematics	Mathematics	29	4.14
(Pitowsky [1991])	Pitowsky	Applied Mathematics	Mathematics	77	3.85
(Heywood and Redhead [1983])	Redhead	General Physics	Physics	96	3.84
(Hirst et al. [2014])	Howick	General and Internal Medicine	Medicine	56	3.73
(Hull [1979])	Hull	General Zoology	Biology	67	3.72
(Winther [2001])	Winther	General Zoology	Biology	69	3.63
(Clifton et al. [2003])	Clifton; Bub; Halvorson	General Physics	Physics	83	3.61
(Bernstein et al. [1984])	Byerly	General Biology	Biology	54	3.60
(Beatty [1982])	Beatty	General Zoology	Biology	57	3.35
(Brigandt and Love [2012])	Brigandt; Love	General Zoology	Biology	23	3.29
(Bernstein et al. [1985])	Byerly	Genetics and Heredity	Biology	134	3.19
(Hansson [1994])	Hansson	General Mathematics	Mathematics	38	3.17
(Malament [1977])	Malament	General Physics	Physics	76	3.17
(Samadi and Barberousse [2006])	Barberousse	General Zoology	Biology	43	3.07
(Ramsey et al. [2010])	Glymour	Neurology and Neurosurgery	Neuroscience	98	3.06
(Smith [1996])	Smith	Computers	Computers	60	3.00

Table 5. (*Continued*)

Name	Name of philosopher(s) involved	Specialty	Discipline	No. of citations in science journals	ARC in science journals
(Fetzer [1988])	Fetzer	Computers	Computers	54	3.00
(Fine [1985])	Fine	General Mathematics	Mathematics	42	3.00
(Burgansky-Eliash et al. [2005])	Glymour	Ophthalmology	Medicine	78	3.00
(Badziąg et al. [2009])	Pitowsky	General Physics	Physics	60	3.00

A.3. How to define and assess a scientific contribution?

Contribution is more difficult to characterize and is more subjective than intervention and visibility. We therefore started with an operational, if limited, approach to contribution. First, contribution is a subset of visibility: no article can be contributive if it has not been cited in a scientific journal. Notwithstanding the difference between contribution and visibility, an article is more likely to be a scientific contribution if it is cited by articles themselves highly cited in this domain. Second, based on (Moravcsik and Murugesan [1975]), we considered a paper to constitute a contribution if its citation in scientific papers was qualitatively ‘rich’:

- Long: The reference to the paper is somewhat developed.
- Non-redundant: The paper is cited on its own (not together with other papers).
- Accurate: The citation is not erroneous in terms of the content of the paper.
- Precise: The citation is not vague, but developed with some detail.
- Determinate: The citation is not neutral or indifferent, but accepts or rejects a claim made by the paper.
- Operational: The citing paper uses results from the cited paper.

None of these criteria were considered necessary or sufficient, but the more of these criteria satisfied to a significant degree by the paper, the more contributive it is likely to be. Conversely, papers not fulfilling these criteria may nevertheless be contributions. In many fields, the usual way that scientific papers are cited does not fulfil these criteria, but they are nevertheless contributive. Some papers may be so central and obviously contributive that they are no longer even cited. Our strategy here, however, was designed to eliminate false positives and borderline cases, which would overestimate the number of contributions or the degree of contribution.

Figure 3 shows how we used the above criteria in the articles mentioned in section 5. These articles were chosen by crossing information on (1) visibility in science,

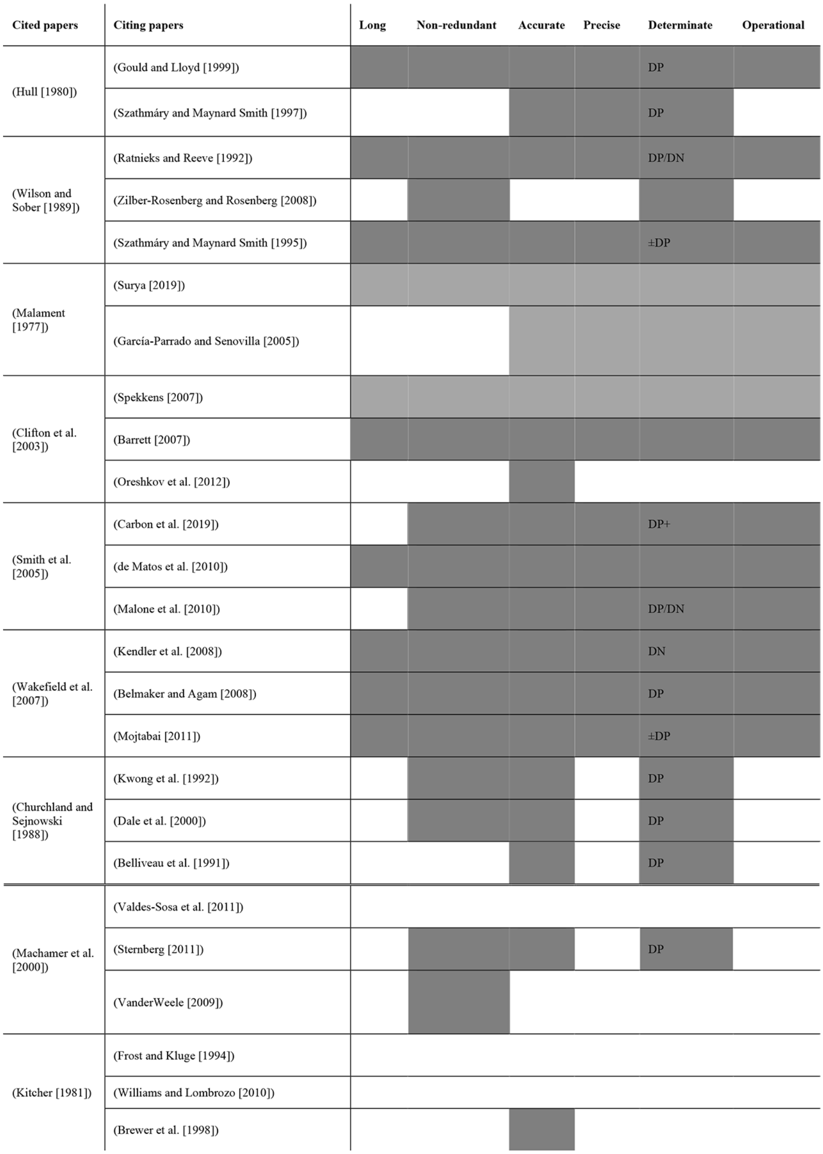

Figure 3. Substantial versus perfunctory citations by scientists to papers written by philosophers of science. ‘DP’ = determinate positive; ‘DN’ = determinate negative. Sources: (Malament [1977]; Hull [1980]; Kitcher [1981]; Churchland and Sejnowski [1988]; Wilson and Sober [1989]; Belliveau et al. [1991]; Kwong et al. [1992]; Ratnieks and Reeve [1992]; Frost and Kluge [1994]; Szathmáry and Maynard Smith [1995], [1997]; Brewer et al. [1998]; Gould and Lloyd [1999]; Dale et al. [2000]; Machamer et al. [2000]; Clifton et al. [2003]; García-Parrado and Senovilla [2005]; Smith et al. [2005]; Barrett [2007]; Spekkens [2007]; Wakefield et al. [2007]; Belmaker and Agam [2008]; Kendler et al. [2008]; Zilber-Rosenberg and Rosenberg [2008]; VanderWeele [2009]; de Matos et al. [2010]; Malone et al. [2010]; Williams and Lombrozo [2010]; Mojtabai [2011]; Sternberg [2011]; Valdes-Sosa et al. [2011]; Oreshkov et al. [2012]; Carbon et al. [2019]; Surya [2019]).

Table 6. Examples of papers fulfilling the three-element condition of philosophy in science (PinS), by category of scientific proposal.

Type of Proposal		Detailed Examples	Other Examples
Results	Experiments	Shimony contributed to the formulation of novel experimental programmes for testing Bell's theorem (Clauser et al. [1969]; Clauser and Shimony [1978]) (Kaptchuk et al. [2010]) is a clinical trial showing that the placebo effect can be obtained even in patients who were told that the substance they were given is not active	(Kwan et al. [2012]) (Wakefield et al. [2007]) (Lenski et al. [2003]) (Nahum et al. [2015]) (Batali and Kitcher [1995])
	Theories	(Clifton et al. [2003]) develops an information-based approach to quantum theory	(Thagard et al. [1990]) (Benci et al. [2013]) (Pollock [1992]) (Smith [1996]) (Malament [1977]) (Bernstein et al. [1984]) (Peterson et al. [2009]) (Bouchard [2011]) (Pacheco et al. [2009]) (Page and Mitchell [1998])
	Demonstrations	(Suppes and Zanotti [1981]) establishes two theorems and a corollary on how to establish that two-valued variables have a common cause, based on Suppes's probabilistic theory of causality	(Fine [1982]) (Greenberger et al. [1990]) (Halvorson [2004]) (Badziąg et al. [2009])
Tools	Methodologies	(Cartwright and Munro [2010]) limits the area of relevance for randomized clinical trials based on the proposed concept of 'capacity' Based on what a justification is, (Koellner [2009]) determines which axioms are justified in lim-	(Churchland and Sejnowski [1988]) (Howick et al. [2009]) (Parnas et al. [2005])

Table 6. (*Continued*)

Type of Proposal		Detailed Examples	Other Examples
		iting the undecidability of some statements in set theories (Griffiths et al. [2015]) proposes a method to quantitatively measure causal specificity in different biological contexts, including DNA coding	(Parkkinen et al. [2018]) (Smith et al. [2005]) (He et al. [2014])
	Conceptual tools	(Ladyman et al. [2013]) reviews features widely associated with complex systems (non-linearity, feedback, and so on), demonstrates that some are neither necessary nor sufficient, while others must be excluded because of their vagueness; it also proposes its own list of necessary conditions and show how those could foster future work (Shimony [1995]) offers not only a conceptual analysis of entanglement in quantum mechanics, but also an approach for quantifying the degree of entanglement (Godfrey-Smith [2015]) provides a novel analysis of the concept of reproduction in evolutionary biology (by distinguishing three types of reproduction: 'simple', 'collective', 'scaffolded'), shedding light on highly diverse of biological examples (Bernat et al. [1981]) distinguishes between a definition and a criterion of death, establishing that total and irreversible loss of functioning of the whole brain should be the criterion of death and give the corresponding definition of death	(Wakefield [1992]) (Cleland and Chyba [2002]) (Ruiz-Mirazo et al. [2004]) (Brigandt [2003]) (Brigandt and Love [2012]) (Hull [1978]) (Hull [1980]) (Gould and Lloyd [1999]) (Winther [2001]) (Regan et al. [2002]) (Samadi and Barberousse [2006]) (O'Malley and Dupré [2005]) (Grünbaum [1986]) (Kitcher [1984])
Debates		(Sarkar [2000]) and (Griffiths [2001]) critique the then-influential view among biologists that genes contain 'information' (for example, Maynard Smith [2000]) (Beatty [1982]) shows that pattern cladistics, largely inspired by a naive 'Popperian' philosophy of	(Worrall [2002]) (Churchland and Winkielman [2012]) (Fetzer [1988]) (Hull [1979]) (Gilbert et al. [2012])

Table 6. (*Continued*)

Type of Proposal	Detailed Examples	Other Examples
	science, is at odds with evolutionary thinking and creates many conceptual confusions (Vandenbroucke et al. [2016]) phrases the presuppositions of the dominant 'restricted potential outcome approach' to causality and highlights its shortcomings	(Gilbert and Sarkar [2000]) (Mameli and Bateson [2006]) (Bapteste et al. [2009])

(2) informal inquiry among specialists in philosophy of science of what the most contributive papers are according to them, and (3) most interventionist philosophers. Two of us (Pradeu, Lemoine) then established a preliminary list, independently applied the criteria above to them and kept only papers they agreed on, saw to it that the major subfields of PinS were represented, then retrieved this list of very significantly contributive articles.

A.4. Examples of papers fulfilling the three-element condition of philosophy in science, by category of scientific proposal

Two of us (Pradeu, Lemoine) independently established a preliminary list of 229 papers with ARC in science greater than or equal to one by coding the presence of each of the three conditions that define PinS independently from the list of philosophical tools mentioned in section 7. They removed articles where they could not agree after independent assessment, then discussion, either that a scientific problem or solution was provided, or that a specific philosophical tool was used. A total of 136 met these criteria according to both reviewers, that is, 59%. Cross-checked with the 76 references of table 6 (minus books and articles by scientists), the total is a list of 163 PinS papers (provided in the online supplementary material). Although far from being exhaustive, this list confirms that PinS constitutes a trend in philosophy of science.

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