The Diffusion of Scientific Innovations: Arguments for an Integrated Approach

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Abstract

Although the diffusion of scientific innovations has been studied for a long time and in various disciplines, little work has been done to integrate findings into a larger framework. In this essay, we offer an integrated approach to studying how scientific innovations spread within and across preexisting and newly emerging research fields. Drawing on 'sociology of science,' 'philosophy of science,' and 'history of science,' we develop a framework that captures how scientific innovations are modified in the process of their adoption. This framework allows to specify conditions under which scientific innovations diffuse and to characterize the process of diffusion. We argue that the time is ripe for such an integrated view and suggest future lines of research for developing it further.

INTRODUCTION

Innovations are at the heart of scientific inquiry. Developing new ideas is a necessary precondition for scientific progress and engaging with them critically is a constitutive element of scholarly activity. However, not every novel idea is ultimately adopted in science. Some ideas spread rapidly, widely, and over long periods of time, both within and across a broad range of contexts (Herfeld & Doehne, 2018). Other ideas lay dormant for a long time before they are taken up or are never broadly recognized at all (Ke, Ferrara, Radicchi, & Flammini, 2015). Sometimes, competing formulations of effectively the same idea result in one being taken up while the other is not (Hegselmann, 2017). These observations raise interesting questions about the defining characteristics of scientific innovations, the conditions under which they diffuse, and the diffusion processes.

The diffusion of innovative ideas in science has been addressed prominently in the 'sociology of science,' 'philosophy of science,' and 'history of

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science'. As the theoretical frameworks used in these fields differ substantially, the benefits of integrating findings across disciplines (or lack thereof) have been a matter of recurrent debates, albeit with differing emphases (Riesch, 2014). While philosophers of science have long focused on rational reconstructions and on justificatory issues involved in adopting novel theories in science, while historians of science have highlighted the contingencies involved in the adoption of new ideas, and sociologists of science have focused on social contexts of knowledge production. While sociologists have acknowledged the benefits of theoretical frameworks for studying science, alongside historians, they have generally dismissed purely conceptual approaches in favor of empirical case studies and analyses (Merton, 1973). In this essay, we argue that one important step toward improving our understanding of the diffusion of scientific innovation is to systematically integrate relevant research findings into a systematic framework. As we observe a confluence in the use of new methodologies across these three disciplines, we propose that it is time to recalibrate, and where appropriate. Relax, disciplinary boundaries when studying the diffusion of novel ideas in science.

In the following sections, we develop this argument in detail. We begin by offering a definition of scientific innovation, which highlights that new theories are modified as they spread within and across preexisting and newly forming fields of academic inquiry. Then, we outline a general account of the diffusion of scientific innovations that focuses on, (i) how new scientific ideas, once formulated, are adopted, and (ii) how novel ideas are thereby integrated into the larger body of knowledge that they become part of. Third, we discuss reasons why historians-, philosophers-, and sociologists of science might welcome a methodologically integrated approach. We conclude with an outlook of how studies of the diffusion of scientific innovations could be developed further in each of the three disciplines.

SCIENTIFIC INNOVATIONS

While a large literature is concerned with scientific innovations, a clear and agreed-upon definition of scientific innovation is missing. Arguably, inflationary use has stripped the concept of "innovation" of much of its substance (Godin, 2015). It is unclear at the outset what counts as an innovative idea or what characterizes an innovative research program. Oftentimes, scientific innovations are not conceptually distinguished from scientific discoveries, inventions in science, new scientific theories, research programs, or paradigms, and newly produced knowledge more generally. This mixes up very distinct endeavors in science. Finally, it is unsatisfactory that philosophers of science, who tackle conceptual questions about the adoption of new theories or the nature of scientific discovery, rarely specify what they mean by a scientific innovation at all (Sturm, forthcoming).

To develop a definition of "scientific innovation," it is instructive to first consider the literature on innovation more generally. Everett Rogers famously defined innovation as "an idea, practice, or object that is perceived as new by an individual or other unit of adoption" (Rogers, 2003 [1962], p. 11). In Rogers view, for something to be an innovation, it must be adopted. This aspect is particularly important in science, where new ideas can lie dormant for a long time before their importance is recognized (Ke *et al.,* 2015). Rogers defines diffusion as a process in which an innovation is communicated among the members of a social system and over time (Rogers, 2003 [1962]). In the same way, novel ideas in science diffuse within and across existing and newly forming communities of scientists and in a social and institutional context within which knowledge is produced.

While Rogers' general definition captures characteristics that are relevant to the diffusion of scientific innovations, it treats the innovation itself as a good whose essential properties remain unchanged in the diffusion process. However, this fails to characterize scientific innovations. Most scientists will consider new ideas—be they innovative theories or models, techniques, instruments, or concepts—only insofar as those ideas relate to their preexisting knowledge base and they can perceive their relevance for problems in their respective fields (Latour, 1987). The adoption of an innovative contribution depends crucially upon its potential of doing so. In its original formulation, a novel idea will often be applicable to some but not necessarily many problems. For it to spread widely and across research fields, a scientific innovation must, therefore, undergo various processes of modification and, sometimes, transformation (see Merz, 2018 for discussions of various accounts). As an inherent part of the diffusion process, a scientific innovation is elaborated upon and clarified in ways that render it applicable to distinct problems in different domains.

The modification of scientific innovations is particularly important in light of another, closely related observation. For a novel scientific idea to be adopted, it must overcome what Kuhn (1977b [1959]) has described as an "essential tension." This essential tension arises from the fact that scientific innovations must be novel on the one hand but must also align with and connect to previous research on the other. Scientists engage with, and adopt, a scientific innovation when it fits not only with accepted epistemic and methodological standards of the field but also with at least parts of the conceptual and theoretical toolbox used in their discipline. As Foster, Rzhetsky, and Evans (2015) have pointed out, this essential tension underlies well-known dichotomies in philosophy- and sociology of science. While sociologists of science have identified tensions between 'succession' and 'subversion' (Bourdieu, 1975) or 'relevance' and 'originality' (Whitley, 2000), philosophers of science have considered tensions between 'conformity' and 'dissent' (Polanyi, 1969) or 'exploration' and 'exploitation' (Thoma, 2015; Weisberg & Muldoon, 2009).

Scientific innovations resolve the essential tension by being modified in ways that fit with the established concepts, theoretical frameworks, and practices of the respective field while preserving their novelty (Kuhn, 1977b [1959]). As epistemic standards, theoretical frameworks, core concepts, and scientific practices vary across fields, the diffusion of scientific innovations demands context-specific modifications. As the problems that a scientific innovation is applied to will vary across fields, many variants of the original innovation can emerge. While each originates in the same innovation, these variants will differ in significant respects. By undertaking such modifications, scientists engaging with the innovation bridge the gap between novelty and alignment in ways that are compatible with their discipline's demands.

Against this background, our basic contention is that studies of the diffusion of scientific innovations must capture these conceptual modifications and how they shape and reconfigure possibilities for subsequent adoptions. While sociologists-, philosophers-, and historians of science have studied scientific innovations and their diffusion, their methodologies seldom account for such conceptual modification processes. Instead, sociologists of science have emphasized how social context, scholarly networks, and institutional conditions affect processes of knowledge diffusion and knowledge production (Kronegger, Mali, Anuška, & Patrick, 2011; Merton, 1973; Whitley, Gläser, & Laudel, 2018), how different institutional contexts shape their diffusion (Abbott, 2001; Crane, 1972), and condition the scientist's choice between high-risk and conservative research strategies (Foster *et al.*, 2015). Historians of science have studied scientific innovations in detailed case studies to highlight the circumstances in which so-called revolutions or fundamental disciplinary changes occurred, such as from Newtonian mechanics to Einstein's relativity theory, or the Darwinian revolution (Godin, 2015; Kuhn, 1962). And philosophers of science have devoted themselves to explicating concepts, studying the logic of scientific inquiry and scientific discovery (Schickore 2018), the nature of scientific progress (Niiniluoto, 2017), rational theory choice and theory change (Kuhn, 1977a; Okasha, 2011), and conditions under which science is a rational enterprise. Rarely, however, have these fields unified their results, let alone have they focused on how the elements they each highlight separately shape the conceptual modifications that are prerequisites for the diffusion of scientific innovations.

AN INTEGRATED APPROACH TO THE DIFFUSION OF SCIENTIFIC INNOVATIONS

We propose an account of scientific innovations that integrates methodological and conceptual findings from philosophy-, sociology-, and history of science. This framework accounts for the modification of the scientific innovation in the process of its diffusion by constructing a network representation of the process outcome. We illustrate this framework by drawing on a study of the early diffusion of Rational Choice Theories (RCT) within and across the social and behavioral sciences (Herfeld & Doehne, 2018). The framework allows tracing the diffusion of scientific innovations across fields and systematically examining the conditions for their diffusion. We take this approach to exemplify how a methodological and conceptual integration can be mutually beneficial for the three disciplines in the study of scientific innovations.

We take up the idea from innovation studies and the sociology of science that innovations spread within social networks and that the relevant actors occupy different roles in such processes (Coleman, Katz, & Menzel, 1966; Rogers, 2003 [1962]; Valente, 1995). We, furthermore, ground our analysis empirically by drawing upon quantitative network analysis. Combining a quantitative method with a historical case study allows for an empirically rich yet systematic study to subsequently generalize from one case to other cases and draw conceptual conclusions that are of interest for philosophical and sociological accounts of scientific innovations alike.

Overcoming Kuhn's essential tension involves a step-wise process of engaging with the novel scientific idea. In the process, scientists and their contributions take on different roles, depending on the type of modifications they undertake in the diffusion process. The proposed framework distinguishes three modification stages that a newly formulated idea undergoes in the diffusion process. These are *elaboration*, *translation*, and *specialization*. Each stage requires the skills of different types of researchers, and each stage brings forth different types of publications. In total, we distinguish four roles that research contributions can occupy in the diffusion process: innovator, elaborator, translator, or specialist. Each contribution plays a distinct but essential role in facilitating the adoption of the scientific innovation. Figure 1 offers a schematic representation of the diffusion process.

First, there is the novel idea itself, the scientific innovation. To identify it, a precise understanding of the (historical) context is needed in which it was first formulated. The benefit of hindsight and the fact that the innovation is by definition adopted in subsequent research facilitates this first step of the analysis. In our case study of the early spread of RCT, for example, we identified John von Neumann's and Oskar Morgenstern's seminal *Theory of Games and Economic Behavior* (1944) as containing the set

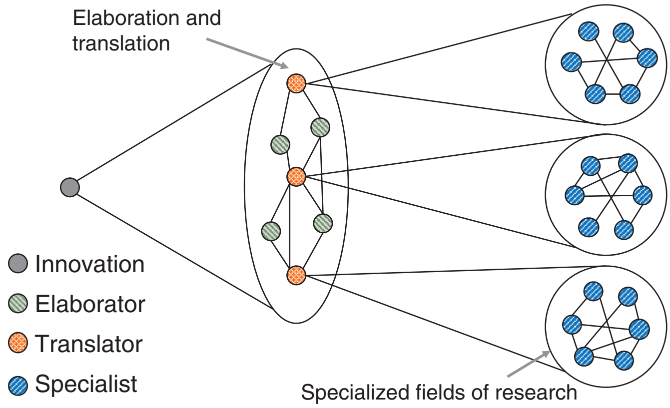

Figure 1 Schematic representation of the different modification steps that a scientific innovation undergoes in its diffusion process.

of novel ideas. The *Theory of Games* contained two innovative contributions to theories of rational decision-making: (i) an axiomatic representation of the long-standing principle of expected utility and (ii) the minimax theorem as a "rule" for rational action in situations of strategic uncertainty. Both contributions were conceptually novel in that they represented human behavior by a set of formal techniques taken from mathematical logic, probability theory, axiomatic set theory, and topology. Nowadays, RCT are used in a large number of disciplines and have been integrated into a variety of social scientific approaches to study individual and social behavior.

An important step in the diffusion of the scientific innovation is its elaboration in ways that develop its conceptual, theoretical, and/or empirical usefulness. At the outset, only a few scientists start engaging with the innovation in its initial formulation. Their primary task is to elaborate the idea's potentials. *Elaborator* contributions clarify open issues, raise new questions in relation to the idea, or reformulate parts of the idea in new terms. While elaborators can suggest new uses for the scientific innovation, they do not themselves motivate a separate line of inquiry, nor do they lead to the formation of new specialities. Rather, they contribute to the innovation's clarification and its conceptual, theoretical, and/or empirical development so that later contributions can draw on it once others have been convinced of its general usefulness.

Scientific innovations are ultimately taken up in specialized areas. This is realized by *specialist* contributions. *Specialists* contribute to what Kuhn (1962) referred to as 'normal science.' They address clearly defined research questions that tackle field-specific problems in their respective specialty. Therefore, specialist contributions adopt a scientific innovation only when it has already been modified in such a way that its usefulness has been established within their community. For instance, RCT became applied in specialized subfields of economics, sociology, psychology, political science, organization theory, and biology, among others (Erickson, 2010) only once scholars recognized their benefits for solving specific problems in those fields.

A scientific innovation spreads into specialties via *translator* contributions. Translators connect elaborator contributions to specialized research fields by and make the innovation accessible, relatable, and applicable to specialist research outside of the domain in which it originated. This requires what Collins and Evans (2007) have referred to as "interactional experts", that is, scholars who have the ability to converse in disciplinary languages other than their own. Translators accomplish this because they are closely connected to their specialty and reach the specialists. For instance, before sociologists and psychologists began using RCT, it required translators from both fields who were well-versed in mathematics without being mathematicians themselves.

This general role typology captures the main characteristics of scientific innovations, it reveals the conditions under which they diffuse, and thereby offers a characterization of the diffusion process. The four roles capture the core modification steps that are required for scientific innovations to overcome Kuhn's essential tension. Elaboration, translation, and specialization are each preconditions for the diffusion of a scientific innovation. Translators, in particular, reflect and absorb the essential tension, as they establish a bridge between the elaborated innovation and specialist subfields of inquiry. They make a substantially novel contribution while aligning the original idea with the expected methodological and epistemic principles of their specialty. As such, successful translator contributions enable the spread of the innovation into specialist fields. Table 1 summarizes the four types of contributions that are needed for a scientific innovation to spread across research fields.

Detailed knowledge of the innovation allows for a qualitative assessment of the status of later publications vis-à-vis the original. Did subsequent contributions elaborate on core themes Or did they translate the innovation and facilitate its spread into newly-forming or preexisting research fields? In our study of the early diffusion of RCT, we used network analysis to systematically identify elaborator, translator, and specialist contributions from their positions in a co-citation network of publications that are cited together with the *Theory of Games* (cf. Herfeld & Doehne, 2018 for details). While this allowed us to identify and characterize each role in a systematic and generalizable way, it would in many cases also be feasible to identify elaborators, translators, and specialists from archival materials, interviews, or field observations.

Table 1
Characterization of the Role Typology

Role	Innovator	Elaborator	Translator	Specialist
Function	Formulates a novel idea	Explicates and clarifies the original idea Contributes to the spread of the idea but does not relate to a particular field of inquiry	Reformulates the idea and makes it accessible to specialist research Resolves the essential tension confronted by the initial idea	Addresses field-specific questions using translated versions of the initial idea

This framework exemplifies the benefits of pursuing an integrated approach to the study of scientific innovations. It draws on philosophy of science to explicate the concept of a scientific innovation and to draw attention to the essential tension that is inherent to the diffusion of scientific innovations. A classification of how particular scholars and their works contributed to the subsequent modification and diffusion of the original idea requires detailed historical and sociological accounts of the processes involved. The task of tracing the diffusion process and classifying subsequent works in terms of their contributions benefits from diffusion studies originating in the sociology of science. As such, the role typology that is summarized in Table 1 is informed by methods from philosophy-, history-, and sociology of science. It serves as a general classification scheme of scientific contributions in the study of scientific innovations. As such, it captures the essential features of the modification process that are characteristic of scientific innovations.

EMERGING TRENDS SUGGEST AN INTEGRATED APPROACH

What do we gain from studying the diffusion of scientific innovations in an integrated way? We suggest that a framework that integrates methodological and conceptual aspects is needed to systematically examine the conditions under which knowledge in general, and scientific innovations in particular, spread. One might argue that disciplinary separations, the strong fragmentation, and reinforcement of the division of cognitive labor cannot be easily overcome. However, we see reason to be optimistic about meeting this challenge. In each of the three disciplines, the history-, sociology-, and philosophy of science, emerging trends in the methods being used point toward a relaxing (or shifting) of disciplinary boundaries. Moreover, we contend that the conceptual and methodological contributions in each of the three fields stand

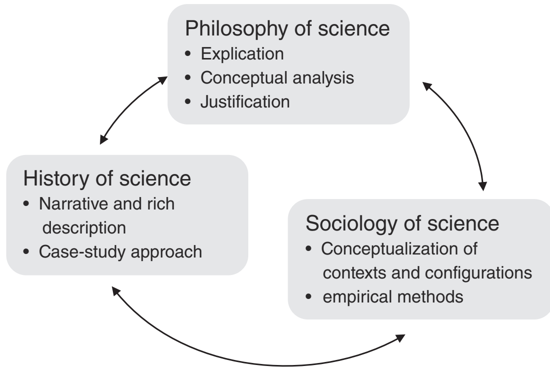

Figure 2 Benefits of an integrated approach on the methodological and conceptual level for philosophy-, history-, and sociology of science.

to enrich the others when studying scientific innovations and their diffusion.[1]

As regards the first reason, we observe that the adoption of new methods is resulting in an (unintended) methodological convergence of the three fields. While generalization about the three fields is misplaced, we note an growing overlap between, and compatibilities among, new methods and instruments being drawn upon in each discipline. This emerging body of work, which draws on simulation methods, quantitative empirical analyses, and increasingly large datasets, speaks to a careful recalibration of longstanding disciplinary divides (Bearman, 2015; Claveau & Gingras, 2016; Herfeld & Doehne, 2018; Klein, Marx, & Fischbach, 2018). The observed use of such methods across disciplines indicates that the involved researchers are less concerned with upholding disciplinary boundaries than with answering pressing questions in their fields. Figure 2 offers a schematic of how scholars in each field stand to benefit from acknowledging the efforts of the other two disciplines respectively.

Some parts of history of science are increasingly characterized by a focus on offering "rich, thickly descriptive, local studies" that emphasize not primarily the ideas and discoveries of great thinkers but the scientific practices that scientists engage in (Lightman, 2016, p. 1). To study different forms of knowledge, how knowledge is constructed in specific contexts, as well as how and why knowledge circulates, historians of science increasingly engage with scholarship from a variety of fields. Some overlap with science studies and the sociology of science is indicative for this. Complementing historical case studies with formal methods such as network analysis, simulation,

1. A large literature in science studies has made contributions toward an integrative approach. While we generally favour this literature, our suggestion is less comprehensive in that we emphasize methodological and conceptual integration.

and data analysis can further substantiate historical case studies (Bearman, Moody, & Faris, 2002). Along these lines, historical episodes in science are being studied by modeling the configurations in which innovations occur (Claveau & Gingras, 2016; Herfeld & Doehne, 2018; Klein *et al.,* 2018; Wright, 2016).

In social epistemology and philosophy of science as well, there is an emerging trend toward using qualitative and quantitative methods from the social sciences and ethnography (Mayo-Wilson, Zollman, & Danks, 2011; Nersessian, 2012). Increasingly, philosophers of science draw upon formal modeling tools from decision and game theory, along with simulation techniques, to study the dynamics and structures of scientific communities (Alexander, Himmelreich, & Thompson, 2015; O'Connor & Bruner, 2017; Weisberg & Muldoon, 2009; Zollman, 2013). While these studies generally justify the roles that scientists occupy in a community on the basis of plausibility considerations, those roles and their impact on outcomes are seldom justified empirically.

Martini and Pinto (2017) have argued that the models being espoused by philosophers of science are too far removed from the empirical reality that they are intended to illuminate. They point out an empirical challenge that future research in philosophy should strive to connect models with their target systems by testing them against data. Similarly, Crupi and Hartmann (2010) have argued that empirical methods can complement formal methods. Turning to sociology- and history of science seems a natural step forward for philosophy of science. Not only would empirical approaches inform philosophical assumptions and concepts. Integrated studies allow for generalizations and conceptual contributions (e.g., the role typology) that inform explication and conceptual analysis in philosophy.

As they turn to bibliometric and other publication-related data (e.g., Web-of-Science) to study scientific innovations, sociologists of science stand to benefit from the work of historians- and philosophers of science. From the historian of science, they can obtain not only the detailed historical knowledge that is needed for casing their analyses but also a finer understanding for idiosyncratic and context-specific features that are relevant to the particular case at hand. Moreover, historical accounts stand to enrich, complement, and validate analytically derived findings. For our own study of the early spread of RCT, for example, we relied on detailed historical accounts and knowledge of the early diffusion process as a baseline for assessing the validity of the empirically derived diffusion measure. Only by comparing our findings with the detailed historical accounts of the period were we able to interpret our findings and assess their validity. Moreover, as sociologists of science turn to the task of evaluating the effects of institutional configurations on publication output and success, philosophers of science can offer normative criteria for appraising ongoing developments. Furthermore, sociologically informed analyses of large data repositories call for conceptual precision and careful explications of the key concepts used in their analyses, particularly as they relate to the justification of normative claims. Philosophers of science can contribute towards achieving both.

OUTLOOK

An integrated approach to the study of scientific innovations and their diffusion allows for a more comprehensive understanding of scientific innovations and the mechanisms underlying their diffusion. On the basis of such an integrated analysis, science policy makers can implement the conditions necessary for scientific innovations to occur where desired; they could design research environments conducive for the development of scientific innovations and for their successful adoption. This is important, as current incentive structures are often counterproductive to basic research or to elaborating on novel ideas of which the impact and success is uncertain. As large funding schemes want to ensure innovative research, project evaluations should also be in proper conceptual foundations and an adequate definition of scientific innovations.

While we suggest that emerging methodological trends in all three fields are conducive to overcoming disciplinary barriers, this methodological and conceptual integration remains to be explicitly fostered within and across those disciplines. Furthermore, general frameworks stand to be validated by applications to a variety of contexts and empirical tests. The framework we have presented here, for example, remains to be applied to other scientific innovations in the natural and social sciences. Promising examples include the early diffusion of Feynman diagrams, bioevolutionary theory, the Lotka–Volterra model, or the prisoner's dilemma. These representations, theories, concepts, and models have been recognized as successful instances of novel ideas and have spread widely within and across fields. Examinations of the early diffusion of these scientific innovations can reveal the extent to which they, too, spread through a process of elaboration, translation, and specialization, as the model we have presented suggests.

A wider application of the role typology and the concepts it introduces will inform further explication of the roles that scientists and/or their contributions occupy in the diffusion process. By offering fine-grained micro-analyses of the processes involved in elaboration, translation, and specialization, historical and sociological analyses help to further specify the definition of the concept of scientific innovations in the first place, a conceptual gap in the literature that needs to be filled. As one example, Lisciandra and Nagatsu (forthcoming) examine why translation of the expected utility principle enabled its diffusion into psychology while the absence of translation prevented the game theoretic concepts of von Neumann and Morgenstern from spreading widely into psychology. Future research should aim at a richer and more complete understanding of the diffusion of scientific innovations by combining a case-study approach from the history of science with conceptual contributions from philosophy of science and empirical methods from the sociology of science.

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